SECTION 6

AMPLIFIER CIRCUITS

PART A. ELECTRON-TUBE CIRCUITS

AUDIO AMPLIFIERS.

APPLICATION.

The audio amplifier is used to amplify input signals whose frequency limits fall within the range of audio frequencies, which are approximately 30 to 15,000 cycles per second.

CHARACTERISTICS.

Input may be an audio signal of extremely small amplitude, *which is to be amplified in amplitude, or it may be of* considerable amplitude, which is to be amplified in power.

Input impedance may be high, medium, or low, depending upon the type and application of the audio amplifier.

Output impedance may be high, medium, or low depending upon the load to which the amplifier furnishes its output signal.

Output signal amplitude may be many times greater than input signal amplitude, if the application is intended for voltage amplification, or it may be only a few times greater than the input, if intended for power amplification. Expressed as voltage gain, the gain may be high for a voltage amplifier, or it may be low for a power amplifier.

Grid bias is such that plate current flows for the entire input cycle, in single-ended circuits, and grid current does not ordinarily flow during any part of the input cycle.

Grid bias may be of such value, in push-pull circuits, that plate current does not flow when no input signal is applied, and flows only during one half of the input cycle of signal voltage when an input signal is applied to the grid.

Frequency response is approximately linear over the range of audio frequencies which comprise the intended bandpass of the amplifier. However, this does not imply that all audio amplifiers have a linear response over the entire audio-frequency range of 30 to 15,000 cps. Some applications of audio amplifiers purposely restrict the bandpass to a very narrow segment of this range, in order to accomplish their intended use.

Output (plate) signal and input (grid) signal are of opposite polarity.

CIRCUIT ANALYSIS.

General. The audio amplifier is a circuit arrangement, composed of a tube or tubes and associated components, which is intended to amplify an a-c signal whose frequency or composite frequencies fall within the audio range, usually considered to extend from 30 to 15,000 cycles per second. This does not mean that all audio amplifiers will amplify all frequencies within this range. Only one particular application — that of the so-called "high-fidelity" audio amplifier — is designed to accommodate the entire range, and amplify all frequencies within the range equally well. *Amplifiers in many of the other applications are designed* to amplify only portions of the audio range. Specifically, any amplifier that amplifies an input signal whose frequency lies between 30 and 15,000 cps — whether the input signal consists of only one particular frequency or a multitude of frequencies — may be classed as an audio amplifier. This point should be borne in mind, because in some piece of equipment a circuit may be encountered which is referenced as an audio frequency amplifier, but which actually handles no "audio" intelligence in the sense that it is *both within the range of audibility and is intelligible to the* human ear. For illustration, the frequency-shift system of transmitting teletype information on a radio-frequency channel utilizes an audio frequency amplifier to raise the audio level of two specific frequencies — one for the "mark" and the other for the "space" in a teletype character — before these frequencies are converted to r-f signals for transmission. *In this case the audio amplifier is required to am*plify only two frequencies, such as 85 cycles and 170 cycles. Additional circuits may be included to actually restrict the response of the amplifier to a narrow range, such as from 30 to 200 cycles, in order to pass only the two frequencies mentioned above. Yet this amplifier is termed an audio amplifier.

Circuit Operation. Audio amplifiers may be divided into two general classifications: voltage amplifiers and power amplifiers. In each of these divisions there are several circuit configurations, each of which may utilize one or more different types of vacuum tubes: triodes, tetrodes, pentodes, or beam power tubes.

The specific characteristics and circuit operation of several configurations in each division are contained in the seven circuits to follow in this section. A brief discussion covering audio amplifiers in general is given in the following paragraphs.

In a voltage amplifier, the primary consideration is the ratio of the alternating output voltage obtained from the plate circuit to the alternating input voltage applied to the grid circuit to produce the output voltage. This ratio is termed the **gain** of the amplifier. The amount of power which is available in the plate circuit is both minute and incidental — the increase in signal voltage is the prime concern. In order to produce the largest possible output signal voltage, which is taken across the plate load, the impedance of this plate load must be as large as practicable.

In a power amplifier, the primary consideration is the delivery of a large amount of power to the load in the plate circuit. Since power is equal to voltage times current, generally speaking, a power amplifier must develop a sufficient voltage across its load to cause the required current to flow. The value of the load impedance is an important factor, because it will govern, to a large degree, the amount of current which will flow with a given voltage. The value of the load impedance is *selected for one of two conditions at a* given minimum allowable level of distortion: maximum plate efficiency or maximum power output. Plate efficiency is the ratio of output power to the d-c input power to the plate, and it is generally low in an amplifier which is designed for minimum distortion. When distortion is permissible, plate efficiency may be relatively high. For a triode, *maximum* power output with minimum allowable distortion occurs when the load impedance is equal to twice the triode's plate resistance.

The circuit used in both a voltage amplifier and a power amplifier may be one of several types: resistance-capacitance coupled, impedance coupled, transformer coupled, or direct coupled. Each type has certain advantages and disadvantages, which adapt it to specific applications. A resistance-capacitance audio amplifier is probably the most widely used type, with its components relatively inexpensive and their weight relatively light. Its frequency response can be designed to be uniform over the entire audio range. Probably its only disadvantage is the somewhat higher power supply voltage, required for the plate circuit, than is demanded by the transformer-coupled and impedance-coupled types.

An impedance-coupled audio amplifier utilizes an inductor in place of the load resistor used in the conventional resistance-capacitance coupled circuit. A large value of inductance is used, to obtain a maximum amount of amplification --particularly at the lower audio frequencies. The amplification is not uniform over the audio range because the load impedance of the inductor varies with frequency, in accordance with the relationship:

$$Z_L = \sqrt{R^2 + (2\pi\ fL)^2}$$

where: Z_L = load impedance (ohms)
R = resistance of inductor (ohms)
f = audio frequency (cycles)
L = inductance of inductor (henries)

The amplification is higher than in the resistance-capacitance coupled circuit with the same plate supply voltage, because the relatively low d-c resistance of the inductor contributes to a higher voltage at the plate.

A transformer-coupled audio amplifier presents its particular advantages and disadvantages. The advantages include a greater value of voltage amplification than is obtainable in any of the other circuit types; direct-current isolation between the output plate and the grid of the following stage without the need for a blocking capacitor; higher plate voltage at the tube because the input (primary) winding of the transformer has far less d-c resistance than a plate load resistor; and — possibly the greatest advantage — providing a means of coupling from a low-impedance source to a high-impedance load, or vice versa. Its disadvantages include greater cost, additional weight, greater space requirements, additional shielding requirements, and a generally non-uniform frequency response, especially at both high and low audio frequencies.

A direct-coupled audio amplifier has the distinct advantage of distortionless amplification, when the operating voltages are properly adjusted for Class-A operation. Its response is uniform over a wide frequency range, especially at the low frequencies — and even to zero frequency (direct current). Its practically instantaneous response allows an absolute minimum value of phase distortion, making it especially useful in the amplification of square-wave pulses, such as are used in teletype communications. Its chief disadvantages are the complexity of the resistance network that is required to obtain the proper plate and grid voltages for each stage and the tendency toward instability of operation, as well as the successively higher voltages required to operate the second and any succeeding stages.

FAILURE ANALYSIS.

No Output. The circuits of audio amplifiers present widely varied configurations, depending upon their mode of coupling and their application. In general, the cause of a no-output condition may be due to a defective tube, the failure of the voltage source which supplies the d-c potentials to the tube, the failure of the input signal, or a discontinuity in the coupling circuitry. If the tube has been found to be capable of operation, the presence of sufficient d-c voltage at the plate terminal of the tube should be checked. Should no voltage be present, the plate load may be open-circuited. In the case of resistance-capacitance coupling, this would be the plate resistor. If transformer coupling or impedance coupling is used, the transformer or inductor may be open-circuited. The cathode circuit should also be checked for an open cathode resistor, as this defect would produce a no-output condition. If the input signal has been checked and found to be present and of sufficient amplitude, and the trouble persists, the cause of faulty operation must be located in the coupling circuitry. An open coupling capacitor, or a "short" in the grid circuit which bypasses the input signal to ground, could be the cause of no output.

Reduced or Unstable Output. A reduced value of output or instability in an audio amplifier could result from a defect in almost any component in the circuit. Assuming that an input signal of sufficient amplitude is present at the input to the circuit, a likely cause of decreased output may be a tube having poor cathode emission, due to age or overloaded operation. An increase in the resistance value of the plate load resistor or the cathode resistor, resulting from overheating during operation, would decrease the plate current, thereby decreasing the output, with a given input signal. If the cathode resistor increased in resistance, the grid bias would also be increased, further decreasing the plate current. A change in the value of the grid resistor may affect the loading of the previous stage, and possibly reduce or distort the output signal. A leaky or shorted input coupling capacitor may allow a positive potential from the output of the previous stage to be applied to the grid of the audio amplifier, biasing the grid to cause increased conduction of plate current and possibly cause grid current to flow, resulting in a distorted output and possibly grid limiting. A leaky or shorted output coupling capacitor, if used, may have a similar degrading effect upon the signal input to the following stage. If the circuit contains a cathode bypass capacitor, and the capacitor became shorted, the audio amplifier would operate at zero bias, with a substantial increase in plate current and possible distortion on the positive input peaks due to saturation or grid current limiting. If the cathode bypass capacitor became open, a reduced value of output signal, without distortion, would be obtained because of degeneration in the circuit. A reduced value of output signal may also be due to a low plate supply voltage, which in turn may be the result of a defective power supply.

R-C COUPLED TRIODE AUDIO VOLTAGE AMPLIFIER.

APPLICATION.

The R-C coupled triode audio voltage amplifier is used to increase the amplitude of an audio-frequency signal voltage when uniform gain is required over the entire audio spectrum and when a medium value of gain (between 5 and 70) is required. It is generally used to amplify low-level signal inputs, such as those generated by an audio oscillator circuit or by a microphone, vibration pickup, or magnetic tape pickup. It commonly appears in the audio section of communications receivers and transmitters, in sonar equipment, and in applications which utilize signal frequencies in the audio-frequency range instead of aural intelligence.

CHARACTERISTICS.

Input is normally an audio-frequency signal of extremely small amplitude.

Input impedance is normally very high, ranging from several thousand ohms to several megohms.

Output impedance is usually high, ranging from several thousand ohms to approximately half a megohm.

Voltage gain ranges from 5 to 70, depending upon the application and circuit design.

Operates Class A; no grid current flows under any conditions.

Frequency response is linear over the range of audio frequency for which the amplifier is designed. This may include the entire audio range, or may be restricted to a portion of it, depending upon the intended application of the amplifier.

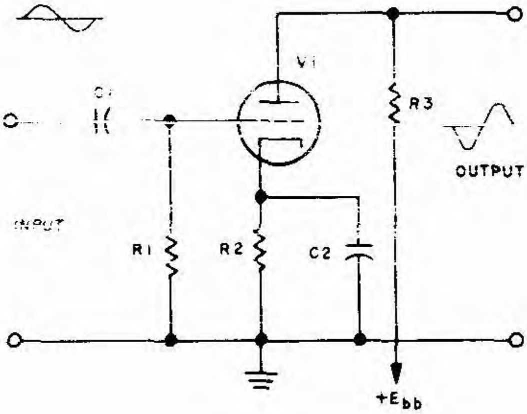
Output (plate) signal and input (grid) signal are of opposite polarity.

Cathode bias (self-bias) is normally used; fixed bias may be used in some applications.

CIRCUIT ANALYSIS.

General. The R-C coupled triode voltage amplifier circuit is one of the most widely used circuits in audio-frequency amplification. It has the advantages of being the least expensive, having the lightest weight components, having good fidelity over a wide frequency range, and being relatively free from undesirable currents induced by stray fields and a-c heater wiring. Probably its only disadvantage is the higher plate supply voltage as compared to that of a transformer-coupled or impedance-coupled circuit; the higher voltage is required to compensate for the voltage drop across the plate load resistor.

Circuit Operation. The R-C coupled triode audio voltage amplifier is used to amplify and reproduce, without distortion, input signal voltages of audio frequency which are applied to the grid of the triode tube. The circuit of a typical amplifier of this type is shown in the following illustration. In this circuit the input signal is applied to the grid of triode V1 through coupling capacitor C1. The grid is returned to ground through grid resistor R1. Cathode bias is furnished by means of cathode resistor R2, which is bypassed by capacitor C2 to maintain the bias at a constant average value and thus prevent degeneration. Plate voltage is furnished from the plate power supply, E_{bb} through plate load resistor R3. In some circuits, especially where several stages of amplification are utilized, an additional resistor may be used, connected in series between the plate load resistor and E_{bb}, with a capacitor connected from the junction of the two resistors to ground, to form a decoupling circuit. This addition prevents the possibility of audio feedback (and its result--oscillation) from an output stage or one operated at a high audio level, back to an input or low-level stage through the power supply, E_{bb}, which could act as a means of common coupling.

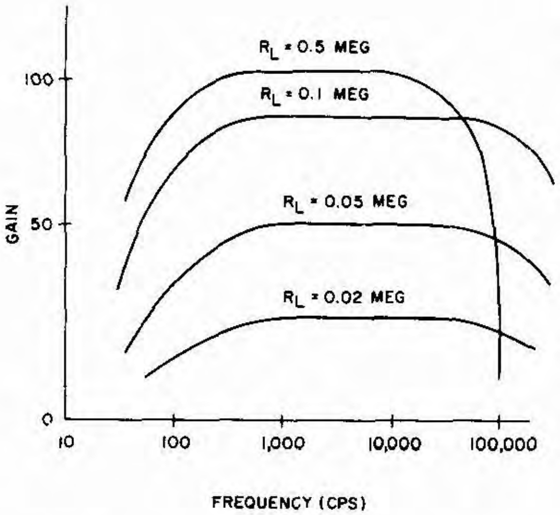


Typical R-C Coupled Triode Audio Voltage Amplifier Circuit

In order to obtain a high value of audio output voltage (a high signal voltage), the resistance value of the plate load resistor should be as high as possible. But this requirement imposes an additional one, because an increase in the resistance of the plate load will cause an increase in the voltage drop across it, resulting in a decrease in the actual voltage at the plate of the triode. In order to obtain the required effective plate voltage, with an increased resistance of the plate load, the only solution is to increase the plate supply voltage, E_{bb}. However, there is a practical limit to the amount by which the plate voltage may be increased. The maximum voltage obtainable from the plate power supply and the voltage rating of the bypass capacitors in the plate supply circuit both serve to establish this limit.

A frequency response curve for a typical R-C coupled triode audio voltage amplifier is shown in the following illustration. It may be seen, from the illustration, that the amplification decreases at both high and low frequencies.

As the frequency increases toward the high end of the response curve, amplification falls off because of the shunting effect of the combination of output capacitance of the stage, the distributed capacitance of the coupling network, and the input capacitance of the following stage. These all act to shunt the higher frequencies to ground. As the frequency decreases toward the low end of the response curve, the amplification also falls off. In this case the reduced gain is caused by the increase in reactance of the coupling capacitor as the frequency decreases, and is also caused by the increase in reactance of the cathode bypass capacitor, which introduces degeneration at the lower frequencies.



Frequency Response of an R-C Coupled Triode Audio Voltage Amplifier With Various Values of Plate Load Resistance

An R-C coupled triode audio voltage amplifier can be designed to give a good frequency response for almost any range of audio frequencies. For instance, an amplifier can be built to give uniform amplification for audio frequencies from 100 to 20,000 cycles per second. By changing the values of the coupling capacitor and the load resistor, the frequency range can be extended to cover the very wide frequency range of the video amplifier. However, this extended range may be obtained only at the cost of reduced amplification, or gain, over the entire range. This may be observed by referring to the previous illustration; it will be seen that the output response is relatively flat from approximately 100 cycles to well over 10,000 cycles when the value of the load resistor, R_L is 0.02 megohm, but the over-all gain is relatively low compared to that obtained using higher values of plate load resistance. Thus, the R-C coupled triode audio voltage amplifier may be made to give a good frequency response over the entire audio range, at medium values of amplification.

FAILURE ANALYSIS.

No Output. A no-output condition in an R-C coupled triode audio voltage amplifier may be caused by any one of several defects. First, the presence of an input signal at the input to the amplifier should be verified. The triode tube should be checked to insure that it is capable of operation. The presence of plate voltage at the plate of the triode should be checked; if no voltage or a very low voltage is present, a defective plate load resistor or a defective plate power supply is indicated. If the voltage at the cathode is very high-approximately equal to the plate supply voltage, E_{bb} -an open cathode resistor may be the cause of no output, assuming that the plate load resistor and the triode have been both found in an operable condition. Finally, an open input coupling capacitor may be the cause of a no-output condition.

Reduced or Unstable Output. Reduced or unstable output from an R-C coupled triode audio voltage amplifier may be due to an aging tube having poor cathode emission, a reduced value of plate voltage due to a defective plate power supply, or an input signal of insufficient amplitude. An open grid resistor would cause severe distortion, greatly reduced output, and possibly intermittent operation due to "grid blocking". If the input coupling capacitor were leaky, distortion would be present in the output signal as a result of the presence of a positive value of voltage at the grid, from the plate of the previous stage supplying the input signal. A reduced value of output, without distortion, may be caused by an open cathode bypass capacitor, which would introduce degeneration into the circuit. An excessive value of bias, caused by too high a value of cathode resistance (or too high a value of bias voltage if a fixed bias is applied), would also be responsible for an output signal of reduced value.

R-C COUPLED PENTODE AUDIO VOLTAGE AMPLIFIER.

APPLICATION.

The R-C coupled pentode audio voltage amplifier is used to increase the amplitude of an audio-frequency signal voltage when uniform gain is required over the entire audio spectrum and when a high value of gain (up to approximately 350) is required. It is used to amplify extremely low-level signals, where a high gain per stage is required and the number of stages which can be accommodated is limited.

CHARACTERISTICS.

Input is usually an audio-frequency signal of extremely low amplitude.

Input impedance is very high, usually greater than 0.1 megohm.

Output impedance is high, and as a rule is considerably higher than that of a triode amplifier.

Voltage gain is much higher than that of a triode ampfier, ranging from 100 to 350.

Operates Class A; no grid current flows under any conditions.

Frequency response is linear over the range of audio frequencies for which the amplifier is to be used.

Output (plate) signal and input (grid) signal are of opposite polarity.

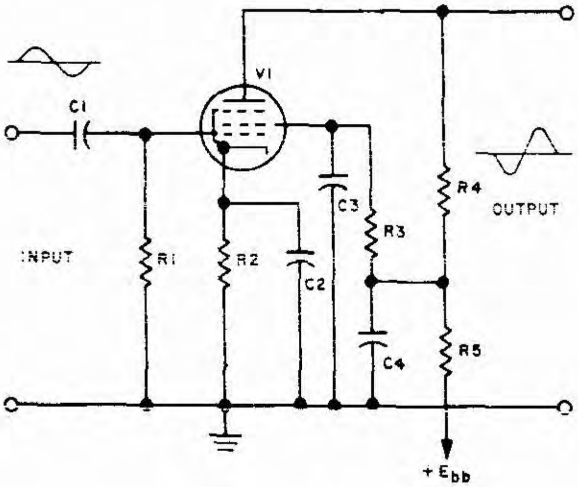
Cathode (self) bias is normally used; special applications may require the application of fixed bias.

Harmonic distortion in the output signal is lower, for the same value of output signal voltage, than that of a triode amplifier.

CIRCUIT ANALYSIS.

General. The R-C coupled pentode audio voltage amplifier is widely used as the input stage in a high-gain amplifier assembly, where the value of the signal input voltage is extremely low. Because its input impedance is high, it can accommodate inputs from various high-impedance, sources by direct connection, without the necessity of impedance-matching transformers to effect the connection. Such sources include crystal and high-impedance dynamic microphones, crystal vibration pickups (including phonograph pickups), and magnetic tape heads. The gain per stage of a pentode amplifier is much higher than that of a triode, and the pentode amplifier produces an output signal voltage of considerably greater amplitude than that of a triode when operated at the same plate supply voltage, E_{bb}. The total harmonic distortion contained in the output of a pentode audio amplifier is less than that of a triode audio amplifier for a given value of output (signal) voltage.

Circuit Operation. The R-C coupled pentode audio voltage amplifier is used to amplify, to a high value, an input signal within the audio-frequency range, and reproduce the original waveform without appreciable distortion. The circuit of a typical amplifier of this type is shown in the following illustration. In this circuit the input signal is applied through coupling capacitor C1 to the grid of the pentode, V1. The grid is returned to ground through grid resistor R1. The pentode is operated with self-bias, with the bias being supplied by means of cathode resistor R2; the resistor is bypassed by capacitor C2 to maintain the bias at a constant average value, thereby avoiding degeneration of the amplified signal. Plate and screen voltages are supplied from the plate power supply, E_{bb}, through decoupling resistor R5 bypassed by capacitor C4, with R3 serving as the screen dropping resistor bypassed by capacitor C3 and with R4 serving as the plate load resistor. The decoupling circuit, composed of R5 and C4, serves to prevent feedback at an audio rate from the output (plate) of V1, back through the low impedance of the power supply to the plate of the previous tube, which furnishes the input signal to the grid of V1.



Typical R-C Coupled Pentode Audio Voltage Amplifier Circuit

An example of the use of this circuit is its application as a servo preamplifier. With a type 5840 pentode used for V1, a plate voltage supply E_{bb} of 250 volts dc, and an input signal of 400 cycles, the circuit affords a voltage amplification of 70 when the following component values are used: R1, 1 megohm; R2, 3.3K; R3, 1.5 megohm; R4, 470K; R5, 220K; C1, 0.01μf; C2, 30μf; C3, 0.1μf; and C4, 16μf.

The pentode tube used in the R-C coupled pentode audio voltage amplifier has a much higher plate resistance than a triode tube; because of this fact, the resistance value of the plate load resistor has a considerable influence on the amplification of the higher frequencies, especially at the upper frequency limit of the designed bandpass. At the lower frequency limit, however, the output coupling capacitor to the following stage may have a somewhat lower capacitance value than in a comparable triode amplifier circuit, and still maintain the same low-frequency response. The effect of the value of the plate load resistor upon the frequency response, or bandpass, of the amplifier may be generalized: with a plate load of 100K, the high-frequency limit is approximately 25,000 cycles per second, while a plate load of 500K gives a high-frequency cutoff in the neighborhood of 5000 cycles. Since 25,000 cycles is far beyond the normal response range of an audio-frequency amplifier, a more realistic high-frequency limit of 10,000 cycles may be obtained by using a plate load resistance of 250K.

From the above discussion it appears that, as the plate load resistance is made lower and lower, the high-frequency cutoff limit becomes higher and higher, and that it would therefore be advantageous in any case to use a low value of plate load resistance. While this is true, a low value of plate load resistance has probably a greater disadvantage: the output signal will have a low amplitude. Therefore, in order to obtain sufficient output signal voltage (amplitude), the value of the plate load resistance must be a compromise between output voltage versus high-frequency response.

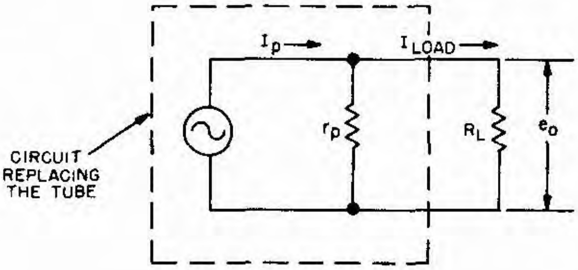
In connection with the use of a pentode as a voltage amplifier, the equation $I_{load} = e_g g_m$ is often used. This expression, along with an equivalent circuit, can be derived from the equation for output voltage, e_o:

$$e_o = -\mu e_g \frac{R_L}{r_p + R_L}$$

By substituting for μ the relationship $\mu = r_p g_m$, we have:

$$e_o = e_g \, g_m \frac{(r_p \; R_L)}{(r_p + R_L)}$$

The terms in parentheses will be recognized as the total resistance of a parallel circuit of r_p and R_L. Hence, the expression suggests the equivalent circuit shown below. As long as the load is purely resistive, this circuit gives exactly the same results as the original equivalent circuit. If the load is reactive, however, an error is introduced in calculations of phase shift unless the plate resistance r_p is large compared to R_L (with pentode tubes r_p is often very large compared to R_L). When this is true the parallel branch r_p can be neglected, and the load current is equal to $- e_g \, g_m$. This speeds up calculations and is especially useful for pentode tubes when their values of r_p and μ are not accurately known.



Equivalent Circuit of a Pentode Voltage Amplifier

FAILURE ANALYSIS.

No Output. If an R-C coupled pentode audio voltage amplifier is defective in that no output is produced, the input signal source should first be checked to see that a signal of proper amplitude is present at the input terminals of the amplifier. The pentode tube should also be checked to insure that it is capable of operation. Plate and screen voltages at the tube socket terminals should then be measured, to determine whether the voltages are of the proper value. If no voltage is present at either the plate or the screen, the plate voltage power supply (E_{bb}) may be defective in that no output is being furnished. Another possible cause may be an open decoupling resistor R5, a shorted capacitor C4, or an open cathode resistor R2. If plate voltage is present but screen voltage is not, screen dropping resistor R3 may be open-circuited or screen bypass capacitor C3 may be shorted. On the other hand, if screen voltage is present without plate voltage, an open plate load resistor R4 is indicated. If, however, both plate and screen voltages are normal and no output is obtained, an open input coupling capacitor C1 could be the cause of the trouble.

Reduced or Unstable Output. If the R-C coupled pentode audio voltage amplifier is defective in that a reduced value of output or instability is evident, the input signal should be checked to see that it is of sufficient amplitude, yet not of excessive amplitude that would overload the amplifier stage. If the input signal is present and has normal amplitude, the trouble may be due to a leaky coupling capacitor C1, which might allow a positive voltage from the preceding stage to be impressed on the grid of V1, thereby introducing distortion. An open or extremely high resistance grid resistor R1 would tend to cause intermittent operation ("motorboating"); if this condition prevails, the grid resistor should be replaced. A reduced value of output could also be caused by an open cathode bypass capacitor C2 or by an open screen bypass capacitor C3, either of which would cause the circuit to be degenerative. Another cause of low output could be an open screen resistor R3, which would make the tube attempt to operate with plate voltage but without screen voltage. A decreased value of screen voltage, due to a leaky screen bypass capacitor C3, could cause low output. A decreased value of plate and screen voltage, due to a defective power supply E_{bb}, could likewise be responsible for low output. Finally, there is a remote possibility that low heater (filament) voltage, brought about by a loose connection or an overloaded circuit, may be the cause of a low value of output.

IMPEDANCE-COUPLED TRIODE AUDIO VOLTAGE AMPLIFIER.

APPLICATION.

The impedance-coupled triode audio voltage amplifier is used to increase the amplitude of an audio-frequency signal where wideband response is not desired, and higher gain than that of the wideband amplifier is desired.

CHARACTERISTICS.

Frequency response is linear over a small band of frequencies, for example from 200 to 10,000 cps, depending upon the design.

Input is normally an a-f signal of small amplitude.

Input impedance is high, usually more than 50,000 ohms.

Output impedance is high (on the same order as the input), and is suitable for cascaded stages or magnetic output devices requiring little power.

Output signal is inverted in polarity from that of the input signal.

Operates class A biased; no grid current flows under normal conditions.

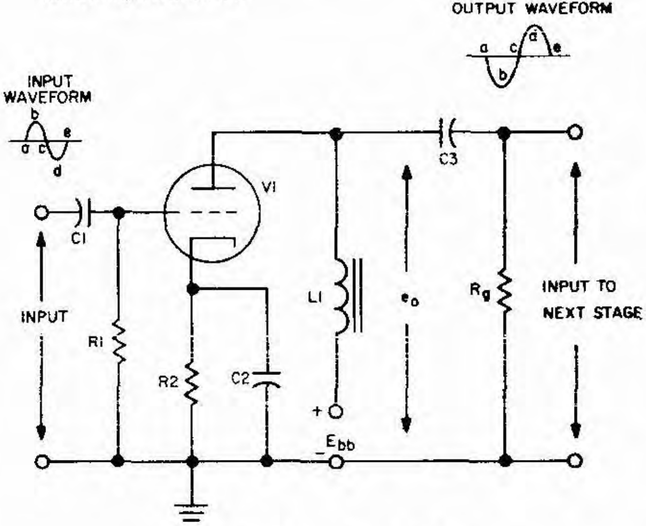
Cathode (self) bias is normally used, but fixed bias may be used in certain applications.

Requires less plate voltage than that of an equivalent R-C-coupled amplifier to produce an equivalent output. In this respect it is similar to the transformer-coupled amplifier.

CIRCUIT ANALYSIS.

General. The impedance-coupled triode audio voltage amplifier resembles an R-C-coupled audio amplifier (previously discussed), except that an iron-core inductance (choke), instead of a resistor, is used as the plate load. It is sometimes referred to as a **choke-coupled** amplifier. Because the choke acts as a *reactance at a-c frequencies,* the impedance determines the drop across the plate load. However, since the d-c resistance of the choke coil is low, only a small d-c voltage drop occurs across the choke. As a result, a much lower plate supply voltage can be used to provide the same effective plate voltage (as compared with an *R-C* amplifier).

Circuit Operation. The schematic of a typical impedance-coupled triode audio voltage amplifier is shown in the following illustration.



Typical Impedance-Coupled Triode Audio Voltage Amplifier

As can be seen, the input signal is capacitively coupled through C1 to the grid of tube V1. Coupling capacitor C1 and grid resistor R1 form an audio voltage divider. The output of this voltage divider is the voltage which appears across R1, and is the signal voltage applied to the grid of V1. Capacitor C1 also acts as a d-c blocking capacitor to prevent the plate voltage of a preceding stage or any d-c voltage existing in the input circuit from adversely biasing V1. The reactance of C1 to an audio-frequency signal is much smaller than R1; thus little signal is lost across the capacitor. Resistor R2 provides cathode bias through average plate current flow, and capacitor C2 bypasses the resistor to prevent degenerative effects (refer to Section 2, paragraph 2.2.1, of this Handbook for a discussion of cathode biasing). Choke coil L1 is the plate load impedance across which the output voltage, e_o, is developed; L1, C3, and R_g form the impedance-coupling network.

With no signal applied, static plate current flows through cathode bias resistor R2, and provides class A bias. *A plate voltage drop across choke coil L1 is produced by the d-c coil resistance.* This drop is constant, regardless of whether a signal is present; thus it produces no output voltage since it cannot pass through coupling capacitor C3. When a positive-going input signal is applied to the grid of tube V1, it reduces the effective *grid bias, and the plate current increases instantaneously.* Assuming a sine-wave input, as the signal rises the plate current also increases until the positive peak of the input cycle is reached. During this half of the cycle (from point a to point b on the output waveform), a continuously increasing voltage drop (negative swing) occurs across the *load produced by the reactance of L1.* This is *the audio-output voltage* which is applied to coupling capacitor C3. With a positive-going input, a negative-going output is developed by the increasing plate current, which drops the voltage across the impedance offered by choke L1. When the grid voltage reaches the positive crest, the plate voltage *is at a minimum value (point b on the output waveform).* As the grid voltage recedes, plate current decreases. Consequently, the voltage drop across L1 becomes less and less, reaching zero (point c on the waveform) at the completion of the positive half-cycle of the input signal.

As the input signal now swings negative, it adds to *the applied bias produced by normal plate current flow,* and reduces the plate current instantaneously. During the negative-going half-cycle of input signal, the plate current continuously decreases (point c to point d) until the negative crest is reached at point d on the input waveform. During this portion of the half-cycle, the plate voltage rises toward the source voltage and produces the positive-going portion of the output signal. At the negative crest (point d on the input waveform), the input signal is equal to the bias, but cutoff is not reached because the initial bias is less than half of the cutoff value to insure that the tube is operated over the linear portion of its grid-voltage plate-current characteristic curve. At this time to plate voltage is equal to the source voltage less the small d-c drop in the plate choke. As the negative input signal swings positive and returns to the zero level, the plate current continuously increases (since the effective grid bias is reduced), and the voltage drop produces across L1 increases. Plate voltage decreases from the maximum value to the static level (point d to e on the output waveform).

Since the input signal can never exceed the bias voltage without producing distortion by driving the grid positive, it can be seen that the peak input voltage is only on the order of a few volts or less. On the other hand, the plate swing is over a range of 100 to 200 volts, depending upon tube characteristics, supply voltages available, and bias values. Since the plate voltage swing is actually the output voltage which is applied to the coupling capacitor, it is easy to understand how a voltage gain from input to output of 100 or greater can be obtained. Because the output voltage reaches a negative peak when the input voltage reaches a positive peak, and vice versa, at any particular instant of time they are considered to be 180 degrees out of phase with each other. Actually, they are of opposite polarity and of the same phase because the current and voltage are both in phase (at extremely low frequencies there may be an actual phase shift). Since only a voltage output is desired, it is unnecessary to match the load impedance to the tube impedance. In fact, exactly the opposite approach is used; the load impedance is always selected to be much larger than the plate resistance (for a triode) so that the greatest output voltage is obtained. Because both positive and negative plate current swings are identical, assuming a sine-wave input, the average current remains the same and is not affected by the input signal. Therefore, the cathode current can be used to provide a steady self-bias (fixed bias may be used if desired).

For ease of discussion, the frequency spectrum over which the impedance-coupled amplifier operates can be divided into three convenient ranges: low- , middle- and high-frequency. The gain drops off at the low frequencies because the impedance of the choke coil becomes less as the frequency is reduced. To increase the low-frequency response, a large number of turns are used to provide a greater inductance. However, the distributed capacitance produced by a coil winding of many turns creates a large shunting capacitive reactance, which causes a drop in the high-frequency response. Over the middle-frequency range the gain is more uniform. It is limited only by the parallel combination of tube plate resistance, plate choke-coil impedance, and the shunting effect of the input resistance (grid resistor) of the following stage. Generally speaking, the plate choke-coil-impedance over the middle-frequency range is very high as compared with either the tube plate resistance or the input resistance of the next stage; thus maximum gain is obtained. The gain of the impedance-coupled amplifier drops over the high-frequency range mainly because of the large distributed capacitance of the choke-coil turns, which effectively shunts the load to ground and offers a low-impedance path to high frequencies.

FAILURE ANALYSIS.

No Output. A no-output condition could be caused by no input signal, an open-circuited condition, lack of plate or filament voltage, a short-circuited condition, or defective tube. The presence or absence of an input signal can be determined by making an oscilloscope or vacuum-tube voltmeter check at the input. An open-circuited or short-circuited condition can be localized to the defective portion of the circuit by making voltage measurements with a high-resistance voltmeter to determine whether the proper filament, cathode or grid, and plate voltages exist. In many instances open filaments can easily be located by observing that the filament does not light and that the tube feels cold to the touch. Where improper or no voltage exists, check the power supply voltage to determine whether the fault is in the amplifier or in the power supply. If there is normal voltage at the output of the power supply, the trouble is in the amplifier. Lack of plate voltage then indicates a defective plate choke, L1. If the choke is open, there will be no voltage between the plate and ground. If it is shorted, there will be no voltage drop across the choke. If there is a short between the plate and ground, the power supply voltage will be dropped entirely across the choke. Removing the tube will clear the short if the tube is defective; otherwise, it can be assumed that the choke insulation has failed and that there is a d-c path through the core to ground. A short-circuited condition is usually indicated by burning or charring of the parts involved, and sometimes can be easily located by a visual examination. If such an examination does not reveal the trouble, it will be necessary to remove the power, discharge the B+ supply, and then remove the part and make a resistance check on it. A short-circuited condition is indicated by a low resistance between points that normally have a higher resistance.

No output can also be caused by an open coupling (input) capacitor, C1. If the signal is present on the input side (as observed on an oscilloscope) but not on the grid side, either the capacitor is open or the grid side is shorted to ground. Use an in-circuit capacitance tester to determine whether the capacitor is defective. If the trouble is not revealed by this test, it will be necessary to disconnect the capacitor from the circuit and check it with a standard type of capacitance bridge. Output coupling capacitor C3 can also cause a no-output indication if it is open; check it in a similar manner, considering the plate side as the input side and the side connected to R_g as the output side. If all voltages appear normal and still no output is obtained, replace the tube with a tube known to be good. Unless shorted or open-circuited, a defective electron tube will usually cause reduced or distorted output rather than none at all.

Reduced or Unstable Output. Reduced output is usually caused by lack of proper plate or grid voltages; unstable output is often caused by oscillation and intermittent circuit operation. Use a high-impedance voltmeter to check the grid or cathode bias voltage. A low bias voltage will cause a drop in output because heavy plate current causes peak clipping effects and distortion. A high bias will also cause lower output. If cathode bypass capacitor C2 is open, sufficient degeneration will be produced to appreciably reduce the output. Poor joints (soldering, etc) will create a high-resistance condition; if the poor joint is in the plate circuit, lower output will result. A leaky coupling capacitor (C1) will improperly bias the stage, causing a reduction in output. If coupling capacitor C3 is leaky, it will improperly bias the next stage, draw more than normal plate current, and cause a d-c voltage drop in L1; this voltage drop will reduce the effective plate voltage and the output, depending upon the amount of leakage. When normal voltage appears on the tube elements and the output is still below normal, the tube is probably defective. A gassy tube can cause high grid current, thus producing excessive bias with a reduction in output after a short period of operation. Normal output with the set initially operated, followed by a progressively decreasing output shortly thereafter is indicative of such a condition. Replace the suspected tube with a tube known to be good. Circuit oscillation at r-f frequencies will also cause the output to drop and show up as a fuzzy pattern on the oscilloscope. If the oscillation is at audio frequencies, a howl or squeal will be apparent in the output, and will be indicated on the oscilloscope as *as a single frequency.*

Unstable output can result from an intermittently open bypass capacitor in the cathode or plate circuit. Motorboating (oscillation at a very low frequency) is sometimes caused by feedback through improper coupling of the grid and plate circuits or through common impedance coupling in the power supply; this is especially true with high-gain cascaded stages. Feedback through the power supply is usually caused by a defective bypass *capacitor in the B+* line. This condition commonly occurs when electrolytic capacitors age and dry out, thus losing their capacitance gradually.

Distorted Output. Distorted output may be caused by poor frequency response, *the introduction of hum, or improper* grid bias. Distorted output due to poor frequency response is obvious when audible monitoring sources are available. To locate the distrotion, use an oscilloscope and a sine-wave generator to follow the signal path through the circuit. Observing where the waveform departs from normal will indicate the portions of the circuit involved. A square-wave generator may also be used. With a square-wave signal applied, a sloping leading edge indicates lack of high-frequency response, while a sloping flat top indicates lack of *low-frequency response. Since* a square wave is made up of many sine-wave frequencies, the application of a 2000 to 3000-cycle square wave will indicate the relative harmonic response over a range up to 5 to 10 times this frequency. Impedance coupling will normally produce a frequency *response intermediate* between that of resistance-coupled and transformer-coupled stages.

Hum distortion can be observed directly on an oscilloscope. When existing on the power supply leads, it indicates lack of sufficient power supply filtering. If it is not on the power leads, but is evident on the grid, plate, or cathode leads, check for induced hum pickup due to the nearness of grid leads to a-c leads.

Improper bias is also a common cause of distortion; coupled with excessive drive, it causes the peaks or troughs of the voice signal to be clipped off. In a very weak tube, lack of sufficient filament emission can cause distortion on the peaks of amplification because of inability to supply sufficient peak current. *While voltage measurements* will determine whether the grid and plate voltages are correct, an oscilloscope must be used to observe the waveform. A distortion percentage of from 2 to 5 percent is normally considered acceptable in commercial audio amplifiers.

TRANSFORMER-COUPLED TRIODE AUDIO VOLTAGE AMPLIFIER.

APPLICATION.

The transformer-coupled triode audio voltage amplifier is used principally for the development of large a-f voltage outputs with a minimum number of amplifier stages and for phase inversion to drive a push-pull amplifier. The limitations of frequency response *generally restrict* the use of transformer coupling to audio circuits, which do not require an exceptionally wide bandpass or frequency response, but do require large voltage outputs.

CHARACTERISTICS.

Utilizes low plate-resistance triodes (7500 to 15,000 ohms) with amplification factors of from 8 to 20.

The transformer step-up ratio usually does not exceed 3:1 for good-quality audio. However, much higher ratios *are sometimes* employed to obtain extreme gain with a sacrifice of frequency response.

Operates class A; no grid current flows under normal conditions.

Frequency response is linear only over a relatively *narrow* band of frequencies (approximately 200 to 10,000 cps).

Cathode bias (self-bias) is normally used, but fixed bias may be used of desired.

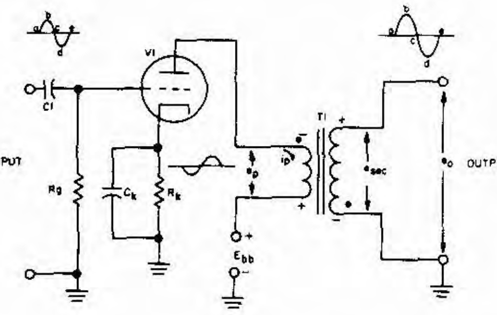
Output signal may be phased so that it is of the same polarity and phase as that of the input signal, or opposite as desired.

CIRCUIT ANALYSIS.

General. The transformer-coupled triode audio voltage amplifier utilizes the transformer as a combined plate loading and coupling device. It is the primary of the transformer which serves as the plate load, while the secondary *functions as the coupling element. The amplified version of* the input signal is developed across the transformer primary. Assuming that the primary impedance is large as compared with the plate resistance of the triode, the voltage developed in the transformer primary is approximately equal *to the amplification factor (μ) of the* tube multiplied by the input signal. Therefore, the induced signal in the transformer secondary, which is applied to the following stage, is approximately equal to μ N, where N represents the step-up turns ratio between the primary and secondary of the *transformer.*

Transformer coupling has several distinct advantages over either R-C or impedance coupling. A lower value of plate supply voltage can be used, as compared with that of an R-C-coupled stage, since the d-c resistance of the *primary* winding is small. The secondary winding of the transformer, when center-tapped, can be used to supply two grid voltages 180 degrees out of phase to a push-pull amplifier, or two in-phase outputs for push-pull operation. The impedance-matching properties of the transformer may also be utilized if needed. Since the primary and secondary of the transformer are not connected together, the following stage (or the output device) is isolated from the d-c plate voltage of the amplifier stage, eliminating the need for an output network (such as a grid resistor and coupling capacitor), thus effecting a reduction of components. The transformer also has several disadvantages. Its cost is high, and it has large bulk and weight. Additional shielding is also required *to prevent the stray fields introduced by* the transformer from interfering with the operation of other stages, or causing unwanted feedback within the stage.

Circuit Operation. A schematic diagram of a typical transformer-coupled audio voltage amplifier with a high-impedance input is shown in the accompanying figure C1 is the input blocking and coupling capacitor, and Rg is the grid return resistance. Resistor Rk is the cathode bias resistor, bypassed by Ck to prevent degeneration. Refer to Section 2, paragraph 2.2.1, of this Handbook for a discussion of cathode biasing methods. Transformer T_1 is the plate input and output transformer, coupling the output to the next stage or to the load.

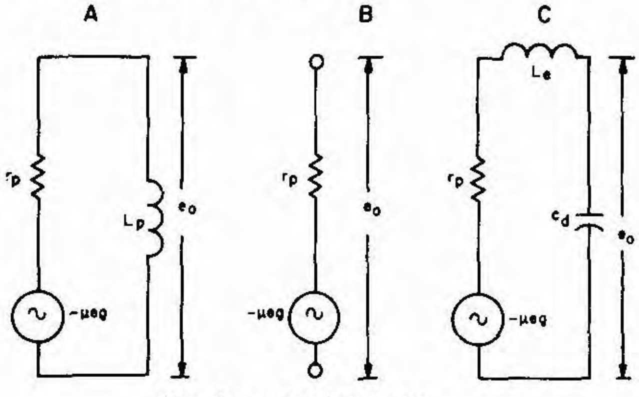


Typical Transformer-Coupled Audio Voltage Amplifier

As can be seen from the schematic, the input signal is capacitively coupled through C1 to the grid of tube V1. Coupling capacitor, C1, and grid resistor, Rg, form an audio voltage divider. The output of this voltage divider is the signal voltage applied to the grid of V1. Capacitor C1 also acts as a d-c blocking capacitor to prevent the plate voltage of a preceding stage, or any d-c voltage existing in the input circuit, from adversely biasing V1. The reactance of C1 to an audio frequency signal is much small than R1; thus little signal is lost across the capacitor.

With no signal applied, static plate current flows through cathode resistor Rk and provides Class A bias. A plate voltage drop (Ep) across the primary of transformer T1 is produced by the d-c coil resistance. This small voltage drop is constant, regardless of whether or not a signal is present; and produces no output voltage since it is not connected to the secondary, but does reduce the available plate voltage by a small amount. When a positive-going input signal is applied to the grid of tube V1, it reduces the effective grid bias, and the plate current increases instantaneously. Assuming a sine-wave input, as the signal rises the plate current also increases, until the positive peak of the input cycle is reached. During this half of the cycle (from point a to point b on the output waveform), a continuously increasing voltage drop (negative swing) occurs in the primary as the constantly increasing plate current flows through the load impedance (consisting of the primary reactance plus the reflected load from the secondary). The increasing plate current induces a voltage (esec) in the secondary of T1 which is the output voltage (eo). When the secondary is properly connected (phased), the input signal and the output signal are in phase with each other, otherwise they remain out of phase. When the grid input voltage reaches a positive crest at point b on the waveform, the drop across the primary of T1 is at a negative maximum, and is 180 degrees out-of-phase with the input, causing the effective plate voltage to reach its minimum value (the plate current is now at a maximum). As the grid input voltage now recedes towards zero, the effective bias is continuously reduced (made more negative), causing the plate current also to reduce. The reduction of plate current changes the direction of the magnetic field produced around the transformer primary, and induces an oppositely polarized voltage in the secondary of T1. While the primary voltage is positive-going, the secondary voltage is negative-going. When the sine-wave signal on the grid reaches point c on the waveform, the positive half-cycle of operation is completed and the tube is again at its quiescent point. Now, the grid signal continues to increase in a negative direction and adds to the cathode bias to make the effective bias still more negative, and reduces plate current flow below the quiescent value. This action continues until the negative crest is reached at point d on the waveform. Since the plate voltage is increasing toward the supply value while the plate current is decreasing, at point d the plate voltage is maximum, and the primary voltage drop is positive and maximum also. Because the induced secondary voltage is opposite that of the primary, the output is a maximum negative voltage (it is in-phase with the input). As the grid input signal again reverses direction and falls back towards zero, the effective grid bias once again is decreased and becomes positive-going. Consequently, the plate current increases towards quiescent or zero value, and in changing direction it again changes the the direction of the field around T1 primary. Thus, a positive-going voltage is again induced in the secondary to complete the negative half-cycle of operation.

For convenience and ease of discussion, the transformer is represented by three equivalent circuits in the accompanying figure. Part A represents the low-frequency range (below) 200 cps), part B represents the middle-frequency range (200 to 8000 cps), and part C represents the high-frequency range (8000 to 20,000 cps).

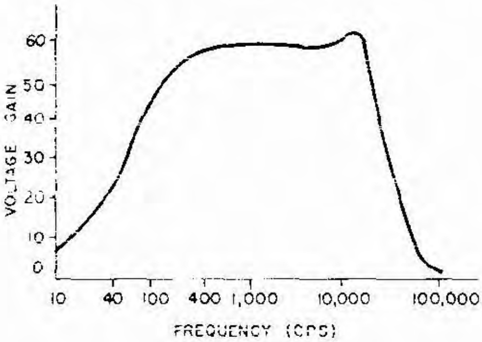


Transformer-Coupled Amplifier, Equivalent Circuits

In part A of the figure, $-\mu e_g$ is considered to be an a-c generator which represents the amplified output voltage of triode V1; r_p represents the a-c plate resistance of the tube, and L_p represents the inductance of the transformer primary. The d-c resistance of the primary winding, which is normally small, can be considered as included in r_p. L_p and r_p form a voltage divider, with the output voltage taken from across L_p. At low signal frequencies, the reactance of L_p becomes small; thus most of the developed voltage appears across r_p, thereby decreasing the voltage dropped across the primary, and hence the output voltage. For a given value of inductance, the lower the frequency the less the output voltage.

In part B of the figure, the reactance of L_p is considered very large as compared with r_p. Consequently, the voltage dropped across r_p is much smaller than that developed across L_p by generator $-\mu e_g$. The magnitude of the output voltage is determined by the tube amplification factor, the plate resistance, the amplitude of the applied signal voltage, and the turns ratio of the transformer. It is over this frequency range that the response is most uniform and the gain is maximum.

In part C of the figure, c_d represents the distributed capacitance between the windings of transformer T1 and interelectrode, stray, and wiring capacitances. The total distributed capacitance, which is appreciably large, shunts the higher frequencies to ground, since its reactance decreases with increasing frequency. L_e represents the equivalent inductance of the transformer (both primary and secondary). The value of L_e depends on the leakage flux and the amount of mutual coupling between the windings. This inductance, together with c_d in the equivalent circuit, forms a series-resonant circuit which resonates at some high audio frequency. At and near resonance, the magnitude of the voltage across c_d is extremely large. If the applied frequency is raised above resonance, the reactance of c_d decreases; hence the output voltage, e_o, decreases. The following figure, a typical response curve, shows a relatively uniform middle-frequency response, a gradual "roll-off" at low frequencies, and a sharper decay at high frequencies (which is preceded by a resonant peak).



Typical Response Curve of a Transformer-Coupled Amplifier

In practice, the gain of a so-called "flat response" transformer varies not less than 1 db and sometimes as much as 3 db or more over the range of 200 cps to 10,000 cps.

FAILURE ANALYSIS.

No Output. Generally speaking, a no-output condition is caused by the lack of an input signal, an open-circuited condition by the lack of plate or filament voltage, a short-circuited condition, or by a defective tube. The presence of an input signal may be determined by using an oscilloscope or vacuum-tube voltmeter to check the input. An open-circuited condition can be localized to the defective portion of the circuit by using a high-resistance voltmeter to determine whether filament, cathode, grid, and plate voltages exist and are normal. Open filament circuits can sometimes be spotted by noting that the filament does not light and that the tube feels cold to the touch. When a lack of voltage is found, the source (power-supply) voltage should be checked to determine whether the voltage is present; if so, the fault is in the amplifier and not in the power supply. In any case, a lack of voltage indicates either a short circuit or an open circuit in the associated component. For example, when B+ is present at the supply end of the transformer primary but not at the plate, T1 is open. If the voltage between the primary and ground is equal on both the supply-side and the plate side, there is no voltage drop across the primary coil. Therefore, either the plate current drain is too little (with the possibility of cutoff bias), or, with normal current drain, a short-circuited primary is indicated. Where the primary resistance is known, a resistance check with the B+ supply off and the filter capacitors discharged will indicate whether the transformer is defective. Usually, a short-circuited condition is evidenced visually by burning or charring of the parts involved.

When all voltages appear normal and an input signal is present, but there is still no output, it is obvious that tube V1 is at fault. Replace it with a tube known to be good. Defects in the tube develop with age, and contribute to below-normal circuit operation, in the form of a low or distorted output rather than no output. However, vibration or excessive voltage can cause the tube to become open or shorted; therefore, this possibility must be considered. Indiscriminate replacement of tubes should be avoided.

Reduced or Unstable Output. Reduced output is usually caused by a lack of proper grid and plate voltages, or low filament emission, while unstable output is usually caused by oscillation or intermittent functioning of circuit components. Check the bias voltage on the grid (or cathode) to determine that it is normal. A low fixed bias voltage can cause reduced output due to heavy plate current and peak clipping effects; these symptoms are not applicable to self-bias, because with this circuit arrangement heavy plate current will increase the bias; thus the circuit tends to be self-compensating. A high bias will cause reduced output. An open cathode by-pass capacitor (c_k) can cause sufficient degeneration to reduce the output appreciably. Poor joints (soldering, etc), which create high-resistance conditions in the plate circuit will also produce reduced output. If all voltages are normal and reduced output still exists, the trouble is likely to be in the electron tube. Replace the suspected tube with a tube known to be good. Circuit oscillation may also cause the output to drop, and will show up as fuzzy pattern on the oscilloscope.

Unstable output can result from a defective, bypass capacitor in the cathode circuit. This trouble manifests itself in the form of erratic operation, accompanied at times by distortion. When in doubt, use an oscilloscope and a sine-wave generator to observe the waveform at the input and output of the tube. In the case of intermittent conditions where oscillation is suspected, the application of a square-wave signal will tend to produce oscillation if instability is the cause of the trouble. Oscillation can result only from feedback caused by improper coupling of the grid and plate circuits, or by common impedance coupling through the power supply in multistage amplifiers, resulting from aging electrolytic bypass capacitors. This form of oscillation is called "motorboating", since it consists of a very low-frequency signal. Direct feedback usually manifests itself as a squeal or howl in the output.

Distorted Output. Improper bias is a common cause of distortion in the amplifier output. Check for the proper voltages in the grid and plate circuits. (Check the transformer for a d-c leakage path between the primary and secondary windings if the bias is positive on the following stage.) Tube performance deteriorates with age, and usually manifests itself in the form of distorted and weak output. In a weak tube, lack of sufficient filament emission can cause distortion on the peaks of amplification because of its inability to pass sufficient current. While voltage measurements will determine whether the grid and plate voltages are correct, it is usually necessary to use an oscilloscope to observe the waveform and determine the cause of the distortion. An oscilloscope and a sine-wave generator should be used to follow the signal path through the circuit; observing where the waveform departs from normal will indicate the defective portion of the circuit. When the observed waveform exhibits a flatening of the negative peak, the current should be checked for abnormal conditions, such as insufficient grid bias, overdrive, and a leaky coupling capacitor. Similarly, excessive bias or grid current flow is evidenced by an oscilloscope waveform pattern with a flattening of the positive peaks. Overloading the amplifier will also produce these same effects; in this case the waveform will show both clipping of the positive and negative peaks.

Oscilloscope waveforms are a valuable aid in failure analysis when poor frequency response is suspected as the cause of distortion. For example, when a waveform which is supposedly a sine wave shows a characteristic "rounded" effect on the positive peak, this is a clear indication of poor low-frequency response of the transformer. In making more precise measurements, a square-wave generator may be used. With a square-wave signal applied, a sloping leading edge indicates a lack of high-frequency response, while a sloping flat top indicates a lack of low-frequency response. Since a square wave is made up of many sine-wave frequencies, the application of a 2000 to 3000-cycle square wave will indicate the relative harmonic response over a range up to 5 to 10 times this frequency.

Hum distortion can be observed directly on an oscilloscope. When it is on the power supply leads, it indicates a lack of sufficient power supply filtering. If it is not on the power leads, but is evident on the grid, plate, or cathode leads, check for induced hum due to the nearness of a-c leads in the wiring. Poorly shielded and inproperly grounded transformers may also be the cause.

SINGLE-ENDED, R-C-COUPLED TRIODE AUDIO POWER AMPLIFIER.

APPLICATION.

The use of the single-ended, R-C-coupled triode audio power amplifier is limited to those applications where relatively small amounts (less than 5 watts) of audio power are required. Such as an audio output stage with a loudspeaker load.

CHARACTERISTICS.

Power gain is relatively low (usually not more than 5).

Plate efficiency is low (on the order of 25 percent).

Power sensitivity is low for triode power amplifiers operating under Class A conditions (power sensitivity is the ratio of output power in milliwatts to the square of the rms grid voltage which produces it).

Distortion is relatively low (5 percent maximum).

Operates Class A at all times; no grid current flows under normal conditions.

Cathode bias (self-bias) is usually used, but fixed bias may be used if desired.

Frequency response is relatively uniform over a range of 200 to 10,000 cps.

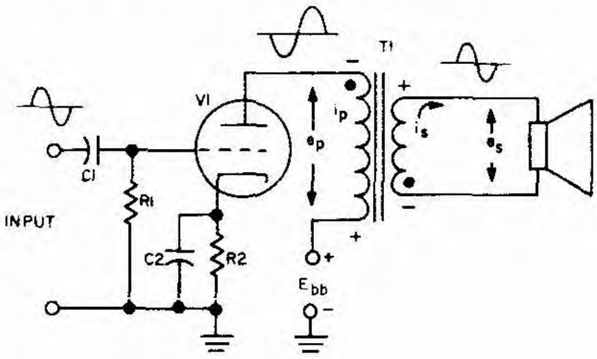
CIRCUIT ANALYSIS.

General. The primary function of a power amplifier is to deliver sufficient power to a circuit load; any increase of voltage is of secondary importance. In fact, the **voltage** amplifier uses the same circuit as the power amplifier. The main difference in the two circuits is that the power amplifier is usually the last stage (the output stage). In some instances a power driver may be employed, for example, to supply the driver power for the grids of a Class B high-power modulator. However, this is a special application in which the full output of the stage is usually not used. Since the objective is to obtain as much power output as possible, with as low a plate voltage as practicable, tubes with a low plate resistance are employed. As a consequence, these tubes are of the low-mu type rather than the high-mu type used in voltage amplifiers. (They are also larger in size, having plates capable of full dissipation of the d-c power involved, use higher plate voltage and current, and are generally more rugged than tubes used as voltage amplifiers.) Because of the low mu, a large grid excitation voltage is usually necessary to drive the power amplifier. Therefore, a voltage driver stage is usually associated with the power amplifier. Consequently, at least three stages are necessary to provide audio power output when triodes are used, namely, a high-gain input stage, a driver amplifier, and the output stage. *When only one tube is employed in the output* stage, it is said to be single-ended. When two tubes are used, they are connected either in push-pull, in push-push, or in parallel. Where power output is considered more important than the distortion products, the parallel connection is generally used to provide about three fourths the rated power of two tubes. For full output and the least distortion, the push-pull connection is used (see the discussion of push-pull Audio Power Amplifiers later in this section). Although pentodes will produce more output than triodes, no further mention of them will be made in this circuit discussion since they are treated separately (see the discussion of Single-Ended, R-C-Coupled Pentode Audio Power Amplifier later in this section.)

Operation under Class A conditions with lack of grid current and an effectively high-impedance R-C-coupled input eliminates any possibility of grid losses. This however, does not mean that the effect of the loading of the input circuit on the output of the preceding (driver) stage may be neglected. Thus, the power-amplifier grid input circuit constants determine to a large extent the total amount of *undistorted voltage drive available.*

The large a-c (audio) power output derived from the single-ended circuit is actually obtained from the d-c plate supply by converting the d-c power to a-c power through tube *action.* Maximum **undistorted** power output is normally obtained when the load resistance is equal to twice the plate resistance of the tube. If the load resistance is made higher than this optimum value, a reduced output will be obtained; however, the distortion will also be greatly reduced. As a result, in those cases where sufficient power output is available, it will be observed that the load resistance is more thantwice the tube plate resistance. For each tube type and given set of circuit conditions, the same set of operating rules does not necessarily apply. Therefore, the preceding discussion is broadly applicable only, and varies considerably with design. It is of interest to note that the distortion present in the single-ended stage consists primarily of second-harmonic signal. While other harmonics are also present, they are of much lower amplitudes and are normally neglected. Output ratings are generally computed for the maximum power output obtained when the second-harmonic *distortion does not exceed 5 percent.* Thus, the stage may be operated at lower power outputs with appreciably less distortion.
This is usually what is done with so-called "hi-fi" (high-fidelity) amplifier systems. For example, a 25-watt output capability is supplied to provide only 2 or 3 watts for normal use. Hence, instead of being 5 percent or more, the distortion is reduced to less than 1 percent. To obtain maximum undistorted power output, the stage must have a properly matched load. That is, the **output load** (usually a loudspeaker) must equal (match) the **desired plate load impedance.** In this case, the output transformer serves as an *impedance-matching as well as a coupling device, and must* be capable of handling the full input power constantly. Since a speaker output load offers a different impedance to different audio frequencies, it is customary to consider it as *offering a purely* resistive load, and to assume that it has no reactive components which may be sensitive to various frequencies. Design is accomplished under these ideal conditions; however, practical operation is not quite the same. An explanation of loading and matching effects is given in the following discussion of circuit operation.

Circuit Operation. A typical single-ended audio power amplifier is illustrated in the accompanying figure. The varying input signal is capacitively coupled through capacitor C1 to the grid of triode V1. Capacitor C1 and resistor R1 form a high-impedance input coupling network. The input voltage is impressed across resistor R1 and is applied to the grid of tube V1. The reactance of capacitor C1 to the a-c input signal is very small; therefore, the alternating input signal voltage is passed on to the grid with little or no attenuation over the audio-frequency range. Resistor R2 and capacitor C2 make up the cathode-bias circuit. (Refer to Section 2, Paragraph 2.2.1 of this Handbook for a detailed discussion of cathode bias.)



Typical Single-Ended Triode Audio Power Amplifier

The varying voltage applied to the grid of tube V1 causes *the instantaneous plate current (ip) to vary through the tube* and through the plate-load impedance (primary of transformer T1). The changing current (ip) through the primary of T1 produces an a-c voltage drop (ep) across the transformer *primary,* and causes an induced voltage (esec) to appear in the transformer secondary. This voltage (esec) causes current to flow in the load circuit. Thus, the transformer forms an output coupling network. It is important to realize that the transformer merely **reflects** into its primary circuit the load which is imposed on the secondary, and (neglecting internal transformer losses) does **not** place a load on the primary circuit unless a load is applied to the secondary. It is the turns ratio between the primary and secondary, not the number of turns in the primary, which governs the reflected impedance.

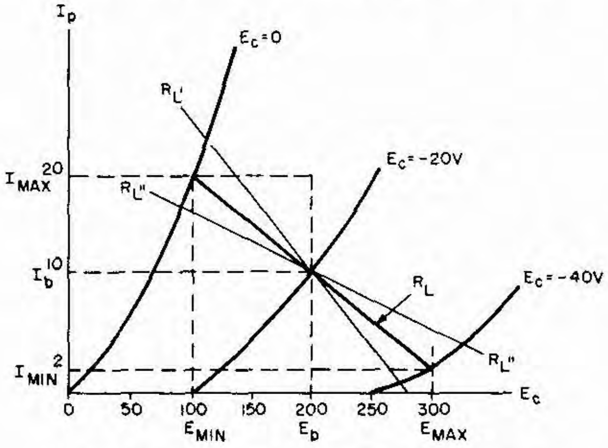
The current which flows in the transformer secondary will be larger than the primary current by the turns ratio. For example, in an output transformer which employs a step-down ratio of 40:1, the secondary current will be 40 times the primary current. The secondary voltage, however, will be only 1/40th of the primary voltage. Assuming that a primary voltage of 400 volts is generated, the secondary voltage will be only 10 volts. The power transferred will, in the case of an ideal and lossless transformer, be the same in both secondary and primary. For example, assuming a primary current of 20 ma, the secondary current will be 800 ma. Since power equals E x I, the primary power will be 400 x .02, or 8 watts, and the secondary power will be 0.8 x 10 volts, or 8 watts also. Assume a loudspeaker load of 4 ohms; since I^2R equals power, a total of 0.64 x 4, or 2.56 watts, will be transferred to the speaker voice coil. With 8 watts in the primary, this represents about 32 percent efficiency. In a practical transformer, inherent losses will reduce this figure closer to the previously specified nominal value of 25 percent.

As far as the circuit action is concerned, the power amplifier operates in a manner identical with that of the Transformer Coupled Triode Audio Voltage Amplifier discussed previously in this section. When a positive signal appears at the grid of V1, the plate circuit develops a negative-going output. When this output is coupled from the primary to the secondary it will also be negative if so phased. When the secondary winding is connected in phase, the output will be positive for a positive input and negative for a negative input. Otherwise, the primary and secondary are always out of phase. The ability to connect the secondary for the desired phase is one of the advantages of transformer coupling.

To obtain maximum undistorted power output it is necessary to properly match the load to the tube. Here again the transformer offers a convenient matching method by choice of the proper turns ratio between the primary and the secondary. When used for impedance matching, the impedance ratio of primary to secondary varies as the square of the turns ratio rather than directly, or, stated mathematically: $N_p/N_s = Z_p/Z_s$, or $R_{pri} = (N_p/N_s)^2 R_{sec}$. Thus, assuming a 40:1 turns ratio, a 1600-to-1 impedance transformation is obtained. With a 4-ohm speaker and a step-up ratio of 40:1 (secondary to primary), the reflected load produced in the primary is 4 x 1600, or 6400 ohms. Such an impedance would be satisfactory as a load for a 3200-ohm plate resistance stage (the load is twice R_p).

The example of impedance matching given above again illustrates the primary difference between the voltage amplifier and the power amplifier. While the impedance ratio is step-up for the load, it is step-down as far as primary to secondary is concerned. Therefore, only a low-voltage can be obtained, but maximum power output with a minimum of distortion is supplied to the speaker. In the event that the amplitude of the grid voltage is held constant, maximum output can be obtained when the load is equal to the tube plate resistace; however, such operation in audio amplifiers is encountered only in special cases, usually where only one frequency rather than a range of frequencies is to be amplified.

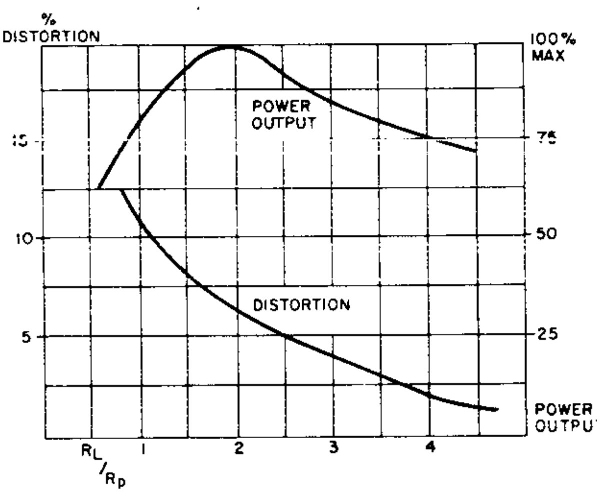
The accompanying figure graphically illustrates typical triode plate current and plate voltage characteristics with an assumed load line, from which both power output and harmonic distortion may be determined.



Graphic Determination of Power Output and Distortion

Note first that since the I_p-E_p characteristics are not straight lines and are not equidistant, the current and voltage swings will be unequal, and some distortion will exist. The load line R_L is drawn equal to the desired load resistance, and the static bias fixes operation at the intersection of the I_b and E_b lines, where the grid bias is −20 volts. Thus, in the ideal construction, equal positive and negative swings would occur, driving the bias to 0 and to −40 volts, respectively. The resulting plate current and plate voltage swings represented by I_{max} and I_{min} then determine the power output. Neglecting the second-harmonic distortion for the present, it can be shown that $P_o = 1/8\ (E_{max} - E_{min})(I_{max} - I_{min})$.

The illustration shows that with lower load resistance (indicated by line R_L') the voltage swings will be smaller and the current swings will be larger than for R_L, and will be unequal; therefore, the power output will be less and the current continuously increases (since the effective grid then higher plate and bias voltages are needed. In this case, as shown by load line R_L'', the plate voltage swings are greater but the current swings are less; thus, the power output is lower, while the distortion is less, since the swings are more nearly equal. For a given tube and plate supply voltage, the desired solution is obtained by adjusting the grid bias. With the proper adjustment, the positive signal peak just takes the total grid voltage to zero, and the negative signal peak just makes the grid sufficiently negative to reduce I_p to its minimum allowable value (without operating on the curved lower portion of the tube characteristics.) The accompanying graph shows the variation of power output and distortion with respect to the ratio of the output resistance and the plate resistance for a triode. It is obvious that the most power is obtained when RL = 2 Rp. On the other hand, if a value of 4 Rp is used, the power drops only 25 percent, but the distortion drops from 7 percent to only 2 percent, which is negligible.

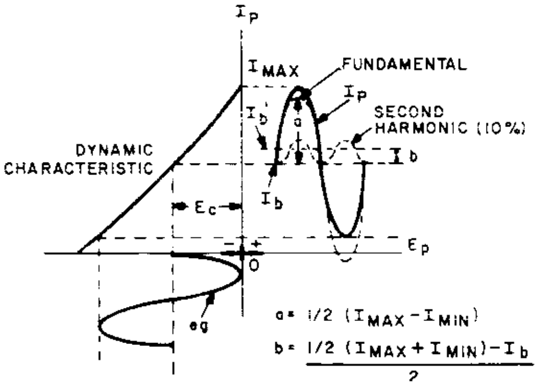


Power Output, Distortion and Load Resistance Relationships

It also can be shown mathematically that RL = Emax – Emin/ Imax – Imin. This is a simple Ohm's law relationship, which, by substitution in the proper formulas, becomes:

RL = 2 rp

The amount of distortion present is determined from the maximum and minimum plate currents, and is illustrated in the following figure



Development of Harmonic Distortion

In this figure a triode Ip – Ep characteristic is shown; with sine-wave voltage eg impressed on the grid, the resultant plate current is represented by Ip. Since the maximum and minimum amplitudes are unequal (the curvature of the characteristic causes partial rectification to take place), the average value of Ib rises to Ib´ when the signal voltage is applied to the grid. This increase in average current is equal to the amplitude of Ib´, shown by **b** in the figure. The fundamental component is **a** = 1/2 (Imax – Imin), while the second harmonic component is **b** = 1/2 (Imax + Imin)–Ib/2; the percentage of second harmonic distortion is equal to 100**b/a**. The rise in average plate current with distortion shows as a fluctuating plate current, with the plate meter wiggling as the signal fluctuates in intensity.

Assuming that the cutoff voltage of the grid is Eb/μ, the maximum power output of a triode under Class A operating conditions can be estimated roughly in terms of its plate supply voltage and plate resistance by:

$$P_o = E_b^2/36\ r_p$$

It is evident from the formula, then, that for moderate plate voltages the internal resistance of the triode **must** be small to obtain relatively large power outputs.

FAILURE ANALYSIS.

General. Since the circuit of the single-ended power amplifier is identical with that of the triode transformer-coupled amplifier, the failure analysis listed for the Transformer-Coupled Triode Audio Voltage Amplifier, previously discussed in this section, is generally applicable.

The power amplifier ordinarily operates at higher voltage and current than the voltage amplifier. Therefore, visual evidence in the case of flashovers and short circuits is usually more apparent. Excessive heating of a component usually indicates as incipient failure, since prolonged heating accelerates the aging process. Lack of proper bias is usually indicated by increased plate dissipation. Tube plates showing signs of color indicate excessive loading or current drain. Since the tube is generally working at full capability, lack of sufficient emission can usually be observed by a reduction of output, together with distortion. When trouble-shooting the circuit, it is important to be certain that the proper load is connected at the output, otherwise, the tube may appear to be operating normally but be incapable of the proper output. To check for proper operation, apply a sustained tone from an audio generator to the amplifier input. Use an oscilloscope to check the waveform from input to output; any distortion will be immediately apparent. Use a vacuum-tube voltmeter to measure the actual a-c input voltage, and substitute a resistor equal in value to the proper load impedance at the output. The a-c voltage measured across this resistive load will, by use of Ohms' law, indicate the power output ($P_o = E^2/R$).

SINGLE-ENDED, R-C COUPLED PENTODE AUDIO POWER AMPLIFIER.

APPLICATION.

The single-ended, R-C-coupled pentode power amplifier is used in applications where a relatively large audio power output is desired from a small input voltage, and where some distortion can be tolerated.

CHARACTERISTICS.

Input impedance is high, usually greater than 0.1 megohm.

Uses an output transformer to match the load to the output device.

Power sensitivity (ratio of output power to grid voltage producing it) is relatively high.

Power gain is high, on the order of 8 to 20.

Distortion is normally higher than that of the triode (always more than 5 percent and generally on the order of 7 to 10 percent) unless special design considerations or negative feedback is used.

Operates Class A at all times; no grid current flows under normal conditions.

Cathode bias is usually used, but fixed bias may be used in some applications.

Frequency response is relatively uniform and linear over a range of 200 to 10,000 cps without requiring any special design considerations or compensation.

CIRCUIT ANALYSIS.

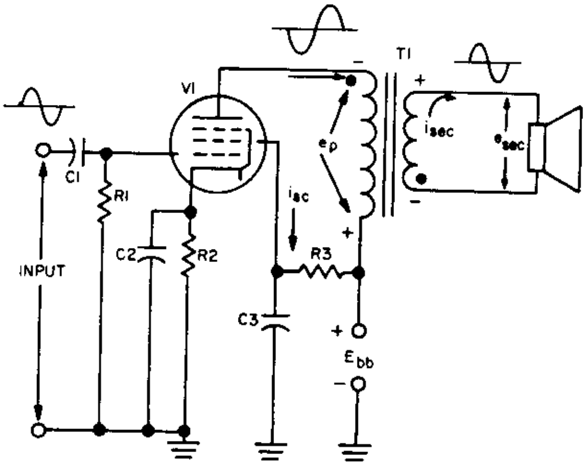
General. While the single-ended triode audio amplifier is characterized by low power sensitivity, low plate efficiency, and low distortion, the pentode counterpart is just the opposite; it is characterized by high power sensitivity, high plate efficiency, and high distortion. Because of its basically higher distortion, the pentode power amplifier requires more attention to design. Fortunately, however, the increase in power obtainable with the pentode permits the use of various feedback methods, and what essentially amounts to mismatching to attain power outputs equivalent to or greater than the triode with the same distortion. Usually the use of a pentode output stage eliminates the necessity of a driver stage, since the pentode can be adequately driven by small signals.

The screen element in the pentode requires a d-c source of power, which does not contribute materially to the output directly and represents an additional constant loss of power (as compared with a triode). Because the Ip-Ep characteristics are parallel, the amount of second-harmonic distortion is very low, and third-harmonic distortion predominates. Consequently, push-pull operation will not materially help in reducing the distortion. On the other hand, when the load is designed so as to produce more second-harmonic distortion, the use of push-pull operation provides cancellation of this component, and the third-harmonic component is also reduced by the load mismatching. See the discussion of Push-Pull Audio Power Amplifiers later in this section for further details on push-pull operation.

As contrasted with the triode, instead of having a load with twice the plate resistance, the pentode uses a load with only 1/5 to 1/10 the plate resistance. Such mismatching is necessary because of the extremely high plate resistance inherent in the pentode.

This discussion also applies generally to tetrodes and beam power tubes, except that the second-harmonic distortion of these tubes is greater, more like that of the triode. However, like the pentode, they do have a higher plate resistance and greater over-all distortion, which requires negative feedback or other compensation to provide an acceptable output.

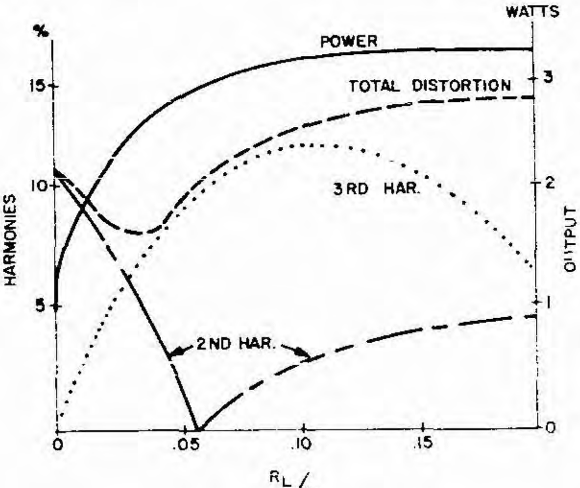
Circuit Operation. The schematic of typical single-ended pentode power amplifier is shown in the accompanying figure. The circuit load is a loudspeaker. The varying audio input signal is applied to the grid of pentode V1, through coupling capacitor C1. Capacitor C1 and resistor R1 make up the input coupling network, and the input signal is impressed across resistor R1. The reactance of capacitor C1 to the a-c signal is very small; therefore, the alternating signal voltage is readily passed on to the grid without excessive attenuation. The bias circuit consists of cathode resistor R2 and capacitor C2. (See Section 2, Paragraph 2.2.1 of this Handbook for a discussion of cathode biasing.) As is evident from the schematic, the cathode and the suppressor grid are maintained at the same voltage level, being connected together internally or at the socket (depending upon the type of tube used). The varying input voltage applied to the grid of pentode V1 causes the instantaneous plate current (ip) to vary similarly through the tube and through the plate-load impedance (primary of transformer T1). Capacitor C3 bypasses the screen to ground to prevent the signal voltage from changing the screen voltage at an audio frequency rate. Capacitor C3 is chosen to present a



Typical Single-Ended Pentode Audio Power Amplifier minimum of reactance to the signal voltage; thus, the screen-grid voltage is maintained at a relatively constant d-c level. The positive screen-grid voltage is obtained from the plate supply through voltage-dropping resistor R3 to avoid the necessity of providing a separate screen-grid power supply. The changing plate current (i_p) through the primary of T1 produces an audio voltage drop (e_p) across the transformer primary, and also causes an induced voltage (e_{sec}) to appear in the transformer secondary. Voltage (e_{sec}) causes current (i_{sec}) to flow in the load (output) circuit. Thus, the transformer secondary forms an output coupling network.

As far as specific circuit action is concerned, the operation is identical with that of the Transformer-Coupled Audio Voltage Amplifier Circuit and the Single-Ended Triode Audio Power Amplifier Circuits discussed previously. When a positive signal is applied to the grid of V1, a negative-going signal is developed in the plate circuit, and coupled *from the primary* to the *secondary of T1 as a* negative-going output signal if T1 is connected in-phase. When a negative signal is applied to the grid, a positive-going amplified signal is developed in the plate circuit, thus inducing a voltage in the secondary of T1. When connected in-phase, the secondary output is positive for a positive input signal and negative for a negative input. Otherwise, the primary and secondary voltages and currents are always out-of-phase.

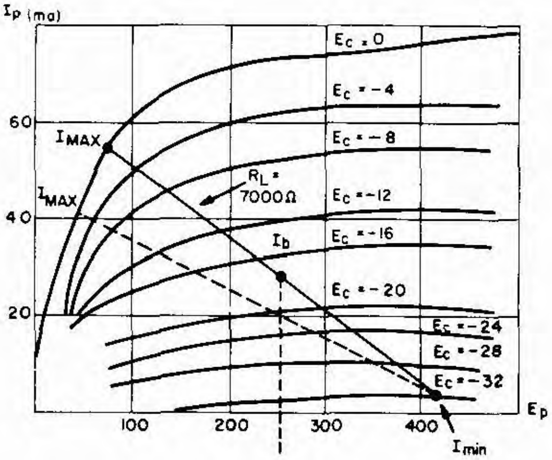
To obtain maximum undistorted output, it is necessary to properly match the load to the tube. The transformer offers a convenient method of accomplishing load matching since the impedance ratio of primary to secondary varies as the square of the turns ratio, rather than directly. Stated mathematically, $Z_{pri} = (N_p/N_s)^2 Z_{sec}$. Thus, with a transformer having a 50:1 turns ratio and a 4-ohm loudspeaker load, the primary would reflect a load of 2500 times the the secondary impedance, or 10,000 ohms. Such a load is suitable for matching pentodes having a plate resistance *of 50,000 to 100,000 ohms, with the least distortion being* obtained from the higher-plate-resistance tubes. The manner in which the output power varies with the ratio of the load and plate resistance of a typical pentode, together with the amounts of distortion produced, is graphically illustrated in the following figure.



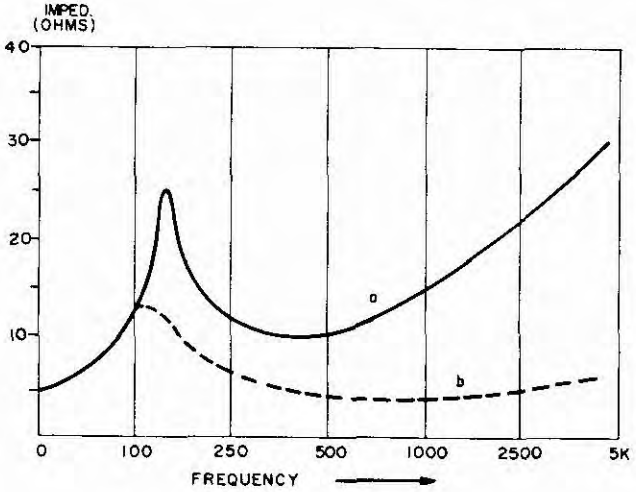
Typical Power Output and Harmonic Distortion Relationships

The large amount of second-harmonic distortion at high load impedances shown in the graph occurs because of the crowding together of the typical pentode plate characteristics at low plate voltages. This causes a greater i_p change during the negative peak than during the positive peak of the output waveform, thus tending to flatten the positive peak. During the interval over which the negative and positive swings are equal, practically no second-harmonic distortion occurs. The large amount of second-harmonic distortion with low load impedance is caused by the unequal spacing of the plate characteristics at low plate currents, which tends to flatten the ngeative peak of the alternating plate current. Because the load for maximum power output is different from the load for minimum distortion, the choice of the load is a compromise between the amount of power output desired and total distortion that can be tolerated. The load is usually chosen so as to produce minimum second-harmonic distortion. While it is possible with some tubes and designs that optimum power output may occur at the point of minimum distortion, this is *the except rather than the rule. Because of the extreme* variations between tube types, simple design formulas like those used for the triode are not obtained; therefore, most of the design must be determined graphically.

The accompanying figure shows the i_p-E_p characteristics for a typical pentode with the proper load line. In this example the plate resistance is 60,000 ohms and the load is 7000 ohms.



Typical Pentode Ip-Ep Characteristics and Load Line



Variation of Loudspeaker Impedance with Frequency

Examination of the plate characteristics reveals that for equal grid swings, equal plate current swings are produced with the 7000-ohm load line. It can easily be seen that if the load line were drawn with less slope (for example, an increased load resistance of 9000 ohms, shown by dotted load line), I'max would be less than Imax, and if the load were increased further the maximum current would change greatly while the minimum would remain practically the same. As a result, second-harmonic distortion would be increased. It is important with pentodes, therefore, to prevent the load from increasing with frequency, as normally happens when a loudspeaker is the load. To minimize this increase in distortion at the higher audio frequencies, a capacitor connected in series with a resistor is used in shunt with the transformer primary (in some cases it is in the form of a tone control, and in other cases only a shunting capacitor is used). The variation of the effective loudspeaker impedance with frequency when the RC network is not used is shown by the solid curve (a) in the following graph, and the variation when the RC network is used is shown by the dashed curve (b). Because of the high plate resistance of the pentode, the effective resistance shunting the loudspeaker is less than that for a triode. This reduction of damping on the speaker sometimes causes objectionable "booming" because of resonances which otherwise would be subdued (damped out). It is also of interest to note that the screen grid of a power pentode is not as effective (as compared with a voltage pentode) in shielding the control grid from the plate. As a result, the plate-to-grid capacitance is larger than in the voltage pentode. In addition, because the control-grid connection is made through the base rather than through a tube cap, the grid-to-cathode capacitance is also larger. Therefore, the total effective input capacitance of the power pentode may sometimes be considerably larger than that of the power triode. The result is to produce greater frequency distortion in the preceding amplifier stage. Because of these facts, the over-all distortion is so large that negative feedback is practically mandatory to keep the distortion within acceptable limits if the full power output of the pentode is is required.

While it is possible to eliminate the cathode bypass capacitor (C2 in the schematic) and thus obtain degeneration to help reduce the distortion, It is usually easier to use negative feedback. Because of the high gain in the pentode, a larger cathode bypass capacitor is required than in a triode amplifier.

Although the load line as discussed above was considered to be a straight line for convenience, in actual operation the dynamic load line is not straight, but varies in accordance with the reactive component of load impedance in the circuit. The result is to shift the operating point slightly about the bias value assumed for the ideal condition, particularly when self-bias is used. With proper design this is of no consequence, since the circuit is arranged to produce equal shifts for the positive and negative grid swings. If unequal shifts are permitted to occur, however, the effect is to obtain performance entirely different from the assumed values of plate current, voltage, bias and, grid drive, with greater distortion and phase shift. Thus, the gain, output, and response characteristics may sometimes be entirely different from those which are assumed or calculated.

FAILURE ANALYSIS.

No Output. A no-output condition is normally caused by the lack of an input signal, an open-circuited condition, lack of plate or filament voltage, a short-circuited condition, or a defective tube. The presence of an input signal can be determined by checking the input with an oscilloscope or vacuum-tube voltmeter. An open-circuited condition can be localized to the defective portion of the circuit by making voltage measurements to determine whether the filament, cathode, grid, plate, and screen voltages are present and are normal.

An open cathode circuit will cause a no-output condition. With an open input circuit (C1 or R1 open), the high gain and high impedance of the pentode may permit a slight output; however, for all practical purposes the output will be so low that it can be considered nonexistent.

If the screen shows color and the plates does not, it usually indicates that the screen is attempting to act as the plate because of an open plate circuit. In this case the plate voltage will be zero.

An open screen resistor, R3, or shorted screen bypass capacitor, C3, will also cause a no-output condition. In *either case no voltage will appear on the screen of the tube.* An open screen resistor will be cool. With a short-circuited bypass capacitor, since the screen resistor will be dropping the full voltage from the plate supply to ground, it will be abnormally hot and probably will eventually burn out; a visual inspection will normally show discoloration or even smoke in this instance.

With an input signal present and normal tube voltages, *either the tube is defective or the transformer secondary* is open. Replace the tube with one known to be good, and check the secondary for continuity with an ohmmeter.

Reduced or Unstable Output. Reduced output is usually caused by improper bias, or low plate or screen voltages. Unstable output is usually caused by oscillation, or by intermittent functioning of circuit components. An open cathode bypass capacitor, C2, will permit sufficient degeneration *to reduce the output appreciably, as will an* open screen bypass capacitor, C3. If the bias is excessive or if cathode bias resistor R2 has increased in value, the output will also be reduced, depending upon the amount of change. If the screen resistance increases in value or bypass capacitor C3 becomes leaky, the increased voltage drop across R3 will produce a lower screen voltage and thus reduce the output by reducing the maximum plate swing. *If the reflected load impedance is too high, the output will* also be reduced. A shorted input coupling capacitor, C1 can place the plate voltage of the preceding stage on the grid of V1, cause increased plate and screen current, increase the cathode bias, and reduce the output. (In some cases it can cause complete cutoff.)

With all voltages normal, the trouble is most likely in the electron tube; reduced emission will cause a loss of output, particularly on the signal peaks when more electrons are needed to increase the plate current.

Unstable output can result from intermittently open or shorted components, and can usually be located by using an oscilloscope to follow the waveform through the circuit. Oscillation can also cause erratic response. If it occurs at radio frequencies, it will show on the oscilloscope as a fuzzy pattern; if the feedback is at an audio frequency, it will be observed as a separate audio frequency. Oscillation will also show in the output as a howl or squeal, or as a very low-frequency "put-put" (motorboating). Howl or squeal is usually caused by undesired coupling between the plate and grid circuits. Motorboating is usually caused by faulty bypassing (in the power supply or B+ leads), particularly where electrolytic capacitors are used; electrolytic capacitors tend to dry out with age and lose their capacitance.

Distorted Output. Improper bias or improper load matching is a common cause of distortion. Check for proper plate and grid voltages. Lack of sufficient emission in the electron tube will also cause distortion on the signal peaks. Where the voltages are normal and the load is correct, the tube is probably at fault; it should be replaced with a tube known to be good. Use an oscilloscope and audio signal generator to follow the waveform through the circuit. Flattening of both the positive and negative signal peaks indicates overdrive (too large an input signal). Flattening of the negative peaks indicates excessive bias or low plate voltage; this symptom can also be caused by low screen voltage. Too low a bias or too high a screen voltage is usually indicated by flattening of the positive peaks. Check the frequency response characteristics. Rounded-off peaks on sine waves or sloping sides or tops on square waves indicates loss of low- and high-frequency response. A *2000- to 3000-cps square wave* applied to the input will provide a signal which can indicate the relative harmonic response over a range of 5 to 10 times this frequency (the square wave is composed of many sine-wave frequencies).

Hum distortion can be observed directly on the oscilloscope. When hum is present on the power leads, lack of sufficient power-supply filtering is indicated. If it is not on the power leads, but is evident on the grid, plate, or *cathode leads, check for induced hum due to the nearness of* a-c leads in the wiring. Additional checks should be made to insure that the transformer is properly grounded and that the shielding is adequate.

PUSH-PULL (CLASS A, AB, AND B) AUDIO POWER AMPLIFIER.

APPLICATION.

The push-pull audio power amplifier is used where large amounts of undistorted audio power are required. This circuit is commonly employed in receiver output stages, in hi-fi and public address systems, and in AM modulators.

CHARACTERISTICS.

Power gain is moderately high, on the order of 4 to 10.

Requires twice the drive of a single tube.

Power output is more than twice that of a single tube (about 2-1/2 times).

Second and higher even-order harmonic distortion is cancelled out in the plate circuit.

Distortion varies with the class of operation; it is minimum for Class A operation, and greatest for Class B operation.

Plate efficiency varies with the class of amplifier; it is lowest for Class A operation, highest for Class B operation, and intermediate between the two for Class AB operation.

Cathode (self) bias is normally used for Class A or AB operation, but fixed bias is usually used for Class B operation. (Specially designed Class B tubes requiring no bias are sometimes used.)

Cathode bypass capacitor is usually omitted in Class A stages, but is included in Class AB stages.

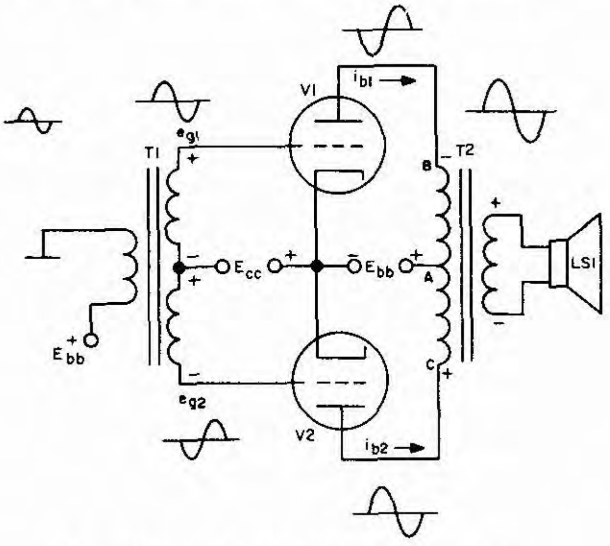
CIRCUIT ANALYSIS.

General. In push-pull operation, the plate current of one tube is increased, while that of the other tube is simultaneously decreased, and vice versa. As originally conceived, one tube was considered to be pushed while the other tube was pulled; hence the term **push-pull.** While this is true of Class A or Class AB operation, it is not strictly true of Class B operation. Class B amplifiers utilize the push-pull circuit; however, one tube effectively amplifies only the positive portion of the input signal, while the other tube amplifies only the negative portion. This occurs because only one tube conducts at a time, while the other tube is cut off. Push-pull stages require twice the grid drive of single-ended stages; however, each tube may be driven to its full capability, and usually more than twice the output possible with a single-ended stage is supplied. Distortion is reduced because the even-order harmonics are cancelled out. For triodes, this provides a maximum reduction of distortion. For pentodes, since the second-harmonic distortion is small or negligible, only a slight reduction in distortion is obtained. However, with special design in which the pentodes are loaded so that they produce more than normal second-harmonic content, a reduction in both second- and third-harmonic distortion is achieved. With the beam-power tube, distortion is also reduced since this tube has a larger second-harmonic content than the pentode, although not as great as the triode.

Since in a balanced push-pull amplifier the plate currents are equal and opposite d-c saturation effects on the core are eliminated; this permits more efficient transformer design, together with a reduction in both amplitude and frequency distortion. Actually, only 40 percent more turns in the primary (as compared with single-ended stages) are needed to handle two tubes in push-pull. Thus, the transformer design is economical. With a balanced input and output, any hum present in either the input or in the output tends to cancel out. This, together with the reduction in harmonic distortion, provides better audio quality.

With triodes, usually Class A or Class AB operation is employed, and the drive is such that no grid current is drawn. With pentode or beam-power tubes, usually Class B operation is used, and some grid current is drawn. As a result, Class B stages usually require power driver stages, while Class A or AB stages require only voltage driver stages.

Circuit Operation. A typical push-pull circuit using a minimum of components is shown in the accompanying figure. For ease of explanation, fixed bias is assumed.

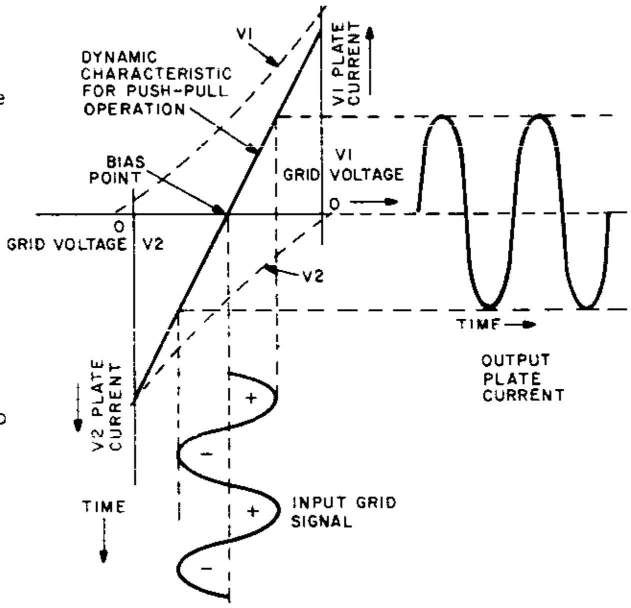


Typical Triode Push-Pull Audio Power Amplifier

(For a discussion of circuit biasing methods, refer to Section 2, paragraph 2.2 of this Handbook.) The circuit load is a loudspeaker.

It is evident from the schematic that the grids of V1 and V2 are biased equally negative with respect to the respective cathodes. With no input signal applied to T1, the tubes rest in their quiescent (static) state, and equal but opposite d-c currents flow in the two halves of the primary of T2. The steady flow of d-c current does not induce a voltage in the secondary of T2, since the current in each half of the primary is equal and opposite in direction, and the magnetic flux around the primary cancels. Thus the core is not subjected to a continuous magnetizing force. Consequently, the possibility of d-c core saturation is minimized (for a specific core, any d-c induced flux adds to the a-c induced flux produced by a signal, and thus limits the total amount of flux that can be carried through the iron without saturating). As a direct result, a higher primary inductance is obtained with the same number of turns. On the other hand, when saturation occurs the inductance is reduced just as if the core size were reduced, and this changes the load impedance and creates distortion. The reduction in saturation effects is an inherent advantage of the push-pull circuit. When an input signal is applied to the primary of transformer T1, equal but opposite voltages are induced in the secondary (the schematic shows the instantaneous polarities for one half-cycle of operation; during the other half-cycle they are oppositely polarized). Therefore, when the plate end of T1 is positive the gride of V1 is driven positive, while the grid of V2 is driven negative (assuming that T1 is connected in-phase). The alternating drive voltages, e_{g_1} and e_{g_2}, are equal and are connected in series with bias voltage E_{cc}. Assume for the moment that the drive voltages are just equal to the bias. It is evident, since they are of opposite polarity, that V1 will conduct heavily (the bias is reduced to zero), and V2 will be biased twice normal, or to zero plate current. The heavy current flow through the primary of T2 to the plate of V1 produces a maximum voltage drop across the load, reducing the plate voltage of V1 to its minimum value. The flux produced by the flow of a-c plate current through T2 induces a voltage in the secondary in accordance with the turns ratio of the transformer (the relationship of transformer turns ratio, impedance, and power output will be discussed in more detail in a following paragraph). The secondary of T2 is assumed to be connected out-of-phase with the primary, so that the polarity of the output for the half-cycle discussed above is positive, as shown in the schematic waveforms.

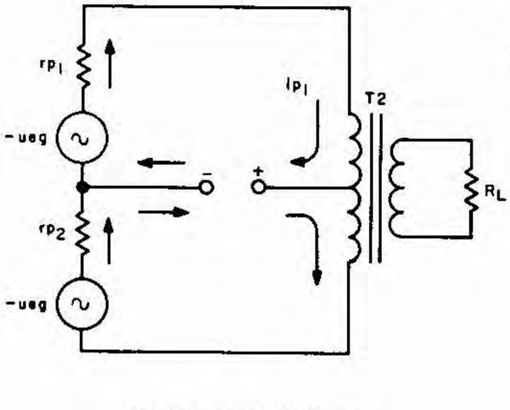
When the plate current of V1 decreases (on the other half of the cycle), the plate current of V2 increases. The alternating currents in the primary of T2 are in phase while the d-c currents and their resulting voltage drops are opposing. The net result is that the magnetomotive force produced by the two halves of the primary is zero with no signal impressed. With an input signal applied, the plate current of the two tubes is equal to a current equivalent to the difference in the current flowing in tube V1 and tube V2, both flowing through one half of the primary winding. For example, assume a quiescent current of 30 milliamperes and a drive signal that causes one tube to increase 10 milliamperes instantaneously. Since the grid swings are equal and opposite, the plate current of the other tube is reduced. For ease of discussion also assume that the tube charactdristic E_g-I_p curves are exactly identical (in practice they are slightly different). Then, the reduction of plate current in the second tube will be exactly 30 minus 10, or 20 milliamperes. With an upward swing of 10 ma to 40 40 ma, the difference in current between the two tubes is 40 minus 20, or a total I_p of 20 ma, which is exactly double that of one tube. With a unity turns ratio between each half of the primary and the secondary, equal a-f voltages are induced in the output. Since they occur simultaneously and are in-phase, they are effectively series-connected and the output voltage is doubled. The same effect would be produced by the difference current (20 ma) flowing through one-half of the primary. Consequently, the dynamic characteristic for two tubes operating in push-pull is constructed by subtracting the currents through the two tubes in order to approximate the effect of the transformer. The accompanying dynamic characteristic curve illustrates Class A operation. The dotted curve labeled V1 represents the dynamic characteristic of one tube, while the dotted curve labeled V2 represents the dynamic characteristic of the other. Both of these characteristics are assumed to be identical. Although the dynamic characteristics of the individual tubes are curved, the resultant push-pull characteristic is straight. As is evident from the figure, the dynamic characteristic for Class A push-pull operation is extended over that for a single tube, and is even more linear. Thus, greater grid-signal, plate-current, or plate-voltage swings are possible without any noticeable increase in distortion. With a greater swing, greater power output is obtained. By projecting the various points of the grid (input) signal to the solid-line, push-pull characteristic shown in the figure, the output waveform is obtained.



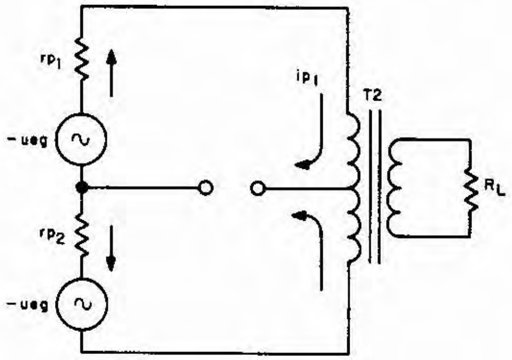
Dynamic Characteristic Curve for Class A Operation

The output transformer turns ratio and load impedance relationships in the push-pull amplifier are based upon a unity turns ratio of secondary to one-half of the primary. Thus, when the whole primary-to-secondary turns ratio is considered, that is, the plate-to-plate load, the ratio is 2 to 1. Since the transformer impedance between the primary and secondary varies as the square of the turns ratio, a 4-to-1 impedance transformation is obtained. For example, with a 1000-ohm load across the secondary, the plate-to-plate load is 4000 ohms, and the individual tube load is 1000 ohms. The proper load for a particular tube varies in accordance with the design and class of the amplifier, and is beyond the scope of this handbook. The effectiveness of the push-pull circuit results basically from the elimination of second-harmonic distortion, which permits the tube parameters to be increased much beyond those of the single-ended stage for an equivalent amount of distortion, thus providing a much greater power output. Another reason is that the apparent internal plate resistance of the push-pull combination is much lower than that of a single tube (on the order of rp/2). Therefore, with the same voltage and bias as that of a single tube, the lower dynamic plate resistance permits much greater output. In addition, the amount of distortion does not increase greatly when the tubes are driven to zero bias or even into the positive region. Therefore, Class B operation becomes feasible, and is used where large amounts of audio power are desired.

The manner in which second-harmonic distortion is eliminated can be more easily visualized if the accompanying equivalent circuits are examined. Part A of the figure shows the fundamental and odd-order equivalent circuit, while part B shows the second and even-order harmonic circuit. Note that in part A of the figure i_p flows in the same direction through the primary of T2; thus the fundamental and odd-order harmonics induce an output in the secondary and appear across R_L. The current flow is in opposite directions through the power supply, however, so that the fundamental cannot appear as feedback through the common supply impedance; thus oscillation from this cause is prevented. In part B of the figure the flux in the primary developed by i_p cancels, and, while the second-harmonic current does exist in the primary, it does not appear in the secondary as long as the circuit is balanced. Even with an unbalanced current, however, any second-harmonic output is considerably reduced. The reduction of second and even-order harmonics also contributes to a much reduced third and odd-order harmonic content. Since the second and third harmonics produce most of the distortion encountered in the amplifier circuit, the push-pull amplifier automatically provides a much larger undistorted output than that of the single-ended stage. The manner in which the output power and third-harmonic distortion vary in accordance with the plate load for a typical two-tube push-pull amplifier is shown in the accompanying figure. The tube types, plate voltage, bias, and grid drive are the same as those used in a similar graph shown in the discussion of the TRANSFORMER-COUPLED TRIODE AUDIO POWER AMPLIFIER, discussed previously in this section of the Handbook. Comparison of these charts shows almost a three-time power increase over that of a single tube for the same load resistance, with a total absence of second-harmonic distortion and very little third-harmonic distortion.

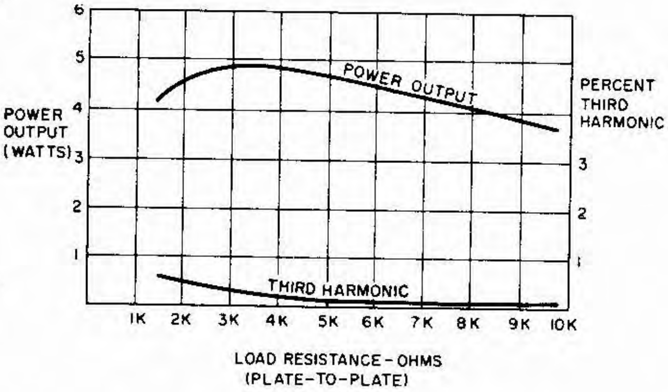


A-ODD-ORDER HARMONICS



B-EVEN-ORDER HARMONICS

Simplified Push-Pull Equivalent Circuits

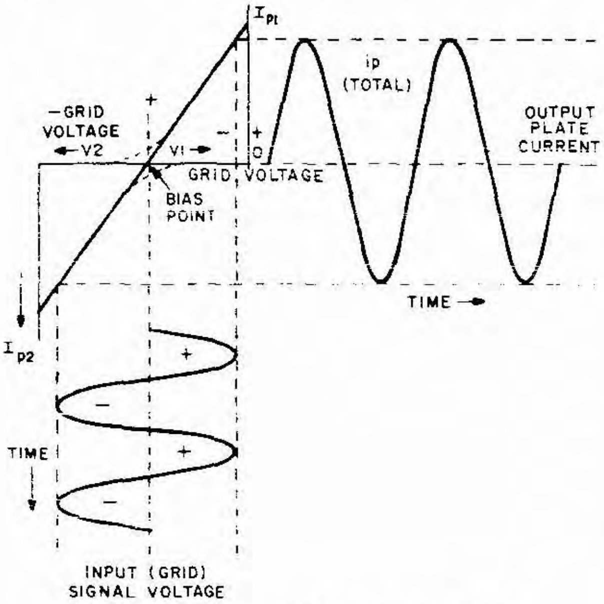


Distortion and Power Output Variation with Load Resistance for a Typical Push-Pull Amplifier

Class AB Operation. In Class AB push-pull operation, sometimes referred to in other texts as Class A prime operation, the grid bias is increased over that of Class A operation, and plate current does not flow during the entire 360 degrees of the cycle. During the peak grid excursions, therefore, some rectification of the grid signal occurs when the plate current is interrupted, causing distortion and high peak plate currents. With self-bias this increases the bias during the peaks and produces nonlinearity, which is the main cause of the increased distortion. With fixed bias the abrupt change which occurs with self-bias is not encountered, and the distortion is less. This occurs because there is no abrupt increase in plate (cathode) current to produce the bias change; instead, the bias at the peaks is determined by the resistance in the grid circuit and any grid current flow so that the change is proportional to the signal increase, it is somewhat more linear, and less amplitude distortion is created. Therefore, self-bias is usually avoided in Class AB operation. Regardless of distortion effects, however, the increase in bias (over that of class A operation) at a particular plate voltage reduces the total operating current and the plate dissipation. Therefore, the efficiency in the plate circuit increases and greater power output is obtained. If desired, the plate voltage (for triodes) may be still further increased to restore the plate dissipation to the full rated value with still greater output. For this reason, Class AB operation is generally preferred to Class A operation where power output is the main consideration and a slight increase in distortion can be tolerated. Since the plate current range, and hence the cathode current (in self-biased operation), is greater than that of Class A operation, a slight unbalance between the tubes usually occurs. Therefore, a cathode bypass capacitor is generally used in self-biased Class AB operation to prevent degenerative effects due to this unbalance. Although matched tubes are desirable, whether or not cathode bypassing is used, it is considered to be more economical and practical to provide a current-balancing control in the bias circuit and to use unmatched tubes. Actually, for Class A or AB operation, it is only necessary to match the quiescent value of current to obtain a balance within 10% over the operating range.

The dynamic characteristic of Class AB push-pull operation is obtained in the same manner as that of Class A push-pull operation. A typical characteristic curve would show that the bias is closer to the plate-current cutoff value than is true of the Class A push-pull circuit. In addition, the resultant characteristic is linear over a greater length as compared with Class A operation. This results in less distortion and greater plate efficiency. Maximum efficiency for Class AB operation is on the order of 50 to 55 percent.

Class B Operation. A typical dynamic characteristic curve for Class B operation is shown in the accompanying figure.



Typical Class B Dynamic Characteristic Curve

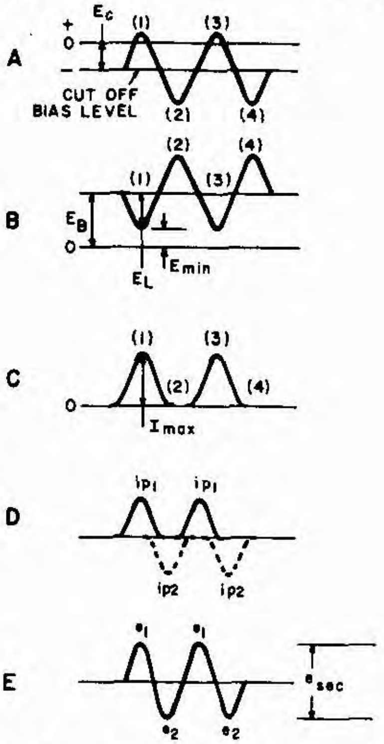
Note that the bias is higher than that for Class AB operation and is nearer to, but not quite sufficient to cause, plate current cutoff. Thus, a slight idling (static) current exists with no input signal. With the greater bias, a greater drive signal is required. Since the grids are usually driven positive and grid current is drawn (that is, Class B operation), a power-driver stage is necessary .

Because grid current flows on the peaks of the input signal, a low-impedance grid circuit is necessary, and is usually provided by using a step-down turns ratio from the primary of the input transformer to the secondary. This also has the effect of reducing the internal plate resistance of the driver tube, and produces better over-all voltage regulation to help diminish distortion on the peak input signal swings. While the circuit operates in a manner similar to that of a Class A or AB push-pull amplifier, it differs in that only one tube is operative at a time. It can be seen, then, with each tube operating separately, that large fluctuations exist in the plate current and voltage, as well as grid current and voltage, and well-regulated power and bias supplies are necessary to avoid distortion. The distortion is caused by flattening of the peaks due to poor regulation. Since the plate current, and hence the cathode current, fluctuates greatly, self-bias is impracticable, and fixed bias is used; in some applications special hi-mu Class B tubes designed to operate at zero bias with very small plate current flow are used. Because only a small static plate current is drawn when no input signal is present, the average plate current is less than that for Class A operation, even though the plate current swing is greater. This is the reason for the higher efficiency produced by the Class B push-pull amplifier. For example, it can be demonstrated that with a plate efficiency of 60%, the power output is 1.5 times the plate dissipation. On the other hand, for a Class A stage operating at 25% efficiency, the power output is only 1/4 of the plate dissipation. Thus, it is possible to obtain six times as much power output from the same tube in Class B operation as in Class A operation .

Because each tube of the Class B push-pull amplifier operates on alternate half-cycles, the cancellation of the second-harmonic component (a feature of the Class A or AB push-pull amplifier) does not exist (except for the period during which both tubes operate). Harmonic distortion at the input is transmitted in amplified form to the output. Any second-harmonic distortion generated in the stage is also induced in the secondary of the plate transformer. This occurs because the only time that flux exists in the core of the output transformer from both tubes is during the small idling period between signals or during static operation. Class B operation also tends to produce second-harmonic distortion because the dynamic characteristic of each tube is not affected by the other tube's plate current; these currents occur separately during opposite half-cycles (unlike the Class A or AB stage, where one current is coupled to the other by flux produced by simultaneous current flow in the primary of the plate transformer). Regardless of the tendency toward distortion, the operation of the two tubes "back to back" in the push-pull circuit permits selection of the straight-line portion of the dynamic characteristic for operation . Since operation in this region is linear, second-harmonic distortion is effectively eliminated. However, if operation occurs in the nonlinear region beyond this, or if the tubes are mismatched badly (10% difference in current will produce 5% distortion), then second-harmonic distortion will be produced and the effectiveness of the push-pull connection will be lost. Despite the apparent disadvantages of Class B operation, when careful attention is paid to design much greater output is obtained with not too much additional distiotion. Therefore, Class B operation is universally used for high-power audio applications, particularly for transmitter modulator stages. Practically, efficiencies on the order of 60 to 66% are obtained, although the theoretical maximum efficiency poassible is $\pi/4$, or 78.5 percent.

The accompanying figure shows typical waveforms developed in the Class B amplifier over two cycles of operation, and clearly illustrates the current and voltage relationships. In part A of the figure the input (grid) signal is shown as a sine wave, with an amplitude sufficient to exceed cutoff bias E_c and drive the grid slightly positive. Half-cycles (1) and (3) are identical, as are (2) and (4). However, the odd and even half-cycles are 180 degrees out of phase with each other. As the input signal swings positive, plate voltage E_b is reduced by the drop across load E_L until the peak value of input signal is reached. This corresponds to E_{min}, as shown in part B of the figure. Simultaneously, as shown in part C of the figure, the plate current of tube V1 increases to value I_{max} at the peak of the signal. As the input signal recedes and falls to the cutoff bias value, E_L decreases to zero (supply value of E_b) at cutoff. At this time, the plate current is at a minimum rather than zero, the plate voltage is that of the supply, and the drop across the load is zero. Actually, this is the time when idling or static current exists, and is some small value other than zero; it is indicated by the overlap of the current waveforms in part D of the figure. Part D also shows the plate currents for the two tubes, where i_{p_1} is that for V1 and i_{p_2} is that of V2. Current i_{p_2} is shown dotted since it is 180 degrees out of phase with i_{p_1} and occurs during the time V1 is cut off. With matched tubes these waveforms are identical, and with unmatched tubes they vary slightly. (A 10% current difference will produce approximately 5% harmonic distortion.)

The waveform for V2 is produced in exactly the same manner as that for V1 by the even-order half-cycles, (2) and (4) in the figure, while (1) and (3) keep V1 nonconducting. Part E of the figure shows the output voltage in the secondary of the plate transformer. The positive and negative swings are produced through the primary on alternate half-cycles of operation. Thus, the output voltage is similar to the input voltage and is twice that produced by one tube.



Typical Class B Current and Voltage Waveforms

For small-amplitude input signals, operation occurs around the point of idling or static (zero) current. In this region the characteristic of each tube is extremely nonlinear and much distortion occurs. However, when large input signals are applied, this area represents only a small fraction of the range; hence its effect is negligible. This nonlinearity at the zero bias point, plus that caused by grid current flow, and unmatched plate currents caused by a difference in tube characteristics, add together to increase the total harmonic distortion. Thus, the Class B amplifier always has more inherent distortion that either the Class A or AB amplifier.

Other Considerations. A special form of Class B operation is that known as Class B **quiescent** operation. In this case the operation is B_1, that is, the grids are never driven into the positive regionl This type of operation is essentially similar to Class AB operation, except that the bias is higher. Because the grids are not driven positive, less distortion is produced and less driving power is required. However, the extremely large output obtained with B_2 operation is not possible; thus it finds rather limited use. Since the theory of operation is similar to those types discussed above, it will not be further explained in this Handbook.

Because of the extremely large fluctuations of current and voltage which occur in the typical Class B amplifier, and because some tubes exhibit a negative resistance effect over part of the cycle, transients may be produced and parasitic oscillations sometimes occur in the grid or plate circuits. These undesirable effects are eliminated by placing small bypass capacitors between the cathode and grid or across the primary of the plate transformer. In some instances, in the plate circuit, a series R-C combination may be placed from plate to plate. In such cases, these components act as simple high-pass filters to reduce transient response. They are not essential to the operation of the circuit, and serve only to prevent the possibility of undesired parasitics. The insertion of these components and the determination of their values are design problems not concerned with circuit operation.

FAILURE ANALYSIS.

No Output. Lack of an input signal, defective input or output transformers, lack of plate or filament voltage, or a defective tube can cause a no-output condition. The presence of plate or filament voltages can be determined by a voltage check . Use an oscilloscope or a vacuum-tube voltmeter to determine whether an input signal exists. Follow the signal through the circuit; when the signal disappears, the trouble will be localized. While an open open input winding (T1 primary) will prevent the development of an output signal, either secondary may be open without stopping operation; in this case the circuit will operate on one tube with reduced output. Likewise, in the plate transformer (T2), while an open secondary will prevent any output, an open primary will not (unless both halves are open). Loss of plate voltage on one tube with normal supply voltage indicates that half of the primary is open. One defective tube will not prevent output; however, if both tubes are defective there will be no output. While short circuits across the input can cause loss of output, it is rather unlikely except where capacitors are placed from grid to cathode or from plate to plate in order to prevent transients and parasitics. If such capacitors are used and no output is observed, the capacitors are probably shorted. A resistance check of the windings **with the power off** will indicate continuity; a resistance reading of less than 1 ohm will probably indicate a short circuit.

Reduced Output. Many conditions can cause reduced output. The most common cause is loss of amplification in one tube. This condition can result from a defective tube, loss of filament or plate voltage, or a short circuited condition. Remove one tube and then the other. If one half of the circuit is operative, the output will be reduced considerably or cease entirely when the good tube is removed. If the tube removed is defective, the output will not change; it may even increase. Loss of plate voltage to one tube can be determined by a voltage check. Visual indications such as the plate showing color indicate excessive plate dissipation in the good tube. However, this is only a relative check, since a short circuit can also exist in the tube showing color. An oscilloscope waveform check will show definitely whether one tube is operating normally, but not the other tube. If this is the case, the plate voltage and bias may be checked on the inoperative tube to determine the fault. Where a tube is suspected, replace it with one known to be good. With normal plate, filament, and grid voltages but with reduced output, the trouble is either a tube (or tubes) or a short-circuited (grounded) transformer winding. Check the output load or device, since improper loading will cause reduced output.

Distorted Output. Improper bias, plate voltage, or load impedance, as well as overdrive, will cause distortion. Distortion resulting from poor frequency response may be caused by poor transformer construction, and also by improper loading. If the transformer is defective, replace it. Also, examine the load to make certain that it is of the proper value . Check for the proper bias and plate voltage with a high-resistance voltmeter. Use an oscilloscope to determine the grid drive and observe the waveform. Excessive second-harmonic content in a Class B amplifier indicates distortion in a previous stage, or nonlinearity of a tube (or tubes). Check the tube for matched currents, or substitute a pair of tubes known to be matched and note whether the response improves. With matched currents (linear response), very little second-harmonic distortion will be present. With unmatched tubes, a 10% difference in currents can produce as much as 5% distortion. In a Class A or AB push-pull amplifier, second-harmonic distortion indicates that the tubes are improperly loaded or that one tube is defective, since this type of distortion will cancel out in the secondary if the circuit is operating normally. If balancing adjustments for bias and plate current are provided in the equipment, a readjustment will probably return the operation to normal. Operate Class A or AB stages with one tube in the circuit at a time and note on an oscilloscope whether both circuits perform identically, observing the waveform at both the input and the output. The source of distortion should be obvious. When Class B stages are operated with one tube only, the output will be highly distorted; both tubes are necessary to minimize distortion.

PHASE INVERTERS.

Phase inverter circuits are used to produce an oppositely polarized signal simultaneously with the normal output signal. Thus two equal and opposite signals are produced for driving push-pull amplifiers. Since the outputs are usually equal in amplitude and opposite in polarity, they are commonly spoken of as being oppositely phased — one signal is always at its minimum when the other signal is at its maximum, therefore, they are out of phase with respect to each other. Any actual change in phase, such as might occur at low frequencies in conventional audio amplifiers, similarly exists in the phase inverter. Because the conventional grounded cathode amplifier inverts the input signal in the plate circuit, simple single-stage phase inverters can be developed by taking one output from the cathode and the other output from the plate. Where cost is no consideration, the most straightforward method is to use transformer coupling with a center tap on the transformer secondary. When properly designed and constructed, the transformer will produce equal and opposite signals operable over identical pass bands. In addition, the low d-c resistance of the secondary permits driving Class B stages, which draw grid current, without excessive grid loss or distortion. When operated at very low or at very high frequencies, however, the response limits of transformer coupling make it more desirable to use RC coupling, for better response. At extremely low frequencies (near zero cps) direct coupling is used to eliminate the reactive effect of the coupling capacitor. Thus phase inverters are similar in design to conventional audio amplifiers, with the exception of the methods used to obtain the phase inversion, and to obtain equal amplitude signals. To obtain more gain and better balance, two-tube phase inversion circuits are used. While plate coupling is normally used, cathode coupling may be used where gain is not of prime importance, and a low impedance output is desired. When exact balance is important and the effects of common signal coupling (induced hum or noise) are to be minimized the differential paraphase inverter provides a more representative and purer output. Each type of circuit is fully discussed in the following paragraphs.

TRANSFORMER TYPE PHASE INVERTER.

APPLICATION.

The transformer type of phase inverter is used for driving push-pull amplifiers, in public address systems where grid current flow is sufficient to cause distortion in other types of inverter circuits.

CHARACTERISTICS.

Uses an output transformer with a common secondary center tap.

Uses self bias, although fixed bias may sometimes be used.

Provides maximum output and gain.

Output amplitude is primarily determined by the transformer turns ratio.

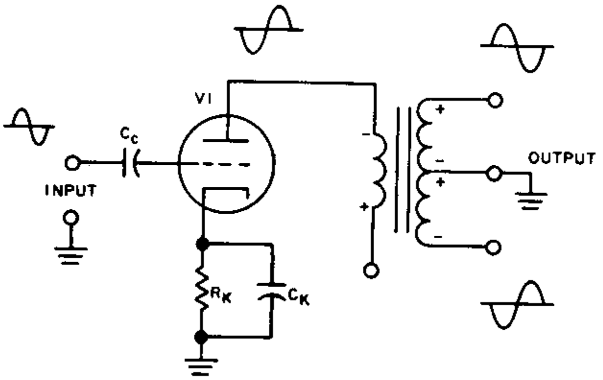
Frequency response is uniform over a range of approximately 100 cps to 5000 cps.

Two outputs, balanced with respect to ground, are supplied.

CIRCUIT ANALYSIS.

The transformer type of phase inverter is basically a transformer coupled audio amplifier with a center tapped secondary. When the center tap is grounded, two opposite polarity outputs are produced which are essentially out of phase with respect to each other. Thus, a single input signal will provide a dual output with polarity and phase correct for driving a push pull stage. Because the transformer secondary has a low dc resistance, this type of circuit is usually employed where grid current is drawn, such as in Class B push-pull stages. While also classed as a phase splitter and paraphase amplifier, these terms are considered to be more applicable to other types of inverters which use special circuit arrangements to obtain the phase difference and dual output.

Circuit Operation. The schematic of a typical transformer type of phase inverter is shown in the accompanying illustration. A triode tube is employed for simplicity, since it will usually supply sufficient drive (output) for moderate powered push-pull amplifiers. Where greater power or drive voltage is required, a pentode tube may be used, or an additional push-pull driver stage can be added.



Transformer Coupled Phase Inverter

The high impedance resistance coupled input uses Cc as the coupling capacitor and Rg as the triode grid resistor. Cathode bias is supplied through cathode resistor Rk bypassed by Ck. Plate voltage is applied to V1 through the primary of T1. The secondary of T1 is center tapped, and the outputs are obtained between each end of the winding and the center tap.

With no signal applied, tube V1 is resting in the quiescent condition, with the voltage drop across cathode resistor Rk supplying Class A bias (plate current flows continuously for the whole cycle). Cathode bypass capacitor Ck prevents degeneration so that instantaneous plate current variations have no effect on the bias. (See Section 2, paragraph 2.2.1 of this Handbook for a discussion of cathode bias.)

When a positive input signal is applied, the grid of V1 is driven positive and increased plate current flows. The increased plate current flow through the primary of transformer T1 produces a greater magnetic field linking the windings and causes a voltage to be induced in the secondary. With a center tap provided at the electrical center of the winding, two outputs can be obtained, as shown by the polarity indicated in the schematic. With opposite polarities, these outputs are of the proper phase for driving a push-pull stage. When the positive half-cycle is completed and the negative half-cycle begins, assuming a sine wave input signal, plate current is reduced. The reduction of plate current flow through the primary of T1 induces a voltage in the opposite direction in the secondary, because the direction of the magnetic field is now changed. Thus a negative output is produced during the negative half-cycle. The polarity of the secondary winding is now opposite that shown on the schematic. However, because of the grounded center tap, points 1 and 2 on the winding will be of equal amplitude, but of opposite polarity, or phase.

FAILURE ANALYSIS.

No Output. Lack of plate voltage, improper bias voltage, as well as a defective tube will cause a loss of output. Loss of plate voltage or improper bias, may be determined by making a voltage check with a voltmeter. With plate voltage at the supply but not on the plate of V1, transformer T1 primary is open or V1 is shorted. With V1 shorted there will be a larger than normal voltage drop indicated across the primary resistance of T1. Replace V1 with a known good tube, when in doubt, and recheck the plate voltage. With proper plate and cathode-bias voltage, and no output, either grid resistor Rg is open or the secondary of T1 is open. Make a resistance and continuity check of these parts with an ohmmeter to determine which is at fault.

Low Output. Low plate, or high bias voltage, as well as a defective tube can cause a low output. If abnormal plate current is drawn, the plate voltage of V1 will be lower than normal and the cathode bias will be higher than usual and thus less output will be obtained. Use a voltmeter to check plate and bias voltages. If bias and plate voltages are normal, replace V1 with a good tube, since low tube emission can also cause a reduced output. If the low output condition persists after tube replacement, transformer T1 is probably defective. A slight increase in plate voltage with a reduced primary d-c resistance, as checked with an ohmmeter, coupled with poor low frequency response is an almost positive indication of a partially shorted primary. Any short or high resistance condition in the secondary will usually show on a resistance check of the secondary, and will probably cause a reduction in one of the output signal amplitudes, if not in both. Use an oscilloscope or VTVM to compare output voltage indications.

Distortion. Use an oscilloscope to observe the input signal waveform and amplitude, then check the output waveforms. If any difference of waveform occurs between the two output signals, the distortion is probably caused by the tube or transformer, particularly when normal plate and bias voltage readings are obtained. Substitution of a known good tube or transformer will determine the part at fault.

SINGLE-TUBE PARAPHASE INVERTER.

APPLICATION.

The single-tube paraphase inverter supplies a push-pull output from a single-ended input. It is used mainly to drive audio push-pull power amplifiers in public address systems, or modulators, and in receiver audio-stages.

CHARACTERISTICS.

Self-bias is usually used although fixed bias may be used, if desired.

Two out-of-phase outputs are provided, one from the plate circuit, and one from the cathode circuit.

Frequency response is relatively uniform from about 100 to 15,000 cps.

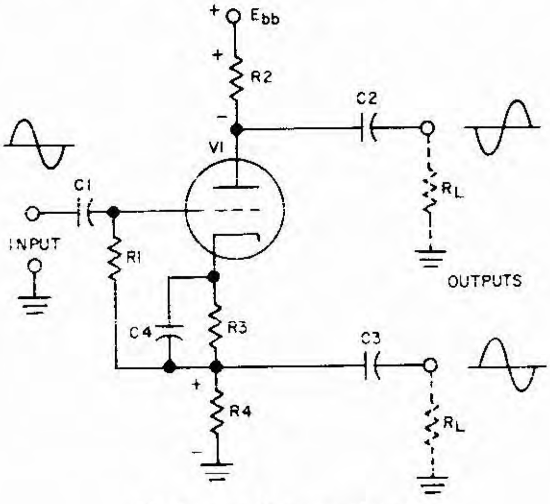
Either triodes or pentodes may be used (pentode provides slightly higher output with improved high frequency response).

Provides less gain than is possible with transformer coupling (output is always less than the input).

CIRCUIT ANALYSIS.

General. The single stage paraphase inverter, also known as a **phase splitter** utilizes the phase inverting property between the grid and plate of the electron tube to supply a 180 degree out-of-phase output. The plate output together with an in-phase output, which is taken from the cathode, provides the desired push-pull output. Since balanced signals are desired, the amplification is limited to that which can be obtained from the cathode, which is always less than unity for a cathode follower. Thus, when plate and cathode outputs are made equal, the output is always less than the input signal. This circuit, however, is more economical to produce and has a better overall response than the transformer coupled circuit. Hence it is usually used in lower priced equipment. For best results two-tube paraphase circuits are preferred, since the overall amplification and response may be arranged to provide better performance with a larger output than either the transformer coupled, or the single-tube stage.

Circuit Operation. The schematic of a typical single-tube paraphase inverter is shown in the accompanying illustration.



Single-Tube Paraphase Inverter

The input signal is RC coupled through C1 and R1 to the grid of triode V1. Cathode bias is supplied by R3 bypassed by capacitor C4. The outputs are developed across plate load resistor R2, and cathode load resistor R4, and are capacitively coupled to the push-pull driver or output stage by C2 and C3.

With no signal applied, V1 rests in the quiescent condition with Class A bias supplied by cathode current flow through cathode resistor R3. Since grid coupling resistor R1 is returned to the ground side of R3, any voltage developed across R4 by cathode flow has no effect on the bias between the grid and cathode of V1. Furthermore, since the voltage developed across R4 in the quiescent condition is steady (DC) no output appears from coupling capacitor C3. Likewise, any plate voltage drop developed across plate resistor R2 is also a steady DC and no output appears from C2.

Assume a sine-wave audio input signal is applied to the input terminals. During the positive excursion, the grid of V1 is driven in a positive direction in the conventional manner and an increasing plate current flows. When plate current increases, electrons flow from ground, through R4, and C4 (which bypasses R3), within the electron tube from cathode to plate, and through plate resistor R2 to the voltage supply, creating the polarities shown on the schematic. Note that the cathode voltage is positive, is in phase with and follows the input signal, while the plate voltage drop is negative and out-of-phase with the input signal. Since these two voltages are constantly varying at an audio frequency they appear as outputs across C2 and C3, and ground. The values of R2 and R4 are made approximately equal so that equal amplitude output signals are produced.

When the input signal reaches its peak positive excursion and swings in a negative direction, the plate and cathode current through V1 is reduced, and the output voltage is reduced, likewise. As the input signal reaches the zero level and swings down into the negative region, the polarities across R2 and R4 are reversed. That of R2 rises towards the plate supply source and becomes positive-going, while that of R4 continues towards zero, drops below the quiescent level and is effectively negative-going because of the reduced cathode current flow. Again, two oppositely polarized (phased) and equal output signals are produced from the single input signal. Thus as the input varies at audio frequency, the cathode and plate outputs do likewise, but oppositely. Since R3 is bypassed for audio frequencies by C4 the bias remains unaffected by the signal current variations (see explanation of cathode bias given in paragraph 2.2.1 in Section 2 of this Handbook).

As long as R2 and R4 are equal, and C2 and C4 together with their coupling (load) resistors (RL) are equal, the frequency response of both circuits is almost identical. At frequencies above 20 kc the plate output of V1 tends to drop off because of the effect of the appreciable triode grid-plate capacitance which is usually larger than the grid-cathode interelectrode capacitance. Therefore, where higher audio frequencies are desired, the pentode tube is used instead of the triode so that its reduced interelectrode capacitance minimizes this effect.

FAILURE ANALYSIS.

No Output. Open input or output circuits, a defective tube, improper bias, or lack of plate voltage can result in loss of output. Check the bias and plate voltages with a voltmeter. Use an oscilloscope to observe the input waveform and follow it through the circuit from grid to cathode to plate, and then across the outputs. If an input appears across the input terminals but no signal appears on the grid, coupling capacitor C1 is open. If the grid of V1 reads positive C1 is shorted or leaky. When checking the bias across R3, measure from grid to cathode using the proper polarity, and then from R4 to cathode. If the grid to cathode reading is zero, grid return resistor R1 is open. If an output appears across R4 but does not appear on the plate of V1, either the tube is defective or R2 is open. With plate voltage present from R2 to ground, V1 is defective (if the voltage is equal to the supply on both sides of R2, the resistor is shorted). When an output appears on the plate of V1 but not at the output load, coupling capacitor C2 is open. If C1 is shorted the plate voltage of the preceding stage will drive V1 into saturation, a constant high voltage will appear across R4, and a constant low voltage across R2 (on the plate of V1) and no output will be obtained. When the tube is suspected, replace it with one known to be in good condition before making any further checks.

Low Output. Insufficient bias on V1 due to R3 changing to a lower value (or if C4 is shorted) will cause a low plate voltage and a high cathode voltage, and reduce both outputs. If C1 is leaky the grid of V1 will show a positive voltage to ground. If R1 is open the grid of V1 will tend to block or build up a higher than normal bias, operating at or near cutoff with reduced output. If V1 is leaky or gassy, a positive voltage cause by grid current flow will appear between grid and ground. Should normal bias and plate voltage be indicated by a voltmeter but low output still exists, tube V1 may be low in emission and produce a much weaker than normal signal. When operating properly, the cathode and plate outputs will be equal and just slightly less than the input signal amplitude, because of cathode follower action reducing the gain to less than unity.

Distorted Output. Normally, the output signal will be of the same shape and of only slightly less amplitude than the input signal. Use an oscilloscope to observe the input and output waveforms, with a constant sine-wave input signal applied. Flat-topping or rounding off of the positive peaks of the output signal indicate distortion caused by low emission or reduced plate voltage on V1. If the plate voltage is normal and flat topping occurs the tube is defective. If the tube is operated with too high a bias (near cutoff) the peaks will also be clipped when the tube is driven to cutoff. If cathode bypass capacitor C4 is open, the bias on V1 will change with the signal, and amplification will not be linear, some amplitude distortion will occur and degeneration will cause a drop in output at the signal peaks. For small input signals little or no distortion will be observed. However, on large signals the bias may be driven into the cutoff region causing bursts of distortion. If C4 is open, the cathode bias will vary instantaneously with the input signal variations and show on a voltmeter as a constantly varying (instead of a steady) voltage. With normal plate and bias voltages, distortion can also be caused by overdrive (too large an input signal). When the distortion observed on the oscilloscope at the outputs disappears as the input signal amplitude is reduced overdrive (or improper biasing) is the cause. Since output coupling capacitors C2 and C3, together with the associated load resistance RL, are in parallel across the plate and cathode resistors, any change in these components or in the load can create some distortion. Such a condition will usually create an inbalance and result in different output amplitudes. Leaky coupling capacitors will show a positive voltage on the load side as well as on the plate or cathode sides and are easily detected by a high resistance voltmeter.

TWO-TUBE PARAPHASE INVERTER.

APPLICATION.

The two-tube paraphase inverter supplies a push-pull output from a single-ended input. It is used to drive push-pull audio amplifiers in receivers, public address systems, and modulators, where more amplification or gain is needed, and the single-tube inverter stage will not suffice.

CHARACTERISTICS.

Self bias is usually used, although fixed bias may be used, if desired.

A single-ended input is converted into two out-of-phase outputs.

Amplification may be obtained in addition to the phase inversion.

Either triodes or pentodes may be used, with the pentodes providing higher gain and improved frequency response.

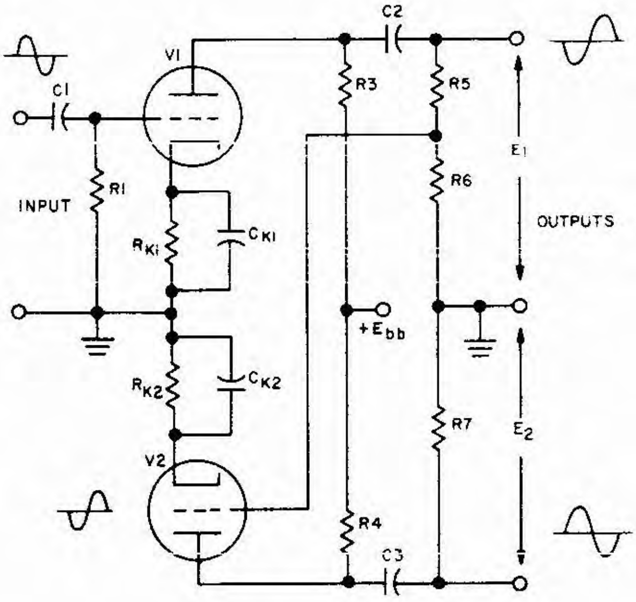
Inherently not self-balancing (usually requires rebalancing if tube is replaced).

Frequency response is relatively uniform from about 100 cps to 15,000 cps.

CIRCUIT ANALYSIS.

General. The two tube paraphase inverter usually employs a single, dual-triode with each half-section connected as a separate amplifier-inverter. Both outputs are taken from the plate circuit, and full amplification can thus be obtained. This type of inverter uses a small portion of the output of one half-section (taken off of a voltage divider across the output) to supply the out-of-phase drive to the second half-section. Balance is primarily determined by the stage gain of the tube. If the gain is different between two tubes (or two half-sections) the voltage divider ratio must be changed (or separate cathode bias resistors are used instead of a common cathode resistor) to keep the outputs equal. Since such balancing is difficult, the two tube circuit usually is subject to a slight unbalance. However, the large amplification possible permits the stage to be used both as a driver and phase inverter (and sometimes as an output stage) thus economically combing two stages into one.

Circuit Operation. The following schematic illustrates a typical two-stage triode phase inverter. Triodes are used to simplify the discussion.



Triode Two-Tube Paraphase Inverter

Pentodes operate in the same fashion as described below for triode operation, except for considerations of the effect of screen current and voltage (for the same plate voltage a larger swing is possible, and a greater sensitivity and output are obtained with a slight increase in overall frequency response).

The input to triode V1 is RC coupled through C1 and R1, while the inverted input to triode V2 is direct-coupled from voltage divider R5 and R6 connected across the output of V1 (a circuit variation is to employ capacitance coupling and a grid return resistor from V2 to ground). Cathode bias is obtained individually from Rk_1 and Rk_2 bypassed by Ck_1 and Ck_2, respectively. (In other circuit variations a common cathode resistor, either unbypassed or bypassed, may be used. Where the single dual-triode is used and separate cathodes are supplied, the circuit shown in the schematic permits closer tube balancing.) Resistors R3 and R4 are the plate load resistors for tubes V1 and V2, respectively, and the outputs are RC coupled through C2, C3, and R5, R6, and R7. Capacitor C2 and voltage divider R5, and R6, provide the output labelled E1 from V1. The inverted input signal for V2 is obtained across R6. Thus R6 also serves as the grid resistor for V2. By direct-coupling from R6 to the grid of V2, any deleterious reactance effects produced by passing the signal through an additional coupling capacitor are avoided (the two coupling capacitors connected in series would reduce the effective low frequency response). Normal operating bias for V1 and V2 is either Class A or Class A prime (AB) operation. Because the input for V2 is taken from across R6, and both R5 and R6 are in series with the grid of the following (output) stage, Class B operation cannot be used (grid current flow on the signal peaks through R6 would produce a distorted input to V2). With no signal applied, the circuit operates in the quiescent condition. Plate current flows through cathode bias resistors Rk_1 and Rk_2 providing normal Class A or AB bias (see Section 2, paragraph 2.2.1 of this Handbook for an explanation of cathode biasing).

Assume that a sine-wave input signal is applied to the grid of V1. As the signal goes through its positive-going excursion, the grid is driven in a positive direction causing the plate current to increase. The increasing plast current of V1 produces a voltage drop across plate load resistor R3, and reduces the instantaneous plate voltage. Thus a negative-going voltage is developed across R3 (during the positive half-cycle) and is applied to coupling capacitor C2. Since the signal is constantly changing the a-c component appears across output resistors R5 and R6, which are connected in series between coupling capacitor C2 and ground. This is the output voltage E1 from tube V1. Resistor R6 is usually one tenth the value of R5, and together they form a voltage divider, so that one tenth of the output of V1 appears as an inverted exciting signal voltage which is applied directly to the grid of V2. This negative-going voltage on V2 grid produces a decreasing plate current in V2, and the voltage across R4 (at the plate of V2) rises towards the source (becomes more positive). The increasing positive-going plate output from V2 is coupled through C3, producing output voltage E2 across R7. Thus the output of V2 is opposite to that of V1 in polarity (out-of-phase) completing the other half of the desired push-pull output. As the plate currents of V1 and V2 rise and fall, the cathode currents do likewise. However, since they are bypassed by capacitors Ck_1 and Ck_2, they do not affect the steady bias voltage developed by average current flow through the cathode resistors.

When the input signal reaches its positive peak and reverses, conditions, likewise, reverse. The grid of V1 is now driven in a negative direction and the plate current of V1 falls. Output voltage E1 now becomes positive-going and continues to increase until the negative input peak is reached. Meanwhile, the voltage across R6 (which is applied to V2 grid) also rises in a positive direction with the plate voltage of V1, towards the voltage of the supply. Therefore, the grid of V2 is effectively driven positive, causes an increase of plate current and produces a negative voltage drop across plate resistor R4. This negative-going output is coupled through C3 and appears across R7 as output voltage E2. When the input signal reaches the negative peak and swings positive again towards zero level, conditions again revert to that of the initial half-cycle. Thus the positive and negative half-cycle of input signal control the grids of tubes V1 and V2 to produce relatively identical, but inverted and amplified signals (the relatively large current flow through the large valued plate resistors develops an output voltage much larger than that of the input voltage). Although V2 grid is excited by the output of V1, operation is practically instantaneous so there is no appreciable delay between the input voltage on V1 and that on V2.

Because the gains of two tubes will vary slightly, there is a difference in amplitude between the two outputs, unless the bias is changed slightly on one tube. Thus the circuit is seen to be inherently unbalanced, and it does not of itself provide any automatic balancing, as does occur in the cathode-coupled or in the differential types of paraphase circuits. While the circuit values are selected properly by the manufacturer and designer, it is usually necessary to change cathode and plate resistance values in one tube when a new tube is substituted, to minimize amplitude distortion (this does not authorize any modifications to be made to Navy equipment, since circuit design is presumed to adequately cover such a condition). In most cases the additional distortion produced by tube gain differences is within acceptable limits and is of academic interest only.

When dual-triodes with a single, common-cathode are used in this type of circuit, bias is obtained by a common cathode resistor. In some cases this cathode bias resistor is also bypassed by a capacitor, and a constant unbalance occurs due to the differences in gain between the two half-sections. In other instances, this cathode bias resistor is not bypassed. When unbypassed, the two instantaneous cathode currents flowing in opposite directions tend to cancel out, as in push-pull amplifiers, so that the steady state bias remains substantially constant. Any remaining signal effects which are not balanced out become degenerative, and add to the bias to reduce the total output. When properly designed, this helps to balance the output signals and provide an increase of linearity and a reduction of inherent distortion. Since these circuit variations are only effective to a limited extent, the self-balanced type of paraphase inverter is usually preferred for use where distortion is to be limited to a absolute minimum. Such circuits are discussed later in other paragraphs in this section of the Handbook.

FAILURE ANALYSIS.

No Output. An open input or output circuit, improper bias, or lack of supply voltage, as well as a defective tube can cause a loss of output. Check for the proper bias and plate voltage on V1 using a high resistance voltmeter. Too high a bias will almost produce plate current cutoff and reduce the output so low that it is practically no output at all. Measure the bias first from cathode to ground, and then from the grid to ground. If normal bias is obtained from cathode to ground but not from grid to ground, R1 is open. If input capacitor C1 is shorted, tube V1 will be driven into saturation by the plate voltage from the preceding stage driving V1 grid highly positive. If C1 is open, no signal will appear on the grid side but will appear at the input (use an oscilloscope to observe the waveform). If a signal appears at the grid, and in inverted form at the plate of V1 but not at the output, either coupling capacitor C2 is open or the output is shorted. Checking the resistance of R5 and R6 to ground will quickly determine if the output is shorted, if not, then C2 is open. Use a capacitance checker to determine if C2 is satisfactory. With proper bias and plate voltage, and an input to V1 but still no output, tube V1 is defective. Replace it with a known good one. Since the output of V1 is used to supply an input for V2, the output of V1 should always be checked first. When there is an output from V1 but not from V2, either the bias is too high, the plate supply or load is open, the output circuit is open or shorted, or tube V2 is defective. With normal plate voltage and cathode bias on V2 but no signal visible on the plate, tube V2 is defective. Replace it with a known good one. The signal should now appear at the plate. If still no output is obtained, coupling capacitor C3 is open, or the output (R7) is shorted. Check from R7 to ground with an ohmmeter to determine if the output is shorted, and check C3 with an in-circuit capacitance checker.

Reduced Output. Improper bias, reduced plate voltage, or a defective tube can cause a reduced output. Check the bias and plate voltage with a high resistance voltmeter. The voltages should be within the limits shown in the instruction book. If the bias is too high on V1, the tube can be driven almost to cutoff on the negative peaks; or if it is too low, V1 may be driven into saturation on the positive peaks. In either case there will be a reduction in output and distortion. Clipping of the waveform can easily be observed with an oscilloscope. If output E_1 is satisfactory, a similar set of conditions can cause a reduction of output in V2. Use the oscilloscope to observe the cathode, grid, and plate of V2. Any signal on the cathode indicates Ck_2 is not properly bypassing or open. Lack of or low grid signal indicates improper voltage division, check R5 and R6 for normal resistance with an ohmmeter. With the signal on the grid of V2 of almost the same amplitude as that on the grid of V1, and an amplified plate signal but a reduced output (E2), check C3 and R7 (either C3 is partially open or low in capacitance, or R7 is low in value or shorted).

Distorted Output. Improper bias, low plate voltage, or a defective tube can cause a distorted output. Use an oscilloscope to follow the signal through the circuit from input to V1 grid and plate, to V2 grid and plate, and note when the distortion appears. Too low a bias will cause clipping on the positive peaks, and too high a bias will cause clipping on the negative peaks. Likewise, low plate voltage or low tube emission will also cause peak clipping. If plate voltage reads normal on the voltmeter, and clipping occurs on the positive peaks, the tube emission is low and insufficient to supply the peak current demand. Replace the defective tube with a known good one. Since V1 drives V2, any distortion which appears on the output of V1 will also appear on V2 grid, and will be amplified and appear in V2 output also. With V1 showing no distortion, and V2 distorted, check V2 bias and plate voltage. If these voltages are normal, V2 is probably in need of replacement. Because of the inherent unbalance of this circuit the outputs of V1 and V2 will usually be slightly different, and a slight amount of distortion, say 1 to 2 percent, can be considered as normal operation. Make certain, also, that overdrive is not causing the distortion. Too large an input signal will cause clipping, which can be observed to disappear as the gain is reduced.

PARAPHASE, CATHODE-COUPLED INVERTER.

APPLICATION.

The paraphase cathode-coupled inverter is used to drive a push-pull audio amplifier from a single-ended source. It is used in audio amplifier systems where self-balance together with amplification is desired, and good frequency response and a minimum of distortion is required.

CHARACTERISTICS.

Self bias is usually used, although fixed bias may be used, if desired.

A single-ended input is converted into two equal and out-of-phase outputs.

Amplification is restricted to about half the maximum value obtainable from a single tube.

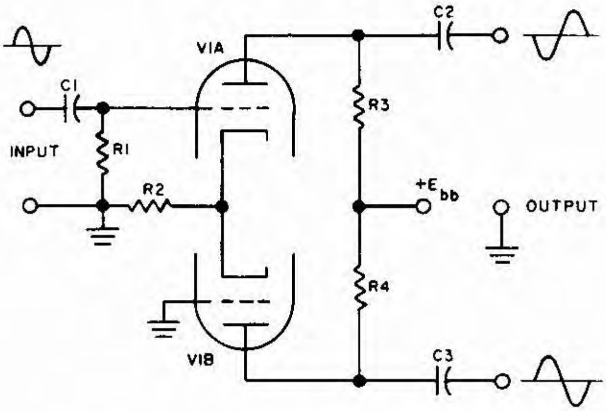
Is self-balancing, with a relatively uniform frequency response of approximately 100 to 20,000 cps.

Either triodes or pentodes may be used, with the pentodes providing higher gain and slightly improved high frequency response.

CIRCUIT ANALYSIS.

General. The cathode coupled inverter is usually used with dual triodes having a common cathode. This circuit offers a saving in space and weight over those of the two tube type of inverters with a slight reduction of components. The inherent self-balancing feature makes it particularly valuable for circuits requiring a minimum of distortion, since a slight amount of degenerative feedback occurs in the cathode circuit and improves the linearity. In addition there is no necessity to rebalance the circuit when tubes are changed, and hum due to cathode-to-heater leakage is kept to a minimum.

Circuit Operation. The following schematic illustrates a typical cathode-coupled paraphase inverter. Although separate cahtodes are shown for simplicity and ease of discussion, the tube is actually a dual section triode with a common cathode.

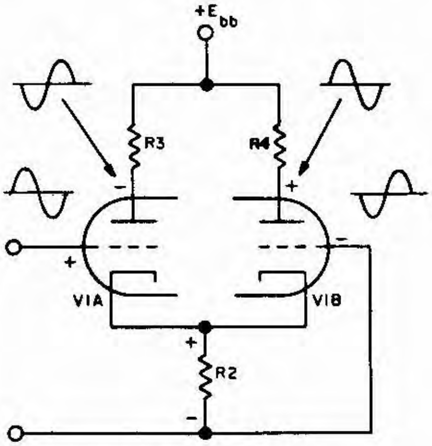


Cathode-Coupled Paraphase Inverter

The input signal is RC coupled through capacitor C1 and grid resistor R1 to the grid of triode V1A, a half-section of dual-triode tube V1. Cathode bias and signal injection for tube V1B, the other half-section of V1, is provided through common cathode resistor R2. The outputs of both half-sections are also RC coupled to the following push-pull stage. Resistor R3 is the plate load resistor for V1A from which the out-of-phase output is coupled through C2, while resistor R4 is the plate resistor for V1B, and the in-phase output is coupled through C3.

In the quiescent condition with no signal applied, both V1A and V1B conduct and develop cathode bias across R2. The value of R2 is chosen so that the bias is set at the center of the tubes dynamic operating range, with about half normal plate current flowing through each half-section of V1. Since a push-pull output is provided, the cathode and plate current of one half-section increases while that of the other decreases. Thus the average bias remains substantially constant and there is no necessity for bypassing the cathode resistor.

When a sine-wave signal is applied to the input it is effectively passed through capacitor C1 and appears across R1. Assume that the sine-wave is starting its positive half cycle of operation, the grid of V1A is driven in a positive direction, and causes an increased plate current to flow. Electron flow is from ground through cathode resistor R2, tube V1A, and plate resistor R3 to the supply. This electron flow creates an instantaneous polarity as shown in the simplified drawing below.



Simplified Polarity Diagram For Positive Half-Cycle of Operation

As can be seen from the drawing, the cathodes of both V1A and V1B become more positive, while the instantaneous plate voltage is decreased by the voltage drop across R3, producing a negative output at the plate. This negative output is coupled through C2 to drive the next stage. The normal grid to plate phase-inverting property of an electron tube is used in this half-section to develop the out-of-phase signal. Meanwhile, with an increasing positive voltage applied to the cathode of V 1B, you recall from basic theory that this is the same as applying a negative signal to the grid, and V1B plate current is, therefore, decreased. As the plate current of V1B is decreased, the plate voltage rises towards that of the supply, and a positive output is developed across R4. This positive output is coupled through C3, as the in-phase signal, to drive the following push-pull stage. When the input signal reaches its positive crest, V1A is heavily conducting while V1B is lightly conducting, and opposite and equal output voltages are produced.

As the input signal changes direction and becomes negative-going, operation reverses and the instantaneous polarity becomes opposite that shown on the drawing. Thus tube V1A plate current reduces and V1B plate current increases. The cathode voltage developed across R2 also reduces, which is the same as driving V1B grid positive and causes V1B plate current to increase. A negative output is now produced by the voltage drop across plate resistor R4, and a positive output voltage is developed across R3 as the plate voltage of V1A rises towards the supply voltage with the reducing plate current. Thus the outputs are reversed to produce the negative half-cycle of input signal.

When the negative input signal peak is reached, operation again changes back to the original state with V1A plate current increasing while V1B plate current decreases.

FAILURE ANALYSIS.

No Output. Too high a bias, lack of supply voltage, an open input or output circuit, or a defective tube can cause loss of output. Check the bias and plate voltage with a high resistance voltmenter. With normal bias and plate voltage and no output, either there is no input signal or coupling capacitor C1 is open, or output coupling capacitors C2 and C3 are open, or the tube is defective. Use an oscilloscope and check for a signal on both sides of C1. If the signal appears at the input but not on the grid side of the capacitor, it is open. Likewise, if the signal appears on the plate but not at the output, the associated output coupling capacitor (either C2 or C3) is open. If grid resistor R1 is shorted no signal will appear on the grid of V1A also. A simple resistance check from grid to ground will reveal if the input is shorted. If both half-sections of V1 are defective, or if V1A is defective no output will be obtained, but if only half-section V1B is defective an output will be obtained from V1A. When the tube is suspected replace it with one known to be in good condition.

Low Output. Improper bias, low plate voltage, or a defective tube will cause a reduced output. If input capacitor C1 is shorted or leaky, a positive voltage will be applied to the grid of V1A, will cause a heavy flow of plate current and bias off the tube near the cutoff point. If extreme, practically no output will occur, otherwise, a reduced output will be obtained depending upon the amount of bias produced. Usually such a condition will be indicated by a high cathode bias, with a positive grid voltage, and a low plate voltage caused by the large drop through the plate load resistor, produced by the excessive plate current flow. If R2 changes to a lower value, the bias across R2 will tend to remain the same because a larger plate current flows, the increased flow of plate current will, however, cause a larger than normal drop across the plate resistor(s), reduce the plate voltage, and hence the output. If the emission of tube V1 is low, apparently normal grid and plate voltages may be measured on the voltmeter, but the output will be weak and distorted when a signal is applied since the plate current will not be able to follow the signal.

Distorted Output. Due to the common cathode and bias arrangement a decrease in plate current flow on one side will be compensated for by an increase on the other side. Hence distortion is kept to a minimum. Use an oscilloscope and compare the input, grid, and cathode waveforms; they should all be uniform and of the same relative amplitude. Now compare the plate and output waveforms. They should be identical and of larger amplitude. If distortion appears and is eliminated by reducing the input signal, overdriving is indicated. If distortion appears in the plate circuit but not in the grid circuit, either the tube needs replacing or the plate voltage or load is at fault. If either of coupling capacitors C2 or C3 are leaky, a reduced plate voltage may be produced because of voltage division effects across the next stage input resistors, and cause unbalance and distortion. Check the plate voltage with a voltmeter, if below normal, check the associated plate load resistance with an ohmmeter and check the coupling capacitor with a capacitance checker.

DIFFERENTIAL PARAPHASE INVERTER.

APPLICATION.

The differential paraphase inverter is used to drive a balanced push-pull audio amplifier from a single-ended (unbalanced) source. It is used in audio amplifier systems where high amplification and good balance is necessary.

CHARACTERISTICS.

Self bias is usually used, although fixed bias may be used, if desired.

A single-ended (unbalanced) input is converted into two equal and out-of-phase outputs.

Almost full tube amplification is obtainable.

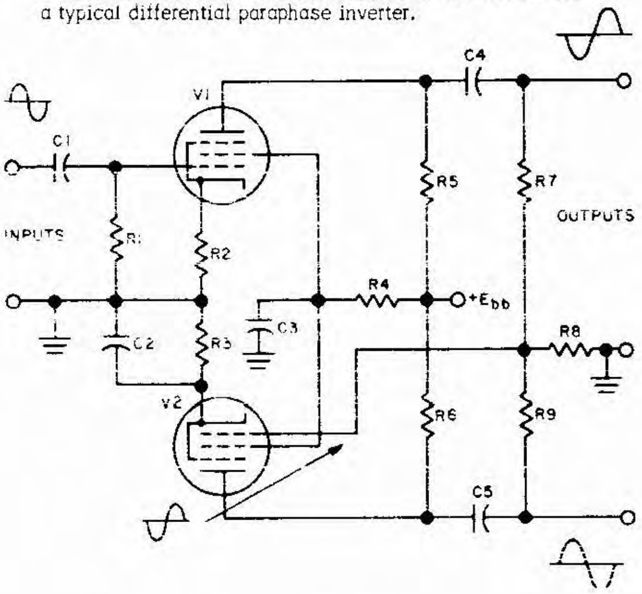
Circuit is self-balancing with a relatively uniform frequency response of 100 to 20,000 cps or more.

Pentodes are used for high gain and increased high frequency response, but triodes may be used in special instances.

CIRCUIT ANALYSIS.

General. The differential paraphase inverter uses the difference between the two output signals to supply the driving signal for the in-phase output. Pentodes are usually employed, since their high gain permits reducing the difference signal to such a small value that for all practical purposes the outputs can be considered identical. The method of obtaining the difference signal provides an effective negative feedback which stabilizes the gain through the circuit and improves its self regulating properties.

Circuit Operation. The following schematic illustrates a typical differential paraphase inverter.



Typical Differential Paraphase Inverter Circuit

The input signal is RC coupled through input coupling capacitor C1 and grid resistor R1 to the grid of V1. Cathode bias for V1 is developed across unbypassed cathode resistor R2, and through R3, bypassed by C2, for tube V2. Screen voltage is obtained from the common plate supply source through series screen voltage dropping resistor R4, and the screens are bypassed to ground by screen capacitor C3. The suppressor elements of the tubes are connected to the cathode. Resistive plate loads and capacitive output coupling is provided. The output is developed across plate resistors R5 and R6, and is applied through C4 and C5 to the output voltage divider consisting of R7 and R9 connected in series with difference resistor R8 to ground. Resistors R7, R8, and R9 also function as grid resistors for the following push-pull stage driven by the inverter.

Tube V1 operates as a conventional resistance coupled amplifier, with the unbypassed cathode resistor providing a slight amount of degenerative feedback to improve the overall response and stabilize the gain. In the quiescent condition, with no signal applied V1, the cathode current consisting of the sum of the screen current and plate current flows through cathode resistor R2 to establish the normal bias level. With a steady screen current flow, a constant voltage drop is produced across screen resistor R4, and together with the screen current of V2, is sufficient to drop the plate supply to the desired screen voltage value. Since R4 is bypassed by C3, the screen voltage remains unaffected by any signal variations when the signal is later applied. Any d-c voltage drop across plate resistor R5 reduces the plate supply to the desired quiescent plate voltage value, and no output is produced. In a similar manner, V2 rests in the quiescent condition with its bias determined by the sum of the screen and plate currents (total cathode current) of V2 through separate cathode bias resistor R3. Since R3 is bypassed by C2, the bias on V2 also will not change with the signal later when it is applied. With both V1 and V2 screens connected in parallel the same screen voltage is applied to both tubes. Although quiescent plate current flow through R6 produces a voltage drop which reduces the supply voltage to that desired for the plate operating value, it is a steady d-c and no output appears from C5. From the discussion and an examination of the schematic, it is evident that V2 also operates as a conventional resitstance coupled stage similar to V1 except for the source of input voltage. With R7 and R9 connected as a voltage divider in series with R8 across the output of V1 and V2, when a voltage appears across R8 an input is applied to V2 grid. Since the outputs of V1 and V2 drive a push-pull stage they are opposite in polarity and equal, and the effective voltage across R8 is zero. However, the bias network is designed so that the output of V1 is always slightly greater than that of V2, the difference voltage then appears across R8 and is the driving voltage for V2.

With the basic conditions now established, assume that a sine-wave input signal is applied to the grid of V1. During the positive half-cycle of the input signal, the grid of V1 causes an increased plate current flow, and produces a negative-going voltage drop across plate resistor R5, which is applied through C4 to output voltage divider R7 and R8. The portion of negative output voltage appearing across R8 is applied to V2 grid, produces a reduction in plate current, and the plate voltage of V2 rises towards the supply value. Thus, a positive-going output is applied across C5 to output voltage divider R9 and R8. The output voltage from V2 appearing across R8 opposes the output developed by V1 across R8, and all but a small fraction of this voltage is cancelled out. This small difference voltage is the actual drive voltage applied V2 grid.

When the input signal on V1 reaches its positive peak and reverses, it becomes negative-going. This negative grid voltage on V1 causes a reduction in the plate current of V1, and the plate voltage rises towards that of the supply. Thus a positive-going output voltage is developed, which is applied through C4 to output voltage divider R7 and R8. The positive portion of voltage across R8 drives V2 grid in a positive direction, and causes an increased plate current flow through plate resistor R6. The voltage drop across R6 is negative-going and is coupled to output divider R9 and R8 through C5. The negative output voltage from V2 cancels all but a small fraction of the positive voltage across R8. Because the plate output of V2 is also connected back to the grid by voltage divider R9 and R8, a feedback loop exists. Since the output of V2 is always out-of-phase with the grid of V2 the feedback is essentially negative. Thus V2 is stabilized and improved response and linearity are obtained. At the same time, this feedback ensures that the output of V2 is always slightly less than that of V1. Since negative feedback is provided from plate to grid, the cathode of V2 is bypassed by C2 so that full amplification without further degeneration may be obtained.

When the input signal reaches its negative peak and reverses, once again it is positive-going and the initial action discussed above for V1 is repeated. Thus alternate positive and negative half-cycles of input signal produce equal and balanced out-of-phase outputs. The V1 output is always out-of-phase with the input, while the output of V2 is always in-phase with the input.

FAILURE ANALYSIS.

No Output. An open input or output circuit, lack of supply voltage, input signal, or a defective tube will cause a no-output condition. Check the cathode bias, and plate and screen voltages with a high resistance voltmeter. If the voltages are normal but no output exists, check the input with an oscilloscope. If the signal appears at the input but not on V1 grid, coupling capacitor C1 is open or R1 is shorted. Check the resistance from grid to ground to determine if the input is shorted. If the signal appears on the grid but not on the plate, make certain that proper screen voltage exists. If C3 is shorted the entire screen voltage will be dropped across R4 and no output will appear, likewise, if R4 is open no screen voltage will be applied either V1 or V2. Loss of screen voltage will be detected during the other voltage tests since both plate and bias voltages will be higher and lower than normal, respectively. With normal plate and screen voltdge applied, if still no signal appears on the plate, either the tube is defective or plate resistor R5 is shorted. Replace the tube with a known good tube, and check the value of R5 with an ohmmeter. If a signal appears on the plate but does not appear at the output, either coupling capacitor C4 is open or R7 and R8 are shorted. Check the capacitor with an in-circuit capacitance checker and the output voltage divider resistors with an ohmmeter.

If an output appears from V1 but not from V2, check with the oscilloscope for a signal on V2 grid. If no signal appears, R8 is either open or shorted. If a signal appears on the grid of V2 but not on the plate, V2 must be at fault. Previous voltage checks were made for bias, screen, and plate voltage so that C2, R3 and R6 cannot be at fault. Replace the tube with a known good one. A signal should now appear on the plate, and an output be obtained from V2. If no output can be obtained either C5 is open or R9 is shorted. Check the capacitance of C5 with an in-circuit capacitance checker, and measure the resistance of R9. Also measure the resistance from C5 to ground to determine that a short does not exist across the output. Such a condition could be caused by a shorted grid-to-cathode element in the following push-pull stage.

Low or Unbalanced Output. Improper bias, low plate or screen voltage, as well as a defective tube can cause a reduced output. If return resistor R1 is open or becomes high in value with age, the grid of V1 will tend to develop a negative bias and block causing reduced output from both tubes. Check the value of R1 with an ohmmeter. If R4 changes to a higher value, the screen voltage and output will be reduced. Check the screen voltage with a voltmeter and the resistance of R4 with an ohmmeter. If C3 is partially shorted or leaky, the excess current drain through R4 will also lower the screen voltage. If the screen voltage rises when C3 is disconnected from ground, replace the capacitor. If the emission of either tube is low, the voltages may show normal, and signals appear on grids and plate, but a reduced output occur because of the inability of the tube plate current to follow the signal completely.

If bypass capacitor C2 becomes shorted, the cathode resistor of V2 will be effectively removed from the circuit, and the tube will operate at zero bias. Such operation will cause an unbalanced output with distortion. Checking the resistance of R3 to ground with an ohmmeter will determine if C3 is shorted. If bias resistors R2 or R3 change in value the balance will also be upset, depending upon the amount of change. An ohmmeter check of the resistors will determine whether they are at fault. If either plate resistor R5 or R6 increase in value the output will be above normal, but if they decrease in value the output will be below normal. While the supply voltage drop may be different for each of these cases, the current will also change and may make the plate voltage reading fall within tolerance values. Therefore, a resistance check of the plate resistors will quickly show if they have changed in value. Changes in voltage divider resistors R7, R8, and R9 will change the gain, drive, and output. Tube V1 output is affected mostly by R9. Defective tubes in the push-pull circuit following this stage can cause a heavy load with a consequently reduced output. When in doubt, replace both the inverter and output stage tubes with known good ones and check to see if the output returns to normal.

Distorted Output. Improper bias, screen or plate voltage, as well as a defective tube or overdrive can cause distortion. Check the bias, plate, and screen voltages with a voltmeter. If all voltages are normal but the output is distorted and low the tubes are probably defective, replace them with known good ones. If the distortion reduces when the input signal is reduced, it is the result of too high a drive for the bias used. Poor balance will also cause distortion. Use an oscilloscope and follow the signal from grid to plate through the circuit, and compare outputs. When the distortion appears the cause will be found in the parts associated with that portion of the circuit.

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CATHODE FOLLOWER.

APPLICATION.

The cathode follower is used for two purposes: To isolate the output of a critical circuit from the loading effects of a circuit to which the output is fed; and to match the output impedance of a signal source to the input impedance of a load circuit. Both purposes are accomplished with an absolute minimum of distortion of the input signal.

CHARACTERISTICS.

Utilizes a single-stage degenerative amplifier, to furnish an output which appears across an unbypassed cathode resistor.

Input impedance is high; no grid current flows.

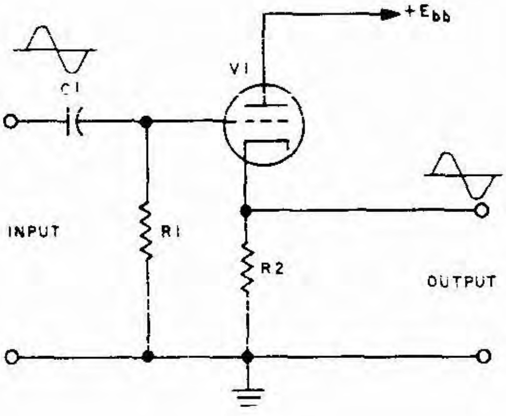
Output impedance is low; output signal is in phase with input signal.

Output voltage gain is less than unity; output exhibits a power gain.

Operated Class A to obtain, in the output signal, a faithful reproduction of the input signal.

CIRCUIT ANALYSIS.

General. In the basic circuit shown in the accompanying illustration, a triode tube is used, but a pentode tube may be employed in a similar manner. In the basic circuit the cathode bypass capacitor is absent, and the plate is tied directly to the supply voltage, $+E_{bb}$. The input signal is applied through coupling capacitor C1 to the grid of the tube, V1, and the grid is returned to ground through a relatively high value grid resistor, R1. The output is taken across the cathode resistor, R2, and since



Basic Cathode Follower Circuit

this resistor is unbypassed, the output signal voltage is a direct function of the plate current which flows through this resistor. As the input signal rises, or goes in a positive direction, the plate current increases, causing an increased voltage drop across the cathode resistor. As the input signal falls, or goes in a negative direction, the plate current decreases, causing a decrease in voltage drop across the cathode resistor. Thus the output signal **follows** the input signal, both in value and in polarity, although the *actual* (voltage) value of the output signal is somewhat less than that of the input signal.

Circuit Operation. In the basic cathode follower circuit, *under conditions of no signal input to the grid*, a certain amount of plate current flows through the tube because of the positive potential applied to the plate from the plate supply (E_{bb}). *This plate current flows through* the cathode resistor, R2, and the resultant voltage drop across R2 establishes the no-signal bias level, with the grid effectively at zero (ground) potential, and the cathode at some positive (above ground) potential.

When a positive signal is applied to the grid, the resulting increase in plate current through cathode resistor R_2 increases the voltage drop across R2, making the cathode more positive. In like manner, a negative signal applied to the grid causes the plate current flowing through cathode resistor R2 to decrease, making the cathode less positive. Thus the signal variation on the grid produces a variation in plate current through the cathode resistor, and the resulting variation in voltage drop across the resistor develops the bias voltage. This bias voltage, being in phase with the input signal, subtracts from the input signal during the positive half cycle, and adds to the input signal *during the negative* half cycle. The resulting change in bias in both cases reduces the amplitude of the grid-to-cathode voltage, producing degeneration of the output voltage. For this reason, the voltage gain of a cathode follower is always less than one.

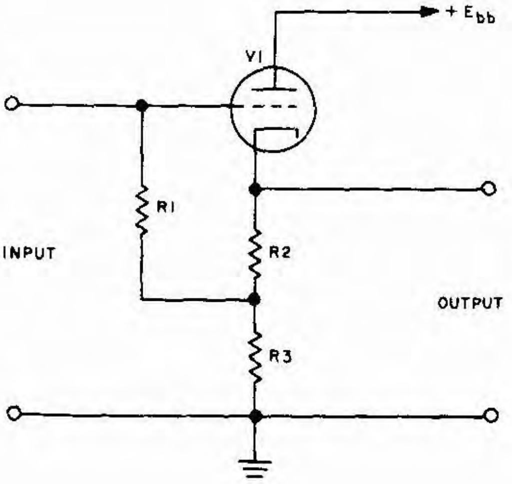
Cathode followers are normally operated with the grid negative with respect to the cathode under conditions of no input signal. The input impedance is high, and remains high when an input signal is applied. When a positive signal is applied to the grid, the degenerative action increases the grid bias to such an extent that no grid current will flow. This is the same result that would be obtained if the input impedance had been increased. When a negative signal is applied to the grid, no grid current can flow, even though the grid bias is decreased through the degenerative action. Thus the input impedance remains high. As a result of this high constant input impedance, the cathode follower presents a negligible loading effect to the circuit driving it.

The *effective* input capacitance of a cathode follower is low, compared to that of a conventional amplifier. This results from the fact that the degenerative action reduces the amplitude of *the a-c component of the grid-to-cathode* voltage, and thus causes less current to flow through the tube capacitances.

The output impedance of a *cathode follower is low;* because of this fact there is a minimum of amplitude distortion of the output signal, under normal operating conditions, even though current is drawn from the output terminals. However, if the amplitude of the input signal is high enough to swing the voltage at the grid too far positive or negative, the tube may be driven to saturation or to cutoff, respectively. When either of these points is reached, limiting action occurs, and any further change in the input signal will not appear in the output waveform. The output signal will thereby be distorted with respect to the input.

Occasionally, a cathode follower circuit may be encountered which is actually designed to operate partially in the region of cutoff. In radar circuitry, video and transmitter trigger pulses, which may be positive pulses, might be applied to a cathode follower which is biased near cutoff. As a result, the cathode follower will pass the signal *in normal cathode follower fashion;* at the same time it will clip any negative transients which may be present in the input signal, and, in addition, it will eliminate the possibility of any d-c *loading effects by allowing* only the signal voltages to be present across the output cathode resistor. Although this type of circuit may be termed a **cathode** follower circuit (because the output is *taken from across* the cathode resistor), it does not satisfy that definition of a cathode follower where the output signal shall follow the input signal without change in waveform. In this respect such a circuit, sometimes referred to as a **cutoff cathode follower,** should more properly be termed a **limiter-follower**.

If limiting occurs only on the negative peaks of the input signal, i. e., if the input signal drives the tube to cutoff but not to saturation, the circuitry of the cathode follower may be modified as shown in the accompanying illustration.



Modified Cathode Follower Circuit to Prevent Negative Peak Limiting

In this modified cathode follower circuit, the grid resistor, R1, is returned to a positive (above ground) potential at the junction of a two-section cathode resistor composed of resistors R2 and R3. The value of the positive potential (the relative values of R2 and R3) is determined by the anticipated input voltage level. By returning the grid resistor to a tap on the cathode resistor in this manner, the grid bias is reduced by the amount of the voltage drop across resistor R3. Therefore, the input signal can swing to a greater negative value without driving the tube to cutoff, than it could had the grid resistor been returned to ground potential. In addition, the input impedance of the circuit is increased to a very high value.

A further modification of this circuit is frequently used as a wide-band cathode follower. This circuit, shown below, contains an input coupling capacitor, C1, and a resistor, R4, of small value in the plate circuit for decoupling purposes. Wide-band cathode followers find extensive use when application requirements demand power amplification over an extreme range of audio frequencies, from 70 to 20,000 cps, such as in high-fidelity audio circuits. In the circuit shown below, these requirements may be met by the use of a single triode section of a type 12AT7 twin-triode, with values of C1 = 0.01 μf, R1 = 1 megohm, R2 = 180 ohms, R3 = 820 ohms, and R4 = 47 ohms. Other values would of course be required with other tube types.

The voltage gain (V.G.) of a cathode follower, when a triode-type tube is used, is given by the following equation:

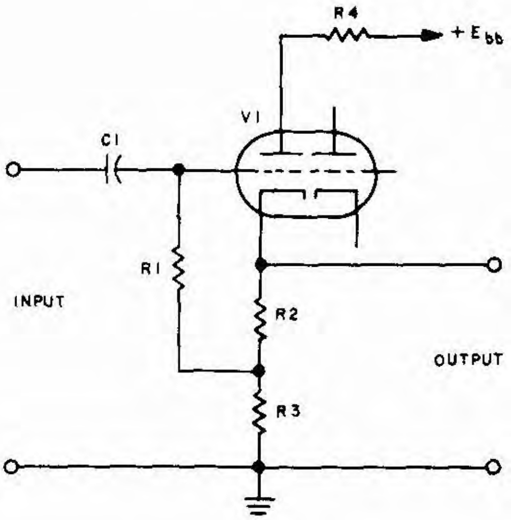
$$\text{V. G.} = \frac{\mu R_k}{r_x + (\mu + 1)\ R_k}$$

When a pentode-type tube is used, μ is large and the term $\mu + 1$ may be reduced to μ. The equation for voltage gain (V.G.) may then be reduced to:

$$\text{V. G.} = \frac{R_k}{\frac{1}{g_m} + R_k}$$

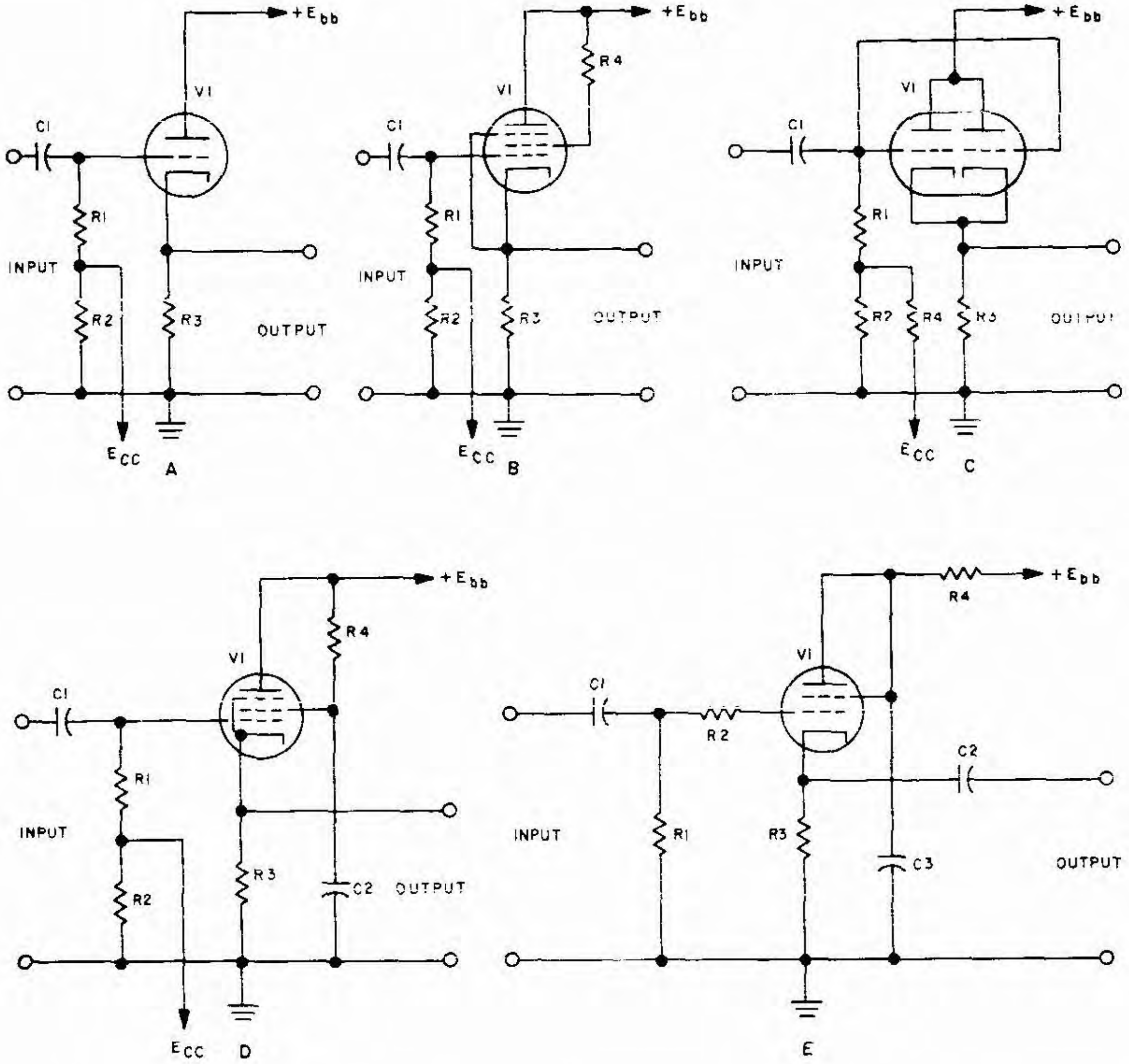
The output impedance (Z_{out}) of a cathode follower is given by the following equation:

$$Z_{out} = \frac{R_k}{g_m R_k + 1}$$



Wide-Band Cathode Follower Circuit

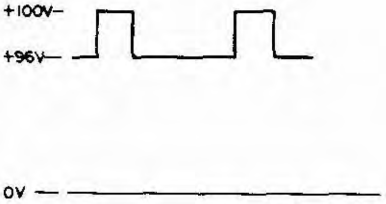
Other modifications of the basic cathode follower circuit are often encountered in radar and communications circuitry. These modifications are included in the following illustrations, which show four circuit variations of cathode followers. In part A, a fixed negative bias is applied, from a power supply, to the grid of a triode at a tap on the grid resistor which is composed of R1 and R2. The output is taken across the cathode resistor, R3. The negative bias applied to the grid, together with the bias developed across the cathode resistor, establishes the initial operating point on the grid voltage-plate current (E_g-I_p) characteristic curve of the particular triode used. The value of negative bias applied depends upon the value of input signal to be handled. This is particularly true in applications where the input signal consists of a series of positive pulses with the interval between each pulse relatively long as compared with the pulse width. For example, if a positive input pulse



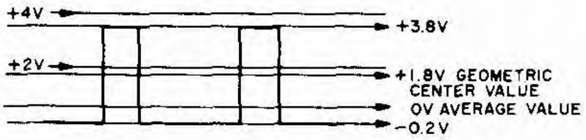
Cathode Follower Circuit Variations

having an amplitude of 4 volts with instantaneous peak values of +96 volts and +100 volts is applied to the input capacitor of a cathode follower circuit, the pulse which appears at the input grid of the tube would settle down to an average a-c value of 0 volts, with most of the pulse appearing above this average value. This is shown in the following illustration, with the input signal shown in part A and the signal voltage which appears at the input grid shown in part B. Fixed biasing is necessary in this situation, in order to place the geometric center of the pulse at the center of the tube's E_g-I_p curve, as shown in part C of the illustration. If, for a given tube, the center of the straight-line portion of the E_g-I_p curve occurs at −5 volts with a given plate voltage, and the input signal is 4 volts peak to peak with the pulse waveform as shown, a total bias of − 7 volts on the tube would be necessary in order to displace the average value of the signal so that its geometric center occurs at − 5 volts (the center of the E_g-I_p curve), as shown in part D of the illustration. If the value of the cathode resistor is such that, when the tube is operating with − 7 volts bias, it produces a 3-volt drop, then the additional amount of fixed bias required is equal to −4 volts.

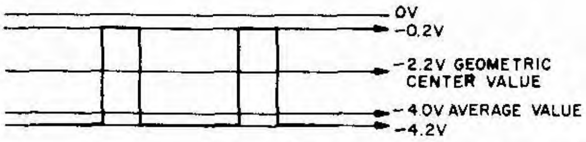
In part B, a triode-connected pentode tube is used, with fixed negative bias applied to the grid in a manner similar to circuit A. Since the power-handling capabilities of pentodes are substantially higher than those of conventional triodes, considerable power output may be obtained from such a circuit. Otherwise, operation of this circuit is generally similar to that of circuit A, with the addition of the screen resistor, R4. This resistor serves to decrease the voltage at the screen grid slightly below the plate voltage, in order to keep the screen dissipation within the operating limits of the tube. When certain tubes are used, or when the plate is operated considerably below the maximum rated voltage, this resistor may be omitted. Since no bypass capacitor is used between screen and ground, the plate and screen currents vary with the input signal, and the tube operates as a triode.



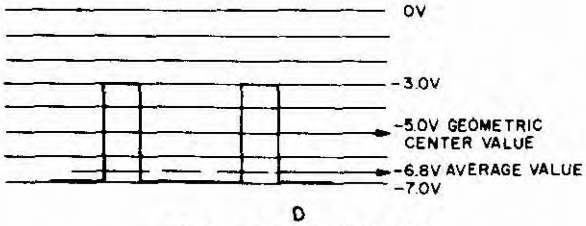
A
INPUT SIGNAL



B
SIGNAL VOLTAGE AT INPUT GRID, DISREGARDING BIAS VOLTAGE



C
SIGNAL VOLTAGE AT INPUT GRID, WITH FIXED BIAS OF -4.0 VOLTS



D
SIGNAL VOLTAGE AT INPUT GRID, WITH FIXED BIAS OF -4.0 VOLTS AND CATHODE BIAS OF -3.0 VOLTS

Cathode Follower Input Waveforms

In part C, a twin-triode is used as a cathode follower, with both sections connected directly in parallel. The use of a twin-triode doubles the power output over that of a single tube section, and in addition provides some measure of assurance of continued output, even though reduced in value, in the event of failure of one of the triodes. The operation of this circuit is similar to that of circuit A, with a few exceptions. A fixed negative bias from a power source is applied through resistor R4 to the grids of both triode sections at a tap on the grid resistor which is composed of R1 and R2. Resistor R4 provides isolation between the grid circuit and the bias voltage supply. The actual bias voltage avilable at the grid will be somewhat reduced, however, because of the voltage divider effect of R2 and R3. The input signal is applied directly to both grids, which are connected in parallel, although in some cases resistors of low ohmic value, used as parasitic suppressors, are connected between the input and each grid to suppress intermodulation effects between the two tube sections. This effect is a result of slight differences in electrical characteristics, such as cathode emission and transconductance, be tween the two sections of the tube. The output from the circuit is taken across R3, which is the cathode resistor common to both sections.

In part D, a pentode tube is used, connected as a conventional pentode. Fixed negative bias is used, as in circuit A. Screen capacitor C2 maintains the d-c voltage at the screen relatively constant with variations in input signal. As a result, the power output obtainable across cathode resistor R3 is somewhat greater with this pentode-connected circuit than it is using the triode connection in circuit B.

In part E, a triode-connected pentode tube is used, although a triode could be connected in an identical manner. In this circuit the grid return is composed of resistors R1 and R2, with R2 providing additional isolation between the input circuit and the tube, and also serving as a grid current limiter. A coupling capacitor, C2, is also employed in the output circuit, to block the d-c component when only the a-c signal output is desired. Plate supply isolation may be employed, by means of the decoupling filter composed of C3 and R4, which in addition helps to prevent variations in the voltage at the plate and screen during positive peaks of the input signal.

Another variation of the cathode follower circuit may be encountered in some equipments, where the cathode resistor and output coupling capacitor are physically located in another chassis, and are connected by means of interconnecting cables. In order to protect the tube against a possible voltage breakdown between cathode and filament, in the event of an open cathode circuit caused by a disconnected or broken cable, an additional resistor of a substantially higher value of resistance may be employed directly at the cathode connection of the tube. Since this resistor is connected in parallel with the main cathode load resistor, its presence will not affect the output during normal circuit operation.

FAILURE ANALYSIS.

No Output. If an input signal is being supplied, an open coupling capacitor C1 in the input circuit or an output coupling capacitor, if used, would interrupt the circuit output, as would also an open cathode resistor R3 or a *shorted plate capacitor* C3. (Refer to Cathode Follower Circuit Variations, circuit E.) Failure of the plate (and screen) power supply, or *an open plate decoupling resistor* R4, if used, or a defective tube, would also be responsible for a condition of no output.

Reduced or Unstable Output. If a normal input signal is being supplied, a weak or intermittently shorted tube, or leaky input or output coupling capacitors may be the cause of reduced or unstable output. A reduction in the applied *plate (and screen)* voltage will cause the output to be reduced, while an unstable supply voltage will cause unstable output signal amplitude. A *change in grid bias*, brought about by a changed value of grid resistors R1 and R2, or of cathode resistor R3, will also affect the output *signal*, and may distort the signal by biasing the tube nearly to cutoff or to saturation.

LOW-LEVEL VIDEO CATHODE FOLLOWER.

APPLICATION.

The low-level video cathode follower is used to match the output impedance of a low-level video source, such as a video limiter, to a low-impedance transmission line, without deteriorating the waveform of the video signal.

CHARACTERISTICS.

Positive output signal is in phase with the positive input signal.

Input impedance is high; *no grid current flows within* the designed operating range.

Output impedance is low; values shown give an actual output impedance of 100 ohms.

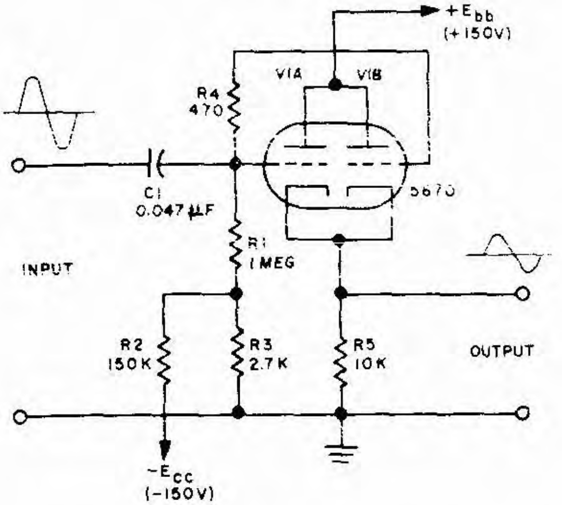
Output voltage gain is less than unity; values shown give an actual gain of approximately 0.5.

Class A output gives undistorted reproduction of input signal within designed operating range.

CIRCUIT ANALYSIS.

General. In the circuit shown in the accompanying illustration, a type 5670 twin-triode is used, with both sections connected in parallel. Actual values of resistance and capacitance used in this circuit are shown in the illustration; these values govern the input and output limits and the operating level discussed under Circuit Operation. An input *capacitor is used in the grid circuit*, and the plates are tied directly to the plate supply voltage, $+E_{bb}$. The grids are returned, through grid resistor R1, *to a fixed negative bias*, $-E_{cc}$, from a voltage divider composed of R2 and R3, which is fed from a −150V bias supply. The output is taken from the paralleled cathodes across cathode resistor R5. Resistor R4 acts as a parasitic suppressor to prevent intermodulation between the two triode sections, due to slight variations between them.

Circuit Operation. This circuit is designed to accept a positive input signal, and reproduce it without distortion in the positive output signal. Under normal operating conditions, the circuit will handle an operating level of 2.2-volt positive input pulses, and produce an output level of approximately 1.0 volt. As a maximum limit, an input signal of 4.2 volts amplitude will produce an output amplitude of 2.0 volts. This output level approaches the grid-current region of the type 5670 tube, and therefore is about the maximum that can be obtained using this tube type. The gain of the circuit is approximately 0.5.



Low-Level Video Cathode Follower Circuit

The input signal is applied through coupling capacitor C1 to the grid of section 1 of a type 5670 twin-triode, and through suppressor resistor R4 to the grid of section 2. A fixed value of grid bias is supplied from a negative 150-volt bias supply, to a voltage-divider circuit composed of 150K resistor R2 and 2.7K resistor R3. The junction of the two resistors, at which the voltage is approximately −2.6 volts, establishes the actual bias to which the grid resistor R1 is returned. The unbypassed cathode resistor, R5, is common to both triode sections, and the voltage drop appearing across it, which is an exact reproduction of the input signal, constitutes the output of the video cathode follower.

A particular form of distortion of the input signal, known as **droop** or **sag,** is of significance in low-level video cathode followers. Droop is the decay in amplitude, with time, of the flat top portion of a positive square wave input signal. The amount of droop is largely determined by the ratio of the pulse length to the RC time constant of the input coupling circuit. For small values, the percentage of droop is equal to the pulse length divided by the RC time constant:

$$\text{Droop (\%)} = \frac{\text{pulse length (seconds)}}{R_{(OHMS)} \times C_{(FARADS)}}$$

For example, for Values of C1 = .05μf and R1 = 1 meg, and a pulse length of 500 μsec,

$$\text{Droop \%} = \frac{500 \times 10^{-6}}{1 \times 10^{6} \times .05 + 10^{-6}} = .01 = 1\%$$

FAILURE ANALYSIS.

No output. Assuming that a signal of the proper positive value is applied at the input to the video cathode follower, the primary cause of no output may be a defective tube. If the tube is found to be operational, an open coupling capacitor, C1, would interrupt the operation of the circuit. An open resistor R3 in the grid bias voltage-divider circuit would allow the full value of the -150-volt bias voltage to be applied directly to the tube grids, cutting off the tube. Failure of the plate supply voltage would interrupt operation of the circuit, as would also an open-circuited cathode resistor, R5, provided that there is no continuous d-c path paralleling R5 in the output circuit.

Reduced or Unstable Output. With a proper positive input signal present at the input to the video cathode follower, a leaky (partially shorted) grid coupling capacitor, C1, may be responsible for a severely distorted output. This leaky condition, acting as a partial short, would allow any value of d-c voltage which is present at the input to be applied to the grid of the tube. This voltage would appear to the tube as a change in grid bias, and shift the operating point on the tube's E_g-I_p characteristic curve into either the cutoff or saturation region. An open grid resistor, R1, may cause the tube to "block", or to "motorboat", or to exhibit no effect other than a distortion of the output waveform. With an open grid resistor the tube may "block" because the grid coupling capacitor, C1, has no readily available discharge path, and **may** gradually accumulate a negative charge, sufficient to cut off the tube, through grid current on the positive peaks of the input signal. Intermittent conduction of the tube, or "motorboating", **may** result if leakage through C1 allows C1 to discharge down to the point where the tube is momentarily "unblocked". In some cases of an open grid resister, no immediately discernible symptoms will be evidenced other than a distortion of the output waveform. This may be caused by the grid "floating" at some intermediate value and the input signal continuing to be coupled through by the capacitive voltage divider action of coupling capacitor C1 and the grid to cathode capacitance of the tube. Since the interlectrode capacitance of the tube is very small as compared with the capacitance of C1, most of the input signal will continue to appear across the grid and cathode, and the tube will react in very nearly a normal manner. Should resistor R2 in the voltage divider network become open-circuited, the fixed negative bias from the -150V power supply would not be applied to the grid. As a result, the input signal may be sufficient to drive the tube to saturation, seriously distorting the output on the positive peaks of the signal. If, on the other hand, resistor R3 became open-circuited, the full value of -150 volts from the bias power supply would be applied to the grid, and the tube would be driven far beyond cutoff. Reduced output may also be traced to an open parasitic suppressor resistor, R4, which would cause one triode section of the tube to be without an applied input signal, reducing the output to half the initial value, with a possibility of distortion on the most positive portion of the input signal due to reduced bias. The reduction in bias would be the result of the "blocked" grid, causing a reduction in current flow through the common cathode resistor, and hence a lower value of voltage drop across the common cathode resistor. If the cathode resistor should change in value, because of age or overload, the output voltage would be changed accordingly.

PULSE CATHODE FOLLOWER.

APPLICATION.

The pulse cathode follower is used as an isolation stage between a critical circuit and the circuit which it feeds as a load, while at the same time preventing any loading effects from appearing at the output of the critical circuit. This is accomplished by means of the cathode follower's characteristic of a high input impedance and a low output impedance.

CHARACTERISTICS.

Output signal is in phase with input signal.

Input impedance is high: no loading effects are reflected at the output of the previous stage.

Output impedance is low: considerable power may be supplied to the output load circuit.

Output voltage regulation is good, due to low output impedance, even though the input signal may have poor voltage regulation due to its high impedance.

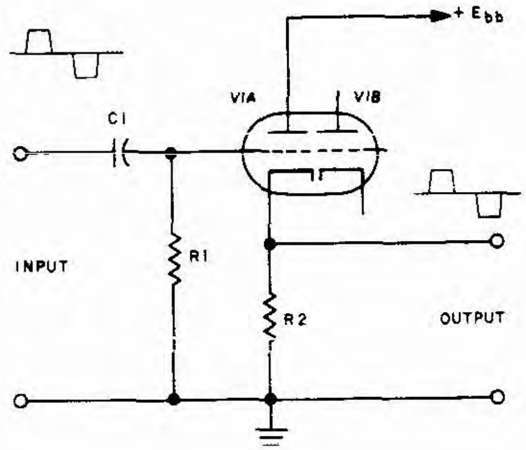
Input capacitance is low: approximately 2.5 $\mu\mu$f excluding capacitance of circuit wiring.

Rise time response is fast: approximately 0.02 μsec.

CIRCUIT ANALYSIS.

General. In the circuit shown in the accompanying illustration, a single triode section of a typical twin-triode such as a type 5814A, is used. Actual values of resistance and capacitance used in the circuit are determined by the operating characteristics desired, and are therefore not given in the diagram. Typical values used to produce specific operating characteristics, and a discussion of the effects produced, are given under Circuit Operation. An input capacitor, C1, is used in the grid circuit, and the grid is returned to ground through grid resistor R1. Plate voltage is supplied directly from the supply voltage, E_{bb}, and the output is taken across the unbypassed cathode resistor, R2.

Circuit Operation. The pulse cathode follower illustrated above, using an input capacitor (C1) of 0.047 μf

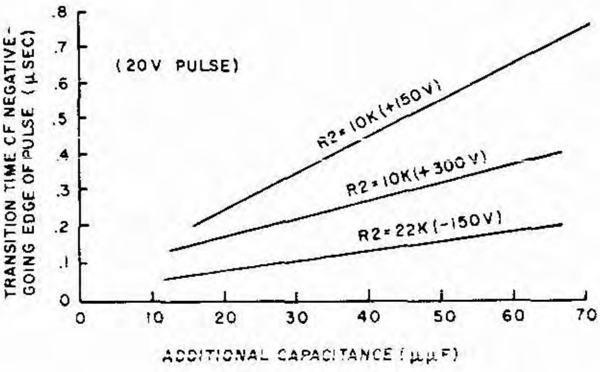


Pulse Cathode Follower Circuit

and a grid resistor (R1) of 680K, with a type 5814A tube (one triode section), has a very low input capacitance of approximately 2.5 $\mu\mu$f, and a fast rise time response of 0.02 μsec. The rise time is in large part dependent upon the transconductance of the tube and its associated interelectrode capacitances. A typical rise time of 0.02 μsec or 0.03 μsec is satisfactory for most radar and other pulse timing applications.

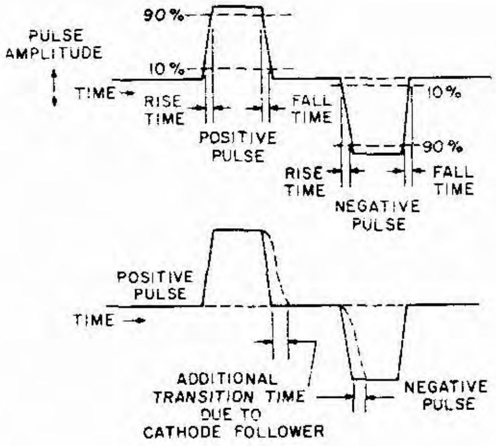
The transition time of the negative-going edges of pulses, such as the fall time of a positive pulse or the rise time of a negative pulse, is increased by a cathode follower. This transition time depends upon pulse amplitude, while the positive-going edges of pulses are unappreciably affected by pulse amplitude. This is due to the fact that the tube transconductance is of a different value during the fall of the pulse than during the rise of the pulse. The tube is nearer cutoff during the fall of the pulse; transconductance is at a low value and the combination of pulse amplitude, capacitance, and the value of cathode resistor all combine to determine the fall time. The negative transition time may be improved by the use of a negative voltage connected to the cathode resistor, from a negative power supply. If this is done, the tube will draw a higher value of plate current in its quiescent state, compared to a similar tube having its cathode resistor returned to ground. As an alternative, the returned end of the grid resistor may be connected to a tap on the cathode resistor. Since a higher value of plate current is now drawn by the tube when quiescent, its operating point is appreciably removed from cutoff. The tube's transconductance is hence at a higher value, and the fall time, or negative transition time, is thereby decreased.

Additional capacitance in the output circuit has an effect on the negative transition time, as shown in the following illustration. It can be seen that the capacitance in the output circuit should be kept to a minimum where small values of negative transition time are required.



Effect of Additional Output Circuit Capacitance on Negative Transition Time

The over-all effect of a cathode follower on the transition time of positive and negative pulses, and a visual definition of transition time as applied thereto, may be better understood by referring to the following waveform illustrations.



Effect on Negative-Going Edges of Pulses Due to Cathode Follower

Typical values of gain, input and output limits, output impedance, rise and fall times, for a single triode section of type 5814A twin-triode operated with plate voltages of

+150 and +300 volts and cathode resistance of 10K and 22K, are given below.

R_k (ohms)	10K	10K	22K (-150V)
E_{bb} (volts)	150	300	300
Voltage gain	0.87	0.87	0.9
Input limit (volts)	0 to 70	0 to 170	-100 to +180
Output limit (volts)	0 to 61	0 to 148	-90 to +162
Output impedance (ohms) for 20-volt input pulse	300	420	300
Rise time (μsec)	0.02	0.02	0.02
Fall time (μsec) for 20-volt input pulse with added 15 $\mu\mu$f	0.2	0.15	0.05

The output impedances given above were measured with a load of such value as to reduce the output voltage to one-half the value of the no-load voltage. The effective output impedance for large values of signal depends upon pulse polarity. As shown above, when a cathode resistance of 22K returned to -150 volts is used, the output impedance is 300 ohms for a positive pulse. For a negative input pulse, however, the output impedance is approximately 1400 ohms. Note the marked improvement in fall time and the increased signal handling capacity gained by returning the cathode-resistor to a negative supply.

FAILURE ANALYSIS.

No Output. The input circuit should be checked to insure that an input signal is being applied to the pulse cathode follower. The tube should also be checked to insure that it can function properly under normal conditions. If the input signal is present and the tube is good, an open coupling capacitor, C1, would prevent the signal from reaching the tube. If this capacitor were shorted, any value of d-c voltage that may be present at the input terminals, from the previous stage, would be applied to the grid of the tube, and would seriously affect its biasing level. Insufficient or no voltage at the plate of the tube, due to failure of the power supply, would obviously result in no output. Another cause may be an open-circuited cathode resistor, R2, assuming that the output circuit has no continuous d-c path which could act as a cathode resistor by paralleling R2.

Reduced or Unstable Output. If it has been ascertained that a normal input signal is present at the input to the pulse cathode follower, several conditions could contribute to a faulty output. A leaky coupling capacitor, C1, would effectively lower the input impedance by providing a path of lower resistance in the grid circuit, thus changing the operating characteristics of the tube. Any d-c voltage present at the input would appear at the grid, thereby changing the bias. If this voltage is positive and of a sufficient value, the tube may be driven to saturation, resulting in severe distortion of the output signal. An open grid resistor, R1, may cause the tube to "block", or to "motorboat", or to exhibit no effect other than a distortion of the output waveform. (For a more detailed discussion, refer to the **FAILURE ANALYSIS** section of the previous circuit: Low-Level Video Cathode Follower.) A change in value of cathode resistor R2, due to aging and/or excessive current, may be the cause of reduced output. A reduced value of plate voltage, due to partial failure of the power supply or to excessive loading of the supply by some other defective circuit, may also be responsible for a reduced value of output from the pulse cathode follower.

VIDEO AMPLIFIERS

The video amplifier is similar to other types of electron tube amplifiers, except for its frequency and phase response requirements. In radar applications, responses of from 30 cps to 8 mc are necessary, and for television, responses of at least 20 cps to 4.5 mc are required. Such a response requirement means that the drooping gain characteristic of conventional amplifiers at low and high frequencies must be compensated for to produce a broad or relatively flat response over the required range. To increase the high-frequency response, shunt-peaking and series-peaking circuits are used (see Section 2, paragraph 2.5.2 for an explanation of R-L peaking circuits). To increase the low-frequency response, bass-boost circuits are needed. Where frequencies lower than 10 cps must be amplified, d-c coupling may be used. Generally speaking, cathode-follower outputs are used to furnish positive video, while negative outputs are obtained by biasing the final video amplifier near cutoff. Thus, the CRT tube may be driven by negative video applied to its cathode, or by positive video applied to the grid. The video can be changed in polarity by using an additional stage of amplification. For example, in receivers, if one amplifier stage follows the detector, the detector output polarity is inverted. If two stages follow, the polarity is the same as that of the detector. A third stage will again invert the signal. In addition to the frequency-response requirements, it is important that the phase relationships of the signal be retained. Otherwise, phase distortion will cause an undesired change in the video waveform. In receivers, where the CRT requires only 35 to 70 volts for drive, one- or two-stage video amplifiers are standard, and triodes or pentodes are used. For amplification of the weak camera signal or for transmission between units of equipment, chain amplifiers consisting of a number of stages are in common use. Either self-bias or fixed bias may be used, and the plate voltage is usually low (from 105 to 150 volts). Circuit discussions of typical video amplifiers follow.

TRIODE VIDEO AMPLIFIER.

APPLICATION.

The video amplifier finds extensive use in television circuits, where actual "picture video" signals are amplified; in radar circuits, where wide ranges in frequency must be handled; and in communications where a number of voice-frequency channels are successively "stacked" in frequency, one above the other, to occupy a complete 6-megacycle channel.

CHARACTERISTICS.

Class A operation is utilized to insure an output which is a faithful reproduction of the input signal.

Polarity of output signal is inverted over that of input signal.

Frequency response is broader than that of a standard R-C coupled amplifier.

Input signal may consist of pulses of either positive or negative polarity, or both.

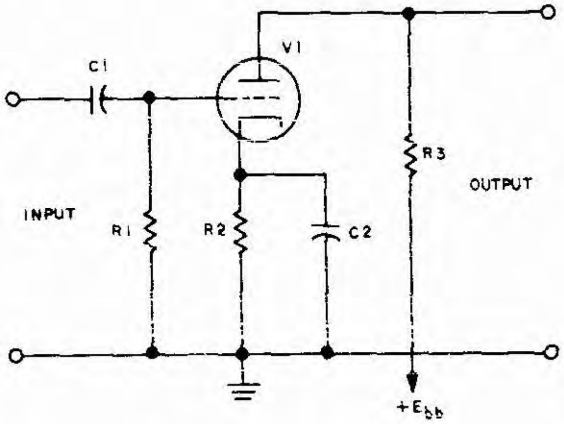
CIRCUIT ANALYSIS.

General. At low frequencies, the gain of an ordinary R-C coupled amplifier decreases rapidly as the frequency decreases, because of the corresponding increase in reactance of the input coupling capacitor with decrease in frequency. The increased reactance causes a greater proportion of the input signal voltage to drop across the capacitor, leaving a smaller proportion of the input signal to appear at the input to the tube, across the grid resistor. In addition, bypassing of the cathode resistor becomes less effective for the same reason, resulting in degenerative effects and further reducing the gain. This loss of gain at low frequencies may be partially overcome by the use of a larger value of coupling capacitance. If, however, too large a value of coupling capacitance is used, the high-frequency response may be adversely affected.

At high frequencies, the gain of an ordinary R-C coupled amplifier also decreases with an increase in frequency. This is due to the capacitive effects of the wiring, the tube and socket, and interelectrode capacitance itself, all of which effectively add capacitance across the plate load, from the plate of the tube directly to ground. This stray capacitance, C_d, acts as a bypass capacitor in the plate circuit in parallel with the output voltage, bypassing the higher frequencies. As the frequency is further increased the gain continues to fall, eventually reaching a point where the amplifier circuit no longer amplifies.

In order to counteract this action and extend the amplification range in the direction of increasing frequency, the plate load resistance must be decreased. As an approximation, the response may be extended from a given limiting value, such as 10 kc, to a value ten times as great (1 mc) by decreasing the value of the plate load resistor in the same proportion, such as from 220K to 22K. However, by so doing, the over-all gain of the amplifier, including the middle and lower frequency gain, is considerably reduced. This loss must either be tolerated, if the extended frequency response is required or overcome by using additional stages of amplification.

Circuit Operation. The schematic shown below illustrates a triode video amplifier circuit. The input signal, composed of video pulses of either positive or negative polarity, is applied to the grid of the triode amplifier through coupling capacitor C1. The grid is returned to ground through grid resistor R1. The combination C1R1 forms an R-C circuit at the input to the tube, and the time constant of this circuit limits the low-frequency response of the amplifier. The time constant must be long, in comparison to the period of the lowest frequency to be amplified. At the middle and high frequencies, the value of C1 is sufficiently large that its reactance is negligible, and the full input



Triode Video Amplifier Circuit

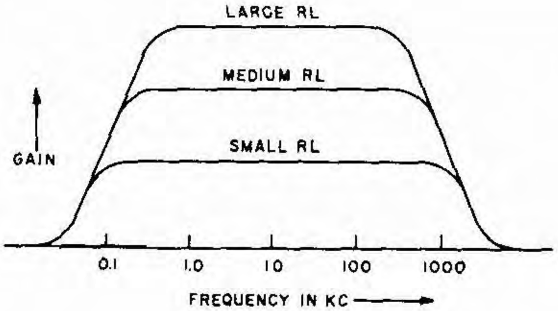
voltage appears across grid resistor R1 and is thereby applied to the grid of the tube. But, as the frequency decreases, the reactance of C1 increases according to the formula:

$$X_{c1} \cong \frac{1}{2\pi f C_1}$$

As a result, the effect of C1 is no longer negligible; its reactance and the resistance of R1 form a voltage divider across which the input voltage is applied. The voltage drop across C1 is lost, for all practical purposes, and only that value which appears across R1 is effective at the grid of the tube. The voltage drop across C1 may be reduced by increasing the capacitance of C1, which will decrease its reactance, but the extent to which C1 can be increased is limited because an increase in physical size results in an increase in stray capacitance. The stray capacitance, in turn, acts in the same manner as a bypass capacitor in the plate circuit, to decrease the gain at the high frequencies.

The grid bias, in the triode video amplifier circuit, is obtained by utilizing the voltage drop across resistor R2, connected in series with the cathode of the tube. The total electron current flowing through the tube passes through this resistor. Since the tube current varies with the variations of the applied signal voltage, a corresponding varying voltage is developed across cathode resistor R2. In order to obtain a steady value of grid bias voltage, these signal variations must be bypassed around the bias resistor by means of a filter capacitor, which is the cathode bypass capacitor C2. The reactance of this capacitor must be low, in order to provide a low-impedance path around the resistor for the alternating current components of the signal. This capacitor must have a value of 5 microfarads or greater for audio-frequency amplifiers. For video-frequency amplifiers, which may be required to pass frequencies much lower in value, the capacitance of the cathode capacitor C2 must, in many cases, be much greater, such as 100 microfarads or more. As a general rule, the time constant of R2 and C2 must be long in comparison to the period of the lowest frequency to be passed by the video amplifier. In order to provide effective bypassing for the a-c components of the signal around the cathode resistor, the value of capacitive reactance at the lowest frequency to be amplified is generally accepted to be one-tenth (or less) the resistance value of R2.

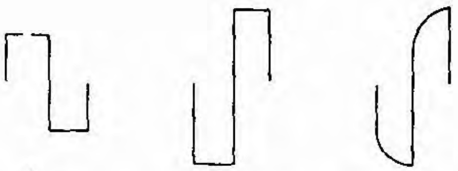
The value of plate load resistor R3 has a controlling effect, not only on the gain of the amplifier, but on its frequency response as well. The gain increases with higher values of plate load resistance, but the bandpass of the circuit becomes less. Conversely, lower values of plate load resistance will decrease the gain of the amplifier, but will extend its frequency response. This is illustrated in the following diagram.



Effect of Value of R_L on Video Amplifier Bandpass

The value of the plate load resistor may be decreased down to approximately 1.5K in some applications. Further extensions of the frequency range require the use of high-frequency and low-frequency compensating networks.

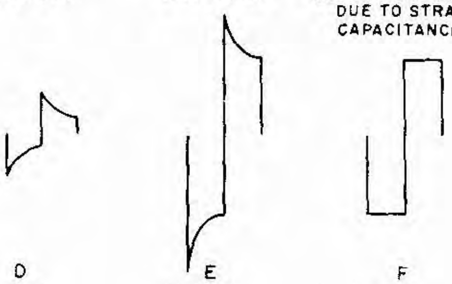
Stray (or distributed) capacitance, due to the capacitance of the circuit wiring and the interelectrode capacitance of the tube, is a cause of poor high-frequency response, and, therefore, distortion. The distortion of the output waveform, as a result of poor high-frequency response, is shown in part C of the following illustration, while the input waveform and the ideal output waveform are shown in parts A and B, respectively. If the parallel combination of the plate resistor, R3, and grid resistor R_g of the following stage allows the stray capacitance, C_d, to charge and discharge quickly, the output will show little or no distortion.



A
INPUT
WAVEFORM

B
IDEAL OUTPUT
WAVEFORM

C
DISTORTED
OUTPUT WAVEFORM
DUE TO STRAY
CAPACITANCE



D
BACK EMF
ACROSS
INDUCTANCE

E
DISTORTED
WAVEFORM
DUE TO
INDUCTANCE
ALONE

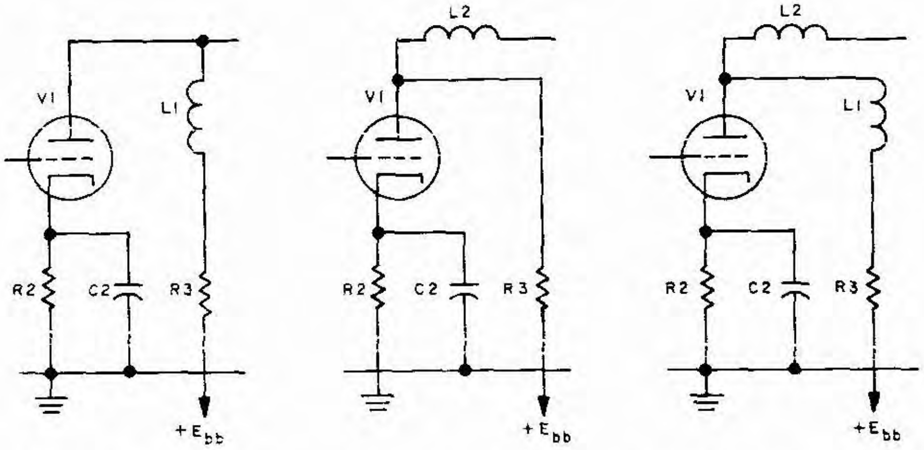
F
OUTPUT WAVEFORM
DUE TO
INDUCTANCE
AND STRAY
CAPACITANCE

Intercircuit Waveforms

If, however, R3 and R_g are large values of resistance, C_d will require a relatively long time to charge or discharge, and the steep sides of an applied square wave will be distorted, as shown in part C of the illustration.

This condition may be overcome in one of two ways. The first is to reduce the size of C_d by using special amplifier tubes with low values of input and output capacitance between the lead wires and ground. The second is to decrease the time required by C_d to charge or discharge. This can be accomplished by reducing the value of R3 or R_g. If R_g is reduced, however, the low-frequency response will suffer. If R3 is reduced, the gain of the stage will be reduced in turn, but this may be overcome by using additional stages of amplification.

The decreased response at high frequencies is caused principally by the shunting effect of the distributed capacitance of the circuit and the interelectrode capacitance of the tube, which together act to reduce the impedance of the plate load. This effect may be compensated for, and the high-frequency range may be extended, by the addition of a small value of inductance, L1, in series with plate resistor R3, as shown in part A of the following illustration. This inductance serves to boost the response of the high frequencies, while having practically no effect upon the lower frequencies. The boost in response at high frequencies is due to the high inductive reactance of the inductance, L1, which produces a back EMF, resulting in a sharp peak at high frequencies, as shown in parts D and



A. SHUNT COMPENSATION B. SERIES COMPENSATION C. SERIES-SHUNT COMPENSATION

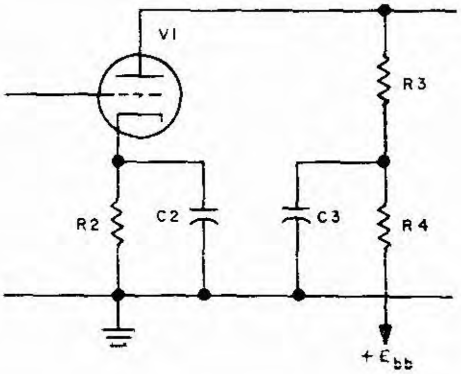
Triode Video Amplifier Frequency Compensation Circuits

E of the *illustration.* This sharp peak, or introduced distortion, will counteract that caused by the stray capacitance, and the resultant output will be *almost* a pure square wave, as shown in part F. At low frequencies, the inductive reactance of the inductance is low, and has negligible effect on the circuit. This method, known as shunt compensation, is effective when the maximum-frequency limit is not too high, and there are only a few stages of amplification.

Another method of compensating for this effect, known as series compensation, is shown in part B above. In this method, a small value of inductance, L2, is connected in series between the plate and the output to the following stage. This small inductance resonates with the input capacitance of the following stage at high frequencies, and acts to cancel the shunting effect of the input capacitance by the increased impedance of the series resonant circuit. This results in an increased voltage at the input to the following stage, and, therefore, an increase in gain.

The advantages of both of the above methods may be combined in a single circuit. This circuit, known as series-shunt compensation, is shown in part C above. This combined method utilizes both the inductance L1 in series with plate resistor R3 and the inductance L2 in series with the plate and the output. The combination gives the high-frequency peaking effect of the shunt-compensation circuit along with the increase in gain at high frequencies due to the resonant effect of the series-compensation circuit.

The decreased response at low frequencies is caused principally by the increased reactance of the input coupling capacitor, which reaches an appreciable value as the frequency decreases below 200 cycles. This decreased response, or loss of gain, can be counteracted by the addition of a low-frequency compensation network, or filter, in series with the load resistor. This compensation network consists of a capacitor, C3, and a resistor, R4, connected into a filter circuit as shown below. The filter, connected in series with plate load resistor R3, accomplishes two purposes:

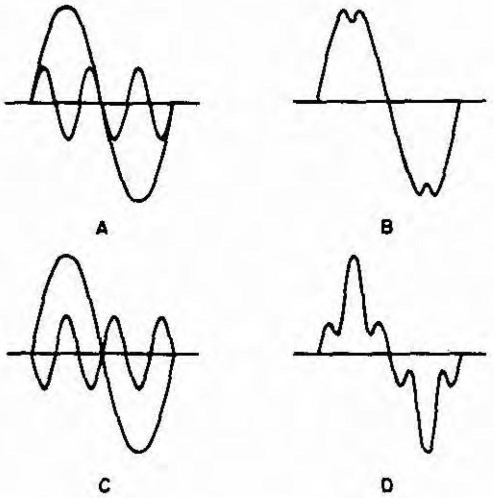


Low-Frequency Compensation Circuit

(1) It introduces a phase shift into the plate circuit which compensates for the phase shift in the output coupling circuit. (2) It increases the effective plate load impedance at low frequencies, and thereby maintains the low-frequency gain. This is explained as follows: At low frequencies R4 plus R3 make up the plate load of the circuit. The addition of R4 will increase the gain of the circuit, and the low-frequency response. The capacitive reactance of C3 will

be high, thereby preventing any shunting effect. At high frequencies the reactance of C3 is lower, causing the signal to be shunted around R4, effectively removing R4 from the circuit. In this manner the plate load becomes lower at high frequencies, and the high-frequency response will not suffer.

Frequency response is an important consideration in video amplifiers, but it is not the only one. Phase distortion, which can be tolerated in an audio amplifier, is capable of destroying the image on a cathode-ray-tube screen. Phase distortion is produced when the time or angular relationship of electric waves to each other changes as they pass through any electrical system. As an example, consider the wave shown in part B of the figure below.

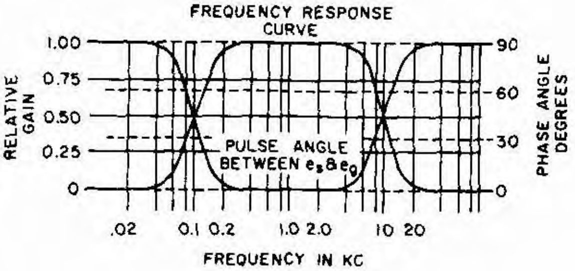


Composite Waveforms of Fundamental Plus Third Harmonic

This wave is actually composed of a fundamental frequency in combination with its third harmonic, as shown in part A of the illustration. If the effect of the circuit on each of these two waves is different, the two waves may appear as in part C of the illustration, where the third harmonic has changed its position with respect to the fundamental. That is, its phase relationship has changed. The resultant of these two waves will now assume the shape given in part D of the illustration, which is certainly different from the original waveform shown in part B.

At low frequencies, the phase of the voltage at the grid of the amplifier is governed by the amount of opposition offered by the coupling capacitor to the a-c waveform passing through the circuit. The coupling capacitor and grid resistor are, in effect, a series circuit. As the applied signal becomes lower and lower in frequency, the ever-increasing capacitive reactance causes the circuit current to lead the applied (signal) voltage in ever-increasing amounts approaching 90 degrees. The voltage drop across the grid resistor is in phase with the current through it, and would also lead the applied voltage by the same amount. In the middle range of frequencies, from 200 to 2000 cycles, the capacitive reactance of the coupling capacitor becomes small enough with respect to the reactance (resistance) of the grid resistor to have a minimal effect on the passing waveform; therefore, phase shift can be considered negligible in the middle-frequency range. At the high-frequency end of the band, the input capacitance between the grid and the cathode becomes important and must be considered. The input capacitance and the grid resistor form, in effect, a parallel circuit. As the capacitive reactance of the input capacitance becomes less and less with increasing frequency, the current in the parallel combination will become more and more capacitive and will begin to lead the applied voltage by ever-increasing amounts approaching 90 degrees. Another way of expressing this thought is that the voltage across the parallel combination will begin to lag by ever-increasing amounts as the applied frequency is increased. The shift in phase angle at the grid of the tube is opposite to that caused at the low frequencies, but in either case the result is the same: phase distortion. An illustration of the relationship between phase distortion and frequency response in an ordinary amplifier is given below.

The high-frequency and low-frequency compensating networks previously described, in addition to compensating for frequency response, help to correct for phase distortion, as they shift the phase back in an opposite direction to make the circuit appear resistive over a wider frequency range.



Phase Distortion and Frequency Response Characteristics of an Ordinary Amplifier Stage

FAILURE ANALYSIS

No Output. With a video signal of sufficient amplitude applied at the input to the video amplifier, a defective tube is the primary cause of no output in the majority of cases. If the tube is found to be operational, an open coupling capacitor C1 would prevent an input signal from reaching the video amplifier grid. An open cathode resistor R2 would interrupt the operation of the circuit, resulting in no output. If a compensation circuit is employed in the plate circuit, a shorted capacitor C3 would prevent the application of plate voltage to the tube, and would probably burn out plate resistor R4. (Refer to Low-Frequency Compensation Circuit diagram.) Failure of the plate supply voltage would interrupt circuit operation in the same manner. Application of plate voltage to the tube would also be interrupted if plate resistors R3 or R4 became open-circuited, again resulting in no output.

Reduced or Unstable Output. Assuming that a video signal of proper amplitude is present at the input to the video amplifier, a partially or completely shorted grid coupling capacitor C1 may be the cause of a reduced or severely distorted output. If the capacitor is partially shorted, any value of a d-c voltage which may be present at the input terminals of the circuit would be applied to the grid of the tube. Appearing to the tube as a change in grid bias, this voltage, if positive, may shift the operating point of the tube toward or into the saturation region, causing severe distortion by limiting the positive peaks of the input signal. If grid resistor R1 became open-circuited, grid blocking would result from the accumulation of charges due to the signal voltages on the grid, which could not return to ground. Should cathode capacitor C2 become shorted, the cathode bias would be removed, and the cathode would operate at a fixed ground potential. This would change the operating point on the tube's E_g-I_p characteristic curve, allowing more plate current to flow, and probably operate into the saturation region, with the consequent severe distortion in the output signal. If, on the other hand, cathode capacitor C2 became open-circuited, the cathode voltage would rise and fall with the grid input signal in cathode follower fashion. This would introduce degeneration, which would result in a reduced value of output signal. If the video amplifier circuit contains low-frequency compensation, and capacitor C3 in the compensation network became open-circuited, the compensation characteristics would be lost, and distortion might result, although this distortion might not be very noticeable.

PENTODE VIDEO AMPLIFIER.

APPLICATION.

The pentode video amplifier is used to amplify, without attenuation, a band of frequencies between approximately 10 cycles and 6 megacycles. This amplifier is normally used to amplify a higher level of input signal than the triode video amplifier, and as a result it can furnish an output signal of considerably higher power than may be realized from a triode amplifier. The pentode video amplifier is used in television and communications applications, and in particular in radar receivers, where it often follows the detector stage.

CHARACTERISTICS.

Operated as a Class A amplifier to obtain an output signal which reproduces the input signal without distortion.

Output signal is of reverse polarity to that of the input signal.

Input signal may be continuous or pulsed, and of either positive or negative polarity, or both.

Frequency response is more linear throughout the operating range than that of a triode video amplifier.

Over-all gain per stage is higher than that of a triode video amplifier.

Output voltage is higher that that of a triode video amplifier when operated from the same supply voltage as a triode.

Harmonic distortion is less, for the same output voltage, than that of a triode.

CIRCUIT ANALYSIS.

General. Pentode video amplifiers may be classified in four circuit variations, according to the type of bias and the type of screen supply. The bias may be either zero-bias or self-bias, while the screen supply may utilize either a screen resistor or a fixed value of screen voltage. The basic circuits for each of these variations are shown in the accompanying illustration.

The pentode video amplifier has higher plate efficiency and greater power sensitivity than a triode video amplifier, as a general rule, but at the same time it suffers higher odd-harmonic distortion. In order to reduce this type of distortion to a minimum, negative or degenerative feedback may be used. However, this reduces the over-all gain of the amplifier. The output circuit usually utilizes resistance coupling or resistance-capacitance coupling, although in some applications transformer coupling or inductance-capacitance (choke) coupling may be used. When resistance coupling (or resistance-capacitance coupling) is used, the load resistance for maximum power output is usually within 10 percent of the value obtained by the formula:

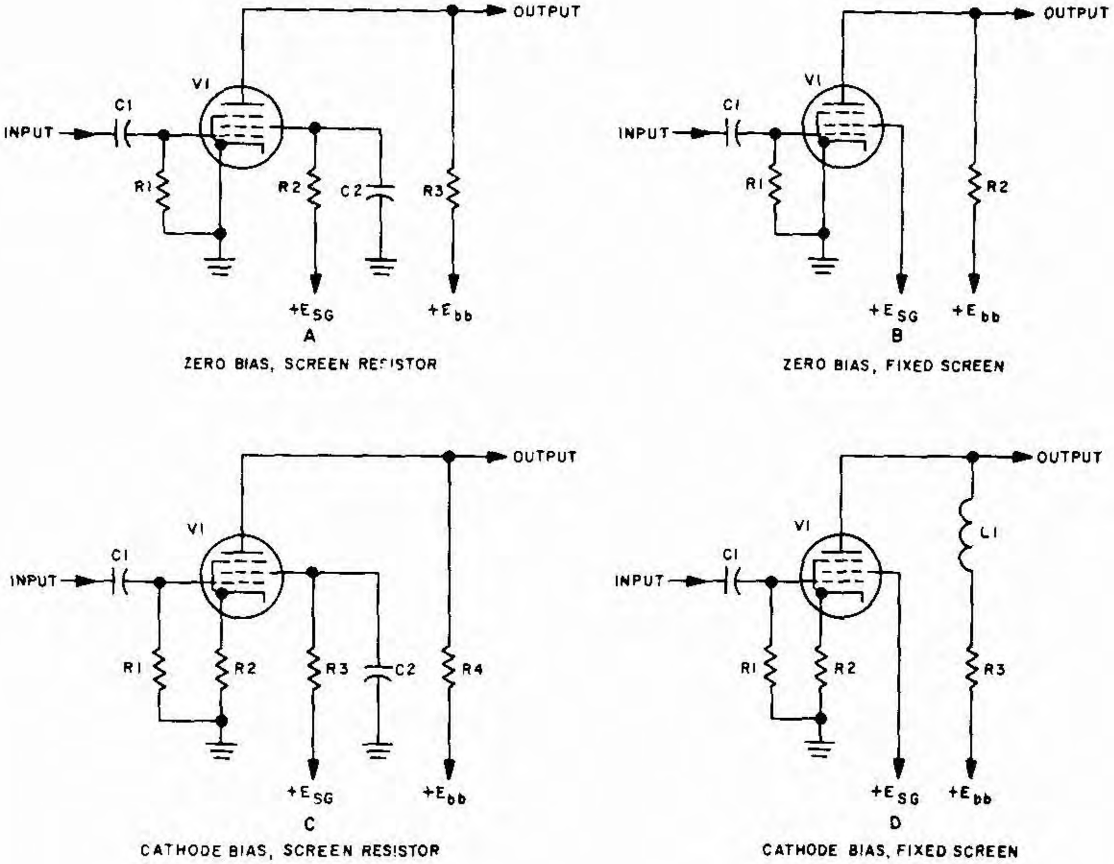
$$R_L \cong \frac{0.9\,E_{bb}}{I_p}$$

where: R_L = plate load resistance
E_{bb} = plate supply voltage (on the source side of R_L)
I_p = plate current

The power output is less than the value $\frac{E_{bb}\,I_p}{2}$, because of the power loss in plate resistor R_L. Plate efficiency, for a total harmonic distortion of less than 10 percent, is approximately 35 ± 7%. The overall output circuit efficiency is lower than this value, since the output efficiency is a function of both the plate current and the screen current, and the screen current is wasted insofar as the output is concerned.

Circuit Operation. The schematics shown previously illustrate four basic circuit variations of the pentode video amplifier. In circuit A, the tube is operated at zero bias, with the cathode grounded, and the screen voltage is supplied through screen resistor R2, which is bypassed by capacitor C2. In circuit B, the tube is operated at zero bias, but the screen is held at a fixed voltage through a direct connection to the screen power supply. In circuit C, the tube is operated with cathode bias obtained through the use of cathode resistor R2, which is left unbypassed to provide degeneration, in order to improve the over-all frequency response. The screen voltage is supplied through screen resistor R3, which is bypassed by capacitor C2. In circuit D, the tube is operated with cathode bias by means of cathode resistor R2, which is left unbypassed to provide degeneration. Inductor L1 is connected in series with plate-load resistor R3. Inductor L1 and resistor R3 act to extend the response to the higher frequencies.

In circuit A, the pentode is operated at zero bias, since no cathode resistor is used, and the grid is returned to the grounded cathode through grid resistor R1. Cathode circuit degeneration at low frequencies, and the resultant loss of gain, is thereby eliminated. This loss of low-frequency gain is evident in circuits using cathode bias, with a bypass capacitor shunting the cathode resistor, because of the increasingly higher capacitive reactance offered by the bypass capacitor as the frequency is decreased below a few hundred cycles. The disadvantage of zero bias, however, is the limitation imposed on the input signal, in that the input signal must not be so great as to drive the grid to saturation and the condition of grid current flow. The screen voltage is supplied, from the power supply, through screen resistor R2, in order to operate the tube at the proper screen potential, which under normal conditions is of a lower value than the plate voltage. The screen resistor is usually bypassed by a screen capacitor, C2. The R-C circuit which results from the combination of R2 and C2 provides a small amount of degeneration similar to that provided by an unbypassed cathode resistor. Since the normal screen current is only a small percentage of the plate current (10 to 15 percent), the amount of degeneration is proportionally


A
ZERO BIAS, SCREEN RESISTOR

B
ZERO BIAS, FIXED SCREEN

C
CATHODE BIAS, SCREEN RESISTOR

D
CATHODE BIAS, FIXED SCREEN

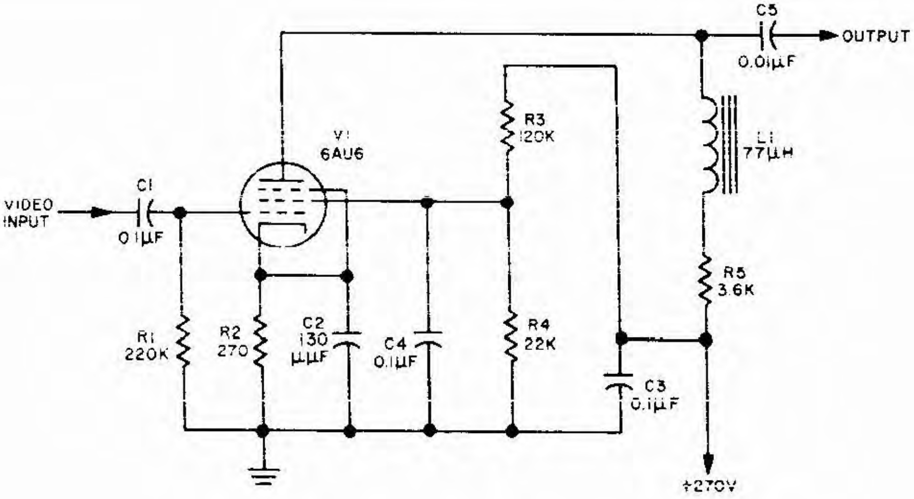
Pentode Video Amplifier Basic Circuit Variations smaller. The degeneration approaches a negligible value when the time constant of the R-C circuit, R2 and C2, is greater than four times that of the lowest frequency which is to be passed by the amplifier.

In circuit B, the pentode is operated at zero bias, similar to that of circuit A. The screen, however, is supplied directly from the power supply, without the use of a screen dropping resistor. By this means the screen voltage is held to a practically constant value, assuming that the impedance of the power supply is of a relatively low value. As a result, no degeneration is provided by the screen circuit, and the voltage gain of this circuit is slightly higher than that of circuit A.

In circuit C, the pentode is operated with cathode bias, the amount of which is determined by the values of the cathode resistor and the plate and screen currents. The cathode resistor is left unbypassed, in order to provide degeneration, which increases the over-all frequency response of the amplifier and reduces the distortion and/or noise which may be introducted within the amplifier itself. In a number of amplifier circuits, including those designed for audio frequencies, the cathode resistor is bypassed by a capacitor of a relatively large value. The capacitor acts as an extremely low impedance path for all frequencies higher than approximately 200 cycles. As the frequency of the signal to be amplified decreases below this value, the reactance offered by the bypass capacitor increases very rapidly, and as a result the gain at lower frequencies decreases. In order to avoid this decrease in gain in the video amplifier, this bypass capacitor is omitted from the circuit. The gain at the low frequencies is thereby held to approximately the same value as the gain at the medium frequencies, but the over-all gain of the circuit - at all frequencies - suffers a decrease in value, because of the degeneration introduced by the cathode resistor. The screen voltage is dropped, from the power supply potential, through screen resistor R3 to the proper value for pentode operation. The effect of the screen resistor-capacitor combination is similar to that described for circuit A.

In circuit D, the pentode is operated with cathode bias, in a manner similar to that of circuit C. The screen is supplied by a fixed potential directly from the power supply, and no screen resistor is used. Degeneration due to the screen circuit is thereby avoided, as in circuit B. In this circuit, however, an inductance, L1, is connected in the plate circuit, in series with plate load resistor R3. This comprises a shunt peaking circuit, which acts to keep the response flat to a much higher frequency than may be obtained with a simple resistive plate load. A more complete discussion of compensation circuits, including shunt peaking, is given in connection with the triode video amplifier, previously described.

A practical application of some of the circuit variations already discussed is given in the following illustration, which shows the pentode video amplifier circuit used in the AN/SPS-10D Radar Set. In this circuit, the video input signal is applied through coupling capacitor C1 to the grid, which is returned to ground through grid resistor R1. The amplifier tube, a type 6AU6, is operated with cathode bias obtained by means of cathode resistor R2. Partial bypassing is provided by capacitor C2, which, because of its low value of capacitance (130 $\mu\mu f$), offers a low impedance only to the higher frequencies. The screen grid is held at a relatively fixed potential from the power supply, through the voltage divider R3 and R4 and its filter network C3 and C4. In this case, the R-C circuit consisting of R4 and C4 provides negligible screen degeneration, because the junction of R4 and R3 is held at a relatively constant potential by voltage-divider action. A shunt peaking compensation circuit is provided in the plate circuit, by means of inductance L1 in series with plate-load resistor R5. The use of plate shunt peaking maintains the output response flat to a much higher frequency than possible without its use. The



Pentode Video Amplifier Circuit used in AN/SPS-10D Radar Set

output of the video amplifier is taken through C5, the output coupling capacitor.

FAILURE ANALYSIS.

No Output. Assuming that a signal of sufficient amplitude and proper polarity is applied at the input to the pentode video amplifier and no output is obtained, the tube should be checked for proper operation. An open coupling capacitor C1 or an open cathode resistor, if used, would interrupt the operation of the circuit. An open plate resistor or screen resistor, if used, or failure of the plate or screen power supply would likewise be a cause of no output. If shunt peaking is used in the plate circuit, an open-circuited inductance L1 would interrupt the plate current and result in no output.

Reduced or Unstable Output. With a video signal of proper amplitude and polarity present at the input to the pentode video amplifier, a leaky or shorted input coupling capacitor C1 may be the cause of a reduced or unstable output. A leaky capacitor may allow a d-c voltage from the output of the previous stage to be present on the input grid; this would change the value of bias and cause distortion in the output signal, or reduce the output to a low value or even to zero. An open grid resistor R1 would probably cause grid blocking, or audio oscillation at a slow rate. If the cathode bypass capacitor C2 became open-circuited, if one is used, degeneration would be introduced and the output would be considerably reduced in value. If the capacitor became shorted, the cathode would operate at zero bias, and the output would probably be distorted although of a higher value. Should the screen bypass capacitor become shorted, the output would be reduced to an extremely low value, and in addition the screen resistor would probably overheat or burn out, because of excessive current flow. Another cause of reduced output may be traced to a reduced value of plate or screen voltage, due to a faulty power supply. If a voltage divider is used in the screen voltage supply, similar to that shown in the illustration of the AN/SPS-10D video amplifier circuit, an open resistor at the ground end of the voltage divider would increase the voltage at the screen. This would probably increase the plate current sufficiently to overload or burn out the tube. In either case, the output signal would be severely distorted.

TRIODE VIDEO DRIVER AMPLIFIER.

APPLICATION.

The video driver amplifier is used to amplify radar or other video signals to the proper level for driving the cathode-ray indicator tube.

CHARACTERISTICS.

A negative output signal is provided for application to the CRT cathode.

Cathode bias is used, in combination with a fixed negative bias on the grid.

A positive video-input signal is required.

The cathode is partially bypassed at high video frequencies to provide gain stabilization and high-frequency compensation.

The tube elements are connected in parallel to provide increased transconductance.

Shunt or series peaking is not required.

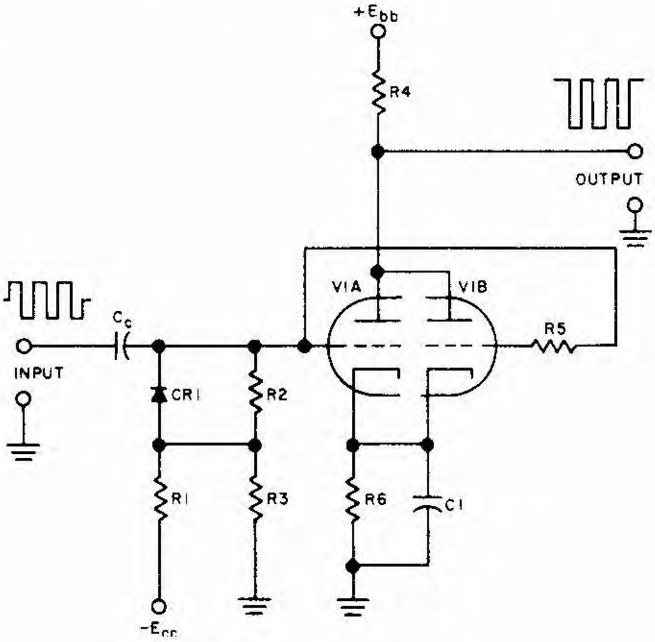
D-c restoration is provided by a separate diode.

Low coupling resistance provides improved frequency response.

CIRCUIT ANALYSIS.

General. A negative video output provides some definite advantages over a positive video output. Since the tube is necessarily biased near cutoff, the quiescent or resting current is much lower than would be required for positive video. As a result, the maximum tube rating for plate dissipation is seldom reached, even when the tube is overdriven. By using a dual-triode with low coupling resistance, more gain can be obtained for a given bandwidth than from a single pentode stage. By connecting the triode elements in parallel, the theoretical transconductance is doubled; however, full advantage cannot be taken of this circuit arrangement, because a low value of loading resistance is employed in order to widen the bandwidth. Since the capacitances of both tube elements are in parallel, the effective input capacitance and output capacitance are greater. The triode driver stage is usually the final (output) stage in a video amplifier chain. This stage always drives the cathode-ray indicator tube, which requires a large voltage drive for intensity modulation of the CRT beam (little power is required); therefore, it is usually spoken of as a "video-driver stage" rather than a "video power-output stage".

Circuit Operation. The accompanying schematic shows a typical dual-triode video driver. The negative output of the driver is usually applied to the cathode of the indicator tube to reduce the cathode bias and illuminate the tube with full beam intensity at the negative peak of the output signal (which occurs at the positive peak of the input signal).



Triode Video-Driver Circuit

Capacitor Cc is the input coupling capacitor; the output of the stage is usually direct-coupled to the CRT cathode. Fixed negative bias is obtained from a voltage divider, consisting of R1 and R3, to supply a few volts of negative bias to the dual-triode grids through common grid resistor R2. Grid resistor R5, in series with the grid of V1b, is a parasitic suppressor, or "grid stopper", which prevents high-frequency oscillations due to the parallel connection of elements. Diode CR1 is a d-c restorer which operates as a biased clamp on the input signal, so that the output signal always produces the same intensity on the CRT for identical input signals. Cathode bias is also supplied by R6, which is bypassed by C1 so that cathode degeneration occurs, improving the frequency response; thus, special video-frequency compensating circuits are not needed in the plate circuit. A positive input pulse produces an amplified negative output pulse across plate load R4.

With no signal applied, the fixed bias prevails and holds both half-sections of V1 near cutoff. (The total quiescent current flow is on the order of 0.5 to 1 milliampere.) The output voltage is zero, and practically the full plate voltage is applied, since the drop across load resistor R4 is less than 2 volts. Similarly, the cathode bias developed for the quiescent value of current is only a small fraction of a volt, and thus has practically no effect on the circuit at this time.

Assume that a positive-going video signal is applied through coupling capacitor Cc. The positive input voltage reduces the fixed negative bias, thus increasing the plate current flow. The increased flow of plate current produces a voltage drop across plate load resistor R4 and cathode resistor R6. The plate voltage drop appears in the output as a negative and amplified output voltage, while the cathode voltage increases the applied fixed bias. Thus, as the amplitude of the input signal increases, the cathode bias also increases, and the effective bias is the total of both the fixed negative bias and the instantaneous cathode bias. The use of combined bias in this fusion provides a more linear input-versus-output voltage relationship. Normally, adequate cathode bypassing prevents instantaneous changes in bias from producing degenerative voltages which oppose the effect of the input voltage. In this circuit, however, the value of the cathode bypass capacitor is selected to be sufficient only for the very high frequencies—not for medium and low frequencies. Thus, at high video frequencies the average cathode voltage remains constant, while at the lower frequencies the instantaneously developed cathode voltage opposes the input signal and reduces its amplitude. As the frequency becomes lower, the reduction is correspondingly greater. Thus, cathode degeneration assumes the form of inverse feedback and attenuates those frequencies which are normally amplified the most. The over-all result is to produce a wider and more uniform passband with a slight reduction in gain.

When the video input signal swings in the negative direction, the signal adds to the bias and reduces plate current flow. The voltage drop across the plate load resistor is correspondingly reduced, and the output voltage rises toward zero. The negative-going input signal eventually reaches the fixed bias level, at which time the circuit *is again in the quiescent condition.* If the negative input signal drops below the bias level, the cathode of clamping diode CR1 becomes negative with respect to the anode and *the diode conducts, shunting the signal around grid* resistor R2 so that no further reduction in output voltage can occur. The diode conducts until the input voltage equals *or becomes more positive than the bias;* during this time the output remains at the zero level. When the input signal again goes positive, plate current again flows, producing a *voltage drop across* R4 *and a negative* output.

By using a fixed negative bias of the proper value, the tube operates in the Class A1 region and the zero output *level is fixed to be almost that of the plate supply voltage.* Thus, full advantage can be taken of the large supply swing available; that is sufficient voltage drive can be obtained from a single driver stage without using excessively high plate voltage or large values of quiescent current, as would be required in Class A operation, so that more output voltage is obtained for the same input signal. With the input signal operating on a low duty cycle and consisting of short-duration pulses, the amplitude is usually less than the bias *level and the clamping diode will not operate.* However, with large input signals greater than the bias level, and operating on a high duty cycle, the clamping diode will operate and *hold the output at the same zero level.* By properly selecting the value of the cathode bypass capacitor, sufficient cathode degeneration is produced to reduce the rise *time to the same value as would normally occur in a* properly bypassed driver cathode circuit with shunt peaking employed in the plate circuit. This eliminates the necessity of providing compensating *inductance in the plate load,* and avoids any adverse affect on the transient response of the amplifier. When properly designed, this circuit will produce a rise time of less than .05 *microsecond without* exessive overshoot or undershoot.

FAILURE ANALYSIS.

No Output. Lack of an input signal, improper bias, loss of plate voltage, a defective tube, or an open cathode circuit can result in no output. If coupling capacitor Cc is open, no signal will appear at the grid and there will be no plate output. Check for an input signal with an oscilloscope or a VTVM. If bias divider resistor R3 is open, *full* supply bias will be applied to the grid; thus, the tube will be biased far beyond cutoff and will not operate. If R3 is open, the voltage measured from R3 to ground will be the same as the bias supply voltage. If grid resistor R2 is open, no bias will be applied to the V1 grid and the tube will conduct heavily, with cathode bias from R6 biasing it near cutoff. In this case, with very large drive there is a possibility that a small output will be obtained. Ordinarily, however, this output will probably be so small as to be considered no output at all. If bias divider R1 is open, a similar result will occur because of a lack of fixed bias on the grid; if it is shorted, the full bias supply voltage will appear on the grid, thus cutting off the plate current and the output. Use a voltmeter to determine whether the bias appears and, if so, whether it is normal. If cathode resistor R6 is open, the circuit will be incomplete (open) and no output will occur. If R6 is open, shunting the cathode to ground will produce an output, in which case R6 should be checked with an ohmmeter with the power off. (With the power on and R6 open, the voltmeter may act as a high-value return resistor and cause the stage to be biased off; or when used as an ohmmeter and properly polarized the batteries in the meter can furnish an almost normal bias to V1 cathode and cause an erroneous indication.)

If plate resistor R4 is open, no plate voltage will be applied and no output will be obtained. Check the supply, first with a voltmeter to determine that voltage is present, and then check the plate voltage to ground. If plate voltage is normal, and no output can be obtained with proper bias and input signal, V1 is defective; replace it with a known good tube.

Low Output. Improper bias, low plate voltage, or a defective tube can cause a low output. If the bias is low the diode restorer will clip off part of the input signal and cause a reduced output. Likewise, if the bias becomes too high it will take a larger drive to obtain the same output. Check the bias supply and voltage across R1, R2, and R3 with a voltmeter. If diode CR1 is shorted, grid resistor R2 will be removed from the circuit and the grid signal voltage will be developed across R3 alone. This will lower the grid input impedance and reduce the drive, resulting in a reduced output. Check CRI for forward and reverse resistance with an ohmmeter. If R2 is large, which it normally is, the diode need not be disconnected for this check. If there is no difference between forward and reverse indications and a low resistance is measured the diode is shorted. If a high resistance is indicated in both directions, it is open. Check the supply voltage and then the plate voltage with a voltmeter. If the plate voltage is low the output will be reduced. If plate resistor R4 increases in value with age an abnormally low plate voltage will result. Measure the resistance of R4 with plate voltage OFF, when the plate voltage appears to be extremely low, and the supply voltage is normal. A similar symptom can be produced by a defective tube which causes heavy plate current flow, or by low bias. Replace the tube with a known good one and check that the plate voltage returns to normal with proper bias applied. If not, there is a possibility that the tube is oscillating and that the value of R5 is insufficient to prevent it. Check R5 with an ohmmeter with the plate voltage off. If resistance is normal, connect an oscilloscope across the grid and ground, and then across the plate and ground. If the waveform is found obscured by a broad, light, solid band across it the circuit is oscillating at radio frequencies. Check the wiring, particularly the parallel connections to the tube elements, to be certain they have not been lengthened or changed, substitute another tube, and as a last resort change the value of R5 to a much larger value.

Distorted Output. If the cathode degeneration is changed because bypass capacitor C1 is open or shorted, frequency distortion will occur. The high frequency output (without degeneration) will be lower than the output at medium and low frequencies, and the stage will act like an uncompensated amplifier. Use an oscilloscope and a square wave input. Observe the input and output waveforms; with a positive input, the output signal should be negative, larger in amplitude, and of the same general waveform. A sloping vertical edge on the square wave indicates the rise or fall time is excessive, while a sagging flat top indicates low frequency distortion. C1 can be roughly checked by temporarily shorting it while observing the waveform on the oscilloscope. If the circuit is operating properly the waveform will be more distorted when C1 is shorted. If no change is observed, C1 is either open or shorted. Check C1 with an in-circuit capacitance checker, or disconnect it and check for the proper capacitance value and for leakage. Excessive leakage will cause C1 to act as resistor in parallel with cathode resistor R6. Checks for distortion should be made at frequencies which are not effectively bypassed by C1. If the check is made at a frequency to which C1 offers little or no reactance, the signal will probably appear slightly distorted whether C1 is working properly or not.

Check the rise and fall of the waveform for overshoot and undershoot. In test equipment applications it should be less than 1%, in TV or Radar applications 5% to 10% is satisfactory, while in Servo-equipment 40% to 50% is acceptable. These tests should be made on a normally operating equipment so that the technician is familiar with the correct waveform appearance and permissable amount of distortion before trouble occurs. Waveforms are not required to be any better than those shown in the appropriate Technical Manual covering the equipment under test.

BEAM-POWER VIDEO DRIVER AMPLIFIER.

APPLICATION.

The beam power video driver is widely used in search radars to amplify video signals to the 35-to 60-volt level necessary for intensity modulation of the cathode ray indicator tube.

CHARACTERISTICS.

Fixed negative bias is employed to provide operation in the Class A1 region.

A negative output is produced for a positive input signal.

Shunt peaking is used to compensate for increased rise time produced by the higher output capacitance of the pentode.

D-C restoration is provided by a separate diode.

Provides greater output, more amplification, and better linearity than a single triode driver operating at the same voltages.

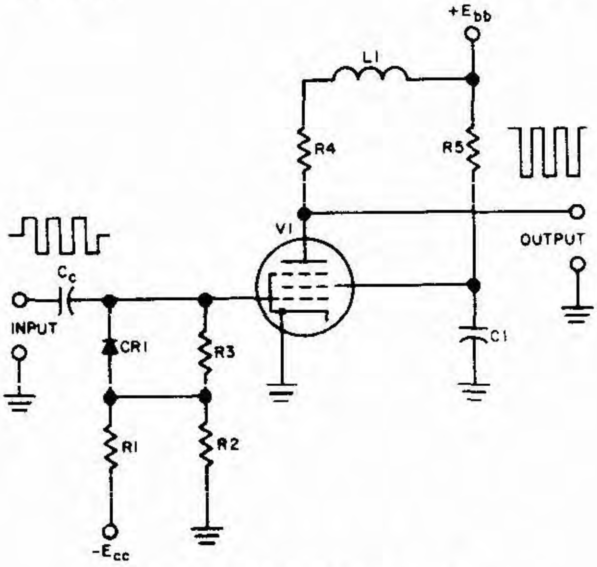
Requires more d-c power than the triode (screen is added) and plate current is larger.

CIRCUIT ANALYSIS.

General. The beam-power video driver is similar to the triode video driver previously discussed in this section of the Handbook. The use of a beam-power pentode tube provides greater amplification than the triode with an increase of linearity. The low input capacitance of the pentode decreases the rise time considerably, however, the large output capacitance greatly increases the rise time, so that the overall result is to increase the rise time to about double the triode value. Consequently, it is necessary to include a shunt compensating inductance in the plate circuit, since cathode degeneration, as used in the triode, is unable to provide sufficient compensation. The shunt-peaking compensating circuit is designed to reduce the total rise time to from 40 to 50 percent of that obtained without compensation, depending upon the tube type used. Because of the compensating circuit inductance the overshoot is increased to about 3% or about double that of a triode driver. The addition of the screen element in the pentode causes additional d-c current to be drawn over that of the triode, which, since it does not directly contribute to useful output, causes a greater d-c power loss and a drop in overall efficiency. It is necessary that the screen be bypassed to ground effectively for all frequencies employed. While the screen bypass capacitor is effective for the higher frequencies, it usually offers sufficient impedance at the low frequencies to provide a droop in low frequency output, which does not occur in the triode. The low frequency component of screen current, in effect, produces an inverse feedback voltage across the screen bypass impedance, which lowers the instantaneous screen voltage and reduces output at these frequencies. This action is similar to the degenerative action developed across a lightly bypassed cathode resistor. Unfortunately it is greatest at the very low frequencies near the d-c level (1 to 15 cps) which are normally amplified less than frequencies above this range, unless special low frequency compensation is used. Hence such screen degeneration cannot be used to flatten the overall response since it only further attenuates the low frequencies.

Although the single triode driver lacks the amplification of the beam-power driver, the parallel-connected, dual-triode driver usually provides equivalent performance and amplification without the problem of low frequency droop introduced by the screen element. With proper design, either circuit is effective in driving the indicator tube.

Circuit Operation. The schematic of a typical beam-power video driver stage is shown in the accompanying illustration.



Typical Beam-Power Video Driver

Resistance coupling is employed in the input circuit; Cc is the coupling capacitor and R3 is the grid resistor. The output circuit is usually direct-coupled to the CRT cathode. Diode CR1 is a d-c restorer connected across the grid resistor, and fixed bias is obtained from voltage divider R1, R2 connected across the separate negative bias supply. Screen voltage is obtained from the plate supply through series dropping resistor R5, bypassed by C1. Resistor R4 is the plate load resistor, and L1 is the shunt-peaking inductance.

With no input signal, V1 rests in a quiescent condition with a plate current of approximately 18 milliamperes, as determined by the fixed-bias voltage divider, R1 and R2. The bias is in the Class A1 region and is on the order of 10 volts negative. For small input signals or for short duty cycle signals diode clamp CR1 has no effect, but for large input signals with long duty cycles, it clamps the bias at the fixed value, and prevents the grid from being driven into cutoff. Whenever the input signal makes the cathode of CR1 more negative than the bias value applied to its anode, forward conduction occurs, and the signal is shunted across grid resistor R3 to ground via R2. Thus the zero output level is maintained at the fixed bias value (see section 16 of this Handbook for a discussion of biased clamp operation). When a positive-going input signal appears on the grid of V1, plate current is increased. As the plate current is increased, a voltage drop occurs across plate load resistor R4; this is the negative-going output voltage. When V1 is operating, current flows from the cathode, through the grid wires, through the screen wires, and to the plate. A small d-c screen current flow is caused by the positive screen absorbing some electrons as they pass through the screen wires. This screen current flows through screen voltage dropping resistor R5 to the plate supply and ground. The voltage drop across R5 maintains the screen voltage at the desired value. The effective screen voltage is that of the supply less the drop in R5, since screen current flow is in a direction which develops a voltage that opposes the supply voltage. Any instantaneous (a-c) variations in screen current are bypassed through C1 to ground. However, at the very low frequencies the impedance of C1 develops an additional instantaneous voltage drop between the screen and ground. This voltage is degenerative and opposes the screen voltage. Since the capacitive reactance of C1 varies inversely with frequency, the screen voltage is reduced at these instants, proportionately to the frequency, and the amplification is, likewise, reduced since the screen voltage controls the plate current. Thus, there is a droop in the waveform at the lower frequencies which are not adequately bypassed by screen capacitor C1.

When the trailing edge of the positive input signal returns towards zero it is negative-going and the plate current is reduced. The reduced voltage drop across R4 produces the positive-going trailing edge on the negative output waveform. Any excessive drive in the negative direction is eliminated by the clamping diode as explained previously above. When the plate current changes direction, the inductance of L1 tends to continue current flow in the same direction and causes a slight overshoot. Because the overshoot is kept below 3% by proper design and selection of component values, it causes only a slight amount of distortion. Peaking coil L1 is connected in series with plate load R4, and the total drop across this combination load varies in accordance with its impedance. As the frequency is increased, the reactance and hence the impedance of L1 increases as does the high frequency output, thus high frequency compensation is achieved. For further information on this type of frequency compensation see the previous discussion of the TRIODE VIDEO AMPLIFIER in this section of the Handbook.

FAILURE ANALYSIS.

No Output. Improper bias, lack of plate or screen voltage, an open input circuit, or loss of input signal, as well as a defective tube can cause a loss of output. If voltage divider resistor R2 is open, the full negative bias supply voltage will be applied to V1 grid, the plate current will be cut off, and no output can occur. The same condition will occur if R1 is shorted except that, in this instance, the entire bias supply will be dissipated across R2, will cause it to heat, smoke, and eventually burn out. In either case check the voltage across R2 with a voltmeter. If either R1 or R3 is open no bias will be applied to V1, heavy plate current will flow and overload R4 and L1; eventually this will cause the weakest one to burn out. Meanwhile, the output will be held at a constant maximum negative value, causing the CRT to be constantly illuminated, and no signals will appear. Check the bias supply to ground, first with a voltmeter, then from R1 to ground, and finally from the grid of V1 to ground. Lack of voltage indicates that the failure is between the bias supply and the point measured. If the coupling capacitor Cc is open, no signal will appear on the grid, and no output will occur even though normal bias and plate voltage are indicated on the voltmeter. On the other hand, if Cc is shorted the plate voltage of the preceding video amplifier will drive V1 heavily into conduction and cause an indication similar to that of no-bias. In this case, the voltmeter will show a large positive voltage on the grid of V1.

If the plate supply is at fault, no plate or screen voltage will exist on V1, and no output will be obtained. Check the supply with a voltmeter and then check the voltage from screen to ground. If R5 is open, no voltage will appear on the screen, and the plate current will be so small that practically no output will be obtained. A shorted screen capacitor (C1) will also cause a lack of voltage indication at the screen, since the entire supply will be dropped across R5. In this instance, R5 will heat abnormally, and will probably smoke and then burn out. If either R4 or L1 are open, no plate voltage will appear on V1; the screen of V1 would then attempt to function as a plate, and the heavy current flow will cause the screen to heat and glow red, and will also overload R5, cause it to smoke, and burn out. With normal bias voltage and screen voltage, and a higher than normal plate voltage, if no output voltage exists and an input signal is known to be applied, either tube V1 is defective, or R4 is short circuited. Replace the tube with a known good one, and if no output is obtained, turn off the plate voltage and check R4 for continuity, and proper resistance.

Low Output. If clamping diode CR1 is shorted, the input signal will be shunted to ground through R2 and a lower than normal output will be obtained. Should R2 increase in resistance the bias will be higher than normal and a reduced output will also occur. In the case of R2 the bias value can be checked with a voltmeter. However, to check the diode, it must either be removed from the circuit, or the plate and the bias supplies must be disconnected and the forward and reverse resistance measured. If the diode resistance is low, and is the same in both directions, it is shorted. If it reads a high resistance in both directions it is open. (It will normally indicate a high resistance in the reverse direction and a low resistance in the forward direction.)

If V1 is low in emission a low output will be obtained. Replace the tube with a known good one. If R5 increases in value, the screen voltage will measure lower than normal with rated supply voltage, and the output will also be low. A similar condition may be caused by a high resistance leak to ground through screen capacitor C1. Check C1 with an in-circuit capacitance checker, or measure R5 with an ohmmeter, with the power OFF. When C1 is disconnected the screen voltage will return to normal if the capacitor is defective.

If the plate supply is low, both the screen and plate voltages will be proportionately lower. If the supply and screen voltages are normal, but the plate voltage is low, replace the tube to make certain that it is not the cause.

With the same condition persisting after V1 is replaced, check L1 and R4 individually for resistance, with the supply voltage OFF. A poor soldered joint, or an increase in the resistance of L1 or R4 will cause a lower than normal voltage. If L1 measures more than 20 ohms, check its rated dc resistance in the equipment technical manual. Small inductors and chokes showing a higher than normal resistance will usually increase greatly in resistance when loaded, but appear close enough to normal to be within the allowable tolerance of a resistance check (20 percent maximum). In any event, the d-c voltage drop when operating should only be a few volts.

Distortion. Usually a simple voltage and resistance check of the circuit will determine defective or off value parts. To determine distortion, however, it is necessary to observe and compare waveshapes, and check the input waveform against the output waveform against the output waveform. Also check the waveforms against the specific waveshapes indicated in the equipment technical manual. Use an oscilloscope to observe the operating waveform. The point where it departs from normal indicates roughly the circuit area at fault. Remember, also, that all amplifiers have a slight amount of distortion, but there are tolerances which must not be exceeded. For example, the excessive output capacity of the beam driver circuit and that of the CRT cathode to ground, plus the wiring capacitance, will reduce the rise time. Thus, the leading and trailing edges may have a slight slope rather than being ideally vertical. Likewise, the flat top portion of the pulse can be expected to droop or sag slightly. With inductive parts in the plate circuit there will also be some overshoot and undershoot, caused by the effect of inductance on the transient response. Thus the output waveform will never be identical to that of the input waveform, but they will resemble each other closely. The response of the vertical amplifiers in the test oscilloscope will also affect the apparent waveshape appearing on the screen. When checking waveforms, always make certain that the test equipment is capable of producing the same result as that of the original.

When sloping vertical shapes are observed, look for deteriorated high frequency response caused by an excessive shunting capacitance to ground. For sloping horizontal lines, look for deteriorated low frequency response caused by a defective low frequency compensating circuit, or inadequate cathode and plate, or screen bypassing. By temporarily paralleling the suspected component with a similar part it is usually easy to determine if the suspected part is having the effect on waveshape for which it was designed. Do not make any unauthorized modifications in Navy equipment because it may appear to be better to you, since you may be overcompensating instead.

CHAIN (MIXER, AMPLIFIER, AND DRIVER) VIDEO AMPLIFIER.

APPLICATION.

The chain video amplifier is used in a radar display *system to mix positive radar video with positive marker* pulses, to invert the combined signals, and amplify them to a level sufficient to intensity modulate the cathode ray indicator.

CHARACTERISTICS.

Consists of three basic circuits combined together in cascade.

Uses fixed or self bias, as applicable.

Uses dual triodes to save space and provide adequate amplification.

Requires positive inputs, and supplies a negative output.

Amplification is variable from 30 to 60 times.

Minimum rise time is 80 nanoseconds, with a maximum delay time of 50 nanoseconds.

Droop is not greater than 6% for a 500 microsecond pulse.

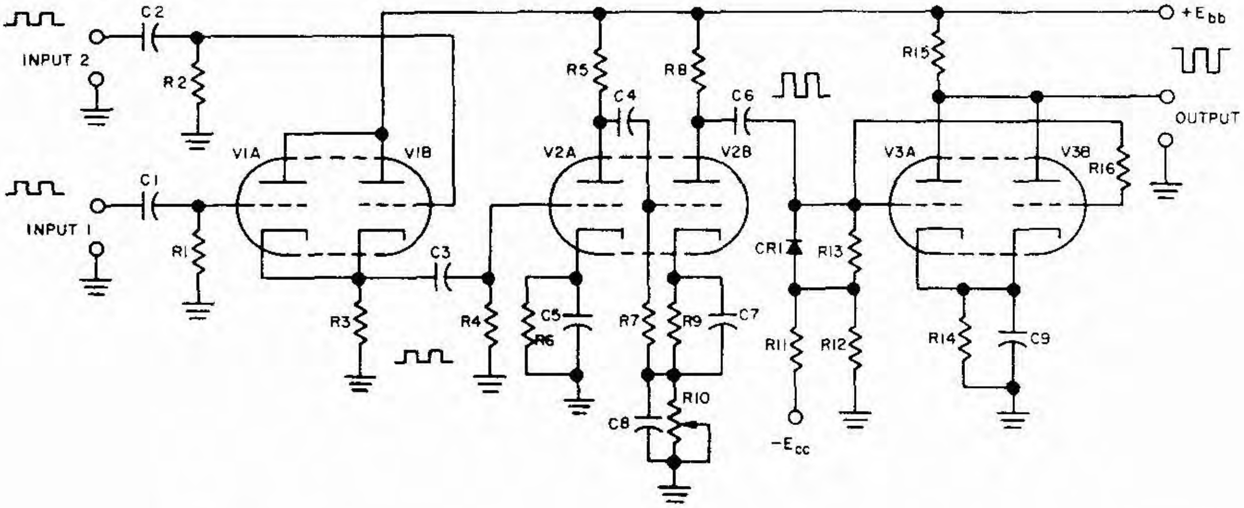
Maximum input signal is 1-volt peak, with a maximum duty factor of 0.05.

Maximum output is 50 volts peak.

CIRCUIT ANALYSIS.

General. The chain amplifier consists of three basic circuits: a common cathode type video mixer, a two-stage intermediate amplifier, and a video driver. Each of these basic circuits is described separately in this Handbook. For an explanation of the video mixer, see COMMON CATHODE VIDEO MIXER in section 12 of this Handbook. The intermediate amplifier consists of two identical stages, with the exception that a volume control is added in the cathode of the second stage. See the discussion of the TRIODE VIDEO AMPLIFIER, and that of the TRIODE VIDEO DRIVER AMPLIFIER in section 6 of this Handbook for a detailed discussion of these two basic circuits.

Circuit Operation. The accompanying schematic illustrates a typical chain video amplifier.



Chain Video Amplifier

Since each of the basic circuits is fully described elsewhere in this Handbook, as stated above, the circuit operation discussion will be limited to a simple functional signal description with characteristics. See the specific basic circuits for any additional information.

Tube V1 is a dual-triode connected as a common cathode video mixer. Resistance coupling is used to supply two identical, high-impedance, grid-input circuits. The plates are paralleled and the output is taken from cathode resistor R3, which is common to both circuits. When a positive input is applied to either grid of V1 a positive output voltage is developed across the cathode output resistor. Because of the cathode follower connection, the circuit is degenerative and no gain is obtained. With approximately 1-volt positive input, about 0.65 volt positive output is developed. For equal amplitude inputs which are in time coincidence, the output is additive and at a maximum. The extent of the adding, primarily, depends upon the value of the cathode resistance and the input signal amplitude. Generally speaking, the largest input signal tends to dominate the output, and the additive factor becomes zero if one of the signals is more than double the amplitude of the other. The low impedance output of V1 is RC coupled to two intermediate level, cascaded triode video amplifiers. V2 is a dual triode using each half-section as a separate stage of video amplification. The positive signal from the cathode of V1 is applied to the grid of V2A, which develops a negative output signal across plate load resistor R5. The plate of V2A is RC coupled to the grid of second half-section V2B, so that both stages are cascaded. When the negative driving signal appears on V2B grid, a positive output is developed across plate load resistor R8 for application to the driver stage grid. The cathodes of both stages supply cathode bias through partially bypassed resistors R6 and R9, to provide degeneration at the lower frequencies and thereby improve high frequency response. The fixed cathode resistors of these two stages are identical, however, they are bypassed, with different values of capacitance, because additional resistance in the form of gain control R10 is connected in series with cathode resistor R9 of the second stage and ground. Gain control R10 is only partially bypassed to retain the full degenerative action of these cascaded stages. Overall gain is approximately 15 times, and the gain control permits control of volume over a 2 to 1 range.

The positive output of V2B is also RC coupled to driver stage V3, another dual triode. The elements of V3 are paralleled to provide greater transconductance and more gain. Fixed bias is applied the V3 grids from separate bias source, with partially bypassed cathode resistor R14 supplying degenerative cathode compensation so that plate peaking circuits are not required. The driver stage supplies a gain of approximately 6, and uses a diode d-c restorer (CR1) as a biased negative clamp for high level signals. When a positive signal is applied to the grid of V3, a negative output is developed across plate resistor R15 for application to the CRT cathode. A maximum peak voltage drive of 60 volts is obtained for intensity modulation of the CRT indicator. The low output capacitance of the triodes provides good rise time response, and the small quiescent current of 0.5 milliampere provides efficient operation. The overall pass band is useful from 10 cps to 1.7 megacycles; by changing values and using subminiature tubes, the pass band can be extended to about 3.8 megacycles. The high frequency limit is affected slightly by the setting of the gain control, because of the increased degeneration afforded at the low gain settings. Because of the limits permitted by tube specification MIL-E-1, the amplification may be changed by 25% if the tubes are all selected for a high tolerance. A ten percent change in both filament and plate voltage will only vary the amplification 12.5 percent overall. The previously stated values of input, output, and pass band are made assuming normal plate and filament voltages, and tubes of average tolerance.

FAILURE ANALYSIS

General. The detailed failure analysis for the individual stages is discussed at the end of each of the separate circuit discussions referenced at the beginning of this circuit description.

Use an oscilloscope and a square wave generator to isolate the trouble to a basic circuit, then troubleshoot the defective circuit in accordance with the detailed failure analysis for the specific circuit. For example, apply a 400 cycle square wave input signal to one input and observe the output with the oscilloscope. If the output waveform is normal, apply the square wave to the other input and observe that a similar output occurs. Any difference in output indicates trouble in the individual channels of stage V1. Then apply two equal signals simultaneously to both inputs and check for a similar but larger output. If no output, a low output, or a distorted output is obtained during any of these checks connect the oscilloscope successively to the output of each stage. Proceed from the output back towards the input and note when the signal observed on the oscilloscope assumes its normal shape and approximate output level. As an example, assume that with normal input applied both input channels, the driver output is found to be almost normal in amplitude, but distorted. When the oscilloscope is removed and connected to V3 grid, the signal amplitude is reduced, but the distortion is still evident. However, when the oscilloscope is connected to the grid of V2B the distortion disappears. The trouble then exists in tube V2B, its associated circuit, or in the coupling circuit between V2 and V3. Observing the waveform at the plate of V2B will quickly eliminate the coupling circuit. A voltage check of V2 will then reveal if the element voltages are normal, if the voltages are normal tube V2 is probably at fault, and replacing it with a known good tube will restore operation to normal.

Note that in this case no tubes were replaced or voltages measured until the approximate location of the trouble in this circuit was pin-pointed by the visual waveform check. While the tubes could have been replaced and the element voltages measured as soon as the output was seen to be abnormal, it is evident that a procedure of this sort is basically a waste of time, and even though the trouble might have been eliminated in this manner, three tubes would have been replaced when only one tube actually was defective. Further tests of the tubes would then be neccessary to determine which was at fault.

When operation of the circuits is understood and the trouble symptoms are carefully evaluated, much needless testing can be avoided. The cause of the trouble can usually be determined by applying basic circuit theory. In the doubtful cases, a systematic method of testing such as just described will prove superior to any cut-and-try methods, or hit-and-miss guessing.

CATHODE-COUPLED (IN-PHASE) VIDEO AMPLIFIER.

APPLICATION.

The cathode coupled video amplifier is used as an input matching amplifier, or as an intermediate level video amplifier in cascaded direct-coupled video stages.

CHARACTERISTICS.

Usually is self-biased, although combination fixed- and self-bias can be used.

Usually employs a twin triode for space and economic reasons.

Operates in-phase (a negative output occurs for a negative input and vice-versa).

Provides a high input impedance with a moderate output impedance.

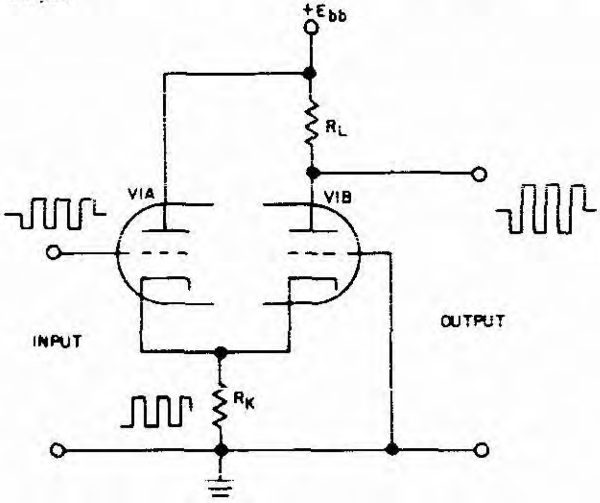
Requires no special frequency compensating circuits.

Inverse feedback from the degenerative cathode produces wideband response.

CIRCUIT ANALYSIS.

General. The cathode-coupled video amplifier can be considered to be a combination of two basic circuits (a cathode follower and a grounded grid amplifier) connected in a cascade arrangement without any coupling elements. The elimination of the necessity for coupling elements through the use of direct-coupling improves the low frequency response. Since most detectors provide a negative output, this circuit may also be conveniently direct-coupled to the detector, and can be either d-c or a-c coupled at the output. All the advantages of the cathode-follower input are maintained, while the grounded-grid output circuit provides more gain with greater stability and less tube noise. The output circuit can also be easily matched to the following stage for maximum output by proper choice of load resistor. Since the cathode degeneration is effective for both input and output stages, increased linearity is obtained with better overall frequency response and a wider pass band than for conventional plate-coupled stages.

Circuit Operation. The accompanying schematic illustrates a typical cathode-coupled circuit with an in-phase output.



Cathode-Coupled (In-Phase) Video Amplifier

A twin-triode tube is used, with one half-section, V1A, operating as a cathode follower, while the second-half-section, V1B, operates as a grounded grid output stage. Cathode resistor Rk functions as a common cathode resistor which supplies bias for both tubes, and as the load across which the input is developed and applied to the output stage. The output voltage is developed across plate resistor RL in the second half-section of V1.

With no input signal applied, both tubes rest in the quiescent condition, and, since Rk is common to both tubes, the initial bias is determined by the total cathode current of both tubes. When a negative input signal is applied to the grid of V1A the plate current is reduced, and less cathode voltage is developed across Rk. Since the cathodes of both half-sections are connected together, the instantaneous cathode bias is reduced, and both half-sections tend to draw more plate current. Plate current flow through V1A is determined by the effective bias, which is the difference between the input signal and the developed cathode bias. Current flow through Rk is in a direction which places a positive polarity on the cathodes and a negative polarity at ground. Since the grid of V1B is grounded the reduction of cathode voltage has the same effect as if the grid of V1B were driven less negative, or in a positive direction. Thus plate current flow through load resistor RL increases and produces a plate voltage drop. The increased drop across the load resistor appears as a negative-going output voltage. Thus the output polarity is the same as the input polarity. The increased plate current flow in V1B, in turn, increases the total cathode current through Rk and produces an increasing positive cathode bias. Thus circuit operation is degenerative and operates with the effect of inverse feedback. Design is such that the common cathode resistor is lower in value than the plate load resistor. Hence, for any change in plate current of V1B the degenerative cathode voltage developed is less than the output voltage. The effective drive voltage for V1B is the difference between the degenerative voltage developed across the cathode resistor and the input signal applied to the grid of V1A. It is less than the input voltage, because the cathode follower stage has less than unity gain, otherwise, the input signal would be cancelled out and no output would occur.

When the input signal swings positive, the opposite action occurs. Plate current in V1A is increased, and produces an increased cathode current and larger bias across Rk. The larger bias is applied as a negative swing to the grid of V1B and reduces the plate current, likewise. Reduction of plate current in V1B causes a reduced cathode current flow through Rk. This inverse or degenerative feedback reduces the total output voltage over what it would normally be without degeneration, but still permits effective amplification of the overall output.

Design is such that the total amplification is about half of that normally obtainable from the same stage, using plate coupling instead of cathode coupling. Although full tube gain is not obtained, cathode degeneration provides an improvement in linearity and prevents any possibility of overdrive and distortion occuring. In addition, the overall response of the amplifier is broadened by the degenerative feedback. Any tendency of the amplifier to amplify a signal of one frequency more than another frequency is reduced automatically by the increased degeneration produced by the stronger signal. Thus the amplification is made more constant over a wider range than normal, so that the response curve is flattened, resulting in a wider pass band. The use of direct coupling between the two stages eliminates any problem of phase shift in the coupling capacitor or any reactive effects which would attenuate the lower frequencies. Consequently, shunt- or series-peaking circuits are not required to produce satisfactory video response. In some applications, two twin triodes are cascaded to supply maximum gain.

If a plate load resistor is connected in series with the plate of V1A, operation is substantially the same, except that an out-of-phase output can be obtained. With resistors in both plates, dual and opposite outputs can be obtained with the circuit operating as a phase inverter for push-pull operation.

FAILURE ANALYSIS.

No Output. Lack of supply voltage, plate voltage, or improper bias will cause loss of output. If either half-section of V1 is defective, or if no signal exists on V1A no output will be obtained. A simple voltage check of the supply, and then from plate to ground will determine if lack of plate voltage is the cause. A check of the bias voltage developed across Rk, with no signal applied, will determine if the proper bias exists; if not, either the tube or resistor is at fault. Replace the tube with one known to be good if the tube is suspected. Loss of input signal can be checked with a VTVM or by observation with an oscilloscope.

Low Output. Improper plate or bias voltage, a defective tube, or a reduced input signal will cause a reduced output. Check the plate and bias voltages with a voltmeter. If the input signal is normal in amplitude as observed on an oscilloscope or VTVM, but the output is low, replace V1 with a known good tube.

Distorted Output. Distortion can best be observed with an oscilloscope and a known input (apply a signal from a signal generator connected to V1A grid, or use a steady input signal to the detector). Observe the waveform on V1A grid, a similar waveform, but reduced in amplitude should appear at the cathode. Then check the waveform at the plate of V1B, a similar but amplified signal should appear. When distortion is visible at any of these points the cause is in the preceding circuit.

SQUELCH CIRCUITS.

Squelch circuits are used to silence the receiver audio output and minimize noise when tuning between stations, or while monitoring a frequency when no signal is present. Communications receivers of high sensitivity usually contain a delayed AGC circuit which keeps the receiver at maximum sensitivity for weak signals. When no signal is present, or the incoming signal is too weak to develop gain control voltage, a maximum of noise output occurs. When monitoring a channel, this noise is particularly annoying in the period between transmissions, and especially where the noise due to external causes is beyond control of the operator.

The squelch circuit is normally employed as an automatic switch to turn the audio output of the receiver off when no carrier appears, when the received signal is too weak for communication and will not open the squelch, or when no signal is present. The audio output is turned on when a carrier appears, or a signal strong enough to operate the squelch is received. Where a high noise level exists, the squelch threshold control may be adjusted so that only signals above the noise level operate the squelch. Occasionally bursts of man made noise, or static, are encountered which are sufficient to overcome the squelch and produce a momentary burst of noise. These short noise burst do not materially contribute to operator fatigue as much as the continuous noise output from an unsquelched receiver.

Although a number of systems are in use, most squelch circuits involve a d-c amplifier which produces a control bias large enough to cut off the receiver first audio amplifier when no signal is present. The negative AGC voltage developed by the received signal is used to remove the control bias (squelch) and allow the audio stage to operate normally. Use of the receiver AGC voltage to control the squelch action provides a convenient and automatic method for operating the squelch.

AGC-CONTROLLED AUDIO AMPLIFIER.

The AGC-controlled audio amplifier is used to silence the receiver until a signal of usable level is received, and to reduce the noise output as the receiver is tuned from one signal to another. It is particularly useful in mobile and controlled net operation.

CHARACTERISTICS.

It is turned off by a positive AGC delay voltage.

It is turned on by a negative AGC voltage.

It may be rendered inoperative by a separate switch.

Operating threshold is determined by a manual bias control.

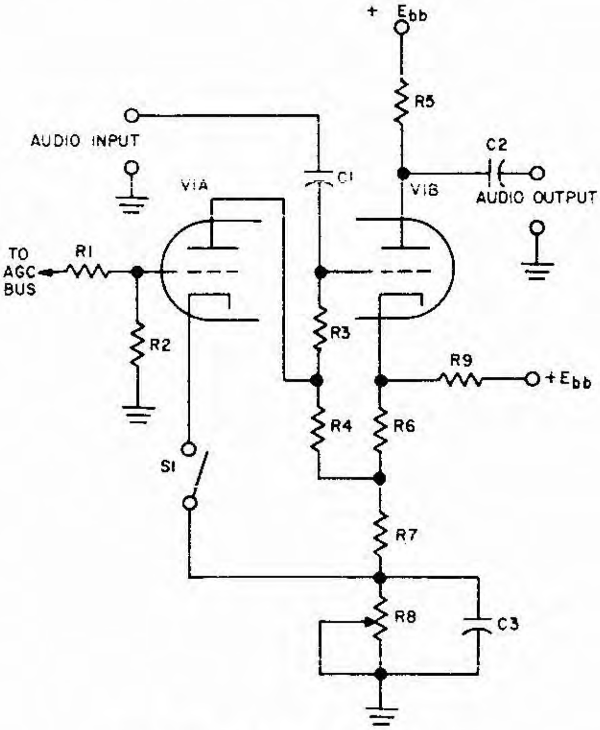
It is operated by a negative AGC voltage of from 0 to 35 volts.

May be packaged as a self-contained accessory, or supplied as an integral part of the receiver.

CIRCUIT ANALYSIS.

General. To ensure that the squelch is opened by the weakest readable signal, it is necessary that a high sensitivity level be maintained. To achieve this high sensitivity without excessive background noise from various sources, the squelch circuit bias is determined by a threshold control. Thus the operator may adjust the operating threshold to suit local operating conditions. To permit operation of the receiver without squelch action, the squelch circuit is normally completed through a switch. When this switch is open the squelch circuit is inoperative. Although not necessary for circuit operation, both the threshold control and the squelch off-on switch are usually provided for convenience in operation.

Circuit Operation. A typical audio squelch operated by receiver AGC voltage is shown schematically in the accompanying illustration.



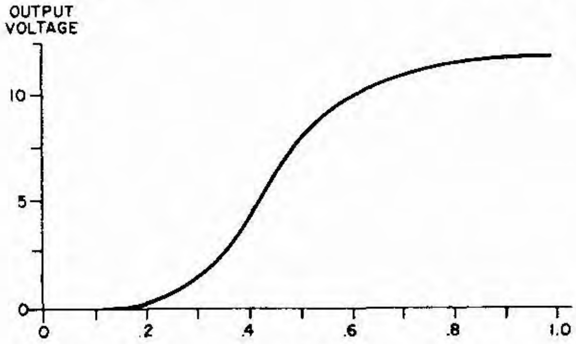
AGC Controlled Audio Amplifier Circuit

A twin-triode electron tube is used, with half-section V1A connected as a d-c control amplifier, and half-section V1B operating as the bias controlled first audio stage. The grid of V1A is direct-coupled to the AGC control circuit, and is supplied with a portion of the control voltage by voltage divider R1, and R2. Resistor R1 is also connected in series with V1A tube grid and acts as an isolation and current limiting resistor. Normally, the cathode circuit of the squelch tube is completed through off-on switch S1. The plate of V1A is direct-connected to the grid of V1B through grid resistor R3, and the audio input to V1B is capacitively coupled through C1. Resistor R4 is the plate resistor of V1A, which is connected to a bias voltage divider between the plate supply and ground formed by R9, R6, R7, and R8. The cathode of V1B is connected to this voltage divider at the junction of R9 and R6, while plate-dropping resistor R4 is connected at the junction of R6 and R7. In this manner the cathode of V1B is always more positive than the plate of V1A, a typical direct-coupled biasing arrangement. Resistor R8 is variable and acts as the threshold control. Tube V1B is resistance-coupled to the second audio stage, R5 is the plate load resistor, and C2 is the coupling capacitor. Cathode bypassing for V1A is accomplished by C3.

With no signal applied, the receiver AGC delay voltage of approximately +1.5 volts is applied to input voltage divider R1 and R2. Since the grid of V1A is connected across R2 only that voltage appearing across R2 is effective in driving the grid; approximately one-fifth is dropped and lost across R1. Because R1 is connected in series between the AGC bus and the grid of V1A, any loading of the AGC bus by grid current flow is prevented by the high resistance of R1. Cathode bias for V1A is developed across threshold control R8, which is bypassed for audio frequencies by C3. Thus the average cathode bias remains unaffected by the signal or by instantaneous changes in the plate current of V1A. Switch S1 is normally closed to complete the cathode circuit; when it is open the squelch circuit is made inoperative.

As the positive input (AGC delay) voltage causes V1A to conduct, a negative voltage drop is produced by plate current flow through R4. Current flow is from the cathode of V1A to the plate, through R4, and through the voltage divider to the supply. Thus the end of R4 which is direct connected through R3 to the grid of V1B is always driven negative when plate current increases in V1A. This negative bias on the grid of V1B biases the audio stage to cutoff, silencing the receiver. The point at which cutoff occurs is determined primarily by the setting of threshold control R8. When R8 is adjusted so that heavy plate current flows in V1A, a large bias is produced and only a very small positive signal is necessary to drive the squelch sufficiently to produce cutoff control bias.

When the incoming signal produces a negative AGC voltage in the receiver it causes plate current flow through V1A to be reduced. The reduced plate current produces a smaller voltage drop across R4, thus reducing the bias applied to V1B grid, and permitting the audio stage to operate. The audio output reaches maximum when squelch tube V1A is cut off. In a typical circuit, an AGC voltage of −0.3 volt will ungate the audio stage and the output will increase until the AGC voltage reaches 0.8 volt. At this time, the squelch tube is completely cut off, normal bias is applied to the audio stage, and full audio output is obtained. the accompanying chart shows a typical squelch sensitivity curve.



Squelch Sensitivity Curve

Once the squelch tube is completely cut off, normal fixed bias for operation of the audio stage is supplied by the voltage divider connected to the cathode. By employing R6 and R7 as unbypassed cathode resistors, some cathode degeneration is provided to improve the linearity of the first audio amplifier. Any audio signal appearing on V1B grid will not affect squelch operation, because squelch tube V1A is cut off when full output is obtained. During the time the squelch is biasing off V1B and partially reducing the audio output, any audio voltage coupled through R3 to the squelch plate is attenuated by the large resistance value of R3 and has no effect on circuit operation. Although there is a slight delay from application of the signal to the receiver until the circuit is completely ungated, it is only a few microseconds (which appears to be instantaneous) and has no effect on the intelligibility of the audio signal.

FAILURE ANALYSIS.

Squelch Inoperative. Lack of proper input signal, an open plate or cathode circuit, or a defective tube will prevent squelch tube V1A from operating. If the receiver does not supply a positive delay voltage, or if R1 is open, or R2 is shorted, the circuit also will not operate. Measure the voltage from the grid of V1A to ground with a voltmeter, also the voltage on the AGC bus. Voltage at the bus, but not at the grid indicates either R1 is open, or R2 is shorted. Use an ohmmeter to check these resistors. If S1 is defective, the cathode circuit will be open and the squelch will not operate. Make a continuity check of the switch. If plate resistor R4 is either open or shorted, no bias will be developed to control the audio stage and the squelch will not operate. Measure the plate voltage on V1A. No plate voltage indicates R4 is open. With plate voltage on the plate of V1A and the squelch inoperative either the tube is defective, R4 is shorted, R3 is open, or threshold control R8 is set too high. Replace V1A with a known good tube and adjust the threshold control. If the squelch still will not operate, remove plate power and check the resistance of R4, and R3. If R3 is shorted, the squelch will operate but the audio will be reduced when the squelch is inoperative. On the other hand, if R3 is open there will probably be a reduced audio output and the squelch will not operate.

Squelch Operates, Audio Output Low. When the squelch operates, but the audio output is low, the receiver may be applying a weak audio signal, or the audio stage is improperly biased. Check the bias voltage divider with a voltmeter to locate the defective resistor. Apply an audio signal from an audio signal generator to the grid of V1B. A larger output indicates the amplifier is operating and that the receiver is not supplying sufficient input.

R-F AMPLIFIERS.

R-F amplifiers are similar in many respects to other forms of electron tube amplifiers, but differ primarily in the frequency spectrum over which they operate. There are two general classes of r-f amplifiers, the untuned amplifier and the tuned amplifier. In the untuned amplifier, response is desired over a large r-f range, and the main function is amplification alone. In the tuned r-f amplifier, very high amplification is desired over only a small range of frequencies, or at a single frequency. Thus, in addition to amplification, selectivity is also desired to separate the wanted from the unwanted signals. The use of the tuned r-f amplifier is generally universal, while that of the untuned r-f amplifier is relegated to a few special cases. Consequently, when r-f amplifiers are mentioned, they are ordinarily assumed to be tuned unless otherwise specified. The tuning element usually consists of a parallel-resonant L-C circuit. It may be inductively tuned by a movable slug, with the tank capacitance fixed in value or consisting of the stray and distributed capacitance existing in the circuit. Or, as is usually the case, a fixed or slightly adjustable inductor determines the high-frequency limit, and a tuning capacitor is used to tune to the desired frequency or over a range of frequencies.

In receiving equipment, the r-f amplifier serves to both amplify the signal and choose the proper frequency; in addition, it serves to fix the signal-to-nois ratio. A poor r-f amplifier will make the equipment able to respond only *to large input signals, whereas a good r-f amplifier will* bring in the weak signals above the minimum noise level (determined by the noise generated in the receiver itself) and thus permit reception which would otherwise be impossible. The r-f amplifier is also used as an i-f (intermediate-increased, since a slightly lower positive potential now frequencies lower than the input frequency (for medium- and high-frequency receivers), and provides high gain *combined with extreme selectivity. In transmitters, the r-f* amplifier serves to amplify a single frequency (including any sideband frequencies produced by modulation) to a value suitable for application to the antenna. Basically, the receiver r-f amplifier is a voltage amplifier, while the the transmitter r-f amplifier is a power amplifier.

As might be suspected, since the r-f amplifier is employed over the entire r-f spectrum, careful attention to design parameters is necessary to obtain proper operation. In the medium-, low-, and high-frequency ranges, conventional tubes and components are used. In the VHF, SHF, and microwave ranges, specially designed tubes and components are required to obtain optimum results (for example, the traveling-wave tube and the multi-cavity klystron).

In addition to the design requirements imposed by frequency, other considerations are often involved to obtain less noise and good selectivity with sufficient amplification, such as those involved in cascaded and cascoded stages. In other instances the r-f amplifier not only amplifiers, but also serves to multiply the frequency. Each of the various types and classes of r-f amplifiers will be discussed in the following paragraphs.

PENTODE R-F VOLTAGE AMPLIFIER.

APPLICATION.

The pentode r-f voltage amplifier is universally used as the input stage in receivers or other cascaded r-f amplifier stages to provide a high signal-to-noise ratio with maximum voltage amplification.

CHARACTERISTICS.

May be either tuned or untuned.

Operates at a specific r-f frequency or is tunable over a range of r-f frequencies.

Provides high gain (100 or better).

Uses impedance coupling at input or output where high gain is not required, and transformer coupling with or without tuning for high gain.

Uses cathode bias, or contact bias for small input signals.

Operates Class A at all times.

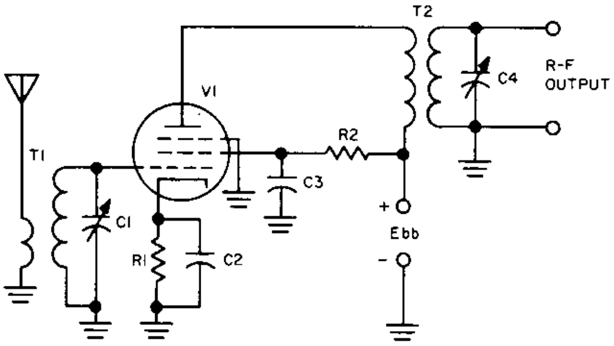
CIRCUIT ANALYSIS.

General. The pentode r-f voltage amplifier may be either tuned or untuned. When untuned, the stray wiring and distributed circuit capacitance plus the tube capacitance to ground limit the high-frequency response, and hence the highest r-f frequency at which it can be used. On the other hand, the tuned r-f amplifier uses a parallel-resonant circuit to supply a high impedance across which the load voltage is developed. In this instance, the stray, distributed, and tube capacitances merely add to the value of tuning capacitance so that higher frequencies and greater amplification (as compared with the untuned stage) at these higher frequencies is obtained. Therefore, the tuned r-f amplifier is universally used, and the high gain of the pentode provides amplification not possible with a triode or untuned stage. The tuned r-f amplifier is further subdivided the narrow-band amplifier and the broad-band amplifier into two classes: Narrow-band amplifiers are used to amplify CW or voice- modulated signals (including broadcast signals), whereas broad band amplifiers are used to amplify television, video, or pulse-modulated signals. Narrow-band amplifiers accept a maximum of 5 to 10 kc around the center frequency, whereas broad-band amplifiers cover the range of 5 to 10 mc around the center frequency. Generally speaking, narrow-band amplifiers used the same types of pentode tubes used with resistance-coupled audio amplifiers, and broad-band amplifiers use the same type of pentode as is used with video amplifiers.

The tuned r-f amplifier may also be subdivided into two other classes: single-tuned and double-tuned. Since the double-tuned type is usually employed in tuned interstage amplifiers and cascaded stages, and these are the subjects of separate discussions later in this section of the Handbook, only single-tuned amplifiers are discussed here.

The use of the pentode, with its high transconductance and amplification factor, results in a high value of voltage amplification. In addition, the low grid-to-plate capacitance of the pentode reduces the tendency toward plate-to-grid feedback and self-oscillation. A lower effective tube input capacitance also increases the high-frequency limit of operation. By the use of coils with a high ratio of inductance to resistance (Hi-Q), the amplification provided by each stage of the tuned r-f amplifier can be made greater than that of the amplification factor of the electron tube alone. Since the amplification of the r-f amplifier depends greatly upon the transconductance of the tube, it is also possible to vary the grid bias for the stage in accordance with signal amplitude, and hence automatically control the gain.

Circuit Operation. The accompanying schematic shows a typical pentode signal-tuned r-f voltage amplifier circuit.



Pentode R-F Voltage Amplifier

In the schematic, T1 is an r-f transformer which matches the antenna to the control grid of the pentode. Tuning the secondary of T1 with C1 permits a larger signal to be developed across the Hi-Q tuned circuit, and applied to the grid, than if no tuning at all were employed. Resistor R1 and capacitor C2 form the conventional cathode bias resistor and bypass capacitor. See Section 2, paragraph 2.2.1, of this Handbook for a discussion of cathode bias. Resistor R2 is the screen voltage-dropping resistor, and capacitor C3 is the screen bypass capacitor, which stabilizes the screen voltage and prevents it from being affected by the signal. The suppressor element of V1 is grounded directly. In some circuits it is connected externally to the cathode; in certain types of tubes it is connected internally to the cathode. R-F transformer T2 acts as the plate load and couples the output to the next stage. The output winding is tuned by C4 to the desired r-f output frequency. While C4 could be placed across the primary of T2 and the secondary left untuned, the conventional approach is to tune the secondary. With proper design the circuit is effective either way, and the secondary load is reflected into the plate circuit.

When a signal appears on the antenna, it is coupled through the primary of T1 to the tuned secondary (grid input) circuit. With capacitor C1 tuned to the frequency of the incoming signal, a relatively large r-f voltage is developed across the tuned circuit and applied to the grid of V1. The r-f signal, if unmodulated, consists of equal-amplitude positive and negative cycles occurring at the frequency to which the circuit is tuned. For the moment, any fading or noise is considered negligible and the input signal is considered to be of constant amplitude. On the positive half-cycle the grid bias is decreased, causing a plate current increase. On the negative half-cycle the bias is increased, causing a plate current decrease. This changing plate current flowing through the primary of output transformer T2 induces an output in the tuned secondary winding. This operation is practically identical with that of the Transformer-Coupled Audio Voltage Amplifier previously discussed in this section of the Handbook.

For ease of discussion, the signal is considered to be a sine wave with equal-amplitude positive and negative r-f swings. The average plate current flow, therefore, will be constant, and cathode bias may be employed. It is important to note that the r-f amplifier operating as the first stage in the receiver is usually a small-signal amplifier. That is, the input voltage is on the order of microvolts, except in strong-signal areas. Therefore, a small signal voltage change causes only a very small bias change, and it is necessary to employ high-transconductance electron tubes to produce effective amplification. The pentode tube is admirably suited for this purpose, since it has both a high amplification factor and a high transconductance. By using a large value of inductance and a small tuning capacitance for the frequency involved, and also as small a coil resistance as is practicable, the tuning circuit exhibits a Hi-Q. Thus, its effective impedance is much larger than that presented by a tuning tank of low Q. Hence, a large input voltage is developed between grid and ground across the tuned circuit. With a step-up turns ratio from transformer primary to secondary, if closely coupled, a still larger input voltage is produced. The step-up of voltage in the transformer and the Hi-Q tuned grid tank increase the small input voltage before it is applied to the tube for further amplification. Normally, Class A bias is used to produce linear swings and to minimize distortion. With very small input signals however, operation occurs over the curved portion of the plate-current grid-voltage characteristic. For example, typical bias values range from 0.5 to 1 or 2 volts maximum. Thus, the tube is clearly operating very close to zero bias, and the Eg-Ip curve in this region is never straight. This results in uneven positive and negative swings, and this produces distortion. For r-f amplifiers where the input signal is large, as in cascaded or i-f stages, a larger bias and a more linear portion of the curve are used.

When the input signal is modulated, each r-f cycle may be of different amplitude; thus, considering each cycle to be amplified linearly, the modulation is likewise amplified proportionately producing an over-all modulation envelope which is almost identical with that of the original modulation. A slight difference (usually a reduction in modulation factor) exists; this is produced by distortion, which will be discussed in more detail under Failure Analysis.

When small values of bias are used in the input stage and large signals are applied, distortion occurs because the signal is partially clipped off in the plate circuit. In addition, grid current flow creates a low-resistance (shunt) path between the grid and the cathode, which effectively lowers the grid tank Q. As a result, the input signal and over-all amplification of the stage are reduced. Therefore, it is common practice to employ a variable cathode resistor for manual gain control, or to provide some means of automatic bias (gain) control. For a complete discussion of AGC circuits, refer to Section 21, Control Circuits, in this Handbook.

FAILURE ANALYSIS.

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No Output. Loss of plate, screen, or filament voltage, or a defective tube, can cause no output. The voltages can be checked with a voltmeter, and a open filament can sometimes be observed by noting that the tube is not illuminated and feels cold to the touch. If the plate, screen, and filament voltages are normal, substitute a tube to be good. If there is still no output, check the input transformer by applying a modulated voltage from a signal generator to the input terminal and observe whether there is an input voltage on the grid (use a VTVM or an oscilloscope and r-f probe as the indicator). An open screen resistor (R2) will be indicated by the lack of screen voltage. Similarly a shorted screen capacitor (C3) will drop the screen voltage to zero and cause R2 to heat abnormally. The short circuit condition may be observed visually by smoke from or discoloration of the resistor. An open or shorted cathode bypass capacitor (C2) will not necessarily produce a no-output indication; however, an open bias resistor (R1) usually will. In fact, on very small signals either trouble may not be obvious or may show only as a slight increase in distortion. If tuning capacitor C1 or C4 is defective, depending on whether it is short-circuited or open-circuited, there may be no output or a considerable reduced output, respectively. Since each capacitor is shunted by a coil, it will be necessary to disconnect one end to check for capacitance or a short. Where an open coil is suspected, it can be checked for continuity with an ohmmeter.

Reduced Output. When there is an open circuit in either transformer T1 or T2, if sufficient capacitive coupling exists between the windings (especially at the higher frequencies), the output will be reduced, rather than nonexistent. On the other hand, at the lower r-f frequencies the output may be reduced practically to zero. A check with an ohmmeter will determine whether there is continuity in the coils. A change in the value of screen resistor R2 to a higher value will lower the screen voltage and reduce the output. Likewise, a reduced plate voltage caused by a high-resistance joint or winding will lower the output. Low output can also be caused by a defective tube, that is, a tube with low filament emission or an internal short. If the tube has an internal short, it will draw a heavy cathode current, thus producing a much greater than normal bias and reducing the output accordingly. A defective antenna or transmission line can cause a weak input signal and an apparent lack of output. In this instance the circuit will check normal in every respect, and changing tubes will make no difference. Substitute another signal from a different antenna, if possible, or apply an input from a signal generator with a calibrated attenuator. If a large value of attenuation is required to reduce the output signal to a low value or zero, the stage is operative and the trouble is external.

Distorted Output. Improper plate or screen voltage will cause a certain amount of distortion. While improper bias will also cause distortion, it will depend to a great extent on the tube used, the input signal amplitude, and the value of bias. Intermodulation between the side (modulation) frequencies of a modulated input signal will create a slight amount of distortion due to the curvature of the tube Eg-Ip characteristic. Normally, special test equipment is required to determine this condition; besides, it is of little consequence except to the designer. Likewise, a change in the modulation factor is caused by the fact that the individual modulated r-f cycles are of different amplitudes. Thus, the larger signals are amplified more than the smaller signals because of the curvature of the tube characteristic; this is also a design problem. Hum distortion may occur because of induced hum on the carrier at low signal levels. This is normally minimized by proper filament bypassing and plate supply filtering, together with screen bypassing. There should be no hum distortion in the equipment as originally supplied, except where the filters or bypass components are defective. The use of an oscilloscope will show where the hum appears and usually localize the source.

Curvature of the tube characteristic can also cause distortion which appears in the form of intermodulation between two strong applied r-f voltages, one of which may be outside the range of the tuning, [illegible] sufficiently to be annoying in the reception of the desired signal it can be eliminated only by attenuating the undesired frequency. Intermodulation distortion is recognized by the fact that the distortion occurs to the modulation frequencies of signals which are normally loud and clear. It should not be confused with selective fading, which also causes frequency distortion in AM reception.

Another prevalent form of distortion which occurs when two strong modulated signals are nearby is cross modulation.

This actually causes modulation of the carrier of the desired signal by that of the undesired signal. Cross modulation is recognized as a form of "monkey chatter" heard in the background of broadcast stations, particularly where strong adjacent-channel signals are present. It is also recognized in voice communication by the clear, undistorted, but weak reception of the undesired station superimposed on the desired station. In the pause between syllables and words, the cross-modulating station can be heard clearly. The interfering signal may not be within the tuning range of the receiver used, although usually it is. Here again, the fault is due to curvature of the tube characteristic, and is eliminated by attenuation of the unwanted signal, either by selectivity or some other means. While usually a design problem, these types of distortion are mentioned here because it is possible in certain instances that design specifications may be overridden by circumstances beyond the control of the technician, such as when the ship is temporarily located close to another station. In this event, needless time might be spent looking for trouble with-in the circuit.

If too great a selectivity is employed, the sidebands will be partially clipped from a modulated signal, resulting in a form of frequency distortion. This can result from an incorrect setting of a selectivity control or from regeneration within the stage, which will produce sharper tuning. Regeneration can be produced by operating with too low a screen voltage or insufficient screen bypassing, and by improper lead-dress when components in the grid or plate circuits are replaced.

TRIODE GROUNDED-GRID R-F AMPLIFIER.

APPLICATION.

The triode grounded-grid r-f amplifier is used in receivers as a tuned voltage amplifier, particularly in the ultra-high-frequency ranges where it is impossible to use pentodes or beam power tubes. It is also used as a Class C linear power amplifier, especially in television transmitters.

CHARACTERISTICS.

No neutralization circuit is necessary.

Can use either fixed or self-bias.

Has low power gain, but relatively high voltage gain.

Requires more driving power than a grounded-cathode stage.

Grounded grid effectively isolates plate from cathode.

Operates Class A biased for reception, and Class C biased as r-f power amplifier.

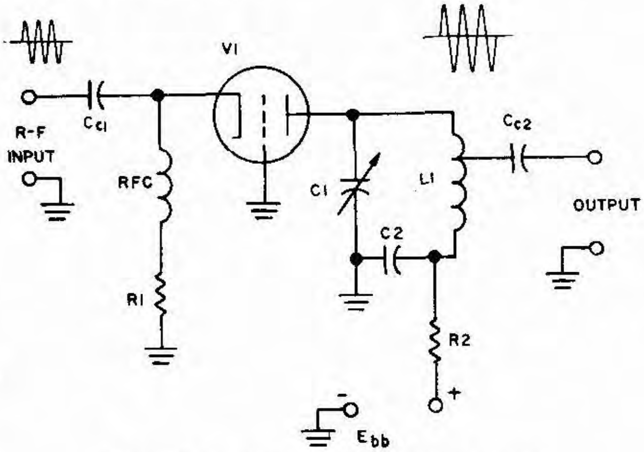
Usually used with disc seal or pencil-type, closely spaced triodes at frequencies where coaxial lines are used as tank circuits.

Particularly useful in wideband applications such as TV, because it produces increased output power and efficiency in a particular tube for a given bandwidth.

CIRCUIT ANALYSIS.

General. While the grounded-grid amplifier is most useful at UHF, it is sometimes used on lower frequencies for its inherent stability, and to avoid neutralization. With proper design, it also helps reduce "first stage noise" in receivers. However, the grounded-grid circuit is not generally used at the lower frequencies because of the extremely high gain possible with grounded-cathode pentodes. In transmitting applications it is usually used as a Class C linear amplifier, particularly in those applications where the driver stage has surplus driving power, because only a small amount of power is absorbed by the grid circuit, and the remainder is "passed through" to the plate circuit and adds to the total output because of the grounded-grid connection.

Circuit Operation. The accompanying schematic illustrates a typical grounded-grid circuit. For convenience, the tank circuit is shown as a conventional LC parallel-tuned circuit; in actual practice, however, coaxial lines or cavities are used at the high frequencies, where this circuit is usually used.



Typical Grounded-Grid R-F Amplifier Circuit

Input coupling capacitor Cc_1 functions as both a coupling capacitor and a d-c blocking capacitor to isolate the input circuit from the antenna or previous stage. Thus, the cathode bias is not affected by the input circuit. Radio-frequency choke RFC keeps the cathode above ground, since the grid is grounded to the chassis. Resistor R1 is a conventional but unbypassed cathode bias resistor which supplies Class A bias for V1 (see section 2 paragraph 2.2.1 for a discussion of cathode bias). The plate of V1 is series-fed through voltage-dropping and decoupling resistor R2 and tank coil L1. Bypass capacitor C2 keeps the lower end of tank coil L1 at ground potential, and bypasses R2 for rf. C1 is the tank tuning capacitor, and the rotor is grounded to eliminate body capacitance effects when tuning. The output is capacitively coupled through Cc_2 to the next stage.

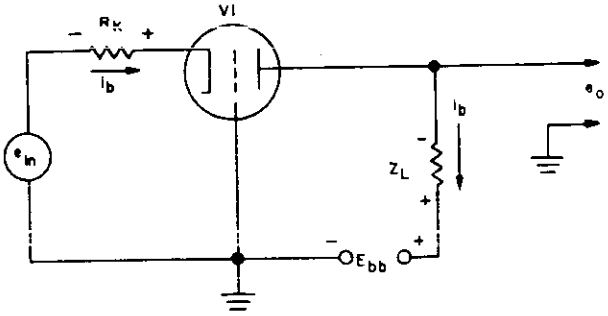
When an r-f signal appears at the input, the low reactance of Cc_1 allows it to appear on the cathode of V1 without any appreciable attenuation. The input signal may be from an antenna or a preceding r-f stage, and in some cases it may be that output of a tuned tank circuit. With the grid at ground potential, V1 is biased by the total cathode current flow through R1. With a positively biased cathode, the grid is effectively biased negative, and only quiescent Class A plate current flows. With no input signal there is no change in plate current and, consequently, no output.

Assume that an unmodulated r-f signal of constant amplitude appears at the cathode of V1. Since this signal appears between the cathode and ground, it can be considered as being supplied by a generator connected in series between the V1 cathode and ground. The r-f choke presents a high impedance to ground, and prevents shunting of the input signal to ground through bias resistor R1. On the positive r-f half-cycle the cathode is momentarily more positive resulting in the grid becoming more negative, so that a reduction of plate current occurs. In the plate circuit, the tuned parallel tank circuit, L1, C1, appears as a high impedance to the r-f component of the plate current. With less plate current flowing through the tank impedance, less voltage drop is developed across it and the plate voltage rises toward the source voltage (becomes positive-swinging). Thus, a positive output signal is developed and fed through Cc_2 to the next stage. It is evident that the grounded-grid circuit produces an output signal which is in phase (of the same polarity) with the input signal producing it.

During the negative half-cycle of operation, the cathode becomes less positive (is driven in a negative direction). A negative cathode swing causes the plate current to increase, and produces a large voltage drop across the output load impedance (tank circuit). Since the voltage drop across the tank causes the effective plate voltage to be less, a negative output swing is developed. Again the output signal is in phase with the input signal. (This action is opposite the conventional 180-degree phase shift produced in the grounded-cathode circuit, and corresponds with the action of the common (grounded)-base circuit in semiconductors). With the grounded-grid amplifier operated Class A, and with equal positive and negative swings, the average value of plate current does not change. The current flow from the cathode remains steady and occurs during the entire cycle; thus, cathode bias can be used, since the plate current is never interrupted. At the same time, the instantaneous signal changes cause larger (amplified) instantaneous r-f pulses of plate current, which produces the voltage drop across the tank impedance and an amplified output voltage. Note that the tank circuit must be tuned to the r-f signal to produce a high impedance and develop an output. Thus, signals with a frequency outside the tuned circuit pass band are not amplified, or are greatly discriminated against.

From the above description of circuit functioning, it can be seen that the basic functioning of the grounded-grid circuit is similar to that of other types of r f or audio amplifier circuits. Further consideration is necessary to develop the actions that are peculiar to this circuit alone.

Consider the following simplified equivalent of the grounded-grid circuit.



Simplified Equivalent Circuit

The input signal is shown as an a-c generator connected in series with input resistance RK. Actually, the cathode input impedance is inherently very low, and electron flow is from ground to the cathode, through the grid to the plate, and back into the supply, producing the polarities shown in the simplified circuit. Since the grid is placed between the cathode and the plate, when grounded it acts as a shield which divides the circuit into two parts – an input circuit and an an output circuit, both at above-ground potentials. Hence, any coupling is effectively minimized by the grounded grid. Since electrons flow from cathode to plate, some electrons will be intercepted by the grid and carried to ground. Thus, there will be a greater flow of grid current than in the grounded-cathode circuit, where the grid is isolated from ground by a relatively high impedance. For this reason, the grounded-grid amplifier requires more drive than the conventional grounded-cathode amplifier. Since feedback resulting in oscillation normally occurs from capacitive coupling between the output and input circuits, the good shielding of the grounded grid reduces this effect to a minimum. In addition, the interelectrode capacitances are reduced. The output capacitance is the grid-to-plate capacitance, which is usually the lowest in an electron tube; thus, capacitive shunting effects on the output are reduced at the higher radio frequencies to provide better performance. In addition, the plate to cathode capacitance is reduced, since it is the series capacitance produced by the plate-to-grid and grid-to-cathode interelectrode capacitances. Actually, in practical tubes it is reduced to a value on the order of 0.2 picofarad, which is negligible, so that neutralizing is not normally required.

Since signal voltage ein is connected between the cathode and ground, it is effectively in series with the tube plate circuit; thus, in tuned r-f voltage amplifiers the output voltage is produced as though the circuit were driven in the normal manner (grounded cathode), but had an increased amplification factor of $\mu + 1$. Hence, high voltage gain is obtained.

It is important to remember, however, that the matter of gain is relative. A low amplification factor tube will not give as much amplification as a high amplification factor tube. Nor will a triode give as much gain as a pentode at the lower frequencies. Thus, even though we speak of the grounded-grid circuit as providing high gain, it does not mean that the gain is as great as that provided by the grounded-cathode circuit using the same tube and voltages. At the ultra-high frequencies where this circuit is most useful, the performance and gain are better because of the poor performance of the pentode. At the lower radio frequencies, it usually requires two stages of grounded-grid amplification to obtain results equivalent to those obtained with a single grounded-cathode pentode stage.

In power amplifier applications, low power gain is obtained because of the increased drive requirement and the low input impedance. The low input impedance, however, does not absorb all of the input (driving) power and cause a complete loss. Instead, the driving power is fed into the plate circuit (it is connected in series with the plate and cathode circuit), and adds to the total plate power (less the amount needed to drive the tube). The additional plate power supplied by the driver is distributed between the internal tube plate resistance and the tank circuit, so that only a portion is lost or dissipated in the tube plate. The total output power in watts is equal to $I_p(e_{in} + E_p)$, where e_{in} is equivalent to the rms value of grid voltage (E_g).

In r-f power amplifiers with directly heated filaments, since the filament is also the cathode, it is necessary to use r-f chokes in the filament leads, or provide some other arrangement to keep the filament above ground and balanced. If the filament is not kept above ground, the filament and grid would be short-circuited, and the circuit would not operate.

When employed as a modulated power amplifier, the small portion of drive power which is inserted into the plate circuit remains unmodulated, making it practically impossible to obtain 100 percent modulation when plate modulation alone is used.

FAILURE ANALYSIS.

No Output. With proper bias and plate voltage, as checked with a voltmeter, only an open input circuit, lack of an input signal, or an open output circuit can result in no output. With input coupling capacitor C_{c_1} open, no signal will be applied to the cathode and there will be no output. With output capacitor C_{c_2} open, the signal will not appear at the output. Likewise, if the tube is defective, no output signal will appear. If capacitor C2 is shorted or R2 is open, there will be no plate voltage on the tube plate; thus, no output will be obtained. The capacitors can be checked with an in-circuit capacitance checker, while R2 can be checked with an ohmmeter. If the tube is suspected, substitute a tube known to be good. Do not neglect the possibility that the plate supply fuse may be open. The voltmeter check will usually indicate any abnormal operation. An open plate circuit will be indicated by no voltage at the plate. If the tuned output circuit is shorted, plate voltage will appear to be normal at the supply, but will be entirely dropped across R2 and thus be zero at the tube plate. If the plate voltage is low, and excessive plate current is the cause, it will also cause a high cathode bias. If the bias is sufficient, the tube will be almost at cutoff and the output will be so low as to be mistaken for no output at all. If the cathode r-f choke is shorted, the bias and plate voltage will appear to be normal, but the input signal will be bypassed to ground through cathode resistor R1, and there will be no output. Where V1 acts as a power amplifier, if C_{c_1} is shorted or leaky, the cathode will be biased excessively by the plate voltage of the driving stage; this bias may cause plate current cutoff, and result in no output.

Low Output. If the bias is high, the plate voltage low, or the tube defective, a low output will be obtained. Check the bias and plate voltage with a voltmeter; if the voltages appear to be normal, replace the tube with a tube known to be good. With selective tank circuits, a small amount of detuning of capacitor C1 will attenuate the signal considerably. Likewise, a high resistance in the tank circuit, caused by a poorly soldered connection, may cause sufficient loss of signal because of low circuit Q (and reduced selectivity) to produce a reduced output. An increase in the resistance of R2 due to aging will cause an increased voltage drop, low plate voltage, and low output. A change in the output load can cause a detuning effect on the tank and a reduction of output; the detuning can be compensated for by a slight readjustment of the tuning capacitor. If bypass capacitor C2 opens, the tank circuit, C1, L1, will tune broadly and resonate over a different range of frequencies, and, if R2 is sufficiently small, will cause loss of signal through absorption by the power supply.

Distortion. The grounded-grid amplifier is subject to the same distortion possibilities as other r-f amplifiers. If the bias is too low, large r-f signals will in effect drive the grid positive, causing nonlinearity and saturation effects; thus, the plate waveform will be clipped at the peak of the cycle. If the bias is too high, the negative peaks will drive the tube to cutoff, clipping off the bottom of the signal. In both cases, a distorted output will result. Where modulated signals are amplified, it is important that the pass band of the tuned circuits be wide enough to avoid sideband cutting, or the missing frequencies will cause distortion. The possibility of increased selectivity due to regeneration is less with the grounded grid than with other circuits; however, the good shielding between the input and output may be nullified if the lead dress is changed during a repair. Hence, when distortion seems to occur only at certain frequencies or over a narrow portion of the tuning range, or if whistles or squeals occur, neutralization or a lead dress correction may be required.

CASCADE R-F AMPLIFIER.

The cascade r-f amplifier is generally used in tuned radio frequency receivers to supply high gain and selectivity before detection.

CHARACTERISTICS.

Uses a number of stages connected in cascade.

Operates Class A for linear amplification.

Usually operated self-biased, although fixed bias may be used.

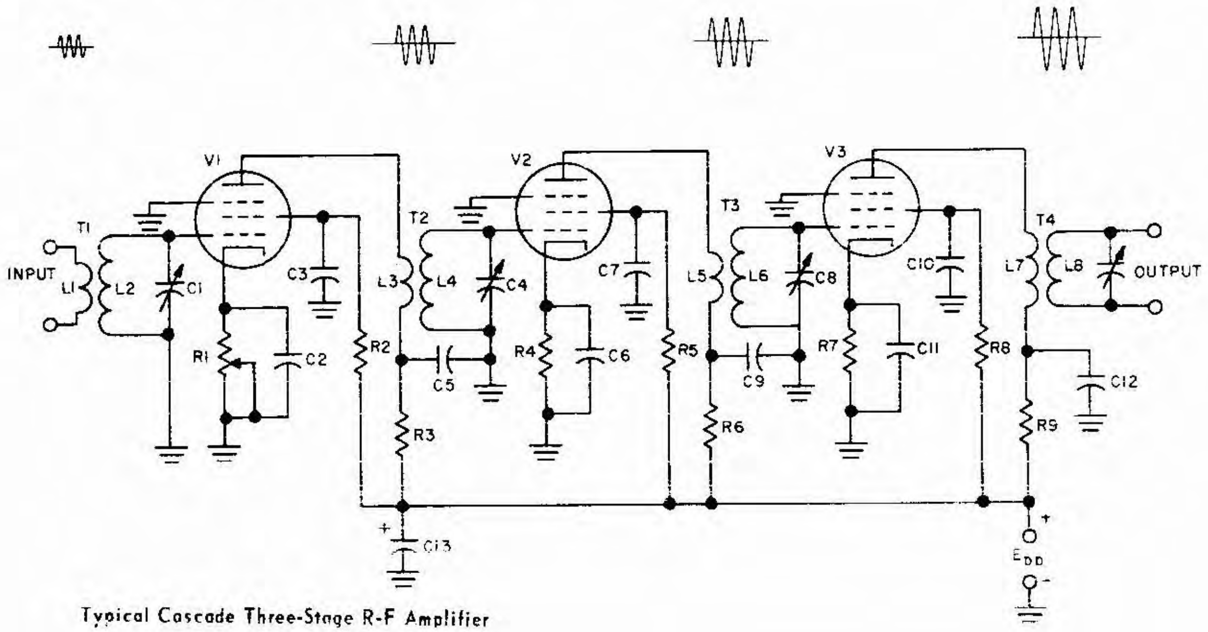
Uses a single tuned stage in the grid circuit of each tube, for selectivity.

Uses pentode tubes for high gain, although any tube type may be used.

CIRCUIT ANALYSIS.

General. The cascade r-f amplifier is a conventional amplifier whose output is connected to the input of a similar stage, which, in turn, is connected to another similar stage. Thus, the outputs are cascaded from one stage to the other, and a number of similar stages are used to provide high amplification. Usually three tuned stages are used, and the amplification varies as the cube of the single stage gain (a gain of 10 (per stage produces a total gain of 1000). While it is not necessary that the stage be tuned (untuned stages may also be cascaded), a higher gain is obtained from the tuned stage than from the untuned stage. Hence, the untuned r-f amplifier is generally used only for special, wide-band applications. Likewise, it is apparent that either triodes or pentodes may be employed. However, with triodes less over-all gain is obtained and the high grid-to-plate interelectrode tube capacitance produces inherent instability. Thus, to avoid the problem of neutralization and to achieve high gain per stage, the pentode tube is usually employed.

Circuit Operation. The schematic of a typical cascade r-f amplifier is illustrated in the accompanying figure. Three stages of r-f amplification are provided, using transformer coupling for convenience. While all stages are basically identical, the component values are not always the same. Usually the bias, plate, and screen voltages are different in the various stages, or at least they differ between the first and the remaining stages. Since each stage handles the output of the preceding stage, the bias is usually the smallest on the first stage and the largest on the last stage; the large bias on the last stage is necessary for this stage to handle the large output voltage swings developed in the first and second stages. Since the first stage plate swing is the smallest, it can operate with a lower plate voltage and thus produce less "shot noise", to provide a better signal-to-noise ratio without loss of gain. The final stage, of course, has the largest plate voltage. The screen voltage is usually the same for all stages, except perhaps the first stage.



Typical Cascade Three-Stage R-F Amplifier

In the schematic, T1, T2, T3, and T4 are tuned radio frequency transformers. T1 is the input transformer, and T4 is the output transformer; T2 and T3 are interstage transformers. The primaries of the r-f transformers are untuned, while the secondaries are tuned by variable capacitors. Although not shown in the schematic, these tuning capacitors are mechanical ganged together for single-knob tuning; otherwise, each of the tuning capacitors would have to be tuned separately for maximum response when a different frequency is selected. The use of a parallel-tuned circuit provides a high impedance at the grids of V1, V2, and V3, thus producing high gain and good selectivity. Resistors R2, R5, and R8 are screen voltage-dropping and decoupling resistors, which are bypassed to ground for rf by screen bypass capacitors C3, C7, and C10, respectively. Resistors R3, R6, and R9 are plate voltage dropping and decoupling resistors for tubes V1, V2, and V3, respectively, and are bypassed by capacitors C5, C9, and C12. Cathode (self) bias is supplied by resistors R1, R4, and R7 for V1, V2, and V3, respectively. The cathode bias resistors are bypassed by capacitors C2, C6, and C11. (See section 2, paragraph 2.2.1 of this Handbook for a discussion of cathode biasing and bypassing.) Capacitor C13 is a large filter capacitor used to minimize hum components in the supply source and possible impedance coupling effects due to the use of a common supply. The input may be from an antenna or other source, and the output can be applied to other r-f stages or to a detector.

In the absence of a signal, each tube is resting and drawing its static value of screen, plate, and cathode current. Electron flow is from ground through R1, R4, or R7, through the grid and the screen to the plate, through primary coil L3, L5, or L7 and plate resistor R3, R6, or R9, back to the supply. The cathode current is the total space current through the tube, including both the screen and plate current (also including grid current, if allowed to flow), which biases the grid negative because of the voltage drop developed across the cathode resistor. Similarly, screen current flow through the screen resistor produces a voltage drop with a polarity which opposes the source voltage, and thus reduces the screen voltage to the desired value. Screen bypass capacitor C3, C7, or C10 bypasses the r-f current variations to ground (when a signal appears), so only d-c current can flow through the screen resistor. The quiescent value of plate current flowing through transformer primary L3, L5, or L7 is steady and this produces no output. However, in flowing through plate resistor R3, R6, or R9, it produces a voltage drop with a polarity which opposes the supply voltage, thus reducing the effective plate voltage to the desired value. Capacitor C5, C9, or C12 bypasses any r-f current variations to ground (when a signal appears) so that only direct current flows through the plate resistor. Thus, any r-f variations cannot change the d-c plate voltage. With no signal applied, there is no output from any of the stages (except for slight thermal variations of plate current which produce noise); hence, there is no final output at T4.

When a signal is applied to the primary of the input transformer, signal current variations through L1 produces a varying magnetic field which induces a voltage in secondary L2 by transformer action. When tuned to resonance by C1, a large voltage is developed between the grid of V1 and ground, across the tuned circuit, and the turns ratio between L1 and L2 determines the impedance presented by the input to the V1 grid. In the case of an antenna input, a step-up turns ratio matches the low antenna impedance to the high impedance of the parallel-tuned circuit, for efficient power transfer. Assume for the moment that the r-f signal is increasing in a positive direction. The instantaneous positive grid swing produces a large instantaneous current flow in the plate circuit. This plate current flowing through the impedance presented by primary coil L3 produces a voltage drop across the T2 primary, and the changing value of plate current also induces a voltage into secondary L4. When L4 is tuned by C4 to the same frequency as the input signal, a large voltage is also developed across this tuned circuit and is applied to the grid of V2. Stage V2 operates in a similar manner and supplies an output to stage V3, which further amplifies the signal and produces a final negative output from T4. (An even number of stages would produce an output of the same phase or polarity as the input.)

When the input signal decreases, the plate current through V1 is reduced, and the reduction in current flow through L3 induces a smaller input voltage in V2, and likewise in V3, with a resultant smaller total output. With each tube operating Class "A", equal positive and negative input signals produce amplified output signals of the same shape, but of larger amplitude and opposite phase. Cathode resistor R1 is variable to provide manual control of the first stage bias, and allow adjustment to prevent strong input signals from driving the tube to saturation and producing distortion.

As can be seen from the above explanation, operation of the cascade r-f amplifier is similar to that of any other pentode r-f amplifier (discussed previously in this section of the Handbook), but with each stage designed to handle the full output of the preceding stage. The cascade r-f amplifier is the counterpart of the tuned interstage (i-f) amplifier, discussed in this section of the Handbook. It differs principally in the fact that it operates at a higher frequency, is continuously tunable over a large range of frequencies, and has somewhat less selectivity because only single-tuned circuits are used, with slightly less gain (depending upon the operating frequencies and number of stages employed). While simple transformer-coupled stages are shown and discussed, it is possible to use capacitively coupled stages, or other bandpass arrangements.

The suppressor grid is shown grounded in the schematic to minimize plate-to-grid coupling through the interelectrode tube capacitance, and to provide better shielding between the input and output; thus, at high radio frequencies, the possibility of oscillation due to regeneration is rather remote, so that no neutralizing arrangement is necessary. At the lower radio frequencies, the suppressor may be connected to the cathode without causing undesirable effects, since the r-f feedback is less.

FAILURE ANALYSIS.

General. The failure analysis for each stage of the cascade r-f amplifier is essentially the same as that for the single-stage pentode r-f amplifier discussed previously in this Handbook. In fact, the first-stage components of the cascade amplifier and the components of the single-stage amplifier are identically symbolized, except that the plate decoupling filter (R3 and C5) was not included in the single-stage amplifier. Therefore, this failure analysis will be confined to generalities concerning multistage circuits.

No Output. Any trouble which produces a no-output condition in a single stage will result in either a similar condition or a considerably reduced output in the multistage circuit. Because of the high gain and the possibility of signal feed-through to a following stage by stray capacitive effects at radio frequencies, it is possible for a single stage to be inoperative and still have a substantial output from cascaded stages. In this special case, the loss in amplification can be observed by inserting an input from a signal generator and noting the output. Then, by successively applying the signal to the following stage inputs (grids) again observing the output produced by the signal generator, it will be noted that the output suddenly increases when the defective stage is passed. Ordinarily, the output would decrease from stage to stage, requiring a constantly increased signal generator output as each stage is passed. If plate decoupling filter R3, C5, or R6, C9, or R9, C12 fails (either the resistor opens or the capacitor shorts), the plate voltage of the affected stage will be zero and no output will be obtained (neglecting the possibility of stray coupling).

Check the plate, screen, and cathode voltages to ground with a voltmeter; any abnormal voltage will localize the trouble to a specific stage and to the parts associated with that tube element. Be certain to check the supply voltage also; there may be a defect in the power supply. With normal voltages and no output, either an r-f transformer or a tube is defective. Replace doubtful tubes with tubes known to be in good operating condition.

Low Output. High bias, low plate or screen voltage, and a defective r-f transformer or tube can cause the output to be low. First check the plate, screen, and cathode voltages of each tube to verify that the d-c bias and operating conditions are normal. Connect an output indicator to the output terminals, and insert a strong signal (within the tuning range) from a signal generator to the grids of V3, V2, and V1, respectively, (use a d-c blocking capacitor in series with the generator output). As the generator is moved from stage to stage, adding additional amplification, it should be necessary to decrease the generator output to maintain a constant output indication; otherwise, a lack of gain is indicated. If an oscilloscope and an r-f probe are available, the signal generator can be left connected to the input, and the signal traced from the grid to the plate of each stage with the r-f probe. With the generator set to a specific frequency, tune the tank capacitors about this frequency. An increase in amplitude should be obtained as the signal is peaked; if an increase is not obtained, the tuned circuits are probably defective. Since the screens and cathodes are grounded (for rf) through bypass capacitors, no signal will be observed at the screen or cathode unless one of these capacitors is inoperative. Remember that placing the r-f probe across a circuit adds the probe capacitance, and will cause detuning of the circuit at radio frequencies. Best results are obtained when the signal or output is inserted in the circuit immediately ahead, or taken immediately after the point to be checked. For example, if the output of the first stage is to be checked, the input should be applied to the grid of V1 and the output measured across the T2 secondary. If the signal is applied to the plate of V1 instead, and measured at T2, the loading effects of the signal generator will affect the tuning of T2 and, therefore, the V2 gain. By inserting the signal at the plate of V2, only r-f transformer T2 will be checked, whereas by inserting the signal at the grid of V2, both the amplification of V2 and the operation of T2 will be checked. Loss of gain due to aging of tubes over a long period of time can occur in multistage (cascaded) r-f amplifiers, and may not be apparent until the reduction is severe. In this case all indications and voltages appear normal, except that the equipment does not seem to be performing satisfactorily and most signals are weak. Where maintenance standards are provided for the equipment, a simple comparison will reveal the deficiency. It should be kept in mind that each stage should produce additional gain; therefore, any stage showing no gain is probably defective.

Distortion or Poor Selectivity. Low bias or plate voltage will cause distortion, as will low screen voltage. Since the screen voltage fixes the range of plate swing, it has more effect in producing distortion than a similar change in plate voltage. Driving the plate voltage below the screen voltage will produce distortion, and in some instances cause a negative resistance condition resulting in unwanted self-oscillation. In multistage amplifiers, the possibility of cross-modulation and intermodulation distortion exists to a greater extent than in single stages; however, the causes are the same.

In tuned radio frequency amplifiers a strong signal tends to block the amplifier and broaden the response curve, so that cross modulation effects are not as noticeable. By adjustment of the manual gain control, the effective amplification can be reduced to prevent overloading on strong signals; thus, the nonlinearity introduced is avoided, and any cross modulation and intermodulation distortion are minimized. Poor tracking of ganged tuning capacitors can also produce either a loss of gain or distortion by cutting off frequencies outside the pass band of the individual stage. However, single-tuned r-f stages are usually so broad in tuning that slight differences (in pass band or resonance) merely broaden the over-all response curve, so that only poor selectivity results. Proper adjustment of trimmer and padding capacitors will restore the initial selectivity, but cannot compensate for poor design.

CASCODE R-F AMPLIFIER.

APPLICATION.

The cascode r-f amplifier is employed as a high-gain, low-noise r-f input stage to high-frequency receivers.

CHARACTERISTICS.

Two triodes provide the equivalent maximum gain of a pentode with reduced noise.

Noise equivalent is equal to that of a single triode stage.

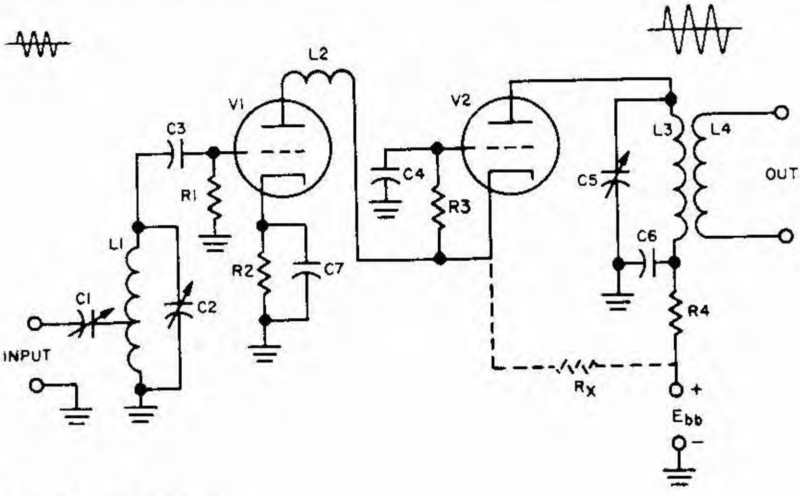
Grounded-grid stage stabilizes the circuit so that neutralization is not normally required.

Uses Class A self-bias, although-fixed bias can be used.

CIRCUIT ANALYSIS.

General. The cascode circuit consists of a single, conventional grounded-cathode input amplifier, connected in series with a grounded-grid amplifier stage which contains the output load. In most instances the two tubes are triodes, although they could be triode-connected pentodes or a combination of pentode input and triode output. To obtain the low-noise feature, the triode output must be used. This circuit, like the grounded-grid circuit discussed previously in this section of the Handbook, is usually employed at frequencies where the effective amplification of pentode and beam power tubes drops off as a result of high-frequency effects. It is seldom used at frequencies lower than 30 megacycles, since equivalent or better performance can be obtained with careful design by using a single pentode tube.

Circuit Operation. The accompanying schematic illustrates a typical triode cascode r-f amplifier circuit.



Typical Cascode R-F Amplifier

In the schematic, C1 is a coupling capacitor tapped on the lower end of tank coil L1. It is made variable to provide a slight amount of input tuning. Input tank circuit L1, C2 is coupled through capacitor C3 to the grid of V1. The low reactance of C3 to the r-f signal allows maximum signal (developed across the tank) to appear on the V1 grid and prevents the d-c shunting of the grid signal to ground through L1. Cathode bias is provided by R2 bypassed for rf by C7, and R1 is the grid-return resistor. Tube V1 is connected as a conventional grounded-cathode amplifier, with V2 acting as the plate load impedance. Inductor L2 helps match the low input impedance of grounded-grid stage V2. The grid of V2 is returned to the cathode by R3, which develops contact bias, and is grounded for rf by C4. The plate load of V2 consists of the parallel-tuned tank, L3, C5, with output winding L4 inductively coupled to it. Resistor R4 is a plate decoupling and voltage dropping resistor, bypassed by C6. This series-feed plate arrangement allows the rotor of C5 to be grounded to avoid body capacitance effects when tuning.

Operation of the cascode circuit can be better understood if operation of each tube is considered separately, and then operation of the two tubes combined. V1 represents a conventional triode r-f amplifier using cathode bias and shunt grid feed, with the plate direct-connected to the next stage. The plate voltage for V1 is obtained through V2, which acts simply as a dropping resistor. Thus, assuming equal plate currents and plate resistances, the plate voltage of V1 is half that applied to V2 less the cathode bias of V1. Cathode bias is supplied by R2, since the total currents of V1 and V2 flow in series through it. Signal current variations do not affect the bias because R2 is bypassed for rf by C7. (See section 2, paragraph 2.2.1 in this Handbook for a discussion of cathode bias.) Bias is selected so that plate current flows at all times (Class A), and so that V1 operates over the linear portion of its grid-voltage, plate-current transfer characteristic curve. The grid of V1 is returned to ground through R1 so that electrons cannot accumulate, bias-off the tube, and block operation. The value of R1 is large enough that none of the input signal is shunted to ground. Thus, when an input signal appears on C1, it is coupled into the tuned tank consisting of L1, C2. By tapping C1 down on tuning coil L1, autotransformer action is obtained to step the low antenna impedance up to the large value of parallel impedance offered by the tuned tank. Thus maximum power transfer is obtained between the antenna and the tank. The input signal appears as an r-f voltage across the tuned input circuit, and is applied to the V1 grid through coupling and blocking capacitor C3. Since C3 is in series with the input, the grid of V1 is isolated from the input circuit as far as dc is concerned, but is connected for rf.

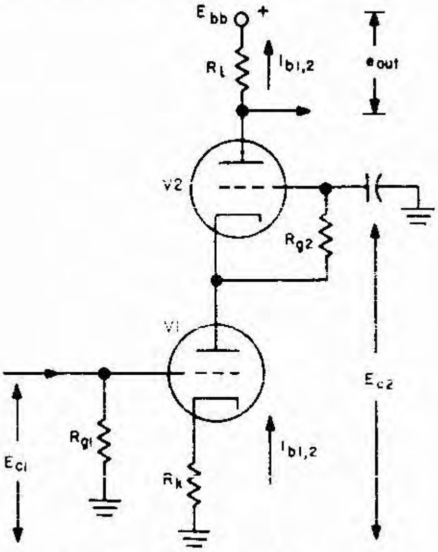
When an input signal is applied, it is coupled through C1 to the tank L1, C2, which at resonance provides an increased signal to C3 and develops a voltage across R1, which, in turn, is applied to the grid of V1. Assuming that the input signal is increasing in a positive direction, the grid bias on V1 is decreased and causes the cathode and plate current to increase. The instantaneous increase of cathode current has no effect on R2 since it is bypassed by C7. However, the increased plate current flow through L2 (and tube V2) drives the cathode of V2 more negative, and since the grid of V2 is held at ground potential the effect is as though a positive voltage were applied to V2 grid. Thus the plate current of V2 also rises and the drop across the plate tank develops a tank current flow in L3, C5 which is inductively coupled to the output by secondary coil L4. With the output winding connected in-phase, an output voltage that is in phase with the input signal is produced.

Conversely, when the input signal to V1 is operating over the negative half-cycle, the bias on V1 is increased by the input signal, and plate current flow in V1 is reduced. The reducing plate current flow in V1 allows the plate voltage to rise towards the supply value, driving the direct-coupled cathode of V2 in a positive direction. When V2 cathode becomes more positive, the plate current of V2 is reduced, while the plate voltage rises and induces an increasing voltage in tank. When connected in-phase the tank output is negative during a negative input signal to V1. Since both V1 and V2 are connected in series, the output voltage is only half of what it normally would be with one tube. The noise, however, is only one quarter of that produced by a single high-gain tube. So that a large reduction in tube noise occurs in the amplified output signal. In addition to noise reduction, the circuit is prevented from oscillating (stablized). This action and the effect of circuit loading are explained in the detailed functioning of portions of the circuit as discussed below.

Assume for the moment that the input signal is again going positive. The bias on the V1 grid is momentarily decreased and an increased plate current momentarily flows. In flowing through L2 the current develops a small emf, which is out-of-phase with the voltage fed back from plate to grid through the plate-grid interelectrode capacitance, and helps prevent self-oscillation of V1. When the input signal goes negative, the bias on V1 is momentarily increased and a decreased plate current flows. Normally, in the conventional amplifier, this change in plate current through the load produces a varying voltage drop which is the output. However, the plate load for V1 consists of V2 and its associated tank circuit, L3, C5. In addition, the reflected load from output winding L4 affects C5 tuning and the value of total impedance presented to the V2 plate. Since V2 is connected in series with V1, the plate resistance of both tubes in series is effectively paralleled with the plate load of V2. The input resistance of V2, the grounded-grid stage, also shunts the output of V1 to ground, but is increased by the series reactance added by L2. This, L2 also helps match the V2 grid to the V1 plate. Because V2 is direct-coupled to V1, any signal appearing on the plate of V1 also appears on the cathode of V2, and, since the grid of V2 is grounded, in effect appears as an oppositely polarized signal on the grid. Thus, a positive output on the cathode of V2 appears as a negative signal on the grid of V2, and causes a decrease in the plate current of V2. Conversely, a negative cathode signal appears as a positive grid signal, and causes an increase in the plate current of V2. Since the input and output of the grounded-grid stage are in phase, both tubes operate in the same direction. That is, as the current of V1 increases, so does the current of V2 (both in the same direction). This is necessary since both V1 and V2 are series-connected, and the same current flows through both tubes. When the plate current of V2 increases, a voltage drop appears across tank coil L3, and an output voltage is induced in coupling coil L4 through transformer action. Similarly, when the plate current decreases, an output voltage of opposite polarity is developed.

The discussion above covers the individual operation of the separate stages of the cascode amplifier without considering the effects of combined operation. To complete the discussion of circuit operation it is now necessary to examine the manner in which these amplifiers operate when connected in series across the plate supply. The normal cascaded amplifier operates in parallel with the supply, and with its grid connected effectively in series. The cascode stage operates in exactly the opposite manner. Both tubes are fed their plate voltage in series, so that the plate resistance of one tube acts as a dropping resistor for the other tube. Although one stage is grounded-cathode and the other is grounded-grid, their grids are effectively connected in parallel.

The simplified equivalent schematic below shows the d-c representation of the circuit. It is clear that there is no d-c connection between the grid and ground or between the cathode and grounded of V2 except through V1.



Simplified Equivalent Circuit

With no signal applied, the tubes are resting in a quiescent condition, with the same plate current flowing through both V1 and V2. The plate voltage of V1 is determined by the drop across V2 and R4, and is further reduced by the amount of cathode bias developed across R2. As the V1 plate voltage increases (with a signal), the V2 plate voltage decreases, since the total supply voltage does not change. The V1 grid voltage is the cathode voltage drop produced by the total cathode current times cathode resistance R2, plus any signal-excitation voltage. With a practically constant cathode current, this bias voltage changes very little. When the plate current through V1 decreases (because of a negative-swinging input signal), the plate voltage of V1 increases; at the same time the V2 grid voltages increases, since the plate voltage increase of V1 is applied directly to the cathode of V2. Thus, the current through V2 is caused to decrease also to correspond with that of V1. Any increase or decrease in plate current through V1 and V2 (caused by the input signal) produces a corresponding increase or decrease in output voltage across load resistance R_L. This load resistance is the impedance offered by the tuned tank at the frequency of the input signal. The result is to provide a relatively constant amplification through V1 and V2, equivalent to that of a single triode tube operated with a reduced plate voltage.

Although maximum gain is obtained, since it is produced at a relatively low plate voltage with a minimum change in plate current, less noise is produced than for an equivalent gain obtained with a large change in plate current. The isolation provided between the input and output circuits by grounded-grid stage V2 minimizes any feedback between the input and output. Therefore, self-oscillation is prevented and neutralization is unnecessary. (Although in some circuit versions V1 is neutralized, this is not done to prevent oscillation, but rather to increase the input admittance so that high gain may be obtained.) By maintaining a relatively constant plate current, the circuit produces a very linear output signal, because the gain is independent of plate resistance and equal to the tube amplification factor at all times. Thus, the normal dropping off in effective amplification at high radio frequencies is overcome by the cascode circuit. The decrease in noise output and the increased gain at high frequencies make this circuit most useful, and provide a much better signal-to-noise ratio than any other circuit combination.

The reason for the decreased noise is not the reduction in shot-effect alone (random variations in the rate of electron emission from the cathode produce a hissing noise called **shot effect**), because of the low plate voltage used. The decreased noise is also due to a reduction in the "induced grid noise" and the "flicker effect". The induced noise is reduced because of the low effective impedance of the grounded-grid circuit. The flicker effect, which occurs because of small temperature changes in oxide-coated cathodes, is reduced by holding the plate current relatively constant. Thus, the space charge within the tube remains relatively large and constant, and any increase caused by flicker effect is swamped out, since any increase in the negative space charge returns the stray electrons to the cathode rather than to the plate.

The combination of a cascaded grounded-cathode and grounded-grid stage is also often used and referred to as a **cascode amplifier.** This change in circuit is accomplished by adding plate voltage dropping resistor Rx, shown in dotted lines in the schematic above. This circuit is not two series stages with a common plate voltage; it is simply two separate circuits connected in cascade. Although constant gain is not achieved by keeping the plate current in V2 relatively constant, almost identical results are obtained. In fact, the cascaded form of cascode circuit provides additional gain, since each stage operates separately as an amplifier. However, the flicker effect is not eliminated, and as each stage usually operates at a slightly higher plate voltage than each stage in the original cascode circuit, slightly more shot noise is produced. Because of the increased signal gain, however, the increase in the noise figure is not very evident, since the signal tends to override the noise.

FAILURE ANALYSIS.

General. The failure analysis applicable to the grounded-cathode r-f amplifier and the grounded-grid r-f amplifier may be used as a guide, particularly where the cascaded form of cascode circuit is used. Since the tubes normally have their plates series-connected, the following analysis applies only to the orginal cascode circuit.

No Output. In the series plate circuit consisting of R4, L3, V2, L2, V1, and R2, any open circuit will prevent operation and thus cause loss of output. Normal plate and cathode voltages will indicate either no signal applied, a defective tube, or an open input or output circuit. Always check the supply voltage when checking plate and bias voltages, to verify that the supply is operating normally. If the input circuit is defective, placing the antenna (or other input) directly on the grid of V1 should produce an output. A resistance check of L4 will verify continuity, but not necessarily indicate a short circuit since the coil resistance is usually less than 1 ohm in either case. With an oscilloscope and r-f probe, the signal can be checked at the plates of both tubes; if the signal is present, L4 is defective. If R3 opens, the grid of V2 can become blocked by the accumulation of electrons on C4. A resistance check will indicate whether R3 is of the proper value. If either C1 or C3 is open, no signal will be applied to the V1 grid. Use an incircuit capacitor checker or temporarily add a capacitor equivalent in value to C1 or C3 to determine whether an output can be obtained. If the tubes are suspected, replace them with ones known to be in good operating condition. A no-voltage indication on the plate of V2 can be caused by a shorted bypass capacitor C6. If C6 is shorted, the entire plate supply will be dissipated across R4, causing it to overheat, smoke, and possibly burn out.

Low Output. Low plate voltage, high grid bias, or a defective tube will produce a reduced output. The plate and bias voltages can be checked with a voltmeter. If C7 is open, the output will be reduced because of cathode degeneration. Likewise, if either C2 or C5 is detuned or open, the output will be reduced. If C1 or C3 is defective but stray capacitive coupling exists, low output may also be obtained. Use an incircuit capacitance checker to check the capacitors. If grid return resistor R1 or R3 is open or increases in value with age, it is possible for the associated tube to block or have reduced output after a strong signal. Use an ohmmeter to check the values of R1 and R3 when in doubt. Since the output is an r-f signal, L4 can be open and yet a low output be obtained through stray capacitive coupling.

Distortion or Poor Selectivity. The cascode amplifier is subject to the same causes of distortion and poor selectivity as other types of r-f amplifiers. Low bias or plate voltage will cause clipping and distortion. Use a voltmeter to determine whether the proper bias and plate voltages are present. High resistance in the tunned circuits, caused by poorly soldered joints, will cause board tuning and poor selectivity. Such joints in the antenna or transmission line system can cause rectification of the r-f signal and produce spurious responses or beats which might be misinterpreted as distortion. Changeing the antenna will usually cause this condition to disappear. When in doubt, insert a modulated signal from a signal generator tuned within the range of operation. Use an oscilloscope and r-f probe to follow the signal from input to output. Any distortion will be visible as a change in pattern on the scope. Any cross-modulation effects will be due to overloading by strong local signal, and can be eliminated only by attenuating the signals or by inserting circuits that provide additional selectivity before the input.

TRAVELING-WAVE TUBE AMPLIFIER.

APPLICATION.

The traveling-wave tube amplifier is used at super-high frequencies as an untuned r-f amplifier (or mixer) in microwave receivers, as a linear amplifier in transmitters, and in test equipment. Its broad-band characteristics make it particularly useful for high-band television and electronic countermeasures (ECM) applications.

CHARACTERISTICS.

Range of operating frequencies is from approximately 200 megacycles to 15,000 megacycles.

Efficiency varies from 10 to 40 percent.

Power handling capabilities vary from as low as 100 microwatts to 1 kilowatt for continuous-wave emissions. Peak power capabilities for pulsed operation extend up to 50 kilowatts.

Power gain in a single tube varies from 20 to 60 db maximum.

Noise figures from 5 db to 30 db can be obtained, depending on the frequency (increases with frequency, but not linearly).

Uses positive bias and high voltage to control emission of an electron gun.

Amplifies by virtue of a distributed interaction between an electron beam and a traveling wave.

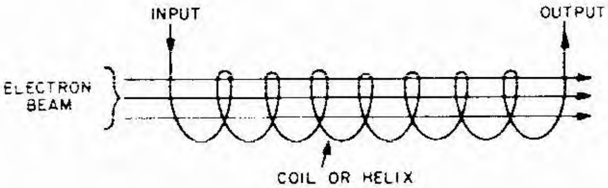
Is a nonresonant device inherently capable of enormous bandwidths.

Usually employs magnetic focusing of the electron beam; however, electrostatic focusing is sometimes employed.

CIRCUIT ANALYSIS.

General. Traveling-wave tubes are used for both large and small signal applications; each tube is rated for a specific power-handling capability over a certain frequency range. They supplement the presently available microwave tube types, such as planar triodes, klystrons, and magnetrons. They are particularly useful for wideband applications where a large range of frequencies must be covered. Since the tube is completely self-contained and nonresonant, it has no bulky cavities or large magnets to pose a design problem. Either coaxial or waveguide input and output fittings are provided, depending upon the frequency range in use, so that only filament and collector power are needed in addition to the input and output leads to provide an operating amplifier. Although the traveling-wave tube has high gain and is easily tuned by changing the collector voltage, it possesses noise characteristics that are somewhat less desirable than those of some of the other types of microwave tubes. Recent improvements along this line have produced noise figures of 6 db at 3000 megacycles and 11 db at 10,000 megacycles, or better, as compared with 30 db for the early versions. The 6-db figure is approximately the same as that obtained with a crystal mixer. It is well known that crystals are easily damaged by r-f energy. However, the traveling-wave tube is not so easily damaged since an input over-load will merely cause saturation (instead of burnout as in the case of the crystal); hence, with this tube, a simpler duplexing system may be used.

Circuit Operation. The accompanying figure shows the essential elements of a traveling-wave tube. These are a long, narrow electron beam and a circuit capable of sustaining a slow electromagnetic wave with a longitudinal component of electric field, which can travel along in synchronism with the beam. The slow-wave circuit usually consists of a helix or long coil of wire. In such a circuit the wave travels along the wire with approximately the speed of light. If the lenght of the wire is 13 times as long as the axial length of the coil or helix, the wave will travel along

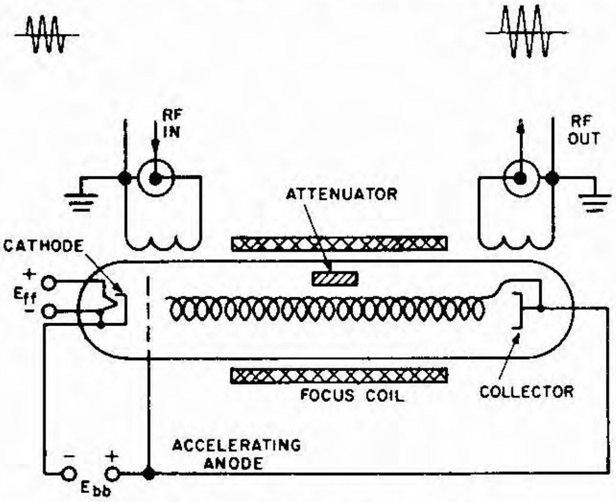


Basic Traveling-Wave Tube Elements

the electron beam at one-thirteenth the speed of light, and the electrons in the beam, passing through the center of the coil, will be in synchronism with this slow traveling wave if they are accelerated by about 1500 volts. The speed of the electron beam is controlled by the potential applied to the accelerating anode. Since the helix is connected to the collector at the end opposite the cathode, the helix also serves as an additional accelerating anode. An axial magnetic field is used to focus the electron beam, to keep the beam from spreading and to guide it through the center of the helix.

When the electrons travel along in synchronism with the slow wave, there is a cumulative interaction which results in amplification of the traveling wave. At wavelengths of around 10 centimeters, the power gain may be of 1000 to 10,000 times or even greater, in a distance of 10 inches. Because no resonant circuits are involved, the traveling-wave tube is inherently broad-band; substantial gain has been obtained over bands of thousands of megacycles and of several octaves. Waves traveling backward, against the electron stream, are practically unaffected by its presence. To make a stable and useful amplifier, attenuation of the backward wave must be added in the slow-wave circuit. Usually, it is lumped near the center of the tube, and introduces a loss to the backward wave which is much greater than the amount by which it reduces the forward gain. The necessity for the attenuator and its reduction of forward as well as backward gain is a basic limiting parameter, which hinders high-power tube development.

The following figure illustrates a typical traveling-wave tube amplifier using a solenoid type of magnetic focus coil. The electronic beam is obtained from a Pierce electron gun, which produces a series of essentially parallel-path electrons. The tendency of the parallel electrons to be deflected or to stray from the parallel path is overcome by adding a solenoid on the glass envelope of the tube whose axis is in the longitudinal direction. The focusing field of the solenoid deflects any stray electrons back into the electron stream so that they must travel through the center of the helix.

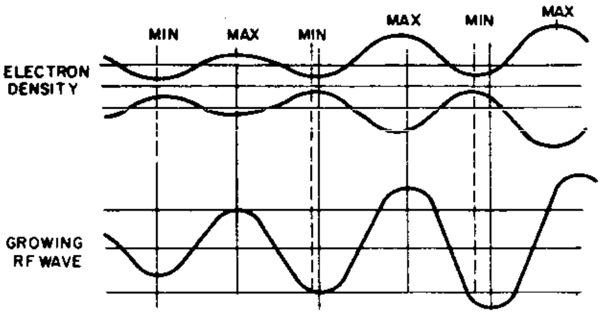


Typical Traveling-Wave Tube Amplifier

The r-f input signal is fed into the helix at the cathode end of the tube, while the r-f output signal is taken from the opposite end of the tube, near the collector (or anode). The accelerating anode creates the initial electric field which attracts the electrons from the cathode, while the collector (or anode) serves to collect the spent electrons after they have passed through the helix, and return them to the power source. The helix is connected to the collector internally, and also acts as an accelerating anode for the electron beam. The r-f signal is coupled to and from the helix inductively. There is no direct connection between the helix and the input and output circuits. The helix consists of a continuous spiral of wire or strap 10 to 12 inches in length, whose natural resonant frequency is much lower than the range of operation so that it acts as a nonresonant device. The purpose of the helix is to provide a path for the input signal in proximity to the electron beam so that interaction can occur between the beam field and the signal field. When the r-f input signal is induced on the helix, a conductive path is provided by the helix from the cathode end to the collector end of the tube, through which the r-f signal current flows. Signal current flow induces a field around the helix which travels with the signal from input to output; thus, a traveling wave is produced along the helix. While the electron beam and r-f signal both travel at the speed of light, the path around the helix is longer. Therefore, the signal field progresses from turn to turn through the helix at a much slower speed than the electron, which travels through the center of the helix and follows the shorter direct path between cathode and collector.

When the input signal field opposes the field of the electrons passing through the center of the helix the electrons are decelerated, and are overtaken by other electrons. During the time the beam electrons are decelerated, they relinquish kinetic energy to the field of the r-f signal, and tend to form in bunches. When the signal field increases, it enhances the electron field and accelerates the electrons, and energy is transferred from the r-f field to the electron field. As the signal field and electron beam progress through the tube, more bunching occurs. Thus, more electrons are available to give up kinetic energy while a particular bunch is passing through a decelerating field. Since more time is spent by an electron in a decelerating field than in an accelerating field, it gives up more energy to the r-f field than it receives. Thus, as the signal progresses along the helix, it increases in strength, and is amplified.

No energy transfer is possible until electron bunching commences. As bunching increases, the signal amplitude increases and causes even greater deceleration of the electrons (in the following bunch). This causes the signal strength to increase exponentially, as shown in the accompanying illustration. Eventually, a point is reached at which the electrons in the bunches are slowed to the extent that



Development of Growing Wave

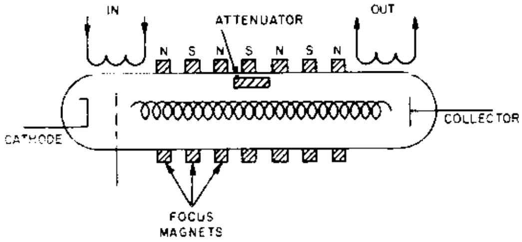
they are no longer in synchronism with the signal field. At this time the forward speed of the beam electrons and that of the signal are no longer near the same value, and the efficiency drops.

Operation of the traveling-wave tube is sometimes explained on the basis of a total of four waves existing within the tube, three forward waves and one backward wave. The three forward waves are the result of the division of the input into three components, each with an amplitude of one-third the input strength. The first wave (which is the one we have been discussing) travels more slowly than the electron beam, and increases in strength. Another wave also travels at this same speed and diminishes in strength (as it gives up its energy to the first wave). The third wave travels at the fastest speed, faster than the electrons, and maintains a constant strength. The resultant of these three waves is the constantly growing signal or output.

The gain of the traveling-wave tube is also affected by the input and output coupling circuits. For amplifying a wide frequency band, high gain can be maintained by changing the helix voltage with frequency to maintain the necessary synchronism between the helix velocity and the beam velocity. In addition, the maximum output power depends upon the input (drive) power, and the power-handling ability of the helix. The amount of power in the beam limits the amount that can be taken from it; thus, the beam input power is a factor. Also, since the output end of the helix is heated by r-f currents and electron bombardment, if the beam disperses before passing the output end, the power-handling ability of the helix is another factor. Dispersement of the beam and bombardment by beam electrons can be caused by a maladjustment of the magnetic focusing field. Since a helix mounted in glass has a low heat-dissipating ability, the power output at the present state of the art is limited to values less than 100 watts unless special cooling systems are employed. High-power tubes use either water or forced-air cooling.

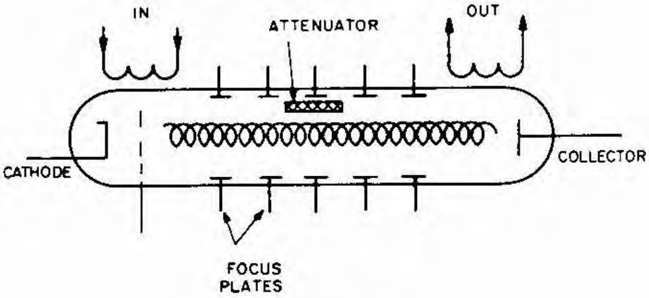
The thermal noise of the electrons in the beam affects the noise figure of the traveling-wave tube amplifier, just as it affects the noise figure of other types of amplifiers. The noise signal is induced onto the helix and is amplified in the same manner as any other signal. Lowering the operating voltage will generally result in a slower beam velocity and less thermal noise. If the gain per unit length is low, less noise amplification will also occur; tight focusing of the beam will also produce less noise. Uneven cathode emission, particularly from an aging tube, will produce a nonsymmetrical beam and noise, as will ion movement caused by gases within the tube. When the signal injection point is properly spaced from the end of the electron gun, a reduction in noise occurs because of certain periodic fluctuations in noise current within the tube. Thus, injection of the signal at a point of low noise current results in a greater signal-to-noise ratio.

When the long solenoid focusing coil of the traveling-wave tube is replaced by a series of small coils spaced along the tube, as shown in the accompanying illustration, less energy is required to focus the electron beam, and tighter focusing is achieved. The same effect is produced by using a series of permanent magnets to produce a periodic magnetic field. These types of tubes are called PPM (periodic permanent magnet) traveling-wave tubes. Better over-all efficiency is obtained, since the loss of beam current through dispersion of stray electrons is prevented.



Periodic Electro Magnet Focusing

When a series of opposing electrodes or plates are placed along the tube inside the glass and connected to a d-c source as shown in the accompanying illustration, an electrostatic field is produced between the electrodes. This is similar in all respects to the magnetic field produced by the solenoid or the periodic permanent magnets. Focusing in this instance, is done electrostatically, and no change in operation occurs. Because the construction of this tube is more difficult and more expensive, and since the performance is about the same, the electrostatic type of traveling-wave tube is seldom used.



Electrostatic Focusing

The attenuator which prevents the backward wave from causing oscillation and loss of amplification is provided by spraying a resistive film (produced by an aquadag solution) on the helix and tube envelope at the proper location. In a high-power tube the attenuation is concentrated near the center of the tube, while in a low-power tube it is usually not more than one-third the distance from the cathode.

While more could be said about the various phases of design, the discussion above is sufficient to acquaint the reader with the primary functioning of traveling-wave tubes. Since the tube is a fixed package, there is nothing the electronic technician can do to change its operation. Of course, faulty operation can result from incorrect connections or operating voltage and polarities. Therefore, further discussion at this time is unnecessary. Additional data can be obtained, when desired, by reference to other texts or to manufacturers' information sheets.

FAILURE ANALYSIS.

No Output. Lack of input signal, an open output circuit, or a lack of filament or plate voltage can cause loss of output. Use a voltmeter to determine whether the filament and plate voltage are correct. WARNING: **High plate voltage** exists between the collector and ground; be certain to observe **all safety precautions** when measuring this voltage. Since the cathode is usually connected to one side of the filament, measure the filament voltage **only when the plate voltage is off.**

The input and output circuits can be checked for continuity with an ohmmeter, with the power off. If the external circuits appear to be satisfactory, use a signal generator to supply an input to determine whether there is loss of input signal. Likewise, in the output a dummy load may be substituted. If the input and output circuits are apparently satisfactory and proper electrode voltages are applied, a no-output condition will probably indicate a defective tube. When possible, substitute a tube known to be in good operating condition.

Low Output. Low output can be caused by improper plate or filament voltage, low drive, or a defective tube. Check the plate and filament voltages, observing all safety precautions. When operating normally, most traveling-wave the bias of V3B; in addition, an improper setting of variable plied, the output should meet the design specifications. In transmitting applications, insufficient r-f drive will cause reduced output. In the special case where sweep voltages are used to tune automatically over a band of frequencies, it is important that the drive waveform and sweep waveform be of the shapes and amplitudes specified; otherwise, reduced performance will occur. Low tube emission can sometimes be found by noticing that the output fluctuates in amplitude and that a high noise is developed in the output. The beam current in this case will be reduced, and low output will occur. Unfortunately, other conditions, such as load reflections or a change in accelerating voltage or collector voltage, will also change the beam current. Where solenoid focusing coils are used, lack of sufficient field will also cause a reduction in the beam current, and can be caused by a defective coil, low focusing voltage, or loss of power to the coil. In this case, the focus supply can be checked with a voltmeter and the resistance of the coil determined by means of an ohmmeter, with the power off. Comparison with a good coil will indicate whether the resistance is high, low, or normal.

Because of the few parts involved, usually a voltage check, a waveform check, and a beam current check are the only simple checks possible. If normal results are obtained from these checks, substitution of the tube, the input, or the load will be necessary. In tubes having a low noise figure, disconnecting the antenna from the input in receiving applications will reduce the noise, and serve as a rough indication that the tube is functioning. However, in tubes having high noise figures this change may be masked by the tube noise. Thus, a more positive check is to insert a signal from a known source and determine whether normal amplification is obtained. A change in load should also cause a change in beam current, as should a change in focusing-magnet current.

In the case of overdrive, increased current usually occurs, followed by a reduction in output as the collector is heated by electron bombardment. Once saturation is reached, no further increase in current occurs as the drive is further increased; this indication can sometimes be mistaken for reduced output.

TUNED INTERSTAGE (I-F) AMPLIFIER.

APPLICATION.

The tuned interstage (i-f) amplifier is universally used in superheterodyne receivers to supply high r-f amplification and the desired selectivity.

CHARACTERISTICS.

Uses pentode-type electron tubes to obtain high voltage gain.

Uses double-tuned tank circuits to obtain sharp selectivity.

Uses radio-frequency transformers to isolate input and output circuits, for voltage step-up and impedance matching.

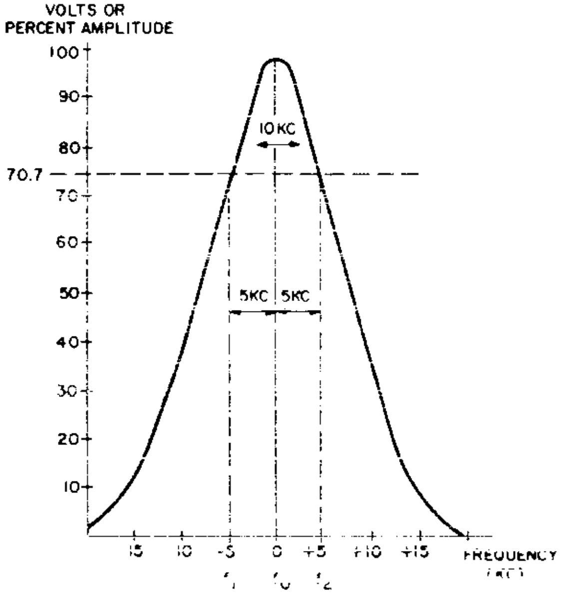
Operates Class A, self-biased to minimize distortion, although fixed bias can also be used if desired.

Uses a number of similar stages connected in cascade to obtain greater gain and selectivity.

Employs fixed tuning, adjustable over a narrow range, for exact alignment of each stage.

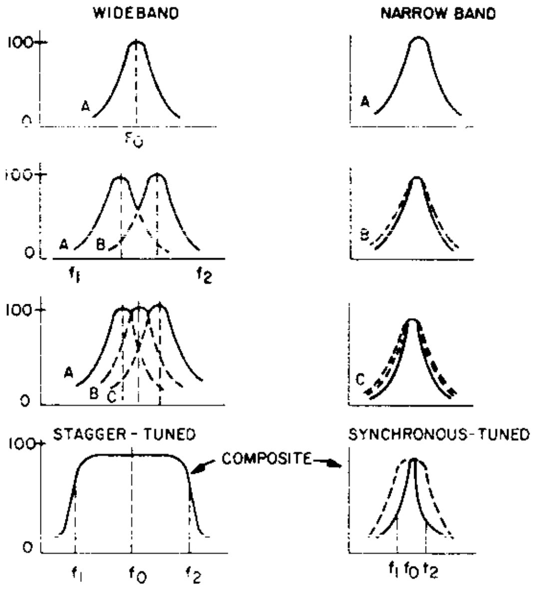
CIRCUIT ANALYSIS.

General. The tuned i-f amplifier may consist of a single stage, or as many as six or more cascaded similar stages to obtain the desired amplification and selectivity. Generally speaking, one to two stages are used for radio broadcast reception, while two to four stages are used in selective communications receivers, and six or more stages are used for radar, television, and microwave reception. The intermediate frequency chosen usually determines the number of stages. The lower frequencies, such as 50, 175, and 250 kc, produce more amplification and better selectivity than 450 kc; at 21 or 44 mc (as in TV applications) or at 30 or 60 mc (as in radar applications), less gain per stage is obtained, and the response curves are broader, so that more stages are needed. In addition, the band-pass requirement introduces another factor, since a simple 5 to 10-kc band pass can be obtained with a few tuned circuits, whereas a broad band pass of 4 to 5 megacycles with sharp cutoff, which is required in TV and radar receivers, requires a number of stagger-tuned stages. The band pass is measured at the half-power points of the receiver response curve, that is, at 70.7 percent amplitude each side of the i-f center frequency. For example, if we have an i-f amplifier output of 100 volts at the center intermediate frequency, and it drops to 70.7 volts when the amplifier is detuned 5 kc each side of resonance, the amplifier band pass is 10 k c, as illustrated in the accompanying figure.



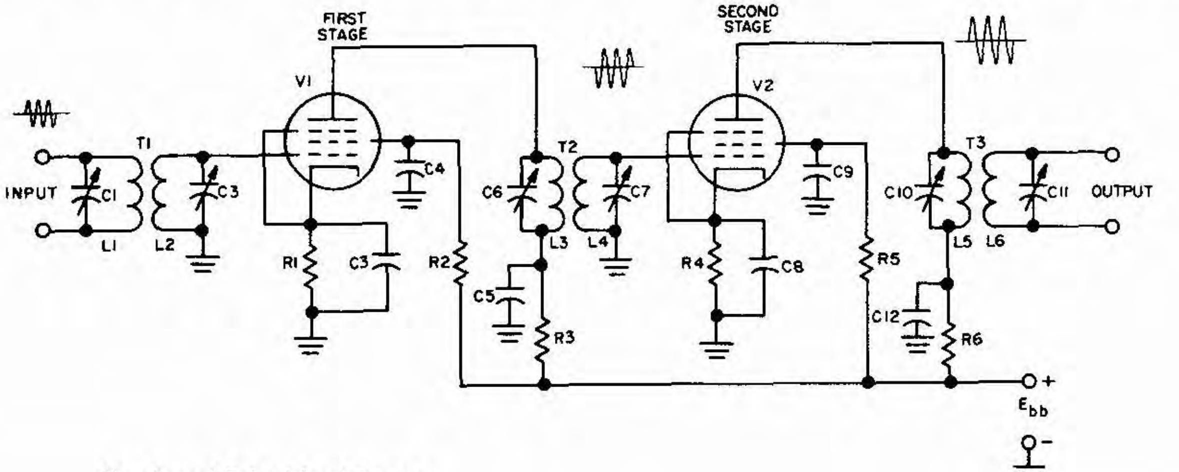
Typical I-F Response Curve

The manner in which the shape of the response curve selectivity) is changed by stagger-tuning (each tank tuned to separate frequencies) to achieve a broad band pass, as compared with synchronous tuning (each tank tuned to the same frequency), assuming optimum coupling between the i-f primary and secondary coils, is shown in the accompanying illustration.



Stagger-Tuning and Synchronous-Tuning Response Curves

Circuit Operation. The schematic of a typical two-stage i-f amplifier is shown in the accompanying illustration. The dashed line divides the circuit into two separate stages. Note that in the inter-stage amplifier T2 is common to both stages. Thus, T2 matches and couples the output of V1 to the input of V2 for efficient signal trasnfer. Since the stages are operating Class A, no grid current flows and power transfer is not a real concern; however, maximum voltage transfer is important.



Two-Stage I-F Amplifier Schematic

Transformer T1 couples the grid of V1 to the plate of the preceding mixer or converter stage, while T3 usually supplies the i-f signal to the detector. Any change in impedance between the primary and secondary circuits can be accommodated by changing the turns ratio in the transformers. Normally, a 1-to-1 ratio is used, and any difference in impedance between the plates and grids of the cascaded stages is usually of academic interest only, since the primary and secondary of each i-f transformer are high-Q, parallel-tuned circuits and they both present a high impedance to the circuits in which they are connected. The high impedance produced by the plate circuit tank causes a large voltage drop across the primary, and by transformer action a large voltage is induced in the secondary. At the same time, the secondary presents a high impedance to the following tube grid circuit so that maximum voltage is developed on the grid, and grid losses are kept to a minimum. Thus, it is seen that double-tuning in itself always provides sufficient matching for efficient voltage transfer, provided that the coupling between the primary and secondary is optimum. It is also evident that the largest voltage is developed across either tank at the frequency to which it is tuned, since it presents the highest impedance at resonance. While there are some shunting effects due to grid-to-ground and plate-to-ground capacitance, plus internal leakage in the transformers, this is taken care of in design calculations.

Further examination of the schematic also reveals that the stages are simple pentode r-f voltage amplifiers. Self-bias for the stages is provided by cathode resistors R1 and R4, bypassed for rf by C3 and C8, respectively. Screen voltage is obtained through voltage-dropping resistors R2 and R5, while plate voltage is supplied through R3 and R6. The screen resistors are bypassed to ground for rf by C4 and C9, and the plate resistors are bypassed by C5 and C12, which also form a decoupling network.

With no signal applied, both V1 and V2 are resting in their quiescent condition. Plate and screen currents flow steadily through cathode resistors R1 and R4, and develop a positive bias at the cathode, which is the same as a negative bias on the grid. (See paragraph 2.2.1 in Section 2 of this Handbook for a discussion of cathode bias.) Screen resistors R2 and R5 drop the supply voltage to the value of screen voltage necessary to provide sufficient plate current swing. Likewise, plate resistors R3 and R6 drop the plate voltage to the proper operating value. Since each of these resistors is bypassed to ground, any r-f variations of plate current (when a signal is applied) are eliminated so that steady plate and screen currents flow throughout the cycle (with or without signal), and cathode bias can be used.

When an input signal is applied to T1 primary, a high impedance is offered the signal at the resonant frequency to which C1 tunes L1. With secondary L2 tuned to the same frequency by C2, a high impedance appears between the grid of V1 and ground. When the input signal causes an increase in current through L1, a corresponding increase in voltage is induced in L2 by transformer action, and the increased voltage appears on the V1 grid. As the grid of V1 is made more positive on the first half-cycle of operation, a larger plate current flows through the primary of T2. With tuned circuit L3, C6 tuned to the same frequency as the signal, a high impedance is presented to plate current flow, the plate voltage is reduced toward zero, and a large voltage drop occurs across L3. This voltage drop induces a negative-going signal in the secondary of T2 by transformer action. When tuned circuit L4, C7 is resonant at the signal voltage, a large negative voltage also appears between the grid of V2 and ground.

Since V1 and V2 are biased at the center of their grid-voltage plate-current transfer characteristic curve, large positive or negative swings of voltage can be accommodated without causing any distortion. Thus, the amplified input signal from V1, which appears on the V2 grid, is reproduced in amplified form in the plate circuit of V2. The operation of tube V2 is similar to that of tube V1 except that the signal is oppositely phased. The negative grid signal from the first stage causes the plate current of V2 to decrease, and the plate voltage of the second stage rises toward the supply voltage (goes positive). At the same time, the primary of T3 offers a high impedance to current flow. The reduction in plate current flow through tuned primary circuit L5, C10 produces a large positive-going voltage and induces a voltage in the secondary of T3. When secondary circuit L6, C11 is tuned to the same frequency as the signal, it produces a high impedance, and a large output voltage is developed across it.

When the input signal at the first stage goes negative, on the remaining half-cycle of operation, the action of V1 and V2 is exactly the opposite of the described above. As the plate current of V1 is reduced by the input signal, a positive-going voltage is produced across the T2 primary, and this voltage is applied to the V2 grid. In turn, the V2 plate current is increased, producing a negative output voltage across T3. Since Class A bias is employed, a sine-wave input produces a larger and amplified sine-wave output. As long as the grid signal does not drive the grid of V1 or V2 to the point where it draws current, and the plate voltage does not fall below zero and cause plate current cutoff, no distortion occurs. The output waveform of the amplifier is the same as the input waveform, but is much larger in amplitude.

Since the grounded-cathode circuit inverts the input signal, the output of an even number of stages is of the same polarity as the input. Therefore, any feedback from output to input will produce regenerative oscillations. However, the very small plate-to-grid capacitance of the pentode reduces any such feedback to a negligible value, and neutralization is not required. The use of plate decoupling capacitors C5 and C12 prevents feedback through common impedance coupling in the power supply. Thus, a stable, high-gain, and highly selective amplifier is produced by connecting the two double-tuned stages in cascade. From the discussion above it is clear that the operation is identical to that of the single-stage pentode r-f voltage amplifier in all respects, except for the effects of the double-tuned circuits in providing higher gain and selectivity than is possible in a single stage.

FAILURE ANALYSIS.

General. The discussions of failure analysis for the Pentode R-F Amplifier and the Cascade R-F Amplifier, previously discussed in this section, are generally applicable to the interstage i-f amplifier.

No Output. A defective i-f transformer, an open bias resistor (R1 or R4), loss of screen or plate voltage, or a defective tube can cause loss of output. Check the plate, screen, cathode, and supply voltages with a voltmeter. Lack of plate voltage can result from a defective power supply, an open plate resistor (R3 or R6), a shorted plate bypass capacitor (C5 or C12), or a defective transformer (T2 or T3). If the voltage is zero at the junction of C5 and R3, or C12 and R6, the cause is either an open plate resistor or a shorted plate bypass capacitor. A resistance check, using an ohmmeter (with the power off), will determine which is at fault. With plate voltage at C5 and C12, but not at the plate of one of the tubes, an i-f transformer primary is defective, or the primary and secondary are shorted; in either case, replacement of the transformer is necessary. An open plate circuit in a screen-grid tube can usually be determined quickly by noting that the screen is red, because of an overloaded screen, which tries to take the place of the plate. In this case screen resistor R2 or R5 will be excessively hot; it may smoke, and will eventually burn out. Where voltage exists on the plate of one of the tubes, but not on the screen, bypass capacitor C4 or C9 may be shorted, or screen resistor R2 or R5 may be open. A resistance check from each screen bypass capacitor to ground (with the power off) will indicate zero if the capacitor is shorted, and a resistance check of the screen resistor will reveal the condition of the resistor. Since the screen voltage determines the plate current of a pentode, to a great extent, it is not always necessary for the screen voltage to be zero in order to cause loss of output. Since cathode resistor R1 or R4 is in series with the tube, if the resistor is open the circuit to ground will be incomplete and the tube will not operate. Likewise, if it increases in value sufficiently the tube can be biased off to almost zero plate current, and cause such a small output as to be considered practically no output at all.

If the tube is defective and no emission occurs, the cathode voltage will be zero. With C3 or C8 shorted, there will also be no cathode voltage, but the output will be distorted because of heavy plate and screen current; in this case the plates will get red and the tube may be damaged. Where the indications are otherwise normal, the tube should be suspected; replace the tube with one known to be in good condition. In simple receivers it is sometimes easier to first replace the tube to determine whether it is at fault. However, such a procedure can cause additional trouble in multi-tube i-f amplifiers, particularly in those having a high intermediate frequency. This occurs because the i-f tuning is affected by the tube capacitance, so that replacing the tube in a different socket (or with another tube) throws the set out of alignment, which can cause a large loss of gain; this condition can also be mistaken for no output. With normal plate, screen, and cathode voltages and no output, even with good tubes, it is certain that the secondary of output transformer T3 is open or totally detuned. Usually such a condition will produce a slight output because of stray capacitive coupling between windings, but it could be mistaken for a no-output condition.

Low Output. Low output can be caused by a defective tube, low screen or plate voltage, or too high a bias. First check the tube element voltages with a voltmeter. A low voltage on the plate or screen indicates excessive current drain in that circuit (producing a large voltage drop through the series resistor), an off-value plate or screen resistor, or a leaky bypass capacitor. The resistors can be checked by means of an ohmmeter (with the power off), and the capacitors with an in-circuit capacitance checker. Larger than normal plate and screen current will also cause a corresponding increase in bias voltage, since cathode bias is produced by the sum of all currents flowing in the tube. A leaky screen or plate bypass capacitor will cause reduced plate or screen voltage, reduce the cathode current flow, and hence decrease the bias. Low tube emission is usually indicated by higher than normal plate and screen voltages, with reduced cathode bias. As the condition becomes worse, the output will continue to decrease progressively until the tube emission is insufficient to produce an output. When all voltages appear normal and the output is low, either a tube may be defective or the alignment my be at fault. Replace the tubes one by one, noting whether there is any slight increase in output. If very little or no increase in output can be obtained by tube replacement, recheck the alignment. If during alignment one of the tuning capacitors (or tuned inductors where inductive tuning is used) does not seem to have any effect, the transformer being tuned is defective; replace it with a good one.

When the set suddenly blocks on receiving a loud signal and becomes almost inoperative, the i-f amplifier is probably oscillating and developing sufficient bias to cause the reduction in the output signal. Sometimes blocking will not occur, but a strong squeal or howl will occur instead. In either case a plate or screen bypass capacitor may be open. In some instances drying out of the last electrolytic capacitor in the power supply will cause loss of filtering ability, produce hum, and through common impedance coupling cause a similar effect.

Distortion. Distorted output can be caused by an improper bias, plate, or screen voltage. When the plate voltage drops below zero, plate current cutoff occurs, and this stoppage of plate current flow causes distortion. If the plate voltage is driven into plate current saturation no further change in plate current can occur, and a similar type of distortion will exist. Excessive bias will cut off the lower portion of the drive signal, reduce the plate current swing, and cause distortion. Likewise, excessive input (drive) voltage will cause the bias to be driven to zero (or above) and cause grid current flow; this will cause plate current saturation on one signal peak, and cutoff on the opposite signal peak. Both distortion and reduced signal output will occur. Usually, a voltage check for this condition will indicate improper or fluctuating voltages on the tube electrodes. However, it is easier to use a scope with an r-f probe and observe the signal. A simulated (signal generator) input with modulation applied also provides a simple signal for observation on a scope. Localization of the trouble to a specific portion of the circuit will usually involve only those components in the circuit where the distortion is observed, so that further simple voltage or resistance checks of the parts involved will locate the defective part.

TRIODE R-F BUFFER AMPLIFIER.

APPLICATION.

The triode r-f buffer amplifier is employed in receivers, test equipment, and transmitters as an intermediate amplifier stage, between the oscillator and the output stage, to minimize or eliminate the effect of impedance or load changes in the output on the oscillator frequency.

CHARACTERISTICS.

Operates Class B or C in transmitter applications, and Class A (or AB_1) in test equipment and receiver applications.

Gain and power output are usually low.

Normally operates on the same frequency as the oscillator and output stage.

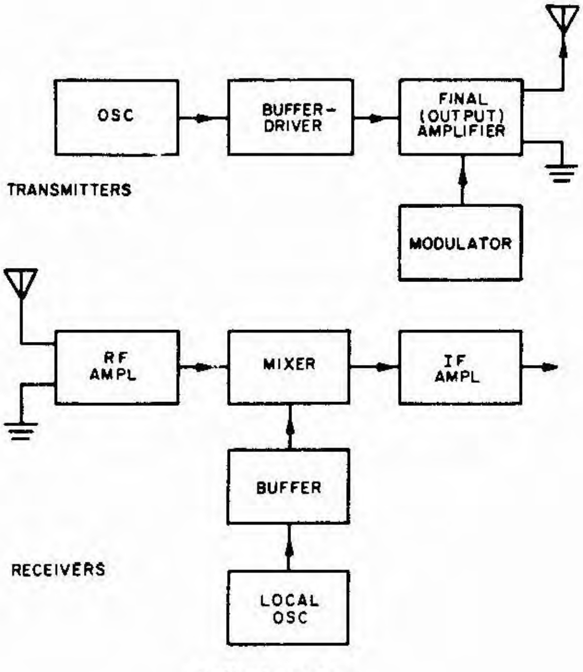
Plate efficiency varies with the bias; Class A is lowest and Class C is highest, with Class B at some intermediate value.

Requires more grid drive than a pentode buffer.

Usually requires neutralization to prevent feedback and self-oscillation.

CIRCUIT ANALYSIS.

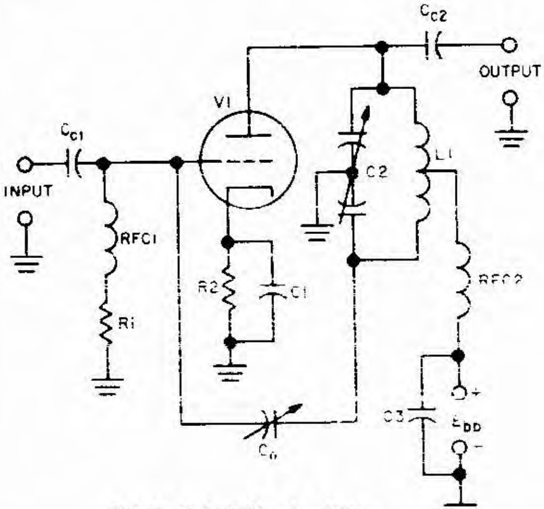
General. In receiver applications, the r-f buffer amplifier is generally used between the local oscillator and the mixer as shown in the accompanying block diagram. Thus, any changes in mixer operation or load, such as might be caused by automatic volume control, affect only the buffer



Buffer Locations

stage, and the oscillator frequency is not pulled or changed. This type of operation is used mostly for single sideband reception, where the oscillator frequency must be kept stable within a few cycles of the desired fundamental or output frequency. In transmitters, the buffer amplifier is used to isolate the high-level modulated r-f output stage from the oscillator, to prevent frequency modulation effects on the carrier and to avoid distortion. It is also used in low-level stages for the same purpose, and in cw operation it prevents sudden changes in load with keying from affecting the oscillator frequency. It is sometimes used as a dual-purpose amplifier to supply additional drive power, plus isolation. When used as a power amplifier, however, its isolating effect is nullified with the larger outputs and loads, so that sometimes more than one power buffer stage may be used. In test equipment, the r-f buffer is not necessarily used only to provide a stable oscillator frequency, but may be used to prevent the changing of load in the stage from having any other effect on the stage preceding the buffer. Because test equipment and receivers require linear operation with minimum distortion, these buffer stages are always operated Class A (or AB_1). Although the transmitter buffer stage could also be operated Class A, it would result in an unnecessary loss in efficiency; hence the reason for Class B or C operation. Because the Class C stage requires a large drive and this grid current requirement loads the preceding stage, Class C operation is not used when Class B operation will suffice. Since only an r-f carrier is amplified, the tank circuit eliminates any distortion caused by single-tube Class B operation.

Circuit Operation. The schematic of a typical triode r-f buffer amplifier is shown in the accompanying illustration.



Triode R-F Buffer Amplifier

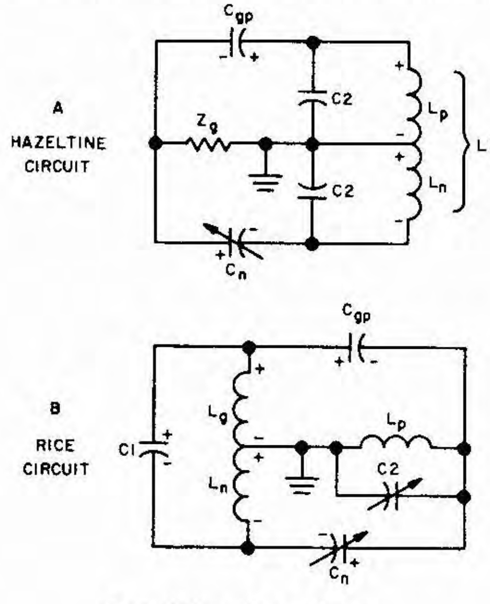
Capacitive input and output coupling are provided through C_{c1} and C_{c2}, respectively. Both fixed grid bias and protective cathode bias are employed (although either could be used alone). Resistor R1 provides the grid bias by means of the grid current flow in V1, obtained through grid drive from the oscillator input. Radio-frequency choke RFC1 keeps the input rf from being shunted to ground through the grid return resistor. Protective cathode bias is supplied by R2, bypassed by C1 for rf. The plate tank consists of L1 and C2, with C2 being a split-stator type of variable capacitor. Thus, with the center plate of C2 grounded, the tank is balanced, and opposite polarities exist at the ends of the tank coil. One end of the tank coil is coupled through C_{c2} to the next (output) stage, while the other end of the coil is fed back through C_n to supply a neutralizing connection, and the plate voltage is applied to the center of the coil. RFC2 keeps the rf in the tank out of the power supply, and C3 assures this by bypassing any remaining residual rf around the power supply to ground.

C_{c1} and C_{c2}, respectively. Both fixed grid bias and pro-

In the absence of an input signal, cathode current flow through R2 develops a protective cathode bias which is sufficient to prevent damage to the tube, but is not sufficient for normal operation. When the oscillator input signal is applied through C_{c1} to V1, grid conduction occurs during the positive half-cycles. Grid current flow from the cathode to the grid, charging the coupling capacitor. During the negative alternation, the grid current is cut off by the negative signal and the bias voltage developed by the charge on the coupling capacitor discharging to ground through R1. After a few alternations this signal bias develops a steady bias voltage, as explained in Section 2, paragraph 2.2.2, of this Handbook. The total tube current flow through V1 and cathode bias resistor R2 adds a slight amount to the signal bias, and the operating bias is a combination of both. Normally, the tube operates Class B, and plate current is cut off during the negative half-cycle (when operated Class AB only a portion of the negative half-cycle is cut-off). Thus, plate-current pulses flow only during the positive half-cycle, and loss of the negative half-cycle would normally cause distortion. However, the tuned tank circuit, consisting of L1 and C2, acts as a reservoir for rf and supplies the missing negative half-cycles. This action occurs because, once the tank circuit is excited, oscillations do not immediately cease unless there are heavy losses in the tank. Otherwise, once the source of rf is removed, the circuit continues to oscillate with diminishing amplitude each cycle until the rf is dissipated in the resistance of the tank. Since pulses of rf energy are supplied each positive half-cycle, the tank is effectively returned to its initial amplitude once each cycle. Any tank losses are thus supplied by the cycle during which conduction occurs. Therefore, than tank operates as though it were continuously excited, and no distortion in the output exists because of the loss of the negative half-cycle of operation. Single-tube, Class B operation is possible in an r-f amplifier because of the tuned tank circuit. In an audio amplifier, two tubes are necessary, one operated by the positive half-cycle and the other by the negative half-cycle, to provide an undistorted signal.

With the output tank tuned to the same frequency as the input (drive) signal, positive feedback can occur through the large grid-to-plate capacitance of the triode. Although the polarities of the grid and plate are opposite in the common or grounded-cathode circuit, the capacitive feedback voltage leads the predominantly inductive (high-Q) tank voltage, and is, therefore, of the proper phase to combine regeneratively with the input signal. Hence, neutralization is necessary to prevent self-oscillation. Neutralization is accomplished by feeding back an equal but oppositely polarized voltage through C_n from the other side of the tank. Since at any instant the opposite ends of any tank coil are of opposite polarity, taking the feedback voltage off the end of the coil opposite the plate always provides the correct polarity for neutralization. The use of a center-tapped coil with a split-stator tuning capacitor insures a completely balanced tank. Thus, it is only necessary to adjust C_n to approximately the same value as the grid-to-plate capacitance to obtain neutralization.

The manner in which the neutralizing circuit forms a reactive bridge with equal arms is shown in part A of the following simplified schematic. This plate-to-grid feedback system is known as the **Hazeltine or neutrodyne** type of neutralizing circuit. A similar form of feedback from grid to plate is known as the **Rice** system, and is shown in part B of the schematic. While other forms of neutralization are also used, these two types are the most popular and commonly used circuits. In part A of the illustration, Z_g is the input impedance, and coils L_p and L_n together form tank coil L1 in the plate circuit. The voltage across C_n is equal, and opposite in polarity, to that across C_{gp}; thus, there is no flow of current from output to input, and complete neutralization results. In part B of the figure, the opposing voltages are developed in the grid tank across L_g and L_n; otherwise, the operation is the same.



Typical Neutralizing Circuits

Although the triode buffer described above uses capacitive input and output coupling, inductive coupling can be used instead. In this case the grid circuit usually contains a tank, with a coupling coil, and the plate likewise. The operation is the same except for the inductive input and output coupling, which merely transfers the signal into the input tank and out of the output tank. Push-pull stages may also be used as buffer amplifiers, in which case neutralization is easily accomplished by using cross-connected grids and plates, since they are oppositely phased and polarized.

The basic triode r-f buffer amplifier originally consisted primarily of a low-gain voltage amplifier which did not draw grid current and was lightly loaded, since it only supplied the grid current (drive power) necessary for the final output stage. Therefore, it offered no load to the self-excited oscillator, and allowed it to operate at maximum stability. At the same time, the tube was chosen with a power rating which was more than sufficient to supply the grid power needed by the final amplifier. Thus, the buffer stage effectively isolated the oscillator from the output stage, so that it was affected very little by any modulation peaks, or on-off keying of the output stage. For satisfactory performance Class A operation of the buffer was required, and low efficiency was obtained. In later years oscillators of better stability were produced, and Class B operation permitted a more efficient output with slight oscillator loading. Thus, as the state of the art advanced and electron tubes and parts improved; it was found that even Class C operation could be used. Hence, the buffer amplifier is now generally considered to be any amplifier used between the oscillator and output stages and operating on the fundamental frequency. By using Class AB_1 operation, high efficiency with no grid current flow can now be obtained. However, the high gain of the pentode has virtually made the triode buffer obsolete except for special applications.

When operated Class A, the operation is the same as that described previously except that it is not necessary for the tuned tank to supply the negative portion of the waveform.

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FAILURE ANALYSIS.

No Output. Lack of an input signal, loss of plate voltage, a defective tube, or a detuned output tank will cause loss of output. The supply voltage should be checked with a voltmeter to determine whether the proper voltage is available. The grid drive may be checked by reading the grid voltage developed across R1 (in stages where grid current is drawn). Usually, transmitters are equipped with a milliammeter to read grid and plate current for tuning indications. Plate current indications will usually pinpoint the trouble to a particular location. For example, no plate current indicates an open plate or cathode circuit, a defective tube, or lack of plate voltage. In this case, it is a simple matter to turn off the plate power, **discharge the filter** with a shorting stick, and then make a resistance check of cathode resistor R1, and a continuity check of L1 and RFC2. If plate current is present, tune C2 for minimum dip in plate current. With sufficient drive, there should be a large current off resonance and a small current at resonance. If the drive is lacking, the ratio between the nonresonant and resonant condition will be small. If the ratio is large and the resonant current is lower than normal, there is no load or only a light load on the output, and C_{c_2} is *probable open. In this instance, an r-f indicator will show* rf on the plate side of the capacitor, but not on the output side; use a small coil connected directly to the vertical plates of an oscilloscope (not through the scope amplifier) to couple to the plate tank and indicate rf. Lack of grid drive will show as a large plate current indication which cannot be dipped to a normal low value, since the bias will be only that provided by R2. If C3 is shorted, the power supply plate fuse or circuit breaker will open, no plate voltage will be applied, and loss of output will occur. Where the plate voltage is normal and the grid drive is sufficient, but the plate current is low (or slowly decreases as the stage operates), the emission of the tube is probably low. Replace the tube with one known to be good, when possible.

Low Output. Low plate voltage, low grid drive, improper bias, or a defective tube can cause low output. The plate supply voltage and grid bias across R1 and R2 can be checked with a voltmeter. It is important to not the difference between receiving and transmitting r-f amplifier voltage measurements. In the receiver stage, any rf on the grid or plate is usually so small that it will not damage the meter; however, in the transmitter stage, large r-f circulating currents are produced in the grid and plate circuits which *can damage the meter when d-c measurements are made to* ground. Therefore, it is necessary to use a radio-frequency choke in series with the voltmeter, or use a probe which is adequately filtered for rf. A vacuum-tube voltmeter may be used on receiving equipment, but it is usually unable to *withstand the high voltage present in transmitters.* As a general rule, therefore, all d-c voltage measurements are made in portions of the circuit which are "cold" to rf (no rf exists), and other indications, such as plate current, are used instead. (In special instances, r-f voltmeters can be used.)

With proper plate voltage and bias, low output will be obtained if the r-f grid drive is not sufficient to make the tube draw the proper value of plate current. Likewise, low emission will make it impossible to obtain the proper plate current, and thus the proper output. When all indications other than plate current are normal, the tube is probably at fault. Replace the suspected tube with one known to be in good operating condition, if possible.

If cathode capacitor C1 opens, plate current variations occurring at radio-frequency rates will momentarily develop high cathode bias voltages, produce degeneration, and cause reduced output. Temporarily grounding the cathode in this case will restore operation and the output to normal, and prove that C1 is defective. Do not try grounding the cathode unless grid drive is present; otherwise, the tube will operate at zero bias, will be overloaded, and will be damaged if current is allowed to flow for a prolonged period of time. Sometimes low output will be obtained because of parasitic oscillation at a very low frequency. This occurs when a feedback loop occurs through the neutralizing circuit and an associated r-f choke and bypass or tank tuning capacitor(s). The symptoms are high plate current will low r-f output at the desired frequency and larger than normal grid current. Once started, these oscillations will usually continue when the normal grid excitation is removed. If the circuit operates and tunes normally with reduced plate voltage and at a reduced output, but will not do so when full plate voltage is applied, parasitics are probably the cause. Usually, this will not occur in Navy equipment when initially received, but can sometimes be caused by a change in components with age, by a part failure, or by improper bias, or charge of lead dress during a repair.

Improper Neutralization. When a stage is incompletely *neutralized or misadjusted, operation will become erratic.* The tube may operate normally and then suddenly start oscillating when shocked by a transient pulse. To determine whether the stage is properly neutralized, **remove the plate voltage** and tune the plate capacitor through resonance while observing the grid meter indications. A steady, unchanged meter reading indicates complete neurtalization; a slight change or sharp flick of grid current as resonance is passed indicates that neutralization is incomplete. Adjust the neutralizing capacitor while tuning the plate through resonance until the grid meter remains steady.

PENTODE R-F BUFFER AMPLIFIER.

APPLICATION.

The pentode r-f buffer amplifier is universally used in receivers, test equipment, and transmitters as an isolation stage. It is generally used between an oscillator and an output stage to prevent modulation or load changes from affecting the oscillator frequency.

CHARACTERISTICS.

Usually operated Class A or AB, self-biased, although Class B or C operation is sometimes employed.

Has relatively high voltage and power gain.

Provides more output than a triode r-f buffer amplifier, with less drive.

Does not normally require neutralization.

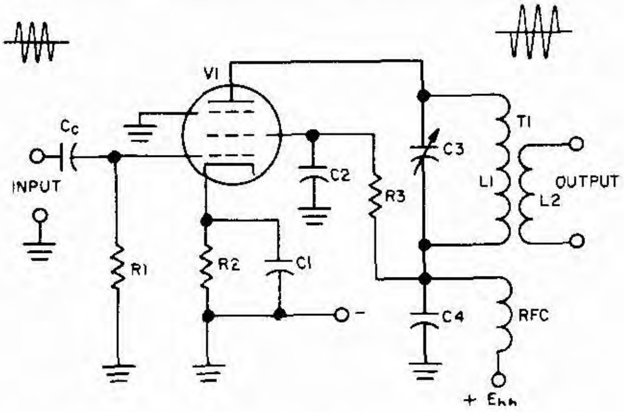
Operates on same frequency as input and output stages.

Has greater isolating effect than a triode.

CIRCUIT ANALYSIS.

General. The pentode r-f buffer amplifier is an effective isolation amplifier because of the low grid voltage drive required for full output, which places very little loading on the oscillator (or input) stage. Thus, the oscillator can be designed for maximum stability under a light or idling load. In addition, the effective shielding supplied by the screen and suppressor elements of the pentode reduces the grid-to-plate capacitance to such a small value that feedback is practically eliminated. Therefore, no neutralizing circuits are needed, so that fewer parts are required and the neutralizing adjustment is eliminated. Finally, the high amplification factor of the pentode produces a large output voltage under the control of only a small grid voltage. Since the screen prevents plate current variations from affecting the grid or input circuit to any marked extent, a much larger power can be developed in the pentode plate circuit than in a triode operating at the same plate voltage. Because of the small drive required, the pentode r-f buffer amplifier may also be used to drive another pentode (or tetrode) output tube without losing its ability to act as an isolation stage. The resultant transmitter output, then, is equivalent to that developed by two or three triodes operating at higher plate voltage and currents.

Circuit Operation. The accompanying illustration is a schematic of a typical pentode r-f buffer amplifier.



Typical Pentode R-F Buffer Amplifier

The grid of V1 is capacitively coupled through Cc to the oscillator. Resistor R1 is the grid return resistor, across which the input voltage appears. Cathode bias is supplied by R2, which is bypassed for rf by C1. Screen voltage is obtained through dropping resistor R3, which is bypassed to ground for rf by C2. The plate voltage is series-fed through L1 to the plate of V1, and is tuned to resonance by C3. L2 is the output coil, which is inductively coupled to L1 (L1 and L2 form r-f transformer T1). The radio-frequency choke (RFC) prevents any rf from entering the supply and is bypassed to ground for rf byC4.

When the oscillator operates, a signal which is approximately a sine wave is developed in its plate circuit, and is applied through Cc to the V1 grid. The low reactance of Cc ensures that a minimum voltage drop (and very little loss of signal) occurs across the coupling capacitor. Grid resistor R1 provides a high impedance across which the oscillator signal is developed. Since the grid does not normally draw any grid current, no current flows through R1 at any time (unless Class B or C operation is employed). Cathode resistor R2 provides bias voltage which is developed across it by space charge current flow, that is, the sum of both the screen and plate currents. When plate and screen voltage is applied to V1, current flows from ground through R2, producing a positive cathode bias which is equivalent to a negative bias voltage applied to the grid. Since R2 is bypassed by C1 for rf, no change occurs in bias when an input signal appears across V1 (between grid and ground). Any r-f current variations are bypassed around R2 by C1; hence, the bias is affected only by a steady change in plate or screen current, and not by instantaneous r-f variations. Thus, as the load changes the bias will also change accordingly. It is important that the load be held constant to produce the desired operating bias. When operated Class A (in receivers and test equipment), the operation is over the linear portion of the Eb-Ib curve. In Class AB operation a slightly higher bias is used. (See Section 2, paragraph 2.2.1, of this Handbook for a discussion of cathode bias, and paragraph 2.3 for a complete discussion of classes of amplifier operation.)

As the oscillator signal is applied to the grid of V1, assuming a sinusoidal input signal, the positive half-cycle of operation causes the plate current to increase, and the negative half-cycle causes the plate current to decrease. The plate current swing is determined by the screen voltage appearing on the screen of V1, which is controlled by the value of R3. The screen resistor is chosen so that with the proper plate voltage applied, and with no signal, the V1 screen and plate current flowing through cathode bias resistor R2 provides the normal bias. During operation, the screen current flows steadily, producing a voltage drop across R3 of sufficient value to drop the plate supply voltage to the desired screen voltage value. Any electrons striking the screen are bypassed to ground through capacitor C2. Likewise, any change in plate current will not effect the screen voltage, since R3 is always kept at ground potential for r-f variations; hence, only d-c current flow determines the screen voltage, and this does not vary with the signal. Since the screen is closer to the grid than to the plate, it exerts a strong control over the plate current; also, since it is grounded for rf through C2, no feedback can exist between the grid and the plate (it acts as a shield). Thus any possibility of feedback and self-oscillation is eliminated, and neutralization is unnecessary. Tank circuit L1, C3 is connected in series with the plate of V1, and when tuned to resonance offers a high impedance. Thus, as the input voltage swings positive, the plate current of V1 increases, and in flowing through L1 induces a voltage in secondary L2 by transformer action. Meanwhile, the high impedance of the tank produces a large plate voltage drop and the actual plate voltage falls toward zero. The design is such that the plate voltage is not allowed to drop below the actual screen voltage. (Otherwise, the screen of V1 would tend to act as a plate; thus it would be overloaded and cause distortion.)

As the oscillator signal changes its cycle and swings negative, the V1 plate current is reduced, and the reduced value of current through L1 induces an oppositely polarized output voltage in L2 by transformer action (the current now flows in the opposite direction). At the same time, the plate voltage rises toward the supply voltage. The actual plate voltage is almost equal to the supply voltage at the negative peak of the input cycle. The gounded-cathode circuit produces a polarity (or phase) inversion. When the input signal goes negative, the plate output signal is positive and of opposite phase or polarity; conversely, when the input signal goes positive, the plate output signal is negative. The output voltage induced into secondary coil L2 is polarized similarly when it is connected in-phase. If connected out-of-phase, the output signal polarity is the same as that of the input signal.

Capacitor C4 keeps the lower end of tank C3, L1 at r-f ground potential, and the RFC ensures that any residual rf is offered a high impedance, so that it flows to ground through C3 rather than attempting to flow through the low impedance offered by the output filter capacitor of the plate supply.

If tank circuit L1, C3 *is not tuned to the oscillator or input frequency*, a very small impedance is offered in the plate circuit and little or no output voltage is developed. The unloaded Q of the tank circuit is made high, so that the loaded Q (at resonance) provides sufficient selectivity to pass only a narrow band of frequencies between the half-power points, and the tank is able to discriminate between wanted and unwanted signals. While in Class A operation plate current flows at all times during the cycle, in Class AB or B operation part of the signal is missing (it is beyond cut-off). During this period, r-f energy is supplied from the tank circuit so that the operation is the same as if *plate current* flowed constantly without any interruption of output, and no distortion is developed. The plate tank is reinforced during each positive half-cycle with sufficient rf to overcome any tank losses, so that the tank is never depleted.

Grounding the suppressor grid provides a shielding action between the screen and plate, and thus prevents *secondary emission from the plate*. Therefore, coupling between the plate and grid is only through the electron stream, and is at a minimum. In those tubes with suppressors internally connected to the cathode, the operation is identical except there is slightly more coupling between the grid and plate through the electron stream.

Although the input is shown capacitively coupled, it is sometimes inductively coupled, in which case a tuned tank is used in the grid circuit in place of resistor R1. The operation is the same except for the development of a slightly larger grid excitation, since the parallel-tuned tank usually offers a higher impedance than the grid resistor and will cause the input voltage to increase at resonance. Thus, when Class B or C operation is employed, the tank is sometimes added to provide better grid regulation, since grid current tends to shunt the input and lower the grid input impedance.

As is evident from the discussion above, the buffer amplifier operates in practically the same manner as the pentode r-f voltage amplifier previously discussed as a separate circuit. The only actual difference is in the design considerations, which are based upon light grid and plate *loading to provide maximum isolation* rather than output voltage or power.

FAILURE ANALYSIS.

General. The discussion of failure analysis for the Pentode R-F Voltage Amplifier, previously discussed in this section of the Handbook, is generally applicable, and is particularly slanted toward receiving applications.

No Output. Loss of plate, screen, or filament voltage, a defective tube, defective coupling capacitor Cc, open output coil L2, or shorted grid return resistor R1 can cause no output. *Check the tube voltages and supply voltage with a voltmeter.* WARNING: Voltages dangerous to life usually exist in the plate and screen circuits; be certain to observe all safety precautions when checking these voltages. An open filament can sometimes be observed by noting that the tube is not illuminated and feels cold to the touch. If the plate, screen, and filament voltages are normal, substitute a tube known to be good, if possible. If there is still no output, coupling capacitor Cc is probably open; check for proper capacitance with an in-circuit capacitance checker. Using a vtvm or voltmeter with an r-f probe (or an oscilloscope), *check for voltage between the input and ground.* If there is a voltage indication on one side of the coupling capacitor but not on the grid of V1, the capacitor is open or R1 is shorted. (If Cc were shorted, a high positive voltage would appear on the grid from the oscillator plate and cause high cathode bias voltage.) An open screen resistor (R3) will be indicated by lack of screen voltage, although a shorted screen capacitor (C2) will give a similar indication. In the latter case, however, R3 will heat abnormally and drop the screen voltage to zero. This short-circuit condition may be observed visually by smoke from, or discoloration of, the resistor. If the short is prolonged, the resistor will burn out. An open or shorted cathode bypass capacitor (C1) will not necessarily produce a no-output condition; however, if cathode resistor R2 is open, no output will be obtained.

If there is no plate voltage, coil L1 or the RFC may be open (be certain to check the supply voltage to ascertain that the power supply is not defective). If plate bypass ca*pacitor C4 is shorted, the plate supply will be dropped* across the RFC, which will heat up and burn out. Coil and RFC continuity can be checked with an ohmmeter **with the power off.**

Usually, a milliammeter is provided in transmitters for measuring the plate current (or a meter can be connected in series between the plate supply and the RFC.) No plate current indicates loss of supply voltage or an open circuit (either in the meter or in the plate circuit). If no dip in plate current can be obtained as C3 is tuned through resonance, either C3 is shorted, there is no drive, or L2 is partially shorted. If the plate current is low and C3 can be dipped properly, but no output exists, output coil L2 is open.

Reduced Output. Excessive bias, insufficient screen or plate voltage, lack of drive, or a defective tube can cause reduced output. Check the bias, plate, screen, and supply voltages with a voltmeter. Low screen voltage will cause insufficient plate and screen current, and will result in low bias and reduced output. Low plate voltage with normal screen voltage will cause the screen to act as a partial plate; the screen may run hot, depending on the value of plate voltage. This can result from a high resistance in the plate circuit caused by a poorly soldered connection, or from a defective tube. If the tube is suspected, replace it with one known to be in good operating condition, when possible.

If C3 cannot tune L1 to resonance at the output frequency, a reduced-output condition will be obtained. This can result from a lack of sufficient inductance in L1, caused by a shorted turn, or by a short or open in C3 itself. A check with a grid-dip oscillator, or a wavemeter, will reveal whether the tank circuit is resonant at the wrong frequency. In either case, part substitutions will probably be required, since C3 cannot be checked for continuity or for capacitance with the in-circuit capacitance checker without disconnecting one end of the coil (the low coil resistance effectively shorts the capacitor).

A leaky or shorted input capacitor (Cc) will place a positive bias on the grid and cause larger than normal plate current to be drawn; at the same time the cathode bias will be increased, so that the effective plate voltage will be reduced. Depending upon the amount of leakage voltage applied to the V1 grid, the output will be reduced, and, because the operation is at the bottom of the transfer characteristic curve, the positive signal peaks will be clipped by plate current saturation, causing some distortion in the output. If R1 opens or becomes too high in value with age, coupling capacitor Cc will charge through V1 when the grid is positive with respect to the cathode, but cannot discharge except through existing leakage paths; therefore, the capacitor will tend to accumulate a negative charge and block V1 from operating. Actually, when Cc is charged, no further grid current flows. When the input signal becomes negative-going, Cc discharges through the high shunt leakage paths in the tube and grid circuit, producing a negative bias. Since the capacitor cannot completely discharge before the next conduction period, it eventually accumulates sufficient charge to hold the grid at cutoff.

If screen capacitor C2 opens, the screen voltage will vary with the signal, and cause a reduction in the output. It is also possible for self-oscillation to occur.

Distortion and Other Effects. The buffer amplifier is subject to all forms of distortion common to other r-f amplifiers, except that buffer operation usually implies the amplification of only a single radio frequency. Since tuned tank circuits are used, any tendency toward distortion is usually swamped out by the tank. The tuned tank also minimizes any distortion caused by multiples of the original frequency, or harmonics. Although harmonics exist, they are not selected by the tuned circuit and are greatly attenuated in the output. Clipping and bottoming can cause a tendency toward peak flattening, but the tank circuit tends to supply the energy during the cutoff periods. Thus, the usual effect is to produce a reduction in amplitude and to retain the sinusoidal waveform. When the buffer also acts as a power amplifier, this reduction in distortion may not be obtained to as large an extent. Normally, no neutralization is required; however, it is possible to change the lead dress during repair and cause external feedback because of inductive or capacitive coupling between the relocated leads. Do not change the lead dress of r-f amplifiers unless absolutely necessary.

FREQUENCY MULTIPLIER (RF).

APPLICATION.

The frequency multiplier stage is used to provide an output frequency which is some integral multiple of a fundamental crystal-controlled, or self-excited oscillator frequency. It is universally used in receivers, test equipment, and transmitters.

CHARACTERISTICS.

Uses Class C operation at all times.

May be self-biased, fixed biased, or a combination of both.

Output frequency is always some multiple of the fundamental.

Normally doubles or triples, but can operate up to about the seventh harmonic.

Efficiency varies inversely with frequency.

Maximum usable efficiently is on the order of 70 percent, and lowest efficiency is about 45 percent.

Grid bias is higher than in the normal Class C amplifier.

Requires more grid drive than would be necessary for operation at the fundamental frequency.

Does not require neutralization.

CIRCUIT ANALYSIS.

General. Although either triode or pentode tubes may be used as frequency multipliers, the pentode is more commonly used because of the reduced grid drive required for pentode operation, plus the larger power output obtainable for the same plate voltage. Since grid current flows in Class C operation, the multiplier stage requires a slight amount of power from the oscillator to drive it. The reduced drive of the pentode, therefore, allows the oscillator to operate more stably, and permits a lower-rated oscillator tube to be used. Normally, a Class C amplifier is biased at 2 to 2-½ times cutoff. The frequency multiplier is essentially a Class C stage which utilizes its rich harmonic content, or, rather, is operated so as to develop a greater harmonic content than normal. Selection of the desired harmonic by a tuned output circuit produces a relatively large output at that harmonic. To produce the distorted plate current with its rich harmonic content, the stage must be biased higher than for normal Class C operation, and must be driven harder than normal. Thus, plate current flows only during a small fraction of the cycle, roughly from 60 to 120 electrical degrees (depending upon the amount of harmonic multiplication desired). Therefore, the normal grid bias for a multiplier is usually 3 to 4 times cutoff. Because the plate output tank is tuned to a different frequency from that of the input (drive) signal, no plate-to-grid feedback occurs. Therefore, neutralization is never required, regardless of whether triodes or pentodes are used.

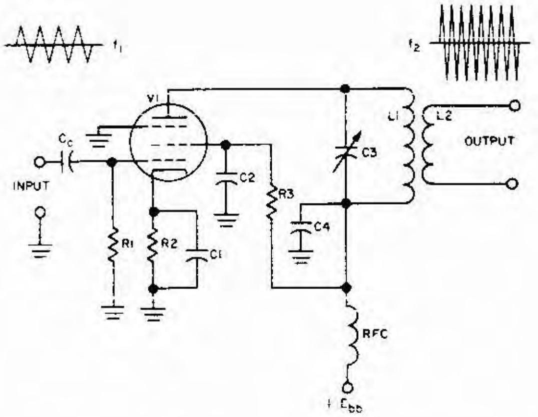
A harmonic generator consists merely of a number of frequency-multiplier stages connected in cascade. They are used in receivers, being driven by a stable local oscillator which operates at a low fundamental frequency and is multiplied through several stages to supply an oscillator signal to a VHF or UHF mixer. Likewise, in test equipment, a suitable oscillator has its output frequency multiplied for use as a signal generator or frequency standard, or for other purposes. In a transmitter, the multiplier stage (or stages) allows the use of a single crystal to provide drive for r-f amplifiers operating on harmonically related output frequencies, or it may be used to supply a crystal-controlled output at higher frequencies, where crystal operation at the output frequency is not feasible.

The power output of the multiplier stage varies roughly as the reciprocal of the number of multiplications. Thus, a frequency doubler produces about one-half the output power of a conventional Class C r-f amplifier stage, and a frequency tripler produces about one-third the power; hence, the necessity for cascaded operation at the higher multiples. For example, two doubler stages operated in cascade will deliver twice the power of a single quadrupler stage.

The loaded tank circuit impedance increases roughly in proportion to the number of harmonic multiplications required, since the output power decreases and a greater impedance is necessary to provide the same voltage drop across the tank. This places a practical limit on the number of multiplications possible in a single stage.

Circuit Operation. The accompanying figure illustrates a typical pentode frequency multiplier stage. Schematically, the stage appears identical with that of the conventional Pentode R-F Voltage Amplifier or the Pentode R-F Buffer Amplifier previously discussed. However, there are differences in parts values to provide the correct bias and operation, and the plate tank resonates at a multiple of the fundamental frequency. Detailed differences in operation are discussed below.

The oscillator output is capacitively coupled through C_c to the grid of V1. Grid bias is obtained through grid current flow in R1, and protective cathode bias is supplied by R2, which is bypassed for rf by C1. The screen voltage is dropped to the proper value by screen resistor R3, bypassed for rf by C2. Variable capacitor C3 and inductance L1 form the output tank circuit, which is inductively coupled to output coil L2. While series plate feed is employed, one end of the tank is bypassed to ground by C4, and the radio-frequency choke (RFC) insures that any residual rf remaining flows to ground by way of C4 rather than through the low impedance of the power-supply filter.



Typical Frequency Multiplier Circuit

With no signal applied no grid bias is developed, and the plate and screen current flow through cathode resistor R2 provides sufficient cathode bias to limit the static current flow to a safe value. When the oscillator signal is applied, the low reactance of coupling capacitor C_c allows practically all of the input to appear across R1 and the V1 grid. On the positive half-cycle of the input signal the plate current increases, and on the negative half-cycle it decreases. During the positive half-cycle C_c charges, and during the negative half-cycle it discharges from the capacitor to ground, a negative bias is developed across R1; this grid bias voltage and the cathode voltage stored in C1 produce a high bias many times the cutoff value. (See Section 2, paragraphs 2.2.1 and 2.2.2. of this Handbook, for a further discussion of cathode and grid-drive, or signal bias.)

Because of the extremely high bias, the plate current conduction period is reduced to a small fraction of the total cycle. Actually, it is less than a half-cycle and varies with the amount of multiplication desired. For a frequency doubler it is about 120 electrical degrees, and for a quintupler it is about 60 degrees. The short time during which plate current flows produces a very distorted plate pulse which is rich in harmonics. When plate tank C3, L1 is tuned to the desired output frequency, it offers a high impedance at the frequency, so that a large drop in plate voltage occurs across the tank. With an increasing plate current, caused by the positive input signal, the plate voltage is dropped toward zero; during cutoff, produced by the negative portion of the input signal, the plate voltage increases to almost the full value of the supply voltage. A decreasing plate voltage induces a negative output signal in L2 by transformer action, since it is coupled to tank coil L1, while an increasing plate voltage induces a positive output signal in L2.

The instantaneous current and voltage relationships in a frequency doubler are graphically illustrated in the accompanying illustration.

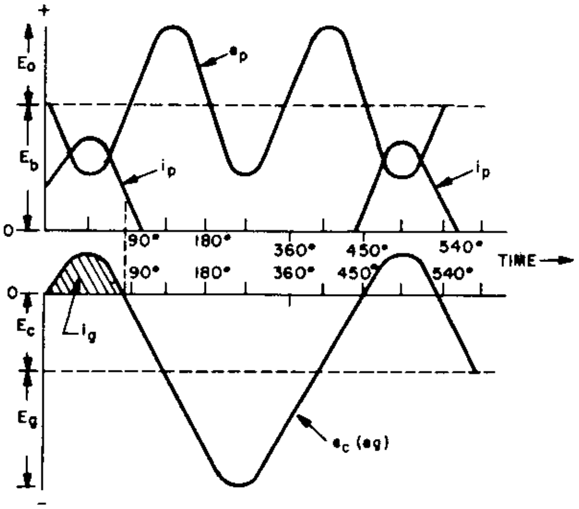


Plate Current and Grid Voltage Relationships

As can be seen from the figure, the plate current flow time is longer than the grid current flow time, but both maximums occur together. Thus, as instantaneous grid voltage e_c starts its positive excursion, no plate current or grid current flows until the grid voltage reaches cutoff. At this time plate current starts to flow. Slightly later, at zero bias, grid current flows also. The grid current flow is supplied from the oscillator or drive source. The increasing plate current (obtained from the power supply) causes a voltage drop across the plate tank impedance (tuned, for example, to twice the frequency of the oscillator). When the plate current is at its maximum, the plate voltage is at its minimum. At this time some plate power is absorbed by the tuned tank circuit. As the drive signal reverses and causes the instantaneous grid voltage to fall toward zero, the plate current decreases and the plate voltage increases. The grid signal continues to swing in the negative direction while the plate voltage rises (in a positive direction). At the static d-c level of plate voltage (E_b), the grid drive is approximately equal to the d-c bias (zero bias), and as the grid voltage increases toward cutoff, e_p continues to rise. At cutoff, the tank circuit supplies power, and e_p rises, even though the plate current ceases. This is the so called "flywheel" action of the tank circuit, which continues operation during the time the tube is inactive beyond cutoff. When the instantaneous negative grid voltage reaches the d-c bias level (E_c), plate voltage e_p reaches its positive peak and is approximately equal to E_o, the output voltage.

As the instantaneous grid signal continues to decrease beyond the d-c bias level, the plate voltage now falls and becomes negative-going, since the tank is operating at twice the grid frequency, and the input signal, being highly negative, has no effect on the plate current. At the negative peak of drive voltage E_g, plate voltage e_p completes its second negative excursion and starts its second positive excursion. The drive voltage also swings positive again and now starts back toward cutoff and zero bias. When the drive is again equal to the d-c grid voltage, the second positive peak excursion is reached and the plate voltage starts dropping. As the grid voltage passes cutoff, plate current is again drawn and the plate voltage continues to drop until it reaches the third minimum, when the plate and grid currents are again at a maximum. Once again the plate power is absorbed by the tank to overcome the losses in the tank and to recover the energy supplied to the circuit during the inactive period.

With the tank replenished; it is again ready to supply the flywheel effect of the next cycle of operation. Note that always during the short pulses of plate current flow, the tank is absorbing power from the plate circuit. While on the negative grid swing (where the tube plate current is normally cut off and no output should occur), the tank circuit continues to oscillate and thus supplies the missing portion of the signal. Since the tank oscillations are twice that of the fundamental oscillator frequency, two peaks occur for every fundamental peak (in the tripler three peaks occur). The greater the number of oscillations required between the periods of pulses of plate current, the more the energy required from the tank to sustain these oscillations. Hence, the efficiency and output drop off as the multiplication of frequency is increased. In addition, the flywheel action of the tank maintains an approximately sinusoidal waveform in the output, while the fundamental plate current pulses are greatly distorted. When the grid bias and drive voltage amplitudes, as well as plate voltage, are adjusted for maximum output at a particular frequency, a slightly distorted output may be obtained; however, this can usually be compensated for by a slight adjustment of the tank tuning capacitor.

While push-pull operation can be used to supply more power output, more drive is required and only the odd harmonics are multiplied, since the even harmonics cancel out in the plate circuit. Therefore, push-push operation is employed, as explained in the next circuit discussion.

FAILURE ANALYSIS.

General. The discussion of failure analysis for the Pentode R-F Voltage Amplifier, and for the Pentode R-F Buffer Amplifier, discussed previously in this section of the Handbook, are generally applicable to the frequency multiplier.

No Output. Lack of grid drive, plate, screen, or supply voltage, or a defective tank, output coil, or tube can cause loss of output. Check with a voltmeter to make sure that the supply voltage is normal. If the cathode voltage is also normal, the proper plate and screen currents probably exist, so that either the plate tank is detuned or insufficient drive is indicated. Connecting a milliammeter in series with R1 and ground will indicate the amount of grid current flow; this will show that R1 is not open and serve as a check on Cc. If Cc is open, no drive would be present to cause current flow through R1; if it is shorted, the plate voltage of the preceding oscillator stage will bias the grid heavily positive, cause a large plate current flow, and produce a high cathode bias with practically no output. If cathode bypass capacitor C1 is open, degeneration will reduce the output but not completely eliminate it; if C1 is shorted, a large plate current will flow in the absence of drive voltage, but the plate current will appear normal as long as enough drive is present to produce sufficient signal bias. If screen capacitor C2 is open, self-oscillation and erratic operation (with some output) will probably occur; if C2 is shorted, the supply voltage will be normal but will be entirely dropped across R3. Therefore, R3 will heat, probably discolor or smoke, and eventually burn out. Meanwhile, no plate output will be obtained because of the lack of screen voltage to attract electrons from the cathode. Although a very small plate current may flow because of plate voltage attraction, this output will be practically negligible.

If plate bypass capacitor C4 is shorted, a similar condition will exist, with the entire supply voltage being dropped across the RFC, eventually causing the choke to burn out. Although screen voltage will be present, the plate voltage will be zero and no output can occur. In addition, the screen will tend to act as the plate and collect all electrons, so that excessive screen current will flow; in this case the screen will be overloaded and heat sufficiently to show color, and if prolonged the tube may be damaged.

If C3 will not tune L1 to resonance at the desired harmonic, no output will be developed across the tank, since its impedance will be too low to produce an output. The resonant frequency of the tank can be checked with a grid-dip meter or a wavemeter. If all voltages are present, but the screen and plate voltages appear higher than normal while the cathode bias is lower than normal, and with low plate current and no output, either output coil L2 is open or the tube is defective. Check L2 (and the load) for continuity with the power off; if satisfactory, replace V1 with a tube known to be in good operating condition, if possible.

Low Output. With a low screen or plate voltage, a low drive, a high-resistance plate circuit, or a defective tube, a reduced output will be obtained. The plate, screen, and cathode bias voltages can be checked with a voltmeter. Use an r-f choke in series with the meter and check the voltage across R1; this will determine whether grid bias exists and also whether sufficient drive exists. If the bias is low because of lack of drive, the stage will operate Class A, lose efficiency, and result in reduced power output. If screen resistor R3 increases in value with age, the screen voltage will be reduced, as will the output. A similar condition can be caused if screen bypass capacitor C2 is leaky. Check C2 with an in-circuit capacitance checker, or disconnect it from ground and check for a constant voltage between the capacitor and ground by use of a voltmeter. A similar condition can also occur if plate capacitor C4 is leaky. A high resistance in the tank can be caused by a poorly soldered joint. This will usually show as a broad dip in plate current with tuning, rather than the normal sharp dip. Leaky insulation on C3 can also cause a loss of rf and output. Check the capacitor insulating supports for indications of an r-f burn, or accumulated dirt and moisture, which can produce a shunting resistance to ground (particularly salt deposits from spray). Remove the capacitor, and clean and dry it thoroughly if it appears to be dirty; normal grayish oxidation of plates and metal supports does not indicate the need for cleaning. Do not lubricate the capacitor bearings because of rotor binding (adjust the tension screw instead); otherwise, bad contact will create a high r-f resistance. When the bias and voltage indications appear normal, but the plate current is low and cannot be increased to a normal value (or if it drops immediately after turn-on, or progressively decreases), low tube emission is probably the trouble. Replace the tube with one known to be good, whenever possible.

PUSH-PUSH FREQUENCY MULTIPLIER (RF).

APPLICATION.

The r-f push-push frequency multiplier is used as a frequency doubler in transmitters and test equipments that require a greater output and better efficiency than is possible with the single-tube multiplier.

CHARACTERISTICS.

Uses Class C bias at all times.

May be self-biased, fixed-biased, or a combination of both.

Provides approximately twice the output of a single-tube multiplier stage.

Provides efficiency almost equivalent to that of a normal Class C amplifier.

Requires a push-pull input connection and a paralleled-plate output.

May use triode or screen-grid tubes.

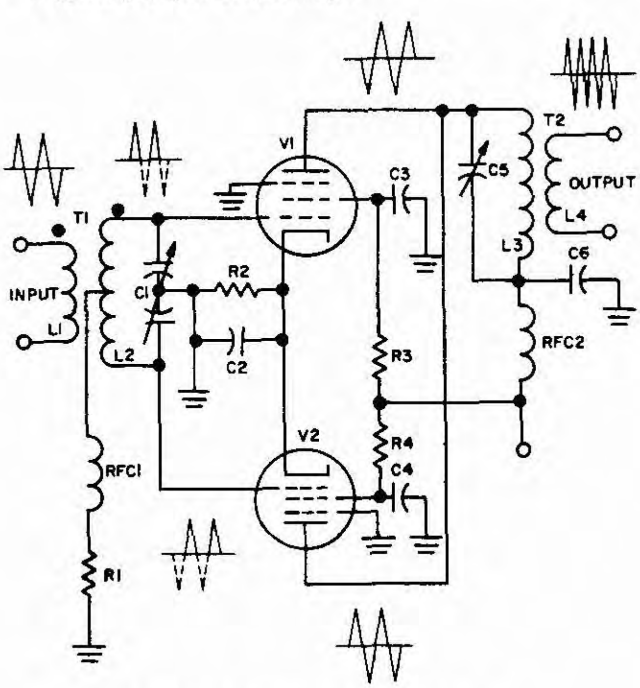
Operates push-push intstead of push-pull (a plate pulse is provided for each cycle of operation).

Does not require neutralization, since output frequency is double the input frequency.

CIRCUIT ANALYSIS.

General. Like the single-stage frequency multiplier, previously discussed in this section of the handbook, pentodes are used in preference to triodes, since the low drive requirement provides less load on the input stage, and a greater output is obtainable than from a triode operating at the same plate voltage. Where the single-stage multiplier may be used to double triple, or further multiply the input frequency, the push-push stage is usually operated only as a doubler. While it will also operate as a quadrupler (since only even harmonics can be produced with appreciable output), the same output can be more easily obtained with two single-stage doublers, which require slightly less than half the drive power. Thus, push-push operation is more limited in its application than the basic single-stage multiplier. It is mainly used where a large doubler output is required, since it will produce this output without any loss because of multiplication. This is true because a plate current pulse is provided for each positive half-cycle of the input signal, or one for each output cycle. Thus, the tank circuit requires less replenishing, and greater output and efficiency are obtained. Although a push-pull input is required, this can easily be obtained with a grid tank circuit. In addition, harmonics of odd order, which can sometimes cause a final output on an unwanted frequency, are minimized, and a purer output waveform is supplied than that by the single-tube doubler stage.

Circuit Operation. The accompanying illustration shows a typical push-push doubler stage.



Push-Push Frequency Multiplier Stage

As is evident from the schematic, a push-pull input is provided by r-d transformer T1. L1 is the primary, and L2 is tuned by split-stator capacitor C1 to the fundamental frequency. Signal bias is supplied by grid drive, causing grid current flow through R1, with RFC1 keeping any rf out of the bias circuit. A protective cathode bias is also supplied by R2, which is bypassed for rf by C2. Tubes V1 and V2 are pentodes with their suppressors directly grounded, although tubes having the suppressor connected to the cathode internally could also be used. Screen voltage for the tubes is dropped to the proper value by R3 and R4, which are bypassed for r-f by C3 and C4, respectively. The plates of V1 and V2 are parallel-connected to plate tank L3, C5. The secondary of r-f transformer T2, winding L4, provides an inductively coupled output, although capacitive coupling could have been used as well. Series plate feed is used, and the d-c plate voltage is applied through RFC2 to the bottom end of L3, which is bypassed for rf by C6. Thus, any rf at this point flows to ground through C6 rather than through the power supply filter capacitor, and any body capacitance effects which otherwise would occur when tuning tank capacitor C5 are also eliminated.

When the input signal is applied to input transformer T1, the input voltage in primary winding L1 induces a voltage into secondary winding L2 by transformer action. The center of the L2 secondary is connected to ground through RFC1 and R1. The windings are polarized so that the top end of L2 (connected to the V1 grid) is positive when the top end of L1 is positive. Thus, when the top end of L2 is positive, the bottom end of L2 is negative. Since the bottom end is connected to the grid of V2, V2 is negative when the V1 grid is positive, and vice versa. Thus, a push-pull input connection is provided. Tuning capacitor C1 is a split-stator type which provides a balanced tank arrangement to ground, and also resonates L2 to the operating frequency of the oscillator, or input stage.

In the absence of an input signal, protective cathode bias is provided by plate and screen current flow through R2. The cathode bias and the signal bias are effectively series-aiding, so that the total Class C bias is a combination of both. (See paragraphs 2.2.1. and 2.2.2 in Section 2 of this Handbook for a complete discussion of cathode and signal bias.) As the input signal is applied, either the V1 or V2 grid conducts on the positive half-cycle of operation, and grid current flows through R1, producing the signal bias, which is added to the cathode bias. Since only one tube conducts at a time, the cathode bias at any particular instant is produced essentially by only one tube. (When signal bias is absent both tubes will conduct, so the protective bias is produced by both tubes.)

On the positive half-cycle of input signal when V1 conducts, plate current flows for approximately 120 electrical degrees of operation. During the remainder of the cycle, tube V1 is cut off. When the input signal goes negative, a positive grid voltage is induced in L2 and applied to V2, while V1 is held at plate current cutoff by a negative signal. The positive grid input to V2 causes plate current to flow for a period similar to that of V1. Both plates are parallel-connected, so that a pulse of plate current occurs for each half-cycle of input signal. During current flow, the plate voltage is dropped across the high impedance of output tank L3, C5, which is tuned to twice the input frequency. Each time the plate voltage is reduced to its minimum value, energy is absorbed by the plate tank. Hence, it receives a push to keep it oscillating each negative half-cycle, from which action the term **push-push** was derived. Note that in push-push operation each tube operates alternately while the other tube remains at rest; this should be distinguished from push-pull operation, where the current of one tube increases while the current of the other tube decreases (both simultaneously).

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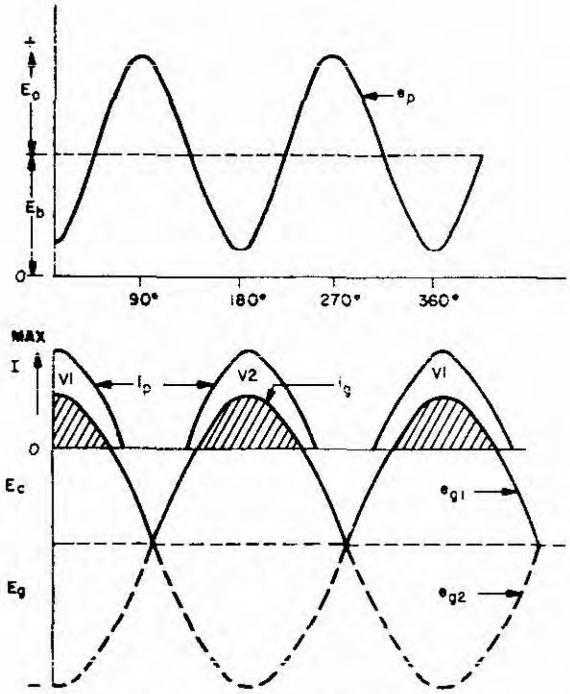


Plate and Grid Waveforms and Their Relationships

The relationships of the grid voltage and plate current, and grid current and plate voltage waveforms is shown in the accompanying figure. As the grid voltage (e_{g_1}) to V1 rises in a positive direction, it drives the tube above cutoff, and plate current flows. Plate current i_p, in flowing through the tank impedance at the resonant frequency, produces a voltage drop which opposes the applied plate voltage and reduces it toward zero. As the grid voltage continues to increase grid current flows when zero bias is reached, and develops a bias voltage across R1. RFC1 prevents shunting of the r-f input to ground through R1, so that only the rectified d-c bias current flows through R1. The current flow is from ground through cathode bias resistor R2, to the cathode, to the grid, and back through R1 to ground. The cathode bias is increased by the small amount of grid drive current, but this bias remains constant as long as grid current flows, and averages to a somewhat smaller value over the entire cycle. Because of the low value of cathode resistance employed, the over-all bias is enhanced by only a volt or two. Most of the bias voltage is developed across R1, which is a large value of resistance (10K to 50K). As the grid current reaches its peak, so does the plate current of V1. At this time the plate voltage of V1 reaches a minimum value, and power is absorbed by the resonant tank circuit. When the input signal reaches its positive peak and changes direction (assuming a sine wave), it swings negative and falls toward zero. Meanwhile, the plate current and grid current also fall. When the grid voltage drops below zero bias, the grid current stops flowing and the plate current continues to decrease, while the plate voltage increases still further. The plate voltage continues to increase, even at cutoff when the plate current ceases, because of the flywheel action of the tank circuit. At this time the tank is supplying energy to the circuit while the tube is inoperative.

When the input signal on the V1 grid reaches zero and continues further in a negative direction (the negative half cycle), a positive-going signal is induced on the V2 grid through T1. Thus, as the V2 grid rises above cutoff, plate current again flows, but this time in V2. The flow of plate current causes a plate voltage drop across the high tank impedance, and the effective plate voltage of V2 follows. At zero bias, grid current flows in V2 and produces a negative bias equal to that produced by V1 on the opposite half-cycle. When the grid current in V2 is at a maximum, so is the plate current, and the effective plate voltage is again at a minimum. As the input signal reaches its negative maximum and reverses direction it swings positive, as does the plate voltage. Simultaneously, V2 plate current decreases, first zero bias and then cutoff is reached, and V2 stops conducting. Meanwhile, since the tank circuit is oscillating in synchronism, the plate voltage continues to rise until the positive peak voltage is reached. At this time e_{g_1} and e_{g_2} are equal to bias voltage Ec and to each other, plate current is completely cut off and the tank is again supplying energy to the circuit. As e_{g_2} goes more negative, e_{g_1} goes more positive. When cutoff is reached V1 conducts again, and the plate voltage again drops toward its minimum value. At the plate voltage minimum, the plate current is again at its maximum value (as is the grid current), and the tank again absorbs power from the plate circuit. Since the tank oscillates in synchronism, completing one oscillation for each half-cycle of input, the output is twice the input frequency. *Because the tank is reinforced for each half-cycle of the input,* or once for each cycle of operation, not as much power is expended from the tank as in a single-stage circuit. The plate efficiency, therefore, increases over that of the single stage, since only half as much energy is expended by the tank, and less is absorbed from the plate. As the input signal continues, the action just described is repeated over and over again. Since L4 is inductively coupled to L3, the circulating tank current induces an r-f voltage in L4 by transformer action, and the output is approximately equal to the plate voltage drop developed across one tube. Any other harmonics in the plate circuit are offered a very small impedance, since the tank is not tuned to that frequency; thus, *only the desired harmonic frequency exists in the output.*

Although the pulses of plate current occur for only 120 degrees and are highly distorted, the flywheel action of the tank circuit tends to smooth the output into approximate sine waves at double the frequency. Since frequency multipliers are usually never modulated, any remaining waveform distortion is of little significance.

FAILURE ANALYSIS.

No Output. Lack of an input (drive) signal, loss of screen or plate voltage, an open output circuit, or defective tubes can cause loss of output. Check the plate, screen, and supply voltages with a voltmeter. For no output it is usually necessary for both tubes to be defective; if one tube is operative, the output will be reduced rather than eliminated entirely. If cathode bias resistor R2 is open, the circuit will be incomplete and no output can occur. If r-f transformer T1 or T2 is open or shorted, no output can occur. Lack of input (drive) is indicated by no bias voltage, as measured across R1. Likewise, no input will produce high plate and screen current because of the loss of grid bias, and thus cause the protective cathode bias voltage across R2 to be larger than normal. Similarly, if either RFC1 or R1 is open, no grid bias will be obtained, and R2 will produce a larger than normal protective bias with no output. When in doubt, a resistance check of L1, L2, R1, R2, and RFC1 with the power OFF can be quickly and easily made – or either an oscilloscope or a VTVM can be used to check the grids of V1 and V2 for rf. If no drive exists and C2 is shorted, the tubes will show color and be damaged (if the short is prolonged), while no output will be obtained.

If screen resistor R3 or R4 is open, or if capacitor C3 or C4 is open or shorted, there will be a reduction in output, but not complete loss of output; however, if both resistors are open or if both capacitors are shorted, no screen voltage will appear and there will be no output. If either C3 or C4 is shorted, R3 or R4 will heat abnormally, show color, or smoke, and will eventually burn out. If plate choke RFC2 is open, no plate voltage will be applied to either V1 or V2, and there will be no output. A similar condition will result if C6 is shorted; in this case the supply is dropped across the r-f choke, which will probably cause it to smoke and burn out. If C5 does not resonate L3 to the proper frequency, little or no output will be developed. Check L3 for continuity with an ohmmeter, with the plate voltage OFF. Use a grid dip meter or a wavemeter to check the tank resonant frequency. If the condition of C5 is in doubt, coil L3 must be disconnected checking C5 with a capacitance checker. If secondary L4 opens, no load will appear on either V1 or V2 and a lower than normal plate current will be indicated. L4 can be checked for continuity with an ohmmeter.

A milliammeter can be inserted in the grid and plate circuits to facilitate the location of trouble. It will indicate the grid current, which shows whether sufficient drive is present; it will also indicate the plate current, which can be checked for a dip (indicating resonance) and for proper loading. A sharp dip in the plate current with very low minimum current and no output indicates that the load is not coupled sufficiently or that the output circuit is open.

Low Output. No voltage or low voltage on the screen or plate, insufficient drive, or a defective tube will cause low output. The screen and plate voltages can be checked with a voltmeter; the grid drive can also be checked with a voltmeter by measuring the grid bias voltage developed across R1. If either R3 or R4 is open, no screen voltage will be applied to V1 or V2, respectively, and reduced output will result. Likewise, if either C3 or C4 is shorted, a similar condition will occur. Low screen voltage can be caused by a change in value of resistor R3 or R4, or by a leaky capacitor C3 or C4. A milliammeter inserted into the supply side of each screen resistor will indicate whether proper screen current is obtained. Inability to obtain the rated screen current at the correct voltage indicates a defective tube. If RFC2 is open or if C6 is shorted, no plate voltage will be applied to either V1 or V2. In this case the screen will tend to act as the plate, get hot, and eventually be damaged (if the condition is prolonged). A high resistance due to a poorly soldered joint in the plate circuit of V1 or V2 will cause reduced voltage and output, and will usually be indicated by broad tuning of tank capacitor C5, with low plate current. If the output is low and the voltages appear normal, remove one tube at a time, noting whether the output rises or drops. A partially shorted tube can cause the output to rise when the defective tube is removed. Normally the output should drop to about half value; if no change occurs, the removed tube is probably defective. When in doubt, replace both tubes with tubes known to be good, if possible.

Incorrect Output Frequency. If other than the desired output frequency is obtained, one of the tubes is probably inoperative. Since a push-push circuit can produce only even harmonics (2nd, 4th, 6th, etc), an odd harmonic can be produced only by single-tube operation. In this case the output will usually be reduced. Normally, the tank circuit does not tune through more than one harmonic. However, in multiband equipment using shorting switches to change the inductance, it is possible for a poor or open contact to allow the incorrect value of inductance to be used, and thus cause resonance at some undesired harmonic.

SINGLE-ENDED (CLASS B OR C) R-F AMPLIFIER.

APPLICATION.

The single-ended Class B or C r-f power amplifier is used universally as an intermediate r-f power amplifier (driver) stage, or output (final) amplifier for transmitters, and in special instances for test equipment. (Normally, receivers and test equipment use Class A amplifiers.)

CHARACTERISTICS.

Uses either Class B or Class C bias.

Output efficiency varies with bias; approximately 50 to 60 percent for Class B operation, and 70 to 75 percent for Class C operation.

Uses a tuned r-f tank circuit to develop the output frequency.

Is neutralized for triodes, but not for pentodes or screen-grid tubes.

Input frequency is usually the same as the output frequency.

Provides high output power and current gain.

Requires grid drive power equivalent to approximately 10 percent of plate output power, or less, depending upon type of tube used.

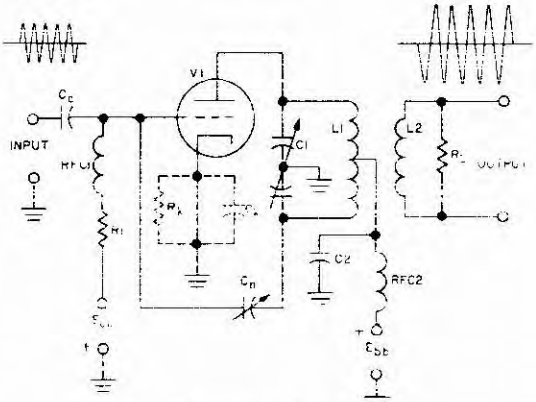
Normally uses fixed bias, but can also use self (signal) bias and protective cathode bias, or a combination of both.

CIRCUIT ANALYSIS.

The alternating component of plate current in a Class B r-f amplifier is proportional to the amplitude of the input (exciting) signal. Therefore, the power output varies as the square of the excitation (drive) voltage. Normally, in CW operation, maximum drive and maximum output are used. When used to amplify a modulated r-f signal, the output must vary linearly with the input so that no distortion is produced; also, the output varies in amplitude in accordance with the modulation. Consequently, for operation as a linear r-f amplifier, more stringent limits must be placed on bias, excitation, and plate voltage than for CW operation. In addition, to allow for the constant load and provide an overload safety factor, the stage is usually operated at a 20 percent reduction in rated maximum (CW operation) power. (Since the CW stage is keyed, it does not operate at full power continuously, and can therefore be used at the higher ratings without damage.) Other considerations which are applicable to the modulated Class B linear amplifier will be discussed at the end of this article, since slightly different operating conditions are necessary to provide for modulation amplitude increases.

The Class C r-f amplifier is similar to the Class B r-f amplifier, except that it operates at a much higher grid bias, it requires correspondingly greater excitation with more drive power, and it usually operates at higher plate voltage and current. As a result, greater output and efficiency are obtained. In the Class C stage the alternating component of plate voltage is directly proportional to the plate voltage (not the grid voltage as in Class B operation). Thus, the output power is proportional to the square of the plate voltage. This is why high-level modulators vary the plate voltage of the Class C r-f amplifier stage to produce amplitude modulation.

Circuit Operation. The schematic of a typical Class B or C triode r-f power amplifier is shown in the accompanying illustration.



Class B or C Triode R-F Power Amplifier

Although pentode, tetrode, or beam-power tubes could have been used in place of the triode, the triode is used here for ease and simplicity of discussion. Considerations involving other types of tubes will be discussed at the end of this article. The input circuit is shown capacitively coupled by Cc, although any other form of coupling could be used instead. Grid bias (in addition to bias from the fixed supply) is produced by the driving signal, which causes rectified grid current flow through R1; RFC1 prevents shunting of the drive signal to ground via R1. (Protective cathode bias is sometimes provided by cathode resistor Rk bypassed by Ck, and is shown in dotted lines since it may not be used. When it is not used, the cathode is connected directly to ground.) See section 2, paragraphs 2.2.1 2.2.2 of this Handbook for a complete discussion of cathode and shunt grid-leak (signal) bias. The tuned plate tank consists of C1 and L1, with output link coil L2 inductively coupled to it (capacitive coupling or another form of coupling such as a pi-network is sometimes used instead of L2). The plate voltage is series-fed through RFC2, which is bypassed by C2 for rf (shunt plate feed is also often used). This arrangement ensures that any rf at the center tap on L1 is bypassed to ground through the low-impedance path offered by C2 rather than the high-impedance path offered by RFC2 and the power supply filter capacitor. With the center of L1 grounded, both ends of the coil are at opposite and equal potentials. Split-stator tuning capacitor C1 maintains the balanced arrangement, and permits the rotor to be grounded in order to avoid body capacitance tuning effects (shunt plate feed permits the capacitor and coil to be directly grounded). A neutralizing voltage is taken from the end of the tank opposite the plate, and is fed back to the grid through capacitor Cn. In this plate neutralization method, Cn effectively forms part of a bridge circuit which balances out the plate-to-grid interelectrode tube capacitance and prevents feedback and self-oscillation of V1.

As is evident, the schematic is similar to that of a neutralized r-f voltage amplifier, which has been previously discussed in this section of the Handbook. The difference in operation is due to the use of cutoff bias, greater drive, and short pulses of plate current conduction, which provide greater power output. Class B and Class C amplifiers are discussed separately in the following paragraphs because of the differences in their operation.

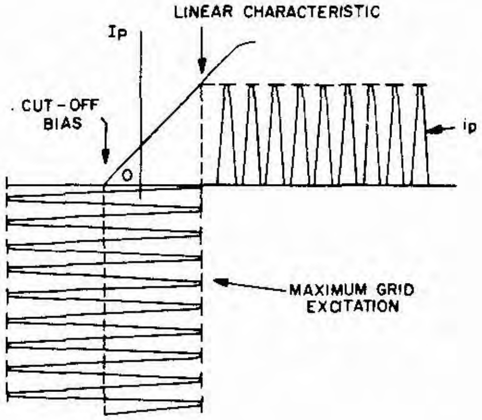
Class B Operation. Normally, V1 conducts for only a portion of a cycle, usually for 180 electrical degrees, but not less than 160 degrees (otherwise, the operation becomes Class C). The tube is supplied with energy from the tank circuit during the nonconducting portion of the cycle, which provides a so-called "flywheel effect" to keep the circuit oscillating despite the absence of plate current flow for the nonconducting half-cycle of operation. Thus, the r-f output is continuous and a steady output signal is maintained, as long as the key is down. (In Class B audio (untuned amplifier) operation, another tube is needed to supply the energy for the negative half-cycle.)

When the drive signal (r-f excitation) is applied through Cc, the grid of V1 is momentarily driven positive when the positive half-cycle of input signal exceeds the fixed negative bias voltage, and both plate current and grid current flow during this interval. Plate current flow is not continuous throughout the cycle, but is in the form of short pulses of energy, one for each cycle. During this time d-c grid current flows from ground to the cathode and charges Cc; when the input goes negative, Cc discharges through R1 back to ground. Electron flow is in the direction which makes the grid end of R1 negative, thus producing a signal bias. Radio-frequency choke RFC1 presents a high impedance to the exciting r-f signal and prevents it from being shunted to ground through R1. Thus, only the rectified d-c component of grid current flows through R1 to develop the bias. The amount of d-c grid flow is averaged over the complete cycle to provide a steady d-c bias voltage. This signal bias is in addition to the negative d-c fixed bias voltage, which is applied between R1 (or the grid of V1) and ground. The fixed bias automatically provides protection in the event that the grid drive is interrupted, so that complete loss of bias cannot occur. The total bias is the sum of both the fixed bias and the signal bias. Regardless of the type of bias employed, the operation is similar. Tube V1 does not conduct until the exciting voltage drives the grid above cutoff. Once above cutoff, plate current flows and increases as the grid voltage increases. Grid current does not flow until the grid-drive voltage reduces the total bias to nearly zero. From this point on grid current also flows, reaching its peak at the same time as the peak of plate current flow.

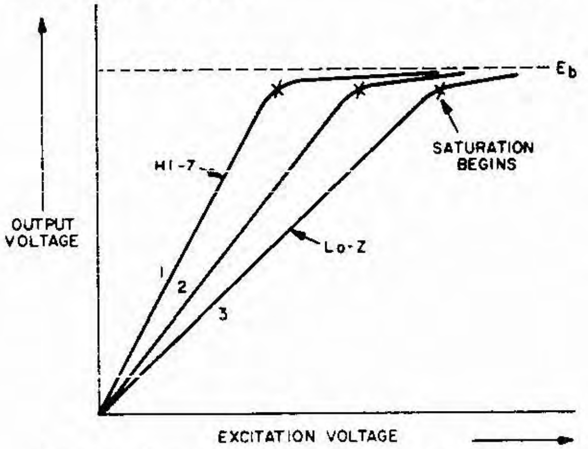
When plate current flows, the tuned tank circuit offers a resistive impedance at the frequency of resonance, which drops the effective plate voltage to its minimum value at the peak of the conduction cycle. At this time the tank circuit absorbs energy from the plate circuit. At the same time the plate is also dissipating some energy; this plate dissipation is at a minimum, since the effective plate voltage is at its minimum also, and maximum efficiency is obtained.

As the amplitude of the grid excitation now decreases toward zero and then swings negative on the following half-cycle, the grid bias is increased and the plate current is decreased. When the plate current decreases, the voltage drop across the load (or tank impedance) also decreases and the plate voltage rises. When plate current cutoff is reached, the plate voltage is just equal to the source. However, the circuit does not cease operation, since the tank circuit contains r-f energy which is now released to the load. From the moment of cutoff until current is again drawn on the next half-cycle of operation, the tank keeps supplying the energy. This is so-called "flywheel" action of the tank circuit. During this time (when no plate current flows) the tank circuit is completing its half-cycle of operation, and the instantaneous plate voltage continues to rise until the peak tank voltage is reached. The plate voltage at this point is higher than the source or supply voltage, but, since the tube is biased far below the point of conduction, it has no effect on V1. The tank circuit now swings negative and the plate voltage drops toward the d-c supply voltage. At the same time, the peak of negative grid swing is reached and the grid drive signal swings positive, thus reducing the total bias. Eventually, cutoff is passed and the tube is driven into conduction again. As the positive drive voltage increases, the effective bias decreases and plate current flow continues to increase. The plate current flow causes a voltage drop across the impedance of the load (or tank circuit), and the effective plate voltage is again reduced. Near zero bias grid current again flows, increasing to maximum at the peak of the drive signal, which corresponds with the point of minimum plate voltage. The cycle now repeats over and over again as long as the circuit is completed (key is held down).

The accompanying illustration shows the manner in which the plate current varies with grid voltage. The grid-plate transfer characteristie curve is assumed to be linear. Actually, there is always a slight amount of curvature near zero bias (the bottom) and near saturation (the top). Therefore, in linear operation the bias for "projected cutoff", which is slightly different than for actual cutoff, is employed, and any curvature near cutoff is neglected (it will produce only a small amount of distortion, which can normally be tolerated). As can be seen from the figure, the plate current is proportional to the drive signal amplitude up to saturation. After the saturation region is reached, the plate current will vary only slighly for a large change in excitation until full saturation is reached, at which point there is practically no change in plate current for any further change in excitation. This is shown more clearly in the following graph, which also indicates how linearity and saturation are affected by different load impedance in the plate tank. Note that in the first curve, produced by a high load impedance, it takes less grid excitation voltage to reach saturation than for moderate and low impedances, as shown in curves 2 and 3. The closer the curve is to saturation, the nearer the output voltage is to the plate voltage. The output voltage never equals or exceeds the plate supply



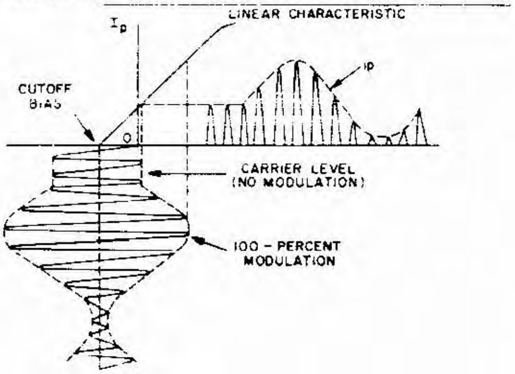
Grid Voltage and Plate Current Relationship for Unmodulated Class B Linear Amplifier



Saturation Curves, Showing Effect of Load Impedance

voltage, since the minimum plate voltage is always made greater than the peak value of the grid excitation voltage in order to prevent excessive grid current flow. If the positive grid were allowed to become greater than the effective plate voltage the grid would then act as a plate and tend to carry all the cathode current. Besides causing grid overload and damage to the tube structure, the plate current would actually be interrupted, which is the same as if the plate were driven negative at this time, and distortion would be produced. Recall that at the peak of grid swing the plate current is greatest and rf is being absorbed by the tank circuit; thus, an interruption of current at this point cannot be tolerated.

In CW operation it is unimportant whether or not the transfer curve is exactly linear, since no modulation is applied and maximum output with a usable waveform is all that is necessary. Any slight distortion due to nonlinearity is effectively swamped out by the effect of the tuned tank circuit, so that approximately a sine-wave output is always supplied. Even when driven into heavy saturation the plate waveform will be satisfactory, but more drive power than is needed will be used, and the driver tube may be overloaded. On the other hand, when a modulated signal is to be amplified, it is important that the characteristic curve be linear in order to retain the shape of the modulation without distortion. The following grid-voltage, plate-current curve shows the relationship when modulation is applied.



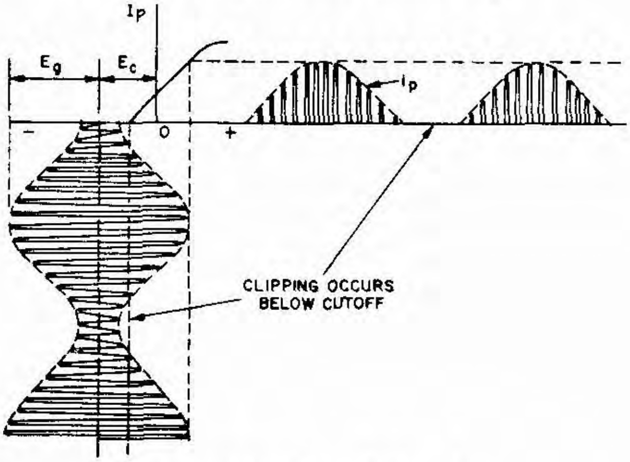
Grid-Voltage, Plate-Current Relationships for Modulated Class B Linear Amplifier

As long as the linear portion is not exceeded (the drive is adjusted correctly), no distortion exists. This is normal Class B linear operation. Should the drive be too low the output will be undistorted, but the full amplified power output will not be obtained and the efficiency will be lower than normal. Since the linear amplifier must provide four times the resting power for full 100 percent modulation capability, the carrier level is normally adjusted for half the maximum current with full excitation and no modulation. When the current doubles on the modulation peaks, the power output will vary as the square of this current, and produce a peak output four times normal. When modulated, the Class B r-f amplifier stage has stricter requirements. The grid bias must not vary with modulation; hence, only fixed bias is used and a constant plate voltage supply is required. Usually, the driver is larger than necessary for CW operation and the grid of the linear amplifier is loaded down with resistance to provide better regulation with a more nearly constant load on the driver. Since maximum plate dissipation occurs in the resting (or quiescent) condition, the efficiency at this point drops to about 33 percent, and reaches maximum efficiency at the peak of the modulating signal of about 65 percent. Since the peaks on voice modulation are of short duration, the total over-all efficiency drops (where in CW operation full power and efficiency are obtained constantly), so that a maximum of 50 to 55 percent is obtained under modulation. To ensure that the tube is not overloaded in the resting (quiescent) condition, lower plate voltage is used than for CW operation. Since Class C operation allows the amplifier to be driven harder and greater efficiency to be obtained, Class B linear operation is used mostly for amplifying low-level AM modulated signals. In the case of single-sideband operation, the linear Class B stage is the only type of amplifier suitable for producing undistorted amplication of the r-f sideband signal (Class C would cause distortion). Where the modulation is developed in the output (high-level modulation), the Class C amplifier is always used.

Class C Operation. The Class C stage is biased far beyond cutoff (2 to 4 times), so that the conduction occurs only over a range of 100 to 120 electrical degrees of the cycle. Since plate current flows for a shorter period of time, greater efficiency is obtained (the losses are less), reaching a maximum of 75 to 80 percent. The circuit is identical with that of the Class B stage, but higher plate voltage and more grid drive are required (the bias is much higher). During the nonconducting portion of the cycle, energy is supplied to the circuit from the tuned tank, just as in the Class B stage. The operation is identical except that the plate conduction period is shorter, and the output is no longer proportional to the amplitude of the excitation signal. Instead, the output is now proportional to the plate voltage. The r-f drive is kept constant at maximum amplitude in order to drive the tube to full saturation. The Class C amplifier is also linear, but with respect to plate voltage. If the plate voltage is doubled, the plate current is also doubled, and the power output is then four times normal.

In CW operation, maximum drive and maximum plate voltage are used to obtain a greater output. Because of the greater efficiency obtained, the power output of the Class C power amplifier for a given plate voltage is greater than that obtained from a Class B amplifier for the same plate voltage.

When a modulated signal is applied to the grid of a Class C amplifier, the amplifier conducts only while the signal is above cutoff, and a distorted plate output signal appears with part of the modulation cut off. This is shown graphically in the following illustration. On the other hand, if the modulation is applied in the form of an a-c plate voltage which alternately adds to and subtracts from the normal d-c plate voltage instantaneously in accordance with the modulation, then the modulation envelope will be reproduced without distortion, since the instantaneously varying plate voltage produces a varying output of similar waveform, as shown in the accompanying illustration.



Grid-Voltage, Plate-Current Relationships in a Modulated Class C Amplifier

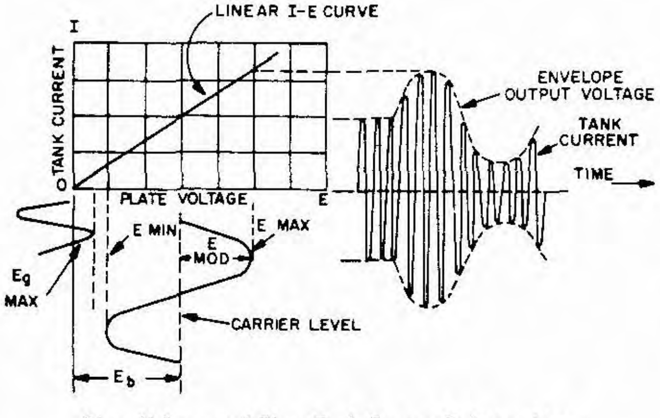


Plate Voltage and Plate-Tank Current Relationships in a Modulated Class C Amplifier

Note that the tank circuit current variations produce equal positive and negative swings so that a symmetrical output envelope is generated, and a minimum plate voltage greater than exciting voltage E_g always occurs. Thus, at no time is the grid voltage more positive than the plate voltage, and excessive grid current cannot flow. The following waveforms show the instantaneous voltage and current relationships in both the grid and plate circuits on the same time basis. Plate voltage variation is shown in part A of the figure, grid current and plate current variations are shown in part B and grid voltage is shown in part C.

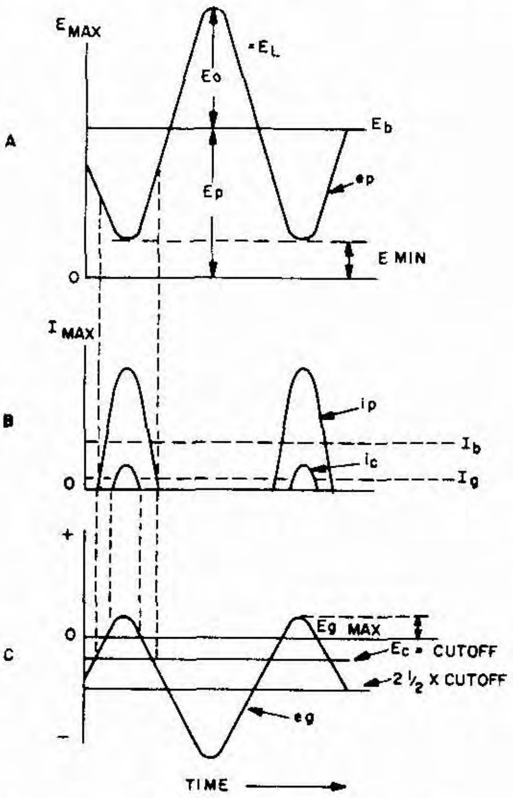
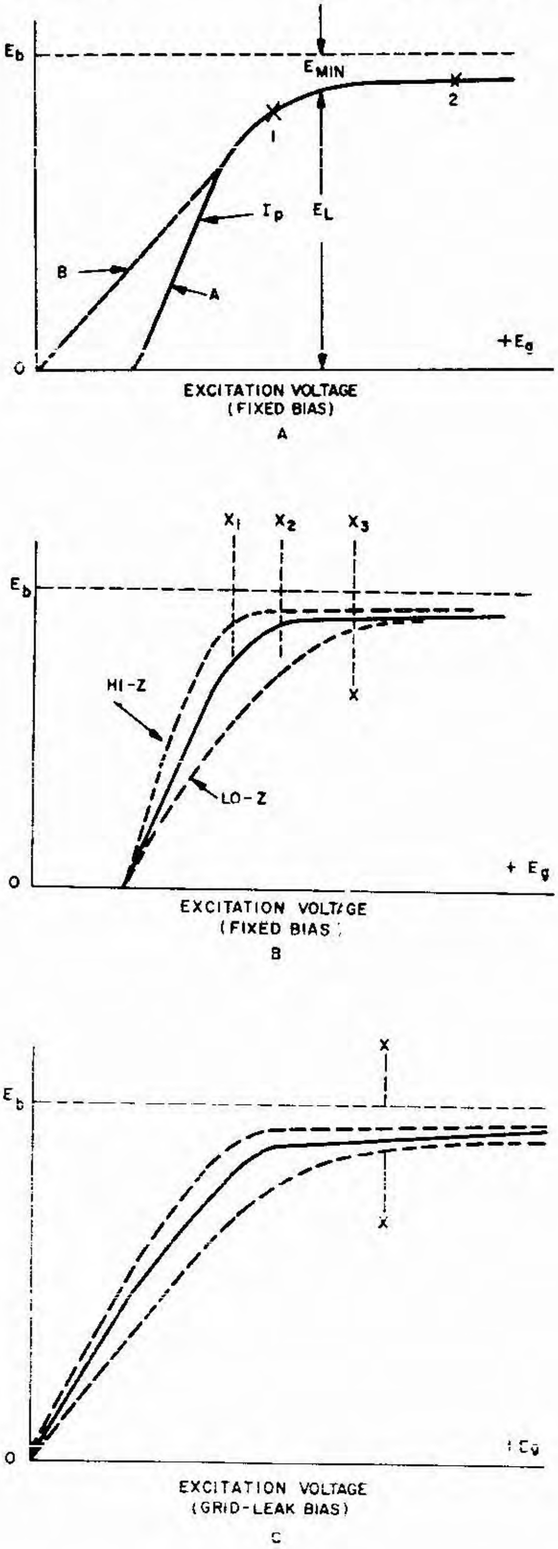


Plate and Grid Waveforms in Class C Operation

The grid bias is shown as E_c and the exciting or drive voltage as E_g. The supply voltage is E_b, and the a-c plate voltage drop across the load is E_l, which is also the output voltage, E_o. Note that E_{min} and $E_{g\,max}$ always occur simultaneously, and that all waveforms are sinusoidal since they are developed across tuned tank circuits. (If the grid circuit of V1 does not contain a tuned tank, the effect of the driver stage tank produces the same result.) The plate-current pulse is always much less than half a cycle, and grid current i_g flows only when the grid is positive. The total instantaneous cathode current is the sum of i_p and i_g (in a pentode the screen current is added). The average value of the plate-current pulse over a complete cycle is the direct current, I_b, which is drawn from plate supply E_b. Likewise, the average value of the instantaneous grid current, i_g, is the d-c grid current, I_g (averaged over a complete cycle). The plate input power is $I_b \times E_b$. The plate load impedance is connected in series with the plate supply to develop the desired output voltage when plate current pulses flow. The output magnitude is controlled by varying the coupling of the load to the tuned plate circuit. While the plate tank appears as a purely resistive load at resonance, the actual load is the antenna and associated transmission line. When matched, this combination is resistive also, but if not properly matched it may produce a reactive effect (either capacitive or inductive), and require that the plate tank be returned to resonance. This detuning will vary with the degree of coupling to the load. The division of energy between the tuned circuit and the tube is always proportional to the respective voltage drops across them. The drop across the tuned circuit (and reflected load represents useful r-f output, while the drop across the tube resistance represents a loss of energy which is dissipated by the plate as heat. This plate loss is equal to the instantaneous plate current multiplied by the instantaneous plate voltage ($i_p \times e_p$); except for the small amount lost in the resistance of the tank circuit, the plate loss represents the bulk of the inefficiency, which is usually not more than 25 percent.

The accompanying figure shows the saturation characteristics of a typical Class C amplifier for different values of bias and degrees of excitation. In part A the solid curve, "A", represents Class C operation, and the dotted curve, "B", represents Class B operation. The Class B stage is always operated between zero and point 1, where saturation begins. This region is linear; that is, the output varies directly with the input. The Class C stage, however, is always operated to the right of point 1, and usually around point 2, which is in the heavy saturation region. Thus, no current flows until sufficient excitation exists to drive the tube into conduction. As the drive is increased, the current also increases quickly to light saturation at point 1. From point 1 to point 2 there is not much increase in plate current with an increase in drive, and beyond point 2 there is practically no change at all. This is the normal operating point at heavy saturation, and represents the most efficient operation. While below point 1 the output will vary with the input, it is not linear and much distortion will be produced. In part B, the start of saturation is indicated for various values of loading. The high-impedance load at X_1 will require less drive than that at X_2 for the medium-load impedance, and much more drive is needed to reach X_3 with a low-load impedance. In each of these cases the operation is still Class C, but the plate currents, minimum plate voltages, and drive power required are all different. A small tuning capacitance (lo-C) is used to produce the high-impedance condition, while a large tuning capacitance (hi-C) is used for the low-impedance condition. The hi-C tank will also have more losses because of heavier circulating current, and, since the minimum plate voltage is also



Comparison of Saturation Characteristics of Class C Amplifier higher, the output voltage will be less and the efficiency will be at its lowest value. Part C of the figure shows the effect of grid-leak bias on saturation. In this case, the operation is always set at point X to avoid distortion, loss of efficiency, and reduced output. Since the grid bias will vary with the amount of excitation, a low drive current will change the operation into the Class B region, or somewhere between Class B and Class C, with reduced output and distortion.

Thus, it can be seen from the figure that full saturation is always required in a Class C amplifier to prevent any change in drive from affecting the output. With a saturated drive, a larger output can be obtained only by increasing the plate voltage.

Other Considerations. Beam power, pentode, and screen grid tubes are generally used instead of triodes because they require less drive and a larger output can be developed. Also, the screening effect of the screen grid provides reduced grid-plate capacitance and minimizes feedback, so that oscillation will not usually occur, and no provision for neutralization is required. Thus, an over-all saving in parts is obtained. Since the plate is farther from the grid than the screen, it is important to keep the screen voltage higher than the excitation; otherwise, the grid current becomes excessive. However, the minimum plate voltage can now be made lower, and a larger plate swing obtained. The limiting factor is usually the screen voltage, since if the plate voltage were made much lower than the screen voltage the screen would have a greater attraction for electrons which should go to the plate, and the screen would tend to act as the plate.

At high frequencies, where the transit time becomes an appreciable portion of the cycle, the pulses of plate current are lengthened and distorted, causing reduced output power and lower efficiency. Electrons which are in transit when the negative part of the cycle occurs are driven back to the cathode, and cause a heating effect which can result in damage to the cathode. In addition, extra driving power is required because of power lost in the grid circuit. As a result, different tube designs have been developed to eliminate or at least reduce these effects. As the frequency increases, interelectrode lead inductance and capacitance limit the highest resonant frequency obtainable with grid or plate tank circuits. Lead losses increase and lower the highest value of impedance which can be obtained with reasonable efficiency. Hence, transmission lines are used instead, and grounded-grid circuits are employed to minimize external coupling between the grid and plate circuits, and to reduce feedback within the tube.

The application of modulation and its effect on amplifier operation and performance have been mentioned at appropriate points throughout this circuit discussion. For further information, the interested reader is referred to Section 14 in this Handbook, where the subject is covered in detail.

FAILURE ANALYSIS.

No Output. An open or shorted input or output circuit, a defective tube, or lack of supply voltage can cause a no-output condition. If coupling capacitor C_c is open, no grid drive will be obtained. No current will be indicated on the grid meter, and the plate meter will also read zero, since the fixed bias will keep the tube beyond cutoff. An open grid choke, RFC1, or grid resistor, R1, will remove the bias from V1; in this case sufficient plate current will be drawn to blow the plate fuse or supply breaker. Such a condition cannot occur where cathode bias is supplied by R_k, since the tube current will be limited by the cathode resistor to a safe value. If either plate choke RFC2 or tank coil L1 is open, or if bypass capacitor C2 is shorted, no plate voltage will be applied to V1 and an output cannot occur. The open-circuit condition will be indicated by no plate meter reading, while the short-circuit condition will be indicated by an off-scale deflection of the meter and the blowing of the plate fuse or supply fuse. If output coil L2 is open, no output can be obtained; the grid meter indication will be normal, with a low plate meter indication. If tank capacitor C1 is shorted, high plate current will be indicated and a blown plate fuse will result; on the other hand, if C_1 is open, a minimum plate current dip at the usual resonance position will not be obtained, and the plate current will most likely be high since the circuit is out of resonance. When driven to full saturation, detuning of the tank circuit off-resonance will usually cause excessive plate current (two or three times the normal value). Leaving the tank detuned will probably cause the plate fuse or breaker to open. This is normal, and is due to improper operation rather than a circuit failure. If neutralizing capacitor Cn is shorted, full plate voltage will be applied to the grid of V1, excessive plate current will be indicated, and the fuse or breaker will open.

Where trouble is indicated by high or low meter readings, the bias and plate voltages can be checked with a voltmeter, to be certain they are present and correct. Open circuits indicated by zero current can be checked for continuity, with the POWER OFF and the filter capacitors discharged, using an ohmmeter. Be certain to observe all safety precautions. Since the voltages used in the grid and plate circuits of transmitters are usually very high and extremely dangerous, your first mistake may be your last! Replace any suspected tubes with ones known to be good.

Reduced Output. Low bias or plate voltage, as well as improper drive, will cause reduced output. In modulated amplifiers, lack of sufficient filament emission or inability of the power supply to furnish full peak current will also cause a reduction in the output, with distortion. Bias and plate voltages can be measured with a voltmeter. When measuring d-c voltages in r-f circuits, inaccuracies and meter burnout can occur if sufficient r-f filtering is not employed. It is the usual practice, therefore, to measure the voltages on the d-c side of the circuit, and rely on continuity measurements in the r-f circuit, using plate and grid current meters and, when available, r-f tank current meters to indicate when the circuit is operating properly. Usually, low bias should be suspected when both grid and plate currents are larger than normal, and the tube plate shows excessive plate dissipation. Insufficient drive is usually found by noting that the grid current is below normal. With normal grid current, low plate current indicates either low plate voltage, improper load, or a weak tube. Under certain loading conditions where excessive reactance is reflected into the circuit, tuning for minimum dip may reveal that the dip is very broad or hardly noticeable. In this case, the tuning should be adjusted for maximum r-f output as indicated on a thermocouple meter.

When tubes other than triodes are used, the screen voltage becomes important in determining the plate current and hence the output. Make certain that the proper screen voltage is applied, and that normal screen current is obtained. Inserting a meter in the screen circuit (when a meter is not provided) will enable a more certain check of the operation. Normal screen current indicates that the trouble is elsewhere. Low screen current indicates insufficient drive or screen voltage, while high screen current usually indicates high screen voltage or a defective plate circuit. Maximum screen current at the point of minimum plate current is normal, provided that it does not exceed the rated value.

Reduced output is sometimes due to trouble in the antenna or transmission line; therefore, it is always good practice to use a dummy load when checking out the transmitter to make certain that the trouble is not outside the unit. A rough check on tube emission can be made by temporarily detuning the plate tank and immediately returning it back to the proper setting, meanwhile observing that the plate current increases considerably. If held off resonance too long, it is possible to damage the tube. Where the tube is normally operated so that there is no trace of color, and a reduced output is obtained with color showing on the plate, a loss of efficiency is indicated, most probably involving bias and drive.

In equipment where a C battery is used to supply the fixed bias, the battery voltage should be measured with the equipment inoperative; the battery should be replaced when its voltage drops below 15 percent of the rated value.

In triode amplifiers, improper neutralization can cause reduced output and erratic operation. The neutralization should be checked when reduced output is obtained with greater than normal plate current indication, usually accompanied by increased plate dissipation. The same symptom is also possible when parasitic oscillations exist either at low frequencies or at extremely high frequencies. This should not occur in properly designed and tested Naval equipment, but sometimes will occur in off-the-shelf commercial procurements, or after repair and replacement with a part having a slightly different value. In this case a wavemeter or grid-dip meter will indicate the frequency of the undesired parasitic oscillation. If low-frequency parasitics exist, the bias and plate r-f chokes and bypass capacitors will usually be at fault (they form a tuned tank at that frequency). If high-frequency parasitics exist, they are usually easily eliminated by installing parasitic suppressors in series with the plate lead, between the plate and the tank circuit (the closer to the plate connection at the tube, the better).

Distortion. In CW operation any distortion that exists will be in the form of harmonics; usually, only the 2nd or 3rd harmonics are of great enough amplitude to be of any importance. In this case, besides wasting some useful output, they may radiate at frequencies which may interfere with other services. Placing a low-pass filter between the transmitter and the antenna will eliminate any unwanted harmonic radiation. A reduction of the bias and drive, plus an increase in the tank circuit Q, will also minimize this type of distortion. (This is not to be considered as authorization to make unapproved changes in the equipment, but is discussed in case such conditions are encountered in the field.) When modulated, nonlinearity of the transfer characteristic and improper bias or drive will cause a distorted modulation envelope. The waveform may be observed on an oscilloscope (use an r-f probe or connect directly to the plates); adjust the equipment so that the values used are those which eliminate the distortion. It is also important to determine that the modulation is not distorted before being applied to the amplifier suspected of being at fault. Normal oscilloscope checks will reveal the cause (compare with typical faulty waveforms).

PUSH-PULL (CLASS B OR C) R-F AMPLIFIER.

APPLICATION.

The push-pull Class B or C r-f power amplifier is used universally at high frequencies as an intermediate (driver) stage, or as the final output stage for transmitters, where a large output with reduced second harmonic distortion is required.

CHARACTERISTICS.

Uses either Class B or Class C bias. Fixed bias is normally used, but self bias (either signal or cathode bias) may also be used; sometimes a combination of both types of bias are used.

Uses a tuned r-f tank circuit to develop the output frequency.

Output efficiency varies with bias; approximately 50 to 60 percent for Class B operation, and 70 to 80 percent for Class C operation.

Triodes require neutralization, other tube types do not.

Input and output frequencies are usually the same.

Provides high output power and current gain.

Requires approximately twice the grid-drive power of the single-ended stage, and a push-pull input.

Second harmonic output is considerably reduced or eliminated.

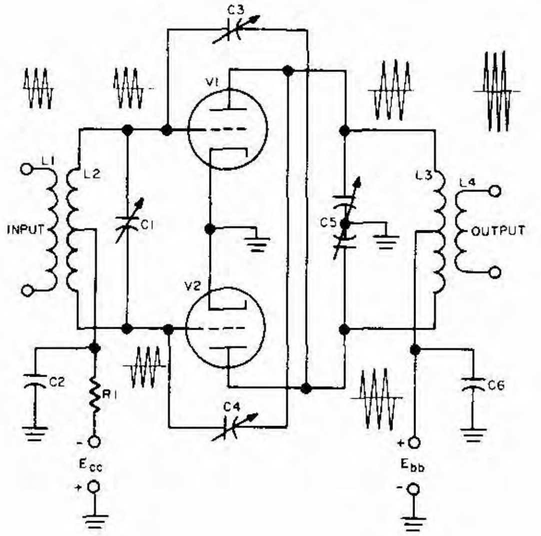
Input and output capacitance is half that of the single-ended stage.

CIRCUIT ANALYSIS.

General. In the push-pull configuration, the input and output capacitances of the tubes are effectively connected in series. Therefore, only about half the normal grid and plate tuning capacitance is required for a specific frequency. Consequently, high frequency tanks are easier to construct and use of this type of circuit is more prevalent on the higher frequencies (above 30 mcs) although it can be, and is, used on the lower frequencies. The push-pull grid input also provides a step up of input impedance of about four times over that of a single tube. Thus it is easier to drive the push-pull amplifier, since the driver stage can be more easily matched. Because two tubes are driven, twice the drive power of a single-ended stage is required. It should be noted that the Class B or C power amplifier although connected in push-pull, does not actually operate in push-pull fashion like the Class A stage. That is, instead of increasing the current of one tube while simultaneously decreasing the current of the other tube (the action from whence the name push-pull was derived), each tube operates separately. Operation occurs only during the positive portion of grid swing when the drive exceeds the bias, and plate current flow is cut off during the negative portion of the cycle as the tank circuit supplies the output. While not operating in true push-pull fashion, this circuit retains most of the advantages of the basic circuit. Since the individual plate load is one quarter the total load, low impedance triodes can be used to develop a high power output. And, although the second and even harmonic content is not cancelled out in the primary of the r-f output transformer, the even harmonics are eliminated in the output circuit (the secondary). The push-pull connection also affords a slight increase in power output; normally, 2-1/2 to 3 times the single tube rating can be obtained, particularly in unmodulated operation (CW). When triode type tubes are used, their large grid-plate capacitance causes feedback, and the circuit tends to operate like a tuned-grid, tuned-plate oscillator; therefore, triodes are always neutralized. The pentode, tetrode, or beam power tube types normally do not require neutralizing because of reduced interelectrode capacitance and better shielding. However, arrangement of components is sometimes such as to permit external coupling (particularly at high power and at high frequencies) and neutrulization is then necessary.

Although cutoff bias is required, cathode bias may be used since one of the tubes is always conducting (both conduct alternately). However, since the push-pull circuit is a balanced circuit is a balanced circuit, it is usually easier to apply a fixed negative bias and avoid selecting or matching the tubes to get equal currents. Since grid current is always drawn, a grid leak resistor is usually connected in series between grid and ground to provide some signal bias, and reduce the voltage requirement on the separate C-bias supply.

Circuit Operation. The schematic of a typical triode push-pull r-f power amplifier is shown in the accompanying illustration. The triode is used for ease of explanation. Considerations for screen grid and other type tubes will be discussed at the end of this article.



Triode Push-Pull R-F Power Amplifier

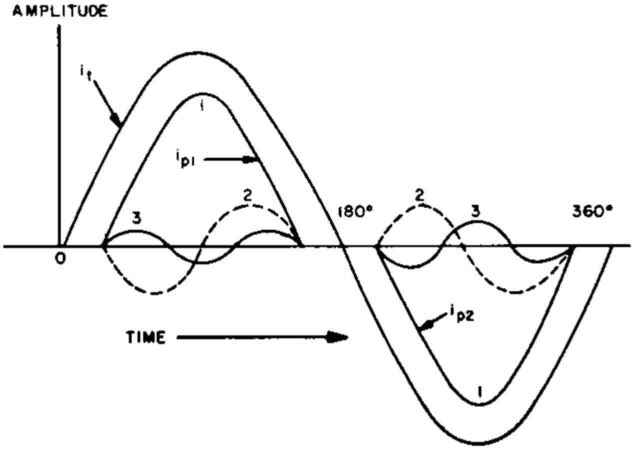
Coil L1 couples the output of the driver stage to tuned input circuit L2, C1. Grid bias is supplied to a tap on L2 from a fixed bias supply, supplemented by signal bias provided by R1, and bypassed for rf by C2. The cathodes of V1 and V2 are grounded, and the plate tank consists of split stator capacitor C5 and coil L3; the output is inductively coupled through L4. Cross neutralization is provided, with the plate of V1 coupled through neutralizing capacitor C4 to the grid of V2, and the grid of V1 coupled to the plate of V2 by neutralizing capacitor C3. Series plate feed is used with the supply tapped to the center of tank coil L3, and bypassed by rf by C6.

With a fixed negative bias applied to the center tap on L2 from the separate negative bias supply, the grids of tubes V1 and V2 are biased far beyound cutoff (about 2-1/2 times). In the absence of excitation, both tubes are cut off, no current flows and no output is obtained. When r-f excitation is applied to coil L1 a similar r-f voltage is induced in tank coil L2. Since the center tap of L2 is bypassed to ground for rf it is effectively at r-f ground potential (zero voltage) and the ends of the coil to which the grids of V1 and V2 are attached are at equal and opposite r-f potentials. When a positive voltage appears on the grid of V1, a negative voltage appears at the grid of V2. With a balanced input the voltages are of equal amplitudes and of opposite polarities. Grid tank capacitor C1 tunes the input tank to resonance at the frequency of the drive voltage. The maximun current flows in the closed tank circuit, and maximum drive voltage is developed across the parallel-connected tank and applied to the grids. Assuming a sine wave exciting signal going positive on the grid of V1, the grid of V2 is driven further negative into cutoff and no plate current flows in V2. As long as the signal on V1 grid is below the cutoff level no current flows in V1 also, and both tubes remain cut off. As the positive-going input signal rises above the bias level on V1, the tube is eventually driven into conduction, and plate current flows. Since the tubes are fixed biased *beyond cutoff, plate current flows only during the time the* grid is above cutoff, or for about 120 degrees of the positive half cycle of excitation signal. As the positive grid voltage increases, plate current increases, reaching its peak at the same time the excitation voltage reaches its crest. At the beginning of the conduction cycle the grid voltage is only sufficiently positive to reduce the fixed bias voltage so that the effective bias is just above cutoff (but still negative). However, as the amplitude of the drive voltage increases, the grid is driven to the zero bias level and then positive. At or near zero bias grid current also begins to flow, increasing to its peak value at the crest of the cycle. Grid current flow is from the cathode of V1 to the grid, through coil L2 and the center tap to grid resistor R1, then to the bias supply and ground. In flowing through R1, a negative voltage is developed across R1 which adds to the instantaneous bias. The value of R1 is chosen so that the maximum desired bias is produced with a specified grid current drive before the crest of the cycle is reached, with light saturation for Class B amplifiers, and with heavy saturation for Class C amplifiers (see Single-Ended (Class B or C) R-F Power Amplifier circuit in this section of the Handbook for an explanation of saturation, and Section 2, paragraph 2.2.2 for a discussion of signal bias).

When plate current flows in V1 there is a flow of electrons from the cathode through the grid wires to the plate, and from the plate through the top half of tank coil L3, out the center tap to the plate supply and ground. Current flow through half of L3 produces an electric field around the coil (which acts as the primary of a transformer), and the magnetic lines of force link output coil L4 (which acts as the secondary) inducing an output voltage in it. At the same time, the field around the lower half of L3 induces a voltage which is in a direction to continue current flow through L3. This induced current charges the lower half of split stator capacitor C5 negatively, while the upper half of the capacitor is charged positive. The effect is the same as if the split capacitor were a single capacitor connected across L3 with the upper plate positive and the lower plate negative. Since tank L3 and C5 are parallel resonant at the output frequency, a circulating current is built up within the tank which continues to oscillate back and forth. Reinforced first by V1, and then by V2 as it operates. The resonant tank selects the desired output frequency and discriminates against any harmonics which also tend to develop across the tank impedance. The tank impedance is a maximum at the fundamental output frequency and very low at any of the harmonic frequencies. Thus maximum voltage is developed *across the maximum impedance presented at the desired* fundamental frequency. The tank coil also acts as a tapped autotransformer with a turns ratio of one half to one (2 to 1). Since transformer impedance always varies as the square of the turns ratio, it presents a load impedance to the single tube of one quarter the plate to plate load impedance. At the positive crest of the drive cycle the voltage drop across the tank impedance is maximum and *causes the effective plate voltage to be at a minimum* value. At this time the tank is absorbing, or being charged with r-f energy, and only a small amount is applied to the plate for dissipation in the form of heat. This is the most efficient part of the operating cycle.

As the excitation voltage passes the crest and reduces the amplitude it becomes negative going. The effective bias becomes more negative and plate current flow is reduced. This action continues until zero bias is reached and grid current flow, likewise, reduces and ceases. From here until cutoff the plate current continues to reduce, and ceases when cutoff bias is reached. While the plate current is reducing, it induces a tank current flow in the opposite direction causing the tank capacitor to discharge. This discharge continues beyond cutoff when both V1 and V2 are non-conducting, and is the so-called "flywheel" effect of the tank, which continues to supply an r-f output even though neither tube is operating. When the positive half cycle of drive is completed, the negative half cycle starts, the grid of V1 is driven further into cutoff and is held inoperative for the remaining portion of the half cycle.

V2 grid is now being driven positive by the negative half-cycle of input signal. (The input signal is inverted by the push-pull input tank.) During the negative half-cycle, tube V2 is made to operate exactly as described above for V1. The effective bias is reduced until plate current flows, and as the bias decreases grid current flow starts near zero bias, reaching its peak at the negative crest of the drive signal (the grid voltage applied V2 is positive). Plate current flow through V2 and the lower half of the tank coil, now flows in the other direction and charges C5 in the opposite direction to the previous half-cycle of operation. Actually, operation is only over 120 degrees as mentioned before, and the tubes are quiescent over 60 degrees of the 180 degree half-cycle. Thus it can be said that the tank alone supplies energy for a total of 120 degrees, and the tubes for 240 degrees out of a single cycle of operation. Operation of V2 is identical in every respect with that of V1, their currents and voltages are, however, 180 degrees out of phase, but there is no canceling effect since each tube operates separately. The tank circuit, meanwhile, continues to oscillate first in one direction for 180 degrees and then in the other direction for the remaining 180 degrees of the complete cycle, being reinforced each half-cycle by a different tube. Output coil L4 supplies a continuous r-f output to the antenna or transmission line from the tuned tank circuit to which is is inductively coupled. Since the tank is tuned to the fundamental frequency, even harmonic content is almost entirely cancelled in the secondary (L4) since equal and opposite voltages are produced. The closer the circuit is to a balanced condition the more nearly is the even harmonic output reduced to zero. Since the odd harmonics occur in-phase a small amount also appears in the output. The amount is dependent upon the impedance the tank presents to odd harmonics. Usually it is so small as to be considered negligible. However, in extremely high powered stages (megawatts) this output may be on the order of tens of watts (or more) and require extra filtering to prevent it from being radiated on the undesired harmonic frequency. The manner in which the tank current and the fundamental and harmonic plate current components vary is shown in the accompanying figure to illustrate the manner in which the even harmonics are cancelled.



Tank Current versus Fundamental and Harmonic Plate Currents

The instantaneous tank current it varies continuously throughout the cycle flowing first in one direction (shown as positive) and then flowing in the opposite direction (shown as negative). During a portion of this time ip1 and ip2 (curve 1) flow alternately as V1 and V2 operate. Any second and third harmonic currents flow as shown in curves 2 and 3, respectively. Since the second harmonic current is always out-of-phase with the fundamental plate current it cancels out. The third harmonic current (curve 3) in in-phase more than it is out-of-phase, therefore, a small amount of odd harmonic distortion remains in the output. The selectivity of the output circuit also helps discriminate against any harmonics, since the impedance it offers to these frequencies determines the output amplitude, and most output circuits are resonant at the fundamental frequency.

With the grid V1 and V2 cross connected to the opposite tube plate through neutralizing capacitors C3 and C4, equal and opposite feedback voltages are applied which cancel out any in-phase plate to grid feedback and prevent the stage from going into self-oscillation. The additional capacitance added by the neutralizing circuit reduces the input impedance, hence, triodes are only used when necessary, or the push-pull grounded-grid circuit is used instead. The use of a well shielded tetrode or pentode makes neutralization unnecessary, because the plate and grid are shielded from each other by the screen grid and its associated bypass capacitor, which holds the screen at r-f ground potential. The low excitation requirements of the tetrode or pentode makes them especially suitable for use in the intermediate stages of a transmitter. When the power used by the screen grid is considered, however, the overall efficiency of these tubes is not as great as the triode. Because of the easier drive requirement and the lack of neutralization provisions, the tetrode, or beam power tube is generally favored over the triode. Particularly in band-switching transmitters where a neutralizing adjustment is not required for each band.

FAILURE ANALYSIS.

No Output. Loss of excitation (drive), bias, supply voltage, or defective tube(s) can cause a no-output condition. If input coil L1 is open, no drive will be obtained and the tubes will rest in the cutoff condition. Lack of both grid current and plate current will be indicative of this condition. Check L1 for continuity with the POWER OFF. If drive is present in L1, but L2 is open, or C1 is shorted or nonresonant, a similar condition will exist. If L2 is open the symptoms will be the same as when L1 is open. However, if C1 is shorted no drive will appear on V1 or V2 grid and the fixed bias supply will be grounded through R1. Usually extremely heavy grid current will flow and R1 will heat, may smoke, and will eventually burnout if the condition is prolonged. Meanwhile, the plate current will also be extremely high because of loss of bias and will usually blow the plate fuse or open the plate circuit breaker, if provided. The same symptoms will occur also if grid bypass capacitor C2 is shorted. Check V1 and V2 grids with a voltmeter for the proper negative bias. If L2 is not open and C1 or C2 is not shorted the proper d-c bias will appear on both tubes (make this check with driver plate voltage OFF, otherwise, r-f drive may burn out the meter). If C1 is not tuned to resonance, sufficient drive may exist to produce a low output, but normal loading and output will not be obtained. Normal bias voltage aslo indicates that both neutralizing capacitors C3 or C4 are not shorted. When either C3 or C4 are shorted, plate voltage will be applied to the grids of both V1 and V2, cause heavy plate current, and blow the fuse or breaker.

When the loss of output is caused by lack of plate voltage it may be due to shorted plate bypass C6, a defective power supply, shorted tank capacitor C5, or defective tube(s). Check the supply voltage first with a voltmeter, be certain to observe all safety precautions since the plate voltage is dangerously high. Make certain that the transmitter plate switch is OFF when checking the supply. If either C5 or C6 is shorted and the supply is good the plate fuse or breaker will operate, and high plate current with normal or slightly higher than normal grid current indication will be obtained momentarily. Usually C5 can be checked visually since arcing will occur as the rotor is varied throughout its range and whenever it touches or moves too close to the stator. If not, make certain the plate voltage is removed, and use a shorting stick to discharge the capacitors in the plate circuit. Disconnect plate bypass capacitor C6 and check continuity to ground with an ohmmeter, no continuity should exist and the resistance should be infinite. Then disconnect C5 and L3, and again check for continuity to ground. With the tank disconnected check the plates of V1 and V2 to ground; any resistance other than infinity probably indicates a defective tube. Note: be certain to observe the polarity of the ohmmeter so that a negative potential is applied from plate to ground. Otherwise, if the plate is made positive and the tube filament is operating there will be a flow of current, and a false resistance-to-ground reading will be obtained.

Check output coil L4 for continuity at the same time to avoid making a later check. Where the tube(s) are suspected, replace them with tubes known to be in good operating condition.

If proper grid current indication is obtained, but a very low plate reading (or a high plate reading) rapidly tuned C5 back and forth to determine if a minimum dip indicating resonance can be obtained. With a sharp minimum and a reduced plate current either L4 is open, and load is not connected, the drive is too low, or L4 is not coupled sufficiently close to tank coil L3. In the case of heavy plate current and broad dip, usually some output will be obtained, and too large, or an overcoupled load is indicated.

Use of grid and plate meter indications, plus the tuning of C1 and C5, should be made to determine whether normal currents and tuning are obtained, since these offer a quick means of trouble-shooting. In most instances, moderate and high power transmitters and tanks are constructed mechanically and electrically rugged so that visual observation will locate grounded parts (usually some sign of an arc such as charred insulation or a black spot will mark the point of improper grounding due to the high voltage and currents involved).

In the event of tube trouble, usually both tubes must be defective to cause no output in a push-pull circuit, since the stage is capable of operating at reduced output with only a signel tube. In this case, replacing each tube separately and then rechecking operation each time will determine which tube was not operating.

Reduced Output. Low drive, grid bias, or plate voltage, as well as a defective tube can cause a reduced output. Low drive will be indicated by a low grid current reading usually with reduced plate current, and output. Low grid bias will usually cause operation in the Class A or AB region with a higher than normal plate current. Check the bias with a voltmeter from the junction of C2 and R1 to ground; this will indicate the sum of both the fixed bias and the signal bias, and should be made with C1 tuned to resonance and normal grid current. Closer coupling between L1 and L2 will increase the drive if necessary. If the plate current suddenly increases and the output reduces, particularly during voice modulation (or while being keyed off and on), improper neutralization can be suspected. Remove the plate voltage and tune tank capacitor C5 through resonance, the grid current indication should hardly change as resonance is passed. If it flicks sharply, adjust C3 and C4 in small increments, simultaneously, first in one direction and then in the other. No change in grid current will be observed at the point of proper neutralization.

Normal plate voltage and loading accompanied by reduced plate current indicates the possibility of low tube emission. Substitute two known good tubes to eliminate the tubes from suspicion. If plate voltage is low with normal load the power supply rectifiers are probably in need of replacing. A dynamic check on the power supply can be made by quickly detuning and resetting C5 to resonance. The heavy off-resonance current should not cause the plate voltage at C6 to drop more than approximately 25 or 30 volts. If it does, the power supply regulation is poor. A poor soldered joint or bad connection can introduce a high resistance in the plate circuit and cause a reduction in applied plate voltage with a low plate current indication. To check this, remove plate voltage from the driver AND final, discharge the filter capacitor with a shorting stick, and check the resistance between the tap on L3 and the plates of V1 and V2. Indication should be zero or a few tenths of an ohm.

MULTICAVITY KLYSTRON R-F AMPLIFIER.

APPLICATION.

The multicavity klystron r-f amplifier is used to supply high r-f power to the transmitting antenna of television, radar, microwave, and electronic counter-measures equipment operating in the VHF, UHF, SHF, and EHF regions.

CHARACTERISTICS.

Uses a positive grid voltage.

Uses a number of cavities tuned to the same frequency for narrow-band operation (synchronous tuning), or is stagger-tuned to different frequencies for wide-band operation.

Power gain is on the order of 30 to 50 db.

Power-handling capabilities range from microwatts in receiving or test equipment applications, to the tens of megawatts in transmitting applications.

Efficiencies of 40 to 50 percent are possible.

Uses velocity modulation of an electron beam to form electron bunching for amplification.

Each cavity provides additional amplification, and extremely high gain is thus obtained.

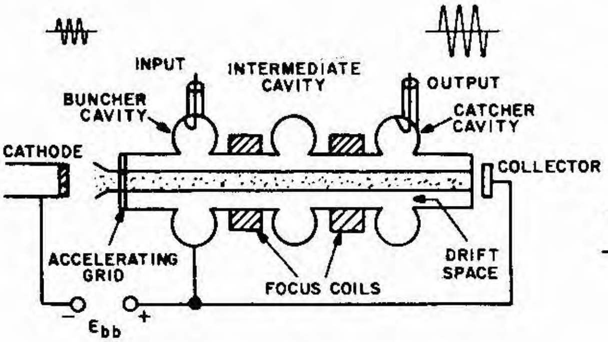
External magnetic beam-focusing is usually employed to improve efficiency.

CIRCUIT ANALYSIS.

General. The basic multicavity klystron consists of an electron gun, an input (buncher) cavity, an output (catcher) cavity, and a collector anode. The cavities may be integral within the tube or constructed externally so that the tube can be inserted within them. A focusing coil arrangement is usually included to prevent divergence of the electron beam, loss of electrons, and consequent reduction in efficiency. . Any number of cavities can be used by increasing the tube length, as long as the transit time across the lips of the cavity is short as compared with the wavelength of the signal. The high-power klystron operates at voltages of 25 to 100 kilovolts or more, and the current is in terms of amperes or tens of amperes, rather than milliamperes. The unit is usually shielded as a protection against high voltage, and special lead shields minimize the X-radiation produced as a consequence of the high electron voltages used. Since the physical construction of the various tubes available are slightly different for different manufactures, the following discussion applies generally as far as basic theory is concerned. The effects of cavity shape and construction, windows, and apertures or coupling loops are generalized so that the discussion will be applicable to most types of klystrons. Moderate-power tubes use forced-air cooling, while the high-power units use hollow water jackets with forced-water circulation to provide artificial cooling.

Because of the noise produced by the electron beam (noise figure averages 25 db), the multicavity klystron is normally used for transmitting applications instead of receiving applications. While feedback can be employed between the cavities to provide oscillation, the multicavity klystron is generally used as a linear r-f amplifier, being driven by a lower-power klystron or a traveling-wave tube.

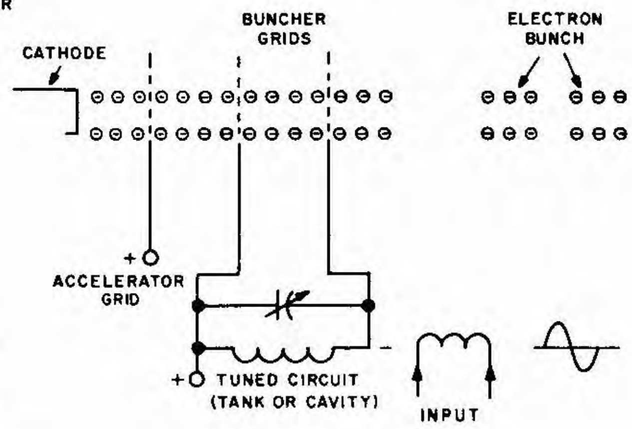
Circuit Operation. The simplified schematic of an elementary multicavity klystron is shown in the accompanying illustration.



Simplified Klystron Multicavity Amplifier

At the left is the cathode of the electron gun, from which the long electron beam is accelerated, and at the right is the collector, which finally collects the beam. The electron beam first passes through the input resonator. The input signal produces a longitudinal electric field across the part of the resonator through which the beam passes. This field alternately retards and accelerates the electrons passing through the resonator. The retarded and accelerated electrons all travel along through the drift space between the cavities. There, some of the accelerated electrons catch up with some of the retarded electrons which left the input resonator earlier, so that bunches are formed. These bunches are composed of electrons which passes through the input resonator while the field was changing from retarding to accelerating. These bunches eventually pass through the output resonator (or catcher) and induce a current from which the output is derived. In the 3-cavity klystron, an intermediate resonator is placed between the input and the output cavities to provide, in effect, a two-stage amplifier in one tube envelope. The bunched electron beam produces a field across the intermediate resonator, and this again retards and accelerates the beam (that is, velocity-modulates it anew). In tubes for very broad-band operation, several intermediate resonators may be used.

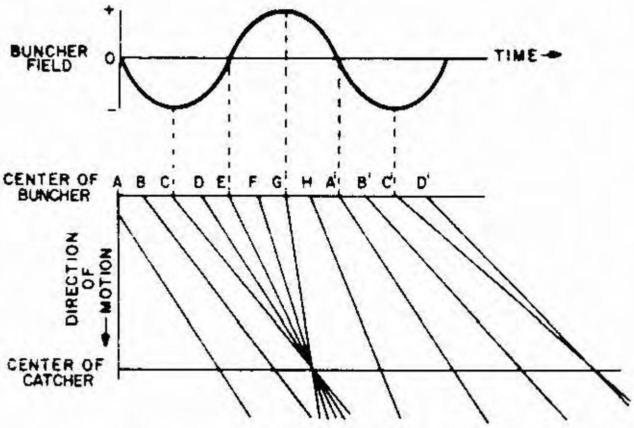
The manner in which the electron beam is formed and bunched can be understood by following the action step by step. The initial electron beam is produced by a Pierce-type electron gun. The electrons emanate from a flat cathode under the attraction of a positive accelerating field produced by an accelerating grid located near the cathode (between it and the input resonator). This electrode is shaped to permit passage of the electrons through a small orifice. In low-power guns the electrode may contain an actual grid structure through which most of the electrons pass without hindrance and form an essentially parallel-path beam of electrons. The tendency of these electrons to expand around the axis of the beam and disperse is corrected by a magnetic field placed along the axis of the tube by a focusing coil (permanent magnets are also used). Any electrons which tend to fly off at a tangent, or in a radial direction, are forced back into the beam path by the parallel flux lines from the coil. In extreme cases they cause the recalcitrant electrons to follow a spiral path back to the axis of the beam. The parallel beam of electrons, all traveling at the same speed, passes through a pair of buncher grids, as shown in the accompanying illustration.



Electron Gun and Buncher Grids

Each of the buncher grids is connected to one side of a tuned circuit (cavity). (The tuned circuit and the buncher grids are at the same d-c potential as the accelerator grid.) The input signal is usually inductively coupled into the tuned circuit or cavity, and produces an a-c field between these grids. Assuming a sine-wave input, when the buncher grid closest to the cathode is positive, the buncher grid farthest away is negative. These voltages add to or subtract from the applied d-c accelerating voltage. Therefore, the alternating (signal) voltage between the buncher grids causes the velocity of the electron leaving the buncher grids to differ, depending upon the time at which each electron passes these grids.

An electron that passes the center of the buncher cavity at the same time the input signal is passing through zero leaves the buncher at the same velocity at which it entered (since no change in accelerating potential occurs). The position of the electrons plotted against time is shown in the following Applegate diagram, which indicates how bunches are formed. The slope of the lines in the figure represents the velocity of the electrons.

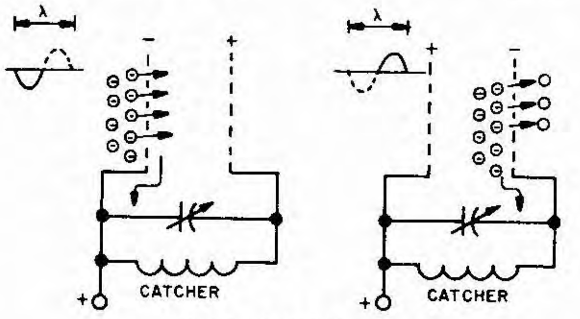


Applegate Diagram of Electron Bunching

Electrons which pass the center of the buncher a few electrical degrees earlier than the point of zero voltage (such as at C and D in the diagram) encounter a negative opposing field, and leave the buncher with reduced velocity, since the decreased voltage of the buncher slows them up. Electrons which pass a few electrical degrees after the instant of zero voltage, as at F and G in the diagram, leave with increased velocity since the buncher voltage is now slightly higher than the voltage of the accelerator grid (positive signal adds to positive electrode voltage). In the field-free drift space between the buncher and the intermediate cavity, faster electrons F and G catch up with electron E, which previously passed the bunch with no change in velocity. Slower electrons C and D lag behind, and hence draw near to E. At some point between the two cavities, electrons C, D, E, F, and G draw close together in a group. Now consider electron A', which leaves the buncher a half-cycle later than E. In this case its neighboring electrons draw away, since H is slightly slower and B' will be slightly faster. Consequently, the electron stream along the tube consists of electron bunches separated by regions in which there are few electrons. From the diagram, it appears as though bunching occurs in the first half-cycle of operation. Actually, bunching really occurs two or three cycles later in the relatively free drift-space between cavities. Also, bunching occurs twice in the three-cavity klystron (once between the input and center cavities, and once again between the center and output cavities). Since it is less complex and somewhat easier to understand, this diagram is used to emphasize bunching action, although it really is a representation of a two-cavity klystron with the retardation and acceleration of electrons overemphasized by using a much greater electron-line slope than actually occurs.

Since a continuous stream of electrons enters the buncher grids, the number of electrons accelerated by the alternating (signal) field between the buncher grids on one half-cycle of alternation is exactly equaled by the number of electrons which are decelerated on the other half-cycle. Therefore, the net energy exchange between the electron stream and the buncher is zero over a complete cycle (assuming a sinusoidal signal), except for any losses that occur in the tuned circuit or buncher cavity. As the electrons travel down the tube, they pass through the intermediate cavity grids and induce an oscillation into the middle cavity. Thus, an a-c potential similar to the input signal is produced between the middle cavity grids. When the middle cavity is tuned to a frequency slightly higher than that of the buncher cavity, it presents an impedance with an inductive component. This provides a phase relationship between the cavity voltage and the electron stream which causes further velocity modulation of the electron stream. In this case, since the cavity is a high-Q resonant circuit, it causes a voltage build-up which is larger than that of the input signal. Therefore, the electrons are again bunched; this time they are formed into denser bunches, and the free electrons between the bunches are still further reduced (some are absorbed into the new bunches). The new bunches of electrons form in the drift space between the middle cavity and the output (or catcher) cavity, pass down the tube, and enter the catcher cavity.

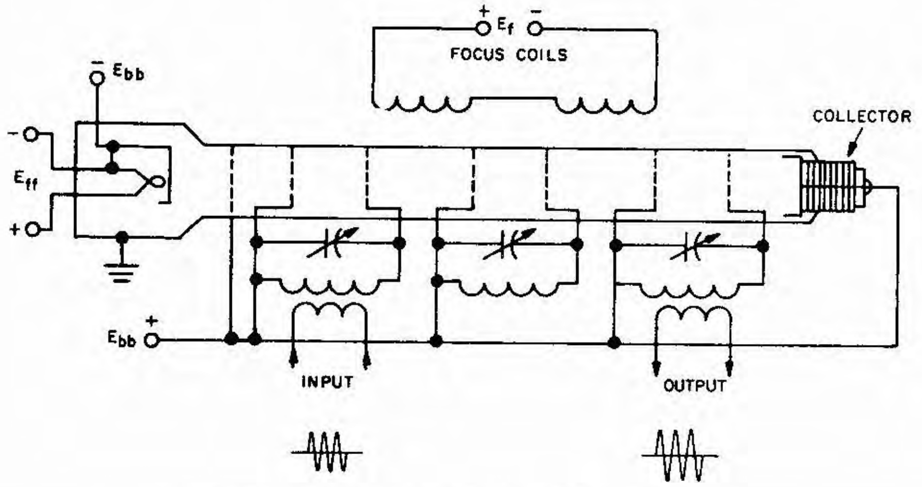
The conditions at the catcher cavity are somewhat different. This cavity is located along the tube so that the passage of the electron stream in bunches through the first grid creates a negative potential upon it. This negative potential retards the electrons, and, in slowing them down, absorbs energy from them. The spacing between the two catcher grids is equivalent approximately to a half-wavelength at the frequency of operation. Thus, by the time the first bunch reaches the second catcher grid, the first catcher grid has reversed polarity and becomes positive, while the second catcher grid is now negative, as shown in the accompanying illustration.



Catcher Grid Polarity

Since the second grid is also negative, it further slows down the electrons and again absorbs energy from them. Thus, in delivering energy to the tuned cavity connected to the catcher grids, the speed of the electrons is greatly reduced. After passing this second set of catcher grids the spent electrons are collected and removed from the tube by the positive collector plate.

A complete multicavity klystron r-f amplifier can be shown schematically as illustrated in the accompanying figure. The operation is exactly as described in the paragraphs above; therefore, it will not be repeated.



Multicavity Klystron R-F Amplifier Schematic Diagram

FAILURE ANALYSIS.

No Output. Lack of or improper accelerating voltage, loss of drive power, or improper cavity tuning can result in loss of output. Usually, excessive beam current indicates improper tuning or voltage. A voltage check will indicate whether the voltage is sufficient. WARNING: **Dangerous High Voltage** is present; all safety precautions should be taken to make certain that no shock hazard exists. In practice, the shell of the tube is grounded and a high negative voltage is applied to the cathode. It is particularly important **not to remove any lead shielding** while troubleshooting; otherwise, X-radiation effects will produce a hazard to maintenance personnel. Normally, a no-output condition will be caused by an open circuit (or short circuit) or by a defective tube, rather than by mistuning or low voltage, since in these latter cases some small output normally occurs. When both filament and anode voltages are correct and the proper drive voltage exists, the tube is probably at fault. Substitution of a tube will not immediately restore full output, since the proper tuning and adjustment procedure must be followed to enable the tube to function properly. Use the manufacturer's recommended procedure for tuning and placing the unit in service, and note any deviations in performance or any abnormal indications as the procedure is followed. Investigate each deviation as it occurs, and make certain that is is cleared up before proceeding further.

Reduced Output. Low filament, drive, or anode voltage, as well as mistuning, can cause reduced output. Check the filament and plate voltages with a voltmeter, observing all safety precautions. An increased beam current can result from improper tuning or improper load. Check the drive, using a dummy load at the input to be certain that sufficient power is available. With sufficient drive established, connect a dummy load to the output and follow the proper tuning procedure. As the tuning procedure is performed, the beam current should reduce, more r-f drive should be required, and a greater output should result. Where focusing coils are used, loss of focus magnetism will show as a reduction in focusing-coil current and a reduction of beam current (the stray electrons are absorbed before reaching the collector). An increase in beam current can usually be traced to improper cavity tuning. For maximum output, both the input and output cavities should be tuned to the same frequency. In broad-band operation it is necessary that each cavity be tuned to the proper frequency; otherwise, loss of output or of frequency range will occur. As with all other power amplifiers, the proper load must be attached; otherwise, improper impedance relationships will cause unwanted reflections and a loss of power. In receiving applications, low cathode emission will usually cause an increase in noise because of uneven electron emission.

DIRECT-COUPLED (D-C) AMPLIFIER.

APPLICATION.

The direct-coupled amplifier, commonly known as the **d-c amplifier,** is used where it is necessary to amplify extremely low-frequency signals extending down to, and including zero frequency (direct current). The most common application of the d-c amplifier is in the d-c vacuum-tube voltmeter. This amplifier also finds use in a balanced bridge circuit, where two d-c voltages are to be compared, and the difference between them is to be indicated on a meter. Another important application is in the signal input amplifier of an oscilloscope which is designed to accept low-frequency or direct-current inputs for waveform display. Other uses of a direct-coupled amplifier are: to isolate two d-c circuits while allowing a transfer of signal from the first circuit to the second but not in the reverse direction; to add two or more d-c voltages to produce a d-c output proportional to their sum multiplied by a constant factor; and to reverse the polarity of a d-c voltage while either keeping its numerical value unchanged or increasing its numerical value by a constant factor.

CHARACTERISTICS.

The connection between the output (plate) of one stage and the input (grid) of the d-c amplifier is a direct metallic connection, without the use of any intervening coupling device such as a capacitor, impedance, or transformer.

Amplification of very low frequencies, or very slow variations of voltage, is accomplished without distortion and with uniform response.

Speed of response is practically instantaneous; pulse signals may be amplified without any distortion due to differentiation.

Input impedance is high; no grid current flows.

Output impedance is very low; can be made as low as one or two ohms.

Polarity (phase) of output signal is reversed by a single stage, or odd number of stages, of amplification. An in-phase output signal may be obtained by use of an even number of stages.

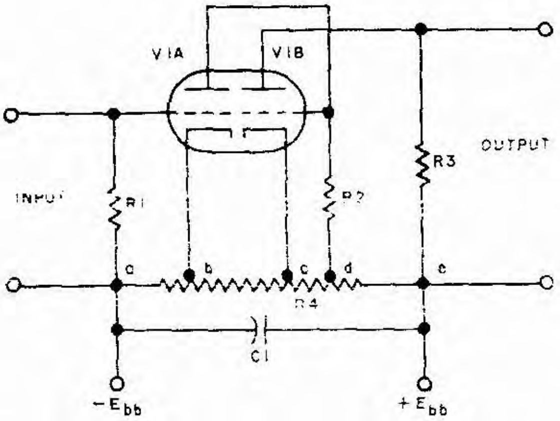
CIRCUIT ANALYSIS.

General. In most vacuum-tube amplifier circuits, the coupling device used between the output (plate) circuit of the preceding stage and the input (grid) circuit of the amplifier stage allows only the alternating components of the output signal to pass through. At the same time, the coupling device serves to isolate the highly positive voltage, which often has a value of several hundred volts, at the plate of the preceding stage, from the low signal bias voltage at the grid of the amplifier stage. In resistance-capacitance-coupled and impedance-coupled amplifier circuits, the coupling capacitor prevents the plate supply voltage from being applied to the grid of the succeeding stage. In transformer-coupled amplifier circuits, the electrical isolation between the primary and secondary windings prevents the plate supply voltage, which is present in the primary winding, from being applied to the grid circuit, which includes the secondary winding.

In the direct-coupled (or d-c) amplifier, the output (plate) of the preceding stage is connected **directly** to the input grid of the amplifier, without the use of any intervening means of coupling such as a transformer or capacitor. This requires a more complex method of supplying the required voltages to the amplifier tubes, since the plate of each tube must be supplied a positive voltage with respect to its cathode, and the grid of the following tube must be supplied a negative bias voltage with respect to its cathode; this grid, of course, is already supplied with the positive plate potential of the preceding plate through a direct connection. A special voltage-divider network is therefore required to supply the various values of bias and plate voltage for each amplifier stage.

Circuit Operation. A typical d-c amplifier circuit is shown in the following illustration. In this circuit, the input signal is applied, across grid resistor R1, directly to the grid of the first section of twin-triode tube V1, which

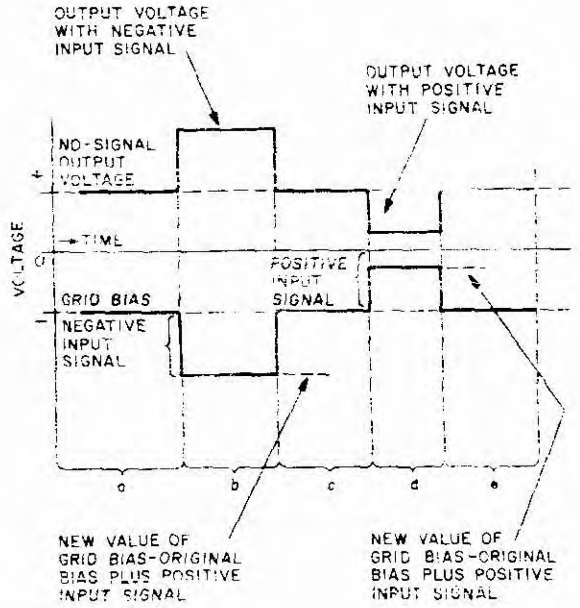
is used as a two-stage *triode amplifier*. The grid resistor is returned to the most negative point on voltage divider R4, designated as point a. The cathode is connected to point b on R4, which establishes the proper grid bias for operation of V1A, since point a is more negative than point b. The exact location of point b on voltage divider R4 is somewhat critical, since the terminal voltage at point b depends upon the values of current flowing at each of the voltage divider taps b, c, and d, as well as upon the applied voltage, E_{bb}. Plate voltage is taken from tap d on R4, and applied through plate load resistor R2 to the plate of V1A. Plate load resistor R2 also serves as the grid resistor for the second amplifier stage, V1B, and the plate current flowing through the resistor establishes the grid voltage of V1B at the value existing at point d less the voltage drop across resistor R2. The location of point d on the voltage divider is such that approximately one half of the total power supply voltage, E_{bb}, is applied to the first amplifier stage, V1A.



Two-Stage Direct-Coupled Amplifier Circuit

The cathode of the second amplifier stage, V1B, is connected to the voltage divider at point c, where the voltage is more positive than the voltage at the grid of V1B by the amount of the desired grid bias. (The voltage at point c is more positive than that at the grid of V1B because of the voltage drop through resistor R2.) The plate of the second stage furnishes the output of the amplifier, which is taken across plate resistor R3 by direct connection without the use of any intermediate means of coupling. Resistor R3 is connected to the high side of voltage divider R4 at point e, and capacitor C1 acts to smooth out any ripple from the power supply. The entire circuit comprises a resistance network which, because of its complexity, requires careful adjustment at the voltage-divider taps, in order to obtain the proper grid and plate voltages for both tubes. When these voltages are properly adjusted to obtain Class A operation, the circuit acts as a distortionless amplifier, having a uniform frequency response over a wide range, and a response time which is practically instantaneous.

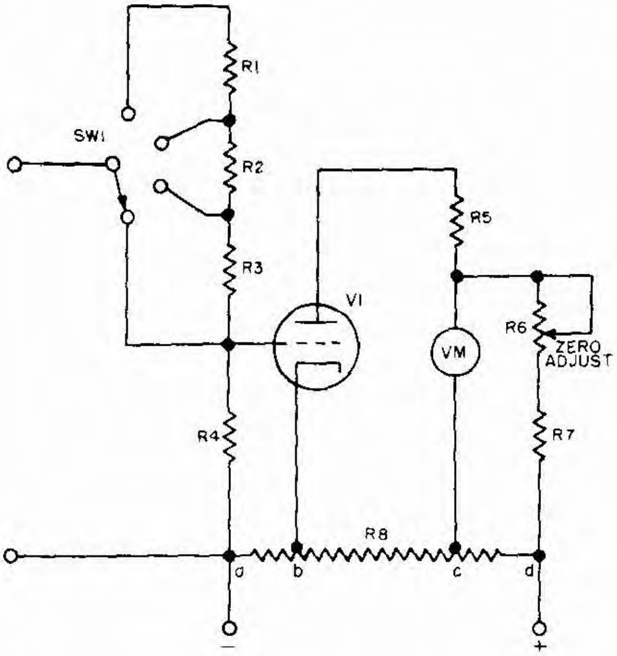
Assuming that the voltages have been adjusted for Class A operation, the normal voltage conditions of the circuit with no signal applied to the input are shown in part a of the following illustration. The fixed value of grid bias, from the power supply, is indicated as a negative voltage, and the no-signal output voltage is indicated as a positive voltage. This is the value of voltage drop across plate resistor R2, resulting from the plate current flowing under no-input-signal conditions. In part b of the illustration, a negative input signal voltage of fixed value has been applied to the grid. The negative input voltage adds to the fixed value of grid bias voltage, which is also negative, to make a new value of grid bias, shown by the lower solid line in part b. This more negative grid voltage causes less current to flow in the plate circuit through plate resistor R2, producing a higher voltage at the plate, as indicated by the upper (output voltage) solid line in part b of the illustration.



D-C Amplifier Input-Output Voltage Characteristics (For a Single Stage)

In part c the input signal has been removed, and the grid bias and output voltage values have returned to the levels shown in part a. In part d a positive input signal voltage has been applied to the grid of V1. The positive input voltage subtracts from the (negative) fixed value of grid bias voltage, to produce a new value of grid bias which is less negative, as shown by the lower solid line in part d of the illustration, close to the zero voltage bias level. (If the positive input voltage is too high, the grid will be driven into the positive region, grid current will flow, and the output signal will be distorted. Under such conditions, the amplifier will not operate within Class A limits.) As a result of this less negative bias voltage, a greater current is caused to flow in the plate circuit, through plate resistor R2, and a lower voltage is produced at the plate, as indicated by the upper (output voltage) solid line in part d of the illustration. In part e the voltages have returned to their original values, following the removal of the input signal.

For purposes of explanation, the discussion of the effects of the input signal and the output voltage has referred to only one stage (V1A) of the two-stage direct-coupled amplifier circuit illustrated. The operation of the second stage (V1B) is identical. It should be noted that the signal at the output of the first stage is reversed in phase by 180 degrees. This is evident from the illustration of the input-output characteristics, where the negative input signal produced a positive output signal. An additional 180-degree phase reversal is produced by the second stage, giving an output signal from the two-stage amplifier circuit which is in phase with the input signal.



Vacuum-Tube Voltmeter Utilizing Direct-Coupled Amplifier Circuit

A very practical application of the d-c amplifier circuit is found in its use as a d-c vacuum-tube voltmeter. This circuit, utilizing a single triode, is shown in the following illustration. The voltage to be measured is applied, through a range switch, SW1, to a tapped voltage divider which allows several ranges of voltage to be measured. The voltage divider is composed of several resistors, R1 through R4, with R4 also serving as the grid resistor for the triode d-c amplifier, V1. Plate load resistor R5, having a value of 22K or higher, acts as a current-limiting resistor to protect the meter in the event of excessive input voltages. Variable resistor R6 functions as a balance control to allow the voltmeter to indicate zero volts with no applied input voltage. Voltage divider R8, connected across the input voltage from the power supply, is tapped to provide the proper grid bias and voltmeter balance voltages. When variable resistor R6 is adjusted for a zero voltmeter indication with no input signal, the voltage at point c on voltage divider R8 is exactly equal to the voltage at the junction of R5 and R6. Now when an input signal is applied, additional plate current flows through R5, R6, and R7, causing the voltage at the junction of R5 and R6 to drop to a lower value, while the voltage at point c on voltage divider R8 remains relatively constant. When properly calibrated, the meter indicates this voltage drop as the applied input voltage.

A disadvantage of this direct-coupled vacuum-tube voltmeter circuit lies in its poor stability of calibration. The plate current of the tube varies in a somewhat unpredictable manner with variations in filament temperature, age of the tube, and variations in resistance of the coupling element with temperature variations. These variations are especially evident when an attempt is made to read small voltages accurately.

FAILURE ANALYSIS.

No Output. Assuming that a signal whose amplitude (either positive, negative, or a combination thereof) is within the design limits of the d-c amplifier, is applied to the input terminals, the primary cause of no output is a defective tube. If the tube is capable of satisfactory operation, the cause of a no output condition is obviously an incorrect voltage, or lack of voltage, at some point in the circuit. Referring to the first illustration (two-stage direct-coupled amplifier circuit), an open voltage divider R4 would cause one or more of the voltage taps to fail to supply the required voltage to either the cathodes of V1A or V1B or the plate of V1A. As a result, either V1A or V1B would fail to operate. An open resistor R2 would remove plate voltage from V1A, resulting in no output; a similar condition would occur if plate load resistor R3 opened, removing plate voltage from V1B.

Reduced or Unstable Output. Assuming that a satisfactory signal is present at the input to the direct-coupled amplifier, an open grid resistor R1 would cause unstable output, along with intermittent grid blocking, or "motorboating." A change in the supply potentials for any tube in a multi-stage d-c amplifier would cause the currents and potentials of all succeeding stages to vary. If, for example, the grid potential of the first tube varies slightly, the gain of the amplifier will cause the current in the last tube to vary by a large amount, even to the point of decreasing to zero, or of increasing to an excessively high value. In either case, distortion will be introduced. A changed value of R4 (or portions of R4), or of plate resistors R2 and R3 would all have the effect of changing the supply potentials of the tubes. The amount of unbalance created, and, consequently, the amount of output distortion, will depend on whether the gain of one or both stages is involved in amplifying the unbalance. An open or partially shorted filter capacitor C1, if used, may cause hum or reduced output because of inadequate filtering of the input power, $+E_{bb}$. A decreased value of input power, $+E_{bb}$, due to a defective power supply, would also be a cause of reduced output.

PUSH-PULL DIRECT-COUPLED (D-C) AMPLIFIER.

APPLICATION.

The push-pull direct-coupled amplifier (as well as the single-ended direct-coupled amplifier) can be used where it is necessary to amplify signals having a wide band of frequencies, especially in the lower-frequency range, which may extend down to and include zero frequency (direct-current). When, in addition, the requirements demand the amplification of a signal which has a larger voltage swing above and below a zero voltage level than can be handled by the single-ended type, the use of the push-pull direct-coupled amplifier is mandatory. One application is in certain types of d-c vacuum-tube voltmeters, while another is in the signal amplifiers of an oscilloscope that is capable of displaying waveforms of various values of direct current. The push-pull d-c amplifier is often utilized in the video circuitry of radar display systems. In communications, it may be used as the amplifier for those teletype mark and space signals that consist of two voltage levels of direct current.

CHARACTERISTICS.

The connections between the plates (outputs) of one stage and the grids (inputs) of the push-pull d-c amplifier are direct, metallic connections; no intervening coupling devices such as capacitors, impedances, or transformers are used.

Amplification of direct-current signals of varying voltage levels, as well as signals of very low frequency, is realized without distortion and with uniform response.

Distortion due to differentiation is eliminated; pulse signals of large amplitude may be amplified without change in waveform.

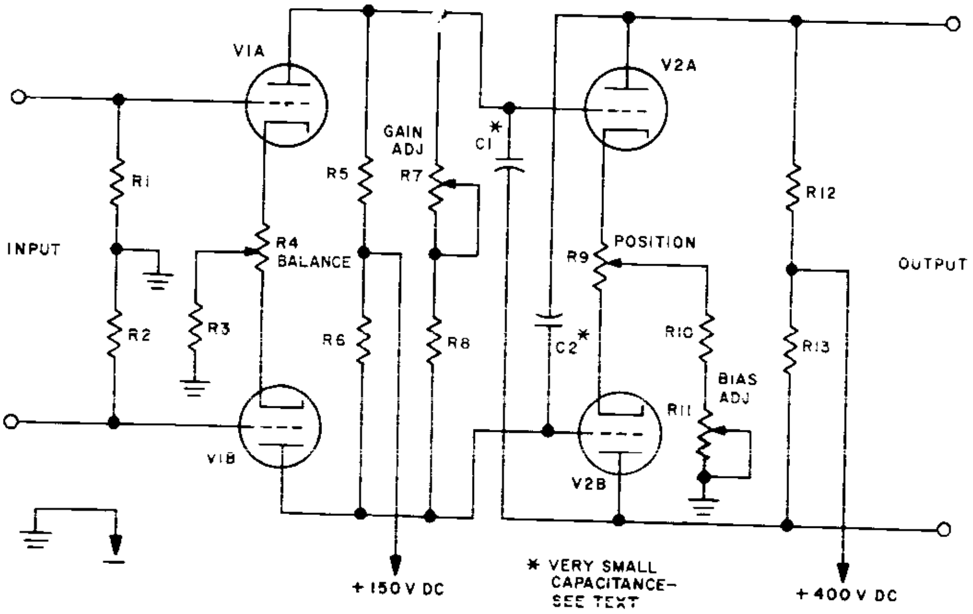
Speed of response is practically instantaneous.

Input impedance is high; Class A operation allows no grid current to flow.

Relative phase (with respect to ground) of the output signal is reversed over that of the input signal when a single stage, or odd number of stages, is used.

CIRCUIT ANALYSIS.

General. The gain of an ordinary R-C coupled amplifier falls off rapidly as the frequency of the input signal is decreased below 40 cycles, because of the rapid increase in reactance of the coupling capacitor with a decrease in frequency. Therefore, the R-C amplifier is unsuitable for use in applications which require the amplification of very



Typical Two-Stage Push-Pull Direct-Coupled (D-C) Amplifier low frequencies, including zero frequency or direct current, without substantial loss of gain.

The push-pull direct-coupled amplifier is well suited for such applications, since the input signal is applied directly to the grids of two tubes, without the use of coupling capacitors. Frequency response is flat down to and including zero frequency, allowing the use of this circuit for amplification of steady-state d-c voltages. The response at very high frequencies is limited by the stray capacitances in the circuit, which have a shunting effect, similar to that of the ordinary R-C coupled amplifier.

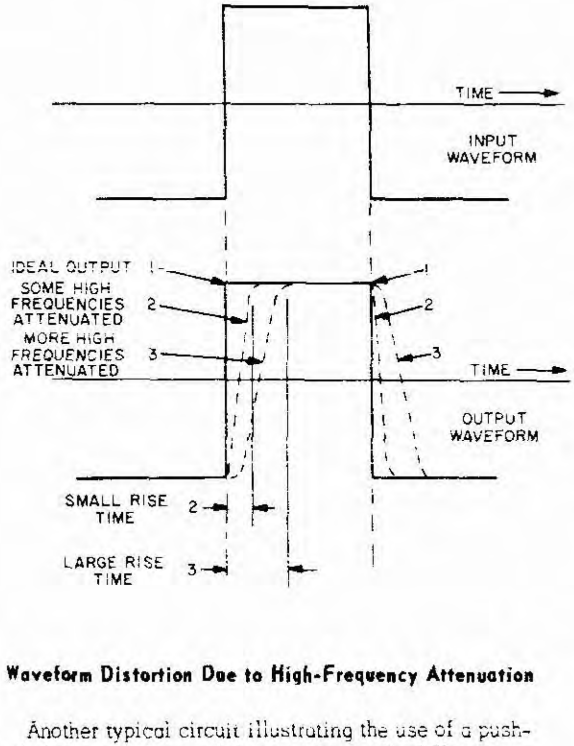
Circuit Operation. The schematic shown above illustrates a typical two-stage push-pull direct-coupled (d-c) amplifier. This type of circuit may be found in applications such as the deflection amplifiers of radar scopes designed for electrostatic deflection, and the signal amplifiers (vertical-deflection amplifiers) of high-quality test oscilloscopes designed for direct-current waveform analysis.

The input signal, which may consist of positive or negative pulses, or both, or simply of a positive or negative d-c level, is applied across the grids of V1A and V1B. These two triodes may be enclosed in the single envelope of a twin-triode such as type 12AU7A. Self-bias is provided both triodes by means of the common cathode resistor, R3, in combination with potentiometer R4, which provides a balance control for use in equalizing the gain of V1A and V1B. Plate voltage of a medium value (+150 volts) is applied through plate load resistors R5 and R6. Variable resistor R7 functions as a gain adjust control, and fixed resistor R8 connected in series with it sets the low limit for the variable value of the total resistance between the two triode plates. This combination, R7 and R8, affords a relatively simple means, from the standpoint of circuit components, of adjusting the over-all gain of the amplifier, and thereby the amount of vertical deflection in oscilloscope applications. Resistor R8 should have a minimum resistance value on the order of 1.5K, in order to maintain this minimum value of resistance as a plate-to-plate load when R7 is adjusted to its zero-resistance position. As R7 is adjusted from its maximum value, toward zero resistance, loading of the signal output from V1A and V1B is increased, reaching a minimum value when R7 is adjusted to remove its resistance from the circuit. The maximum positive and maximum negative excursions of the signal to be amplified may thereby be adjusted, while maintaining the over-all frequency response of the amplifier.

The amplified output signal from the plates of both triodes, V1A and V1B, is applied directly to the grids of the second stage triodes, V2A and V2B. Since the grids of the second stages are at the same positive potential as the plates of the first stage (some value less than +150 volts due to the voltage drop through R5 and R6), the cathodes of V2A and V2B must be placed at a somewhat greater potential than +150 volts (above ground), in order that the grids may be properly biased, i.e., negative with respect to cathodes. In this circuit, which utilizes self-bias, this is accomplished by the use of a large value of cathode resistance, composed of potentiometer R9 and resistors R10 and R11. Potentiometer R9 serves as a balance adjustment to equalize the gain in both halves of the second stage; in this application, it serves to "position" the waveform under observation on the oscilloscope screen. The bias on the cathodes is adjusted by means of variable resistor R11, while the total resistance of the combination R9, R10, and R11 establishes the total bias voltage at the cathodes of V2A and V2B. This relatively large value of cathode resistance, which amounts to approximately 12K, would introduce degeneration into the circuit, resulting in a decrease in gain, if this were an unbalanced (single-ended) stage. In this (push-pull) circuit, however, the degenerative effect of one half of the circuit at any instant immediately cancels an opposite effect of the other half of the circuit, and no loss of gain occurs. Conversely, any tendency toward an unbalance in one half of the circuit introduces degeneration which acts in opposition to the initial tendency, thereby keeping both halves of the circuit balanced. Such a tendency toward an unbalanced condition might be caused by circuit drift, due to unequal cathode emission in the two triodes.

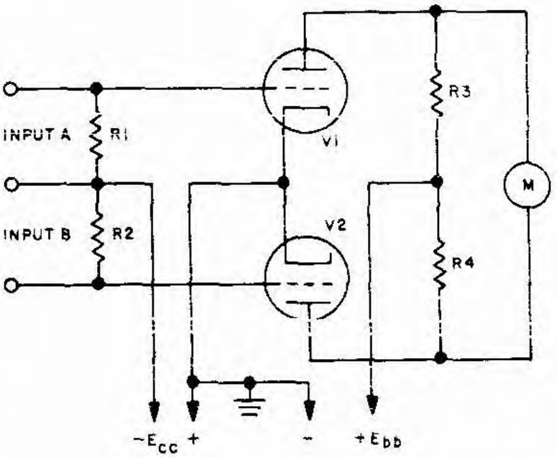
Plate voltage for the second stage triodes is applied, from a considerably higher voltage source than that of the first stage, through plate load resistors R12 and R13. Although an applied voltage of +400 volts, dc may appear to be excessive, it should be noted that the actual voltage at the plates of V1A and V1B cannot exceed 250 volts positive with respect to the voltage at the grids, under any conditions (within Class A operating limits). Under normal operating conditions, with plate current flowing, the voltage at the plates will be considerably less than 250 volts positive with respect to the grids, due to the voltage drop in the plate load resistors, assuming that similar tubes are used in both stages (V1 and V2) with similar plate load resistors, and that no input signal is applied.

In the circuit illustrated, capacitors C1 and C2 are used in a compensation circuit; C1 connected between the ouput plate of one half of the circuit and the input grid of the opposite half, and C2 connected between the output plate of the second half of the circuit and the input grid of the first half. These capacitors are of very low value of capacitance, such as 0.5 mmf, and function to allow positive (in-phase) feedback of the high frequencies only, leaving the mid-frequency and low-frequency response unaffected. When the proper values of capacitance are used (these values vary with the values of plate resistance, operating voltages, and tube types), the response of the over-all circuit, which normally drops off with increasing frequency, may be maintained flat to a considerably higher frequency than would be possible without this compensation. The value of capacitance used is somewhat critical, in that if the capacitance is too high the amount of positive feedback will be excessive, resulting in oscillation and severe frequency distortion. In addition to maintaining the high-frequency response over an extended range, the use of high-frequency feedback offers an additional advantage: When direct current input waveforms are being amplified, in the case of the circuit illustrated, the extended high-frequency response acts to decrease the rise time of the leading edge of the input waveform. If, for instance, the input waveform is a direct current whose voltage increases instantaneously (the leading edge of a square wave) from one value of voltage to a more positive value, this perpendicular wavefront will be found, upon analysis, to be composed of an infinite number of frequencies. If all of these test frequencies could be passed by the amplifier circuitry, the output would be a perfectly perpendicular wavefront, as shown by 1 in the following illustration. Since no amplifier can pass frequencies which approach infinite values, without attenuation, the output of the amplifier will not be a waveform whose wavefront is perfectly perpendicular. Instead, the wavefront will begin to slope away from the perpendicular, causing an increased rise time, as shown by 2 in the illustration. As more and more of the high frequencies are attenuated by the amplifier circuitry (stated in another way, as the amplifier becomes more inferior in its high-frequency response), the sloping of the wavefront away from the perpendicular increases. *Thus the originally perpendicular wavefront now becomes markedly sloped, with rounded corners as illustrated by waveform 3 below, whereas the original wavefront had sharp, 90-degree angles.*



Waveform Distortion Due to High-Frequency Attenuation

Another typical circuit illustrating the use of a push-pull direct-coupled amplifier is given in the following illustration. Here, a voltmeter M having a zero-center scale is used in a vacuum-tube voltmeter circuit designed to indicate any unbalance between the inputs to two halves of the push-pull circuit, and the direction and extent of *such unbalance*. The input circuit is center-tapped, to enable a comparison to be made between input A and B. The two direct-coupled triode amplifiers, V1 and V2, are connected *in two legs of a bridge circuit*, with the two input voltages to be compared applied to the grids of V1 and V2, respectively. The grids are returned through grid resistors *R1 and R2 to a negative fixed bias voltage. Plate voltage* is applied through plate load resistors R3 and R4, with a voltmeter M shunted across both plates. With tubes V1 and



Push-Pull Direct-Coupled Amplifier Used in Vacuum-Tube Voltmeter Circuit for Two-Input Comparison

V2 and resistors R1 and R2 properly matched, and no input signal applied to input A or input B, the circuit is perfectly balanced and no difference of potential across the plates of V1 and V2 will be indicated by voltmeter M. This results from the fact that equal currents flowing through resistors R3 and R4 will give equal voltage drops across R3 and R4, and identical voltages will be present at the plates of both tubes. When a signal is applied across input A, the grid of V1 becomes more (or less) positive than the grid of V2, depending upon the polarity of the applied signal. If the input signal is positive, the more positive grid of V1 causes an increase in plate current through R3, creating *an unbalance in the output circuit.* As a result, the increased voltage drop across R3 causes the plate of V1 to become less positive than the plate of V2, and the difference between *the two plate voltages* will be indicated by voltmeter M. Voltmeter M is a center-scale-zero meter, and if the polarities of its connections in the circuit are correct, it will indicate a negative voltage. If a more highly positive signal is applied across input B, with the first signal remaining across input A, the grid of V2 will become more positive than the grid of V1. This will cause a higher value of current to flow through R4 than is already flowing through R3 due to the signal at input A, and the voltage at the plate of V2 will become less positive than the voltage at the plate of V1. As a result, the pointer of meter M will swing through zero to indicate a positive value of voltage difference between the two input signals.

FAILURE ANALYSIS.

No Output. If a signal having an amplitude within the design limits of the push-pull d-c amplifier is furnished at the input terminals, a defective tube should be first suspected as the cause of no output. Note that the defective tube will cause a no-output condition in a push-pull circuit **only** if this tube is a twin-type, and then only if both halves become defective at the same time. Referring to the first illustration (typical two-stage push-pull direct-coupled (d-c) amplifier), if V1A and V1B are the two halves of a twin-triode such as a type 12AU7A, and if the V1A section of the tube should become defective, the V1B section will still operate to furnish a reduced output. In a similar manner, the failure of any single resistor in the plate or grid circuits would **not** be a cause of a no-output condition, because the other half of the circuit would continue operating. However, if common cathode resistors R3, R10, or R11 should become open-circuited or if the plate power supply to either stage (+150 VDC or +400 VDC) should fail, there would be no output.

Reduced Or Unstable Output. Assuming that a satisfactory signal is present at the input to the push-pull direct-coupled amplifier, a number of conditions could contribute to a reduced output, which ordinarily would be a cause of a no-output condition in a single-ended amplifier. The failure of a single section of a twin-triode, or of a single triode where single-triode type tubes are used, would cause a reduced output, as discussed in the previous paragraph. An "open" in any grid or plate circuit would also cause reduced output, because the other half of the circuit would continue to operate. The output, however, would probably be distorted, because either the positive or negative half of the input signal would be cut off. If either balance control R4 or position control R9 should become open-circuited at some point of rotation, an erratic output would be obtained when the control is operated across the point where the "open" exists. A simple misadjustment of R4 or R9, or of bias adjust control R11, with all other components operating normally, would contribute toward an unbalance which might result in reduced or distorted output. If capacitors C2 or C3 should change in value or become shorted, the circuit would become unstable and possibly go into oscillation. In this particular circuit, which is self-biased, a reduced value of plate voltage caused by a defective power supply would, in all probability, only result in a somewhat reduced output, the quality of which may remain acceptable. If, however, a circuit which employs fixed bias should operate with reduced plate voltage, the output might be distorted, in addition to being reduced in value.

DEFLECTION AMPLIFIERS.

APPLICATION.

The deflection amplifier is used to amplify the signals before they are applied to the deflection plates of an electrostatic-deflection type of cathode-ray tube or to the deflection coils of an electromagnetic-deflection type of cathode-ray tube. Two separate amplifiers are associated with each cathode-ray tube: the horizontal deflection amplifier, which normally amplifies the horizontal sweep signals, and the vertical deflection amplifier, which normally amplifies the input waveform to be displayed on the screen of the cathode-ray tube.

CHARACTERISTICS.

Horizontal Deflection Amplifier. Input impedance is high; loading of the preceding horizontal generator circuit is thereby prevented.

Input capacitance is low; attenuation of high frequencies is thereby prevented.

High-frequency response is good, but not generally as good as the response of the vertical deflection amplifier.

Bandwidth usually covers 10 cycles to 100 kc; certain applications may require a range of 1 cycle to 500 kc; other applications (such as fixed sweeps of radar deflection) may require only a limited range in bandwidth.

Output impedance depends on intended application: impedance is high if amplifier is designed for voltage (electrostatic) deflection; impedance is relatively low to match the impedance of deflection coil if designed for current (electromagnetic) deflection.

Gain of the amplifier depends on application; the gain is usually lower than that of the vertical deflection amplifier, because the sweep generator output normally feeding the horizontal deflection amplifier is ordinarily higher and more constant than the input signal feeding the vertical deflection amplifier.

Balanced output (push-pull) is desirable, to prevent distortion caused by unequal amplification of positive and negative signals.

Vertical Deflection Amplifier. Input impedance is very high; loading of the preceding output circuit, with the consequent waveform distortion, is thereby prevented. (Special applications may require a low input impedance, which must then be matched to the source impedance of the input signal.)

Input capacitance is very low; attenuation of high-frequency components of input signal is thereby prevented.

High-frequency response is very good; application generally demands a better response than that of the horizontal deflection amplifier.

Bandwidth usually covers 10 cycles to 1 megacycle; certain applications may require a range of 2 cycles to 10 megacycles; other applications may require a range which includes zero cycles (direct current), but at the same time they may require only a limited high-frequency response.

Output impedance depends on the intended application, in the same manner as in the horizontal deflection amplifier. The impedance is high if the amplifier is designed for voltage (electrostatic) deflection; it is relatively low and must match the impedance of the load (deflection coil) if the amplifier is designed for current (electromagnetic) deflection.

Gain of the amplifier depends on its intended application: it must be sufficient to produce a pattern of acceptable size, on the particular cathode-ray tube used, from the smallest (voltage) input signal required to be displayed on the screen.

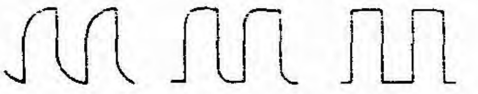
Balance output (push-pull) is desirable—more so than in the horizontal—in order to reduce pattern distortion and beam defocusing. Since the input signal to the vertical deflection amplifier is generally much lower in amplitude than that of the horizontal input signal, the amount of gain required of the vertical amplifier is generally higher, and hence the possibility of distortion is also higher.

CIRCUIT ANALYSIS.

General. A deflection amplifier is intended to accept, as an input, a signal whose waveform may be simple (as in the case of a direct-current waveform) or exceedingly complex (as in the case of several fundamental frequencies in combination with a multitude of their harmonics), amplify it, and furnish an output in which the original waveform remains unchanged. An amplifier intended for use as a horizontal deflection amplifier is required to increase the amplitude of the sawtooth sweep waveform, in order to produce sufficient horizontal deflection. In radar displays of certain types, a triangular type of sawtooth waveform is used for a horizontally swept timebase. An amplifier intended for use as a vertical deflection amplifier is required to increase the amplitude–sometimes to enormous proportions–of almost any type of waveform. Since the requirements of the vertical deflection amplifier are generally more stringent than those of the horizontal deflection amplifier, insofar as gain, bandwidth, and frequency response are concerned, the following discussion will be particularly applicable to the amplifier intended for vertical deflection.

The most complex waveform which may be required to be amplified is a perfect square wave. Such a wave contains a fundamental frequency and an infinite number of odd harmonics. It has zero rise and decay times, and a perfectly flat top and bottom. The voltage changes from a maximum positive value to a maximum negative value instantaneously. In order to amplify a waveform containing an infinite number of harmonics, without distortion, an amplifier having an infinite bandwidth would be required. Such a waveform and such an amplifier do not exist, for the following reasons: Any change in voltage, no matter how abrupt, requires a certain amount of time to occur. The presence of shunt capacitance, which in some amount is always present in a circuit, causes the rate of change of voltage to be further reduced. This results from the fact that the voltage across a capacitor cannot change instantaneously. In addition, every amplifier, no matter how careful the design, introduces some degree of distortion, which deteriorates the (perfect) square wave.

In actuality, the square wave applied to a vertical amplifier contains several hundred (rather than an infinite number) odd harmonics. The illustration below shows the output waveforms from amplifiers in which the high-frequency response was purposely restricted. The input to the amplifiers, in each case, was a "perfect" square wave.



A. 10 HARMONICS B. 100 HARMONICS C. GREATER THAN 500 HARMONICS

Output Square Waves Having Restricted Odd-Harmonic Content

In A, the output was restricted to the tenth harmonic of the fundamental frequency. In B the output waveform contained frequencies as high as the one-hundredth harmonic of the fundamental, while in C the output contained over five-hundred harmonics. In order to reproduce a square wave with reasonable fidelity the vertical deflection amplifier should have a bandwidth sufficiently wide to pass the tenth odd harmonic of the fundamental frequency. Note that this is a frequency which is 21 times the fundamental. More accurate reproduction of the input waveform requires a bandwidth wide enough to pass the fortieth odd harmonic (81 times the fundamental) of the fundamental frequency.

A waveform having a very short time duration, such as a timing pulse, requires a different method of calculating the minimum high-frequency response required of the deflection amplifier. The minimum upper limit of response required is inversely proportional to the pulse duration, as follows:

$$f_{max} = \frac{1}{d}$$

where: f_{max} = required minimum upper limit of amplifier response, in megacycles

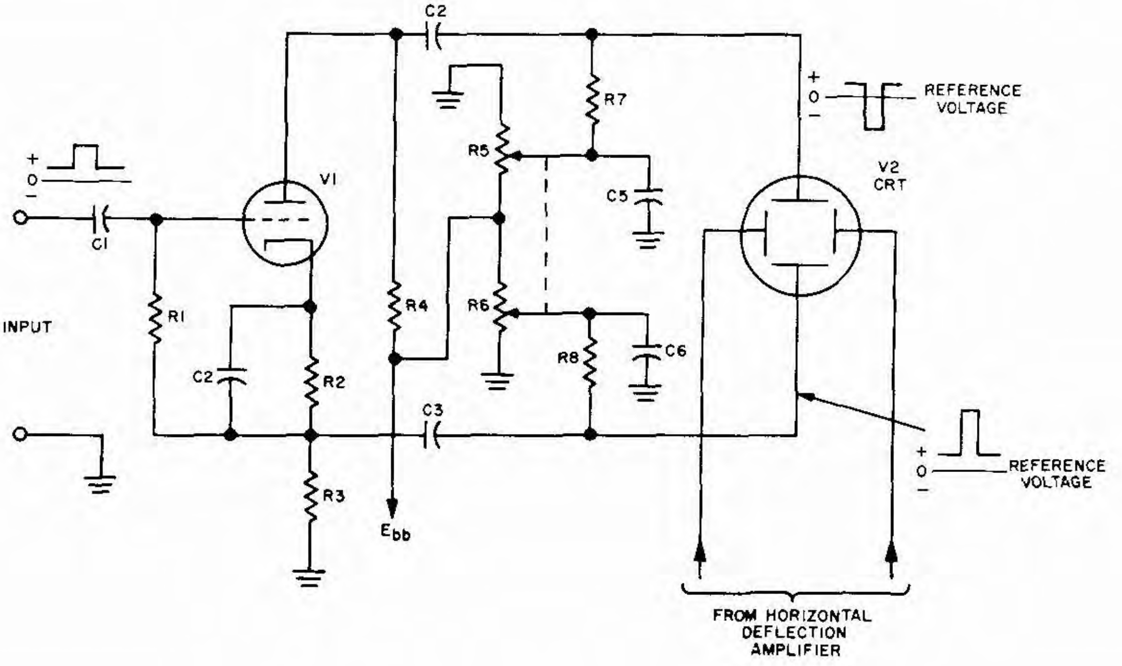
d = pulse duration, in microseconds

As an example, a 1-microsecond rectangular pulse requires a minimum frequency response which is uniform up to 1 megacycle. A 1/4-microsecond rectangular pulse requires a minimum frequency response uniform up to 4 megacycles.

In addition to pulse duration, the high-frequency response requirements of the vertical deflection amplifier also depend upon the rise time of the pulse to be amplified. The rise time is the time required for the pulse to increase from 10 percent to 90 percent of its maximum amplitude. The shorter the rise time required, the higher the frequency response of the vertical deflection amplifier must be to reproduce the waveform.

Finally, in order to accurately reproduce the original waveform in the amplified output, the vertical deflection amplifier must have an absolute minimum of phase shift. That amount of phase shift which is present must be proportional to the frequency of the component frequencies of the input waveform. As an example, suppose a complex waveform which is composed of a fundamental sine wave plus its second harmonic is applied to the vertical deflection amplifier. Suppose, further, that the amplifier delays the fundamental by the interval of time equal to one-quarter cycle. In order to preserve the original waveform, it is necessary that the second harmonic be delayed by an equal interval of time, to maintain the time relationship between the fundamental and the second harmonic. In order to obtain the same interval of time delay, the second harmonic must be delayed by one-half cycle. A third harmonic, if present in the input waveform, would have to be delayed by three fourths of a cycle. By this means a linear phase shift is produced in which the angular degree of phase shift is directly proportional to the frequency ratio of the harmonic to its fundamental.

Circuit Operation. The schematic shown below illustrates a typical deflection amplifier used to produce vertical deflection. This circuit is a basic type of circuit and is given only for the purpose of discussion. More de-



Typical Deflection Amplifier Used for Vertical Deflection

tailed discussion on actual circuits used as deflection amplifiers will be found in the two amplifier circuits to follow: Voltage Deflection Amplifier and Current Deflection Amplifier.

The circuit illustrated is actually a simple paraphase amplifier, which is used to produce two output voltages, equal in amplitude and opposite in phase (polarity). Since 50 volts per inch is a common deflection sensitivity for cathode-ray tubes, and since the gain of the stage (V1) is less than one, the amplitude of the input signal to this stage should be on the order of 50 volts. The input signal is applied through coupling capacitor C1 to the grid of the deflection amplifier tube, V1. The grid is returned to cathode through grid resistor R1. Plate voltage is applied through plate load resistor R4, and the cathode is biased by means of R2, which is bypassed by C2. The values of R3 and R4 are equal, and the same current passing through them will produce signals which are equal in amplitude but opposite in phase (polarity) at the plate and cathode. These two outputs, which provide push-pull deflection, are coupled, through C3 and C4, respectively, to the vertical deflection plates of cathode-ray tube V2. Equal deflection above and below a zero-voltage base line is provided by a centering control network consisting of dual control R5/R6, and resistors R7 and R8, which are bypassed by C5 and C6, respectively. Capacitors C5 and C6 insure that any electrons striking the deflection plates will be removed, to prevent a negative charge from building up. If a positive pulse of short time constant is applied at the input to the circuit, to C1, the output at the plate of V1 will be an inverted, or negative pulse, which is shown at the top plate of cathode-ray tube V2 as a pulse below the reference voltage. The output at the cathode of V1 will be an upright, or positive pulse, which is shown at the lower plate of V2 as a pulse above the reference voltage.

FAILURE ANALYSIS.

No Output. If a signal having an amplitude within the input limits of the deflection amplifier is applied to the input terminals, a defective tube is the most probable cause of a no-output condition. An open coupling capacitor C1, a shorted grid resistor R1, an open cathode resistor R2 or R3, or an open plate resistor R4 would also be responsible for no output, as would also a power supply failure.

Reduced or Unstable Output. In the typical circuit illustrated, the failure of a component is more likely to cause a reduced, distorted, or unstable output, rather than no output whatsoever. A leaky coupling capacitor C1 or a change in value of any resistor would contribute to a reduced or unstable output. If cathode resistor R2 or R3 changed in value, the outputs from the plate and cathode would be shifted from the designed center (which may or may not be at ground potential, depending upon the designed application), and the output would be shifted with respect to the zero reference. If shifted too far, peak distortion may result. A similar condition would occur if resistor R5, R6, R7, or R8 became either open-circuited or changed in value, or if capacitor C3, C4, C5, or C6 became leaky. If capacitor C3 or C4 became open-circuited or if capacitor C5 or C6 became shorted, one half of the normal output signal would be removed from the cathode-ray tube, which would then display only the positive or the negative portion of the signal, depending upon the half of the circuit which continued to function.

VOLTAGE DEFLECTION AMPLIFIER (FOR ELECTROSTATIC CRT).

APPLICATION.

The voltage deflection amplifier is used to amplify the input signals before they are applied (normally) to the vertical deflection plates of an electrostatic-deflection type of cathode-ray tube. It is also used to amplify the output signals of a sweep generator, before they are applied as a horizontal sweep voltage to the horizontal deflection plates of an electrostatic-deflection CRT.

CHARACTERISTICS.

Horizontal Deflection Amplifier. Input impedance is high, thereby preventing any loading of the preceding horizontal generator circuit.

Input capacitance is low, thereby preventing the attenuation of high frequencies.

High-frequency response is good, within the design limits of the amplifier (which in many cases are more restricted than those of the vertical deflection amplifier).

Low-frequency response is good, but only in exceptional cases do the requirements demand response down to zero frequency (direct current).

Bandwith depends on application design: usually covers a range of approximately 10 cycles to 100 kc; special applications may require a range of 1 cycle to 500 kc; other applications may require only a limited range, as in the switch-selected fixed sweeps used in radar deflection.

Output impedance is high, since no current need be supplied to the deflection plates of a CRT.

Gain depends on application design: as a rule it is relatively high, but not as high as that of a vertical deflection amplifier, because the input to the horizontal deflection amplifier is usually furnished by a sweep generator having an output level of appreciable value.

Balanced output, furnished by a push-pull type circuit, is desirable, in order to obtain a uniform deflection field, and avoid pattern distortion and defocusing effects inherent in single-ended output.

Vertical Deflection Amplifier. Input impedance is extremely high, thereby preventing any waveform distortion due to loading of the preceding output circuit supplying the signal to be displayed on the CRT. (Special applications may require a low value of input impedance, which must then be matched to the source impedance of the input signal. Normally this would occur only when the deflection amplifier is permanently connected to a signal source. This would not be true in the case of a deflection amplifier used in a test oscilloscope, which must function with widely varying source impedances.)

Input capacitance is very low, thereby preventing the attenuation of the high-frequency components of the input signal.

High-frequency response is very good, generally better than that of the horizontal deflection amplifier.

Bandwidth depends on intended application; usual range is 10 cycles to 1 megacycle. Test oscilloscopes of high quality may have a vertical amplifier bandwidth covering 2 cycles to 10 megacycles. Other applications, such as oscilloscopes designed for use in teletype and audio work, may require a range which includes zero cycles (direct current), but they may require only a limited range in the higher frequencies.

Output impedance is high, since only a potential difference (no current) is required by the deflection plates of a cathode-ray tube.

Gain is usually high, and a gain control is usually included in the circuit, calibrated both in step and vernier values of voltage gain and/or decibels.

Balanced output (push-pull) is desirable-more so than in the horizontal deflection amplifier, because the gain required of the vertical deflection amplifier is usually much higher than that of the horizontal amplifier, in order to obtain a uniform deflection field and reduce the effects of beam defocusing and pattern distortion.

CIRCUIT ANALYSIS.

General. The most versatile voltage deflection amplifiers are those used in the horizontal and vertical deflection circuits of high-quality test oscilloscopes. For this reason, the discussion that follows will be directed toward this application. In this way, circuitry peculiar to other applications will, in most cases, be included in this discussion as a matter of course.

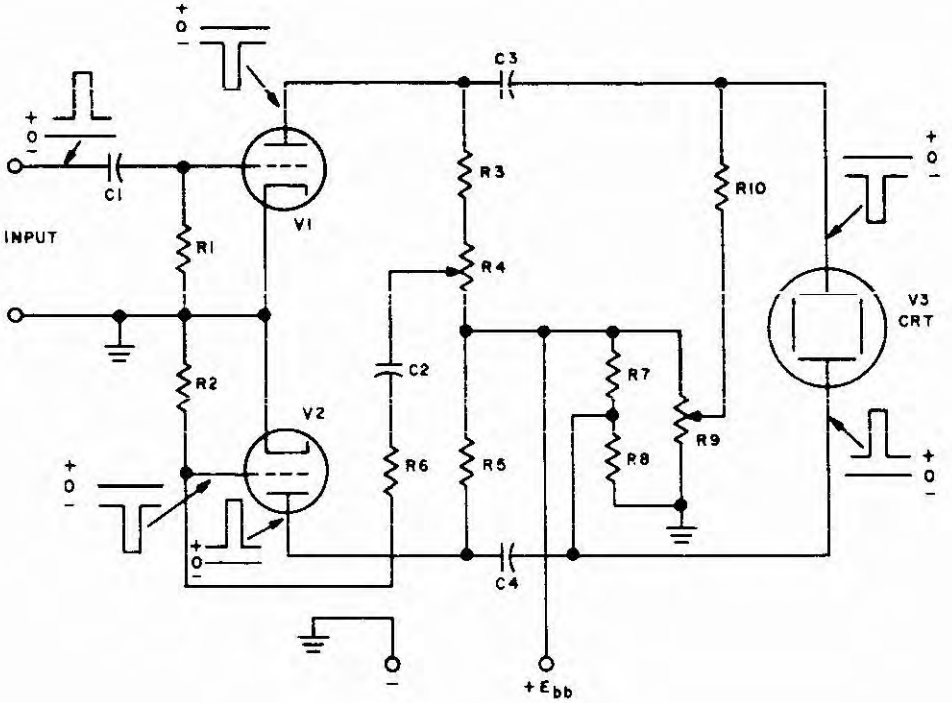
A horizontal (voltage) deflection amplifier is designed to amplify the signals from a sweep generator, and apply the amplified (sawtooth waveform) signals to the horizontal deflection plates of an electrostatic deflection type of cathode-ray tube. The sawtooth sweep voltage is applied to the grid of the amplifier tube through a potentiometer, which affords control of the amplitude of the signal used as the horizontal time base. This control is normally front-panel mounted and captioned HORIZONTAL AMPLITUDE. In order to amplify a sawtooth waveform of voltage whose frequency may be (in a test oscilloscope) switch-selectable to a range which may include 10 cycles and 50 kc as the low and high limits, respectively, the high-frequency response must be maintained up to 350 kc. The reason such high-frequency response is required is that, in order to reproduce a sawtooth waveform without appreciably distorting it, it is necessary to pass all frequencies up to the seventh harmonic of the fundamental frequency of the sawtooth wave. Thus, to pass a 50-kc sawtooth wave, a minimum bandpass up to seven times this value is required.

A vertical (voltage) deflection amplifier is designed to amplify the input signals – often extremely minute in value – which are to be displayed on the cathode-ray tube screen. The waveform of the input signal may vary from one extreme – a direct current, or zero frequency – to the other extreme – a square wave whose fundamental frequency in itself is relatively high. In order to pass a signal of zero frequency, a direct-coupled amplifier is the only choice. In order to pass a square wave with reasonable fidelity, a bandpass is required that includes the tenth **odd** harmonic of the fundamental frequency, which is a frequency of 21 times the fundamental. Therefore, the over-all bandpass required of the vertical amplifier has an extremely wide range. High-frequency compensation is usually included in the circuit, in order to extend the high-frequency response to the limits required. The gain is usually adjustable by means of both "coarse" and "fine" controls. The coarse adjustment, when provided, usually consists of a set of resistance-capacitance networks designed to have various degrees of attenuation. The networks of resistors and capacitors are used to maintain the attenuation of any one network constant over a wide range of frequencies. The fine adjustment of vertical gain is usually a potentiometer, located in the grid circuit of some stage of amplification other than the first. Here, it is isolated from the critical constants of the attenuation networks (which are located in the first stage), and does not vary the input impedance presented by the circuit to the signal source.

In small and inexpensive vertical deflection amplifiers, a single output tube is sometimes used. The output signal is coupled directly from the plate of this tube to one deflection plate of the CRT, while the other deflection plate is grounded. This is an unbalanced output, and has the following disadvantage: Each time the ungrounded deflection plate goes positive, on a peak of signal voltage, the average potential of the two vertical deflection plates rises to a considerable value above that of the second anode. This causes the electrons in the beam to be accelerated to a higher velocity than that imparted to them by the second anode potential. As a result, the trace brightens on positive peaks of the signal, and the beam is not deflected as much by a given increment of signal voltage because of the higher velocity. Negative peaks have an opposite effect, in that they reduce the average potential of the deflection plates, decelerating the beam to a lower velocity. As a result, the trace is reduced in brilliance on the negative peaks, and the sensitivity is increased because the beam is deflected more than it should be by a given increment of signal voltage. These effects may be eliminated by the use of a balanced, or push-pull, type of output circuit.

In both vertical and horizontal deflection amplifiers of better design, balanced or push-pull deflection is always used. In this type of circuit, signals that are equal in amplitude and opposite in polarity are applied to both deflection plates, neither of which is grounded. The positive side of the high-voltage power supply, which is connected to the accelerating anode of the cathode-ray tube, is grounded. These connections produce a minimum difference of potential between the accelerating anode and the deflection plates. As a result, two advantages are realized: First, the effect of the accelerating anode potential in distorting the deflection field is minimized, because of the fact that as one deflection plate is charged to a potential which is positive with respect to the accelerating anode (which is at ground potential), the opposite deflection plate is simultaneously charged to a potential which is an equal amount negative with respect to the accelerating anode. Under these conditions, a line of equal potential midway between the two charged plates is maintained at the same potential (ground) as that of the accelerating anode. This results in a minimum of beam defocusing and pattern distortion. The second advantage of the positive-grounded connection of the high-voltage power supply is that no high-voltage insulation is required between the accelerating anode and the deflection plates and their associated circuitry. In this respect the problems common to high-voltage circuitry, such as corona and high-voltage breakdown, are eliminated from the region of the cathode-ray tube which includes the neck, the flared portion, and the face (screen), as well as from the output circuits of the deflection amplifiers which feed the signals to the deflection plates. The high (negative) voltage is contained within a small portion of the tube neck at the base, wherein are located the filament and cathode, and the first anode.

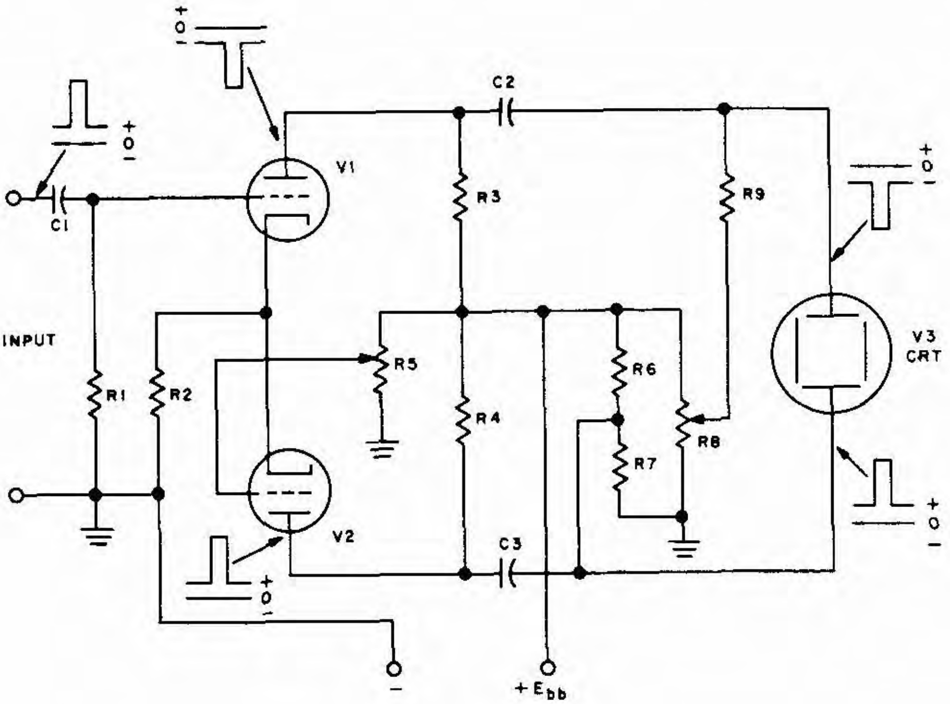
Circuit Operation. The schematics shown below illustrate two common types of deflection amplifiers used for electrostatic deflection. The first shows a phase inverter used to obtain two output voltages, equal in amplitude and opposite in polarity, from a single-ended



Typical Phase Inverter Used as Voltage Deflection Amplifier

input signal. In this circuit, the input signal, which is shown as a positive pulse, is applied through a coupling capacitor, C1, to the grid of a triode amplifier, V1. The grid is returned to ground through grid resistor R1. The amplified output, which is a negative pulse due to phase inversion in the tube, is taken from the plate and applied, through coupling capacitor C3, to one of the vertical deflection plates of the cathode-ray tube, V3. The plate voltage is applied through plate load resistor R3 and potentiometer R4. The negative output pulse at the plate of V1 also appears across R3 and R4, which act as a voltage divider. A reduced value of the negative output pulse is taken from a tap on the voltage divider by means of potentiometer R4 and applied, through coupling capacitor C2 and resistor R6, to the grid of the phase inverter tube, V2. Resistor R2 serves as the grid return for this tube. The output at the plate of V2 is a positive pulse, the amplitude of which is exactly equal to (although of opposite polarity) the amplitude of the output of V1, **provided that** potentiometer R4 is properly adjusted to furnish the correct value of signal input voltage to the grid of V2. This positive pulse output of V2 is coupled, through C4, to the other vertical deflection plate of the cathode-ray tube, V3. In this manner, equal and opposite signals are applied to the two deflection plates, to provide a balanced deflection.

A shift circuit is usually included as part of a deflection amplifier for electrostatic deflection, by means of which the electron beam of the cathode-ray tube may be positioned in the exact center of the screen, or may be moved to any desired initial position under conditions of no input signal. Although the shift circuit is not, in a strict interpretation, actually part of the deflection amplifier (because the amplifier furnishes its output at the point of coupling to the CRT - at coupling capacitors C3 and C4 in the previous schematic), it is usually shown along with the amplifier circuitry in order to show the complete load circuit. In the illustration shown, the shift circuit is composed of equal resistors R7 and R8, isolation resistor R10, and potentiometer R9. The bottom deflection plate of cathode-ray tube V3 is fixed at a potential half-way between + 250 volts and ground, by the voltage-divider action of resistors R7 and R8. When the adjustable arm of potentiometer R9 is set exactly half-way between the two ends of its resistance, the voltage at this point - which is furnished through isolation resistor R10 to the top deflection plate - will be exactly equal to the voltage at the junction of R7 and R8. Hence, the fixed d-c voltages applied to the top and bottom deflection plates will be equal, and the electron beam will



Typical Paraphase Amplifier Used as Voltage Deflection Amplifier

be positioned midway between them. By adjusting the movable arm of potentiometer R9 away from its center position, the top plate of the CRT may be made positive or negative with respect to the bottom plate, thereby positioning the beam above or below the center position on the screen.

The second type of deflection amplifier used for electrostatic deflection is the paraphase amplifier, shown in the following illustration. In this type of circuit a balanced output is obtained from a single-ended input signal by means of common coupling in the cathode circuit of both tubes, which accounts for the circuit being known as a cathode-coupled paraphase amplifier. The input signal, again shown as a positive pulse, is applied through coupling capacitor C1 to the grid of triode amplifier V1, with the grid returned to ground through grid resistor R1. Cathode bias is obtained by means of cathode resistor R2, which is common to both V1 and V2. Since R2 is unbypassed, the input signal at the grid of V1 also appears at the cathode, while the inverted signal appears at the plate as one output of the circuit. The signal at the cathode of V1 is applied, through direct connection, to the cathode of V2. The grid of V2 is connected to a balance potentiometer which acts as a voltage divider between E_{bb} and ground, to furnish the proper bias so that the output signal of V2 can be adjusted to equal that of V1. The positive pulse at the cathode of V2 will increase the bias, decrease the plate current, and produce a positive output at the plate of V2. The output signal at the plate of V2 is reversed in polarity from the input signal, as in any ordinary vacuum-tube amplifier. But, because the input to V2 is the signal voltage developed across cathode resistor R2, and because this signal is applied to the cathode of V2, which has its grid returned to ground through R5 and is thereby at ground potential insofar as the signal is concerned, the output signal at the plate of V2 has the same polarity as the input signal at the cathode of V2 or the input signal at the grid of V1. In this way, the output signals from the plates of V1 and V2, which are applied to the deflection plates of the CRT, are equal in amplitude but opposite in polarity (phase). Resistors R5, R6, and R8 and potentiometer R7 comprise a shift circuit which allows the electron beam to be positioned on the screen of the cathode-ray tube as desired, in the same manner as described in the preceding typical phase inverter circuit.

The circuit operation and the schematics given above have, for simplicity, omitted the additional compensation networks which are often included in specific applications. In order that deflection amplifiers do not restrict the bandwidth of the input signal, they must have wide frequency response, low distortion, and time delay proportional to frequency, similar to the characteristics of video amplifiers. Compensation circuits similar to those discussed under the paragraphs on Video Amplifier Circuits are used in deflection amplifiers, depending upon the amplifier design and intended application

FAILURE ANALYSIS.

No Output. Assuming that a signal of proper amplitude (and polarity if the deflection amplifier is specifically designed for single-polarity pulse operation) is applied to the input terminals, a defective tube should first be suspected as the cause of a no-output condition. An open input coupling capacitor C1, a shorted grid resistor R1, or an open common cathode resistor R2 (refer to paraphase amplifier circuit diagram), or a failure of the power supply would individually be responsible for no output. An open plate resistor on the input side of the circuit (R3 in the illustrations) would also result in no output. Components peculiar to a specific circuit may also be cause of circuit failure. As an example, referring to the second illustration on a typical paraphase amplifier, if plate resistor R4 became shorted, the high value of plate current that would flow through V2 would of course flow through the common cathode resistor, R2. As a result, both cathodes would be at a high positive potential. The grid of V1 would therefore be highly negative with respect to its cathode, and might possibly be biased beyond cut off. No signal output would thereby be obtained.

Reduced or Unstable Output. In both of the typical circuits illustrated, a number of conditions could contribute to a reduced, distorted, or unstable output. The failure of out-of-phase amplifier tube V2, its plate resistor, or its output coupling capacitor, if open, would be responsible for an output of approximately one-half the normal amplitude. An open output coupling capacitor from the plate of V1 would also result in an output signal of one-half normal amplitude. A change in the value of input grid resistor R1 would change the input impedance to the stage; this might affect the amplitude and possibly the waveform of the input signal. An open-circuited positioning potentiometer or its associated resistor (R9, R10 in typical phase inverter circuit; R7, R8 in typical paraphase amplifier circuit) would prevent the positioning of the waveform display on the screen of the CRT in the normal manner. An open resistor in the voltage divider connected across the positioning potentiometer (R7 or R8 in the typical phase inverter circuit; R5 or R6 in the typical paraphase amplifier circuit) would also be responsible for the failure of the positioning potentiometer to properly position the waveform display on the CRT screen.

CURRENT DEFLECTION AMPLIFIER (FOR ELECTROMAGNETIC CRT)

APPLICATION

The current deflection amplifier [illegible] input signals [illegible] vertical deflection coils of the deflection yoke used with [illegible]. In addition, it is used to supply the sweep signals which are used [illegible] to the horizontal deflection coils of the deflection yoke used with an electromagnetic-deflection CRT.

CHARACTERISTICS.

Horizontal Deflection Amplifier. Input impedance is high; loading of the preceding horizontal generator circuit is thereby prevented.

Input capacitance is low; attenuation of high frequencies is thereby prevented.

High-frequency response is very good: must be so to avoid the possibility of distorting the trapezoidal input waveform of voltage which is required to produce a sawtooth waveform of current through the horizontal deflection coils.

Low-frequency response is good, but does not include zero frequency.

Bandwidth depends on application design: may cover a range of 10 cycles to 100 kc, but the range is usually more limited because the specific application normally requires only a few fixed sweep frequencies.

Output impedance is relatively low, and must be matched to the load (deflecting coil) for maximum transfer of current with minimum waveform distortion. This requirement acts to restrict the bandwidth.

Gain depends on application design: the current gain (power gain) is usually high, but the voltage gain may be low -- even less than one.

Balanced output, furnished by a push-pull type circuit, is desirable, in order to obtain a uniform deflection field. However, the principal applications of the electromagnetic deflection type of cathode-ray tube, namely, radar and television, do not require the precise duplication of the input waveform that is essential in the principal applications of the electrostatic deflection CRT, namely, waveform analysis and complex wave amplitude measurement.

Vertical Deflection Amplifier. Input impedance is normally extremely high, in order to prevent any waveform distortion due to loading effects on the circuit supplying the input signal. However, since any particular application of an electromagnetic deflection type of cathode-ray tube normally operates with a permanently connected input circuit, the input impedance of the amplifier may be of a fairly low value, which must be matched to the source impedance of the input signal.

Input capacitance is low, in order to prevent the attenuation of high frequencies.

High-frequency response is very good: must be so in order to respond to extremely sharp input pulses without introducing appreciable time delay.

Low-frequency response is good, but does not include zero frequency.

Bandwidth depends on application design: may cover a range of [illegible] cycles to 100 kc, but the range may be more limited when only the leading edge and the length of an input pulse, and not the shape of the top of the pulse is of consequence, as in pulse display applications (radar).

Output impedance is relatively low, and must be matched to the load (deflecting coil) for maximum current transfer [illegible] waveform distortion.

Gain depends on application design: the current gain (power gain) is high, but the voltage gain may be low.

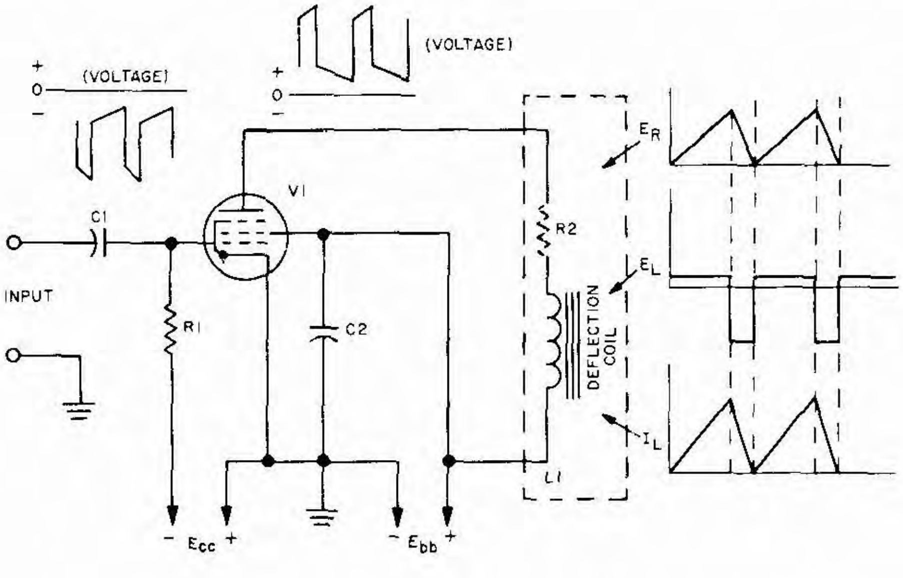
Balanced (push-pull) output is desirable, both from the standpoint of the high power output with minimum distortion required for magnetic deflection, and the need for an absolute minimum of beam defocusing when pinpoint radar target presentation is required.

CIRCUIT ANALYSIS.

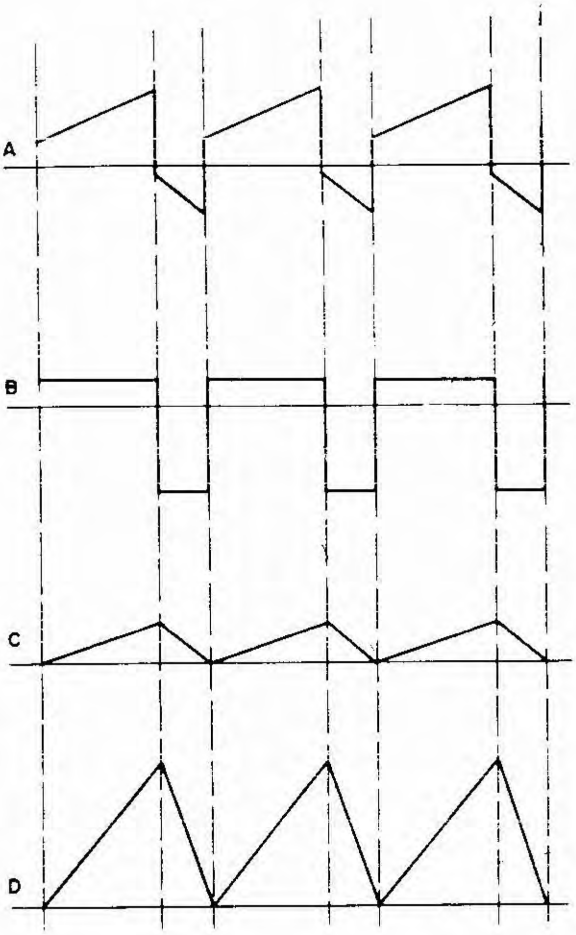
General. The deflection of the electron beam in an electromagnetic deflection type of cathode-ray tube is proportional to the strength of the magnetic field set up within the tube, which is in turn proportional to the value of current passing through the deflection coil. Since it is desirable to deflect the electron beam linearly, the current through the coil must increase linearly with time. When the end of the sweep is reached, the electron beam must be returned to its starting point quickly. The current wave required for electromagnetic deflection must therefore be of sawtooth shape if the resultant sweep is to be linear. It should be observed that it is the **current** wave which must be of sawtooth shape for an electromagnetic tube, not the **voltage** wave as in an electrostatic tube.

The deflection coils, through which the deflection amplifier output current flows, consist of wire wound around either a non-magnetic core or an iron core. The wire used in the coil has, in addition to the desired inductance, some amount of resistance. As a result, the sawtooth current must flow through the equivalent of a series resistive-inductive (R-L) circuit. Since a square wave of voltage will produce a sawtooth wave of current in a pure inductance, while a sawtooth wave of voltage will produce a sawtooth wave of current in a pure resistance, the combination of a square wave and a sawtooth wave of voltage is required to produce a sawtooth wave of current in a circuit containing both resistance and inductance. Such a combined waveform has the shape of a trapezoidal waveform of voltage. This, then, is the waveform which must be amplified by the current deflection amplifier.

Circuit Operation. The schematic shown below illustrates a simplified typical deflection amplifier for producing a horizontal time base using magnetic deflection. The input signal, which is a trapezoidal waveform of voltage as shown in the illustration, is applied through coupling capacitor C1 to the grid of pentode amplifier V1. The amplifier is operated as a Class A stage, with fixed bias applied from a negative power source. Sufficient negative bias is applied to the grid, through grid resistor R1, to prevent the grid from going positive with maximum signal input. The amplifier tube, V1, is a pentode or a beam power type, in order to obtain the power amplification that is required to furnish sufficient current to the deflection coil. This coil may require between 50 and 100 milliamperes of current for maximum beam deflection. The output of V1 is applied to the deflection coil, which in the illustration is represented by an inductance, L1, with a resistance, R2, in series with it, shown as a dotted resistance because it is actually a part of L1. The output voltage waveform at the plate of V1 is trapezoidal; when this waveform is applied to the series R-L circuit (deflection coil), the voltage waveform appearing across the resistance is resolved to a sawtooth shape, while that appearing across the inductance is resolved to a square-wave shape. The square wave of voltage across the inductance causes a sawtooth wave of current through it, which is the required waveform for producing a horizontal time base deflection on the screen of the cathode-ray tube. The development of the sawtooth current waveform from the trapezoidal voltage input waveform is shown in the following illustration. The trapezoidal voltage input waveform to the grid of amplifier V1 is



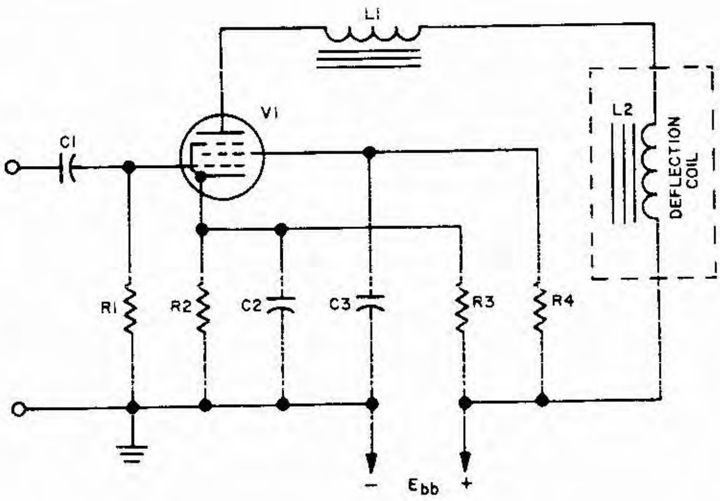
Typical Current (Electromagnetic) Deflection Amplifier



Development of Sawtooth Current Waveform in Deflection Coil from the Trapezoidal Voltage Waveform Input to Amplifier

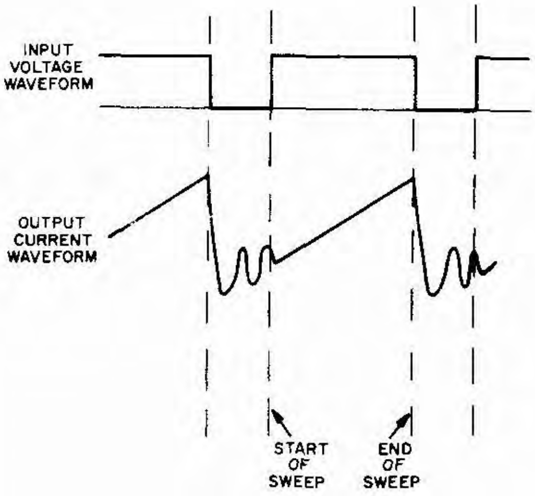
shown at a; differentiated voltage which appears across the inductance is shown at b; the integrated voltage which appears across the resistance (of the coil) is shown at c; the current through the deflection coil, which is the composite result of waveforms b plus c, is shown at d.

A second circuit for producing a horizontal time base for magnetic deflection is shown in the illustration below. The input signal to this amplifier is a square wave, instead of the trapezoidal wave required in the previous circuit. This signal is applied, through coupling capacitor C1, to the grid of a pentode or beam power amplifier, V1. The grid is returned to ground through resistor R1. The positive voltage applied to the cathode of V1, from the plate supply by means of the voltage-divider action of resistor R3 and cathode resistor R2, maintains V1 biased to cutoff in the absence of an input signal. When the first positive pulse of the input square wave reaches the grid, the tube conducts heavily. The resulting plate current, flowing through deflection coil L2 and inductor L1, rises exponentially toward a value which would be limited only by the resistance of the circuit. Before this limiting point is reached, however, conduction of the tube is suddenly interrupted by the negative-going end of the square-wave input pulse. In this way, only a relatively linear portion of the exponentially rising waveform is utilized. When the conduction of the tube is interrupted at the end of the positive square wave, V1 is cut off, and the current decays rapidly to zero. This rapid decay is due to a change in the time constant of the circuit between the rise and fall of the current. During the rise of current, the circuit time constant (which is given as inductance divided by resistance, or L/R) is long, because of the large value of inductive reactance (due to the large inductance) and the small value of resistance in the circuit. The resistance is composed of cathode resistor R2 and the low value of plate resistance of V1. During the decay of current, the time constant is made short, as a result of the increase in the value of plate resistance when V1 stops conducting. With the shortened time constant, the current decays rapidly. The additional value of inductance in the circuit due to inductor L1 increases the time constant, to produce a slow build-up of current. Inductor L1 may be effectively removed from the circuit, by shorting across it, when faster sweep deflection rates are required.



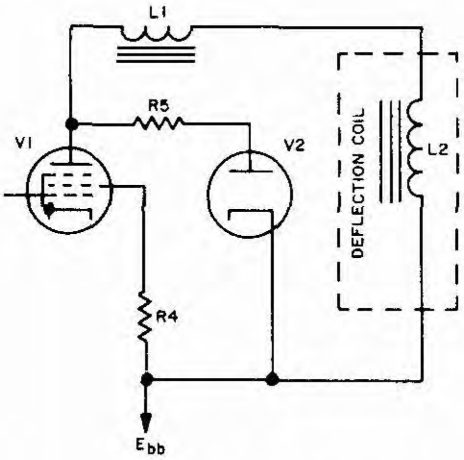
Current (Electromagnetic) Deflection Amplifier Utilizing Square-Wave Input

The sudden decay in current flowing in the deflection coils, when the tube stops conducting, causes a counter e.m.f. to be produced in the coil which opposes the current decay. In addition, the circuit may be shock-excited into oscillation by the sudden change in value of current. Although the oscillations gradually die out, they may continue into the following sweep, especially if the circuit Q is high. This condition may result in a nonlinear start of the build-up of current in the coil, and therefore a nonlinear sweep, as shown in the following illustration.



Undamped Oscillations in Deflection Coil Current

These oscillations may be eliminated, or damped out, by lowering the Q of the circuit by means of a resistor shunted across the coil. However, this wastes some of the deflection current; a more satisfactory method incorporates the use of a damping diode shunted across the deflection coil, as shown in the illustration below. In this circuit diode V2 acts to damp out the oscillations in the following manner: When the current through V1 is increasing (during the rise of the sawtooth, current wave shown in the illustration above) to provide the sweep deflection, the voltage at the plate of V1 is lower than the plate supply voltage by the amount of voltage drop in the deflection coil and inductor. The cathode of damping diode V2 is therefore more positive than its plate, and the diode will not conduct. When the current through V1 falls to zero (at the end of the sawtooth current wave illustrated), the voltage at the plate tends to rise above the plate supply voltage due to the fact that the counter e.m.f. generated by the inductance adds to the plate supply voltage. When this condition is reached, damping diode V2 conducts, and any oscillations are dissipated in resistor R5.



Deflection Amplifier Output Circuit With Damping Diode Added

Balanced output (push-pull) circuits, when used, usually operate by means of a phase inverter circuit fed from a single-ended source, as described in the previous circuit on Voltage Deflection Amplifiers. In some cases in radar deflection circuitry, the two outputs obtained by means of a phase inverter are separately amplified by individual single-ended deflection amplifiers, and then applied to the two separate windings of a split-winding deflection yoke.

FAILURE ANALYSIS.

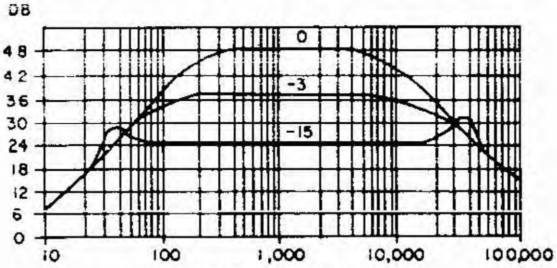
No Output. Assuming that a signal of proper amplitude and waveform (square wave or trapezoidal wave, depending on circuit design) is applied to the input terminals, a defective tube would be the most likely cause of a no-output condition. If the tube is found capable of operation, an open input coupling capacitor C1 or open grid resistor R1, or open cathode or screen resistors, if used, may be the cause of no output. Since a current-deflection amplifier is characterized by a relatively high value of plate-current flow, a common source of trouble is an open deflection coil. If the coil is open-circuited, and the circuit is similar to those previously shown under Circuit Operation, the application of screen voltage to the tube with no plate voltage present may result in a burned out tube or poor emission, because of excessive screen current. The same condition may prevail if the deflection coil is remotely located from the amplifier, and the interconnecting cable is inadvertently disconnected during operation. No output may also be due to failure of the plate voltage supply.

Reduced or Unstable Output. A change in value of almost any of the circuit components, due to age or partial failure, may contribute to a reduced output. If the capacitance of input coupling capacitor C1 changed or the resistance of grid resistor R1 changed, the output would be affected. If the cathode bypass capacitor (if one is used) became either open or shorted, the bias would be changed, resulting in either decreased output due to degeneration (if open) or distortion due to no bias (if shorted). If the circuit incorporates fixed cathode bias obtained through a voltage divider from the E_{bb} line, an open resistor on the E_{bb} side of the cathode (R3 in the second circuit illustrated) would interrupt the fixed bias, and the circuit would operate with self-bias, which may produce distortion under high signal input conditions. A decrease in the voltage of the plate supply, due to faulty operation, would also be responsible for a reduced output.

FEEDBACK AMPLIFIERS.

Feedback amplifiers are divided into two basic types, those employing positive feedback, and those employing negative feedback. Positive feedback consists of feeding back a portion of the signal in-phase with the input so that the overall output is increased because of the feedback. If left uncontrolled the additional output, in turn, supplies a proportionately larger input and the overall output is further increased. This cumulative effect of building up the signal amplitude is termed **regeneration.** When the output of an amplifier is fed back into the input in a regenerative manner the final result is to cause the circuit to oscillate at some particular frequency or over a small range of frequencies. Thus the r-f oscillator is basically a regenerative feedback amplifier, which eventually stabilizes at some maximum amplitude. Generally speaking, the use of positive feedback is restricted to oscillators, or special regenerative receivers operating at radio frequencies. It is also used sometimes at lower frequencies (within the audio range) to supply high gain over a single stage of amplification, which is controlled by additional stages with negative feedback.

When the feedback is made 180 degrees out-of-phase with the input signal so that it reduces the overall output of the amplifier, it is considered to be **degenerative** and is known as negative or **inverse** feedback. Although the application of negative feedback reduces the gain of the amplifier below that which would normally be obtained without feedback, it provides many desirable features. In general, it improves the behavior of the system, and increases the bandwith. It improves the linearity of the system, and consequently produces less intermodulation and harmonic distortion. At the same time, the input impedance is increased and the output impedance is decreased. Any noise generated within the amplifier system itself is reduced, but it has no effect on any externally induced noise. Since a portion of the output is fed back to the input, any change in circuit values is in effect automatically compensated for, so that the circuit gain is stabilized. The following graph shows the overall frequency response and gain for an amplifier without any feedback, and amplifier with 3 db of negative feedback, and one with 15 db of negative feedback. Although the overall amplification is decreased by the feedback, the frequency response is increased, and is made flatter over a greater range. The peaks occurring at the extreme low and high frequencies are due to phase shift caused by reactance effects changing the feedback at these frequencies from negative to positive. The loss of amplification when feedback is used can be recovered by employing additional stages of amplification. In fact, with good design it is possible to use a single stage of positive feedback to provide the lost gain, with the remaining amplifier stages using inverse feedback. Typical positive and negative feedback circuits are discussed in the following paragraphs.



Typical Negative Feedback Response Curves

POSITIVE FEEDBACK (DIRECT, REGENERATIVE) AMPLIFIER.

APPLICATION.

The positive feedback (regenerative) amplifier is used in audio and r-f stages to supply a greater output than is possible through normal gain in a single-tube amplifier.

CHARACTERISTICS.

Uses self-bias, but fixed bias may also be used if desired.

Provides the amplification of two or three tubes in a single stage.

A portion of the output voltage is fed back (in-phase) with the input signal.

Distortion is increased in proportion to the amount of feedback.

Feedback may be accomplished by resistive, inductive, or capacitive methods.

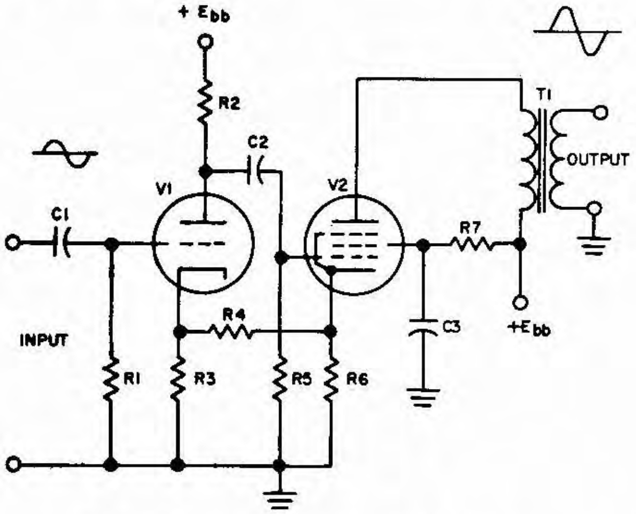
Usually only one stage of positive feedback is employed.

Oscillation may occur at extremely low or extremely high frequencies because of reactance effects.

CIRCUIT ANALYSIS.

General. Because the electron tube amplifier inverts the signal in the plate circuit, it is necessary either to use a transformer to reverse the phase, or to pass the signal through another stage to obtain positive feedback. The input circuit operates as a mixer and adder, with the output signal being the sum of the input signal and the positive feedback voltage, multiplied by the gain of the stage. In r-f amplifiers, general practice is to couple a portion of the plate output back to the input through an r-f transformer, and to vary the coupling between the two coils mechanically or electrically to control the amount of feedback. Since the design and operation is unique for each application, the following typical circuit shows only one particular arrangement of positive feedback. It will serve, however, to illustrate and describe the basic principles and operation of positive feedback so that they can be applied in the analysis of similar circuits even though the circuits are not identical.

Circuit Operation. A typical cathode feedback arrangement using positive feedback to overcome degeneration provided by unbypassed cathode resistors with improved audio gain and response is shown in the accompanying schematic.



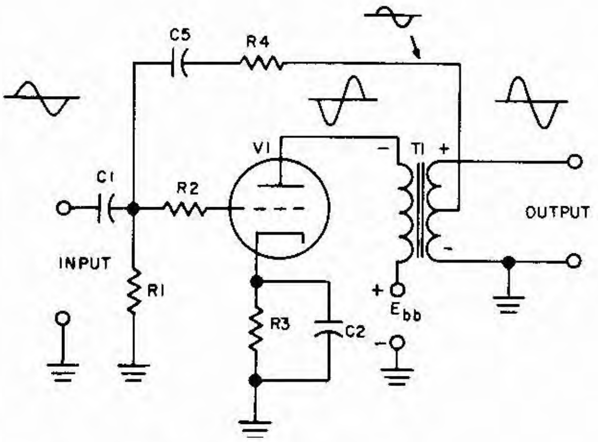
Cathode Coupled Positive Feedback Amplifier

The two-stage amplifier consists of a triode resistance-coupled stage driving a pentode transformer-coupled output stage. Capacitor C1 and resistor R1 form the RC input circuit to triode V1. Cathode self-bias is provided by cathode resistor R3, and the output is developed across plate resistor R2. Capacitor C2 and resistor R5 are the RC coupling circuit for driving pentode V2, with cathode bias supplied by R6. Both cathode resistors R3 and R6 are unbypassed, which normally provides degeneration. However, by connecting the cathode of V2 to the cathode of V1 through feedback resistor R4, the positive feedback voltage cancels the degenerative effects of cathode resistor R3. Thus, the output of V1 is increased by the feedback voltage. Resistor R7 is the screen voltage dropping resistor for V2, bypassed by C3. The output of V2 is transformer coupled through T1 to a loudspeaker or to another amplifier stage, as desired.

Assume a sine-wave input signal applied to C1 and is passed to the grid of V1, appearing across R1. On the positive excursion of the signal, V1 grid is driven in a positive direction. The increasing plate current through plate resistor R2 produces a negative-going output voltage, which is coupled through C2 to drive the grid of pentode V2. The negative driving voltage appears across R5, and causes the plate current of V2 to decrease. The changing plate current through the primary of output transformer T1 induces an output in the secondary. Screen voltage is obtained by dropping the supply voltage through R7, which is held at ground potential for audio voltage changes by screen bypass capacitor C3, so that the screen voltage remains a constant dc and is unaffected by the signal variations. When the plate current of V2 decreases with the negative driving signal, the cathode voltage developed across R6 is negative-going. A portion of this voltage is coupled back through feedback resistor R4 to the cathode of V1. Thus as the increasing plate current of V1 causes an increasing (positive-going) cathode voltage across R3, the negative voltage from V2 cathode cancels it and prevents the input signal from producing a degenerative cathode voltage on V1. Thus instead of the instantaneous bias on V1 increasing it is held at the same level, or even slightly decreased by the negative feedback voltage from V2 cathode. When the feedback is made sufficient to produce a slightly decreasing bias on V1, the output voltage is increased by this positive feedback. The effect is as though the grid input signal were increased.

On the negative-going portion of the input signal the opposite action occurs. The negative swinging grid voltage causes V1 plate current to decrease, and produces a smaller bias across cathode resistor R3. At the same time, the plate voltage of V1 becomes positive-going and drives V2 grid in a positive direction. Thus the plate current of V2 is increased, and a higher cathode voltage is developed across V2 cathode resistor R5. This positive voltage, in turn, is fed back through R4 to the cathode of V1, which is the same as increasing the bias, or applying a larger negative-going input signal. The plate output of V1, therefore, is greater. Since R4 is larger than R3 and R6, the cathode voltage developed across R3 has little effect on V2. Because of the feedback arrangement, the output resistance (plate resistance) of V2 is decreased to a lower value and less turns are needed on T1 to produce an appropriate output match, and a large power output is developed. The reduced turns on T1 produces a reduction in total capacitance between turns and increases the effective high frequency response over that which would normally be obtained.

Circuit Variations. A typical positive feedback circuit using a tapped output transformer to supply voltage feedback over a single stage is shown in the accompanying schematic.



Transformer Coupled Positive Feedback Amplifier

From an examination of the schematic, it is seen to be a conventional audio amplifier, with a resistance coupled input and transformer coupled output, except for the special feedback provisions. This consists of current limiting resistor R2 in series with V1 grid, and the feedback arrangement of R4 and C5 connected from the secondary of the output transformer back to the grid of V1. While T1 secondary is tapped, a similar arrangement may be produced by using an untapped secondary with a resistive voltage divider across it. The important point to remember about T1 is that the secondary is phased to produce a positive feedback signal. Normally, the primary signal of T1 is inverted from that of the input signal by conventional tube action, thus it *is necessary that the secondary winding be phased so as to* again invert the signal (otherwise an additional stage of amplification would be necessary to complete the inversion). When the input signal is applied, assuming a positive-going sine wave, the increased positive signal on the grid of V1 causes an increasing plate current. This change of current through the primary of T1 induces a positive-going output in the secondary. The amount of feedback between the tap and ground is applied in shunt with the input signal, and both *signals are combined across R2. Thus the input signal is* increased and the output likewise. On the negative-going excursion, the opposite action takes place. The decreasing plate current through the primary of T1 induces a positive-going voltage in the secondary, which is phased by reversing the winding to be a negative-going signal, and a portion of this voltage is fedback through R4 and C5 to enhance the negative swinging input signal and further decrease the output. By using capacitor C5 the feedback becomes phase controlled. The *larger the feedback capacitor, the greater* the effect on low frequencies, while R4 acts as an attenuator and a phase shifting resistor. With proper proportioning of these parts the feedback is stabilized and prevented from developing into negative feedback (because of excessive phase shift at the lower frequencies). However, positive feedback used alone tends to increase distortion, hence it is usually combined with negative feedback in following amplifier stages to accomplish the increase of gain with reduced distortion.

FAILURE ANALYSIS.

No Output. Lack of plate voltage, improper bias, as well as a defective tube, open coupling capacitors or output transformer can produce a loss of output. Measure the plate and bias voltages with a high resistance voltmeter. If no voltage appears on the plate of V1, R7 is open, while if no voltage appears on V2 plate, the primary of T1 is open or shorted to ground. Use an ohmmeter to check for resistance and shorts to ground. If no signal appears at the input on V1 grid when using an oscilloscope, coupling capacitor C1 is open. Likewise, if a signal appears on V1 plate but not on V2 grid, coupling capacitor C2 is open. If a signal appears on V2 grid but not on V2 plate, either V2 is defective, or screen resistor R7 is shorted by capacitor C3. If screen resistor R7 is open, a small output signal will appear on V2 plate because of the tube acting like a triode. If the tube is considered at fault replace it with a known good one. When a signal appears on the grid of V1, but does not appear on the plate and the measured cathode bias is normal, replace V1. If cathode resistors R3 or R6 are open no signal can appear on either V1 or V2, respectively.

Low Output. Low screen or plate voltage will produce a low output. Check for proper plate, bias, and screen voltage with a voltmeter. Too high a bias caused by heavy plate current from an external short or defective tube will cause the tube to operate near saturation or cutoff and reduce the output accordingly, usually with noticeable distortion. If feedback resistor R4 opens degeneration will cause a reduced output. If C2 is leaky, the bias on V2 grid will show positive and the tube will be held in heavy saturation producing little or no output.

Distorted Output. With positive feedback it is normal for greater distortion to occur than for the same stage without feedback, unless compensated for by a later stage using negative feedback. Excessive distortion can be caused by low plate or screen voltages or by improper feedback voltage. There may even be oscillation occuring at extremely low or extremely high frequencies because of phase shift effects. Use an oscilloscope to follow the signal through the circuit and note where the distortion appears, then check the associated parts.

NEGATIVE FEEDBACK (INVERSE, DEGENERATIVE) AMPLIFIER.

APPLICATION.

Negative feedback is used in speech amplifiers, modulators, and high-fidelity sound systems to improve the overall response and stabilize the gain.

CHARACTERISTICS.

Uses self bias, but fixed bias may also be used, if desired.

Usually requires an additional stage or more of amplification to make up for the loss produced by negative feedback.

A portion of the output voltage is fed back out-of-phase with the input signal.

Distortion is decreased in proportion to the amount of feedback.

Oscillation may occur at extremely low or high frequencies because of adverse phase shifts causing the feedback to change to positive instead of negative.

Noise or distortion generated within the amplifier is always reduced.

Externally induced noise (such as thermal noises generated in preamplifier stages) is not affected.

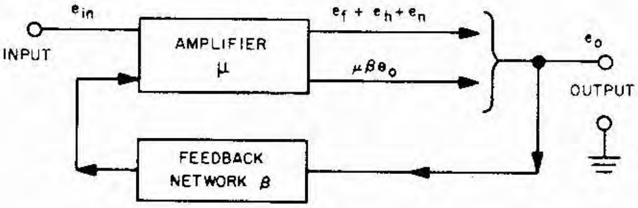
Bandwidth and linearity of the system is improved, and output impedance is reduced.

Change of circuit values is automatically compensated for so that circuit gain is stabilized and operation is improved.

CIRCUIT ANALYSIS.

General. There are many methods of developing negative or inverse feedback. It may be used over a single stage or over a number of stages (usually not more than three). Since the feedback must always be degenerative, and odd number of stages are usually used. Either voltage or current feedback may be employed. Although the circuit is usually arranged so that the feedback is accomplished in series with the input signal, it may be connected in shunt, if desired.

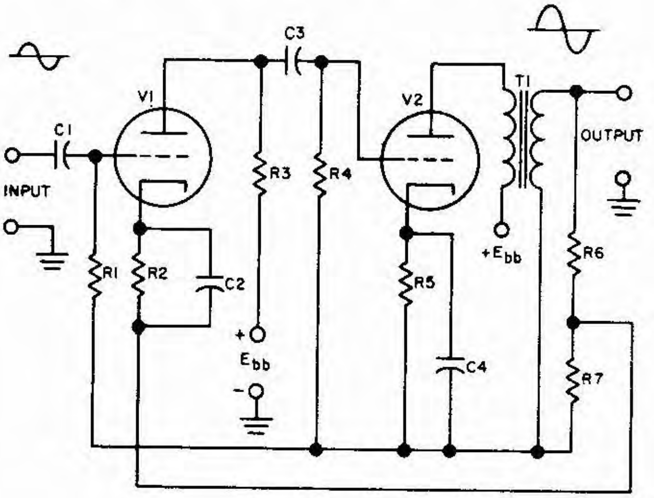
The accompanying block diagram shows the manner in which feedback is normally accomplished.



Typical Inverse Feedback Arrangement

The total output voltage is made up of two parts: that resulting from the input voltage e_{in} and that resulting from the feedback input βe_o. The first part consists of fundamental output e_f which is equal to μe_{in}, plus harmonic and intermodulation distortion components e_h, plus any noise e_n generated within the stage. The sum of these components is the total output e_o, which would normally exist without feedback. With feedback voltage βe_o applied to the input, the second part of the output voltage is $\mu\beta e_o$, which contains a portion of all the three previously mentioned components, plus new harmonic and intermodulation distortion components. Since the feedback opposes the normal signal, the noise and harmonics are reduced by the inverse feedback to a negligible value, and the fundamental output is also reduced. Mathematically it can be demonstrated that both the fundamental, harmonics, and noise are reduced by the factor $1/1\text{-}\mu\beta$, where $\mu\beta$ is the feedback factor.

Circuit Operation. The accompanying schematic shows a typical two-stage triode inverse feedback amplifier.



Two-Stage Triode Negative Feedback Amplifier

Except for the feedback connection, V1 and V2 form a conventional triode resistance coupled amplifier chain, using an output transformer in the final stage. The negative feedback is inserted in series with the cathode bias resistor of V1 through a voltage divider consisting of R6 and R7 connected across the secondary of the output transformer. When a positive input signal is applied, it passes through C1 and appears across grid resistor R1, driving the grid of V1 in a positive direction and increasing plate current flow. The increased plate current flow through plate resistor R3 causes a voltage drop, which is applied as a negative-going driving voltage through C3 to the grid of output amplifier V2. For the moment, assume that V1 cathode resistor, R2, is grounded, so that only the d-c bias developed by average current flow appears. Since R2 is bypassed by C2, any instantaneous changes in signal current have no effect on the bias and full tube amplification is obtained. With the negative driving voltage from V1 appearing across grid resistor R4, V2 plate current reduces, and the reduction of current through the primary of T1 induces an output voltage into the secondary winding of the output transformer. V2 is also cathode biased, with average plate current flow through R5 developing the d-c bias, and is bypassed by C4 so that the signal variations have no effect on bias voltage. With the positive side of the T1 secondary connected to voltage divider R6 and R7, a positive-going portion of the output voltage taken across R7 is applied in series with cathode resistor R2 of tube V1 (R2 is grounded through R7). Thus, this small portion of positive output voltage instantaneously increases the cathode bias, reducing the output accordingly.

When the input signal goes negative the opposite action ensues, a negative output voltage is developed across the feedback voltage divider, and is applied V1 cathode to decrease the bias and increase the output. In both instances, the feedback voltage acts in opposition to the normal effect of the input signal, just as if a voltage 180 degrees out-of-phase with the input signal was inserted on the grid of V1. Since the feedback voltage is only a fraction of the input (about one tenth), the input signal is only slightly reduced, but the additional amplification obtained through the gain of the amplifier increases the amount of feedback voltage in the plate of the output stage. Thus, the overall gain is considerably reduced over what it would normally be without feedback. The net effect is to flatten out the amplifier response curve so the gain at low, mid-band, and high frequencies is about the same. Hence with a flatter response greater fidelity is obtained. Any hum produced by the final amplifier supplies a correcting feedback voltage which effectively cancels and reduces the hum, and any harmonic distortion is affected likewise. When the input signal is increased in amplitude, the output also increases but the gain remains relatively constant because of the feedback. Thus the amplifier may be driven harder and still produce better fidelity and less distortion than without feedback. The limit of drive is reached when grid current flows in the input stage, since the input signal itself becomes distorted and feedback will not correct this condition. With proper design, up to three stages of high gain amplification may be used. Beyond this, excessive phase shift is produced through the feedback, network, so that the feedback changes from negative to slightly positive at the low and high frequency ends of the response curve and usually causes oscillation and distortion, which makes the extra amplification useless.

FAILURE ANALYSIS.

No Output. An open input, cathode, or plate circuit, lack of plate voltage, or a defective tube can cause a loss of output. Check the plate voltage and cathode bias with a high resistance voltmeter. This will verify that resistors R2, R7, and R5, as well as R3 and the primary of T1 are not open, and that neither C2 or C4 is shorted. Check for an input signal using an oscilloscope, if the signal appears at the input but not on the grid of V1, either C1 is open or V1 has a grid to cathode short. Replace the tube with a known good one, if the condition persists check the capacitance of C1 with an in-circuit capacitance checker. If the signal appears on the grid but not on the plate, and normal plate voltage exists, replace V1. If the signal appears on the plate of V1 but not on the grid of V2, capacitor C3 is open or V2 is defective. Replace V2 with a known good tube. If the condition persists check the capacitance of C3. If the signal appears on the grid of V2 but not on the plate, either the tube is defective or T1 primary is shorted. A resistance check will determine if T1 is shorted. If the signal appears on the plate of V2 but not at the output, the secondary of T1 is either open or shorted. Check the resistance and continuity of T1 with an ohmmeter.

Reduced Output. If the plate voltage is low, or the cathode bias is too high, there will be a reduction of output. A defective tube can cause both low plate voltage and high cathode bias, because of heavy conduction due to a shorted condition. Likewise, low emission will also cause a reduced output. Replace both tubes with known good ones and observe if the output returns to normal. Check the plate and bias voltages with a voltmeter if the condition persists, since aging plate or bias resistors may increase in value and cause either a reduction of plate voltage or bias, or both. If either coupling capacitor C1 or C3 is leaky or shorted, the output will be reduced because of improper bias (plate voltage from the preceding stage will be applied the grid). If either the primary or secondary of T1 is partially shorted or develops a low leakage to ground the output will be lower than normal. If an oscilloscope check shows all grid and plate signals normal except that for V2 plate, replace T1 with a good transformer.

Distorted Output. Since the negative feedback practically eliminates harmonic distortion, excessive distortion indicates failure of the feedback loop. Check R6 and R7 with an ohmmeter for the proper value. Replace tubes V1 and V2 with known good tubes, and check to be certain that the input signal itself is not causing the distortion. Any other condition will be revealed by bias and plate voltage checks. Too low or too high a bias or too low a plate voltage can cause distortion.

PART B. SEMICONDUCTOR CIRCUITS

AUDIO AMPLIFIERS.

The semiconductor type of audio amplifier is similar to its vacuum tube counterpart; however, there are a number of significant differences which must be considered. For example, the electron tube audio amplifier normally operates as a voltage amplifier except for the final output stage, while the transistor audio amplifier operates as a current amplifier in all stages. Thus, the electron tube represents a high-impedance, voltage-sensitive device, while the transistor represents a low-impedance, current-sensitive device.

Since the transistor is basically a low-resistance device, it may draw current from the input source or the preceding stage. (Except in class B audio amplifiers, the drawing of grid current in tube amplifiers represents distortion and is never used. While class C amplifiers do draw grid current in normal operation, they are never used for audio amplification.) In this respect, each transistor amplifier stage may be considered as a current or power amplifier operating at a current or power level higher than that of the preceding stage, but lower that that of the following stage.

While the types of transistor amplifiers are similar to the types of electron tube amplifiers, such as preamplifiers, driver-amplifiers, and output stages, the power levels employed are much lower. Thus, transistor preamplifiers generally operate in the microwatt range, amplifiers and driver stages operate in the low milliwatt range, and output stages operate in the high milliwatt or low watt range. At present, power outputs of 50 to 100 watts for transistor audio amplifiers are normal, whereas power outputs of 1 to 10 watts were considered high until recently. Therefore, any general statements relating to powers applicable to the following circuits must not be taken too literally, since they will change with the state of the art. Actually, except for extremely high-powered transmitter applications, the transistor audio amplifier today compares very favorably in many respects with the electron tube audio amplifier. The small size and reliability of the transistor, plus its long life and low heat-producing ability make its use popular in equipments normally requiring many stages; in addition, the ability to operate at low voltages makes the transistor particularly useful in portable and mobile equipments operating from battery supplies. In larger equipment, power for transistor operation may be obtained from special low-voltage power supplies employing semiconductor diodes and regulators, thus eliminating the need for batteries.

Transistor amplifiers may be operated class A, B, AB, or C, just as with electron tube amplifiers. When operated class A, they are operated on the linear portion of the collector characteristic. The class A biased transistor has a continuous flow of collector current during the entire cycle, whether a signal is present or not, which corresponds with the action in its electron tube counterpart. They may be operated in this manner, in either single-ended or push-pull circuits. Class B amplifiers can be biased either for collector current cutoff or for zero collector voltage. They are always operated push-pull to avoid serious audio distortion. The best power efficiency is obtained when they are biased for collector current cutoff, since collector current will flow only during that half-cycle of the input voltage that aids the forward bias. When biased for zero collector voltage, a heavy current flows when no signal is present, and practically all the collector voltage is dissipated across the load resistor. Although heavy current flows, the power dissipation in the transistor is very low because power is the product of both **current and voltage**, and the voltage is practically zero (due to the small voltage drop across the very low impedance of the transistor). The collector current varies only during that portion of the cycle when the input voltage opposes the forward bias. Under these conditions low efficiency is obtained and the forward current transfer ratio (α_{fb}) is appreciably reduced. The class AB transistor amplifier is biased for either collector voltage cutoff or current cutoff for less than a half-cycle of operation. In this case the efficiency is somewhat greater than that for class A, but less than that for class B, and the statements just made concerning the class B amplifier also apply to the class AB amplifier. Class C amplifiers are biased so that the collector current or voltage is zero for more than a half-cycle; thus, they are not used for audio amplification because of the serious audio distortion produced. However, they can be used single-ended or push-pull (or push-push) for r-f applications.

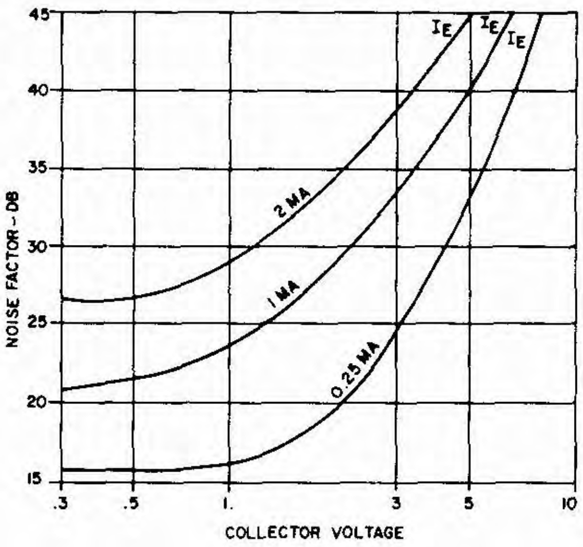
The most important factors to be considered in an analysis of audio amplifiers are input and output impedances, signal and noise levels, and required frequency response. Since the transistor is basically a low-level current device it is most important that the input and output impedances be matched to obtain maximum power gain. (In the electron tube circuit this is usually only a problem in the output stage.) The ratio of signal-to-noise power at the input to signal-to-noise power at the output gives the noise factor

(figure), $F_n = \frac{S_{in} / N_{in}}{S_{out} / N_{out}}$. The smaller this

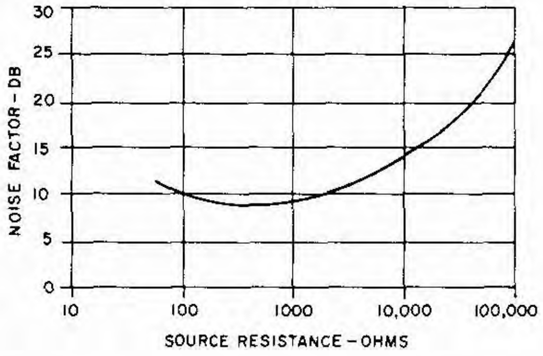
ratio (F_n), the better the noise quality of the amplifier. The noise factor is affected by the operating point, the signal source resistance, and the frequency of the signal amplified. The accompanying chart shows a typical variation of noise factor with collector voltage and emitter current.

This figure shows several curves for various values of operating emitter current and collector voltage. As can be seen, the best condition for low noise is operation at emitter currents of less than 1 milliampere and at collector voltages of less than 2 volts. Note that an increase in collector voltage will increase the noise more rapidly than will a similar increase in emitter current. This corresponds to a similar condition in tube amplifiers where high-gain stages are operated at low voltages to reduce noise.

The effect of a change in the signal source resistance upon the noise factor is indicated in the following graph, which indicates that best operation is obtained with an input resistance of 100 to 3000 ohms.

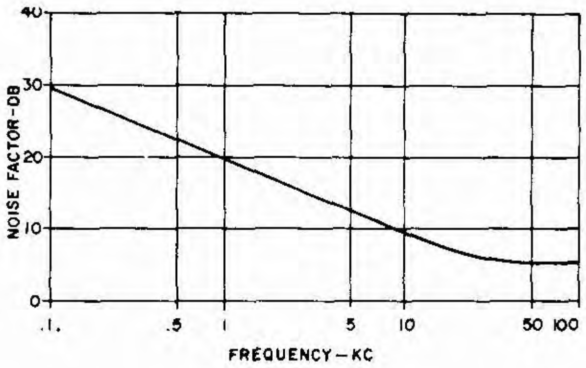


Variation of Noise with Operating Point



Source Resistance Versus Noise Factor

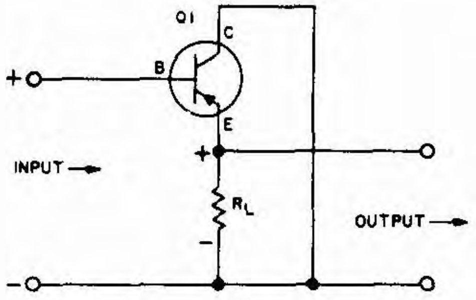
The manner in which the noise varies with frequency is indicated in the following graph. For very low frequencies the noise is high, and for higher and higher frequencies it tends to decrease until at about 50 kc the curve changes direction and noise again starts to increase. In particular, this illustration predicts that low-noise d-c amplifiers are difficult to achieve and design.



Noise Variation with Frequency

The necessity for matching input and output circuits for greatest power gain dictates that particular circuit configurations be used. For example, a low input resistance can be obtained by using the common base (CB) circuit for values of 30 to 150 ohms, and the common emitter (CE) circuit for values of 500 to 1500 ohms. Although a high input resistance produces more noise, its use is necessary when a high-impedance device such as a crystal microphone or a transducer is used. Otherwise, a transformer is required for proper matching.

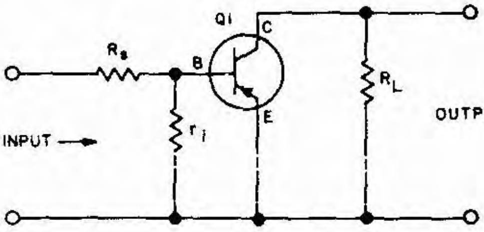
The common collector (CC) circuit, which is similar to a cathode follower in electron tube usage, provides a relatively high input impedance, as shown in the following basic circuit.



CC Input Circuit

The high input resistance is produced by the large negative voltage feedback in the base-emitter circuit. As the input voltage rises, the opposing voltage developed across R_L substantially reduces the total voltage across the base-emitter junction, and the current drawn from the signal source remains low. A low current produced by a relatively high voltage indicates low resistance (by Ohm's law); thus, if a 500-ohm resistor is used as R_L, the input resistance for a typical transistor will be approximately 20,000 ohms. Unfortunately, however, small current changes in the circuit, caused by functioning of the *following stage, produce* large variations in the input resistance value; therefore, this type of input circuit is not very desirable.

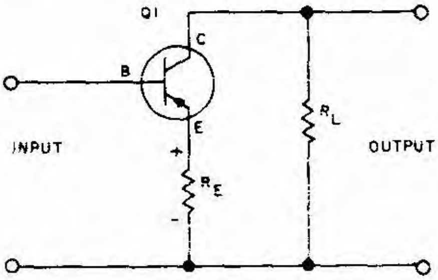
A better input circuit can be obtained by use of the CE configuration with series resistance, as shown in the following schematic.



Series CE Input Circuit

In this figure, r_i represents a typical base-emitter resistance of 2000 ohms with a load resistance of 500 ohms. To achieve the 20,000-ohm input resistance of the circuit previously described, an 18,000 ohm series resistor, R_S, is employed; 18,000 ohms plus the initial 2000 ohms will produce the required value. By use of the series 18,000 ohm resistor the total input resistance can be kept relatively constant at 20,000 ohms, unaffected by variations in transistor parameters or by the current drain of the following stage. The disadvantages of this circuit are a small loss in current gain and the large resistance in the base circuit. The use of a large resistance in the base circuit can lead to *bias instability* if the bias voltage is fed to the transistor via this resistance.

The following input circuit represents the best overall compromise.



***Degenerative* CE Input Circuit**

The signal voltage developed across the unbypassed emitter resistor, R_E, develops a voltage in opposition to the input signal. This degenerative (or negative) feedback voltage causes an increase in the input resistance. When a 500-ohm load resistor, R_L, is used with a 500-ohm emitter resistor, R_E, the total input resistance is approximately 20,000 ohms for a typical transistor. In addition, the emitter resistor *acts as a swamping* resistor, to help stabilize the transistor and minimize thermal variation effects.

Because the common-emitter configuration provides thermal stability (by means of emitter swamping), a relatively high input resistance, and high voltage-and-current gain, it is usually employed to the exclusion of other configurations. Therefore, the circuits to be discussed in later paragraphs will use the common-emitter configuration; the other forms of these circuits will not be mentioned unless considered germane to the discussion.

The transistor audio amplifier is usually classified as a **small-signal** amplifier or a **large-signal** amplifier. Actually, the small-signal condition represents excursions of the input signal over only a small range about the operating point (bias level), on the order of fractions of a volt. Small-signal conditions are normally calculated by appropriate formulae, since the values remain relatively linear or mathematically constant over the small range involved. On the other hand, with large-signal conditions, which are associated with the power amplifier (or output stage), there may be considerable departure from the formula for large values, thus, the power amplifier must be analyzed and designed *graphically*. In this respect, the transistor is somewhat different from the electron tube, with inherent nonlinearities which vary considerably from unit to unit. As a result, matched pairs of transistors are used to produce the desired results where the individual parameter variation is too large.

DIRECT-COUPLED AUDIO AMPLIFIER

APPLICATION.

The direct-coupled audio amplifier is used where high gain at low audio frequencies, or amplification of direct current (zero frequency) is desired. The direct-coupled audio amplifier is also used where it is desired to eliminate loss of frequencies through a coupling network. This circuit has numerous applications, particularly in computers, measuring or test instruments, and industrial control equipment.

CHARACTERISTICS.

Uses common-emitter circuit for high gain.

Usually requires thermal stabilization to prevent runaway.

Frequency response extends to zero frequency (direct current).

Responds equally well to pulses or sine waveforms.

CIRCUIT ANALYSIS.

General. The transistor is a device which uses the change of current flow through a resistor to produce amplifying action. D-C bias potentials are applied to the transistor elements to fix the point of operation. In a-c-coupled amplifiers, the d-c biasing potentials are effectively isolated and remain unaffected by the operating signal. In d-c-coupled amplifiers, however, a change in voltage on one element (either a-c or d-c) appears also as a similar or amplified change on another element, so that the biasing point changes with the signal. In cascaded stages these changes are cumulative and thus present a problem in stability. Since transistors are also subject to thermal changes, it is evident that a thermal change appearing at one element is also applied to another element. No problem results if the circuit can be arranged so that the temperature increase or decrease is self-correcting in the following transistor. In most instances, however, thermal instability becomes a major problem if more than two stages of d-c amplification are cascaded.

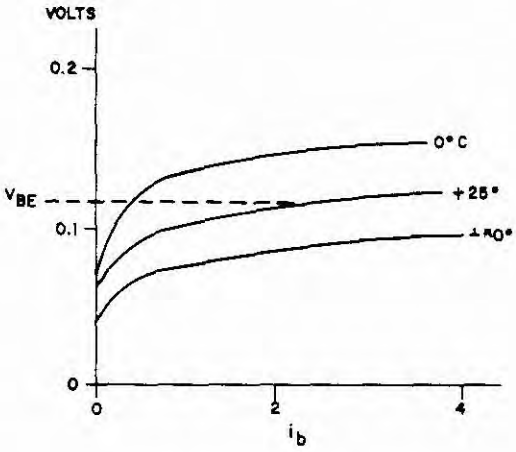
Germanium transistors are more subject to thermal instability than are silicon transistors, but in either case it is usually necessary to provide some form of temperature compensation if the temperature exceeds 55 degrees centigrade. The complexity of the compensation circuitry is dependent upon the amount of correction needed. Because of the rapid changes which are occurring in the semiconductor field, it is likely that temperature compensation will be eliminated or minimized to a great degree in the future. Even so, however, the primary limitation of direct coupling still remains, namely, the necessity for cumulatively increasing the bias and operating values as each stage is cascaded. While the use of low bias and collector voltages permits somewhat more range than can be obtained with the electron tube, the transistor, like the electron tube, is subject to maximum breakdown or reverse potential limitations.

In addition, noise is a problem since the d-c amplifier amplifies any internal noise as well as the signal, and transistors are prone to produce greater noise at the lower audio frequencies. Thus, the ability of the d-c amplifier to extend its response to low frequencies not normally available through other coupling methods is somewhat nullified by the amplification of the inherent noise in the transistor. Generally speaking, we can say the low-frequency response of the d-c amplifier is limited only by the signal-to-noise ratio, while the high-frequency response is limited by the frequency-response characteristics of the transistor.

In the direct-coupled amplifier, the collector of the input stage is directly connected to the base of the second amplifier stage; therefore, any collector supply variation also appears at the base of the second stage, just as if it were a change in the input signal. Since the transistor in the second stage has no way of discriminating between actual input signal variation and first stage collector supply variation, it is evident that either type of variation will be amplified in the second stage.

By the same type of reasoning it can also be seen that, even in the absence of an input signal, a change in the gain of one stage (or the over-all gain of cascaded stages) as a result of collector supply variations, will produce an output signal. Similarly, a change in bias level in any stage or on any element will be amplified proportionally, and a change of output will occur. Such changes in bias levels normally occur as a result of temperature variations, aging, difference in transistor characteristic due to manufacturing processes, or changes in transistor leakage current, and are referred to as **drift.** (This has no connection with the process which occurs in drift transistors.)

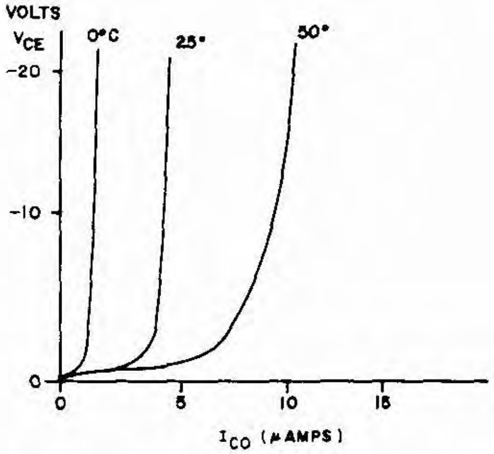
The variation of the forward bias characteristics of a typical germanium diode with temperature is shown in the accompanying graph. The forward bias variation is usually expressed as a change in bias voltage with temperature at a constant forward bias current. It is usually small, but becomes significant because of the large amplification it receives because of the direct coupling arrangement.



Emitter-Base Diode Characteristic

The manner in which the collector-base diode varies its reverse saturation current with temperature is also shown in the following graph (for a typical germanium transistor). In this instance, the figure shows that the reverse-current characteristic is highly temperature-dependent, and relatively large current variations are produced as the temperature is increased.

In a similar manner, it can be shown that the forward-current transfer characteristic of a germanium transistor also varies with temperature. However, in this case the gain can either increase or decrease with temperature (silicon types generally increase with temperature). The per-



Variation of Collector-Base Diode Reverse Current

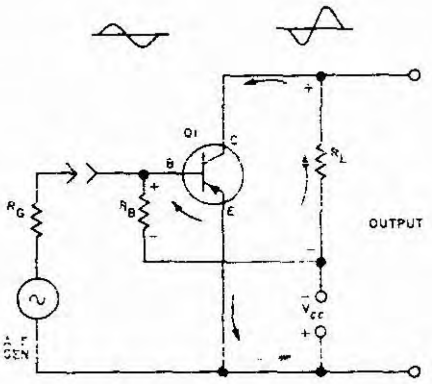
centage variation in gain with temperature varies greatly with the operating point, and many units show a change in sign as well as magnitude. The gain variation of a silicon type may be from two to ten times that of a germanium type. Thus, we can see that the major sources of drift in transistors are changes in the d-c properties of the collector-base and emitter-base diodes, and changes in the d-c forward transfer ratio. Generally speaking, in comparing the operation and performance of germanium and silicon transistors, it can be said that at temperatures below that of the reference temperature, T_O, the two types are comparable. At and above the reference temperature, the silicon type tends to have lower drift. The reference temperature for silicon is 100 degrees centigrade, and that for germanium is 60 degrees centigrade. With low source resistance low values of drift are obtained above T_O, while with high source resistance the best performance occurs at temperatures where the reverse saturation collector current may be neglected.

In d-c amplifiers, low drift is obtained by operating with low values of collector current; this reduces the reverse-leakage current by keeping the voltage between the collector and the base at a low value. This voltage is a forward bias for reverse current. Generally, any design precautions which reduce drift also reduce noise; conversely, with low noise less drift is obtained. When the collector current is reduced, the gain decreases and the internal emitter resistance increases. Because of the reduction of gain, the amount to which the collector current of the first stage can be reduced is somewhat limited. In single-ended amplifier stages, both the current drift and the voltage drift in the second stage tend to help cancel the input stage drift; in a differential d-c amplifier, however, the drift in the second stage may either aid or oppose that of stage 1, depending upon the design.

Despite the apparent disadvantages of the d-c amplifier, it does produce (for a two- or three-stage unit) high gain and good fidelity, particularly in the low-frequency portion of the spectrum. It also provides amplification with as few parts as possible; thus, it is economical to build. In actual practice the d-c amplifier is usually limited to one or two stages of amplification because of drift, especially where dc must be amplified or where frequencies of 0 to 12 cycles are of importance. To overcome the effects of drift in d-c amplifiers a special "chopper amplifier" has been developed; this amplifier converts the dc into ac so that the stages can be isolated and thus prevent the cumulative drift which normally occurs. This is a special type of amplifier, which will be discussed later in this section of the Handbook.

Circuit Operation.

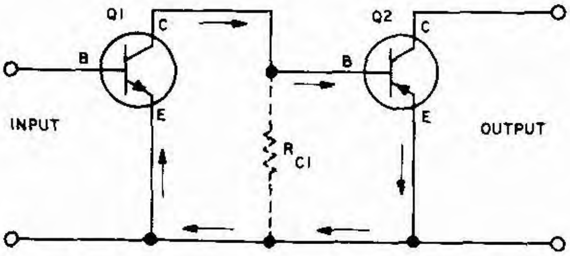
1. **Basic Circuit.** The schematic of a basic common-emitter d-c amplifier is shown in the accompanying illustration. The input signal is represented by the a-f generator with an internal resistance equal to R_G. The input signal is applied between base and emitter. Transistor Q1 is biased by R_B, using the form of external PNP self-bias explained in Section 3, paragraph 3.4.1. (R_B and the internal resistance of the base-emitter junction form a voltage divider across the collector supply, and a forward bias is developed across R_B.) The input signal opposes the bias between base and emitter, which is normally chosen for class A operation. The direction of electron current flow through the collector output load resistor, R_L, is indicated by the arrows. The polarity of the resulting d-c voltage across the load resistor is as shown. When the positive alternation of the input signal is applied to the base, the base-to-emitter bias is reduced (since the signal and bias voltages are of opposite polarity). Because the base-to-emitter potential is now less than the normal value, the hole current from the emitter to the collector is lowered and electron flow through the output load resistor is reduced. The decrease in voltage drop across R_L produces a negative swing and, consequently, produces a negative output signal across R_L. As the sine-wave input signal goes negative, the bias potential is aided by the input signal; and as the base-to-emitter bias is increased, more hole current flows to the collector. This produces more electron flow through the collector circuit, increasing the voltage drop across R_L, and produces a positive output signal swing during the time that the input signal is negative. This effectively produces an opposite-polarity output signal (sometimes referred to as a 180-degree phase reversal). Since R_L is the load for both dc and ac, there is only one load line, and any internal noise voltages flowing through the load resistor add to the developed output voltage. Since the output across R_L is applied directly to the base of the next stage, it can be seen that these noise components appear across the following input circuit. In an a-c coupled circuit these noise components, consisting of dc or very low frequencies, are usually eliminated (blocked by the coupling capacitor). These noise components are produced by thermal effects, and also result from electron flow through the load resistor. They include the so-called **white noise** generated by diffusion-recombination effects within the transistor (similar to shot noise in the electron tube), and surface and leakage noise from the transistor, which is sometimes referred to as **semiconductor** or **1/f noise** to distinguish it from white noise. Such noise is mostly confined to the region of from 1-to-10 kc for white noise (in the



Basic D-C Amplifier (CE)

audio range), with the semiconductor noise predominating and increasing for frequencies lower than 1Kc. The d-c noise results from supply voltage variations. Thus the noise components usually eliminated by the a-c coupling capacitor in other types of amplifiers, creates a design problem in the small-signal type of d-c amplifier. In large-signal amplifiers these noises are usually masked by the large input signal. Note also that any d-c bias changes caused by thermal instability of the stage also appear across the load, and are applied to the input of the next stage. This is an inherent disadvantage of the d-c amplifier. On the other hand, with proper input and output matching, maximum gain is obtained in the stage; moreover, with no coupling network to create a loss between stages, maximum output and efficiency are produced. Since all frequencies are present, including dc (zero frequency), and are applied equally to the next stage, it can be understood why the d-c amplifier presents maximum gain with excellent frequency response, particularly at the lower frequencies.

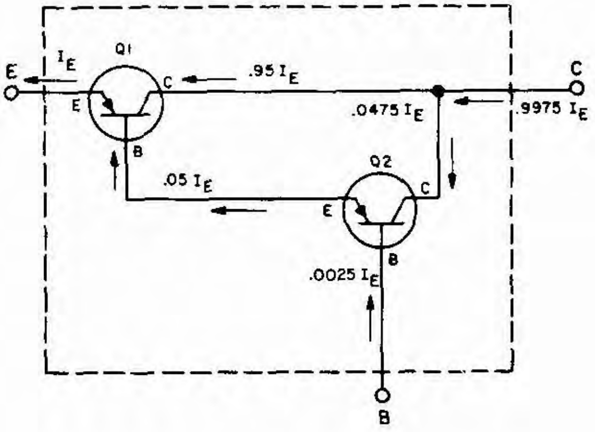
2. **Cascaded Stages.** Because of the high gain possible per stage, many applications require only a single stage of d-c-coupled amplification. Where more than one stage is required, transistors offer circuit arrangements that are not possible with electron tubes. For example, through the use of **complementary symmetry** it is possible to connect the collector of the input stage directly to the input of the second stage without disturbing bias arrangements, and to use the same supply. By using alternate arrangements of NPN and PNP transistors, only one supply is needed. Recall that in the vacuum-tube d-c amplifier, as each stage progresses the plate voltage is increased, with the grid being tapped back onto the preceding stage plate voltage to obtain the bias. Only tandem arrangements of similar type transistors can follow this principle. The term **complementary symmetry** is derived from the fact that the NPN transistor is the complement of the PNP transistor, with both circuits operating identically, but with opposite polarities. The accompanying figure shows a simple direct-coupling circuit using complementary symmetry.



Tandem Coupling Arrangement

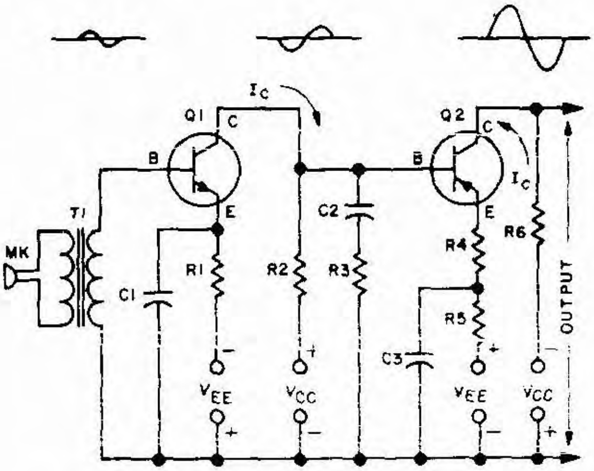
In this figure, the direction of electron flow is shown by the arrows. It is evident that the base-emitter junction of the second stage carries the collector current of the first stage. If the collector current of the first stage exceeds the maximum base-emitter current rating of the second stage, the collector resistor shown in dotted lines must be used. Otherwise, this resistor is not needed and proper design produces a saving in components. To do this, of course, the transistors must be of opposite types, (NPN to PNP, or PNP to NPN).

By the use of a special compounding connection, two transistors may be employed as a special type of d-c amplifier to obtain linearity and almost unity gain (alpha). The accompanying figure shows the compound transistor connection using the common-base configuration.



Compound Connection

Note that the input to the second stage is the base current of the first stage. Effectively, the input impedance is the series combination of the two transistors, while the outputs are in parallel. Such a circuit is roughly analogous to the push-push electron-tube circuit. Actually, this circuit is employed as a single-transistor compounded-type circuit, with emitter, base, and collector resistors used externally. The direction and relative values of current flow are shown in the figure, assuming the use of two transistors with an equal a_{fb} of .95. When these values are converted to a_{fe}, the total combination value (.9975) is equal to a gain of 399 as compared with an a_{fe} of 19 for a single transistor, or more than the normal gain of two stages in cascade (19 x 19 = 381). Compounded transistors may be employed single-ended, or in complementary symmetry as push-pull stages, exactly as for single transistors. They represent a special and unique circuit alone; however, they are shown here to illustrate how they are derived from the basic d-c amplifier. In most applications the compounded circuits form the output stages of an amplifier, or are used as the d-c amplifier in a voltage-regulator circuit. A typical high-gain preamplifier using an NPN and a PNP transistor in a direct-coupled, cascaded, complementary-symmetry amplifier is shown in the following schematic. For simplicity and convenience, separate bias and collector supplies are shown. The output of the microphone is transformer-coupled (for proper matching) to the base of transistor Q1. Fixed class A bias is supplied to the emitter from a separate supply, and emitter swamping is provided by R1 shunted by C1. Use of emitter swamping provides temperature stab-



Two Stage D-C Amplifier (CE)

ilization for germanium transistors up to normal room temperatures, and for silicon transistors up to 100 degrees centigrade. The output of the first stage appears across collector resistor R2, and is direct-coupled to the base of PNP transistor Q2. Capacitor C2 and resistor R3 form a low-frequency compensating circuit (or filter) across the load, shunting the higher frequencies to ground and effectively boosting the lower frequencies. This helps to compensate for loss of low frequencies in the microphone and transformer circuits. Transistor Q2 is emitter-stabilized by swamping resistor R5, bypassed by C3. Resistor R4, which is unbypassed, is placed in series with the emitter to provide degenerative feedback for improvement of the linearity and response. Resistor R6 is the collector load across which the output is developed. Fixed emitter bias is used with a separate collector supply for simplicity and convenience.

Assume that a sine-wave signal is applied to the input of T1; as the signal increases in a positive direction it adds to the forward bias of NPN transistor Q1. The increased flow of electrons through Q1 increases the emitter, base, and collector currents, and the external electron flow out of the collector produces a negatively polarized voltage drop across collector load resistor R2. Thus, for the entire half-cycle that the input signal goes positive and aids the forward bias, the output signal (at the collector of Q1) goes negative.

As the input signal changes polarity and becomes negative, it opposes the forward bias, causing a decreased electron flow through the transistor, and a proportional reduction in the emitter, base, and collector currents. The voltage drop across R2 is reduced and the collector voltage approaches that of the source, so that a positively polarized output is produced. Thus, for the entire half-cycle that the input signal goes negative and opposes the forward bias, the output signal (at the collector of Q1) goes positive.

Since emitter resistor R1 is bypassed by C1, changes occurring during the audio cycle will have no effect. However, any slight changes in emitter current (produced by temperature variations in the transistor) which occur at a very slow rate develop a voltage across R1; this voltage increases or decreases the bias in a direction which opposes the change; see Section 3, paragraph 3.4.2, BIAS STABILIZATION, for a complete discussion of this action. Any noise voltage, thermal bias changes not compensated for by R1, and the amplified signal appear across collector resistor R2, and are applied directly to the base of Q2. Note that the signal at this point is opposite in polarity to that of the input stage. Capacitor C2 and resistor R3 form a high pass filter between the base and emitter of Q2, which shunts the high frequencies to ground; this effectively boosts the base response of the amplifier and compensates for any loss of low frequencies in the input transformer.

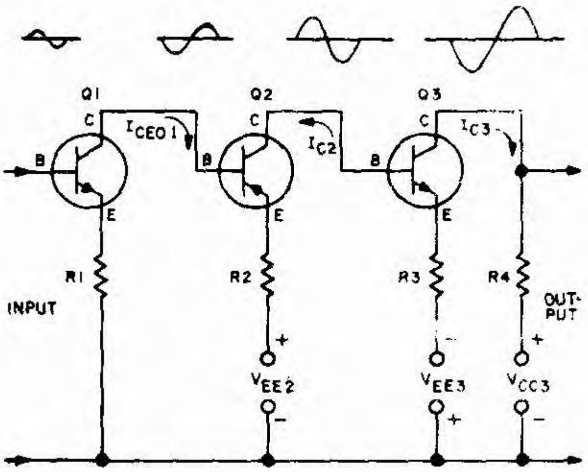
Transistor Q2 is a PNP type; the function of Q2 is just the opposite of the functioning of Q1. When the input to Q2 is positive, it opposes the fixed emitter bias and effectively reduces the forward bias. With reduced forward bias, the flow of hole current through the transistor is decreased, and the emitter, base, and collector currents are reduced proportionally. Therefore, the external flow of electron current through collector resistor R6 is reduced, and the collector voltage approaches that of the source, producing a negatively polarized output signal. The output is now of the same polarity as the input signal to transistor Q1, so that during the entire half-cycle that the input signal to Q1 is negative, the output of Q2 is negative.

When the input to Q2 is negative, the polarity is such as to aid the base-emitter bias and increase the effective forward bias. As the forward bias is increased, hole current flow through the transistor increases, and the emitter, base, and collector currents increase proportionally. Thus, the external flow of electron current through R6 into the collector of Q2 is increased, and is in such a direction as to produce a positive output voltage. In a similar manner, this output voltage (of Q2) is of the same polarity as that at the input of Q1; thus, the effect of the two stages is to produce an output signal of the same polarity as the input signal (a similar effect is obtained when two electron tubes are used). To provide an oppositely polarized output signal, the stages must be an odd number.

Swamping resistor R5 is bypassed by C3, so that the audio-frequency changes will have no effect; however, slow thermal variations will produce a voltage across R5 in the proper direction to compensate for the thermal change, thus helping to stabilize the circuit.

Resistor R4, which is unbypassed, has a voltage developed across it for [illegible], noise changes, and audio-frequency changes; since this voltage is in opposition to the bias produced by R5, it is degenerative, thus providing a form of negative feedback. The negative feedback improves the low-frequency response and stabilizes the stage so that input voltage variations are minimized. The amplified output of Q2 is either applied directly to a speaker or other output device, or transformer-coupled to other stages as desired.

A typical three-stage, single-ended d-c amplifier is shown in the accompanying schematic. It represents the minimum of parts and d-c supplies needed for a high-gain, three stage complementary symmetry type of d-c amplifier for small signal applications.



Typical Three-Stage Amplifier

As shown, the base of the input stage is completed through the input device, it is effectively open, it has no driving voltage, and zero base current exists. The collector current, I_{CEO1}, flows through the base of stage 2, which is biased by supply V_{EE2} in series with the emitter of stage 2. Since stage 1 uses an NPN transistor, the positive emitter bias of stage 2 is of the proper polarity to act as collector voltage for Q1. Any change in the collector current of stage 1 appears at the collector of stage 2 in amplified form; that is, $I_{C2} = B_2 I_{CEO1}$, where B_2 is the current gain of stage 2. Stage 2 uses a PNP transistor; therefore, by complementary symmetry, stage 3 must also be an NPN stage similar to stage 1. The emitter bias for stage 3 is supplied through V_{EE3}, which is connected positive to ground. Thus, the collector supply of stage 3 (V_{CC3}) is of series-aiding polarity, and the total collector voltage is that of both the collector and emitter supplies of stage 3. In a similar manner, the collector voltage of stage 2 is supplied by V_{EE2} and V_{EE3}. The collector current of stage 2 is the base current of stage 3. The output of the amplifier appears across collector resistor R4, and the collector current is that of stage 2 multiplied by the amplification factor, or $I_{C3} = B_2 B_3 I_{CEO1}$. Emitter resistor R1, R2, and R3, which are of a low value, provide degenerative feedback; they also act as emitter swamping resistors to help stabilize the amplifier with respect to temperature variations.

Assuming that the input stage has a collector current of 5 microamperes and assuming a gain of 38, the second stage will have a collector current of 190 microamperes. With a gain of 40, the third stage collector current will be 7.6 milliamperes. It is clear that any slight change in the current of stage 1 caused by temperature or noise will be greatly amplified and appear at the output of stage 3. With such sensitivity and amplification, therefore, it is almost mandatory that such an amplifier be temperature-compensated, even if room temperatures do not vary excessively. Naturally, the amplitude of the input signal must be limited if true fidelity is to be obtained. Driving the transistor into cutoff and saturation would clip the peaks of the signal, just as in electron tube operation. It is also evident that low-noise transistors must be used; otherwise, the noise might mask the signal. Note that in this amplifier the small emitter bias of stage 2 operates as the collector voltage of stage 1. Low collector voltage is used to minimize noise generated in the input stage; this is similar to the techniques used for high-gain vacuum-tube amplifiers, where the plate voltage of the input stage is usually about 1/3 that of the other stages.

FAILURE ANALYSIS.

No Output. A no-output condition is generally indicative of either an open or shorted circuit, or a defective transistor. Usually, improper bias will cause distortion or low output rather than no output at all. A resistance analysis should quickly reveal any open-circuited components, since only a few parts are involved. A forward and reverse resistance check of the transistor can be made to determine whether the transistor needs replacement. For a good transistor the forward resistance is low (less than a few ohms), and the reverse resistance is high (50K and higher). With continuity throughout and components of the proper resistance, a simple voltage check should indicate the cause of improper performance. Use a high-impedance vacuum-tube voltmeter; at the normally low voltages involved, the shunting effect of the usual 20,000 ohms-per-volt meter might be too great.

Low Output. Generally, low output results from improper biasing, causing either too great a flow of current or too small a flow of current (but not cutoff). Defective bypass capacitors provide a leakage path for current which, in flowing through an associated series resistor, produces a voltage drop greater than normal. Usually such a condition can be easily checked by means of a voltage analysis. Where high-resistance paths have been introduced, either because of poorly soldered joints or aging components, a loss of output will usually occur. Ordinarily, these paths can be located by means of a resistance analysis. With the small number of components involved, either a voltage check or a resistance check should quickly isolate the trouble to a particular portion of the circuit. When making ohmmeter tests, be sure to observe the correct polarity and not to apply a forward bias to a circuit requiring a reverse bias, or vice versa: exceeding the permissible bias can ruin the transistor. The use of a shorting bar (screwdriver) to ground (an acceptable practice in electron-tube troubleshooting) should be avoided to prevent overload or accidental short-circuiting of the supply through components not designed to withstand the extra current. If the trouble cannot be located quickly by means of the simple voltage and resistance checks described above, the most effective troubleshooting method is to apply an input signal and use an oscilloscope to check the signal path through the circuit. The high-impedance oscilloscope input will have little effect on circuit operation, and the disappearance of the

Self-bias is used with R_B and the internal base-emitter resistance providing the bias (it acts as a voltage divider connected across the supply). Emitter resistor R_E serves as an emitter swamping resistor to provide thermal compensation. (See Section 3, paragraph 3.4.1, of this Handbook for a discussion of bias, and paragraph 3.4.2 for a discussion of stabilization action.) The collector input, which is the signal from the d-c amplifier stage, is direct-coupled, while the chopper (sometimes called "carrier") input may be either direct- or a-c-coupled. In either instance, the circuit bias voltage must be arranged so that the direct coupling does not bias off Q1 in an undesirable mode of operation. Note that the direct-coupled collector input is actually the collector supply voltage. Note also that the a-c waveform shown as the d-c input signal on the schematic represents the signal component produced by increasing the d-c input above the level representing zero to produce a positive waveform, and decreasing the d-c level below this zero level to produce the negative waveform. It actually is a d-c voltage which varies at the signal frequency.

The operation is such that the transistor acts as a switch, being off when de-energized and on when energized. The switching action is obtained from the chopper input signal, which is a rectangular pulse of constant amplitude (usually in the audio range). On the positive peak, the forward base bias is reduced to a value which stops conduction through the transistor. On the negative peak, the foward base bias is increased and the emitter conducts heavily in the saturation region. During the vertical rise and fall times, the bias changes rapidly from one state to the other. It is during this time that the transistor is in its normal operating region, but because of the short duration of the rise and fall time no actual amplification occurs during this period.

Let us consider one cycle of operation. Assume that the transistor is resting in its quiescent state with a small self-bias and with no inputs applied. Transistor Q1 will draw its quiescent value of collector current. Assume that a 1000-cps rectangular pulse is applied as the chopper input to the base electrode. With equal on and off times the transistor will conduct heavily during the negative chopper-pulse when the forward bias is increased. Assume that the d-c input signal is also simultaneously applied to the collector, and that it is positive. This will place a forward bias on the collector (instead of the normal reverse bias), and the transistor will quickly reach a steady saturation current. Note that the d-c amplifier input signal is actually acting as the collector supply voltage. At point A on the schematic the input waveform will appear; however, at point B the input voltage is entirely dropped across collector resistor R_C, as a result of the heavy conduction, and no output appears. When the chopper input signal goes positive the forward base bias is opposed, and, since the square-wave input is always of greater amplitude than the bias, the base is reverse-biased and collector current is effectively reduced to zero. It is not exactly zero because a small reverse current, I_{ceo}, flows through the internal resistance of the base-collector and emitter-base junctions of the transistor. This reverse current produces a voltage drop through collector resistor R_C in opposition to normal collector current flow, from points B to A instead of from points A to B. Therefore, the polarity of this reverse-generated voltage is in opposition to the d-c input signal, and thus reduces it a small amount. However, for the present we may ignore this small loss of input voltage and say that during the nonconducting period the full amplitude of input voltage appears at the output. During the entire positive excursion of the d-c input signal, the output will consist of a series of pulses having approximately the same amplitude as the input signal at the instant the transistor is turned off. When passed through coupling capacitor C_{cc}, this waveform will look exactly like the input since the d-c portion is eliminated and only the varying a-c portion appears at the output. As stated previously, this amplitude is slightly less than that of the input because of the reverse drop through R_C. Therefore, although called a "chopper-amplifier," it is clear that the gain is always less than unity and the function is mainly one of converting the d-c signal to an a-c signal.

Consiser now the operation on the opposite half-cycle of the d-c input signal. In this instance the collector voltage is always negative, which is the normal reverse-biased collector condition. With the same rectangular chopper input signal, the base bias is alternately reduced and aided. In the reduced condition, effective zero collector current is obtained; during the aiding part of the chopper signal, the forward bias is increased. Thus, the same operating conditions prevail, with the transistor alternately driven to saturation (this time by the chopper signal alone) and to effective cutoff. During saturation (the on period) the collector input signal is dropped to zero through the collector resistor, and during effective cutoff (the off period) the signal appears at the output. In this instance, again, there is also a flow of reverse current, which produces a slight opposing voltage so that the input signal is slightly reduced. The output appears as a negative varying voltage which is identical in shape to the input signal. In the collector circuit it consists of a group of pulses with an amplitude equal to the input signal amplitude (minus the reverse drop) during the off period.

The unique property of the transistor which permits it to operate with either a forward-biased or reverse-biased collector also serves to switch the functions of these elements. Thus, with forward bias the collector becomes an emitter, and the emitter functions as the collector. This allows the designer the choice of either connecting the transistor as a common emitter, or of reversing the collector and emitter connections and have it operate in the inverted fashion. In either case the operation is identical except that the terms **collector** and **emitter** must be interchanged in the places they appear in the circuit discussion.

In some applications the emitter resistor is not used since its function is for temperature stabilization by small or incremental changes of emitter current, and the large value of saturation current requires R_E to be a small value to prevent interference with circuit operation. By selecting Class A bias for quiescent operation, the transistor is biased in its mid-range of operation, thus permitting the control signal to swing it equally in either direction for cutoff or saturation. This allows the use of a multivibrator type of chopper input signal as the trigger. With some transistors and design, base resistor R_B is also omitted, with contact bias being supplied by the internal base resistance of the transistor. In any event, the chopper-amplifier is always easily recognized because of the dual inputs, with one of them acting as the collector supply.

To be linear in operation, the output signal must be proportional to the input signal. Unfortunately, the transistor is not a perfect switch. When it is closed there is a finite voltage drop across it, and, as stated previously, when it is open there is leakage current through it. The voltage drop across the transistor in the on condition is referred to as the "offset voltage", and the leakage current is known as the "offset current". It is evident that either one reduces the amplitude of the input signal and thus affects the input signal by fixing the lowest limit of signal which may be chopped. These voltages and currents can be reduced by proper selection of transistors (silicon types are preferred) and by use of the inverted emitter-collector (transposed) connection. With the inverted connection a lower offset voltage is obtained because of the effects of the emitter and collector ohmic spreading resistances. This becomes a design problem since the reverse collector and emitter currents (I_{co} and I_{eo}) are both dependent upon tempeature (they double in value for each 10-degree rise in temperature) and upon voltage (the point of occurence varies with the voltage). With good design, the output is practically zero when the transistor is conducting, and it is almost equal to the instantaneous value of the input signal when it is non-conducting.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of conventional volt-ohmmeters. Be careful also to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. If there is no chopper input to trigger the circuit, or if base resistor R_B is open or transistor Q1 is defective, there will be no output. Check the base resistor for continuity with an ohmmeter and the chopper input signal with an oscilloscope. An open collector resistor, or emitter resistor will also interrupt the output, and can be located by making a continuity check. If all components check normal and inputs to the base and emitter (or collector) are present, the transistor is defective. Replace it with one known to be good.

Reduced Output. Any increase in resistance in the collector or emitter circuit will reduce the amplitude of the output signal. Likewise, a reduction in chopper amplitude can result in insufficient drive for normal operation and produce a partial output. The circuit resistances can be checked with an ohmmeter, and the chopper signal with an oscilloscope. If coupling capacitor C_{cc} is shorted, the output will also be reduced.

Distorted Output. A nonlinear output in this circuit is equivalent to distortion in conventional amplifiers. Once the circuit is designed, only a change in the value of the components, input signals, or the transistor can cause distortion. The chopper input signal can be checked on an oscilloscope, and the components can be checked with an ohmmeter. A leaky or shorted coupling capacitor (C_{cc}) can cause distortion with reduced output, depending upon the voltages existing in the next stage. The capacitor must be disconnected to check for leakage, but it can be checked for short-circuit conditions with an ohmmeter. If all components check normal, the transistor must be defective; replace it with one known to be good.

R-C-COUPLED AUDIO AMPLIFIER.

APPLICATION.

The r-c-coupled transistor audio amplifier is commonly used where good fidelity over a large range of audio frequencies is desired. For example, it is used in the amplifier stages of receivers and communications equipment where little or no power output is required.

CHARACTERISTICS.

Uses common-emitter circuit for high gain and better impedance matching.

Operates Class A for linear operation and minimum distortion.

Usually amplifies small signals, but can be designed to handle large signals in cascaded stages.

Is usually fixed-biased from the collector supply, but may be self-biased in some applications.

Emitter swamping is normally used for thermal stabilization.

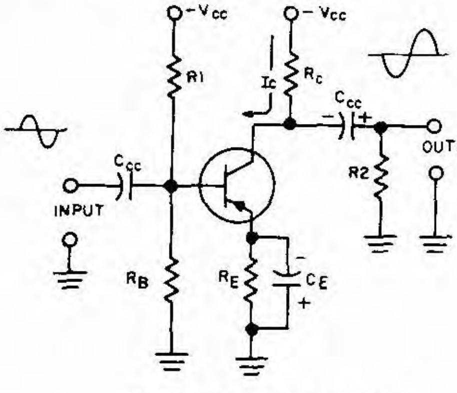
Gain is fairly uniform over a range of approximately 100 to 20,000 cps or more.

Both voltage gain and power gain are high.

CIRCUIT ANALYSIS.

General. The r-c-coupled transistor amplifier is similar in general to the r-c-coupled electron tube amplifier previously discussed in Part A of this section of the Handbook. Use of the common (or grounded)-emitter circuit, permits the analogy that the base is equivalent to the vacuum tube grid, the emitter is equivalent to the tube cathode, and the collector is equivalent to the tube plate. Thus, it is clear from the following schematic that the two r-c-coupled circuits are practically identical. Any differences are due to the internal parameters of the transistor and the matching requirements for maximum output with minimum distortion.

Circuit Operation. The following schematic shows a conventional PNP, triode, common-emitter r-c-coupled transistor audio amplifier circuit.



R-C-Coupled Audio Amplifier

The input is shown capacitively coupled, and voltage divider R1, RB provides fixed bias from the collector supply. Emitter swamping is provided by RE for temperature stabilization; RE is bypassed by CE. (See section 3, paragraph 3.4.1, of this Handbook for a discussion of bias arrangements, and paragraph 3.4.2 for a discussion of bias stabilization methods.) Collector resistor RC is the load across which the output voltage is developed; this voltage is applied through coupling capacitor Ccc to the output circuit. Resistor R2 is the base-to-ground resistor in the next stage when cascaded amplifiers are used, or is the output load resistor (such as a headset) in single-ended stages.

Normally, the amplifier is a small-signal amplifier, with the bias fixed at the center of the transistor dynamic transfer characteristic. With no input signal a steady collector current, IC, flows as determined by the base bias voltage. With R1 and RB connected across the collector supply as a voltage divider, a forward (negative) bias is developed across RB; this bias is sufficient to cause the quiescent value of IC to flow, even though the collector is reverse-biased. When the input signal goes positive, assuming a sinewave input, the forward base bias is decreased instantaneously by the amplitude of the input signal, and collector current IC is reduced. The reduction in collector current causes the voltage across collector resistor RC to rise toward the supply voltage, which is negative (this is exactly the reverse of vacuum-tube action); thus, a negative-swinging output signal is developed. When the input signal becomes negative, it adds to the forward base bias and causes IC to increase. The increase in collector current through RC produces a less negative voltage or positive swing. Therefore, the collector output follows the input signal except that it is reversed in polarity; when the input signal is positive, the output signal is negative, and vice versa. The collector output is developed across RC between the collector and ground, and is applied through coupling capacitor Ccc to the base of the next stage, or to the output load.

In cascaded resistance-coupled stages the base bias resistor and base-to-emitter internal impedance of the next stage transistor offer a shunt path between coupling capacitor Ccc and ground. Therefore, the reactance of Ccc and the total parallel resistance from base to ground form a voltage divider across the collector resistor of the first stage. If the reactance of the coupling capacitor is large, the output voltage is greatly attenuated, and only a small output appears between base and ground of the second stage. Since the reactance of Ccc varies inversely with frequency, the lower audio frequencies are attenuated more than the higher frequencies. For good low-frequency response the coupling capacitor is made sufficiently large in value that its reactance is very small as compared with the base-to-ground resistance. This is similar to vacuum-tube practice, where relatively small coupling capacitors (such as .001 microfarad) are satisfactory, because the vacuum-tube grid-to-ground impedance is very high. Because the transistor base-to-emitter impedance is fairly low (about 500 ohms), a coupling capacitor of 50 microfarads or more is needed to achieve the low impedance required to pass the signal without excessive attenuation. (A 50-microfarad capacitor has a capacitive reactance of approximately 30 ohms at 100 cps.) For good low-frequency response the reactance of the coupling capacitor should always be less than one-tenth the effective base input impedance.

At the higher audio frequencies (above 20,000 cps), the collector-to-emitter capacitance of the first stage and the base-to-emitter shunting capacitance of the second stage tend to bypass the high frequencies to ground, causing a drop in the response. This frequency-attenuating action of the transistor occurs because the width of the internal transistor PN junctions are voltage-sensitive. With higher voltages the transition region is narrow, corresponding to the closely spaced plates of a capacitor with the associated high capacitance. The reverse bias on the collector also reduces the width of this transition region, so that transistors are generally characterized by a high inter-electrode capacitance. For example, an auido transistor may have a collector-to-base capacitance on the order of 50 picofarads, as compared with a vacuum-tube plate-to-grid capacitance of one or more picofarads. The collector-to-emitter capacitance is usually 5 to 10 times the value of the collector-to-base capacitance (in the common-emitter circuit), as compared with 8 picofarads or less for vacuum-tube plate-to-cathode capacitance. Thus, it can be seen how the high-frequency response is affected considerably by internal transistor parameters. Of course, any shunt wiring capacitance will also add to the shunting effects of the transistor. Both low- and high-frequency compensating circuits may be used to increase the effective frequency response of the circuit, as discussed in Wideband Video Amplifier Circuits later in this section.

Over the region of 100 to 20,000 cps, the r-c-coupled amplifier has a relatively flat response, and with proper matching will afford high power and voltage gains. Hence, this form of coupling is universally employed where good audio response is required without any appreciable power output (voltage amplification). The common-base configuration is sometimes employed where better high-frequency response is desired than that provided by the common-emitter circuit, since the collector-to-base capacitance is only 1/5th to 1/10 as great.

Transistor audio amplifiers are also characterized by a high inherent noise which is greatest at the lower audio frequencies. Operation with low values of emitter current and low collector voltages, together with low values of input resistance, tends to minimize the noise. In the common-emitter circuit, degenerative effects produced by an unbypassed emitter resistor tend to increase the input resistance. Thus, it is conventional practice to use large emitter bypass capacitors in the r-c-coupled circuit to avoid any possibility of degeneration. As with the electron tube, external feedback circuits provide better response, although emitter degeneration may sometimes be used. Since fixed bias from the collector supply may be easily obtained by a simple voltage divider, it is used in both large-and small-signal applications. Self-bias is generally restricted in use to very small-signal amplifiers; otherwise, distortion and improper operation with a reduction in gain, or blocking, may occur on large signals. In the r-c-coupled amplifier, the emitter resistor functions mainly as a swamping resistor for temperature stabilization, and prevents large changes in amplification with temperature variations.

In considering the operation of the transistor r-c-coupled amplifier as compared with the electron-tube r-c-coupled amplifier, it should be clear from the above discussion that one circuit is an almost exact counterpart (dual) of the other. The difference is that transistor stages operate with low input and output impedances, at low voltages, and at very low levels of amplification, whereas electron-tube stages operate with relatively high input and output impedances, at high voltages, and at high levels of amplification. Thus, the transistor is basically a current amplifier, while the electron tube is a voltage amplifier. Consequently, the transistor requires closer matching (rather than mismatching) of impedances to produce maximum performance.

FAILURE ANALYSIS.

General. When making voltage checks use a vacuum-tube voltmeter to avoid the low values of multiplier resistance employed on the low-voltage ranges of the standard 20,000 ohms-per-volt meter. Be careful also to observe proper polarity when checking continuity with an ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. A no-output condition may be caused by an open or short circuit, by improper bias or loss of collector voltage, or by a defective transistor. A voltage check will determine whether the bias and collector voltages are normal; also, a VTVM will indicate audio input and output voltages. With the few components involved, simple voltage and resistance checks will usually indicate the source of trouble. If the bias voltage divider is open because return resistor, R_B is defective, the base bias will be sufficient to cut off the transistor. With R_1 open, only contact bias exists and the transistor will very likely conduct heavily in the saturation region. If collector resistor R_C is open, there will be no voltage indication as measured between between the collector and ground. If emitter resistor R_E is open, the circuit will not operate; however, if emitter bypass capacitor C_E is shorted, the circuit will operate but it will be temperature-sensitive. Likewise, if the emitter bypass capacitor is open, it may reduce the output because of degenerative feedback, but normally will not cause complete stoppage of operation. If the input coupling capacitor or the output capacitor is open, no output will result. Check the input and output circuits with an oscilloscope; disappearance of the signal will indicate the location of the defective component. If the coupling capacitor is shorted or leaky, it will affect the base bias if located at the input, but will probably not be sufficient to stop operation. On the other hand, if the output capacitor is at fault, the collector reverse bias (which is normally high as compared with the base bias) will be applied as full forward bias to the base of the next stage and will bias it heavily into saturation; thus, no output will result, and the current may be sufficient to destroy the transistor. If the coupling capacitor is leaky, the effect will depend upon the amount of leakage. With slight leakage there may be practically no observable effect, or possibly distortion; with heavy leakage there will probably be no output. Of course, if the transistor is shorted or otherwise defective, a no-output condition will occur. However, the transistor should be replaced only after all other checks have been made and there is still no output. A rough check of transistor operation can be made (if the transistor can be easily removed from the circuit) by measuring the forward and reverse resistances with an ohmmeter. A high reverse resistance and low forward resistance indicates that the transistor is operable, but does not indicate if the gain is normal. Be certain to observe the correct polarities.

Reduced Output. Improper bias voltage or a change in in the value of a component, as well as a defective transistor can cause reduced output. If the transistor gain is low, the output will also be low; however, transistors should be replaced only after all other checks have been made, unless there is good reason to suspect that improper voltages have been applied. If either of the base voltage-divider bias resistors changes in value, the bias will be either too low or too high and the output will be reduced, with accompanying distortion. A simple voltmeter check will determine whether the bias is correct. If the collector resistor is too high in value, the output will be increased because of the extra voltage drop across the resistor; if the resistor is too low, in value, the output will be decreased. If the coupling capacitors are defective, a loss of output at the low-frequency end of the spectrum will result when the coupling capacitance is less than the design value. A leaky capacitor will likewise cause improper bias voltages and reduced output. Capacitors usually must have one end disconnected from the circuit before they can be tested by means of a standard capacitance analyzer (in-circuit capacitance checkers do not require this).

Distorted Output. If the base bias is too high (reduced forward bias), the transistor will operate on the lower portion of its dynamic characteristic, and the negative input peaks will be clipped (positive collector swings). Likewise, if the bias is too low (increased forward bias), the transistor will conduct heavily and operate on the upper portion of its dynamic characteristic, with corresponding clipping of the positive peaks (negative collector swings). In both cases extreme distortion will be caused. If the bias is proper but the collector voltage is not, similar effects may be caused. If the collector voltage is too high, the negative collector swing will be clipped, and if too low the positive collector swing will be clipped; in either instance heavy distortion will result. An open emitter bypass capacitor will permit degenerative feedback to occur, and, depending upon the amount, will show either as distortion or as reduced output. A change in load resistance produced by a defective collector or load resistor or by a leaky coupling capacitor (causing a heavy shunting of the output load) usually shows as a distorted output with reduced volume because of the mismatching. Use an oscilloscope to follow the signal through the circuit and determine the point at which the waveform departs from normal. In most instances the defective component will then be apparent. Do not overlook the possibility that distortion may be occurring in a previous stage, merely being amplified by the stage under suspicion. Too large an input (overdrive) will cause both positive and negative peak clipping with distortion, just as in an electron-tube amplifier. Apply a square-wave input from a signal generator and observe the output on an oscilloscope. Frequency distortion will be shown by a sloping rise and fall time (poor high-frequency response); a sloping flat top indicates poor low-frequency response. Electron-tube techniques for locating distortion may generally be used for transistor trouble shooting if the proper voltages and polarities are employed.

IMPEDANCE-COUPLED AUDIO AMPLIFIER.

APPLICATION.

The impedance-coupled transistor audio amplifier is used where higher gain than the r-c coupled stage is desired with better response than that provided by transformer coupling.

CHARACTERISTICS

Uses common emitter circuit for higher gain.

Operates Class A for linear operation and minimum distortion.

Usually amplifies small signals, but can be designed to handle large signals in cascaded stages.

Is fixed biased from the collector supply, but may use self bias in some applications.

Emitter swamping is normally used for thermal stabilization.

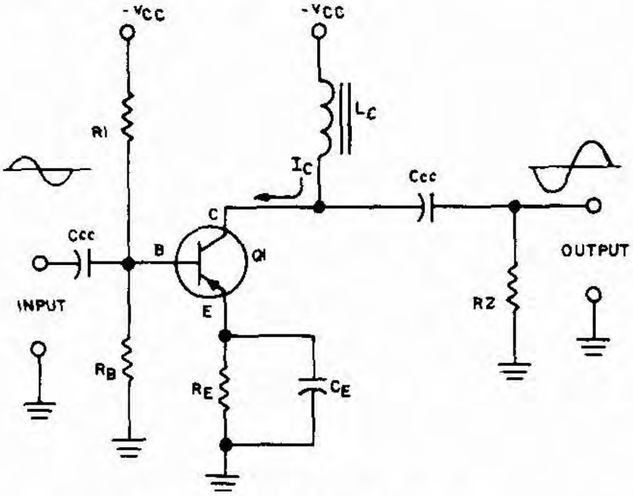
Gain is fairly uniform over a range of approximately 100 to 15,000 cps or more.

Both voltage and power gain are high.

CIRCUIT ANALYSIS.

General. The impedance-coupled transistor amplifier is similar in a general sense to the impedance-coupled electron tube amplifier previously discussed in Part A of this section of the Handbook. Use of the common (grounded) emitter circuit allows use of the analogy that the base of the transistor is equivalent to the electron tube grid, the emitter equivalent to the tube cathode, and the collector equivalent to the tube plate. Thus it is clear from the following schematic that the two impedance coupled circuits are practically identical. Any differences are due to the transistor internal parameters and the matching requirements to obtain maximum output with minimum distortion.

Circuit Analysis. The following schematic is that of a conventional PNP, triode, common-emitter impedance-coupled transistor audio amplifier circuit.



Impedance-Coupled Audio Amplifier

The input is shown capacitively coupled, and voltage divider R1, RB provides fixed bias from the collector supply. Emitter swamping is provided by RE for temperature stabilization; RE is bypassed by CE. (See section 3, paragraph 3.4.1, of this Handbook for a discussion of bias arrangements, and paragraph 3.4.2 for a discussion of bias stabilization methods.) Collector impedance LC is the load across which the output voltage is developed; this voltage is applied through coupling capacitor Ccc to the output circuit. Resistor R2 is the base-to-ground resistor in the next stage when cascaded amplifiers are used, or is the output load resistor (such as a headset) in single-ended stages. (In some applications R2 may be replaced by an iron-cored inductor similar to LC.)

Normally, the amplifier is a small-signal amplifier with the bias fixed at the center of the transistor dynamic transfer characteristic. With no input signal a steady collector current, IC, flows as determined by the base bias voltage. With R1 and RB connected across the collector supply as a voltage divider, a forward (negative) bias is developed across RB; this bias is sufficient to cause the quiescent value of IC to flow, even though the collector is reverse-biased.

When the input signal goes positive, assuming a sinewave input, the forward base bias is decreased instantaneously by the amplitude of the input signal, and collector current IC is reduced. The reduction in collector current causes the voltage across collector impedance LC to de-*crease and rise toward* the supply voltage, which is negative (this is exactly the reverse of vacuum-tube action); thus, a negative-swinging output signal is developed. When the input signal becomes negative, it adds to the forward base bias and causes LC to increase. The increase in collector current through LC produces a large voltage drop across the impedance, reduces the negative collector voltage and produces a positive swing. Therefore, the collector output follows the input signal except *that is is* reversed in polarity: when the input signal is positive, the output signal is negative, and vice versa. The collector output is developed across the impedance of LC between the collector and ground, and is applied through coupling capacitor Ccc *to the base of the next* stage, or to the output load.

In cascaded impedance-coupled stages the base bias resistor and base-to-emitter internal impedance of the next stage transistor offer a shunt path between coupling capaci-*tor Ccc and ground.* Therefore, the reactance of Ccc and the total parallel resistance (or impedance) from base to ground form a voltage divider across the collector resistor of the first stage. If the reactance of the coupling capacitor is large, the output voltage is greatly attenuated, and only a *small* output appears between base and ground of the second stage. Since the reactance of Ccc varies inversely with frequency, the lower audio frequencies are attenuated more than the higher frequencies. For good low-frequency response the coupling capacitor is made sufficiently large in value that its reactance is very small as compared with the base-to-ground resistance or impedance. This is similar to vacuum-tube practice, where relatively small coupling capacitors *(such as .001 microfarad) are satisfactory*, because the vacuum-tube grid-to-ground impedance is very high. Because the transistor base-to-emitter impedance is fairly low (about 500 ohms), a coupling capacitor of 50 microfarads or more is needed to achieve the low impedance required to pass *the signal without excessive attenuation.* (A 50-microfarad capacitor has a capacitive reactance of approximately 30 ohms at 100 cps.) For good low-frequency response the reactance of the coupling capacitor should always be less than one-tenth the effective base input impedance.

In those circuits where an impedance replaces R2 the coupling capacitor and inductor can be made to series-resonate at a low frequency to provide bass boost.

At the higher audio frequencies (above 15,000 cps), the collector-to-emitter capacitance of the first stage and the base-to-emitter shunting capacitance of the second stage together with the large distributed capacitance from turn to turn of the *collector-inductance tends to bypass the* high frequencies to ground, causing a drop in the response. The frequency-attenuating action produced by the transistor occurs because the width of the internal transistor PN junctions are voltage-sensitive. With higher voltage the transition region is narrow, corresponding to the closely spaced plates of a capacitor with the associated high *capacitance. The reverse bias on the collector also reduces* the width of this transition region, so that transistors are generally characterized by a high interelectrode capacitance. For example, an audio transistor may have a collector-to-base capacitance on the order of 50 picofarads, as *compared with a* vacuum-tube plate-to-grid capacitance of one or more picofarads. The collector-to-emitter capacitance is usually 5 to 10 times the value of the collector-to-base capacitance (in the common-emitter circuit), as compared with 8 picofarads or less for vacuum-tube plate-*to-cathode capacitance.* Thus, it can be seen how the high-frequency response is affected considerably by internal transistor parameters. Of course, any shunt wiring capacitance and that of the collector inductance will also add to the shunting effects of the transistor. Both low- and high-frequency compensating circuits may be used to increase the effective frequency response of the circuit, as discussed in Wideband Video Amplifier Circuits later in this section.

Over the region of 100 to 15,000 cps, the impedance-coupled amplifier has a relatively flat response, and with proper matching will afford high power and voltage gains. Hence, this form of coupling is employed where good audio response is required with a moderate power output (for high *output transformer-coupling is used).* The common-base configuration is sometimes employed where better high-frequency response is desired than that provided by the common-emitter circuit, since the collector-to-base capacitance is only 1/5 to 1/10 as great.

Transistor audio amplifiers are also characterized by a high inherent noise which is greatest at the lower audio frequencies. Operation with low values of emtter current and low collector voltages, together with low values of input resistance, tends to minimize the noise. By using an inductor in place of the base-to-ground resistor (RB or R2 in the schematic) a very low input resistance, and a lower noise figure over that of the r-c coupled amplifier is obtained. In the common-emitter circuit, degenerative effects produced by an unbypassed emitter resistor tend to increase the input resistance. Thus, it is conventional practice to use large emitter bypass capacitors to avoid any possibility of degeneration. As with the electron tube, *external feedback circuits provide better response,* although emitter degeneration may sometimes be used. Since fixed bias from the collector supply may be easily obtained by a simple voltage divider, it is used in both large-and-small-signal applications. Self-bias is generally *restricted in use to very small-signal* amplifiers; otherwise, distortion and improper operation with a reduction in gain, or blocking, may occur on large signals. The emitter resistor functions mainly as a swamping resistor for temperature stabilization, and prevents large changes in amplification with temperature variations.

In considering the operation of the transistor impedance-coupled amplifier as compared with the electron-tube impedance-coupled amplifier, it should be clear from the above discussion that one circuit is an almost exact counterpart (dual) of the other. The difference is that transistor stages operate with low input and output impedances, at low voltages, and at very low levels of amplification, whereas electron-tube stages operate with relatively high input and output impedances, at high voltages, and at high levels of amplification. Thus, the transistor is basically a current amplifier, while the electron tube is a voltage amplifier. Consequently, the transistor requires closer matching (rather than mis-matching) of impedances to maximum performance.

FAILURE ANALYSIS.

General. When making voltage checks use a vacuum-tube voltmeter to avoid the low values of multiplier resistance employed on the low-voltage ranges of the standard 20,000 ohms-per-volt meter. Be careful also to observe proper polarity when checking continuity with an ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. A no-output condition may be caused by an open or short circuit, by improper bias or loss of collector voltage, or by a defective transistor. A voltage check will determine whether the bias and collector voltages are normal; also, a VTVM will indicate audio input and output voltages. With the few components involved, simple voltage and resistance checks will usually indicate the source of trouble. If the bias voltage divider is open because return resistor, RB is defective, the base bias will be sufficient to cut off the transistor. With R1 open, only contact bias exists and the transistor will very likely conduct heavily in the saturation region. If collector inductor LC is open there will be no voltage measured between the collector and ground. If emitter resistor RE is open, the circuit will not operate; however, if emitter bypass capacitor CE is shorted, the circuit will operate but it will be temperature-sensitive. Likewise, if the emitter bypass capacitor is open, it may reduce the output because of degenerative feedback, but normally will not cause complete stoppage of operation. If the input coupling capacitor or the output capacitor is open, no output will be obtained. Check the input and output circuits with an oscilloscope; disappearance of the signal will indicate the location of the defective component. If the coupling capacitor is shorted or leaky, it will affect the base bias if located at the input, but will probably not be sufficient to stop operation. On the other hand, if the output capacitor is at fault, the collector reverse bias (which is normally high as compared with the base bias) will be applied as full forward bias to the base of the next stage and will bias it heavily into saturation; thus, no output will result, and the current may be sufficient to destroy the transistor. If the coupling capacitor is leaky, the effect will depend upon the amount of leakage. With a slight leakage there may be practically no observable effect, or possibly distortion; with heavy leakage there will probably be no output. Of course, if the transistor is shorted or otherwise defective, a no-output condition will occur. However, the transistor should be replaced only after all other checks have been made and there is still no output. A rough check of transistor operation can be made (if the transistor can be easily removed from the circuit) by measuring the forward and reverse resistances with an ohmmeter. A high reverse resistance and low forward resistance indicates that the transistor is operable, but does not indicate if the gain is normal. Be certain to observe the correct polarities.

Reduced Output. Improper bias voltage or a change in the value of a component, as well as a defective transistor can cause reduced output. If the transistor gain is low, the output will also be low; however, transistors should be replaced only after all other checks have been made, unless there is good reason to suspect that improper voltages have been applied. If either of the base voltage-divider bias resistors changes in value, the bias will be either too low or too high and the output will be reduced, with accompanying distortion. A simple voltmeter check will determine whether the bias is correct. If the collector inductor develops a high resistance, the output will be decreased because of the extra d-c voltage drop across the choke. If the coupling capacitors are defective, a loss of output at the low-frequency end of the spectrum will result when the coupling capacitance is less than the design value. A leaky capacitor will likewise cause improper bias voltages and reduced output. Capacitors usually must have one end disconnected from the circuit before they can be tested by means of a standard capacitance analyzer (in-circuit capacitance checkers do not require this).

Distorted Output. If the base bias is too high (reduced forward bias), the transistor will operate on the lower portion of its dynamic transfer characteristic, and the negative input peaks will be clipped (positive collector swings). Likewise, if the bias is too low (increased forward bias), the transistor will conduct heavily and operate on the upper portion of its dynamic transfer characteristic, with corresponding clipping of the positive peaks (negative collector swings). In both cases extreme distortion will be caused. If the bias is proper but the collector voltage is not, similar effects may be caused. If the collector voltage is too high, the negative collector swing will be clipped, and if too low the positive collector swing will be clipped; in either instance heavy distortion will result. An open emitter bypass capacitor will permit degenerative feedback to occur, and, depending upon the amount, will show either as distortion or as reduced output. A change in load resistance produced by a defective collector choke or load resistor, or by a leaky coupling capacitor (causing a heavy shunting of the output load) usually shows as a distorted output with reduced volume because of the mismatching. Use an oscilloscope to follow the signal through the circuit and determine the point at which the waveform departs from normal. In most instances the defective component will then be apparent. Do not overlook the possibility that distortion may be occurring in a previous stage, merely being amplified by the stage under suspicion. Too large an input (overdrive) will cause both positive and negative peak clipping with distortion, just as in a electron-tube amplifier. Apply a square-wave input from a signal generator and observe the output on an oscilloscope. Frequency distortion will be shown by a sloping rise and fall time (poor high-frequency response); a sloping flat top indicates poor low-frequency response. Electron-tube techniques for locating distortion may generally be used for transistor trouble shooting if the proper voltages and polarities are employed.

TRANSFORMER-COUPLED AUDIO AMPLIFIER.

APPLICATION.

The transformer-coupled transistor audio amplifier is used where higher gain and power output than that provided by an r-f-coupled or impedance-coupled stage are required, and where the reduction in frequency response can be tolerated.

CHARACTERISTICS.

Uses common emitter circuit for higher gain.

Operates Class A for linear operation and minimum distortion.

Usually amplifies small signals, but can be designed to handle large signals in cascaded stages.

Is fixed-biased from the collector supply, but may use self-bias in some applications.

Emitter swamping is normally used for thermal stabilization.

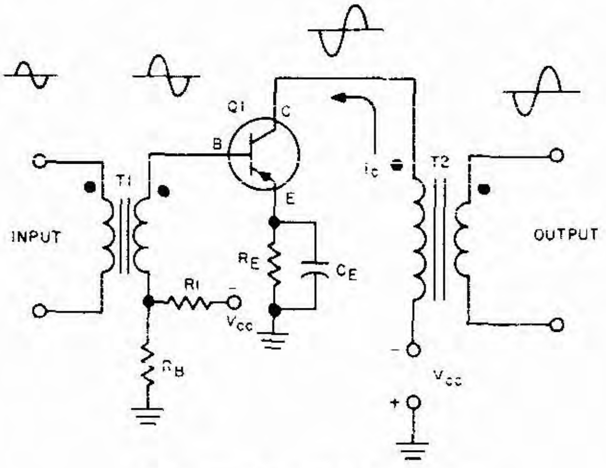
Gain is fairly uniform over a range of approximately 100 to 10,000 cps or more.

Both voltage and power gain are high.

CIRCUIT ANALYSIS.

General. The transformer-coupled transistor amplifier is similar in general to the transformer-coupled electron-tube amplifier previously discussed in Part A of this section of the Handbook. Use of the common-emitter (grounded-emitter) circuit permits the assumption that the base of the transistor is equivalent to the electron-tube grid, the emitter is equivalent to the tube cathode, and the collector is equivalent to the tube plate. Thus, it is clear from the following schematic that the two transformer-coupled circuits are practically identical. Any differences are due to the transistor internal parameters and the matching requirements to obtain maximum output with minimum distortion.

Circuit Operation. The accompanying schematic is that of a conventional PNP, triode, common-emitter, transformer-coupled transistor audio amplifier circuit.



Transformer-Coupled Audio Amplifier

The input is shown transformer-coupled through T1, and voltage divider R1, R_B provides fixed bias from the collector supply. Emitter swamping is provided by R_E for temperature *stabilization;* R_E is bypassed by C_E. (See Section 3, paragraph 3.4.1 of this Handbook for a discussion of bias arrangements, and paragraph 3.4.2 for a discussion of bias stabilization methods.) The output is transformer-coupled through T2.

The use of T1 to apply the input signal to the base circuit provides an almost ideal temperature response characteristic. The low transformer winding resistance produces a low base input resistance, and, when used with emitter swamping resistor R_E, any variation in gain with temperature is reduced to a very small value over a large range of temperatures (greater than for any other type of coupling circuit). Normally, transistor Q1 rests in its quiescent condition, with Class A bias provided by voltage divider R1, R_B. The quiescent collector current, I_C, is steady, producing only a small constant voltage drop across the primary resistance of T2. Thus, practically the full value of collector supply, V_{cc}, *is available. With a steady collector* current no voltage is induced in the secondary of T2, and there is no output (assuming no input signal or noise). When a positive-swinging signal is introduced into the input circuit, current flow through the primary of T1 induces a voltage in the secondary, which is applied to the base of Q1. Assuming that the transformer secondary is connected in-phase with the primary, a positive increase in voltage appears at the base. This positive voltage swing cancels the forward negative bias, and a reduced flow of collector current occurs. As the instantaneous collector current decreases, the primary voltage drop also decreases, and allows the collector voltage to rise toward the negative supply voltage. Meanwhile, the reducing collector current induces a voltage in the secondary winding. The secondary winding is connected in-phase so that a reducing collector current produces a negative voltage swing in the secondary, and an increasing current produces a positive swing.

The emitter current flowing through R_E is the steady quiescent value, and any change in base bias with input signal is bypassed around the emitter resistor through capacitor C_E. Although the capacitor will not pass the quiescent d-c current, it will pass the alternating audio voltage produced by the changing input signal. Thus, only d-c current changes flowing through R_E (the thermally induced changes caused by temperature variation) produce an emitter bias. This emitter bias is in a direction which causes a reduced flow of emitter current, since it reduces the forward bias and hence reduces the collector current back to the original value so that it appears unchanged. If the emitter bypass capacitor were not used, the input signal voltage would produce a degenerative effect, since all collector and emitter current would be forced to flow through the emitter resistor.

Consider next the negative swing of the input signal. In this instance, the forward bias on the base element is increased (the two negative voltages add), and a heavy collector current flow occurs. The increasing i_c through the primary of T2 induces a voltage into the secondary. Assuming the same in-phase connection of the primary and secondary, the output voltage is positive.

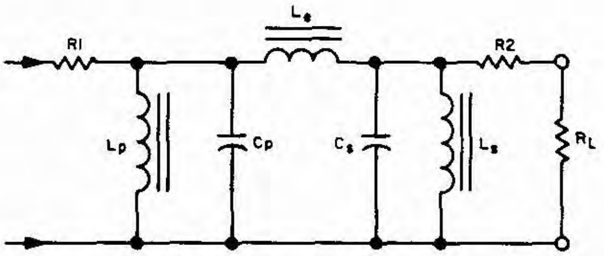
Note that this action is similar to that of the vacuum tube amplifier, except that it is opposite. That is, a positive input to an electron-tube grid increases the plate current, whereas a positive input to a PNP transistor base element reduces the collector current. In each instance, however, the polarization of the output is opposite that of the input. By changing the connections of the secondary winding of either T1 or T2, the signal can be changed so that it is of the same phase at both the input and the output; this is an advantage of transformer coupling.

Since the secondaries of T1 and T2 are not connected to their primaries, the transformers offer a convenient method of separating input or output signals from bias or collector voltages. By using the proper turns ratio, the primary and secondary impedances may be matched. In the base circuit the input resistance is matched, giving maximum gain, likewise, in the output circuit the proper turns ratio reflects the secondary load impedance into the primary, which, when added to that of the transformer primary itself, provides a matched load for maximum output.

Normally, the transformer-coupled stage is operated in the middle of its transfer characteristic to produce linear amplification. It is also a small-signal amplifier when used in preamplifier stages. In following cascaded stages it becomes a large-signal amplifier, operating with a larger bias over the linear range of its transfer characteristic. When necessary, bias resistor R_B is bypassed to ground with a large capacitor to prevent audio signal voltages from causing the bias to change with the signal, particularly in high-gain and large-signal amplifiers.

In cascaded transistor amplifiers the load on the secondary of T2 is the base resistance of the next transistor. Since this is resistive rather than reactive, there is less frequency distortion that would occur in an electron tube, where the load is predominatly reactive (even in output stages the speaker is a varying reactance). In low-power stages the flow of reverse (leakage) current, I_{ceo}, through the collector-to-base junction becomes important when it is a large percentage of the total operating collector current. Thus, the designer chooses a transistor with as large a beta as is possible, and as small a leadage current as can be obtained, in order to get the most gain with the least leakage current. (The flow of reverse current does not occur in electron tubes.)

The frequency response of the transformer-coupled amplifier is lower than that of the resistance-coupled or impedance-coupled transistor audio amplifier. There is more shunting capacitance than in resistance coupling because of the transformer distributed turn capacitance, and there is a leakage inductance between the primary and secondary which does not exist in the impedance-coupled stage. The accompanying figure shows the equivalent circuit of a transformer-coupled stage and the factors that affect the response.



Transformer Equivalent Circuit

In the figure, resistors R1 and R2 represent the d-c primary and secondary resistance, respectively. These resistances must be kept low since they are ohmic losses; also, the full collector current usually flows through R1. Therefore, the slope of R1 determines the d-c load line, and the transformers are designed to have a primary resistance of from 200 to 800 ohms for proper matching of transistors. Inductances L_p and L_s represent the magnetizing inductances of the primary and secondary transformer windings, respectively. The primary inductance is usually made from 2 to 5 times load resistance R_L for good low-frequency response. However, the lower the frequency the less the inductive reactance, so that the response tends to drop at low frequencies. Capacitors C_p and C_s represent the shunting capacitances of the primary and secondary windings, respectively. These include the shunt base-to-ground and collector-to-ground capacitances of the transistor, which are also large. Therefore, the high frequencies tend to be shunted to ground. C_p, L_e, and C_s in combination form an effective low-pass filter, so that the high frequencies are attenuated (L_e is the leakage inductance between the primary and secondary). In substance, then, we see that the high-frequency response is primarily determined by the combination of shunting capacitance with load resistance and leakage inductance, while the low-frequency response is determined by the combination of load resistance and magnetizing inductance. In addition, the shunting capacitance and inductance form resonant circuits which produce humps in the response curve. Practically speaking, the response is very similar to that of the electron-tube transformer-coupled audio stage, with somewhat less high-frequency response. Loss of low-frequency response as compared with the electron-tube circuit becomes apparent when miniaturized transformers are used, because of the difficulty of building transformers with a sufficiently large iron core to provide a high inductance with the limited number of turns available in the space allocated.

Despite the apparent loss of response in the transistor transformer-coupled amplifier as compared with other forms of coupling and the use of electron tubes, relatively good response is obtained by using more stages and low-and-high-frequency peaking circuits where necessary. A maximum efficiency of about 50 percent is obtained as compared with 25 to 30 percent for resistance-coupled stages.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of multiplier resistance employed on the low-voltage ranges of the standard 20,000 ohms-per-volt meter. Be careful also to observe polarity when checking continuity with an ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. A no-output condition may be caused by an open-or short-circuited transformer winding, by improper bias or loss of collector voltage, or by a defective transistor. A voltage check will determine whether the bias and collector voltages are normal; also, a VTVM will indicate audio input and output voltages. With the few components involved, simple voltage and resistance checks will usually indicate the source of the trouble. If the bias voltage divider is open because return resistor RB is defective, the base bias will be sufficient to cut off the transistor. With R1 open, only contact bias exists and the transistor will very likely conduct heavily in the saturation region. If the primary of T1 is open, there will be no voltage measured between the collector and ground. If emitter resistor RE is open, the circuit will not operate; however, if emitter bypass capacitor CE is shorted, the circuit will operate but it will be temperature-sensitive. Likewise, if the emitter bypass capacitor is open, it may reduce the output because of degenerative feedback, but normally it will not cause complete stoppage of operation. If the input transformer or the output transformer is open, no output will be obtained. Check the input and output circuits with an oscilloscope; disappearance of the signal will indicate the location of the defective winding. If the transistor is shorted or otherwise defective, a no-output condition will occur. However, the transistor should be replaced only after all other checks have been made and there is still no output. A rough check of transistor operation can be made (if the transistor can be easily removed from the circuit) by measuring the forward and reverse resistance with an ohmmeter. A high reverse resistance and low forward resistance indicates that the transistor is operable, but does not indicate whether the gain is normal. Be certain to observe the correct polarities.

Reduced Output. Improper bias voltage or a change in the value of a component, as well as a defective transistor or transformer, can cause reduced output. If the transistor gain is low, the output will also be low; however, transistors should be replaced only after all other checks have been made, unless there is good reason to suspect that improper voltage have been applied. If either of the base voltage-divider bias resistors changes in value, the bias will be either too low or too high and the output will be reduced, with accompanying distortion. A simple voltmeter check will determine whether the bias is correct. If the collector winding of T2 develops a high resistance, the output will be decreased because of the extra d-c voltage drop .

Distorted Output. If the base bias is too high (reduced forward bias), the transistor will operate on the lower portion of its dynamic transfer characteristic, and the negative input peaks will be clipped (positive collector swings). Likewise, if the bias is too low (increased forward bias), the transistor will conduct heavily and operate on the upper portion of its dynamic transfer characteristic, with corresponding clipping of the positive peaks (negative collector swings). In both cases extreme distortion will be caused. If the bias is proper but the collector voltage is not, similar effects may be caused. If the collector voltage is too high, the negative collector swing will be clipped, and if too low the positive collector swing will be clipped; in either instance heavy distortion will result. An open emitter bypass capacitor will permit degenerative feedback to occur, and, depending upon the amount, will show either as distortion or as reduced output. A change in load resistance produced by a defective output transformer (T2) or a load resistance change usually shows as a distorted output with reduced volume because of the mismatching. Use an oscilloscope to follow the signal through the circuit and determine the point at which the waveform departs from normal. In most instances the defective component will then be apparent. Do not overlook the possibility that distortion may be occurring in a previous stage, merely being amplified by the stage under suspicion. Too large an input (overdrive) will cause both positive and negative peak clipping with distortion, just as in an electron-tube amplifier. Apply a square-wave input from an audio signal generator and observe the output on an oscilloscope. Frequency distortion will be shown by a sloping rise and fall time (poor high-frequency response); a sloping flat top indicates poor low-frequency response. Electron-tube techniques for locating distortion may generally be used for transistor trouble shooting if the proper voltages and polarities are employed.

AUDIO POWER (CLASS A, AB, AND B) AMPLIFIER, PUSH-PULL, TRANSFORMER-COUPLED.

APPLICATION.

The push-pull transformer-coupled transistor audio amplifier is used where high power output and good fidelity are required. For example, it is used in receiver output stages, public address amplifiers, and AM modulators.

CHARACTERISTICS.

Collector efficiency is high with moderate power gain.

Requires twice the drive of a single transistor stage.

Power output is more than twice that of the single transistor stage.

Second and higher even-order harmonic distortion is cancelled.

Distortion varies with the class of operation; it is least for Class A operation, and greatest for Class B operation.

Collector efficiency varies with the class of amplifier, from 50 percent maximum in Class A to 78 percent maximum in Class B, with an intermediate value for Class AB.

Fixed bias is usually used, but self-bias may be encountered in some Class A applications.

Operates as a large-signal amplifier for all except very small inputs.

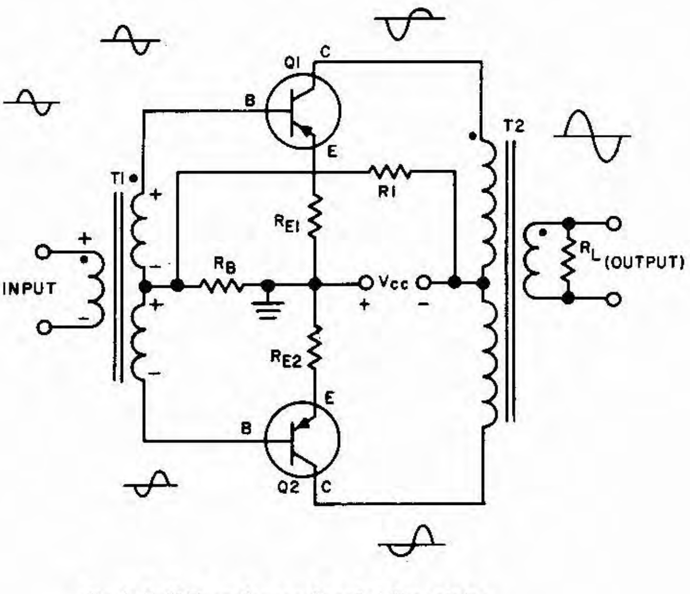
Emitter swamping is used for thermal stabilization.

CIRCUIT ANALYSIS.

General. The push-pull transformer-coupled transistor amplifier is similar in general sense to the push-pull transformer-coupled electron tube audio amplifier discussed in Part A of this section of the Handbook. Use of the common (grounded) emitter circuit allows use of the analogy that the base of the transistor is equivalent to the electron tube grid, the emitter equivalent to the cathode, and the collector equivalent to the tube plate. Examination of the accompanying schematic reveals that the transistor push-pull circuit is practically identical to the electron tube push-pull circuit. Any differences are due to the transistor internal parameters and the matching requirements to obtain maximum power output with minimum distortion.

Push-pull amplifiers can be operated Class A, Class AB, or Class B, as determined by the amount of forward bias. Like the electron tube push-pull circuit, the least amount of distortion and power output is produced in Class A operation, and the greatest amount of distortion and power output is obtained in Class B operation. Class AB stages operate between these levels of distortion and power output. For a given equipment and type of transistor, selection of the operating bias, distortion, and power output is a design problem. The following discussion will cover each type of operation; although the different types of operation are similar, there are significant differences among them.

Circuit Operation. The following schematic shows a PNP push-pull, transformer-coupled output stage. The load resistance may be a loudspeaker, a Class C r-f stage, or other type of load. The load is considered to be resistive unless stated otherwise in the text.



Push-Pull Transformer-Coupled Transistor Power Amplifier

The input signal is applied to the base of both transistors through transformer T1. The polarity for the positive half-cycle of input is shown on the schematic to facilitate proper understanding of the operation. Note that when the top end of the secondary of T1 is positive, the bottom end is negative. Thus, equal and oppositely polarized signals are applied to the base of transistors Q1 and Q2 when an input signal appears in the primary of T1.

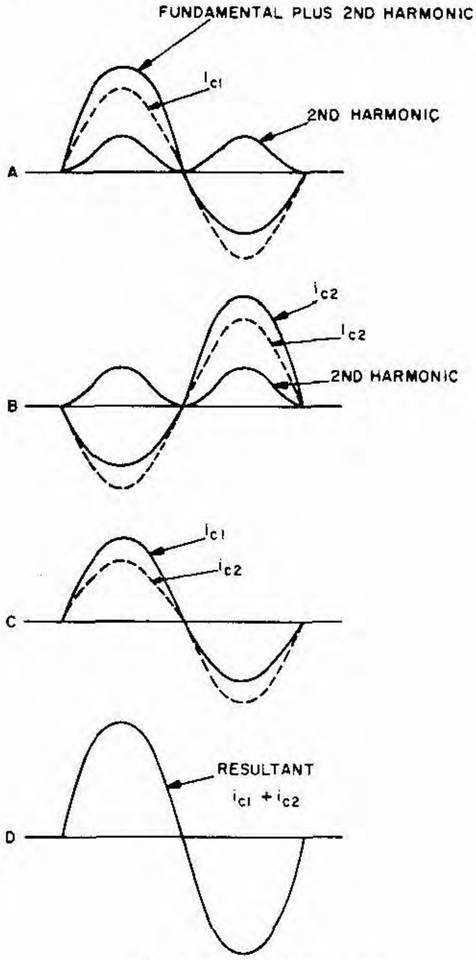
The input signal is obtained from a preceding driver power amplifier stage. Very little power is required for Class A operation; increasingly more drive power is required for Class AB and Class B operation. The actual amount of drive power needed depends upon the circuit design and the transistors used; it is on the order of 2 or 3 percent of the output. Transformer input coupling is used to provide maximum drive power and proper matching of the driver stage. Fixed bias from the collector supply is applied through voltage divider resistors R1 and RB. Resistors RE_1 and RE_2 are the emitter swamping resistors, which are left unbypassed to provide a slight amount of degeneration. Refer to Section 3, *paragraph* 3.4.1, of this Handbook for a discussion of bias arrangements, and to paragraph 3.4.2 for a discussion of bias stabilization methods. The collector load consists of the primary resistance of output transformer T2 plus the resistance reflected from the load connected across the secondary.

Class A Operation. With no input signal, the stage is resting in its quiescent condition, drawing heavy collector current and operating at the point of lowest efficiency. Since no change in collector current occurs, no output voltage is induced in the secondary of T2. Assuming a positive input swing on the base of Q1 and an in-phase connection of T1, the positive voltage of the signal subtracts from the normal forward (negative) bias, effectively reducing the base bias and causing less collector current to flow in Q1. As the collector current is reduced, the changing lines of magnetic flux between the primary and secondary of T2 induce a voltage in the secondary. At the peak of the input signal, the collector current of Q1 is reduced to a small value, and the collector voltage approaches the supply voltage (reaches its most negative value). Thus, the common emitter circuit makes the polarity of the ouput signal opposite that of the input signal. Simultaneously, the input signal in T1 is applied as a negative voltage swing to the base of Q2 (the ends of the secondary winding are oppositely polarized when a voltage is induced), which adds to the forward bias of Q2. The increase in forward bias causes an increase in the collector current through the primary of T2, and induces an in-phase voltage in the secondary of the output load.

The net result of the input signal is to decrease the signal output of Q1 and to increase the output of Q2. These induced output voltages are combined in the secondary of T2 to produce the effect of a collector current equivalent to twice that of a single transistor. Note that this action is the same as the action that occurs in the electron tube push-pull circuit (see Part A of this Section). In the same manner, the collector-to-collector (plate-to-plate) load impedance is also four times the load, since the primary-to-secondary turns ratio is based on a one-to-one ratio of half the primary to the secondary.

During the negative half-cycle of input signal excursion, the opposite action occurs. The negative signal adds to the negative forward bias and increases the collector current of Q1. Meanwhile, the base of Q2 is driven positive at the same time Q1 is driven negative. The positive increase in the input signal reduces the forward bias and causes the Q2 collector current to decrease. Again, the net result is the same as if twice the collector current of a single stage were involved in flowing through T2. Note also that the collector current flows in opposite directions through the two halves of the primary of T1, so that any inphase primary-induced voltage components are cancelled out (second and all even harmonics); thus, the output voltage induced in the secondary consists of the fundamental component and any odd harmonics. The manner in which the second-harmonic component is cancelled out in the secondary is shown in the following illustration. In part A of the figure, the positive signal is enhanced by the second harmonic, while the negative signal is reduced. In part B, the opposite action is shown for the second half-cycle of operation. The separate resultant waveforms are shown in part C. In part D, they are combined together to form a complete amplified signal with no second-harmonic content.

For Class A operation, maximum output efficiency and the least dissipation are obtained with maximum signal swing. To make certain that the power dissipation ratings of the transistor are not exceeded, only half the maximum permissible collector voltage is applied, since the applied voltage tends to double because of the inductive effect of the transformer. For Class A operation, the transistor is biased and operated at the center of the forward transfer characteristic curve, so that equal base current swings will



Elimination of 2nd Harmonic

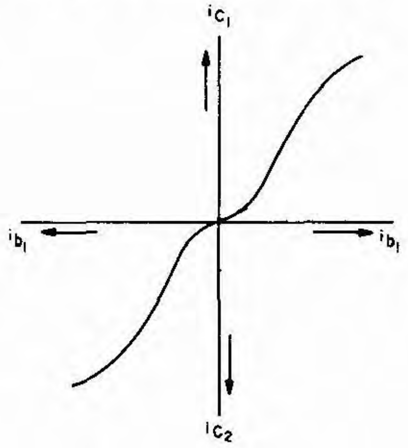
produce approximately equal collector current swings; thus, it functions as a large-signal amplifier. Since a large-signal amplifier operates over a much greater range of current and voltage than a small-signal amplifier, circuit design is accomplished graphically, using the actual transistor currents to determine the range over which minimum distortion and maximum power output can be obtained. Usually, the transistor is slightly less linear than the electron tube, but with good design its operation compares favorably with electron tube operation.

Since much heat is dissipated at the collector for large power outputs, the shell of the power transistor is usually connected firmly to the chassis for direct conduction and reduction of heat (chassis acts as a heat sink). Where the shell must be insulated from the chassis, it is usually separated by a thin wafer of mica (or other suitable material) to provide insulation and yet allow full heat transfer.

Where minimum distortion is required, the transistors are selected in matched pairs, as is true with electron tubes. Because of the high power-handling capability required for Class A operation, transistors are usually operated Class B or Class AB.

Class B Operation. In true Class B operation, the bias is such that no collector current flows for one-half of the cycle. Thus, each transistor reproduces only half of the cycle, and two transistors are required to faithfully reproduce any signal (an exception is the Class B r-f amplifier, discussed later in this section, which uses a tank circuit and amplifies only a single frequency). Since at cutoff a reverse current flows in the transistor, collector current is never completely cut off, and a small quiescent current flows during the inactive half-cycles of transistor operation. (This quiescent reverse current should not be confused with the small forward current which flows in Class AB operation because the bias is not at cut off.)

For two transistors completely biased off, the forward transfer characteristic is as shown in the following illustration. The two transfer curves are placed back-to-back to make the complete dynamic operating curve. Note how this curve is rounded off at the beginning and at the end instead of being a straight line. This is typical of the nonlinearity obtainable at cutoff, and illustrates why Class B operation produces the greatest distortion.



Composite Current Transfer Characteristic, Class B Operation

The accompanying circuit is that of a typical Class B stage operated with zero bias. Emitter swamping resistors R1 and R2 are used for thermal compensation, and are unbypassed to provide a slight amount of degeneration.

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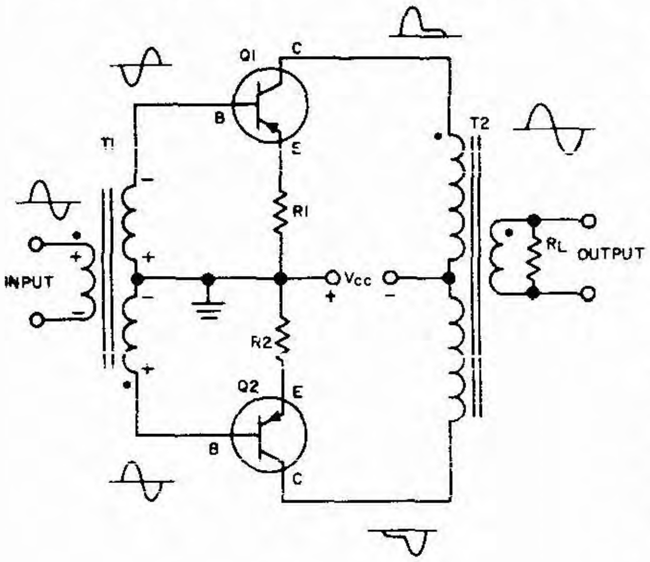


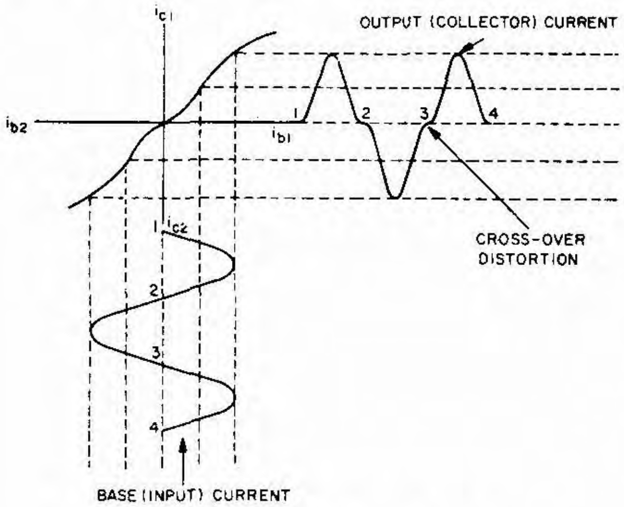
Class B Push-Pull Stage

Note here one of the differences between the electron tube and the transistor. At zero bias the conventional electron tube conducts heavily, and it is necessary to apply considerable negative bias to achieve Class B operation. On the other hand, the transistor always has the collector reverse-biased; thus, in the absence of a forward base bias (that is, at zero bias), no collector current can flow. In this respect the transistor is similar to specially constructed Class B (zero bias) electron tubes.

When a signal is applied to input transformer T1, a voltage is applied to the base of transistor Q1 and an an oppositely polarized voltage is applied to the base of Q2 (the polarity for the initial half cycle is shown on the schematic). With transistors Q1 and Q2 at zero bias, only reverse leakage collector current flows in the absence of a signal. When the input signal is applied, the flow of current in the primary of T1 induces an oppositely polarized signal on the base of Q1 (transformer connected out-of-phase). Thus, the positively swinging input appears as a negative (forward) bias on the base of Q1, causing collector current to flow in the top half of the primary of T2, and induces an output voltage in the secondary. At the same time the input voltage applied to Q2 is opposite in polarity and produces a reverse bias, keeping Q2 cut off. During the entire half-cycle Q1 conducts while Q2 remains cut off. When the input signal reverses polarity, reverse bias is applied to cut off Q1 collector current, and forward bias is applied to Q2. Consequently, Q2 conducts and the increasing collector current through the bottom half of the primary of T2 induces a voltage in the secondary of the output transformer. During this half-cycle Q1 remains cut off while Q2 conducts. Thus, Q1 and Q2 alternately conduct when the input signal produces a forward bias. Since the outputs of Q1 and Q2 are combined in the secondary of the output transformer, the input signal is reproduced in amplified form, but of opposite polarity. If the output transformer is connected in-phase, the same polarity of output exists as in the primary; when it is connected out-of-phase, the opposite polarity exists. This transformer action is identical with that occurring in the electron tube push-pull circuit.

Since there is no heavy flow of quiescent current when no signal is applied, maximum dissipation occurs during the signal (at about 40 percent maximum collector current), and less heat is developed for the same signal as in a Class A amplifier. Hence the transistor can be driven harder to obtain greater efficiency and more power output than is obtained in the Class A stage. The flow of reverse leakage collector current represents a loss of efficiency since no useful action is produced by this current. Such current flow does not exist in the electron tube. To minimize this loss, transistors are selected for a low I_{CEO}. Since audio power is produced, the transistors heat during operation (a maximum of 78 percent efficiency is theoretically obtainable) and the reverse leakage current increases. Emitter swamping resistors R1 and R2 provide a small opposing bias voltage to prevent thermal runaway. They are not bypassed with capacitors as in Class A operation because the capacitors would charge during the operative half-cycle and discharge during the inoperative half-cycle, thus causing a change in bias. Because of the large peak current which flows through these resistors, they are kept to a very low value of resistance to prevent excessive degeneration and loss of amplification. In some applications, by proper selection of transistor types and good design they are not needed. In any event, when used, their main function is to provide thermal stabilization; any beneficial degeneration which may occur from their use is only a secondary consideration. Otherwise, they have no effect on the operation of the circuit.

Since the transistors operate alternately in Class B operation, there is no basic cancellation of second and even-order harmonics in the output transformer as in Class A operation. There is, however, an increase in third-harmonic distortion produced when the waveform passes through zero (this is known as **crossover distortion**). The development of this type of distortion is shown by projecting a sine-wave input signal on the transfer characteristic curve, as shown in the accompanying illustration. The distortion is greatest for small input signals and least for large input signals. This distortion is eliminated by applying a small forward bias to the base-emitter junction of the transistors, or what amounts to operation as a Class AB amplifier. Class B operation is used only when the large amount of third-harmonic distortion can be tolerated.

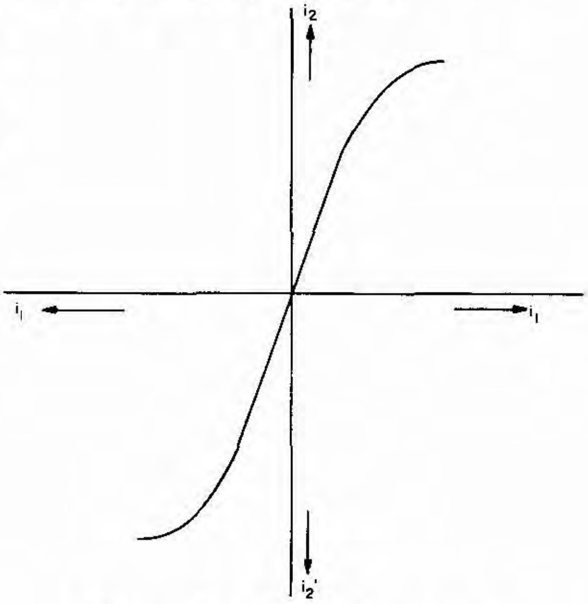


Development of Crossover Distortion

Class AB Operation. The schematic of the Class AB amplifier is basically identical with that of the Class A amplifier shown previously. The only difference is that bias voltage divider resistors R1 and RB are of different values. Only a slight forward bias is applied, and only a small collector current flows with no signal applied. While this current is essentially wasted, it does eliminate the crossover distortion which would be produced if the bias were reduced to zero. It is evident, then, that Class AB operation produces slightly less output than Class B operation. Because of the small resting current, the transistor can be driven harder than the Class A stage; consequently, greater output can be obtained than for Class A operation. The efficiency averages about 65 percent for a well designed Class AB stage.

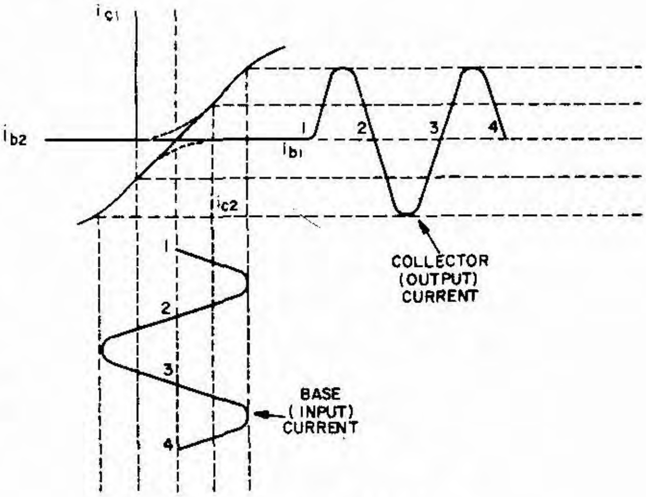
The small resting current, like the average current drawn in Class A operation, cancels out the flux in the primary of the output transformer (each side flows in a different direction), and there is no output produced until a signal is applied. When the input signal is applied, Q1 conducts and Q2 is driven to zero conduction on one half-cycle, while on the other half-cycle Q2 conducts and Q1 is driven to zero. The resultant signal swings are unequal and considerable second-harmonic distortion is produced in the primary of the output transformer; however, it is canceled out in the secondary when both signals are combined (assuming that the transistors are fairly well matched). Thus, only fundamental and third-harmonic distortion can exist in the output. This form of operation is identical with Class A operation except that more odd-harmonic distortion is produced because the transistors operate for less than 360 degrees of the cycle.

The accompanying illustration shows the composite transfer characteristic for a typical Class AB stage. When compared with the transfer curve for the Class B stage shown previously, it is evident that the operation is more linear except for very large signal swings.



Composite Current Transfer Characteristic, Class AB Operation

Projection of the input signal on the composite transfer curve shows the collector output, which, when compared with that of the Class B stage shown previously, indicates the improvement in fidelity obtained with Class AB operation, and the total elimination of cross-over distortion.



Development of Class AB Signal

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance ordinarily employed on the low-voltage ranges. Be careful also to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. A no-output condition can be caused by an open circuit in either the input transformer, T1, or output transformer, T2, or in the swamping resistors, R_{E_1} and R_{E_2}, as well as by lack of supply voltage. The supply voltage can be checked with a voltmeter, and lack of collector or base bias voltage can also be determined. Continuity *checks of the transformers* (WITH THE POWER TURNED OFF) will determine whether one or more of the windings are open, and the resistors can be checked for proper resistance with the ohmmeter. Normally, failure of the transistors will not cause complete loss of output unless both transistors fail completely.

Low Output. Lack of sufficient drive power, low supply voltage, improper bias, or a defective transistor can cause reduced output. The supply voltage and bias can be checked with a voltmeter. Lack of drive power can be determined by observing the waveform with an oscilloscope and noting whether there is sufficient drive to cause eventual flat-topping or bottoming of the output *waveform. A shorted or inoperative transistor can also* cause low output. Depending upon conditions, removing the transistor (from a plug-in socket) will either increase or reduce the output. In the case of a shorted transistor, the output will probably increase when it is removed. A transistor with low gain or poor performance, when removed, will probably cause further reduction of the output. If the shorted transistor is left in the circuit and the good one is removed, there will also be a decrease in the output. Thus, it can be seen that where a transistor is suspected, both transistors should be replaced with ones know to be good in order to determine whether the output comes up to normal. Further checking with a transistor tester will *determine the defective one.*

Distorted Output. Distorted output may be caused by lack of proper bias or supply voltage, by underdrive or overdrive, or by defective transistors or transformers. If one half of a transformer is open or shorted, one transistor will not operate properly and distortion will occur. Likewise, if the bias is too high, clipping will occur on the peak of the input signal, and if it is too low, collector bottoming will produce the same effect at the troughs of the signal. Transformer resistance and continuity can be checked with an ohmmeter, while the bias and voltage can be checked with a voltmeter. In Class A or Class AB stages, one half of the circuit can be inoperative and the unit will function with reduced output and increased distortion. Use an oscilloscope to observe the waveform, checking from input to output. When the waveform departs from normal, the cause of the trouble will usually be obvious.

AUDIO POWER AMPLIFIER, PUSH-PULL, *SINGLE-ENDED COMPLEMENTARY CIRCUIT*

APPLICATION.

The push-pull, single-ended complementary audio amplifier is used where high power output and fidelity are required. For example, it is used in receiver output stages, in public address amplifiers, and in AM modulators, where reduced weight and space is a prime requirement.

CHARACTERISTICS.

Collector efficiency is high with moderate power gain.

Requires only half the drive of the conventional push-pull amplifier.

Power output is twice that of a single transistor stage.

No input or output transformer is used.

Distortion varies with the class of operation.

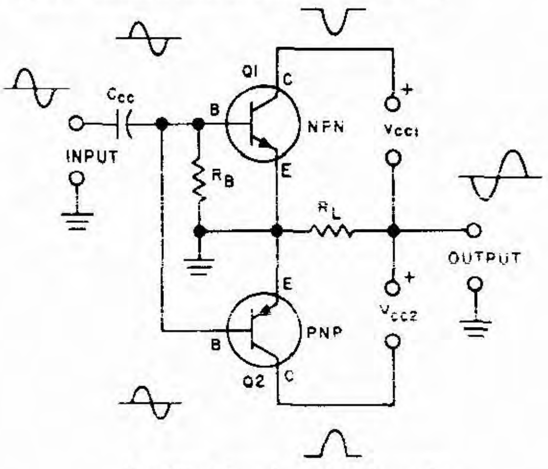
Usually is Class B biased, but may be biased Class A in some applications.

Fixed bias is usually used, but self-bias may be encountered in some applications.

CIRCUIT ANALYSIS.

General. Complementary symmetry is unique with transistors, and has no electron-tube counterpart. Recall from basic theory that a transistor may be either the PNP or NPN type, and that the bias and polarities are opposite. *Thus, two different types of transistors may be used back-*to-back to provide push-pull operation without the necessity for phase-inverting input and output transformers. An economic advantage is gained in that the cost of the transformers is eliminated, and a more uniform response is obtained since the reactive effects of the transformers are also removed from the circuit.

Circuit Operation. The accompanying schematic shows a typical single-ended push-pull complementary symmetry circuit. The operation is Class B at zero bias.



Zero Bias Complementary Symmetry
Push-Pull Circuit

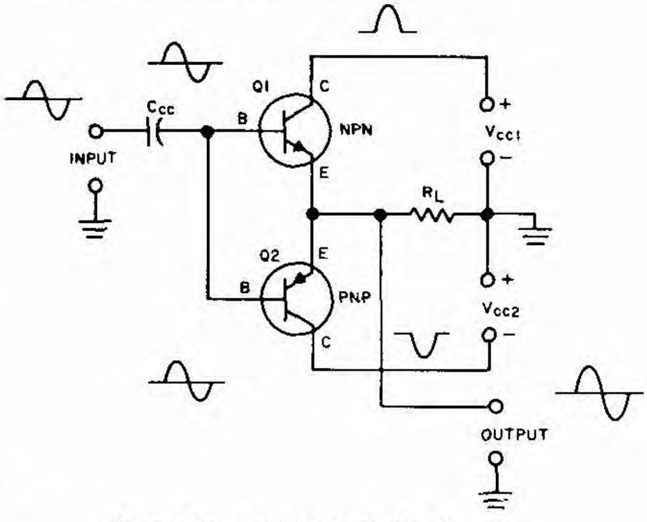
Resistance-capacitance input coupling is used, with Ccc acting as the coupling capacitor and RB as the base return resistance across which the input signal is applied. With both emitters grounded and no bias applied, the bases of the transistors are zero-biased at cutoff. No current flows in the absence of an input signal. When an input is applied, both bases are biased in the same direction. Since Q1 is an NPN transistor, the positive-going input signal produces a forward bias. Q2 is a PNP transistor and requires a negative potential for forward bias; the input signal has no effect other than to reverse-bias Q2 and hold Q2 in a cutoff condition. Thus, during the positive half of the input signal only Q1 conducts. During the negative portion of the input signal Q1 is biased off beyond cutoff by a reverse bias, and a forward bias is applied to Q2, causing collector current to flow for the entire negative half-cycle. Thus, each transistor conducts alternately for half of the cycle, and two transistors are required to reproduce the input signal. Note that the bases are connected in parallel, and, since only one transistor operates at a time, only enough drive for a single stage is required instead of twice the drive as in normal push-pull operation.

Because the transistors are of opposite types, two equal-voltage collector power supplies are required, one negatively polarized and the other positively polarized. (A single supply can be used with proper circuit changes, but twice the collector voltage of a single stage is required.) The load resistor, RL (which may be the voice coil of a loudspeaker), is connected from the common connection between the power supplies and the emitters. In this instance the emitter end is grounded, so that the power supplies are actually floating above ground. When the input signal is applied and develops an output for each half-cycle, the output is added together in the common load and no transformer is required. To develop maximum power, a low-impedance is needed. Otherwise, if high-impedance loads are used, an output transformer will be required for proper load matching. In this instance, however, the winding need not be center-tapped since the output is single-ended. Because the output is single-ended (taken between the collector and ground), the collector load is calculated on the basis of the full primary-to-secondary turns ratio – not on one-half the primary-to-secondary turns ratio as in the conventional push-pull stage. Thus, the loading is 1/4 the normal push-pull output, which accounts for the low-impedance output.

In most electron tube or transistor circuits it is necessary to separate the d-c component in the output from the output from the a-c component by capacitive or transformer coupling (except in the special case of the d-c amplifier). In the complementary symmetry arrangement such provisions are unnecessary. Both d-c power supplies are connected in series with the transistors, and only one transistor is operative at a time; thus, there is no net flow of dc around the circuit. When Q1 conducts, there is a flow of current through RL, the transistor, and the power supply in one direction. When Q2 conducts, the flow is through RL, Q_2, and the power supply in the opposite direction; thus, there is no circulating current, and the dc is effectively removed from the load circuit since only the continuously varying a-c component flows through the load. Likewise, in the base circuit there is no continuous flow of dc, since the current flows out of the base when Q2 conducts, and into the base when Q1 conducts. Therefore, the charging and discharging of the coupling capacitor and its possible effect on changing the base bias are of no consequence in this circuit.

In the preceding discussion it was assumed that the transistors are balanced (or matched), having identical gain and collector currents. Like the conventional push-pull amplifier, this matching is necessary to obtain maximum output with minimum distortion. Unlike the electron tube circuit, which uses identical plate voltages and matches the plate current, the complementary symmetry circuit has identical collector (plate) currents since the transistors are series-connected and the biasing is adjusted to equalize the collector voltages. In the case of Class A or AB operation, the bias point in the base circuit is affected by drive and base current drain . Thus, keeping the signal from affecting the bias is one of the important design problems. So far as the technician is concerned, the practical effect is that with better design less distortion is obtained, with a maximum of amplification.

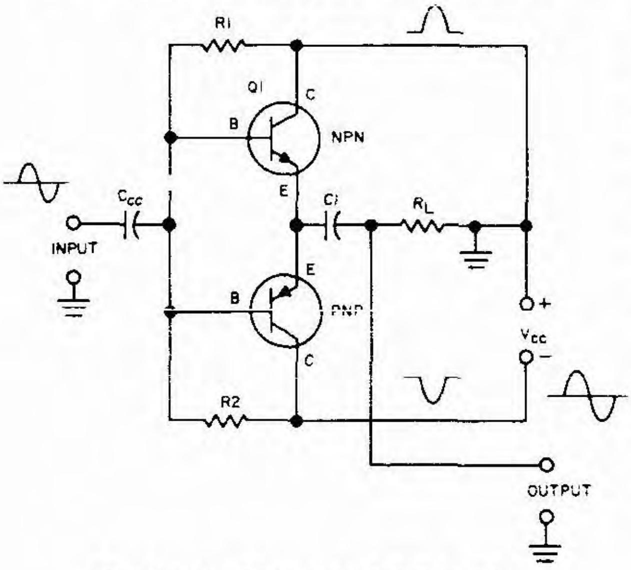
While the common-emitter circuit is used in most transistor amplifiers, better performance is obtained from the common-collector circuit when complementary symmetry is employed. Although the over-all gain and output are slightly less, the stability of the circuit is improved; the collector supply can be grounded in-stead of floating (which reduces power supply ripple), and the effect of negative feedback is obtained, thus requiring less closely balanced transistors and improving fidelity and response characteristics. Both circuits are identical except that the ground is removed from the emitters and placed on the common power supply connection, as shown in the accompanying schematic.



Common (Grounded) Collector Complementary Symmetry Push-Pull Circuit

As in other common-collector circuits, no polarity inversion of the output signal occurs, so that the inputs and outputs are of the same polarity. In operation, the circuit functions in the same manner as the common-emitter push-pull complementary-symmetry amplifier previously described. Only one transistor operates at a time, zero bias is employed, and the output is taken from the emitters to ground. Collector current flows through Q1, power supply V_{cc_1}, and load resistor R_L in one direction, and through V_{cc_2}, Q2, and R_L in the opposite direction, as the transistors are alternately forward-biased by the input signal. There is one difference, however, in that more input (drive) voltage is required to obtain full output because of the degenerative effect of connecting the load between the emitters and ground.

The accompanying schematic shows the complementary symmetry push-pull circuit connected for use with a single power supply, and with feedback from collector to base.



Complementary Symmetry Push-Pull Amplifier with Common Power Supply

Connecting capacitor C1 in series with load resistor R_L permits the use of a single power supply. Since no dc normally flows through the load, the insertion of the blocking capacitor has no effect on either a-c or d-c operation. Since both transistors are connected in series with the power supply, twice the d-c voltage of one supply is necessary. In addition, resistors R1 and R2 are employed to provide a fixed base bias and a slight amount of feedback from collector to base. The feedback reduces the matching requirements, and the d-c bias is adjusted by selecting the values of R1 and R2 so that equal collector voltages are obtained (with the series connection of transistors the same value of current flows throughout the circuit).

As far as dynamic operation is concerned, it is also identical with that of the previously discussed common-emitter complementary symmetry circuit. When a forward bias is applied by the signal, the transistor conducts. With a sine-wave input signal applied, a sine wave of current flows (at audio frequencies) through capacitor C1 and load R_L to develop the output signal.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliammeter testers. Be careful, also, to observe proper polarity when checking continuity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. An open or short circuit in the power supplies or transistors, or an open coupling capacitor or load resistance can cause no output. A voltage check will indicate whether the proper voltage and polarities are applied. Since Class B zero bias operation is normally employed, no base-to-emitter (or ground) voltage exists in the absence of a signal. However, if an attempt is made to measure this voltage with a meter, a false reading may be obtained through the voltmeter shunting resistance. Therefore, only the polarity and supply voltage should be checked, and the input signal should be observed with an oscilloscope. Lack of input signal on the oscilloscope indicates an open coupling capacitor, C_{cc}, or a shorted input circuit caused by a defective transistor. If the supply voltage and polarity are correct and a signal is visible at the input, but not in the load, either the transistor is defective or the load is shorted. A resistance or continuity check will determine whether the load is normal. If it is normal, only the transistors can be at fault. Since only one transistor is operative at a time, both transistors must be defective to cause a loss of output; otherwise, a reduced or distorted output exists. When in doubt, replace the transistors with ones known to be good.

Reduced Output. If one of the transistors is defective, or if one of the supply voltages is low or the supply is defective, a loss of output will occur. Use an oscilloscope to observe where the input waveform or output waveform departs from normal. Check to make sure that there is sufficient drive in the preceding stages. A leaky coupling capacitor will place a fixed bias on the base circuit, causing conduction in one transistor and rendering the other inoperative. Depending on the amount of bias, the circuit may be such as to very slightly reduce the output or to cause severe distortion. Unbalanced collector voltages, if sufficiently different, will cause loss of amplification and distortion on one side of the circuit, which can be observed on the oscilloscope. Since there are only a few components in the circuit, a resistance and voltage check should quickly indicate whether the components or power supply is defective. Where the transistors are suspected, replace both with ones known to be good, or remove them separately and check them on a transistor checker.

Distorted Output. Improper bias or load resistance can cause a distorted output. Use an oscilloscope to determine where the signal departs from normal. The trouble will then be localized to that portion of the circuit showing the distorted waveform. In the common-emitter circuit, if the distortion occurs on the negative portion of the waveform, the trouble is in the PNP transistor circuit, if it is on the positive portion of the waveform, the trouble is in the NPN transistor circuit. Since there is no inversion of polarity in the common-collector circuit, the indications will be the opposite. That is, distortion on the positive waveform indicates trouble in the NPN transistor circuit, and distortion on the negative waveform indicates trouble in the PNP circuit.

AUDIO POWER AMPLIFIER, PUSH-PULL, SINGLE-ENDED, SERIES-CONNECTED CIRCUIT.

APPLICATION.

The push-pull, single-ended, series-connected audio amplifier is used where high power output and fidelity are required. For example, it is used in receiver output stages, in public address amplifiers, and in servo amplifiers, where compactness and reduced weight through elimination of the output transformer are desired.

CHARACTERISTICS.

Collector efficiency is high with moderate power gain.

Requires the same drive as a conventional push-pull amplifier.

Power output is twice that of a single transistor stage.

No output transformer is required, and identical types of transistors are used.

Distortion varies with the class of operation.

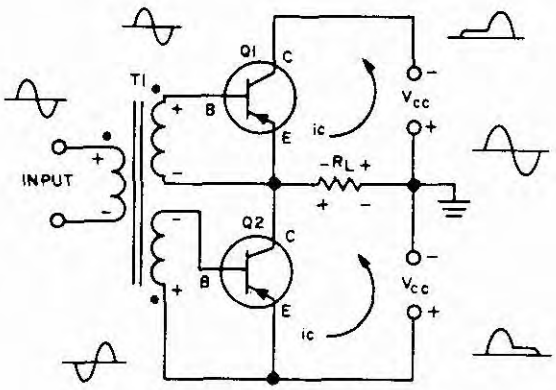
Class B bias is normally used, but Class A or AB applications may be encountered.

Fixed or zero bias is normally employed, but self-bias may be used in some applications.

CIRCUIT ANALYSIS.

General. The series-connected, single-ended push-pull amplifier uses two similar-type transistors in the equivalent of the complementary symmetry circuit to provide a transformerless output. It requires fewer components than the conventional push-pull amplifier, but more than that of the complementary symmetry amplifier, since a push-pull input is necessary; it is single-ended in the output only. A compound-connected transistor input circuit may be used; however, since this circuit requires two additional transistors, an input transformer is usually used instead. Because of the series transistor connection, two separate collector supplies are required, or a center-tapped supply that is twice the value of a single supply is necessary.

Circuit Operation. The schematic of a typical single-ended, series-connected push-pull PNP audio amplifier is shown in the accompanying figure.



Single-Ended, Series-Connected PNP Push-Pull Amplifier Circuit

Note: Read the DIRECT-COUPLED AUDIO AMPLIFIER circuit discussion earlier in this section for any background information.

Transistors Q1 and Q2 are zero-biased and are nonconducting in the absence of a signal. Both transistors are the PNP type. The input transformer has two separate windings rather than the center-tapped arrangement conventionally used in push-pull circuits, to provide out-of-phase (opposite-polarity) input signals to the series-connected common-emitter stages. This provides an input connection which is separate for each transistor; the base of Q1 is driven positive while the base of Q2 is driven negative, and vice versa. With Class B, or zero bias, only one transistor operates at a time. One of the secondaries of T1 is connected so as to invert the signal. Thus, on the positive input signal, Q2 is driven negative and the forward bias causes conduction; meanwhile, the base of Q1 is held at cutoff by a positive input. On the opposite half-cycle, Q2 is held at cutoff while Q1 is driven to conduction by the negative input signal. In this example the secondary connected to Q1 is connected in-phase, while the secondary connected to Q2 is connected out-of-phase.

The load, RL, is connected from the common point of the two power supplies to the emitter of Q1 and the collector of Q2. Disregarding this load connection for the moment, it is clear from observation of the schematic that the two transistors are connected in series with each other and their separate power supplies. In the absence of an input signal no current flows, and, since each transistor conducts separately, with current flow in opposite directions through RL there is no net flow of dc through the load in one direction to unbalance it. Therefore, the voice coil of the speaker may be placed directly in this circuit to act as a load, without requiring any d-c isolation through coupling capacitors or transformers.

When collector current flows in Q1, the electron path is from the emitter, through RL and the power supply, back to the collector. When collector current flows in Q2, the electron path is from the emitter of Q2, through the power supply and load RL, back to the collector. These currents flow in opposite directions through the load resistor, each producing one half-cycle of the signal. There is no continuous flow of dc through the circuit or through the load. In Class A or Class AB stages, a forward bias is supplied to the base, and both transistors conduct continually. D-C current flows through the series transistors and power supplies, but does not flow through the load resistor. This action occurs because, with a balanced circuit and identical collector current flow in both transistors, equal but opposite voltages are developed across the load resistor; therefore, they cancel, producing an effective zero d-c current flow through the load.

In Class A operation, any second-harmonic current is canceled out in the load as in conventional push-pull circuits. In Class B operation, there is no cancelation of second-harmonic current, and the predominant distortion is third harmonic. Thus, regardless of the method by which it is obtained, second-harmonic distortion is reduced in this circuit as in the conventional push-pull circuit.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance ordinarily employed on the low-voltage ranges of conventional volt-ohmmeters. Be careful also to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. A no-output condition can be caused by an open- or short-circuited input transformer, T1, or load, RL, as well as by a lack of supply voltage. The supply voltage and the collector or base bias voltage can be checked with a voltmeter. Continuity checks of the input transformer windings (or the load) will locate any open circuits, and short-circuited windings (or load) will be indicated by ohmmeter readings of less than 1 ohm. In Class A or AB stages the bias resistors can be checked for proper values with an ohmmeter. Normally, failure of the transistors will not cause complete loss of output unless both transistors fail completely.

Low Output. Lack of sufficient drive power, low supply voltage, improper bias, or a defective transistor can cause reduced output. The supply voltages and bias can be checked with a voltmeter. Lack of drive power can be determined by observing the waveform with an oscilloscope and noting whether there is sufficient drive to cause eventual flat-topping or bottoming of the output waveform. Either a shorted or otherwise inoperative transistor can cause low output. Depending upon conditions, removing the transistor (from a plug-in socket) will either reduce or increase the output. In the case of a shorted transistor, the output will probably increase when it is removed. Where the transistor has low gain, a slight reduction of output will usually be noted when it is removed. If the defective transistor is left in the circuit and the good one is removed, a decrease in the output will also be observed. Thus, where a defective transistor is suspected, it is usually good practice to replace both transistors with ones known to be good in order to determine whether the output comes up to normal. Further checking with a transistor checker will then determine the defective one.

Distorted Output. Distorted output may be caused by lack of proper bias or supply voltage, by underdrive or overdrive, by defective transistors, or by a defective input transformer. If the primary winding of the input transformer is open, either no output will occur or a very low output may be obtained by capacitive coupling between the turns. However, if either one of the secondary windings is open or shorted, one transistor will not operate properly and distortion will occur. Likewise, if the bias is too high, clipping will occur on the peak of the input signal; if it is too low, collector bottoming will produce the same effect at the troughs of the signal. Transformer resistance and continuity can be checked with an ohmmeter, while the bias and collector voltages can be checked with a voltmeter. In Class A or Class AB stages, one half of the circuit can be inoperative and the unit will still function with reduced output but with increased distortion. Use an oscilloscope to observe the waveform, checking from input to output. When the waveform departs from normal, the cause of the trouble will usually be obvious.

AUDIO POWER AMPLIFIER, PUSH-PULL, CAPACITANCE-DIODE COUPLING.

APPLICATION.

The push-pull, capacitance-diode-coupled audio amplifier is used where high power and fidelity are required in receiver output stages, public address systems, and modulators. It is usually employed as the power output stage of a resistance-coupled amplifier.

CHARACTERISTICS.

Collector efficiency is high with moderate power gain.

Requires the same drive as a conventional push-pull amplifier.

Power output is twice that of a single stage.

No input transformer is used, and identical types of transistors are used.

Input circuit is push-pull (oppositely polarized signals from either a phase inverter or a push-pull driver are required).

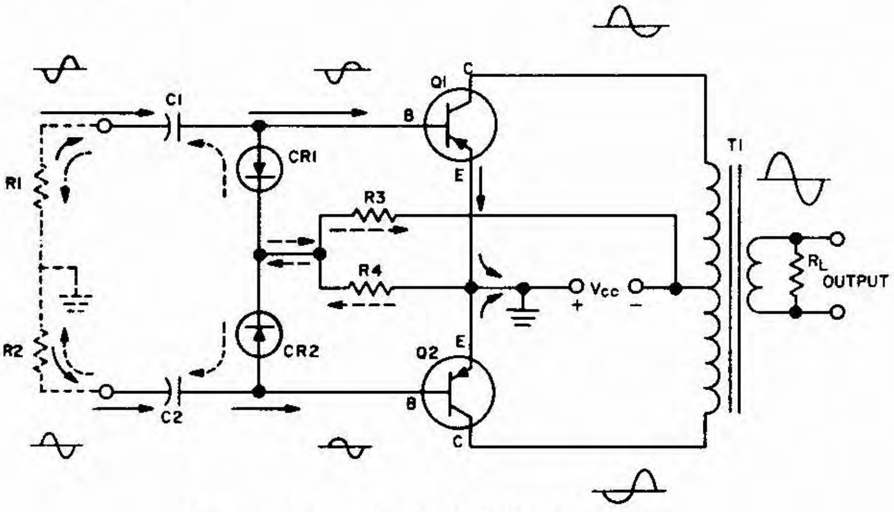
Distortion varies with the class of operation; operation may be Class A, AB, or B, with Class AB use predominating.

Fixed bias is normally used, but self-bias may be encountered in some applications.

CIRCUIT ANALYSIS.

General. The capacitance-diode-coupled push-pull amplifier differs from the conventional push-pull amplifier only in the input circuit. Diodes are used to prevent the charging or discharging of the coupling capacitor from producing a shift of base bias with signal, and causing distortion. The use of capacitive coupling eliminates the necessity for an input transformer and provides a reduction in weight and sapce, and an increase in economy . Any improvement in response characteristics through elimination of the input transformer and its reactive effects are somewhat minimized by the shunting and loading effects of the diodes. Thus, the operation and performance are substantially the same as the conventional transformer-coupled push-pull amplifier, with a slight improvement in the high-frequency response.

Circuit Operation. The accompanying schematic shows a typical push-pull, capacitance-diode-coupled PNP transistor audio amplifier. The operation is considered to be Class B with a slight forward bias to eliminate crossover distortion (actually Class AB), as determined by voltage divider resistors R3 and R4. Because diodes CR1 and CR2 are connected in series opposition across the input, and are isolated by coupling capacitors C1 and C2, conduction through the diodes is necessary to establish a bias on the base of the transistors. With R4 connected between the diodes and ground, a slight negative voltage appears at their cathodes, so that they normally conduct slightly. In the absence of an input signal, conduction through CR1 and CR2 permits a continuous flow of d-c base current, which, in turn, permits a small idling collector current to flow through the forward-biased bases. This static (quiescent) current flows in opposite directions through the primary of the push-pull output transformer, T1, and the effective flow is zero. No secondary output occurs because the flux in each half of the primary of T1, produced by d-c current flow, cancels (as in conventional push-pull operation).



Capacitance-Diode-Coupled Push-Pull Stage

When an input signal is applied, oppositely polarized signals are supplied to coupling capacitors C1 and C2 simultaneously. (Resistors R1 and R2 represent the driver stage output resistance, normally taken between the driver stage collector or emitter and ground.) With a negative-going sine wave signal applied through C1, a forward bias is applied to the base of transistor Q1, causing collector current to flow through the upper half ot the primary of T1 into Q1. At the same time, a positive-going input signal is applied through C2 to the base of Q2, producing a reverse bias, and reducing collector current flow through the lower half of the primary of T1 into Q2. Since Q2 is normally producing only a small current flow, this reduction in forward bias drives the transistor nearly to cutoff. Thus, the current in Q2 is reduced while the current in Q1 is increased (this is conventional push-pull action). When the negative input signal is applied to Q1, it also reverse-biases the anode of CR1, and the diode appears as a very high resistance; therefore, the input signal is not bypassed to ground via R4, and there is no effect on the bias circuit. On the other hand, when the positive input signal is applied to CR2 and the base of Q2, the diode is forward-biased and it conducts heavily. This action permits C2 to discharge rapidly through the low resistance of CR2 and R4 to ground on one side, and from ground through R2 to the other side of C2, as shown by the dotted arrows in the schematic. The electron flow path is from ground through R4, and CR2 to C2 on one side, and from ground through R2 to the other side of C2. Thus, a small instantaneous positive voltage is developed across R4. This voltage further reverse-biases CR1 so that it cannot conduct and affect the operating bias. If CR1 and CR2 were resistors (instead of diodes), the voltage developed through these resistors would appear in series with the bias applied to both transistors and cause a shift in operation. The bias developed would add to the normal bias and place the total bias in the Class C region of operation, thus producing serious distortion and clipping.

With Q1 conducting because of the negative input signal, capacitor C1 charges quickly through the low resistance of the base-emitter junction of Q1 and ground, as shown by the solid arrows in the schematic. When the sine-wave input signal becomes positive-going on the opposite half-cycle, the base of Q1 is reverse-biased and the collector current is reduced. At the same time, CR1 is forward-biased (by the positive input signal) and C1 is quickly discharged through R4 to ground on one side, and through ground and R1 to the other side of C1. The voltage developed across R4 has no effect on the operating bias, since CR2 is reverse-biased while Q2 is conducting. In addition, it should be noted that the voltage produced across R4 by the discharge of C1 or C2 is polarized in a direction opposite that of the normal bias produced by the voltage divider action of R3 and R4. Since the signal is never allowed to exceed the bias, to prevent distortion, this reverse bias is only a fraction of the operating bias and is thus effectively swamped out of the circuit. Only through failure of one of the diodes can it affect the operation of the circuit.

The operation of the collector and output circuits is exactly the same as previously explained for the conventional push-pull amplifier. Second- and even-harmonic distortion is cancelled in the primary of the output transformer, and the output contains only the fundamental and odd harmonics. The collector-to-collector load resistance is 4 times that of the individual collector-to-ground load, as in the conventional push-pull circuit. Since the input circuit uses the reverse-biased diode resistance as the base-to-ground impedance, the capacitance-diode input circuit offers a high input impedance. Thus, the moderate output impedance of common-emitter phase-inverting driver stages may be conveniently matched.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliammeter testers. Be careful, also, to observe proper polarity when checking continuity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. Open coupling capacitors, defective transistors, or a defective output transformer can cause a no-output condition. Observe the signal with an oscilloscope, checking from input to output. Lack of a base signal indicates that coupling capacitors C1 and C2 are open; lack of a collector signal indicates either defective transistors, an open primary on T1, or an open collector supply (check the supply with a voltmeter). Lack of an output across the secondary indicates an open secondary winding. Note that since each transistor will operate separately, a distorted output can be obtained if only one half of the circuit is defective. Thus, both coupling capacitors, both transistors, or both halves of the primary of T1 must be open simultaneously for a no-output condition. Likewise, in the case of a short circuit, one half of the circuit must be biased off while the other is shorted to cause no output. Only an open circuit or a short circuit of the T1 secondary can produce a no-output condition by failure of a single part. Where the transistors are suspected, replace them with ones known to be in good operating condition.

Low Output. Low output can be caused by a number of conditions. Failure of one half of the circuit, regardless of cause, will result in reduced output. If bias resistor R4 opens, the forward bias will increase and full Class A operation will occur. Where the stage is normally operated Class AB or B, an open R4 will cause a reduction in output. The bias voltage can be checked with an ohmmeter, or R4 can be measured with an ohmmeter. If R3 becomes open, the bias will be removed and the stage will operate Class B, zero-biased. If the drive is insufficient, loss of output will occur. With sufficient drive available, however, it is possible for the output to increase, with an increase in distortion. If R3 is shorted, the increased forward bias will hold the stage in heavy conduction and the input signal will most likely be shunted through CR1 and R4 to ground, resulting in reduced output with distortion. If either CR1 or CR2 is shorted, one half of the input signal will be shunted to ground through R4 and the output will be reduced. If either C1 or C2 is leaky, the bias on Q1 or Q2 will be changed, depending upon the polarity of the voltage on the drive side of the capacitors. A negative supply for a PNP driver stage will cause increased forward bias and reduced output. A positive voltage for an NPN driver stage will produce constant heavy conduction through diode CR1 or CR2, and cause shunting of the input, loss of drive, and reduced output. Either or both transistors may be defective and cause loss of output. Shorted primary or secondary windings on T1 will also reduce the output. Therefore, it is necessary to use an oscilloscope to observe the waveform and follow the signal through the circuit. When the waveform amplitude decreases, check the parts in that portion of the circuit for proper resistance or continuity as applicable.

Distorted Output. Improper bias, overdrive, or clipping because of too low a collector voltage can cause distortion. Use an oscilloscope to follow the waveform through the circuit; the source of the distortion will usually be easy to locate when the waveform differs from the input. Leaky coupling capacitors will cause improper bias and possible peak clipping. Defective diodes can also cause clipping of the input signal and consequent distortion. Defective transistors can produce distortion through nonlinearity or unbalance. For the least distortion, matched transistors are usually used. In some instances poor frequency response in the output transformer may also cause distortion. Poor response can also result from an improperly matched load or from a change in the load resistance. In any event, it is necessary to observe the waveform with an oscilloscope to determine whether the distortion increases or decreases as the signal is followed through the circuit.

AUDIO POWER AMPLIFIER, COMPOUND-CONNECTED.

APPLICATION.

The compound-connected power amplifier is used as the output stage in receiver, public address amplifiers, and modulators where large audio power outputs are required. It is also used as a direct-coupled control amplifier in transistorized voltage regulators.

CHARACTERISTICS.

High voltage and power gain are obtained.

Operation is usually Class A.

Fixed bias is normally employed but self-bias may be encountered.

High input resistance is obtained (much greater than for a single CE stage).

Input is series-connected, and output is parallel-connected.

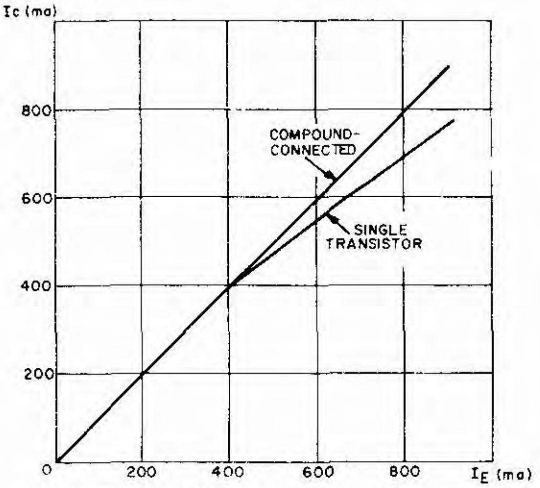
Two or more transistors are required.

Ratio of emitter current to collector current remains constant; there is no drop-off of collector current at high emitter currents.

High current amplification can be obtained with very little distortion (less than ½ percent).

CIRCUIT ANALYSIS.

General. Two compound-connected transistors may be employed as a single transistor and used in other circuit configurations, such as, push-pull audio amplifiers, to obtain greater output and more linear response than can normally be obtained in the circuit. Because the forward current gain does not drop off at high emitter currents, the operation is linear and since the collector current continues to increase proportionally as the emitter current increases, the transistors can be driven to full output without any increase in distortion. The increase in linearity of the collector current which the compound connection provides can be clearly seen from the accompanying graphic comparison of emitter and collector currents.

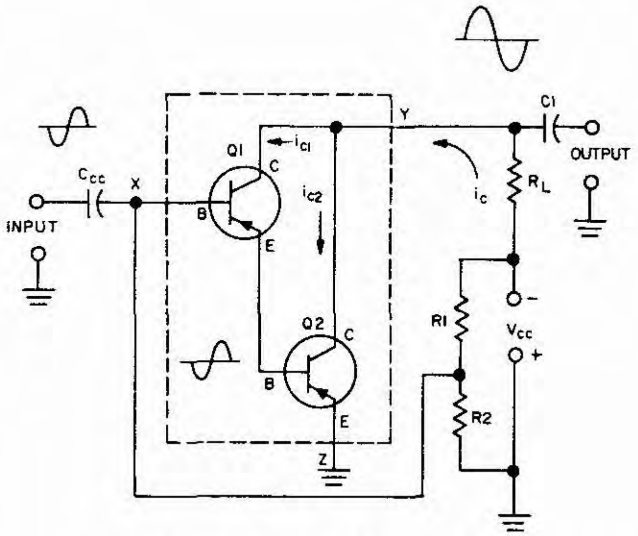


Graph Showing Differences Between Compound-Connected and Single-Transistor Operation

Note that in the graph the ratio of collector current to emitter current for a single transistor remains constant (as indicated by the straight-line portion of the curve) until approximately 400 ma is drawn; then the collector current increases less rapidly as the emitter current increases (as indicated by the curved portion). This is reduction in collector current linearity indicates a loss in forward current amplification, which is most pronounced in power amplifiers that draw heavy emitter current. The variation of the total collector current with input emitter current for compound-connected transistor is also shown in the graph. Observe that the total collector current of the compound-connected transistor does not drop off as the emitter current increases, but varies linearly over the entire range of operation (it is a straight line instead of a curve).

Circuit Operation.

The basis schematic for a pair of compound-connected transistors used as an audio amplifier is shown in the accompanying illustration. The circuit enclosed by the dashed line can be considered as a single transistor with connection points X, Y, and Z representing the base, collector, and emitter, respectively, of the combined transistors.



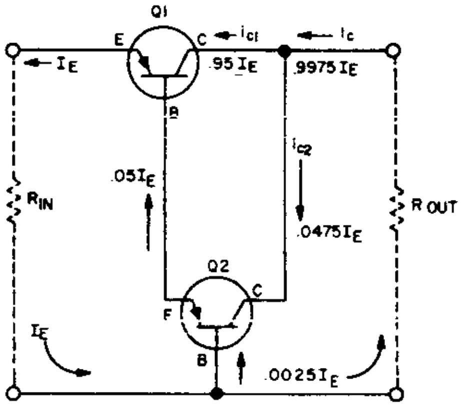
Compound-Connected Common-Emitter Audio Amplifier Circuit

Fixed Class A bias is supplied to the base of transistor Q1 through voltage divider resistors R1 and R2 connected across the common power supply. (See Section 3, paragraph 3.4.1. for a discussion of the types and methods of biasing). The bias on Q2 is supplied by emitter current flow through Q1 and Q2 to ground, the actual value being determined by the emitter current of Q1 and the forward gain of Q2. Capacitive input coupling is provided by Ccc. The output load, RL, is connected in series with both transistors and a common source of power; the collectors are connected in parallel, and thus share a common load.

The output is taken through coupling capacitor C1 (in some circuits R_L and C1 are replaced by a transformer for greater power output).

Both transistors are connected in the common-emitter configuration, and, since the base of Q2 is directly connected to the emitter, which is the common leg of Q1, transistor Q2 provides a certain amount of negative feedback. Because both transistors are series-connected across the input, a much higher input resistance (100 times as large, or more) is offered than with a single CE stage. In the absence of an input signal, both transistors operate in the Class A region, as determined by the fixed voltage divider bias supplied by R1 and R2. The bias on Q2 is just slightly less than that appearing on the base of Q1 because of the small voltage drop between the base and emitter of Q1.

Assume that a negative input signal appears at the base Q1; this increase in forward bias causes the collector current of Q1 to increase to a value determined by the forward gain characteristics of Q1 and the amplitude of the input signal. The flow of iC_1 (and iC_2) through R_L produces the output voltage, which, as in the conventional common-emitter circuit, has a polarity opposite that of the input voltage. At the same time, since the base and emitter of Q2 are in series with the input, a forward bias is also applied to Q2 to increase collector current iC_2. While the amount of collector current through Q2 is not as great as that through Q1, it adds to the output since it flows in the same direction through R_L. The total collector current flowing through R_L is the sum of the two collector currents ($iC_1 + iC_2$). It is not double that of a single transistor, but varies in accordance with the ratio set by the individual forward gain values and the amount of base current drive applied to Q1. It is not necessary that both transistors be matched or have equal forward gain. However, it is convenient to show how the currents are distributed, assuming that the two transistors are identical. In a conventional cascaded stage the gain of two stages would be equal to the gain of the first stage times that of the second. Assuming a value of a fe = 19, the total gain of two stages would be 361, while for a compound connection a value of 399 is obtained (approximately 10% additional gain). This increase in gain is obtained because the collector current does not fall off at high emitter currents. The accompanying figure shows the two transistors compound-connected in the common-base circuit, for ease of explanation. Assuming a forward gain or alpha of .95 for both transistors (equivalent to a CE beta of 19), the current relationships through the circuit are as shown in the figure. In this circuit Q1 handles most of the load current while Q2 provides additional power during peak conditions. The flow of emitter current in the external circuit is from Q2, through the base of Q1, through the input resistance, and back to the collectors of both transistors through the output resistance. The collector current of Q1 is 0.95 I_E; therefore, 0.5 I_E flows into the base, since the emitter current is the sum of the base and collector currents. Since 0.95 I_E flows into Q1 and the total collector current is 0.9975 I_E, the collector current of Q2 is the difference, or .0475 I_E. Finally, since .05 I_L flows from the emitter of Q2 into the base of Q1, the base current of Q2 is the total emitter current of Q2 less the collector current of Q2 or .0025 I_E. While this might be considered to show little contribution of Q2 to the operation of the circuit, recall that in the common-base circuit the gain cannot exceed unity, which for all practical purposes is equal to 0.999999 . . . . etc; thus, a change from 0.95 to 0.9975 represents a considerable increase in gain. Expressed in terms of the common-emitter circuit (as previously mentioned) it is a change of from 19 to 399 in gain, which is a very noticeably increase.



Current Relationships in Compound CB Circuit

Because the transistors are direct-connected in the compound circuit, there is no reactance to deteriorate the frequency response (it extends the low frequency bass response to zero or dc); therefore, although an increase in gain results, no sacrifice in response occurs. With a series-connected input, only sufficient drive for one transistor is required, as the current through a series circuit is uniform. Thus, the additional gain is achieved without requiring more drive. Although it might be thought that the increased input resistance requires more drive for the same input, it does not, since a smaller current through a higher resistance produces the same voltage drop as a higher current through a smaller resistance. With the collectors connected in parallel, the output resistance is lower than that of a single transistor, but not half as might be expected. It is approximately equal to the ratio of the two collector currents and is not of much significance, because the compound connection produces a larger output mainly by its ability to pass a greater current through the same load. In the basic schematic the output is shown capacitively coupled; where large power outputs are desired, an output transformer is usually used as in the conventional single-ended power amplifier. The compound connection may be used in any of the previously described circuits in this handbook to obtain greater linearity and output, but it requires two transistors for each one used in the conventional circuit.

When the load resistance is connected in series with the emitter of Q2 instead of the collector, this compound circuit becomes the cascaded emitter-follower amplifier, sometimes referred to as the **Darlington circuit.** Because of the large amount of degeneration provided the operation is slightly different from that of the compound circuit described above. In other publications, the compound connection is also referred to as the **Tandem connection** or the **Super-alpha connection.**

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliameter testers. Be careful, also, to observe proper polarity when checking continuity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. Lack of supply voltage, either an open or short-circuited input or output or defective transistors, will cause a no-output condition. The supply voltage and the presence of collector and base bias can be checked with a voltmeter. With the proper voltage and polarities existing in the circuit, observe the waveform with an oscilloscope. Loss of signal on the base side of the input indicates either an open coupling capacitor or a shorted input. Since the emitter of Q1 is connected in series with that of Q2, failure of either transistor will produce loss of output. An open output coupling capacitor (or transformer, if used) will also cause loss of output. Leaky coupling capacitors usually will not cause a complete loss of output. On the other hand, a shorted input capacitor can bias the circuit to cutoff or into heavy saturation depending upon the polarity of the collector supply of the preceding driver stage. Since all short circuits will most likey change the bias and circuit voltages, and open circuits will show normal voltages, a simple voltmeter check will determine the type of trouble. With only a few parts in the circuit, they may be checked separately to determine the defective part. When the operation of the transistors is in doubt, replace them with ones known to be good.

Reduced Output. Improper bias, low collector voltage, or defective transistors will cause reduced output. A leaky coupling capacitor will produce a larger than normal bias and cause the transistors to operate closer to cutoff or to saturation, depending upon the polarity of the bias. The reduction in output may be slightly noticeably or very evident, depending on the value of the bias change; and may be easily determined by a simple voltage check. If the bias and voltages are correct and the proper load is connected, a reduced output with normal input indicates that either one or both transistors are defective. When suspected, replace both transistors with one known to be good and check the removed transistors separately, either by means of a transistor checker or by individual substitution in the circuit. Where the wrong load or a short-circuited load is used, the output will be reduced. Check the value of the load with an ohmmeter. Where capacitive output coupling is employed, a leaky or shorted capacitor can cause a steady flow of dc through the output circuit. In the case of a speaker, a steady flow of dc through the voice coil will hold the cone in a steady position and require a large output to move it. Check the output load for a d-c voltage to ground using a voltmeter. Where the load has changed in value, reduced output will usually be accompanied by distortion; the same indication will occur for reduced collector voltage, which can be determined by a simple voltage check. If all else appears normal and it is suspected that the load is defective, the load can be disconnected and replaced with a resistor of the proper value and wattage rating (usually 1 to 2 watts will be satisfactory for average transistor testing), and the output can be observed with an oscilloscope.

Distorted Output. Audio distortion will be obvious when a monitoring speaker or headphone is provided. Improper bias or low collector voltage, an improper load or defective transistors can cause distortion. Check the bias and collector voltages with a voltmeter. Use an oscilloscope to observe the input waveform and to follow it through the circuit. When it departs from normal; the location of the trouble will be obvious. Clipping of one side of the signal indicates improper bias or other voltages, while clipping on both sides indicates over-drive, as it does in electron-tube operating. Make certain that the input waveform is not distorted, since subsequent amplification will increase the distortion, making it appear to originate within the stage. With proper bias and other voltages and with a normal load, if distortion appears the transistors are likely to be defective. Replace them with a pair known to be good.

AUDIO POWER AMPLIFIER, BRIDGE-CONNECTED.

APPLICATION.

The bridge-connected power amplifier is used in receiver output stages and public address systems or other equipments where a large audio power output with low distortion is required, and no output transformer is employed.

CHARACTERISTICS.

Over-all frequency response is improved by direct output coupling.

Operation can be Class A or B, with the least efficiency obtained in Class A, and the most efficiency in Class B operation, as in conventional push-pull stages.

Produces twice the power output of a conventional push-pull stage.

May be operated at twice the normal supply voltage instead of half the voltage as in other circuits.

Each transistor dissipates only half the power of its counterpart in the conventional push-pull stage; therefore, smaller transistors may be used for the same output, or a greater power can be obtained for the same transistors.

A single untapped source of supply voltage may be used.

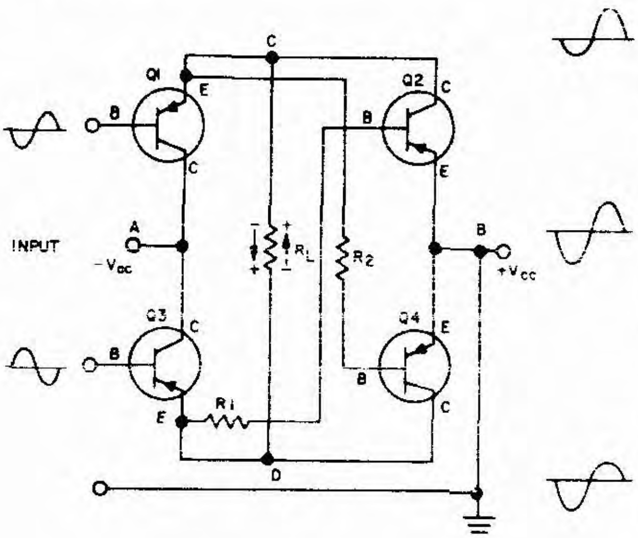
No d-c current passes through the load.

Requires push-pull input (opposite polarity and twice the drive of a single stage).

CIRCUIT ANALYSIS.

General. The bridge circuit is developed from the basic d-c bridge, sometimes called the **Wheatstone bridge,** using equal-ratio arms. In the basic two-transistor circuit, two equal power supplies form the other arms. With equal *transistors and equal power supplies*, the bridge is balanced for d-c flow and there is no flow of dc through the load until the bridge becomes unbalanced by application of a signal. The AUDIO POWER AMPLIFIER, PUSH-PULL, SINGLE-ENDED, SERIES-CONNECTED CIRCUIT previously discussed in this section of the handbook is an example of a simple type of bridge circuit. The full bridge circuit utilizes four identical transistors in a bridge arrangement, or *two PNP and two NPN transistors in a complementary* symmetry arrangement. The use of four transistors as the bridge arms permits operation with a single (or untapped) power supply, and provides twice the power output of the simple bridge circuit, with less distortion.

Circuit Operation. The schematic of a typical four-transistor PNP bridge amplifier is shown in the accompanying illustration.



Full Bridge Circuit

Note that transistors Q1 and Q3 have the load connected in the emitter circuit, while Q2 and Q4 have the load connected in the collector circuit. Therefore, Q1 and Q3 are common-collector configurations (the output is taken from the emitter) with high input impedances requiring large-voltage input signals. Transistors Q2 and Q4 are common-emitter configurations (the output is taken from the collector) with low input impedances requiring low-voltage input signals, to produce an emitter-collector current equal to that of the common-collector connected transistors, and thus equalize the bridge currents.

The input signal is connected in a push-pull arrangement to the bases of Q1 and Q3; the base input to Q4 is taken from the emitter of Q1 through current limiting resistor R2, and the base of Q2 is supplied with a signal from the emitter of Q3, taken through current limiting resistor R1. In this manner the opposite bridge arms are connected to similarly polarized and smaller inputs (as required for the common-emitter circuit); otherwise, a special transformer or a complementary symmetry arrangement would be necessary to provide proper amplitude inputs. When a negative input signal is applied to Q1, the forward bias is increased and both the collector and emitter currents increase. With increased emitter current flowing through R_L, a negative voltage is developed across the load and applied through R2 to increase the forward bias on Q4. Therefore, the collector and emitter currents of Q4 also increase. The transistors are selected for equal gain, and R2 for equal I_c, so that the emitter and collector currents of both transistors are equal.

Meanwhile, an oppositely polarized (positive) input signal is applied to the base of Q3 simultaneously with the input signal applied to Q1. The positive input signal reverse-biases the base of Q3 and reduces any flow of collector and emitter current. Similarly, the emitter voltage of Q3 *developed across* load resistor R_L becomes more positive because of the reduction in current flow, and through R1 places a reverse bias on the base of Q2, causing the emitter and collector currents of Q2 be reduced also. An increased current through one side of the bridge with a reduced current through the other side of the bridge produces the same effect as in conventional push-pull operation. In Class A operation, the total current flowing through *the load is the same as if twice the normal current flow* existed. In Class B operation, only two transistors conduct at a time, while the other two remain cut off.

When the input signal changes polarity on the opposite half-cycle (assuming a sine wave inptu) it becomes positive and a reverse bias is placed on the base of Q1. The reverse bias reduces the emitter current of Q1, producing a positive polarity at the emitter; it is also applied through R2 *to reverse-bias the base of* Q4. Thus, both Q1 and Q4 emitter and collector currents are reduced simultaneously. Meanwhile, the input signal applied to the base of Q3 also changes, becomes negative, and applies a forward bias to the base of Q3, which increases the emitter current. The increased emitter current flows through the load in the opposite direction, as shown by the dashed arrow on the schematic. The change of current flow creates an opposite polarity across R_L.

Since the voltage developed in the emitter circuit of Q3 is negative and the base of Q2 is connected to the emitter of Q3 through R1, a forward bias is also placed on Q2. Thus, the emitter-collector current flow of Q2 is increased simultaneously with that of Q3. As a result, the transistors interchange roles; Q3 and Q2 become conducting, while Q1 and Q4 are driven toward cutoff in Class A operation, or are entirely cut off in Class B operation. Assuming equal transistors, biases, and drives, equal but oppositely polarized voltages are produced across the load resistor by the current flowing in different directions in the bridge arms, so that the effective d-c flow is zero. Since the varying (a-c) load current flows first in one direction during one half-cycle of input and then in the opposite direction during the remaining half-cycle, the output load can be direct-connected in the bridge, and no output transformer in needed to develop the output signal. While the input resistance of the bridge is high, the output resistance is low, and no impedance transformation is necessary to match loudspeaker of servo loads. (The transistors are usually selected to have an output impedance near that of the load, in which case $R_L = V_c/I_c$.)

Because there are always two transistors across the supply, the collector voltage of each transistor is always less than the supply (usually half). Since no transformer is used, the collector voltage can never exceed that of the supply, so that the designer can apply twice the normal collector voltage to both transistors in order to apply the full rated collector voltage to each transistor. Therefore, a greater output can be obtained than would normally be possible in other amplifier circuits where tha maximum collector voltage is never allowed to exceed half the supply voltage. Likewise, since each transistor dissipates only half the power dissipated by each transistor in a conventional push-pull amplifier, a four-transistor bridge circuit can produce twice the output of the conventional push-pull circuit. This accounts for the high output power of the bridge circuit. Because the inputs to Q4 and Q2 are obtained from the emitters of Q1 and Q3, only enough drive is required to drive the bases of Q1 and Q3. Therefore, no additional drive power is required over that of the conventional push-pull amplifier.

In Class A operation, the quiescent currents of the transistors are equal, and no dc flows through the load because the bridge is balanced. During operation, the current through one pair of arms increases while the current through the other pair decreases. On the opposite half-cycle the conditions are reversed. On the other hand, in Class B operation all transistors are zero-biased with no signal applied, and no current flows. When an input is applied, one pair of arms conducts while the other pair remains cut off. During the remaining half-cycle the other pair of arms conducts while the first pair remains cut off. Thus, twice the current of a single transistor flows through the load during either type of operation. Because no transformer is used and the transistors are direct-connected, both low-frequency response and high-frequency response are improved. This accounts for the decrease in distortion of the bridge circuit as compared with any of the other push-pull circuits.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliameter testers. Be careful, also, to observe proper polarity when checking continuity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. If the output load or collector supply is open or short-circuited, no output will be obtained. A short-circuited load will be indicated by a resistance reading of less than one ohm, while an open circuit will be indicated by infinity or a very much larger than normal resistance. Check the supply voltage with a voltmeter to determine whether the supply is defective. On the other hand, since the bridge is normally balanced across the points to which the load is connected, a voltage check across the load will usually not pinpoint an open load. Instead, the voltmeter shunt will replace the load, if open, so that a false reading will be obtained. If a transistor is short-circuited, the other portion of the bridge will operate; thus, a single defective transistor will not produce a complete no-output indication. If transistor Q4 or Q2 is shorted, Q1 and Q3 will still operate. On the other hand, if Q1 or Q3 is shorted, the large input signal will probably bias Q2 and Q4 into cutoff and saturation, producing no output (in some instances a slight output may still be obtained, depending upon the applied bias). If either R1 or R2 is open Q2 or Q4 will not operate and no output will be obtained in Class B operation. Likewise, if Q1 or Q3 is open, the remaining half of the bridge will not operate.

In Class A operation, all four transistors would have to be defective simultaneously to cause no output. Since in Class B operation only two transistors conduct at a time, while the other two are cut off, it will be necessary for two transistors to be defective for no output to occur. Where transistors are suspected, they should be replaced in pairs, and the individual transistors should then be checked out separately in a transistor checker.

Reduced Output. Reduced output may be caused by failure of a single transistor, defective bias resistor R1 or R2, or an open input circuit to one arm of the bridge. The resistors may be checked with an ohmmeter, and the supply voltage may be checked for proper value with a voltmeter. While unbalanced voltages across the separate arms of the bridge may indicate the probable location of the trouble, an oscilloscope check is preferable. Follow the signal from the input and check the output waveform of each transistor. Where the waveform departs from normal, the trouble is in that portion of the bridge. Since the inputs to Q4 and Q2 are taken from the emitters of Q1 and Q3, it will be normal to find the amplitude of Q1 and Q3 larger than that of Q4 and Q2. The emitter outputs of Q1 and Q3 will be of the same phase as their inputs, while the outputs of Q4 and Q2 will be oppositely polarized with respect to their inputs, because of the common-emitter connection.

Distorted Output. Distorted output may be caused by a defective transistor, improper collector voltage, or too large a drive (input signal). The collector voltage may be checked with a voltmeter to determine whether it is normal. Too large an input signal will cause clipping of the signal in the output circuit, as in other amplifier circuits. Too low a collector voltage will produce bottoming, a form of clipping which results when the supply voltage cannot follow the peak signal demands. Hence, it is almost mandatory to use an oscilloscope to check the signal waveform through the circuit. Flattening of the signal at the peaks or troughs of modulation indicates clipping and the resultant distortion. If R1 and R2 and the load are of the proper value, and the supply voltage is normal, the transistors are defective. Replace the transistors in each arm of the bridge, separately with ones known to be good.

PHASE INVERTERS.

The phase inverter uses a single-ended input signal to develop a dual output of opposite polarity suitable for driving an RC-coupled push-pull power amplifier. To supply oppositely polarized outputs, it is necessary to invert one of the signals so that its phase or polarity is opposite that of the other signal. Strictly speaking, the phase inverter does not really invert the phase of the signal; it merely changes the polarity of one of the outputs. By proper choice of load and bias, the phase inverter may also be used to amplify the input signal. The output from a single stage, however, is limited by the degenerative voltage developed in the emitter circuit. Thus, more drive is required than for a conventional single-stage amplifier to overcome the negative feedback developed in the emitter. Two types of circuits are employed in the single-stage phase inverter, one with a balanced output and the other with an unbalanced output. Less distortion is provided by the balanced arrangement, which requires only one more part than is used in the unbalanced arrangement. Where the push-pull output stage driven by the phase inverter is operated Class B, substantial drive power is required, which sometimes cannot be supplied by a single inverter stage. In this instance, the two-stage balanced inverter is employed to supply the additional power needed. Since the two-stage phase inverter uses a separate transistor to develop each output, any further drive power needed is obtained by conventional push-pull drivers. The transistor phase inverter is practically identical with the electron-tube phase inverter, and any general remarks in the previous discussion of electron-tube phase inverters made in Part A of this section of the Handbook are also applicable.

ONE-STAGE PHASE INVERTER.

APPLICATION.

The one-stage phase inverter is used to supply two oppositely polarized outputs, from a single-ended input signal, to drive push-pull amplifier stages. It is used in radio receivers, public address systems, and transmitter modulator stages, usually as the driver stage for the power amplifier.

CHARACTERISTICS.

Requires more drive than for a single-stage amplifier.

Supplies two outputs with one input signal.

The outputs are oppositely polarized and of approximately the same amplitude.

The bias and load resistance are selected to provide equal output signals.

Provides better frequency response than is possible with an input transformer.

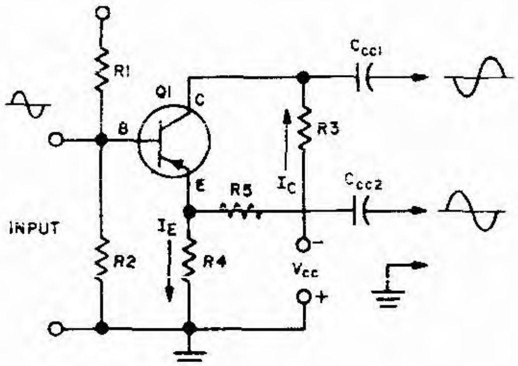
Is Class A-biased for equal swings; normally does not use either Class AB or B operation.

Is usually fixed-biased, but self-biased applications may be encountered.

CIRCUIT ANALYSIS.

General. Where a single-ended stage is used to drive a push-pull amplifier, it is necessary to supply two oppositely polarized input signals to the push-pull stage. While a center-tapped transformer may be used, it has been found that RC coupling generally provides better frequency response, with a saving in economy through elimination of the transformer, plus a reduction in weight and space. The use of the phase inverter circuit provides the necessary dual output. The unbalanced phase inverter uses a load in the emitter and a load in the collector to develop the oppositely polarized outputs, and is sometimes referred to in other publications as the **split-load** circuit. Actually, the load is not split; identical load resistors are used to obtain equal output amplitudes. A balanced output condition may be obtained in the single-stage phase inverter by adding another resistor, as will be explained later.

Circuit Operation. The accompanying schematic is that of a one-stage unbalanced phase inverter.



One-Stage Unbalanced Phase Inverter

Fixed voltage-divider bias is supplied by resistors R1 and R2 (see paragraph 3.4.1 in section 3 of this Handbook for a discussion of bias arrangements). The bias is normally Class A with the transistor operating at the center of its dynamic transfer curve. Thus, equal swings about the bias point (with equal loads) will produce equal output signals. R3 is the collector load, and R4 is the emitter load. Both loads are of the same value to produce equal output signals, which are capacitively coupled through C_{cc_1} and C_{cc_2} to the push-pull stage.

When a negative input signal is applied to the base of Q1, it adds to the forward bias of Q1 and causes the emitter and collector currents to increase. Electron flow is in the direction indicated by the arrows. The emitter current flowing through R4 produces a negatively polarized signal, while the collector current flowing through R3 produces a positively polarized signal. Since R3 and R4 are identical in value, and the collector current is practically equal to the emitter current (less the small amount of base current), equal-amplitude output signals of opposite polarity are produced. On the opposite half-cycle of operation, the input signal becomes positive and reduces the forward bias, thus reducing both the emitter and collector currents. In this instance, assuming that the drive is such as to almost stop conduction, the collector output becomes negative and almost equal to the supply voltage. Simutaneously, the emitter current is reduced almost to zero and the emitter becomes positive with respect to the collector. Thus, the emitter and collector outputs change polarity as the input signal changes; the emitter output signal is in-phase and the collector output signal is out-of-phase with the input signal.

Unfortunately, the collector output impedance is higher than the emitter output impedance, and an unbalanced output condition results. Even though equal-amplitude output signals are developed, the push-pull input is basically mismatched for the emitter output and matched for the collector output. As a result, distortion occurs with strong signals.

A balanced output is provided by connecting R5 (shown dotted in the schematic) between the emitter and C_{cc_2}. In this case, the input impedance becomes high for both push-pull transistors, since the impedance of the emitter is now determined by R4 and R5 connected in series, and their total value is chosen to provide an impedance equal to R3. Thus, the distortion produced by strong signals is eliminated. Because a voltage drop occurs across R5, R4 is made larger than R3 to compensate for the loss in output voltage which would otherwise occur.

Since R4 is unbypassed, the voltage developed at the emitter is degenerative, and in effect opposes the input voltage in essentially the same manner as negative feedback; thus, a larger driving voltage must be applied to the base of the phase inverter than would normally be required for an amplifier without feedback. Where this input drive is limited or unavailable, a two-stage phase inverter is generally used because of its reduced drive requirements.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliammeter testers. Be careful, also, to observe proper polarity when checking continuity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. Lack of supply voltage, no input signal, a defective transistor, or an open collector resistor (R3), emitter resistor (R4), or bias resistor (R2) will produce a no-output condition. The supply voltage can be checked with a voltmeter, and the voltage to ground checked from the emitter, base, and collector, to determine whether normal voltages exist and whether resistor R2, R3, or R4 is open. With an abnormally high voltage between the base and ground, Q1 will be driven into saturation (this indicates that R2 is open). If R2 is shorted, or no input signal is applied, a no-output condition will also exist. If either R3 or R4 is open, emitter and collector current flow will be interrupted and no output will be developed. If either R3 or R4 is shorted, only a single output will be obtained from the portion of the circuit which is not short-circuited. Both resistors would have to be shorted to cause a complete no-output condition. Failure of coupling capacitors C_{cc_1} and C_{cc_2} will cause loss of output only if they are both either open or shorted to ground; if only one capacitor fails, only one output will be affected. If either capacitor is leaky, a reduced-output condition rather than a no-output condition will occur. Where the transistor appears to be at fault, replace it with one known to be good.

Reduced Output. Low supply voltage, improper bias, changed values of load resistors R4 and R3 (or R5), as well as leaky or defective coupling capacitors, can cause reduced output. The supply voltage and bias may be checked with a voltmeter. However, if R2 were open and a voltage check were made between the base and ground, the voltmeter shunt would replace R2. If the shunt were nearly the same value as R2, a false indication of nearly correct value would be obtained. If the values of R3 and R4 (and R5 if used) increase, then the output signal amplitudes will be less, or unequal at best. With an audio input applied, follow the waveform through the circuit, observing it with an oscilloscope. When the waveform departs from normal, the location of the trouble should be obvious.

Distorted Output. If the bias or supply voltages are incorrect, the load resistance is not of the proper value, or the transistor is defective, a distorted output will be obtained. Use an oscilloscope to observe the waveform. Since the operation is Class A, equal swings about the bias point should produce equal-amplitude and undistorted outputs of opposite polarity. If overdriven, the tops and bottoms of the waveform will be clipped (a sine wave will appear as a rectangular wave). In the unbalanced circuit (where R5 is not used), strong signals will cause distortion to appear on the collector output but not on the emitter output. In the balanced circuit, strong signals should not cause distortion until they exceed the bias value, and then both outputs should be equally distorted. If the transistor is suspected, replace it with one known to be good.

TWO-STAGE PHASE INVERTER.

APPLICATION.

The two-stage phase inverter is used in receivers, public address systems, and modulators to produce sufficient power to drive a high-powered push-pull stage from a single-ended input.

CHARACTERISTICS.

Only a small input signal is necessary to drive the stages to full output.

Supplies two output signals for a single input signal.

The output phases (and polarities) are opposite and suitable for a push-pull input.

Operation is usually Class A, although Class AB or B applications may be encountered.

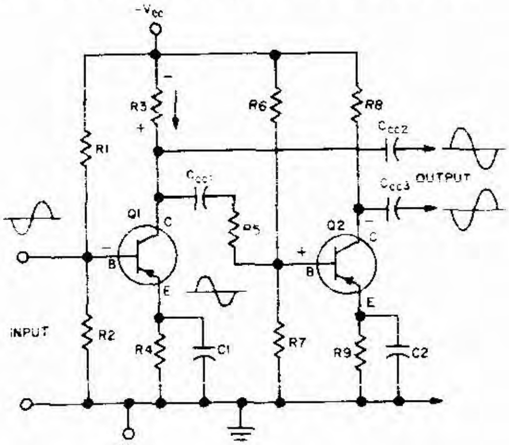
More than twice the power output of a single-stage phase inverter is obtained.

Distortion is equal to or less than that of the single-stage circuit.

CIRCUIT ANALYSIS.

General. The two-stage phase inverter uses two separate transistors operating at their full capabilities in the common-emitter circuit to provide a larger power output than the one-stage phase inverter circuit. Since the output is taken from the collector of each stage, there is no negative feedback in the emitter circuit to overcome (as in the single stage), so that less drive than that required for the single-stage phase inverter is required. As a result, more output power is obtained with less drive than for a single stage.

Circuit Operation. The schematic of a typical two-stage PNP transistor phase inverter is shown in the accompanying illustration. Transistors Q1 and Q2 are basic common-emitter-connected amplifiers, each supplying a single output. Q2 is connected in cascade with Q1, but has R5 connected in series with the base to limit the current and drop the driving signal to a value equal to that applied to Q1. Thus, with the input signal to Q2 held to the same value as the input to Q1, the output of Q2 is made to equal the output of Q1; also, since the CE circuit produces an inverted output polarity, the two separate output signals are equal and oppositely polarized, and suitable for driving a push-pull stage. Fixed Class A bias is provided for both stages through voltage divider resistors; R1 and R2 bias Q1, while R6 and R7 bias Q2. (See section 3, paragraph 3. 4. 1, of this Handbook for types of biasing, and paragraph 3. 4.2 for a discussion of stabilization methods.) Resistors R4 and R9 are emitter swamping resistors used for thermal stabilization, and are bypassed by C1 and C2 to prevent degeneration. Since the capacitors bypass any a-c component of the signal, they are affected only by d-c current variations produced by changing temperature. When a temperature change increases the emitter current, it produces a d-c voltage across the swamping resistors which opposes the operating bias and automatically reduces the emitter current to compensate for the temperature-caused increase. Resistors R3 and R8 are the collector loads of Q1 and Q2, respectively, across which the output voltage is developed. The collector of Q1 is capacitively connected to the base of Q2 by C_{cc_1}, and the push-pull outputs are coupled through capacitors C_{cc_2} and C_{cc_3}.



Two-Stage Phase Inverter

When a negative input signal is applied to the base of Q1, the forward bias is increased and the emitter and collector currents are increased above the resting (or quiescent) value. Electron flow is from the emitter through C1 to ground, and from the collector supply through R3 to the collector. As shown in the illustration, the collector output of Q1 is positive, and is applied through C_{cc_1} to the base of Q2 and through dropping resistor R5 to drive Q2. (The inverted output from the collector of Q1 is supplied to the push-pull circuit by C_{cc_2}.) The value of R5 is chosen to supply an input to Q2 just equal to the amplitude of the input signal applied to Q1. With a positive signal applied to the base of Q2, the forward bias is reduced and the emitter and collector currents of Q2 are reduced. Electron flow is from the emitter of Q2 through C2 to ground, and from the collector supply through R8 to the collector. Since Class A bias is used, and assuming that the base voltage applied to Q2 is just equal to the bias, collector current flow is reduced to zero and the collector voltage rises to that of the negative supply (both ends of R8 are negative with respect to ground). Thus, a negative output is obtained from the collector of Q2 and is applied through C_{cc_3} as the oppositely polarized (in-phase) push-pull driving signal. Since Q2 operates practically instantaneously (there is no inherent delay), the two outputs appear on the push-pull grids simultaneously. (Note that passage through one stage inverts the signal, while passage through two CE stages returns the signal to the original polarity.)

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Assuming a sine-wave input, when the negative half-cycle is completed the signal reverses, and a positive input is now applied to the base of Q1. The positive input reduces the forward bias of Q1 to zero (assuming full swing) and the collector voltage rises to that of the negative supply, thus producing a negative output. The large-amplitude negative collector output is dropped through R5 so that it is approximately equal to the input signal amplitude applied to Q1. This small negative input to the base of Q2 increases the forward bias and causes the collector current flow through R8 to increase. Electron flow is from the supply through R8 to the collector, which produces a positive voltage drop at the collector (the polarity of this voltage drop is opposite that of the previous half-cycle), so that the output from Q2 is now positive. Since there is no inherent delay in the operation of the transistor, the positive output from Q2 and the negative output from Q1 appear practically simultaneously at the push-pull inputs.

Dropping resistor R5 acts as a balancing resistor to equalize the output of both stages. The transistors need only be of similar types; matched pairs are not required. The collector resistors are usually made equal so that identical currents will produce equal output voltages. Where little power is required, such as that needed to drive a conventional Class A push-pull stage, swamping resistors R4 and R9 and their associated bypass capacitors C1 and C2 may be eliminated from the circuit, and the emitters connected directly to ground. In applications where distortion becomes critical, the use of feedback from the collector is resorted to by connecting bias resistors R1 and R6 to their collectors. In this instance resistors R2 and R7 could be eliminated by changing the values of both R1 and R6. Thus, it is evident that the basic schematic may vary slightly, according to individual design, using different bias and stabilization methods. However, the operation is essentially the same since two stages of amplification are used to invert one of the outputs and thus provide a push-pull output.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliammeter testers. Be careful, also, to observe proper polarity when checking contunity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. Lack of collector voltage, improper bias, or an open R3, R4, or C_{cc_1} will prevent Q1 from driving Q2 and there will be no output. The same result will be obtained if Q1 is defective. A defective Q2 or a component in that stage will affect only the output from Q2; the output from Q1 will be unaffected. Measuring the supply voltage, collector voltage, and bias with a voltmeter will usually indicate the portion of the circuit in which the defective part is located. If either R2 or R7 is open, the bias will be determined by the internal base-to-emitter resistance of the transistors. However, when measured with a voltmeter from base to ground, the meter shunt will act as the lower portion of the bias divider, and cause a false indication. Check also for the presence of an input signal (use an oscilloscope or VTVM probe) since the phase inverter is usually RC-coupled to a preamplifier stage. An open output resistor or coupling capacitor in the preamplifier will not permit any input to appear at the base of Q1. Swamping resistor R4 or collector resistor R3, if open, will prevent the flow of emitter and collector current. If R4 is shorted, the circuit will be temperature-sensitive, but it will operate normally otherwise; with a shorted collector load resistor (R3), no output will be obtained from Q1 and, consequently, Q2 also. A leaky coupling capacitor, C_{cc_1} will not produce a no-output condition, but will cause partial clipping of the signal and distortion. If shorted, the increase in bias will drive Q2 into heavy saturation, and, while the output of Q2 will be lost, an output will still be supplied from Q1. If R5 is open, no output will be obtained from Q2; if R5 is shorted, the outputs of Q1 and Q2 will be greatly different in amplitude, and distortion will be present. If bias resistor R6 is open, contact bias will be placed on Q2; and thus the output will be distorted, and of larger amplitude than normal. If R9 is open, there will be no output from Q2. If collector resistor R8 is open or shorted, no output will be obtained from Q2. If the output coupling capacitors are open, no output will result; if they are otherwise defective, only reduced output will occur. Where the transistors are suspected, replace them with ones known to be in good condition.

Reduced Output. Low collector voltage, improper bias, or a defective transistor can cause reduced output. Usually, a voltage check of the supply and bias will determine whether one or more of these voltages are at fault. If either of the swamping resistor bypass capacitors, C1 or C2 is open, the degenerative effect of the swamping resistors will cause reduced output and require greater drive in the stage affected. Since Q1 drives Q2, and open C1 will change both outputs; if only C2 is open; only the output of Q2 will be affected. A leaky coupling capacitor C_{cc_1} will improperly bias Q2 and cause a clipped and reduced output. If one or more of the coupling capacitors are completely shorted, the collector voltage will be placed on the following transistor base, cause heavy flow of forward current, and bias the transistor into saturation, thus reducing the output of the stage to a small value. When normal voltages and bias appear to be present, use an oscilloscope to follow the waveform through the circuit. When the waveform changes amplitude, the location of the trouble should be obvious. If all voltages and resistances check normal and yet the waveform is defective, then the transistor in that portion of the circuit is at fault. Replace transistors with ones known to be good, or use an in-circuit transistor tester if available.

Distorted Output. Improper bias or supply voltage, overdrive, or a defective transistor can cause distortion.

Use an oscilloscope to check the waveform, after checking the bias and collector voltages with a voltmeter. Follow the input signal through each stage to the output, checking for proper amplitude and polarity. The signal at the collector of Q1 should be similar to that on the base, but of opposite polarity. The signal on the base of Q2 should be equal in amplitude to that on Q1, but of opposite polarity also. Both collector outputs to ground should be of equal amplitude but of opposite polarity. If the d-c bias and collector voltages are normal but a distorted collector output occurs, the transistor is probably defective. Replace the transistor with one known to be good. Make certain that the input signal is undistorted; otherwise, the distortion will be amplified and inverted in passing through the circuit. Clipping of the peaks and troughs of the signal indicate that the input drive is too great.

VIDEO AMPLIFIERS.

The frequency range covered by the video amplifier is greatly extended over that of the audio amplifier. Video frequencies extend from dc, or a few cycles per second, to as high as 5 or 6 megacycles, depending upon the type of signals. For example, in television applications the picture information requires a uniform bandwidth of from 60 cps to 4 mc, whereas in radar applications a band width of from about 30 cps to 2 mc is sufficient. In circuits where sawtooths or pulsed waveforms are to be amplified, it is necessary to cover a range of frequencies from about one tenth that of the lowest frequency employed to at least ten times that of the highest frequency. This extended range is necessary because waveshapes which are not sinusoidal contain many harmonics, which must be amplified equally and without any phase delay in order to avoid distortion. The sinusoidal waveform requires only sufficient uniformity of response to pass its second and third harmonics, because any other higher harmonics are of such small amplitude that they can be considered negligible as far as their effect on the shape of the waveform is concerned; on the other hand, the square wave, particularly at the lower frequencies, requires that an infinite number of harmonics be passed for accurate reproduction of the waveshape. In practice, however, it has been found that for square waves, harmonics above the tenth, like those greater than the third for the sinusoidal signal, are actually of negligible amplitude and have little effect on the shape the final waveform.

Since the video amplifier requires the best possible uniformity of reponse, R-C coupling is used rather than transformer coupling (which has a narrow bandwidth), and cascaded stages are used to supply sufficient gain. This requires that the interstage coupling circuits be modified to obtain the required bandpass, and that inverse feedback be used where possible to flatten out the response. Low-frequency response is improved by using large values of coupling capacitance to lower the series reactance and reduce the voltage drop across the coupling capacitor. The values of the coupling capacitor used between transistor circuits are much higher than the values used between electron-tube circuits (on the order of 10 μf). Even so, further compensation is required through partial bypassing of the collector load resistance to improve the low-frequency response and to prevent phase distortion at frequencies lower than 30 cps. Because the gain is highest at the lower frequencies, it is general practice to reduce the low-frequency gain and boost the high-frequency gain, to obtain uniform response for both low and high frequencies. The high-frequency response is increased by using compensating circuits with inductance in the load circuit. The higher load reactance at the higher video frequencies causes a larger output voltage to be developed (when the output would normally be dropping), and thus extends the frequency response. The series inductance in the load circuit also resonates with the stray (shunt) circuit and transistor capacitance, to produce a high-impedance parallel-resonant circuit which is effective over a large range of frequencies; this is known as **shunt peaking**. Further extension of the response at the highest video frequencies employed is obtained by the use of an additional inductor in series with the coupling capacitor. The series inductor and coupling capacitor form a series-resonant circuit at the very high video frequencies, to boost the response at the upper limits of amplification; this is known as **series peaking**. In the transistor video amplifier, the use of combined shunt- and series-peaking circuits provides the maximum extension of high-frequency response.

In the electron-tube video amplifier, further increase in high-frequency response is obtained by using a lower load resistance than normal and by sacrificing some additional gain. Such compensation is not possible with the transistor video amplifier, however, since maximum gain occurs up to f_{max}, which is the upper limit of usable transistor gain. Above f_{max} the transistor gain drops off to practically nothing, and the transistor no longer amplifies. In the electron tube, however, the gain does not drop off until far past the highest video frequency (actually in the high r-f ranges), so that heavy loading can improve the response. Since the common-emitter circuit produces high gain, cascaded transistor stages can be mismatched so that the low-frequency gain is reduced to equal the high-frequency gain, and still provide uniform response with adequate over-all gain. Matching to obtain more gain is usually required only at the transistor cutoff frequency (f_{max}), since excess gain exists at the lower frequencies, because of the extended frequency range, and since the low-frequency gain and forward amplification vary from transistor to transistor, considerable care is necessary in design to avoid regeneration and circuit instability. Partial bypassing of the emitter resistor is generally used to provide some degeneration and thus stabilize the circuit. Where a number of stages are used, an external negative feedback loop is usually provided to improve the stability and response. However, since the use of external negative feedback is not peculiar to video amplifiers alone (it may be employed in many other circuits), it will not be further discussed in this section.

WIDE-BAND VIDEO AMPLIFIER.

The wide-band video amplifier is used to provide uniform amplification of video frequencies in radar and television receivers and display amplifiers before application to the cathode-ray-tube indicator or other video output device.

CHARACTERISTICS.

Common-emitter configuration is used to provide high gain. Transistors used must have an alpha (or beta) cutoff frequency higher than the highest frequency it is desired to amplify.

Class A bias is normally employed to minimize distortion.

Amplifier is specially frequency-compensated to provide wide-band response.

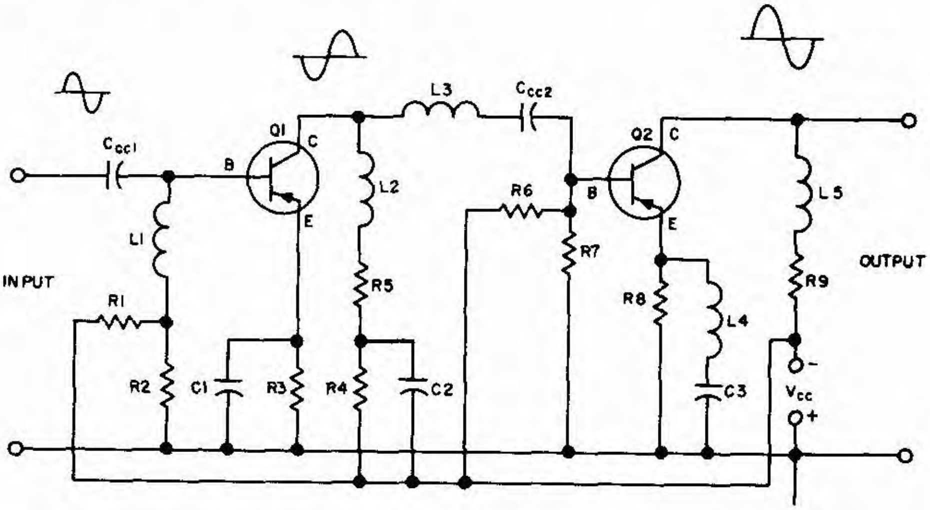
Compensating circuits may be employed in the base, emitter, or collector leads, and even between stages in the coupling circuit, to obtain the desired response curve.

Input impedance is on the order of 10,000 to 15,000 ohms, while the output impedance may be either high or low, depending on the requirements of the output device (high for CRT drive and low for coaxial line drive).

CIRCUIT ANALYSIS.

General. The wide-band amplifier may be either a single stage for light loads, or a number of cascaded stages to supply large driving voltages, where appreciable output power is needed. Usually the CRT indicator is driven by the wide-band amplifier since only a little power is required to drive most cathode-ray tubes. The overall response is usually from 30 cps to 6 megacycles, although the response of television stages may be restricted to 4 mc, and that of radar stages to as low as 2 mc. When a response greater than 6 mc is needed, special design techniques are employed, and the overall gain is usually much lower than that of the average wide-band amplifier. The transistors need not be matched, since design is accomplished for each stage individually, and the CE circuit provides better over-all response for mismatched stages. The relatively high-impedance load provided by a CRT is usually considered to be capacitively reactive, whereas the low-impedance load offered by the video (coaxial) line is normally considered to be resistive, since it is usually terminated by a resistor whose value is equivalent to the characteristic impedance of the line to avoid reflections. The types and methods of compensation are standard, but they may be used differently by each designer. It is usually considered more important to obtain the desired gain and response than to effect a savings by the limit use of parts and transistors. Where high power output is required, an external feedback loop is usually employed to provide stability and to improve the over-all response characteristic, in addition to the internal compensating circuits normally used.

Circuit Operation. The following schematic illustrates a typical wide-band amplifier using two transistors in cascade.



Wide-Band Video Amplifier

In the schematic, C_{cc_1} couples the base of Q1 to the preceding stage, usually the video detector, and prevents the d-c base bias from being shunted through, or affected by, the detector circuit, Resistors R1 and R2 supply fixed voltage-divider bias to Q1, while R6 and R7 perform the same function for Q2. (See section 3, paragraph 3.4.1, for a discussion of bias arrangements, and 3.4.2 for a discussion of stabilization methods.) R3 and R8 are the emitter swamping resistors for Q1 and Q2, which are bypassed by C1 and C3, respectively. L1, L2, L3, L4, and L5 are compensating inductors inserted to improve the high-frequency response, while R5 and R9 are the collector load resistors. R4 and C2 form a low-frequency boost circuit in the collector circuit of Q1. C_{cc_2} is the interstage coupling capacitor. L3, together with the input capacity to Q2 *forms a series peaking circuit* to improve the high-frequency response. The operation of the amplifier is similar to that of any other common-emitter, RC-coupled amplifier except for the effects of the compensating circuits.

When a sine-wave input signal is applied to C_{cc_1}, a voltage is developed across the series impedance of L1 and R2, and is applied to the base of Q1. Assume for the sake *of discussion that the sine wave is increasing in a* positive direction. This positive swing reduces the negative base bias of Q1 and causes a reduction of emitter current. Since emitter resistor R3 is bypassed by C1 no degeneration is produced. However, as the emitter current reduces, collector current flow through R4, R5, and L2 also reduces. As the collector current reduces, the collector voltage rises towards the negative supply voltage and produces a negative-going output voltage. *This output* voltage is applied in series with L3 and C_{cc_2}, appears across base resistor R7, and is also applied to the base of Q2. The negative-going output of Q1 increases the forward bias on Q2 and causes a greater flow of collector current through R9 and L5. At the same time the emitter current in Q2 also increases, but since it is bypassed by C3 only the high frequency component flowing through L4 changes, and the medium and low frequency *components* are not affected. Thus, as the input waveform goes positive, a positive going and amplified output waveform is developed in the collector circuit of Q2.

During the negative half of the input signal, the signal *adds to the negative forward* bias and increases current flow in the collector of Q1. The increased collector current flow creates a large drop across resistors R4 and R5 and inductance L2, developing a positive-going output voltage. This voltage applied in series with L3 and C_{cc_2} appears across R7 and the base of Q2. Since it is positive-going, the forward base bias on Q1 is reduced and causes both the emitter and collector currents to fall also. The collector *voltage of Q2, therefore rises* towards the supply value and develops a negative-going output signal. Thus the input and output waveforms and voltages are in-phase. Since the transistors operate Class A, a linear and amplified output is produced. The frequency response and band pass are affected by the compensating networks as follows.

The low-frequency response of the Q1 stage is basically determined by the time constant of C_{cc_1} and R2. Although L1 is in series with R2, *its effect at low frequencies is* negligible since its reactance is very small as compared with the resistance of R2. L1 is used to provide a high reactance (much larger than R2) at the high video frequencies, to avoid shunting them to ground through the *relatively low resistance* of R2. Since there is more than adequate gain at low frequencies, it is unnecessary to avoid, or to compensate for, any low-frequency shunting at this point. Fixed bias is used so that Q1 *may be kept at* the center of its operating curve for equal positive and negative swings, as is typical of Class A operation. R3 is affected only by d-c changes caused by temperature differentials. When an increased emitter current flows through R3, a positive voltage is produced; this voltage opposes the forward bias, reduces emitter current and returns the operation to normal. Thus, R3 provides conventional emitter swamping action. Since C1 bypasses R3, the a-c (signal) variations of emitter current do not pass *through R3; hence, R3 has no effect* on normal signal operation. As the collector current increases, electron flow is from the supply through R4, R5, and L2 to the collector. At low frequencies the reactance of L2 is very small, and it has practically no effect. Also, at these frequencies the reactance of C2 which bypasses R4 is very large, and can be considered as open. Thus, both R5 and R4 combine to form the collector load at low frequencies. At medium and high frequencies the reactance of C2 becomes very small and can be considered to short-circuit R4. Therefore, as the frequency increases, R4 is shunted out of the circuit, the collector load becomes smaller, and less output voltage is developed. Note that at the lower frequencies the output voltage is increased over what it would normally be without R4 and C2 in the circuit. Consequently, the combination of R4 and C2 function to extend the low-frequency response. *As the high frequencies increase*, the shunt output capacitance of Q1 and the shunt input capacitance of Q2 tend to bypass the signals to ground, thus lowering the output voltage at the higher frequencies. To compensate for this effect, L1 offers an increasing reactance *(as the frequency increases)* and, together with the output capacitance of Q1 (and stray shunt circuit capacitance to ground), forms a parallel-resonant circuit. Since collector resistor R5 is in series *with this resonant circuit*, it is broadly resonant so that the load impedance is increased over the mid-high-frequency ranges, and the output voltages does not drop over these ranges as it normally would. Thus, the bypassed resistor and the series inductor *extend the low-frequency response* and the high-frequency response of the circuit, respectively.

The output of the Q1 stage is coupled through capacitor C_{cc_2} to the base of Q2. Although L3 is connected in series between the collector of Q1 and coupling capacitor C_{cc_2}, it has little reactance at low frequencies and thus has practically no effect on the low-frequency response. C_{cc_2} is large and appears as a short circuit to the output *signal from Q1, so that the signal is applied* to the base of Q2 with practically no attenuation. Although the low value of bias resistance, R7, tends to shunt the input signal to ground, it is not frequency-responsive and does so equally for all frequencies. However, the input capacitance to Q2 is frequency-responsive and shunts the higher video frequencies to ground. To compensate for this loss and to increase the high-frequency response, the value of L3 is chosen to resonate with the input *capacitance of Q2 at the* higher video frequencies. Thus the high-frequency response is extended by this series peaking circuit to compensate for any input shunting effects. The signal at the base of Q2 is, of course, inverted in polarity by passage through the Q1 stage, and is again inverted in the Q2 stage to provide an output polarity which is identical to that of the input signal.

At the low video frequencies, swamping resistor R8 is shunted by C3, even though L4 is connected in series with C3, since the reactance of L4 is negligible at the low frequencies. As the video frequencies increase, however, the reactance of L4 increases while the reactance of C3 decreases. In effect, L4 acts as a choke preventing the passage of high-frequency components around R8. Since the high frequencies must now pass through R8, a degenerative voltage is developed by the flow of signal emitter current through R8. This degenerative voltage opposes the normal forward bias and requires a larger input signal to produce the same output. This is the same action that occurs with a partially bypassed emitter resistor, and is equivalent to negative feedback. Thus, the response at the middle and upper video frequencies is kept uniform, and positive feedback through capacitive coupling of the input and output signals is prevented with a slight loss in gain. At the frequency where the reactances of L4 and C3 are equal, series resonance occurs, and R8 is completely shunted (short circuited); there is no degeneration, and a peak response occurs. For all other frequencies L4 and C3 function as a variable-impedance shunt around R8.

Q2, like Q1, is biased Class A, and operates at the center of its transfer characteristic. Therefore, equal input swings develop equal and undistorted outputs across collector resistor R9. Compensating inductor L5 is connected in series with R9 as a shunt peaking circuit, to improve the high-frequency response and correct for the shunting effects of the collector-to-emitter capacitance of Q2, as well as the stray circuit capacitance in shunt to ground. When the output is applied to the control electrode of a CRT, the value of collector resistor R9 is made large in order to develop a large voltage drive. With a low-impedance output, R9 is usually made to match the impedance of the load, being on the order of 50 to 300 ohms, as required.

The schematic circuit just discussed illustrates the standard forms of frequency compensation employed in video amplifiers; however, each wide-band amplifier varies somewhat because of the desired response characteristics and the differences between the transistors. For example, in one amplifier compensating circuits may not be used in the base or emitter loads, but only in the collector and coupling circuits, whereas in another amplifier compensating circuits may be used in the leads of each transistor element. Usually, the greater the number of compensating circuits used, the greater the bandwidth and the better the uniformity of response.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliammeter testers. Be careful, also, to observe proper polarity when checking continuity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. Lack of an input signal, improper bias, lack of supply voltage, or a defective transistor can cause a no-output condition. Use a voltmeter to determine the supply voltage and bias. Note that the voltmeter shunt will complete the circuit when you are reading voltages across open components; thus, erroneous indications can be obtained, leading to false conclusions. To avoid errors of this kind, it is better to use an oscilloscope to observe the waveform on the base of Q1, and to follow the signal through the circuit, noting where it disappears. The trouble exists between the points where the signal last appears and where it disappears. If a signal exists on the base of Q1 but not on the collector, either R2, R3, R4, R5, L1, or L2 may be open. Continuity or resistance measurements will determine the defective part. This same condition can also be caused if Q1 is defective. When the other parts check properly, substitute a transistor known to be good to determine whether the transistor is at fault. If a signal exists at the collector of Q1 but not at the base of Q2, either L3, C_{cc_2}, or R7 may be open, or Q2 may be defective. A resistance check will determine whether L3 or R7 is open; if neither is open, C_{cc_2} or Q2 must be at fault. Check the value of the capacitor with an in-circuit capacitance checker. If a signal exists at the base of Q2 but not at the collector, either R8, R9, or L5 is open, or Q2 is defective. If R8, R9, and L5 show continuity and proper resistance when checked with an ohmmeter, Q2 must be defective. Replace the transistor with one known to be good.

Reduced Output. Reduced output may be caused by improper bias, low collector voltage, a change in the value of the emitter and collector resistors, or defective transistors. The approximate bias and collector voltages can be determined with an ohmmeter. Then use an oscilloscope to follow the waveform through the circuit, noting where the amplitude of the signal changes to localize the trouble to the defective portion of the circuit. If R1 increases in value, the base bias on Q1 will be lowered; if R1 opens, the fixed base bias on Q1 will be effectively zero. Either condition will cause a reduction in output and probably an increase in distortion. If R6 increases in value or opens, it will create a similar condition for Q2. If either C1 or C3 is open, excessive emitter degeneration will occur and drastically reduce the output. If either R5 or R9 becomes shorted or changes to a lower value, less output voltage will be developed. A similar condition will be caused if Q2 is defective. The resistors can be checked for their proper values with an ohmmeter, and the capacitors can be checked with an in-circuit capacitance checker. Replace Q2 with a transistor known to be good when all other parts check normal.

Distorted Output. Improper bias, overdrive, low collector voltage, or defective transistors can cause distortion. The bias and collector voltages can be determined with a voltmeter. Distortion can be most quickly seen and located by the use of an oscilloscope. Apply an undistorted signal and check the waveform through the circuit. The location of the trouble will be evident when the waveform departs from normal. Overdrive will usually be indicated by a flattening of the tops and bottoms of a sinusoidal waveform, indicating that the signal is exceeding the bias voltage at the peaks. In the case of a square wave the amplitude will be reduced, causing amplitude distortion. Since the wide-band amplifier covers a large range of frequencies, and the low frequencies are particularly susceptible to phase distortion, it is preferable to use a square wave for testing. Because it takes a number of harmonics to produce a square wave properly, the entire audio range may be checked by applying only two different square-wave frequencies, such as 60 cps and 1000 cps. The video response can likewise be checked every 5 kc up to 50 kc (the usual limit of generator range). A sloping response to the leading or trailing edge of the waveform indicates poor high-frequency response, while a sloping flat top indicates poor low-frequency response. By temporarily short-circuiting a specific compensating circuit, the effectiveness of the portion under suspicion can be gauged. Distortion caused by regeneration (positive feedback) sometimes occurs in high-gain amplifiers, and is shown by a large-amplitude response peak (sometimes by oscillation), usually over a small range of frequencies. In comparison with a wide-band amplifier known to be operating properly, it will show as a hump or peak in what ordinarily would be a flat curve of uniform response.

R-F AMPLIFIERS.

General. The transistors used for r-f amplifiers differ in a number of respects from electron tubes. The forward transfer admittance is roughly 15 to 40 times larger than the corresponding tube transconductance. Both the input admittance and the input capacitance are also correspondingly larger. The base-to-collector capacitance may be equal to, or even less than, the grid-to-plate capacitance of an electron tube. However, because of the lower impedance levels involved in the transistor, this capacitance does not have as much importance as it has in tube circuits. The series resistances of the transistor elements also become higher at radio frequencies and produce a number of effects. For example, the base spreading resistance increases the amount of drive power required and causes instability in the amplifier. The emitter series resistance decreases the amount of drive power required, and also limits the amount of usable amplification because of the additional degeneration produced. The collector series resistance adds to the total output impedance to increase the gain, but also reduces circuit stability because of the possibility of regenerative feedback due to the higher gain. A phase shift is also produced in the output because of this collector resistance. Each of the above items will be discussed in more detail at the appropriate points below.

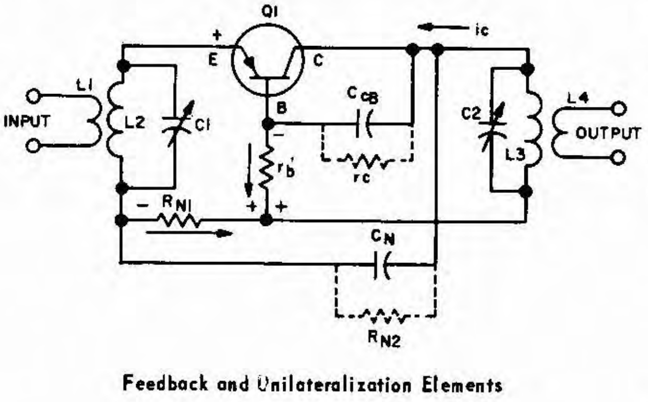
The tuned r-f amplifier is considered to be a narrow-band amplifier rather than a wide-band amplifier because it passes only a relatively small range of frequencies about the center of its band pass. Whereas the video (wide-band) amplifier passes frequencies from zero to 6 mc or more, the r-f amplifier used in communications equipment usually does not pass more than 10 to 15 kc, and in most instances less than this range. On the other hand, it should be noted that the r-f amplifiers used in television service, or for pulsed modulation, require a much larger bandwidth to accomodate the many sideband frequencies associated with these types of transmissions. Such amplifiers are considered to be special wide-band r-f amplifiers, except when the carrier frequency is so high that the modulation frequency is a small percentage of this figure. For example, a 3000-mc carrier with a 10-mc modulating frequency would be adequately handled by a narrow-band r-f amplifier, but a 30-mc carrier containing a 10-mc modulation frequency would require a wide-band r-f amplifier. Since semiconductor wide-band r-f amplifiers are not yet commonly used, the circuits to be discussed later in this section concern the conventional narrow-band r-f amplifier.

R-F amplifiers are used for both receiving and transmitting. A receiver uses a low-power, small-signal amplifier, while a transmitter uses a high-power, large-signal amplifier. Except for the conditions required by the power consideration, both types of amplifiers are similar and operate identically. Unfortunately, however, the transistor response or power gain is reduced as the frequency is increased. The response curve of a transistor is similar to that of a low-pass filter. That is, up to a certain frequency the gain is fairly uniform, and beyond this cutoff frequency the output drops rapidly toward zero. The limit of this upper cutoff frequency and the rapidity of dropoff depend to a great extent on the type of transistor and its composition. Many different types of transistors have been developed to extend the usable high-frequency range, such as the surface barrier transistor, the drift transistor, and others.

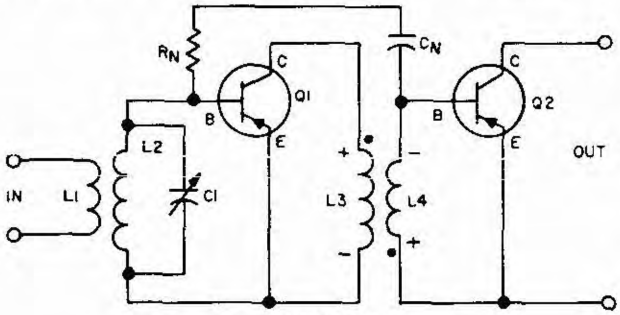
In addition to the loss of gain at the higher frequencies, the action of the transistor becomes complex; the transistor does not operate exactly the same at high frequencies as it does at lower frequencies. The internal resistance changes, and the effects of the junction capacitances become more pronounced. In high-frequency-amplifier applications, the collector-to-base capacitance causes positive feedback that may result in oscillation. The average value of collector-to-base capacitance for high-frequency transistors is on the order of 2 picofarads, as compared with 50 picofarads or more for transistors used at the lower (audio) frequencies. The base spreading resistance (resistance of bulk material of base) of the transistor increases at high frequencies, and the shunting effects of the low-resistance path produced by forward conduction of the base emitter junction tend to lower the input resistance, while the forward bias acts to reduce the width of the depletion areas and thus increase the base-to-emitter capacitance. At the same time, the internal flow of emitter current through the base-collector junction also reduces the width of the PN junction and increases the capacitance between the base and collector. It is this capacitance which causes feedback and tendency toward oscillation as the operating frequency is increased. At high frequencies the collector-to-emitter capacitance may be as high as 100 times that of the base-collector junction capacitance. For this reason, the common-base circuit generally gives better high-frequency response than the common-emitter circuit, but lacks the high gain of the common-emitter circuit. Since the common-emitter circuit tends to be more stable at the higher frequencies than either the common-base circuit or the common-collector circuit, the design trend is to use transistors with a high alpha cutoff frequency, and the CE configuration for highe gain. Both CB and CE circuits will be discussed later in this section.

Unilateralization and Neutralization. In electron-tube r-f amplifiers used at the higher radio frequencies, interelectrode capacitance causes positive feedback and oscillation. Neutralizing circuits are usually provided to prevent oscillation and to insure maximum gain with stability. Likewise, in the transistor r-f amplifier, the effect of the base-collector capacitance and the development of negative resistance through a change in internal parameters also causes oscillation. Neutralization circuits are used to prevent this oscillation and to obtain maximum gain. Neutralization represents a special form of unilateralization at a single frequency. When we speak of **unilateralization**, we are talking about the the methods of making the transistor a one-way device. In other words, the input circuit is unaffected by the output circuit. Recall from basic theory that there is a reverse current effect and common impedance coupling within the transistor. This means that any change of current in the output circuit also develops a feedback current which affects the input circuit, and vice versa. Thus in tuned amplifiers a change of tuning in the output stage reflects back as a change of capacitance in the input circuit, and also as a change in the amount of output fed back into the input. In cascaded tuned stages such effects would cause alignment problems. As each stage was adjusted the preceding stages would have to be readjusted, since each adjustment would change the previous adjustment. The result would be that no two alignments would be alike and, likewise, neither would the performance and selectivity of the r-f amplifiers stages be comparable. Unilateralization deals with the method or circuitry whereby both the resistive and reactive portions of the circuit are cancelled so that there is no feedback from output to input, and, power flows unilaterally in only one direction, from input to output. Unilateralization of the circuit is not frequency-responsive; it is effective for all frequencies. On the other hand, neutralization is effective for only a single frequency or a relatively small range of frequencies. For example, it is only necessary to neutralize an i-f stage because it operates at a fixed center frequency. However, an r-f amplifier used in a multi-band receiver requires unilateralization to prevent the possibility of feedback or oscillation on any of the frequency ranges over which it operates.

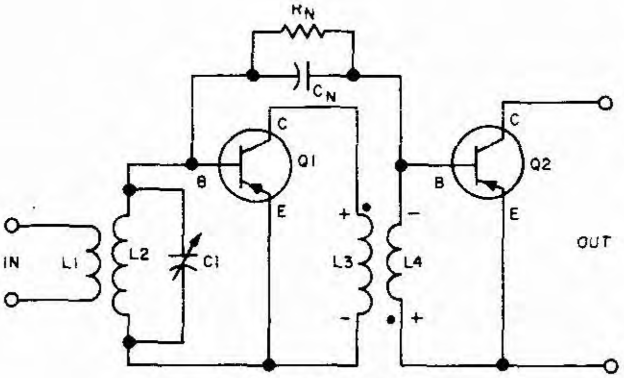
A typical example showing the feedback elements and unilateralization elements involved in a common-base amplifier is illustrated schematically in the accompanying figure. The elements r'_b, r_c, and C_{cb} in the illustration are the internal parameters which cause feedback and oscillation at radio frequencies. Resistor r'_b is the **base spreading resistance,** r_c is the resistance of the collector-base junction, and C_{cb} is the capacitance of the collector-base junction. The resistance of the collector-base junction is very high because of the reverse bias placed on the collector. At very high frequencies C_{cb} effectively shunts r_c. Assume that an input signal adds to the forward bias on the base (the base and collector bias supplies are not shown on the schematic for simplicity) and causes the emitter to be more positive than the base. Collector current i_c increases in the direction shown by the arrow. A portion of the increase in collector current is fed through C_{cb} and r'_b in the direction shown by the arrow, and produces a voltage with the indicated polarity. This internal feedback voltage developed across r'_b is of the same polarity and adds to the input voltage, causing a further increase in i_c; this action is regenerative and represents positive feedback, which will produce oscillation. The external circuit elements inserted to neutralize this action are R_{N_1}, R_{N_2}, and C_N; they correspond respectively, to r'_b r_c, and C_{cb}. Since at high frequencies C_N shunts R_{N_2}, this resistance is necessary only at the lower radio frequencies. It is clearly seen that when the input signal causes a feedback voltage across r'_b, a portion of increased collector current i_c is also fed back through C_N and R_{N_1} to the base. The direction of this external feedback voltage is as indicated on the schematic, and is direct opposition to the voltage developed across r'_b. When the internal and external feedback voltages are made equal, since they are of opposite polarity, they cancel and no positive or negative feedback occurs; thus, the circuit is unilateralized. In the common-emitter circuit, since the polarity of the collector is opposite that of the input, it is necessary to develop an out-of-phase voltage and feed it back to the input. This is done through the use of a transformer, using the secondary winding to invert the feedback voltage, through a tapped tank circuit, or by use of a bridge circuit, as will be shown in some of the following circuit explanations. In some instances an inductance connected in series with a blocking capacitor is used between the collector and the base, with the inductor and the distributed capacitance in the collection circuit operating as a tuned, parallel-resonant circuit. However, inductive arrangements tend to be critical in adjustment since they are resonant only over a small range of frequencies near the center resonance point, and thus are not as frequently used. Partial emitter degeneration is sometimes employed in a similar manner to provide the feedback voltage. The accompanying figure shows some typical feedback circuits used for neutralizing the common-emitter configuration. The parts identifications are identical with those used in the common-base circuit explained above, and operate in exactly the same manner; therefore, no further explanation is included to supplement the figure.



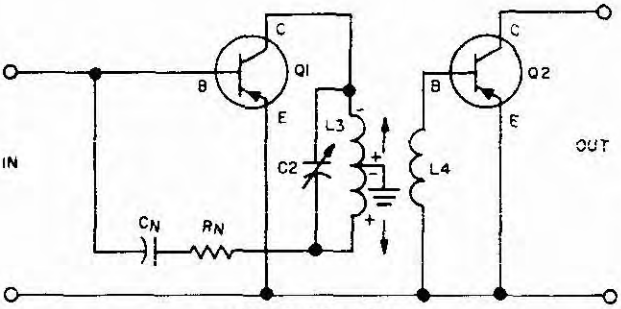
Feedback and Unilateralization Elements



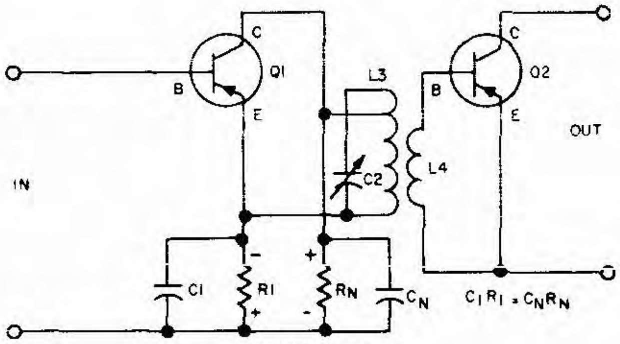
SERIES R-C



PARALELL R-C



TAPPED TANK COIL

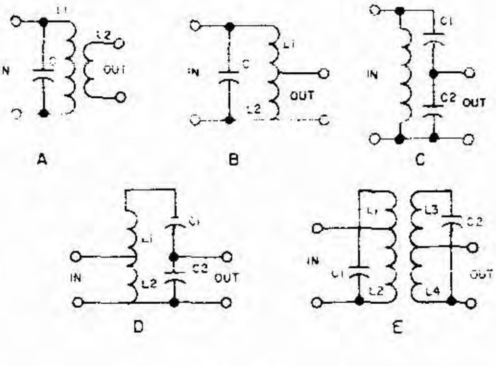


BRIDGE CIRCUIT

Typical Common-Emitter Neutralizing Circuits

Selectivity and Impedance Matching. Since the narrow-band amplifier operates to amplify a band of frequencies around the center (carrier) frequency, tuned circuits are always used to obtain the desired selectivity. R-F amplifiers and i-f amplifiers are almost identical. Both are actually r-f amplifiers, but the i-f amplifier operates at a fixed (intermediate) frequency, which is usually lower than the frequency of the r-f amplifier. The r-f amplifier normally consists of only one (or at the very most two) stages, whereas the i-f amplifier uses a number of cascaded stages to obtain high gain with the desired selectivity at the fixed i-f frequency. While the r-f amplifier is tunable over the entire range of reception, the i-f amplifier is fixed-tuned over only a small frequency range about the intermediate frequency. The selectivity is determined by the Q of the tuned circuit; the higher the unloaded Q, the greater the selectivity. When loaded the Q will drop; thus, the design is based upon the unloaded Q, since the loading is usually determined by the circuit configuration and bias. The pass band of the tuned circuit is considered to be that range of frequencies covered between the half-power points on the selectivity curve (these occur at 70.7 percent of peak amplitude). Thus, a response down 3 db at 5 kc on either side of the center (carrier or i-f) frequency covers a range of 10 kc in band-width.

Although matching input and impedances will provide maximum transistor power gain, this is not always possible. It is sometimes necessary to sacrifice gain to obtain the desired selectivity. In some instances by mismatching stages with individual high gain it becomes unnecessary to unilateralize or neutralize the stages. It is also difficult to obtain a high-Q circuit if the input or output resistance of the transistor which shunts it is low. Therefore, a variety of circuit devices are used to obtain the desired matching impedance while maintaining a high Q for optimum selectivity. Hence we find the simple single-tuned, parallel-resonant tank, so popular with electron tubes, replaced by a tapped tank, or tuned by a capacitance divider for impedance transforming purposes. The following figure shows typical forms of coupling circuits used between cascaded stages of r-f or i-f amplifiers.



Impedance Transforming Circuits

In circuit A, the conventional single-tuned, transformer-coupled circuit is shown; the impedance relationships vary as the square of the turns ratio. In circuit B, a tapped autotransformer is used; L1 plus L2 are the primary, while L2 is the secondary producing a step-down impedance ratio. In circuit C, a capacitance divider is used to reduce the impedance between the input and the output. In circuit D, both the input and output impedances are different, and L1 helps to improve the over-all Q of the tank circuit. In E, a double-tapped transformer is used to supply high-Q primary and secondary tanks with the proper impedance matching for the input and the output. Since the Q of the circuit depends on the ratio of reactance to resistance in a coil, the lower the resistance and the higher the inductance, the larger the Q. Therefore, to match the low values of input and output resistance in the common-emitter circuit, the large inductance is tapped at an appropriate point along the inductance. The square of the turns ratio between the lower and upper halves of the inductance determines the impedance at the tap. For example, in circuit B of the preceding figure, assume that the collector output impedance is on the order of 10,000 ohms and that the tap is located 1/5 of the distance between L1 and L2; since L1 will have 5 times as many turns as L2, a 25-to-1 impedance reduction results (impedance varies as square of turns ratio). The output impedance across L2 then would be roughly 400 ohms, and suitable for matching the input to a common-emitter stage. Naturally, the exact calculation is not as simple as in the example, since the loading effects of circuit capacitance and shunt internal impedance must be considered; however, the example serves to illustrate the basic principle involved. In practice, the exact location of the tap is made experimentally, using the design equations as a guide.

At the higher frequencies, with a smaller number of secondary turns, unity coupling in r-f or i-f transformers becomes difficult to achieve; thus, capacitive coupling is generally used. Where extreme selectivity is desired, the transformers are usually double-tuned (both primary and secondary are tuned). This produces a sharper response, since two tuned circuits are used instead of one, and a flatter over-all response also results. Cascaded stages are often stagger tuned to provide a wider band pass; this is universally done in television i-f amplifiers.

The receiving r-f amplifier uses Class A bias to avoid distortion, while the transmitting r-f amplifier operates Class B or C for efficient power generation. At the present time, the following circuit discussions are limited to receiving types of r-f or i-f amplifiers.

TUNED INTERSTAGE (I-F) AMPLIFIER.

APPLICATION.

The tuned interstage i-f amplifier is used in superheterodyne receivers to produce high gain and the desired selectivity.

CHARACTERISTICS.

Operates at a fixed frequency and is tunable over a small range for alignment and adjustment of band pass.

Uses either single- or double-tuned coupling (i-f) transformers.

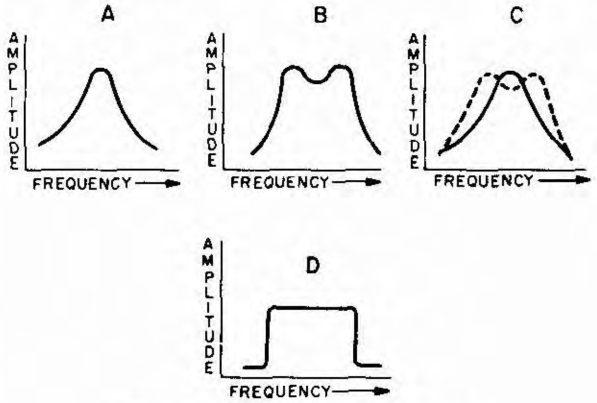
Uses Class A bias to minimize distortion.

Common-emitter configuration normally used, although common-base circuits may be encountered in some applications.

Usually includes a neutralization circuit to prevent internal feedback from causing self-oscillation.

CIRCUIT ANALYSIS.

General. The i-f amplifier in a superheterodyne receiver determines the selectivity and gain. By using a number of cascaded tuned stages operating at a relatively low radio frequency as compared with the fundamental received frequency, higher gain per stage is obtained than would be possible at the signal frequency. By using a number of tuned circuits, the selectivity is increased over that of a single tuned circuit. The accompanying figure illustrates the manner in which the selectivity and band pass are affected by a number of tuned circuits.

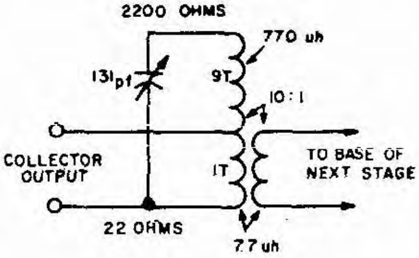


Effect of Tuned Circuits on Pass Band

In part A of the figure, the selectivity curve produced by a single tuned circuit is shown. In part B, the double-humped curve produced by a stagger-tuning two i-f stages is shown (overcoupled circuits also produce a similar response). In part C, the individual response curve are superimposed on each other. In part D, the idealized response is shown. These coupling circuit techniques are similar to those used in electron tube circuits. Since the tuned circuits in the i-f amplifier form a coupling network matching the output of one stage to the input of the next stage, it is necessary to hold losses in the network to a low value. It is also necessary to match the output and input impedance to obtain maximum gain. At the same time, the unloaded Q of the coupled circuits must be kept as high as possible to retain a good selectivity characteristic. Because of the relatively low input and output impedance of the transistor and the large capacitance between emitter, base, and collector, design problems are created which do not occur in the electron tube circuit. For example, the power transfer efficiency between the primary and secondary of a tuned transformer is maximum when **both** the unloaded Q and the band pass are large. Thus, a high power transfer and a narrow band pass pose conflicting requirements. Since the bandpass requirement is determined by the amount of selectivity desired, if the input and output impedance are matched, the power transfer can be improved only by raising the unloaded Q.

The common-emitter circuit has a low input resistance together with a high input capacitance, and the output impedance is moderately high with a large shunt capacitance. Therefore, in interstage coupling transformers an impedance step-down (which varies as the square of the turns ratio) is required to match the high output impedance to the low input impedance of the next stage. In addition, the total circuit capacitance must be considered when determining the inductance needed to resonate at the intermediate frequency. Thus, the reflected input (secondary) capacitance (which varies inversely as the square of the turns ratio), plus the primary shunt collector and wiring capacitance, together with the actual primary tuning capacitor, form the total tank tuning capacitance. When calculated for a given set of design considerations, the inductance is often very small and, at an i-f of 455 kc, requires a very large tuning capacitance to obtain resonance. While the large tuning capacitance has the beneficial effect of swamping out the comparitively small transistor capacitances, it is difficult to build a small inductance with a high Q. Therefore, it becomes necessary to increase the small value of primary inductance to a larger and more practical coil value. By increasing the inductance, (for example 100 times), the tuning capacitance can be reduced to only one one-hundredth of its former value and still resonate at the same intermediate frequency. Although a high-Q circuit, the primary tank now has an impedance of 100 times the original value. To retain the original impedance to match the transistor, the tank is tapped to produce a 10-to-1 turns ratio (the inductance functions as an autotransformer), and the transistor is connected across the lower-impedance portion of the primary winding.

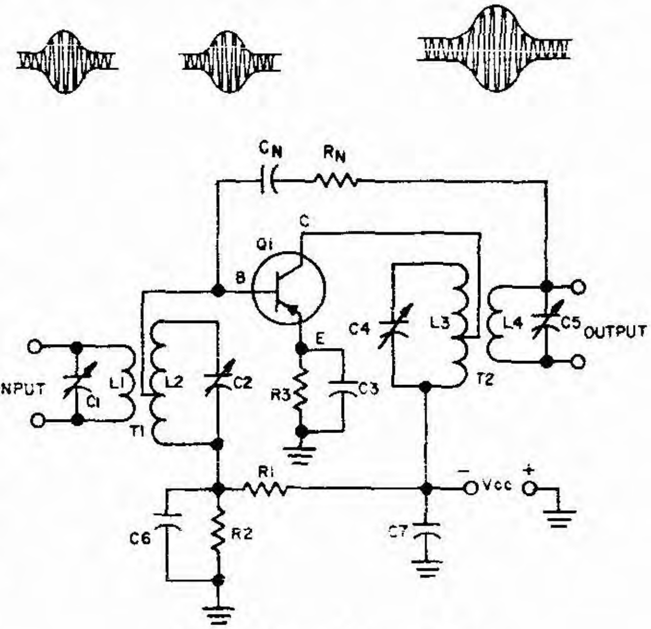
With the primary tank matched for proper power transfer the turns ratio between the entire primary and secondary is selected to produce the proper step-down ratio. Thus, all impedances involved are matched for efficient power transfer. If necessary, the i-f secondary may also be tapped in a similar manner to obtain a high-Q input tank. The following figure illustrates the manner in which the desired selectivity and impedance matching are obtained in a simple single-tuned i-f transformer designed for a 455-kc i-f.



Typical Matching Circuit

Circuit Operation. The schematic of a typical interstage i-f amplifier with neutralization, employing the common-emitter configuration, is shown in the accompanying illustration.

The input signal is coupled to the base of Q1 through T1. I-F transformer T1 is double-tuned, with L1, C1 forming the primary tank and L2,C2 forming the secondary tank. The low, base-input impedance is matched for maximum transfer of power by tapping it down on inductance L2, thereby retaining the high Q necessary for good selectivity. Trimmer capacitors C1 and C2 tune the i-f transformer over a small range about the center frequency, permitting exact alignment at the intermediate frequency. Class A bias is supplied to the base of Q1 through voltage divider R1 and R2. R2 is bypassed for rf by C6. R3 and C3 are the conventional emitter swamping resistor and bypass capacitor. (See section 3, paragraph 3.4.1 for a discussion of biasing methods, and paragraph 3.4.2 for a discussion of stabili-



Typical Common-Emitter i-f Stage

zation methods.) Output transformer T2 couples the collector of Q1 to the base of the following stage. The primary of T2 consists of L3 tuned by C4, and the secondary consists of L4 tuned by C5. L3 is tapped to match the collector output, provide maximum power output, and yet retain the high Q necessary for selectivity. Capacitor C7 is used to bypass the collector supply. Neutralization is provided by RC network CN, RN, connected from the secondary of T2 to the base of Q1. The feedback is taken from the transformer secondary to provide a 180-degree phase shift or polarity inversion, to cancel the internal feedback developed within the transistor.

In the absence of an input signal, the fixed bias determined by the ratio between R1 and R2 causes Q1 to draw its quiescent value of collector current. Q1 operates at the center of its characteristic transfer curve to permit equal positive and negative swings. Since the quiescent current is steady, no output is developed. Assume an input signal within the intermediate frequency band pass is applied to the T1 primary. Primary tank C1, L1 appears as a high impedance to those frequencies within the band pass, and, since it is a resonant load for the preceding stage, it develops a large voltage across L1. This primary voltage, in turn, induces a voltage in the L2 secondary. The secondary is tuned by C2, and is resonant at the same intermediate frequencies. Therefore, a large voltage is developed for those frequencies which are within the band pass, and a portion of this voltage developed between the tap and ground (since C6 provides an r-f shunt around R2, and places the rotor of C2 and the lower end of L2 at ground potential) is applied to the base of Q1. These i-f frequencies are essentially sinusoidal; they consist of the fundamental (or carrier) and modulation which appears as sidebands above and below the center frequency. Assume that a half-cycle of this frequency is negative and adds to the normal forward bias applied to Q1. For the duration of this negative-going half-cycle, the emitter and collector current of Q1 increases sinusoidally, in synchronism with the amplitude of the applied signal.

Since the collector is tapped to L3 any current flow through the tap to the ground end of the coil also induces a voltage in the top portion by autotransformer action. Cacapacitor C4 tunes L3 to the intermediate frequency, and the tank appears as a high impedance to those frequencies within the i-f pass band. Thus, a large voltage is developed across the primary of T2 and induces, by transformer action, a voltage in the tuned secondary circuit. The tapped portion of L3 also provides an impedance transformation. With the lower end of L3 supplying an impedance equal to the collector impedance, maximum power transfer occurs through the transistor. The upper portion of L3 (above the tap) provides a higher impedance, which allows a sufficiently high Q to be obtained to provide sharp tuning and selectivity despite the loading effect of collector current flow through the bottom of the coil. Thus, only frequencies within a narrow band pass around the carrier (i-f) frequency are amplified strongly, and the frequencies outside the band pass are reduced in amplitude and effectively rejected.

During the remaining (positive) half of the single r-f cycle, the signal opposes the forward bias and causes a reduction in the emitter and collector current. These alternate increases and decreases in current occur at i-f rates, and are equivalent to an a-c current flow; thus, the a-c signal variations induce an output voltage in the secondary of T2. If the current did not vary with the signal, but rather remained steady, no transformer action could occur.

While the d-c emitter current flows through R3, the i-f variations are bypassed by capacitor C3 so they have no effect on emitter resistor R3. Thus only small current changes (induced by temperature changes), consisting of slow, d-c variations of emitter current, affect R3. Since electron flow is from emitter to ground, the current changes produce an oppositely polarized voltage which substracts from the normal forward bias and returns the emitter current to its previous value. This is conventional emitter-swamping action.

The output impedance of the collector is reduced by the step-down turns ratio between the primary and secondary to a value suitable for matching the input impedance of the next i-f stage. Tank circuit L4 and C5 is also tuned to the intermediate frequency and selects only the desired signals for application to the next stage. The use of a number of tank circuits provides a relatively flat but sharp selectivity curve, as explained previously in the introduction to this circuit.

When the intermediate frequency is high enough to cause some of the collector output to be coupled back to the base through the collector-to-base capacitance and develop a feedback voltage through the internal base spreading resistance, oscillation occurs in the i-f stage. Therefore, CN and RN are used to feed back a voltage from the secondary of T2, whose phase is opposite that of the collector output, to the base of Q1. With an equal voltage of opposite polarity, the internal feedback voltage is cancelled and oscillation cannot occur. In some circuits RN is not used; CN is sufficient. In some circuit designs, mismatching of the stages is used to avoid feedback and oscillation, with some loss of gain. Usually, only as many stages as are necessary are used to provide satisfactory selectivity, since the more the stages the greater the feedback possibility. Likewise, double-tuned circuits are not used where single-tuned transformers are satisfactory.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of most volt-ohm-milliammeter testers. Be careful, also, to observe proper polarity when checking continuity or making resistance measurements with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

No Output. Lack of an input signal, improper bias, lack of supply voltage, or a defective transistor can cause loss of output. Check the bias and supply voltages with a voltmeter. If R1 is open, the base bias will be zero, which corresponds to Class B operation, and there is a possibility that strong signals may produce a partial output. However, if R2 is open or if the secondary of T1 (L2) is open, the base circuit of Q1 is also open and no output can occur. Should the primary of T1 (L1) be open, there will be no collector voltage applied to the preceding stage, and no transfer of signal to Q1. Since the i-f stage operates at radio frequencies, use an r-f probe in conjunction with a vtvm, or an oscilloscope, to determine whether a signal appears on L1. If R3 is open, the emitter circuit will be incomplete and no output will be obtained. Use an ohmmeter to determine the continuity and resistance of R3. If a voltage exists at the base of Q1 but not at the collector, either T2 is defective or C7 is shorted. A d-c voltage reading between the collector and ground with no output indicates that either Q1 is defective or T2 is short-circuited. Check T2 for shorts with an ohmmeter and then replace Q1 with a transistor known to be good. If neutralizing capacitor CN is shorted, the base of the following stage will be directly connected to the base of Q1 and will shunt transistor Q1. There will be a loss of amplification, but not necessarily a complete loss of output. However, if the capacitor is open, oscillation will occur and may cause blocking due to a change of bias (the transistor will rectify the oscillation and produce a d-c bias). Or, if the oscillation is not strong enough, a partial output may be obtained (with or without distortion). Check the capacitor with a capacitance checker; also check the value of resistor RN with an ohmmeter.

Low Output. A number of conditions can cause reduced output. For example, low collector voltage, low bias voltage, loss of transistor gain, an open or high-resistance tuned circuit in the i-f transformers, and short-circuited or changed values of other parts. Check the bias and collector voltages with a voltmeter. Use an oscilloscope and r-f probe and test from point to point throughout the circuit, to determine where the signal drops in amplitude. The signal at the collector of Q1 should be larger in amplitude than the signal at the base of Q1. If the signal appears at the input to T1 and is greatly reduced at the base of Q1, either T1 or Q1 is defective. If C3 is open-circuited, the emitter current flowing through R3 will produce degeneration and oppose the bias. The output will be reduced in proportion to the amount of degeneration. With a collector output equal to or less than the output at the base of Q1, either T2 or Q1 is defective. Where plug-in transistors are provided, it is usually easier to substitute a transistor known to be good than to substitute an i-f transformer.

Insufficient Selectivity. Lack of selectivity can occur because of poor alignment of tuned circuits, which is usually indicated by loss of gain, together with broad tuning. In most cases, however, special tests are necessary to determine whether realignment is needed, and special procedures and equipment are required for proper alignment. Therefore, readjustment of the i-f trimmers should be attemped only when it is acertained that the circuit is otherwise operating normally. Where i-f transformer (s) are replaced, it is necessary to make proper adjustments to restore the initial selectivity. A rough approximation of performance may be obtained by observing the detected output on an oscilloscope and tuning an r-f signal generator through the i-f pass band. The amplitude of the signal observed on the oscilloscope will be nearly uniform for a flat-topped response curve. The 70-percent response points below and above the i-f center frequency will indicate approximately the low-and high-frequency limits of the pass band. Where lack of selectivity is suspected, the necessary check can be made by determining the equipment specifications, following the manufacturer's recommended alignment procedure, and comparing results, noting the effect of each adjustment of the response curve.

TUNED COMMON-BASE R-F AMPLIFIER.

APPLICATION.

The tuned common-base r-f amplifier is used in receiver input stages to provide low noise, and good selectivity rather than high r-f gain, and to eliminate images and spurious signals in superheterodyne receivers.

CHARACTERISTICS.

Uses common-base configuration.

Uses fixed bias (except when automatic gain control is employed), although self-base applications may be encountered.

Uses a single-tuned tank circuit to provide selectivity.

Transistor gain is less than unity, but tuned resonant circuits provide some gain.

Does not require thermal compensation.

Because of lower output capacitance, is operable at higher frequencies than any other circuit configuration.

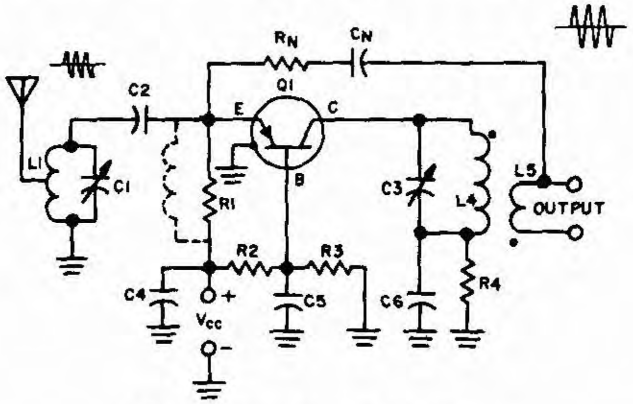
Usually requires neutralization or unilateralization to prevent oscillation.

CIRCUIT ANALYSIS.

General. Because of its lack of gain, the tuned common-base r-f amplifier is generally used as an isolation stage between the antenna and mixer stage, particularly in medium-frequency (broadcast) receivers. While the tuned circuits offer some increase in signal gain, the transistor gain is always less than one. Since images and spurious signals are not discriminated against in receivers having their inputs coupled to the mixer stage, the selectivity and noise reduction effects of the tuned r-f amplifier provide better performance.

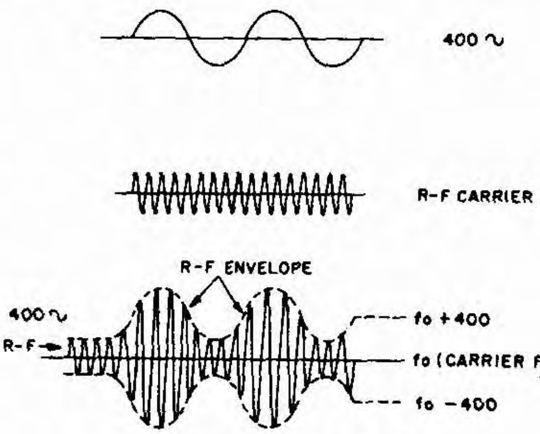
Because of the low base-collector capacitance in r-f transistors, the common-base circuit is usually used for very high frequencies (the shunt output capacitance is much lower, and better performance can be expected). With the base grounded, a low base circuit resistance exists, and thermal compensation is usually omitted. The common-base circuit is also considered to be inherently unstable over the entire range of operation, so that neutralization or unilateralization networks are used to prevent oscillation.

Circuit Operation. The accompanying schematic illustrates a typical common-base r-f amplifier using fixed base bias. For simplicity of circuit discussion, it is assumed that no automatic-gain-control (A-G-C) voltage is applied. (See Part B of Section 21 in this handbook for a discussion of A-G-C circuits.) The tuned input circuit consists of parallel-resonant tank L1, C1, with the antenna tapped at the lower end for proper input matching and maximum power transfer. The circuit is arranged for negative ground, which allows both tuned circuit tanks to be grounded in order to avoid body capacitance effects. The input tank is coupled to the base by capacitor C2 thus avoiding shunting of the emitter to ground through the low value of d-c coil resistance. The emitter d-c return is completed by R1. This is essentially shunt feed bias. While R1 could be replaced with an r-f choke (shown in dotted lines in the figure), it is made resistive to avoid "dead spots" caused by any spurious resonances formed by the stray and element capacitance with the RFC, since the stage usually must be tunable over a wide range of frequencies. Fixed voltage divider bias is provided by R2 and R3. (See Section 3, paragraph 3.3.1 for a discussion of base bias.) C5 places the the base at r-f ground and removes the d-c bias circuits from the radio-frequency path, so that the initial bias is unaffected by signal variations. Output tank C3, L4 is tuned to obtain maximum selectivity, and the collector output is matched to the base of the next stage through r-f transformer secondary L5. The tuned circuit is placed in the primary rather than the secondary, since tuning the secondary would tend to shift the phase relationships between the primary and secondary. Thus, feedback loop CN, RN, provided for neutralization and cancellation of internally developed feedback, remains unaffected by circuit tuning. Transistor Q1 is a high-frequency type of transistor; the case is grounded to provide further shielding and isolation between the input and output circuits. Capacitor C4 bypasses any r-f around the supply, and prevents it from entering the bias circuit.



Typical Common-Base R-F Amplifier

The functioning of the r-f amplifier is basically the same as that of an RC-coupled audio amplifier, with tuned tank circuits L1, C1 and L4, C3 acting in place of the base and collector resistors, respectively. The difference is that the operation occurs at radio-frequency rates rather than audio-frequency rates. Instead of the amplitude of the auido signal itself causing the emitter and collector currents to vary; it is the amplitude of the r-f envlope at any particular instant which causes these currents to vary. In the case of modulated emissions, the modulation varies the amplitude of the r-f envelope in proportion to the modulation. Thus, the received signal can be considered as an r-f carrier which rises and falls sinusoidally in accordance with the amplitude of the modulation, and is amplified exactly as if it were a single audio frequency, assuming that the input and output circuits are properly tuned and have the required bandwidth. If these conditions are not met, the r-f envelope becomes distorted; that is, a differently shaped signal is formed. The r-f envelope is produced by individual radio-frequency cycles varying above and below the zero carrier level. Each cycle produces equal positive and negative alternations, and causes the transistor bias to be increased and decreased equally. The average value over a half-cycle of modulation determines whether the total effect is that of an increased or a decreased signal. Thus, the tips of the r-f pulses trace out a relatively slowly varying signal, which is the audio (or other) modulation, and occurs at an audio (or other) rate - not an r-f rate. Depending upon the rapidity of rate of change of the audio modulation, a few of the r-f cycles could be lost without significantly affecting the over-all modulation waveshape. The accompanying illustration shows the concept of an r-f envelope and the manner in which it is formed, using a single carrier frequency and a single 400-cycle sinusodial modulation frequency for ease of explanation. Other more complex waveforms also produce a similar result, which can be demonstrated by a mathematic analysis beyond the scope of this Handbook.



Development of an R-F Envelope

With no signal applied, Q1 rests at its quiescent value of emitter and collector current as determined by base bias divider R2, R3, together with emitter resistor R1 and collector resistor R4. Since the quiescent current is steady, no output is produced. When a signal is applied to L1 from the antenna, a large resonant voltage is developed across tank L1, C1, and is applied through C2 to the emitter of Q1. For ease of discussion, the input tank can be considered as an r-f generator connected between emitter and ground, with an output amplitude equal to the r-f envelope of the signal.

Assume that the input signal amplitude is increasing and becoming more positive, and that the instantaneous value of the signal adds to the emitter bias. As the emitter bias increases in a forward direction, the emitter and collector or current increase. Internally in transistor Q1, there is a flow of holes from emitter to collector; externally, the flow consists of electrons from emitter to collector. A small base current flows from base to emitter (through the base junction), through blocking capacitor C2 and tank L1, C1 to ground, and through C5 to the base. The collector current flow is from ground through R4 and tank L4, C3 to the collector, and through the collector-to-base junction and C5 to ground. Note that in the common base circuit the collector current is always less than the emitter current ($I_C = I_E - I_B$). When the collector current increases with a signal, a large voltage drop is produced across the output tank impedance, thus developing a positive output signal (the common-base input and output polarities are identical). Since the L5 secondary is coupled to the L4 primary, current flow through the primary induces an output voltage in the secondary by transformer action. The secondary by transformer action. The secondary output may be either in-phase or out-of-phase, depending upon the connections.

Assume now that the input signal amplitude decreases and goes negative. The emitter forward bias is reduced and less collector current flows. As the input signal goes negative, the collector voltage rises toward the supply value. Since the collector is reverse-biased by the negative supply, a negative output signal is produced. Collector resistor R4 prevents large positive swings from dropping the collector voltage past zero, and causing an overshoot which would drive the collector positive and produce a forward collector bias with consequent high current pulse and distortion, by limiting the total available supply voltage. Thus, a large signal can drop the collector voltage to zero, but the supply voltage will still be less than zero by the drop in R4. (This resistor may not be used in some circuits.) Capacitor C6 bypasses the rf around R4 so that it remains unaffected by signal variations, and in effect grounds tank capacitor C3 to avoid body capacitance effects when the capacitor is tuned.

Neutralizing network C_N, R_N is connected between the secondary of the output transformer and the emitter so that it feeds back an out-of-phase voltage to the emitter and prevents oscillation due to internal feedback within Q1. In r-f amplifiers operating over large frequency ranges, this neutralizing network is usually replaced by a more complicated unilateralization network. Thus, the input circuit remains unaffected by any changes in output, or tuning, over the entire range of operation.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of volt-ohmmeters. Be careful also to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

When checking r-f voltages, always use a vacuum-tube voltmeter (VTVM) or an electronic voltmeter with an r-f probe. The conventional voltmeter only indicates dc. Therefore, it is necessary to first rectify the rf before the voltmeter will indicate properly. This is done automatically in the VTVM, and separately by the r-f probe when the electronic voltmeter is used.

No Output. No input signal, a shorted input or output tank, an open emitter circuit or defective transistor, as well as improper bias, can cause no output. If R1 is open, the emitter circuit will be open, and if R4 is open, the collector circuit will be open; in either case there will be no output. If R2 is open, Q1 will operate at approximately zero bias and no output will occur except for extremely strong signals. Check the d-c voltages on Q1 to determine the bias. With a normal supply voltage, for a PNP transistor (with negative ground), all voltages will read positive with respect to ground. The emitter will always be a few tenths of a volt more positive than the base, and the collector will read the lowest (sometimes zero). For example, if R4 were shorted, L4 would be connected to ground, the collector would be at ground potential, and the meter would indicate zero, even though full collector voltage would still be applied.

The tank coils can be checked for continuity with an ohmmeter to determine whether they are open; they must be disconnected when the tuning capacitors are checked. If coupling capacitor C2 is defective, there will be no output. If C2 is open, the emitter voltage will be normal, but there will be no output. If C2 is shorted, the emitter voltage will be low (depending on the resistance of R1), and no output will be obtained. In this case R1 will get hot and possibly burn out.

If bypass capacitor C4 is shorted, the supply will be shorted, with consequent loss of output; if the capacitor is open, only a reduced output may occur. If capacitor C5 is open, the base will be connected to ground through the bias network, and the r-f signal between emitter and base will be attenuated (depending upon the frequency) and will produce either a very weak or practically no output at all. If L5 is open, no output will be obtained (provided that the capacitive coupling between the primary and secondary is very small. Oscillation caused by a defective neutralizing network, if sufficiently strong, can bias off and block the transistor and thus reduce the output to zero. Check the value of R_N with an ohmmeter, and check C_N with a capacitance checker.

Defective r-f tanks can cause a no-output condition. Defective tanks are most easily located in an operating amplifier by observing whether they tune to a specific frequency, particularly when the tuning dial is calibrated, since any change in component values will change the resonant frequency. If the circuit bias voltages appear to be normal and there is no output, connect a modulated r-f signal generator to the antenna, the emitter, the collector, and the output winding, successively. If the input circuit is defective, the signal will appear when the generator is connected to the emitter. If the transistor is defective, the signal will appear after the generator is connected to the collector. With a defective collector tank, the signal will appear when the generator is connected to the output winding. If the signal does not appear, the output coil is open.

It is important to keep in mind that any slight capacitive coupling at radio frequencies will pass a weak signal, so that a weak output is possible under circumstances which at audio frequencies would be impossible. Thus, where more than one r-f stage is used, it is possible to have a "dead" input stage and yet, through stray capacitive coupling, obtain sufficient signal "leak-through" into the following amplifier to produce a weak output.

Low Output. Low output can be caused by improper bias or supply voltage, a defective transistor, high series resistance or impedance, or a low shunting impedance or resistance. The bias and supply voltage can be checked with a voltmeter. If the value of R1 increases, the emitter bias will be increased, and if the value of R4 increases, the collector voltage range will be reduced; both cases will cause reduced output, and can be checked by use of an ohmmeter. If C5 opens, the base return to ground will be through R3, which places it in series with the input signal; thus the input signal will be reduced, as well as the output signal. High resistances produced by poorly soldered connections can also cause reduced output. Applying a hot iron to the defective joint will usually restore operation to normal. If R1 deteriorates to a very low value, the input signal will be partially shunted to ground and the output will be reduced. Where the transistor seems to be defective (less signal appears on the collector side than on the emitter side), replace it with one known to be good. No current gain is obtained through the transistor in the common-base circuit, since the collector current is always less than the emitter current by the amount of base current. Nevertheless, when low impedance is used in the input and high impedance in the output, a relative voltage gain will be obtained because of the greater voltage drop across the larger impedance.

Distorted Output. Receiver r-f amplifiers are operated Class A to avoid distortion. If the bias is too high the peaks will be clipped, or if the bias is too low a similar effect will be caused by overdriving, and saturation will occur on strong signals; both effects are forms of amplitude distortion. If the selectivity is too sharp, frequencies outside the band pass will be cut off entirely or partially attenuated. Thus, on modulated signals some of the sideband frequencies will be lost, and frequency distortion will occur because of the loss of some of the audio signals. Normally, deterioration of parts caused by aging, moisture absorption, etc, will produce a reduction in the tuning circuit Q, and thus result in reduced performance and decreased selectivity, but this will not cause distortion. On the other hand, parts value changes can cause regeneration (positive feedback) at certain frequencies or over a range of frequencies. Such feedback increases the sharpness of tuning and can cause distortion due to sideband cutting. The prime cause is failure of the neutralizing or unilateralization network. Such effects can also be caused by a defective transistor. First check the neutralization network for proper component values, and then check the supply and bias bypass capacitors. In multipke-stage receivers, common impedance coupling can occur through deterioration of the power supply bypass capacitor, thus producing unwanted feedback similar to that encountered in electron tube operation. In cases of this kind it is usually necessary to remove the defective capacitor and replace it with a new one in order to cure the trouble. Just placing the new capacitor across the defective one will not always correct the trouble.

Distortion caused by "cross modulation" from strong local signals sometimes exists, and is primarily a fault in design (lack of sufficient selectivity) or the result of too close coupling to the antenna, which produces fundamental overload. Thus, saturation occurs, and the nonlinearity produced causes the unwanted signal to appear on the desired signal as cross modulation. This effect is most noticeable when operating in the immediate vicinity of strong shore or ship stations. It cannot be remedied by normal parts replacement, but rather by external means, such as changing the input and antenna coupling or inserting a loss network at the input.

TUNED COMMON-EMITTER R-F AMPLIFIER.

APPLICATION.

The tuned common-emitter r-f amplifier is universally used in receivers and test equipment to provide high r-f gain and selectivity, and to eliminate images or other spurious responses.

CHARACTERISTICS.

Uses common-emitter configuration.

Uses fixed bias (except when automatic gain control is employed), and some self-bias combinations may be encountered.

Transistor provides high gain (100 or better).

Usually requires thermal compensation.

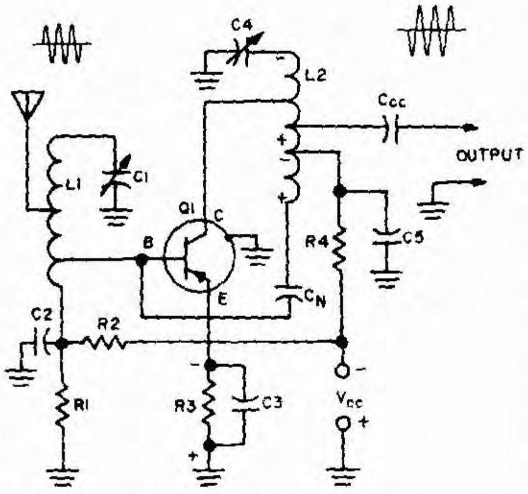
Requires neutralization or unilateralization only at the lower r-f frequencies, since it is inherently stable.

CIRCUIT ANALYSIS.

General. The large collector-to-base capacitance of the transistor tends to shunt the output to ground, when connected in the common-emitter configuration. Therefore, the amplification tends to drop at the higher radio frequencies. On the other hand, a small change in base current causes a very large relative change in collector current. Thus, the small signal input controls a large current which develops the output voltage; this action is similar to electron tube operation using the grounded-cathode configuration. Although the output impedance of the common-emitter circuit is not as high as that of the common-base circuit, the large collector current flow through a moderate output impedance produces a much larger output. Hence, the common-emitter circuit always gives a large gain. Even at the higher radio frequencies where the gain drops off, it may be possible to obtain sufficient gain over that of the common-base circuit to justify use of the common-emitter circuit instead.

The common-emitter circuit also has a higher input impedance than that of the common-base circuit (on the order of a few hundred ohms). Consequently, it is easier to match the input (and the output) circuit for efficient power transfer. As a result, the common-emitter circuit, rather than the common-base circuit, tends to be used universally.

Circuit Operation. The accompanying illustration shows a typical tuned r-f amplifier using the common-emitter configuration. L1 and C1 form the input tuning circuit, with both the antenna and the base tapped onto L1 to provide a proper impedance match. Capacitor C2 bypasses the lower end of L1 to ground for rf, and also bypasses bias resistor R1. Fixed base bias is provided by voltage divider R1, R2. (See Section 3, paragraph 3.4.1 for discussion of bias, and paragraph 3.4.2 for a discussion of stabilization.) Thermal stabilization is provided by emitter swamping resistor R3 bypassed by C3. The output tank consists of C4 and L2, with the supply voltage fed at approximately the center of the coil. Thus, an out-of-phase voltage is obtained and fed through C_N for neutralizing the transistor. L2 is also tapped at appropriate points to match the collector and the output circuit. The output is capacitively coupled through C_{cc}. Capacitor C5 functions to bypass rf around collector resistor R4 and the supply, and also to maintain the center of the coil at ground potential, in order to insure the proper phase relationships between the ends of the tank coil. R4 is a voltage-dropping and isolation resistor in the collector circuit (it is not always necessary to use R4).



Typical Tuned Common-Emitter R-F Stage

Operation of the tuned common-emitter r-f amplifier is very similar to the previously discussed R-C coupled audio amplifier using the common-emitter circuit, with the tuned tank circuits replaced by resistors. The basic difference is that the audio amplifier operates at low frequencies with relatively slowly varying signals, whereas the r-f amplifier operates at much higher frequencies and follows the relatively slowly varying envelope amplitude when modulated. When not modulated, continuous-wave signals within the band pass of the tuned circuits are amplified equally on the positive and negative half-cycles, and vary in amplitude with the average amplitude of the input signal. Thus, as the signal fades in the output signal is larger, and as it fades out the output signal is smaller. The action, meanwhile, occurs at the r-f rate; for example, a continuous r-f signal of 30 megacycles requires a time of only one thirty-millionth of a second to complete one cycle of operation.

At the start of the cycle of operation the transistor is resting in a quiescent condition, with the collector current determined by the d-c base bias, which is fixed for a specific supply voltage by voltage divider resistors R1 and R2. It is usual practice to bias the base negative with respect to the emitter (forward bias). The difference in potential is normally only a few tenths of a volt, and is set at the center of the forward transfer characteristic curve for Class A operation. Since the received signal is normally on the order of microvolts, the low bias value is adequate to prevent overloading (except in the case of strong local signals). Either automatic or manual gain control is usually provided in practical r-f stages to accommodate large signals; this is not shown in the schematic, to avoid circuit complication and for ease of discussion. (See Section 21, Part B, Control Circuits, of this Handbook for the functioning and operation of semiconductor automatic gain control circuits.)

Assume that an r-f signal within the band pass of the tuned input (tank) circuit, consisting of L1 and C1, appears at the antenna. With the antenna tapped onto L1 at the proper number of turns to match its impedance, the low-impedance antenna resistance is transformed by autotransformer action to match the large parallel resonant impedance of the tank. Thus, maximum signal transfer from the antenna to the coil is obtained. In turn, the base is also tapped onto L1 for a proper impedance match, to change the low input resistance offered by the common-emitter circuit to a value that more closely matches the high impedance of the tuned input circuit. With bypass capacitors C2 and C3 effectively grounding the bottom of L1 and the emitter, respectively, as far as rf is concerned, the tuned input circuit is connected between the base and the emitter. Thus, the r-f signal does not flow through the bias voltage divider or the emitter swamping resistor (R3).

Assume, for the moment, that the input signal is swinging negative and adds to the forward base bias, thus producing an increase in collector current, (which is a flow of electrons from the supply through L2 to the collector). Application of the instantaneous negative signal voltage to the base of Q1 causes a flow of holes from emitter to base. This is the same as a flow of electrons from base to emitter, and a circulating base current flow occurs from the emitter through C3 to ground, and through C2 and the lower portion of L1 back to the base. On the positive half of the input signal the forward bias is reduced, and the collector current, likewise, is reduced. Electron flow and base current flow are through the same path as given previously for the negative half-cycle, but is diminished in value. With equal positive and negative swings, an average value of base current flow occurs, and varies in accordance with the signal amplitude. The collector current follows, but it is larger in amplitude since it is approximately equal to beta times the input signal.

Since the input tank circuit is tuned to the frequency of the incoming signal, only r-f signals within the band pass of the tuned circuit appear at the base and affect the collector current. The amount of selectivity of the tuned circuit depends upon the unloaded Q of the tank. When this Q is high, the tuned circuit is highly selective, and only a narrow band of frequencies is accepted by the tuned circuit. Thus, the base current is controlled by the tuning of the tank circuit. When the tank circuit is resonant to the signal, a base current is injected into the transistor; when it is nonresonant, only the d-c (bias) value of base current flow exists.

In the collector circuit, the load impedance across which the output is developed consists of tuned tank circuit L2, C4. Coil L2 is bypassed to ground for rf at the supply voltage tap by C5. Thus, the rotor of tuning capacitor C4 can be grounded to avoid body capacitance effects when tuning. The portion of L2 between the supply and the lower end of L2 forms a neutralizing winding, which furnishes 180-degree phase shift and supplies an out-of-phase voltage back to the base through C_N. Thus, the effect of the tuned input and output circuits being coupled through the transistor collector-to-base capacitance and the internal base spreading resistance of Q1, which causes positive feedback and oscillation, are cancelled out. This type of neutralizing circuit is similar to the Hazeltine neutrodyne method used with electron tube operation. Since the output impedance is the low input resistance of a following common-emitter stage; the coupling capacitor is tapped at some intermediate value of turns ratio between the supply and collector taps. Thus, a step-down ratio is provided to match the transistor output for maximum power transfer and gain. The collector is also shown tapped down on L2 for proper matching, assuming that the tuned tank impedance is higher than the collector impedance. This is usually true at low r-f ranges; however, at high radio frequencies, such as in the UHF region, the tank and collector impedances may be of the same order, in which case the collector may be connected to the top of L2. (In some circuit versions a deliberate mismatch may be arranged and the neutralizing arrangement dispensed with.)

Regardless of the impedance-matching or neutralizing methods used, however, the output signal is developed across the impedance provided by the parallel tuned tank circuit. At resonance the impedance is high, and off resonance it is a lower value. Thus, for frequencies within the band pass of the tuned circuit, the impedance is high, and a large voltage drop occurs across this impedance. With a negative-going input signal the collector current flow causes a drop across the psrallel-tuned tank which reduces the collector voltage toward zero. Since the collector is reverse-biased, the output is positive-going. When the input signal swings positive, the forward bias is reduced, which reduces the collector current also. Less voltage drop occurs across the output tank, and the collector voltage increases in a negative direction, thus producing a negative output signal (common-emitter output and input polarities are always opposite). These positive and negative signal excursions occur at an r-f rate. For a constant-amplitude input, a constant, amplified output signal is developed. If the signal is modulated, the output amplitude follows the waveform envelope, and the output amplitude varies in accordance with the modulation. With signal swings less than the applied base bias, no distortion is produced. If the input signal is greater than the bias, or if the collector voltage is dropped to zero before the peak occurs, then clipping and distortion effects are produced. Resistor R4 is used to drop the collector voltage to the proper value and to act as a decoupling resistor. It also prevents the collector voltage from being driven positive by strong signals, which would forward-bias the collector and cause heavy current flow with distortion. The transistor case is grounded to provide better shielding and prevent r-f feedback.

Normally, swamping resistor R3 is affected only by slow d-c variations of emitter current caused by ambient temperature changes. The increased emitter current flow with temperature produces a voltage across R3 which opposes the bias voltage and reduces the emitter current back to its original value. Any r-f signal is bypassed across R3 by C3. This is conventional emitter swamping action.

The output is shown capacitively coupled since it is usually more economical than providing a secondary winding to couple out of L2, plus the fact that at high frequencies it is sometimes difficult to obtain optimum coupling between windings because of high-frequency effects. Any of the tapped tanks shown in the schematic can be replaced by tuned transformers without any change in operation, if they have sufficient coupling, if they tune to the same frequencies, and if they tune over the same range. Circuit cost and designer's preference usually determine which are used.

FAILURE ANALYSIS.

General. When making voltage checks, use a vacuum-tube voltmeter to avoid the low values of shunting resistance employed on the low-voltage ranges of volt-ohmmeters. Be careful also to observe proper polarity when checking continuity with the ohmmeter, since a forward bias through any of the transistor junctions will cause a false low-resistance reading.

When checking r-f voltages, always use a vacuum-tube voltmeter (VTVM) or an electronic voltmeter with an r-f probe. The conventional voltmeter indicates only dc. Therefore, it is necessary first to rectify the rf before the voltmeter will indicate properly. This is done automatically in the VTVM, and separately by the r-f probe when the electronic voltmeter is used.

No Output. Open base, emitter, or collector circuits or short-circuited input or output circuits, as well as lack of supply voltage or a defective transistor, can cause no output. If either L1 is open or C1 is shorted, no output will be obtained. If L1 is disconnected from C1, both the continuity of L1 and the shorting of C1 can be checked with an ohmmeter. Lack of supply voltage as well as bias voltage can be determined by use of a voltmeter. Proper base bias indicates that the bias divider and lower part of L1 are connected to the base. Likewise, proper collector voltage indicates that R4 and L2 are satisfactory and that tuning capacitor C4 is not shorted. If C5 is shorted, the full supply voltage will be dropped across R4, and there will be no output. If coupling capacitor Ccc is open, no output will be obtained (although there is a possibility that a strong signal may still feed through as a weak signal by stray capacitive coupling). If emitter resistor R3 is open, there can be no output. If neutralizing capacitor CN is open and the feedback is sufficient, the transistor may be blocked, with consequent loss of output, although it is more likely that a low output with squeal and distortion will be obtained. However, if CN is shorted, the base and collector will be shorted through the neutralization coil and no output will be obtained.

Normally, the collector voltage will be lower than the supply voltage because of the drop across R4. A high collector voltage will indicate improper bias on the base, or lack of collector current due to a defective transistor or an open emitter resistor (R3). If the transistor is in doubt, replace it with one known to be in good operating condition.

Low Output. If the forward bias is too low, if the collector voltage is low, or if the transistor gain has deteriorated, a low output will be obtained. High-resistance soldered connections in the input and output tanks or nonresonance can also cause a reduction of the output. If emitter resistor R3 increases in value or bypass capacitor C3 opens, the output will likewise be reduced by emitter degeneration effects. The bias and collector voltages can be checked with a voltmeter, and R3 can be checked with an ohmmeter. An open bypass capacitor C2, C3, or C5 can cause a reduction of the output through loss of r-f signal in the bias and supply circuits and by emitter degeneration; a bypass capacitor can be quickly checked by temporarily shunting an equivalent capacitor across it. An increase in output when this is done indicates that the original capacitance is insufficient. To determine that the tuned circuits are operating properly, insert a modulated signal from a signal generator into the antenna, and use an oscilloscope with an r-f probe to determine whether the signal appears at the base and the collector. Tuning the tank circuits will cause the signal to increase in amplitude at the resonant frequency. If the tuning has no effect, the tanks are open or shorted and must be disconnected and checked individually. When the circuit components appear to be operating normally and the output is low, substitute a transistor known to be good to determine whether the original transistor is at fault.

Where AGC voltage is fed into the base circuit to control the volume automatically, do not neglect the possibility that too great an AGC voltage may be biasing-off the stage. With a properly functioning circuit, the AGC voltage will vary in accordance with the strength of the input signal, or with the tuning, as the desired signal is selected. With delayed AGC it is normal for the AGC bias voltage to be almost zero with weak signals so that full sensitivity is obtained.

Distorted Output or Poor Selectivity. If the bias is too high or too low, the signal may be clipped by operating at or near saturation or cutoff, respectively. If there is excessive regeneration at some frequency, the tuning may be sharpened sufficiently to cause sideband cutoff, and frequency distortion will result from the loss of original frequencies now outside the reduced pass band. Poor selectivity (broad tuning) is usually caused by high resistance in the tuned circuits due to poorly soldered joints or aging. A lowering of the tuned circuit Q can also cause a broadening of the selectivity curve and reduce the apparent gain. With calibrated dials, reception of the signal at the wrong frequency indicates a change in circuit constants in the tank, or a change in the stray and distributed shunt capacitance in the tuned circuit. Usually, a readjustment of the trimmer capacitors will restore the calibration to normal. It is particularly important while repairing or trouble-shooting r-f circuits not to disturb the lead dress or reroute the wiring; otherwise, a change in stray capacitance (or inductance) will cause improper tracking of the tuned circuit. Moisture absorption in coils and dielectrics plus aging effects can cause a loss of Q, which can be restored only by replacing the tuned circuits or by removing them and baking them in an oven to remove the moisture. A salt spray film can cause a low shunt resistance across a tuned circuit and require washing and drying to provide normal results. In [illegible] capacitors.