

# Vacuum Tubes

## 3-1 Diodes

**Rectification** — Practically all of the vacuum tubes used in radio work depend upon thermionic conduction (§ 2-4) for their operation. The simplest type of vacuum tube is that shown in Fig. 301. It has two elements, a cathode and a plate, and is called a *diode*. When heated by the "A" battery the cathode emits electrons, which are attracted to the plate if the plate is at a positive potential with respect to the cathode.

Because of the nature of thermionic conduction, the tube is a conductor in one direction only. If a source of alternating voltage is connected between the cathode and plate, then electrons will flow only on the positive half-cycles of alternating voltage; there will be no electron flow during the half cycle when the plate is negative with respect to the cathode. Thus the tube can be used as a *rectifier*, to change alternating current to pulsating direct current. This alternating current can be anything from the 60-cycle kind to the highest radio frequencies.

Rectification finds its chief applications in detecting radio signals and in power supplies. These are treated in Chapters Seven and Eight, respectively.

**Characteristic curves** — The performance of the tube can be reduced to easily understood terms by making use of tube *characteristic curves*. A typical characteristic curve for a diode is shown at the right, in Fig. 301. It shows the current flowing between plate and cathode with different d.c. voltages applied between the elements. The curve of Fig. 301 shows that, with fixed cathode temperature, the plate current increases as the voltage between cathode and plate is raised. For an actual tube the values of plate current and plate voltage would be plotted along their respective axes.

The power consumed in the tube is the product of the plate voltage multiplied by the plate current, just as in any d.c. circuit. In a vacuum

tube this power is dissipated in heat developed in the plate and radiated to the bulb.

**Space charge** — With the cathode temperature fixed the total number of electrons emitted is always the same, regardless of the plate voltage. Fig. 301 shows, however, that less plate current will flow at low plate voltages than when the plate voltage is large. With low plate voltage, only those electrons nearest the plate are attracted to the plate. The electrons in the space near the cathode, being themselves negatively charged, tend to repel the similarly charged electrons leaving the cathode surface and cause them to fall back on the cathode. This is called the *space-charge* effect. As the plate voltage is raised more and more electrons are attracted to the plate, until finally the space charge effect is completely overcome. When this occurs all the electrons emitted by the cathode are attracted to the plate, and a further increase in plate voltage can cause no further increase in plate current. This condition is called *saturation*.

## 3-2 Triodes

**Grid control** — If a third element, called the *control grid*, or simply the *grid*, is inserted between the cathode and plate of the diode, the space-charge effect can be controlled. The tube then becomes a *triode* (three-element tube) and is useful for more things than rectification. The grid is usually in the form of an open spiral or mesh of fine wire. If the grid is connected externally to the cathode so that it is at the same potential as the cathode, and a steady voltage from a d.c. supply is then applied between the cathode and plate (the positive of the "B" supply is always connected to the plate), there will be a constant flow of electrons from cathode to plate through the openings of the grid, much as in the diode. However, if the grid is given a positive potential with respect to the cathode, the space charge will be partially neutralized and there will be an increase in plate current. If the grid is made negative with respect to the cathode, the space charge will be reinforced and the current will decrease.

This effect of grid voltage can be shown by curves in which plate current is plotted against grid voltage. At any given value of grid voltage the plate current will still depend upon the plate voltage, so if complete information about the tube is to be secured it is necessary to plot a series of curves taken with various values of plate voltage. Such a set of grid voltage vs. plate current curves, typical of a small receiving triode, is shown in Fig. 303.

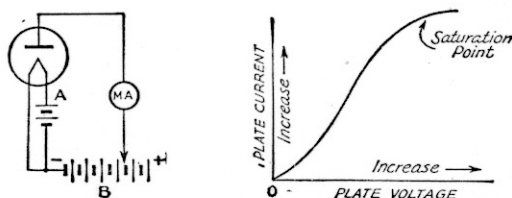
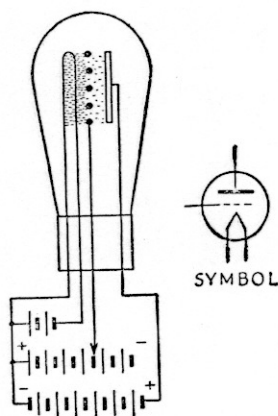


Fig. 301 — The diode or two-element tube and a typical characteristic curve showing plate current vs. voltage.

Fig. 302 — Illustrating the construction of an elementary triode vacuum tube, showing the filament, grid (with an end view of the grid wires) and plate. The relative density of the space charge is indicated roughly by the dot density. Battery symbols follow those of the usual schematic diagrams, while the schematic tube symbol is shown at the right.



So long as the grid has a negative potential with respect to the cathode, electrons emitted by the cathode are repelled (§ 2-3) from the grid, with the result that no current flows to the grid. Hence, under these conditions, the grid consumes no power. However, when the grid becomes positive with respect to the cathode, electrons are attracted to it, and a current flows to the grid; when this *grid current* flows, power is dissipated in the grid circuit.

In addition to the set of curves showing the relationship between grid voltage and plate current at various fixed values of plate voltage, two other sets of curves may be plotted to show the characteristics of a triode. These are the plate voltage vs. plate current characteristic, which shows the relationship between plate voltage and plate current for various fixed values of grid voltage, and the constant-current characteristic, which shows the relationship between plate voltage and grid voltage for various fixed values of plate current.

**Amplification** — The grid evidently acts as a valve to control the flow of plate current, and it is found that it has a much greater effect on plate current flow than does the plate voltage; that is, a small change in grid voltage is just as effective in bringing about a given change in plate current as is a large change in plate voltage.

The fact that a small voltage acting on the grid is equivalent to a large voltage acting on the plate indicates the possibility of *amplification* with the triode tube; that is, the generation of a large voltage by a small one, or the generation of a relatively large amount of power from a small amount. The many uses of the electronic tube nearly all are based upon this amplifying feature. The amplified power or voltage output from the tube is obtained, not from the tube itself, but from the source of e.m.f. connected between its plate and cathode. The tube simply *controls* the power from this source, changing it to the desired form.

To utilize the controlled power, a device for consuming it, or for trans-

ferring it to another circuit, must be connected in the plate circuit, since no particularly useful purpose would be served in having the current merely flow through the tube and the source of e.m.f. Such a device is called the *load*, and may be either a resistance or an impedance. The term "impedance" is frequently used even though the load may be purely resistive.

**Amplification factor** — The relative effect of the grid and plate voltages on the plate current is measured by the *amplification factor* of the tube, usually represented by the Greek letter  $\mu$ . Amplification factor is defined as the ratio of the change in plate voltage required to produce a given change in plate current to the change in grid voltage required to produce the same plate-current change. Strictly speaking, very small changes in both grid and plate voltage must be used in determining the amplification factor, because the curves showing the relationship between plate voltage and plate current, and between grid voltage and plate current, are not perfectly straight, especially if the plate current is nearly zero. Hence the slope (§ 1-10) varies at different points along the curves, and different values will be obtained for the amplification factor as larger or smaller voltage differences are taken for the purpose of calculating it. The expression for amplification factor can be written:

$$\mu = \frac{\Delta E_p}{\Delta E_g}$$

where  $\Delta E_p$  indicates a very small change in plate voltage and  $\Delta E_g$  is the change in grid voltage producing the same plate current change. The symbol  $\Delta$  (the Greek letter *delta*) indicates a small increment, or small change.

The amplification factor is simply a ratio, and has no unit.

**Plate resistance** — Since only a limited amount of plate current flows when a given voltage is applied between plate and cathode, it is evident that the plate-cathode circuit of the tube has resistance. However, there is no simple relationship between plate voltage and plate current, so that in general the plate circuit of the tube does not follow Ohm's Law. Under a given set of conditions the application

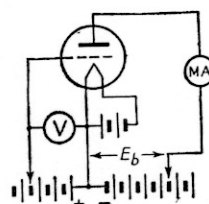
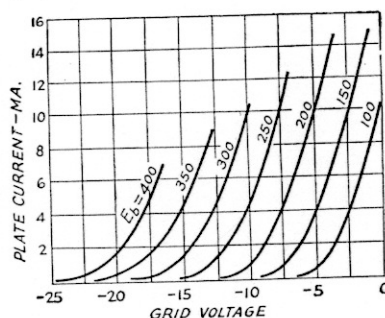


Fig. 303 — Grid voltage vs. plate current curves at various fixed values of plate voltage ( $E_b$ ) for a typical small triode. Characteristic curves of this type can be taken by means of the circuit at the right.

of a given plate voltage will cause a certain plate current to flow, and if the plate voltage is divided by the plate current a "resistance" value will be obtained which frequently is called the "d.c. resistance" of the tube. This "d.c. resistance" will be different for every value of plate voltage and also for different values of grid voltage, since the plate current also depends upon the grid voltage when the plate voltage is fixed.

In applications of the vacuum tube, it is more important to know how the plate current changes with a change in plate voltage than it is to know the relationship between the actual values of plate current and plate voltage. The relationship between plate-current change and plate-voltage change determines the *a.c. plate resistance* of the tube. This resistance usually is designated  $r_p$ . It can be found from the plate voltage vs. plate current characteristic curves by finding the slope of the curve at the point considered. Hence

$$r_p = \frac{\Delta E_p}{\Delta I_p}$$

where  $\Delta E_p$  is a small change in plate voltage and  $\Delta I_p$  the corresponding small change in plate current, the grid voltage being fixed. \*

Plate resistance is expressed in ohms, since it is the ratio of voltage to current. The value of plate resistance will, in general, change with the particular voltages applied to the plate and grid. It depends as well upon the structure of the tube; low- $\mu$  tubes have relatively low plate resistance and high- $\mu$  tubes have high plate resistance.

**Transconductance** — The effect of grid voltage upon plate current is expressed by the *grid-plate transconductance* of the tube. Transconductance is a general term giving the relationship between the voltage applied to one electrode and the current which flows, as a result, in a second electrode. As in the previous two cases, it is defined as the *change* in current through the second electrode caused by a change in voltage on the first. Thus the grid-plate transconductance, commonly called the *mutual conductance*, is

$$g_m = \frac{\Delta I_p}{\Delta E_g}$$

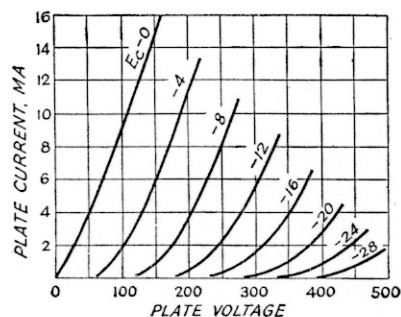


Fig. 304 — Plate voltage vs. plate current curves at various fixed values of negative grid voltage for the same triode as in curves in Fig. 303.

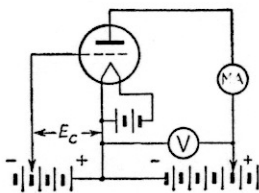
where  $g_m$  is the mutual conductance,  $\Delta I_p$  the change in plate current, and  $\Delta E_g$  the change in grid voltage, the plate voltage being fixed. As before, the sign  $\Delta$  indicates that the changes must be small. Transconductance is measured in mhos, since it is the ratio of current to voltage. The unit usually employed in connection with vacuum tubes is the *micromho* (one millionth of a mho), because the conductances are small. By combining with the two preceding formulas, it can be shown that  $g_m = \mu/r_p$ .

The mutual conductance of a tube is a rough indication of its merit as an amplifier, since it includes the effects of both amplification factor and plate resistance. Its value varies with the voltages applied to the plate and grid. With the plate voltage fixed, the mutual conductance decreases when the grid is made increasingly negative with respect to the cathode. This characteristic frequently can be used to advantage in the control of amplification, since the amount of amplification can be varied over wide limits simply by adjusting the value of a steady voltage applied to the grid.

**Static and dynamic curves** — Curves of the type shown in Figs. 301 and 303 are called *static* curves. They show the current which flows when various voltages are applied directly to the tube electrodes. Another useful set of static curves is the "plate family," or plate voltage vs. plate current characteristic. A typical set of curves of this type is shown in Fig. 304.

A curve showing the relationship between grid voltage and plate current when a load resistance is connected in the plate circuit is called a *dynamic* characteristic curve. Such a curve includes the effect of the load resistance, and hence is more indicative of the performance of the tube as an amplifier. With a fixed value of plate-supply voltage the actual value of voltage between the plate and cathode of the tube will depend upon the amount of plate current flowing, since the plate current also flows through the load resistance and therefore results in a voltage drop which must be subtracted from the plate-supply voltage. The dynamic curve includes the effect of this voltage drop. Consequently, the plate current always is lower, for a given value of grid voltage and plate-supply voltage, with the load resistance in the circuit than it is without it.

Representative dynamic characteristics are shown in Fig. 305. These were taken with the same type of tube whose static curves are shown in Fig. 303. Different curves would be obtained with different values of plate-supply voltage,  $E_b$ ; this set is for a plate-supply voltage of 300 volts. Note that increasing the value of the load resistance reduces the plate current at a given bias voltage, and also





that the curves are straighter with the higher values of load resistance. Zero plate current always occurs at the same value of negative grid bias, since at zero plate current there is no voltage drop in the load resistance and the full supply voltage is applied to the plate.

Fig. 306 shows how the plate current responds to an alternating voltage (signal) applied to the grid. If the plate current is to have the same waveshape as that of the signal, it is necessary to confine the operation to the straight section of the curve. To do this, it is necessary to select an *operating point* near the middle of the straight portion; this operating point is determined by the fixed voltage (bias) applied to the grid. The alternating signal voltage then adds to or subtracts from the grid bias, depending upon whether the instantaneous signal voltage is negative or positive with respect to the cathode, and causes a corresponding variation in plate current. The maximum departure of instantaneous grid voltage or plate current from the operating point is called the *swing*. The varying plate current flows through the load resistance, causing a varying voltage drop which constitutes the useful output voltage of the tube.

The point at which the plate current is reduced to zero is called the *cut-off point*. The value of negative grid voltage at which cut-off occurs depends upon the amplification factor of the tube and the plate voltage. It is approximately equal to the plate-supply voltage divided by the amplification factor.

**Interelectrode capacities** — Any pair of elements in a tube forms a miniature condenser (§ 2-3), and, although the capacities of these condensers may be only a few micromicrofarads or less, they must frequently be taken into account in vacuum-tube circuits. The capacity from grid to plate (*grid-plate capacity*) has an important effect in many applications. In triodes, the other capacities are the *grid-cathode* and *plate-cathode*. In multi-element tubes (§ 3-5), similar capacities exist between these and other electrodes. With screen-grid tubes, the terms "input" and "output" capacity mean, respectively, the capacity measured from grid to all other elements connected together and from plate to all other elements connected together. The same terms are used with triodes but are not so easily defined, since the effective capacities existing depend upon the operating conditions (§ 3-3).

**Tube ratings** — Specifications of suitable operating voltages and currents are called *tube ratings*. Ratings include proper values for filament or heater voltage and current, plate voltage and current, and similar operating specifications for other elements. An important rating in power tubes is the *maximum safe plate dissipation*, or the maximum power that can be dissipated continuously in heat on the plate (§ 3-1).

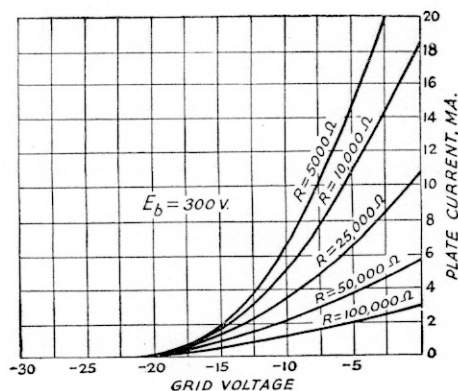
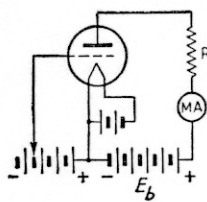


Fig. 305 — Dynamic characteristics of a small triode with various load resistances from 5,000 to 100,000 ohms.

### 3-3 Amplification

**Principles** — The operation of a simple amplifier, which was described briefly in the preceding section, is shown in more detail in Fig. 307. The load in the plate circuit is the resistor,  $R_p$ . For the sake of example, it is assumed that the plate-supply voltage is 300 volts, the negative grid bias is 5 volts, and the plate current at this bias when  $R_p$  is 50,000 ohms is 2 milliamperes (0.002 ampere). If no signal is applied to the grid circuit, the voltage drop in the load resistor is  $50,000 \times 0.002$ , or 100 volts, leaving 200 volts between the plate and cathode.

If a sine-wave signal having a peak value of 2 volts is applied in series with the bias voltage in the grid circuit, the instantaneous voltage at the grid will swing to  $-3$  volts at the instant the signal reaches its positive peak and to  $-7$  volts at the instant the signal reaches its negative peak. The maximum plate current will occur at the instant the grid voltage is  $-3$  volts and, as shown by the graph, will have a value of 2.65 milliamperes. The minimum plate current occurs at the instant the grid voltage is  $-7$  volts, and has a value of 1.35 ma. At intermediate values of grid voltage, intermediate plate-current values will occur. The instantaneous voltage between the plate and

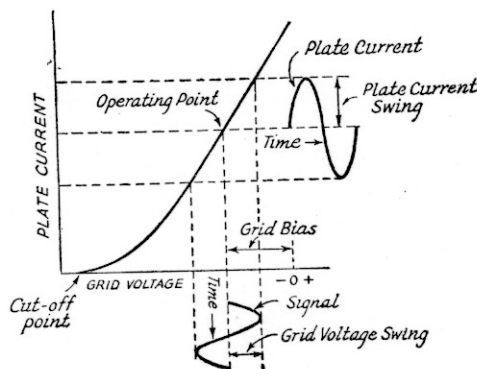


Fig. 306 — Behavior of the plate current of a vacuum tube in response to an alternating signal voltage superimposed on a steady negative grid voltage or bias.



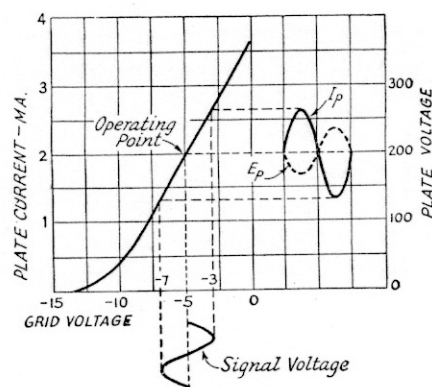


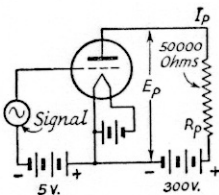
Fig. 307 — Amplifier operation. When the plate current varies in response to the signal applied to the grid, a varying voltage drop appears across the load,  $R_p$ , as shown by the dashed curve,  $E_p$ .  $I_p$  is the plate current.

cathode of the tube also is shown on the graph. When the plate current is maximum the instantaneous voltage drop in  $R_p$  is  $50,000 \times 0.00265$  or 132.5 volts, and when the plate current is minimum the instantaneous voltage drop in  $R_p$  is  $50,000 \times 0.00135$  or 67.5 volts. The actual voltage between plate and cathode is therefore the difference between the plate-supply voltage, 300 volts, and these voltage drops in the load resistance, or 167.5 and 232.5 volts, respectively.

The varying plate voltage is an a.c. voltage superimposed (§ 2-13) on the steady plate-cathode voltage of 200 volts, which was previously determined for no-signal conditions. The peak value of this a.c. output voltage is the difference between either the maximum or minimum plate-cathode voltage and the no-signal value of 200 volts. In the illustration this difference is  $232.5 - 200$  or  $200 - 167.5$ , or 32.5 volts. Since the grid signal voltage has a peak value of 2 volts, the voltage amplification ratio of the amplifier is  $32.5/2$  or 16.25. That is, approximately 16 times as much voltage will be obtained from the plate circuit as is applied to the grid circuit.

Amplifiers in which the voltage output, rather than the power output, is the primary consideration are called *voltage amplifiers*.

It will be observed that only the alternating plate and grid voltages enter into the calculation of the amplification ratio. The d.c. plate and grid voltages are of course essential to the operation of the tube, since they set the operating point, but otherwise their presence may be ignored. This being the case, it is possible to show that the tube can be replaced by an *equivalent generator* which has an internal resistance equal to the a.c. plate resistance of the tube (§ 3-2) at the operating point chosen and which generates a voltage equal to the amplification factor of the tube multiplied by the signal voltage applied to the grid. The equivalent generator, together with the load resistance,  $R_p$ , is shown in Fig. 308. This simplification enables ready calculation of the amplifica-



tion. If the generated voltage is  $\mu E_g$ , then the same current flows through  $r_p$  and  $R_p$ , and hence the voltage drop across  $R_p$ , which is the useful output voltage, is

$$E_o = \mu E_g \frac{R_p}{r_p + R_p}$$

since  $R_p$  and  $r_p$  together constitute a voltage divider (§ 2-6).

The voltage-amplification ratio is given by the output voltage divided by the input voltage, hence dividing the above expression by  $E_g$  gives the following formula for the amplification of the tube:

$$\text{Amplification} = \frac{\mu R_p}{r_p + R_p}$$

This expression shows that, to obtain a large voltage-amplification ratio, it is necessary to make the plate load resistance,  $R_p$ , large compared to the plate resistance,  $r_p$ , of the tube. The maximum possible amplification, obtained when  $R_p$  is infinitely larger than  $r_p$ , is equal to the  $\mu$  of the tube. A tube with a large value of  $\mu$  will, in general, give more voltage amplification than one with a medium or low value. However, the advantage of the high  $\mu$  is less than might be expected, because a high- $\mu$  tube usually also has a correspondingly high value of  $r_p$ , so that a high value of load resistance must be used to realize an appreciable part of the possible amplification. This in turn not only requires the use of high values of plate-supply voltage, but has some further disadvantages to be described later.

**Power in grid circuit** — In the operation depicted in Fig. 306, the grid is always negative with respect to the cathode. If the peak signal voltage is larger than the bias voltage, the grid will be positive with respect to the cathode during part of the signal cycle. Grid current will flow during this time, and the signal source will be called upon to furnish power during the period while grid current is flowing. In many cases the signal source is not capable of furnishing appreciable power, so that care must be taken to avoid "driving the grid positive."

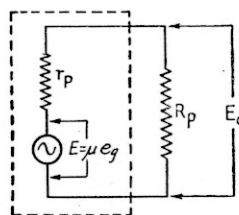
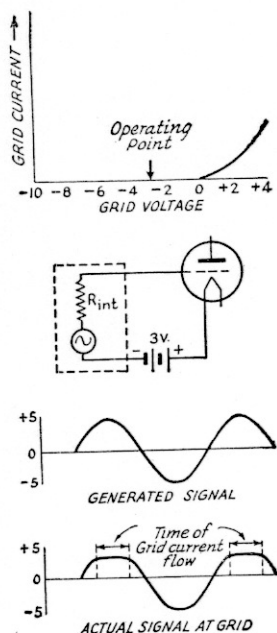


Fig. 308 — Equivalent circuit of the vacuum-tube amplifier. The tube is replaced by an equivalent generator having an internal resistance equal to the a.c. plate resistance of the vacuum tube.

When dealing with small signals the source of signal voltage frequently has high internal resistance, so that a considerable voltage drop occurs in the source itself whenever it is called upon to furnish grid current. Since this voltage drop occurs only during part of the cycle, the

Fig. 309—Distortion of applied signal because of grid-current flow. With the operating point at 3 volts negative bias, grid current will flow as shown by the curve whenever the applied signal voltage is more than 3 volts positive. If there is appreciable internal resistance, as indicated in the second drawing, there will be a voltage drop in the resistance whenever current is flowing but not during the period when no current flows. The signal will reach the grid unchanged so long as the instantaneous voltage is less than 3 volts positive, but the voltage at the grid will be less than the instantaneous voltage when the latter is above this figure. The shape of the negative half-cycle is unaltered.



voltage applied to the grid undergoes a change in waveshape because of the current flow. This is shown in Fig. 309, where a sine-wave signal is generated but, because of the internal resistance of the source, is distorted at the grid of the tube during the time when grid current flows.

If the internal resistance of the signal source is low, so that the internal voltage drop is negligible when current flows, this distortion does not occur. With such a source, it is possible to operate over a greater portion of the amplifier characteristic.

**Harmonic distortion**—If the operation of the tube is not confined to a straight or linear portion of the dynamic characteristic, the waveshape of the output voltage will not be exactly the same as that of the signal voltage. This is shown in Fig. 310, where the operating point is selected so that the signal voltage swings into the curved part of the characteristic. While the upper half-cycle of plate current reproduces the sine-wave shape of the positive half-cycle of signal voltage, the lower half-cycle of plate current is considerably distorted and bears little resemblance to the upper half-cycle of plate current.

As explained in § 2-7, a non-sinusoidal waveshape can be resolved into a number of sine-wave components or harmonics which are integral multiples of the lowest frequency present. Consequently, this type of distortion is known as *harmonic distortion*. Distortion resulting from grid-current flow, described in the preceding paragraph, also is harmonic distortion. Harmonic distortion from either or both causes may arise in the same amplifier.

Harmonic distortion may or may not be tolerable in an amplifier. At audio frequencies it is desirable to keep harmonic distortion to a minimum, but radio-frequency amplifiers

are frequently operated in such a way that the r. f. wave is greatly distorted.

**Frequency distortion**—Another type of distortion, known as *frequency distortion*, occurs when the amplification varies with the frequency of the a.c. voltage applied to the grid circuit of the amplifier. It is not necessarily accompanied by harmonic distortion. It can be shown by a *frequency-response curve* or graph in which the relative amplification is plotted against frequency over the frequency range of interest.

**Resistance-coupled amplifiers**—An amplifier with a resistance load is known as a "resistance-coupled" amplifier. This type of amplifier is widely used for amplification at audio frequencies. A simplified circuit is shown in Fig. 311, where the amplifier is coupled to a following tube. Since all the power output of a resistance-coupled amplifier is consumed in the load resistor such amplifiers are used almost wholly for voltage amplification, usually working into still another amplifier.

A single amplifier is called a *stage* of amplification, and a number of amplifier stages in succession are said to be in *cascade*.

The purpose of the coupling condenser,  $C_c$ , is to transfer to the grid of the following tube the a.c. voltage developed across  $R_p$ , and to prevent the d.c. plate voltage on tube A from being applied to the grid of tube B. The grid resistor,  $R_g$ , transfers the bias voltage to the grid of tube B and prevents short-circuiting the a.c. voltage through the bias battery. Since no grid current flows, there is no d.c. voltage drop in  $R_g$ ; consequently the full bias voltage is applied to the grid. In order to obtain the maximum a.c. voltage at the grid of tube B the reactance of the coupling condenser must be small compared to the resistance of  $R_g$ , so that most of the voltage will appear across  $R_g$  rather than across  $C_c$ . Also, the resistance of  $R_g$  must be large compared to  $R_p$  because, so far as the a.c. voltage developed in  $R_p$  is concerned,  $R_g$  is in parallel with  $R_p$  and therefore is just as much a part of  $R_p$  as though it were

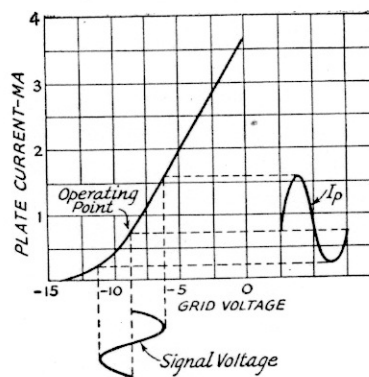


Fig. 310—Harmonic distortion resulting from choice of an operating point on the curved part of the tube characteristic. The lower half-cycle of plate current does not have the same shape as the grid voltage causing it.

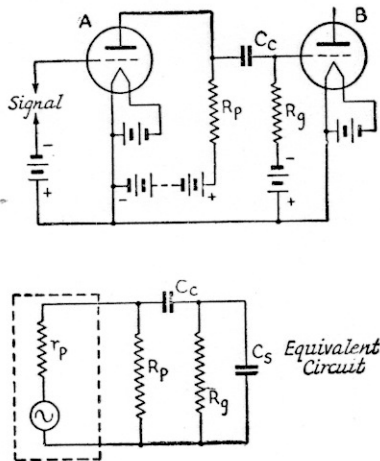


Fig. 311 — Typical resistance-coupled amplifier circuits.

connected directly in parallel with it. (The impedance of the plate-supply battery is assumed to be negligible, so that there is no a.c. voltage drop between the lower end of  $R_p$  and the common connection between the two tubes.) In practice the maximum usable value of  $R_p$  is limited to from 0.5 to about 2 megohms, depending upon the characteristics of the tube with which it is associated. If the value is made too high, stray electrons collecting on the grid may not "leak off" back to the cathode rapidly enough to prevent the accumulation of a negative charge on the grid. This is equivalent to an increase in the negative grid bias, and hence to a shift in the operating point.

The equivalent circuit of the amplifier now includes  $C_c$ ,  $R_p$ , and a shunt capacity,  $C_s$ , which represents the input capacity of tube B and the plate-cathode capacity of tube A, together with such stray capacity as exists in the circuit. The reactance of  $C_s$  will depend upon the frequency of the voltage being amplified, and, since  $C_s$  is in parallel with  $R_p$  and  $R_g$ , it also becomes part of the load impedance for the amplifier. At low frequencies — below 1000 cycles or so — the reactance of  $C_s$  usually is so high that it has practically no effect on the amplification, but, since the reactance decreases at higher frequencies, it is found that the amplification drops off rapidly when the reactance of  $C_s$  becomes comparable to the resistance of  $R_p$  and  $R_g$  in parallel. To maintain the amplification at high frequencies, it is necessary that  $R_p$  be relatively small if  $C_s$  is large, or that  $C_s$  be small if  $R_p$  is large.

Under the best conditions, in practice  $C_s$  will be of the order of 15  $\mu\text{fd.}$  or more, while it is possible for it to reach values as high as a few hundred  $\mu\text{fd.}$  The larger values are encountered when tube B is a high- $\mu$  triode, as described in a later paragraph. Even with a low value of shunt capacity, the shunt reactance will decrease to a comparatively low value at the upper limit of the audio-frequency range; a shunting capacity of 20  $\mu\text{fd.}$ , for example,

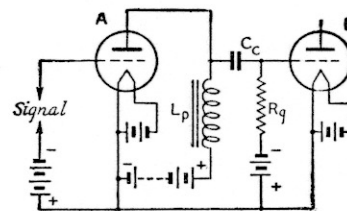
represents a reactance of about 0.5 megohm at 15,000 cycles, and hence is of the same order as  $R_p$  for the type of tubes with which such a low value of capacity would be associated. In order to secure the same amplification at high as at low frequencies, therefore, it is necessary to sacrifice low-frequency amplification by reducing the value of  $R_p$  to the point where the reactance of  $C_s$  at the highest frequency of interest is considerably larger than  $R_p$ .

At radio frequencies the reactance of  $C_s$  becomes so low that the amount of amplification it is possible to realize is negligible compared to that which can be obtained in the audio-frequency range. The resistance-coupled amplifier, therefore, is used principally for audio-frequency work.

**Impedance-coupled amplifiers** — If either the plate resistor or grid resistor (or both) in the amplifier described in the preceding paragraph is replaced by an inductance, the amplifier is said to be *impedance-coupled*. The inductance or impedance is commonly substituted for the plate load resistor, so that the usual circuit for such an amplifier is as given in Fig. 312.

Considering the operation of the tube from the standpoint of the equivalent circuit of Fig. 308, it is evident that a voltage drop would exist across a reactance of suitable value substituted for the indicated load resistance,  $R_p$ , so long as the output of the generator is alternating current. From the physical standpoint, any change in the current flowing through the inductance in Fig. 312 would cause a self-induced e.m.f. having a value proportional to the rate of change of current and to the inductance of the coil. Consequently, if an a.c. signal voltage is applied to the grid of the tube, the resultant variations in plate current cause a corresponding a.c. voltage to appear across the coil terminals. This induced voltage is the useful output voltage of the tube.

The amplitude of the output voltage can be calculated, knowing the  $\mu$  and plate resistance of the tube and the impedance of the load, in much the same way as in the case of resistance coupling, except that the equation must be modified to take account of the fact that the phase relationship between current and voltage is not the same in an impedance as it is in a resistance. In practice, the plate load inductance is shunted by the tube and stray capacities of the circuit as well as by its own distributed capacity. Since the greatest amplification will

Fig. 312 — Impedance-coupled amplifier, in which an inductance,  $L_p$ , is used as the plate load impedance.



be secured when the load impedance is as high as possible, the coil usually is made to have sufficient inductance so that, in combination with these shunting capacities, the circuit as a whole will be parallel-resonant at some frequency near the middle of the audio-frequency range. Under these conditions the load impedance has its highest possible value, and is approximately resistive rather than reactive.

The equation for amplification with resistance coupling shows that, when  $R_p$  is several times the plate resistance,  $r_p$ , a further increase in  $R_p$  results in comparatively little increase in amplification. The load circuit of an impedance-coupled amplifier usually has an impedance value quite high in comparison to the plate resistance of the tube with which it is used, so that the load impedance can vary over a considerable range without much effect on the amplification. This gives the impedance-coupled amplifier an amplification vs. frequency characteristic which is fairly "flat" — that is, the amplification is practically constant with changes in frequency — over a considerable portion of the audio-frequency range. However, the performance of the impedance-coupled amplifier is not as good in this respect as that of a well-designed resistance-coupled amplifier.

If the impedance of the load circuit is high compared to the plate resistance of the tube, which will be the case if the tube is a low- $\mu$  triode and normal inductance values (a few hundred henrys) are used in the plate circuit, the amplification in the optimum frequency range will be practically equal to the  $\mu$  of the tube. At very low frequencies the impedance decreases because of the decreasing reactance of the coil, while at very high frequencies the impedance again decreases because of the decreasing reactance of the shunt capacities. Consequently, the amplification drops off at both ends of the range, usually at a more rapid rate than in the case of resistance coupling.

The frequency-response characteristic of the impedance-coupled amplifier depends considerably upon the plate resistance of the tube. If impedance coupling is used with tubes of very high plate resistance, the response will be markedly greater at the resonant frequency than at frequencies either higher or lower.

Impedance coupling can be used at radio frequencies, since the inductance can be adjusted to resonate with the shunt capacities at practically any desired frequency.

**Transformer-coupled amplifiers** — The coupling impedance in Fig. 312 may be replaced by a transformer, connected as shown in Fig. 313. A.c. voltage is developed across the primary of the transformer in the same way as in the case of impedance coupling. The secondary of the transformer serves as a means for transferring the voltage to the grid of the following tube, and if the secondary has more turns than the primary the voltage across the secondary terminals will, in general, be larger than the voltage across the primary terminals.

As in the case of impedance coupling, the effective capacity shunting the primary of an audio-frequency transformer usually causes the primary circuit to be parallel-resonant at some frequency in the middle of the audio-frequency range. At the medium audio fre-

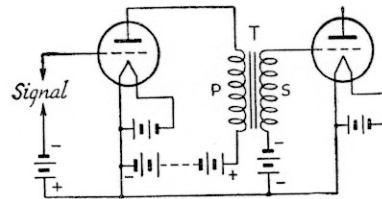


Fig. 313 — Transformer-coupled amplifier circuit.

quencies, therefore, the voltage across the primary is practically equal to the applied grid voltage multiplied by the  $\mu$  of the tube. The voltage across the secondary will be the primary voltage multiplied by the secondary-to-primary turns ratio of the transformer, so that the total voltage amplification is  $\mu$  times the turns ratio. The amplification at low frequencies depends upon the ratio of the primary reactance to the plate resistance of the tube, as in the case of impedance-coupled amplifiers.

At some high frequency, usually in the range 5000–10,000 cycles with ordinary transformers, the leakage inductance (§ 2-9) of the secondary becomes series resonant with the effective capacity shunting the secondary. At and near this resonant frequency the resonant rise in voltage may increase the amplification considerably, giving rise to a "peak" in the frequency-response curve of the amplifier. At frequencies above this resonance point amplification decreases rapidly, because as the reactance of the shunting capacity decreases it tends to act more and more as a short circuit across the secondary of the transformer. The relative height of the high-frequency peak depends principally upon the effective resistance of the secondary circuit. This effective resistance includes the actual resistance of the secondary coil and the "reflected" (§ 2-9) plate resistance of the tube, this resistance being in parallel with the primary of the transformer. Consequently, the height of the peak is affected by the tube with which the transformer is used. The peak can be reduced by connecting a resistance of the order of 0.25 to 1 megohm across the secondary of the transformer. While this helps make the frequency response curve more flat, it also reduces the amplification at medium and low frequencies.

Transformer coupling is most suitable for triodes of low or medium  $\mu$  and having medium values of plate resistance. This is because the primary inductance required for good amplification at low frequencies is proportional to the plate resistance of the tube with which the transformer is to be used, and in practice it is difficult to obtain high primary inductance, a large secondary-to-primary turns ratio ("step-

up ratio"), and low distributed capacity in the windings all at the same time. Increasing the primary inductance usually means that the turns ratio must be reduced, because the increase in distributed capacity as the coils are made larger tends to bring the resonant peak down to a relatively low frequency unless the secondary inductance is decreased to compensate for the increase in capacity. The step-up ratio seldom is more than 3 to 1 in transformers designed for good frequency response.

Transformer coupling can be used at radio frequencies if the transformers are properly designed for the purpose. In such transformers either the primary or secondary (or both) is made resonant at the frequency to be used, so that maximum amplification will be secured.

#### Phase relations in plate and grid circuits

— When the exciting voltage on the grid has its maximum positive instantaneous value, the plate current also is maximum (§ 3-2), so that the voltage drop across the resistance connected in the plate circuit of a resistance-coupled amplifier likewise has its greatest value. The actual instantaneous voltage between plate and cathode is therefore minimum at the same instant, because it is equal to the d.c. supply voltage (which is unvarying) minus the voltage drop across the load resistance. When the signal voltage is at its negative peak the plate current has its least value, with the result that the voltage drop in the load resistance is less than at any other part of the cycle. At this instant, therefore, the voltage between plate and cathode is maximum.

These variations in plate-cathode voltage constitute the a.c. output of the tube, superimposed on the mean or no-signal plate-cathode voltage. Since the alternating plate-cathode voltage is decreasing when the instantaneous grid voltage is increasing (becoming more positive with respect to the cathode), the output voltage is less than the mean value, or negative, when the signal voltage is positive. Likewise, when the signal voltage is negative the output voltage is positive, or greater than the mean value. In other words, the alternating plate voltage is 180 degrees out of phase with the alternating grid voltage. Thus there is a *phase reversal* through the amplifier. The relationships should become clear from the behavior of the signal voltage and  $E_p$  in Fig. 307.

The same phase relationship between signal and output voltages holds when the amplifier

is impedance- or transformer-coupled, in the frequency region where the load acts like a parallel-resonant circuit. However, if the load is reactive the phase relationship is not exactly 180 degrees but depends upon the kind of reactance present and the relative amounts of reactance and resistance. (This is true also of the resistance-coupled amplifier at low frequencies where the reactance of the coupling condenser affects the amplification, or at high frequencies where the reactance of the shunting capacities becomes important.) Since the reactance varies with the applied signal frequency, the phase relationship between signal voltage and output voltage depends upon the frequency in such cases.

**Input capacity and resistance** — When an alternating voltage is applied between the grid and cathode of an amplifier tube, an alternating current flows through the small condenser formed by these elements (§ 3-2) just as it would in any other condenser. Similarly, an alternating current also flows in the condenser formed by the grid and plate, since there is an alternating difference of potential between these elements. When the tube is amplifying, the alternating plate voltage and signal voltage are effectively applied in series across the grid-plate condenser, as indicated in Fig. 314. As described in the preceding paragraph, in the resistance-coupled amplifier the two voltages are out of phase with respect to the cathode, but inspection of the circuit shows that they are in phase so far as the grid-plate condenser is concerned. Consequently, the voltage applied to the grid-plate capacity is the sum of the alternating grid and plate voltages, or  $E_g + E_p$ . Since  $E_p$  is equal to  $A E_g$ , where  $A$  is the voltage amplification of the tube and circuit, the a.c. voltage between the grid and plate is  $E_g (1 + A)$ . The current,  $I$ , flowing in the grid-plate capacity is therefore  $E_g (1 + A)$  divided by the reactance of the grid-plate condenser, and consequently is proportional to the grid-plate capacity.

The signal voltage must help in causing this relatively large current to flow, and, since the reactance as viewed from the input circuit is  $X_g = E_g/I$ , the input reactance becomes smaller as the current becomes larger. That is, the *effective* input capacity of the amplifier is increased when the tube is amplifying. From the above, the increase in input capacity is approximately proportional to the voltage amplification of the circuit and to the grid-plate capacity of the tube. The total input capacity is the sum of the grid-cathode capacity and this additional effective capacity. The total input capacity of an amplifier may reach values ranging from 50 to a few hundred micromicrofarads, if the voltage amplification is high and the grid-plate capacity relatively large. Both usually are true in a high- $\mu$  triode.

When the load is reactive the a.c. grid and plate voltages still act in series across the grid-plate condenser, but since they are not exactly

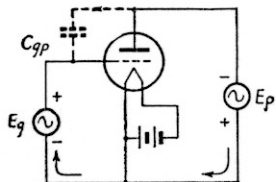


Fig. 314 — The a.c. voltage appearing between the grid and plate of the amplifier is the sum of the signal voltage and the output voltage, as shown by this simplified circuit. Instantaneous polarities are indicated.

180 degrees out of phase with respect to the cathode they are not exactly in phase with respect to the grid-plate capacity. The lack of exact phase relationship indicates that resistance as well as capacity is introduced into the input circuit. Analysis shows that, when the reactance of the load circuit is capacitive, the resistance component is positive — that is, it represents a loss of power in the input circuit — and that when the load circuit has inductive reactance the resistance component is negative. Negative resistance indicates that power is being supplied to the grid circuit from the plate.

**Feed-back** — If some of the amplified energy in the plate circuit of an amplifier is coupled back into the grid circuit, the amplifier is said to have *feed-back*. If the voltage fed from the plate circuit to the grid circuit is in such phase that, when it is added to the signal voltage already existing, the sum of the two voltages is larger than the original signal voltage, the feed-back is said to be *positive*. Positive feed-back usually is called *regeneration*. If regeneration exists in a circuit the total amplification is increased because the feed-back increases the amplitude of the signal at the grid and this larger signal is amplified in the same ratio, giving a greater output voltage than would exist if the signal voltage alone were present in the grid circuit. Many types of circuits can be used to secure positive feed-back. A simple one is shown in Fig. 315. The feed-back coil, *L*, a third winding on the grid-circuit transformer, is connected in series with the primary of the transformer in the plate circuit, so that some of the amplified voltage appears across its terminals. This induces a voltage in the secondary, *S*, of the grid-circuit transformer which, if the winding directions of the two coils are correct, will increase the value of signal voltage applied to the grid.

Positive feed-back is accompanied by a tendency to give maximum amplification at only one frequency, since the feed-back voltage will tend to be highest at the frequency at which the original amplification is greatest. It therefore increases the selectivity of the amplifier, and hence is used chiefly where high gain and sharpness of resonance both are wanted.

If the phase of the voltage fed back to the grid circuit is such that the sum of the feed-back voltage and the original signal voltage is less than the latter alone, the feed-back is said to be *negative*. Negative feed-back frequently is called *degeneration*. In this case the total amplification is decreased, since the grid signal has been made smaller, and hence the amplified output voltage is smaller for a given original signal than it would be without feed-back.

The amount of voltage fed back will depend upon the actual amplification of the tube and circuit, and if the amplification ratio tends to change, as it may at the extreme high or low frequencies in the audio-frequency range, the feed-back voltage will be reduced when the amplification decreases. For example, suppose

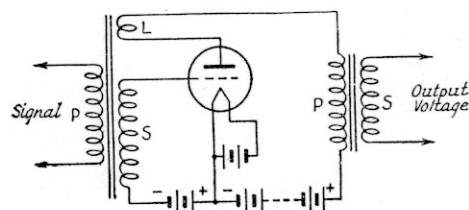


Fig. 315—An elementary form of feed-back circuit. The feed-back may be either positive or negative, depending upon how the coil *L* is connected in the circuit. This type of circuit illustrates the principle of feed-back, but it is not practical for use in an actual audio-frequency amplifier.

that an amplifier has a voltage gain of 20 and that it is delivering an output voltage of 50 volts. Without feed-back, the grid signal voltage required to produce 50 volts output is  $50/20$  or 2.5 volts. But suppose that 10 per cent of the output voltage (5 volts) is fed back to the grid circuit in opposite phase to the applied grid voltage. Then, since it is still necessary to have a 2.5-volt signal to produce 50 volts output, the applied voltage must be  $2.5 + 5$  or 7.5 volts. Now suppose that at some other frequency the voltage gain drops to 10. Then for the same 50-volt output a 5-volt signal is required, but since the feed-back voltage is still 5 volts the total required signal is now 10 volts. With feed-back the gain in the first case was  $50/7.5$  volts or 6.66 and in the second case  $50/10$  or 5, the gain in the second case being 75 per cent as high as in the first. Without feed-back the gain in the second case was 50 per cent as high as in the first. The effect of feed-back therefore is to make the resultant gain more uniform, despite the tendency of the amplifier itself to discriminate against certain frequencies.

Negative feed-back also tends to decrease harmonic distortion arising in the plate circuit of the amplifier. This distortion is present in the amplified output voltage, but not in the original signal voltage applied to the grid. The voltage fed back to the grid circuit contains the distortion but in opposite phase to the distortion components in the plate circuit, hence the two tend to cancel each other. For similar reasons, the over-all amplification is less dependent upon the value of load impedance used in the plate circuit; in fact, if a large amount of negative feed-back is used in an amplifier it is even possible to substitute tubes of rather widely different characteristics without much effect on the over-all performance.

Both positive and negative feed-back may be applied over several stages of an amplifier, rather than being applied directly from the plate circuit to the grid circuit of a single stage.

**Power amplification** — In the types of amplifiers previously described, the chief consideration was that of securing as much voltage gain as possible within the permissible limits of harmonic distortion and frequency response characteristic. Such amplifiers are principally used to furnish an amplified signal voltage,



which in turn can be supplied to a succeeding amplifier. If the succeeding amplifier is operated in such a way that its grid is never driven positive with respect to its cathode, grid current does not flow, and hence the power re-

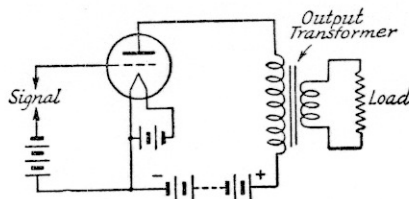


Fig. 316 — An elementary power-amplifier circuit in which the power-consuming load is coupled to the plate circuit through an impedance-matching transformer.

quirements are negligibly small. However, if an amplifier is used to actuate some power-consuming device, such as a loudspeaker or a succeeding amplifier in which it is permissible to drive the grid into the positive region, the primary consideration is that of obtaining the maximum power output consistent with the permissible distortion. In such a case the voltage at which the power is secured is of little consequence, since a transformer may be used to change the voltage to any desired value, within reasonable limits. Hence, the voltage gain of a power amplifier is of little importance.

In power-amplifier operation the grid may or may not be driven into the positive region, depending upon the particular application. The present discussion will be confined to the triode amplifier operating without grid current; other types are considered in § 3-4. The principles upon which such a power amplifier operates are practically identical with those already described. The chief differences between a voltage amplifier and a power amplifier lie in the selection of tubes and in the choice of the value of load resistance. As previously described, if voltage gain is the primary consideration the load resistance should be as large as possible in comparison to the plate resistance of the tube. It can be shown that, in any electrical circuit, maximum power output is secured when the resistance of the load is made equal to the internal resistance of the source of power. This is true whether the power source is a battery, a generator or a vacuum tube. In the case of the vacuum tube the internal resistance is the plate resistance of the tube, so that for maximum power output the load resistance should be made equal to the plate resistance. However, when the tube is operated with such a low value of plate load resistance there is always considerable harmonic distortion, and it has been found that optimum power output, representing an acceptable compromise between distortion and the amount of power obtainable, is secured when the load resistance is approximately twice the plate resistance.

**Power-amplifier circuits** — The plate or output circuit of a power amplifier almost invariably is transformer-coupled to the power-

consuming device or load with which it is associated. This is because the impedance of the desired load seldom is the proper value for obtaining optimum power output from the amplifier. Consequently, the load impedance must be changed to a value suitable for the plate circuit of the amplifier tube. This can be done by using transformers, as described in § 2-9.

A basic power-amplifier circuit is shown in Fig. 316. So long as the amplifier is operated entirely in the negative-grid region and no grid current flows, any of the previously described types of coupling may be used between the grid of the power amplifier and the preceding amplifier. If there is no preceding amplifier, the method of coupling will depend principally on the characteristics of the source of the signal.

In Fig. 316 the load is represented as a resistance. An actual load may have a reactance as well as a resistance component, but only the resistance will consume power (§ 2-8).

**Power amplification ratio** — The ratio of a.c. output power to the a.c. power consumed in the grid circuit (*driving power*) is called the *power amplification ratio* or simply *power amplification* of the amplifier. If the amplifier operates without grid current the a.c. power consumed in the grid circuit is negligibly small, so that the power amplification ratio of such an amplifier is extremely large. With other types of operation the power amplification ratio may be relatively small, as described in § 3-4.

**Plate efficiency** — The ratio of a.c. output power to the d.c. power supplied to the plate circuit of an amplifier is called the *plate efficiency* of the amplifier. It is usually expressed as a percentage:

$$\% \text{ plate efficiency} = \frac{P_o}{EI} \times 100$$

where  $P_o$  is the a.c. output power,  $E$  is the plate voltage and  $I$  is the plate current, the latter two being d.c. values.

The plate efficiency of amplifiers designed for minimum distortion and a high power amplification ratio (operation without grid current) is relatively low — of the order of 15 to 30 per cent. For minimum distortion the operation must be confined to the region where the waveshape of the alternating plate current is substantially identical with that of the signal on the grid, and, as previously explained, this requirement can be met only by limiting the plate-current variations (that is, the alternating component of plate current) to the straight portion of the dynamic grid voltage vs. plate current characteristic. Since with a given load resistance the power output is proportional to the square of the alternating component of plate current, it follows that limiting the plate-current variation also limits the power output in comparison to the d.c. plate power input.

Higher plate efficiency can be secured by increasing the alternating component of plate current, but this is accompanied by increased distortion. Special types of amplifiers have

been devised to compensate for this distortion, as described in the next section. In some applications, as in r.f. power amplification, the fact that the signal applied to the grid is greatly distorted is of no consequence, so that such amplifiers can have high plate efficiency.

**Power sensitivity** — The ratio of a.c. power output to alternating grid voltage is called the *power sensitivity* of an amplifier. It provides a convenient measure for comparing power tubes, especially those designed for audio-frequency amplification where the operation is to be without grid current, since it expresses the relationship between power output and the amount of signal voltage required to produce the power.

The term power sensitivity also is used in connection with radio-frequency power amplifiers, in which case it has the same meaning as power amplification ratio. A tube which delivers its rated output power with a relatively small amount of power consumed in the grid circuit is said to have high power sensitivity.

**Parallel operation** — When it is necessary to obtain more power output than one tube is capable of giving, two or more tubes may be connected in *parallel*. In this case the similar elements in all tubes are connected together. This method is shown in Fig. 317 for a transformer-coupled amplifier. The power output of a parallel stage will be in proportion to the number of tubes used; the exciting voltage required, however, is the same as for one tube.

If the amplifier operates in such a way as to consume power in the grid circuit, the grid power required also is in proportion to the number of tubes used.

**Push-pull operation** — An increase in power output can be secured by connecting two tubes in *push-pull*, the grids and plates of the two tubes being connected to opposite ends of the circuit as shown in Fig. 317. A "balanced" circuit, in which the cathode returns are made to the midpoint of the input and output devices, is necessary with push-pull operation. At any instant the ends of the secondary winding of the input transformer,  $T_1$ , will be at opposite potentials with respect to the cathode connection, so that the grid of one tube is swung positive at the same instant that the grid of the other is swung negative. Hence, in any push-pull-connected stage the voltages and currents of one tube are out of phase with those of the other tube. The plate current of one tube therefore is rising while the plate current of the other is falling, hence the name "push-pull." In push-pull operation the even-harmonic (second, fourth, etc.) distortion is cancelled in the symmetrical plate circuit, so that for the same power output the distortion will be less than with parallel operation.

The exciting voltage measured between the two grids must be twice that required for one tube. If the grids consume power, the driving power for the push-pull stage is twice that taken by either tube alone.

**The decibel** — The ratio of the power levels at two points in a circuit such as an amplifier can be expressed in terms of a unit called the *decibel*, abbreviated *db*. The number of decibels is 10 times the logarithm of the power ratio, or

$$db. = 10 \log \frac{P_1}{P_2}$$

The decibel is a particularly useful unit because it is logarithmic, and thus corresponds to the response of the human ear to sounds of varying loudness. One decibel is approximately the power ratio required to make a just noticeable difference in sound intensity. Within wide limits, changing the power by a given ratio produces the same apparent change in loudness regardless of the power level; thus if the power is doubled the increase is 3 db., or three steps of intensity; if it is doubled again the increase is again 3 db., or three further distinguishable steps. Successive amplifications expressed in decibels can be added to obtain the overall amplification.

A power loss also can be expressed in decibels. A decrease in power is indicated by a minus sign (e.g., - 7 db.), and an increase in power by a plus sign (e.g., + 4 db.). Negative and positive quantities can be added numerically. Zero db. indicates the reference power level, or a power ratio of 1.

**Applications of amplification** — The major uses of vacuum-tube amplifiers in radio work are for amplifying at audio and radio frequencies (§ 2-7). The audio-frequency amplifier generally is used to amplify without discrimination at all frequencies in a wide range (say from 100 to 3000 cycles for voice communication), and therefore is associated with non-resonant or untuned circuits which offer a uniform load over the desired range. The radio-frequency amplifier, on the other hand, generally is used to amplify selectively at a single radio

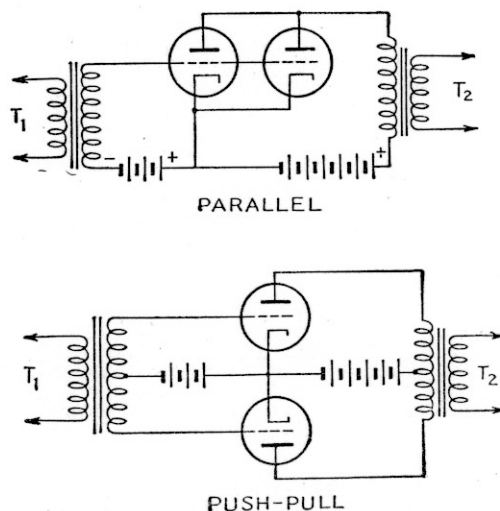


Fig. 317 — Parallel and push-pull amplifier circuits.

frequency, or over a small band of frequencies at most, and therefore is associated with resonant circuits tunable to the desired frequency.

An audio-frequency amplifier may be considered a *broad-band amplifier*; most radio-frequency amplifiers are designed to have relatively narrow bandwidths.

In audio circuits the power tube or output tube in the last stage usually is designed to deliver a considerable amount of audio power, while requiring but negligible power from the input or exciting signal. To get the alternating voltage (*grid swing*) required for the grid of such a tube, voltage amplifiers are used employing high- $\mu$  tubes which greatly increase the voltage amplitude of the signal. Voltage amplifiers are used in the radio-frequency stages of receivers as well as in audio amplifiers; power amplifiers are used in the radio-frequency stages of transmitters.

### 3-4 Classes of Amplifiers

**Reason for classification.**— It is convenient to divide amplifiers into groups according to the work they are intended to perform, as related to the operating conditions necessary to accomplish the purpose. This makes identification easy and obviates the necessity for giving a detailed description of the operation when specific operating data are not required.

**Class A**— An amplifier operated as shown in Fig. 306 or 307, in which the output waveshape is a faithful reproduction of the input waveshape, is known as a *Class-A* amplifier.

As generally used, the grid of a Class-A amplifier never is driven positive with respect to the cathode by the exciting signal, and never is driven so far negative that plate-current cut-off is reached. The plate current is constant both with and without grid excitation. The chief characteristics of the Class-A amplifier are low distortion, relatively low power output for a given size of tube, and a high power-amplification ratio. The plate efficiency is relatively low (§ 3-3).

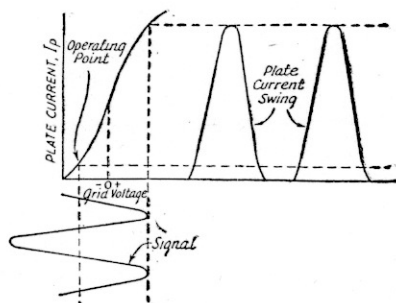


Fig. 318 — Class-B amplifier operation.

Class-A power amplifiers find application as output amplifiers in audio systems and as drivers for Class-B power amplifiers. Class-A voltage amplifiers are found in the stages preceding the power stage or stages in such applications, and as r.f. amplifiers in receivers.

**Class B**— The *Class-B* amplifier is primarily one in which the output current, or alternating component of the plate current, is proportional to the amplitude of the exciting grid voltage. Since power is proportional to the square of the current, the power output of a Class-B amplifier is proportional to the square of the exciting grid voltage.

The distinguishing operating condition in Class-B service is that the grid bias is set so that the plate current is relatively low without grid excitation; the exciting signal amplitude is made such that the entire linear portion of the tube's characteristic is used. Fig. 318 illustrates Class-B operation with the tube biased practically to cut-off. In this operating condition plate current flows only during the positive half-cycle of excitation voltage. No plate current flows during the negative swing of the excitation voltage. The shape of the plate current pulse is essentially the same as that of the positive swing of the signal voltage. Since the plate current is driven up toward the saturation point, it is usually necessary for the grid to be driven positive with respect to the cathode during part of the grid swing. Grid current flows, therefore, and the driving source must furnish power to supply the grid losses.

Class-B amplifiers are characterized by medium power output, medium plate efficiency (50 to 60 per cent at maximum signal), and a moderate ratio of power amplification. At radio frequencies they are used as *linear amplifiers* to raise the output power level in radio-telephone transmitters after modulation.

For Class-B audio-frequency amplification, two tubes must be used. The second tube, working alternately with the first, must be included so that both halves of the cycle will be present in the output. A typical method of arranging the tubes and circuit to achieve this is shown in Fig. 319. The signal is fed to a transformer,  $T_1$ , whose secondary is divided into two equal parts, with the tube grids connected to the outer terminals and the grid bias fed in at the center. A transformer,  $T_2$ , with a similarly divided primary, is connected to the plates of the tubes. When the signal voltage in the upper half of  $T_1$  is positive with respect to the center connection (*center tap*), the upper tube draws plate current while the lower tube is idle; when the lower half of  $T_1$  becomes positive, the lower tube draws plate current while the upper tube is idle. The corresponding voltages induced in the halves of the primary of  $T_2$  combine in the secondary to produce an amplified reproduction of the signal waveshape.

The Class-B amplifier is capable of delivering much more power for a given tube size than a Class-A amplifier. While Class-B audio-frequency operation produces somewhat more distortion than Class-A, for most purposes the distortion is small enough to be neglected.

**Class AB**— The similarity between Fig. 319 and the ordinary push-pull amplifier circuit (Fig. 317) will be noted. Actually the circuits



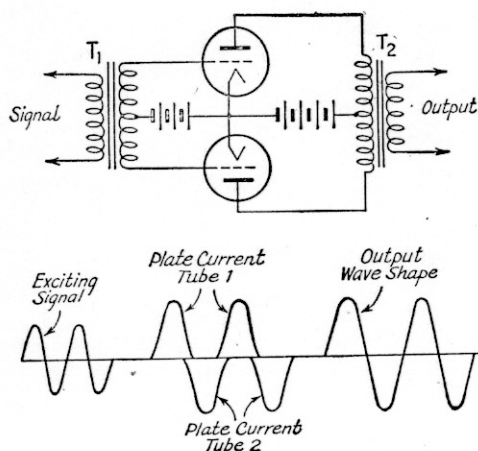


Fig. 319 — The Class-B audio amplifier, showing how the outputs of the two tubes in push-pull are combined.

are the same, the difference being in the method of operation. If the bias is adjusted so that the tubes draw a moderate value of plate current with no signal, the amplifier will operate Class A at low signal voltages and more nearly Class B at high signal voltages. An amplifier so operated is called *Class AB*. The advantages of this method are low distortion at moderate signal levels and high plate efficiency at high signal levels, making it possible to use relatively small tubes in audio power amplifiers.

A further distinction can be made between amplifiers which draw grid current and those which do not. The *Class-AB<sub>1</sub>* amplifier draws no grid current and thus consumes no power from the driving source. The *Class-AB<sub>2</sub>* amplifier draws grid current at higher signal levels, and power must be supplied to its grid circuit.

**Class C** — The *Class-C* amplifier is one operated so that the alternating component of the plate current is directly proportional to the plate voltage. The output power is therefore proportional to the square of the plate voltage. Other characteristics inherent to Class-C operation are high plate efficiency, high power output, and relatively low power amplification.

The grid bias for a Class-C amplifier is ordinarily set at a value at least twice that required for plate-current cut-off without grid excitation. As a result, plate current flows during only a fraction of the positive excitation cycle. The exciting signal should be of sufficient amplitude to drive the plate current to the saturation point, as shown in Fig. 320. Since the grid must be driven far into the positive region to cause saturation, considerable numbers of electrons are attracted to the grid at the peak of the cycle, robbing the plate of some that it would normally attract. This causes the droop at the upper bend of the characteristic, and also may cause the plate-current pulse to be indented at the top. The output pulse-wave-form is badly distorted, but at radio frequencies the distortion is largely eliminated by the flywheel effect of the tuned output circuit.

Although requiring considerable driving power, because of the relatively large grid swing and grid-current flow, the high plate efficiency (ordinarily 70 to 80 per cent) of the Class-C amplifier makes it an effective generator of radio-frequency power.

### 3-5 Multi-Element and Special-Purpose Tubes

**Radio-frequency amplification** — As described in the preceding section, the reactances of the grid-to-cathode and plate-to-cathode capacities (together with unavoidable stray capacities) in an amplifier circuit become very low at frequencies higher than the audio-frequency range. As a result, ordinary resistance, impedance or transformer coupling cannot be used at radio frequencies, because these capacities act as low-reactance by-passes across the input and output circuits; hence the total impedance in either the plate or grid circuit is too low for appreciable voltage to be developed.

When an amplifier is to be operated at radio frequencies it is necessary to use resonant circuits as loads, the circuits being tuned to the frequency to be amplified. Since such circuits consist of coils and condensers, the tube and stray capacities become part of the total tuning capacity and are thus made to serve a useful purpose. As described in § 2-10, the parallel impedance of a resonant circuit can reach quite high values when the  $Q$  is high. Values of parallel-resonant impedance suitable for effective amplification are readily obtainable with reasonably well-designed tuned circuits.

Since maximum parallel impedance, and consequently maximum amplification when resonant circuits are associated with an amplifier tube, is obtained when the circuit is exactly resonant at the applied frequency, it is necessary that the resonant circuit associated with the grid and that connected to the plate be tuned to the same frequency. In practice, it is difficult to maintain exact tuning over a

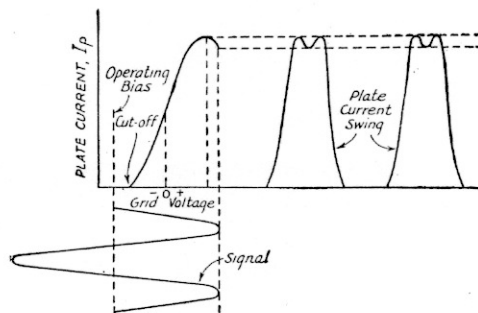


Fig. 320 — Class-C amplifier operation.

period of time. If the amplifier tube is a triode, its input circuit will have a negative-resistance characteristic (§ 3-3) when the plate-circuit load has inductive reactance. If the resonant circuit associated with the plate is tuned slightly to the high-frequency side of exact

resonance, the circuit will have inductive reactance, and energy will be transferred from the plate circuit to the grid circuit. Such a circuit has positive feed-back, or is regenerative. If enough energy is so transferred (very little is required) the tube will generate a self-sustaining radio-frequency current, in which case it is said to be *oscillating*. When oscillation commences the circuit ceases to operate as an amplifier of incoming signals, since it is generating a signal of its own.

Oscillation can be prevented by using special circuits with triode amplifiers, but in practice these are unsatisfactory in receiving applications. Since the feed-back arises because of the grid-plate capacity of the tube, it can be eliminated by eliminating the grid-plate capacity.

**Screen-grid tubes** — The grid-plate capacity can be eliminated, or at least reduced to a negligible value, by inserting a second grid between the control grid and the plate as indicated in Fig. 321. The second grid, called the *screen grid* or *shield grid*, acts as an electrostatic shield (§ 2-11) between the control grid and plate. It is made in the form of a grid or coarse screen rather than as a solid metal sheet, so that electrons can pass through it to the plate; a solid shield would entirely prevent the flow of plate current. The screen grid is connected to the cathode through a path, such as a by-pass condenser, which has low impedance at the radio frequency being amplified. The electric lines of force from the plate practically all terminate on the screen grid, very little of the field getting through to the control grid; similarly, the field set up by the control grid does not penetrate past the screen grid. Thus

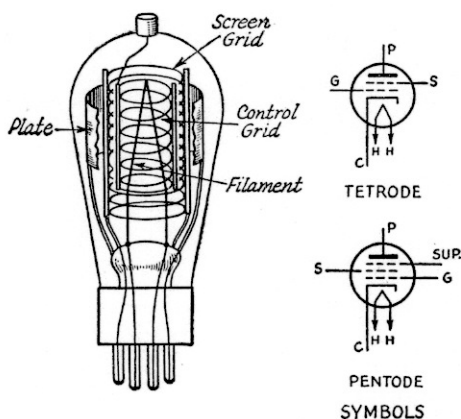


Fig. 321 — Representative arrangement of elements in a screen-grid tube, with front part of plate and screen-grid cut away. The screen grid usually is made longer than either the control grid or plate, so that the shielding will be as effective as possible. In this drawing the control grid connection is made through a cap on the top of the tube, thus eliminating the capacity which would exist between the plate and grid lead wires if both passed through the base. Some modern tubes which have both leads going through the base use special shielding and construction to eliminate capacity. Symbols for pentode and tetrode tubes: H, heater; C, cathode; G, control grid; P, plate; S, screen grid; Sup., suppressor grid.

there is no common field between the control grid and plate, and hence no capacity between these two tube elements.

Since the electric field from the plate does not penetrate into the region occupied by the control grid, which is the region in which most of the space charge is concentrated, the plate is unable to exert an attraction upon the electrons in this region. Consequently, the plate voltage cannot control the flow of plate current as it does in a triode. In order to get electrons to the plate, it is necessary to apply a positive potential (with respect to the cathode) to the screen. The screen then attracts electrons much in the same way as does the plate in a triode tube. In traveling toward the screen the electrons acquire velocity, and most of them shoot between the screen wires into the region where the field from the plate is effective. Those that pass through and are attracted to the plate constitute the plate current of the tube. A certain proportion of the electrons do strike the screen, however, with the result that a current also flows to the screen grid. In a properly designed screen-grid tube, the screen current will be low compared to the plate current with normal operating potentials.

A tube with two grids, such as is shown in Fig. 321, is a *tetrode*, or four-element tube.

**Secondary emission** — When an electron traveling at appreciable velocity through a tube strikes the plate it dislodges other electrons, which "splash" from the plate into the interelement space. This phenomenon is called *secondary emission*. In the triode, ordinarily operated with the grid negative with respect to cathode, these secondary electrons are repelled back into the plate and cause no disturbance. In the screen-grid tube, however, the positively charged screen grid attracts the secondary electrons, causing a reverse current to flow between screen and plate. The effect is particularly marked when the plate and screen potentials are nearly equal, which may be the case during the part of the a.c. cycle when the instantaneous plate current is large and the plate voltage low (§ 3-3).

**Pentode tubes** — To overcome the effects of secondary emission, a third grid, called the *suppressor grid*, may be inserted between the screen and plate. This grid is connected directly to the cathode, and repels the relatively low-velocity secondary electrons back to the plate without obstructing to any appreciable extent the regular plate-current flow.

Although the screen grid in either the tetrode or pentode greatly reduces the influence of the plate upon plate-current flow, it is quite obvious that the control grid still can control the plate current in essentially the same way that it does in a triode, since the control grid is still in the space-charge region. Consequently, the grid-plate transconductance (or mutual conductance) of a tetrode or pentode will be of the same order of value as in a triode of corresponding structure. On the other hand, since

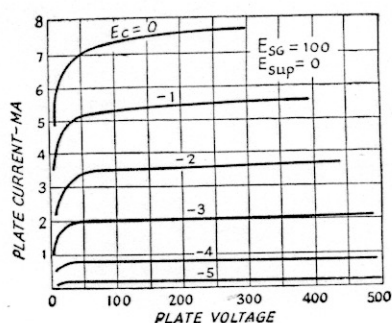


Fig. 322 — Plate voltage vs. plate current curves of a small receiving pentode. Plate voltage has relatively little effect on plate current. In taking these curves, the screen-grid voltage,  $E_{sg}$ , was 100 volts and suppressor-grid voltage,  $E_{sup}$ , zero with respect to the cathode.

the plate voltage has very little effect on the plate-current flow, both the amplification factor and plate resistance of a pentode or tetrode are very high, as is apparent from the definitions of these constants (§ 3-2). In small pentodes used for receiving purposes the amplification factor is usually of the order of 1000, while the plate resistance may be from 0.5 to 1 or more megohms. Because of the high plate resistance, the actual voltage amplification possible with a pentode is very much less than the large amplification factor might indicate. In resistance-coupled audio-frequency amplifiers, a voltage amplification or gain of 100 to 200 is typical.

A typical set of characteristic curves for a small pentode is shown in Fig. 322. That the plate voltage has little effect on the plate current is indicated by the fact that the curves are practically horizontal once the plate voltage is high enough to prevent the electrons in the space between the screen grid and the plate from being attracted back to the screen. The plate potential at which this occurs is considerably less than the screen potential, because the electrons entering the space have considerable velocity and hence tend to move away from the screen despite the fact that the screen has a positive charge.

In addition to their applications as radio-frequency amplifiers, pentode or tetrode screen grid tubes also can be constructed for audio-frequency power amplification. In tubes designed for this purpose the shielding effect of the screen grid is not so important; the chief function of the screen is to serve as an accelerator of the electrons, so that large values of plate current can be drawn at relatively low plate voltages. Such tubes have quite high power sensitivity (§ 3-4) compared to triodes of the same power output, because the amplification factor of an equivalent triode has to be made quite low in order to secure the same plate current at the same plate voltage. Because of the low  $\mu$ , the triode requires a relatively large signal voltage for full output, hence has low power sensitivity. The harmonic distortion is somewhat greater with pentodes and tetrodes than with triodes, however.

**Beam tubes** — A “beam”-type tube is a tetrode with grids so constructed as to form the electrons traveling to the plate into concentrated beams, resulting in higher plate efficiency and power sensitivity. Suitable design also overcomes the effects of secondary emission without the necessity for a suppressor grid. Tubes constructed on the beam principle are used in receivers as both r.f. and audio amplifiers, and are built in larger sizes for transmitting circuits.

**Variable- $\mu$  and sharp cut-off tubes** — Receiving screen-grid tetrodes and pentodes for radio-frequency voltage amplification are made in two types, known as *sharp cut-off* and *variable- $\mu$*  or “super-control” types. In the sharp cut-off type the amplification factor is practically constant regardless of grid bias, while in the variable- $\mu$  type the amplification factor decreases as the negative bias is increased. The purpose of this design is to permit the tube to handle large signal voltages without distortion in circuits in which grid-bias control is used to vary the mutual conductance, and hence the amplification.

The way in which mutual conductance varies with grid bias in two typical small receiving pentodes, similar except in that one is a sharp cut-off type and the other a variable- $\mu$  type, is shown in Fig. 323. Obviously, the variable- $\mu$  type can handle a much larger signal voltage without swinging either beyond zero grid bias or plate-current cut-off (zero mutual conductance) if the bias is properly chosen.

**Multi-purpose types** — A number of combination types of tubes have been constructed to perform multiple functions, particularly in receiver circuits. Among the simplest are full-wave rectifiers, combining two diodes in one envelope, and twin triodes, consisting of two triodes in one bulb for Class-B audio amplification. More complex types include duplex-diode triodes, duplex-diode pentodes, converters and mixers (for superheterodyne receivers), combination power tubes and rectifiers, and so on. In many cases the nature of the tube structure can be identified by the name.

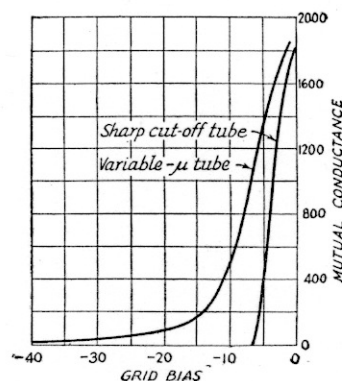


Fig. 323 — Curves showing mutual conductance vs. negative grid bias for two small receiving pentodes, one a sharp cut-off type and the other a variable- $\mu$  type.



**Mercury-vapor rectifiers** — For a given value of plate current, the power lost in a diode rectifier (§ 3-1) will be lessened if it is possible to decrease the plate-cathode voltage at which the current is obtained. If a small amount of mercury is put in the tube, the mercury will vaporize when the cathode is heated, and, further, will ionize (§ 2-4) when plate voltage is applied. The positive ions neutralize the space charge and reduce the plate-cathode voltage drop to a practically constant value of about 15 volts, regardless of the value of plate current. Since this voltage drop is much smaller than can be attained with purely thermionic conduction, there is less power loss in the rectifier. That the voltage drop is constant when the current varies also is an advantage. Mercury-vapor tubes are widely used in power rectifiers.

**Grid-control rectifiers** — If a grid is inserted in a mercury-vapor rectifier it is found that with sufficient negative grid bias it is possible to prevent plate current from flowing, but only if the bias is present before plate voltage is applied. If the bias is lowered to the point where plate current can flow, the mercury vapor will ionize and the grid will lose control of plate current, since the space charge disappears when ionization occurs. It can assume control again only after the plate voltage is reduced below the ionizing potential. The same phenomenon also occurs in triodes filled with other gases which ionize at low pressure. Grid-control rectifiers find considerable application in "electronic switching" circuits.

### § 3-6 Common Elements in Vacuum-Tube Circuits

**Types of cathodes** — Cathodes are of two general types, directly and indirectly heated. Directly heated cathodes or filaments used in receiving tubes are of the *oxide-coated* type, consisting of a wire or ribbon of tungsten coated with certain rare metals and earths which form an oxide capable of emitting large numbers of electrons with comparatively little cathode-heating power.

When directly heated cathodes are operated on alternating current, the cyclic variation of current causes electrostatic and magnetic effects which vary the plate current of the tube at the supply-frequency rate and thus produce hum in the output. Hum from this source is eliminated by the *indirectly heated* cathode, consisting of a thin metal sleeve or thimble, coated with electron-emitting oxides, enclosing a tungsten wire which acts as a heater. The heater brings the cathode thimble to the proper temperature to cause electron emission. This type of cathode is also known as the *equipotential* cathode since all parts are at the same potential, in contrast to the directly heated filament where a voltage drop occurs along the wire because of the heating current which flows through it.

When a tube has a directly heated cathode, the source of filament power — battery or

transformer — necessarily is directly connected to the tube circuit. On the other hand, if the tube has an indirectly heated cathode the source of heating power can be entirely independent of the tube circuit, since the electron-emitting cathode need not be electrically connected to the heating element. This is an advantage in certain types of amplifiers.

While the oxide-coated cathode is the most efficient type, in that it emits large numbers of electrons per watt of heating power, it is suitable only for tubes operating at plate voltages of 1000 volts or less. In the manufacture of the tube there is some tendency for the electron-emitting material to be deposited on the control grid. While this is of little consequence in receiving tubes, it leads to difficulties in power-tube operation. A receiving tube is usually operated with little or no grid current, so that only very small amounts of power must be dissipated by the grid. On the other hand, a power tube operated as a Class-C amplifier or oscillator will take considerable grid current, so that the power the grid must dissipate is relatively high and its temperature will rise correspondingly. In addition, both cathode and plate power dissipation are large in tubes handling large amounts of power, further raising the internal tube temperature, so that the control-grid temperature in a power tube readily may be high enough to cause electron emission from the deposited oxide material. When this occurs, the grid is in effect a second cathode. The plate will attract the electrons so emitted, increasing the total plate current without increasing the power output, with the result that the plate efficiency is lowered and the plate temperature rises. This in turn tends to increase the grid temperature, causing more electron emission, and in a short time the tube will "run away" — that is, its plate current will increase to unsafe values and the power output will decrease.

A second factor which makes oxide-coated cathodes unsuitable for power tubes is bombardment of the cathode by positive ions.

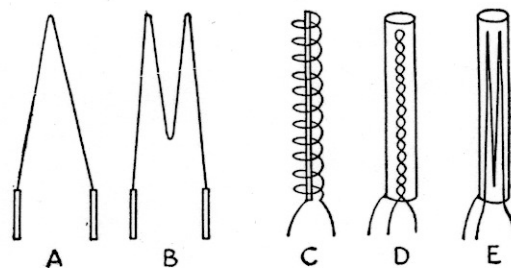


Fig. 324 — Types of cathode construction. Directly heated cathodes or filaments are shown at A, B, and C. The inverted V filament is used in small receiving tubes, the M in both receiving and transmitting tubes. The spiral filament is a transmitting-tube type. The indirectly heated cathodes at D and E show two types of heater construction, one a twisted loop and the other bunched heater wires. Both types tend to cancel the magnetic fields set up by the current through the heater.

Although by far the greater part of the air is pumped out of the tube, it is impossible to obtain a complete vacuum; there is always some residual gas. The gas molecules will become ionized when the tube is operating (§ 2-4), separating into an electron and a positively charged ion, with the latter having practically all the weight of the molecule. The heavy positive ion is repelled by the positive charge on the plate and driven at high velocity into the cathode. The force of the collision breaks up the electron-emitting material, frequently stripping whole sections of it from the heating wire or sleeve.

Tubes intended for operation at voltages up to about three or four thousand volts usually are made with *thoriated-tungsten* cathodes. This type of cathode always is directly heated, consisting of a filament of tungsten containing dissolved thorium. The presence of the thorium makes the filament much more efficient as an electron emitter than tungsten alone, but the thoriated filament is in turn less efficient than the oxide-coated type. However, it is free from the grid-emission effects described above. While it is less susceptible to positive ion bombardment than the oxide-coated type, partly because less gas is trapped or "occluded" in the cathode itself, the beneficial effect of the thorium can be destroyed (at least temporarily) by bombardment.

Since the bombardment increases with higher plate voltages, thoriated filaments become unusable at very high voltages, and tubes built to operate at several thousand volts are provided with cathodes of pure tungsten. This material must be operated at high temperature (white heat) for reasonable electron-emission efficiency, but even under this condition is very much less efficient than either the thoriated or oxide-coated cathode. However, it is the only type which is satisfactory in high-voltage operation.

The operating temperature of a thoriated tungsten filament is fairly critical, particularly with respect to good life characteristics, and the filament voltage should be maintained within a few per cent of the value specified by the manufacturer. These filaments, as well as oxide-coated cathodes, eventually "lose emission"; that is, the emission efficiency of the cathode decreases to the point where it is impossible to obtain sufficient electron emission for satisfactory tube operation without raising the cathode temperature to an unsafe value. Pure tungsten cathodes do not lose emission, but the high operating temperature makes them more susceptible to "burn-out."

**Methods of obtaining grid bias**—Grid bias may be obtained from a source of voltage especially provided for that purpose, such as a battery or other type of d.c. power supply. This is indicated in Fig. 325-A. A second method, utilizing a *cathode resistor*, is shown at B; d.c. plate current flowing through the resistor causes a voltage drop which, with the

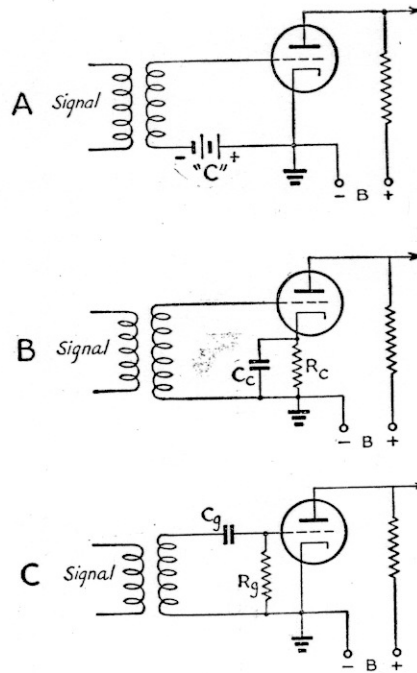


Fig. 325 — The three basic methods of obtaining grid bias. A, fixed bias; B, cathode bias; C, grid-leak bias.

connections shown, has the right polarity to bias the grid negatively with respect to the cathode. The value of the resistor is determined by the bias required and the plate current which flows at that value of bias, as found from the tube characteristic curves; with the voltage and current known, the resistance can be determined by Ohm's Law (§ 2-6):

$$R_c = \frac{E \times 1000}{I_c}$$

where  $R_c$  = cathode bias resistor in ohms

$E$  = desired bias voltage

$I_c$  = total d.c. cathode current in milliamperes.

If the tube is a multi-element type, the screen and suppressor-grid currents should be added to the plate current to obtain the total cathode current. The control-grid current also should be included if the control grid is driven positive.

The a.c. component of plate current flowing through the cathode resistor will cause an a.c. voltage drop which gives negative feed-back (§ 3-3) into the grid circuit, and thus reduces the amplification. To prevent this, the resistor usually is by-passed (§ 2-13),  $C_c$  being the *cathode by-pass condenser*. To be effective, the reactance of the by-pass condenser must be small compared to  $R_c$  at the frequency being amplified. This condition generally is satisfied if the reactance is 10 per cent or less of the cathode resistance. In audio-frequency amplifiers, the *lowest* frequency at which full amplification must be secured should be used in calculating the required capacity.

A third biasing method is by use of a *grid leak*,  $R_g$  in Fig. 325-C. This requires that the ex-

citing voltage be positive with respect to the cathode during part of the cycle, so that grid current will flow. The flow of grid current through the grid leak causes a voltage drop across the resistor, which gives the grid a negative bias. The time constant (§ 2-6) of the grid leak and grid condenser should be large in comparison to the time of one cycle of the exciting voltage, so that the grid bias will be substantially constant and will not follow the variations in a.c. grid voltage. For grid-leak bias,

$$R_g = \frac{E \times 1000}{I_g}$$

where  $R_g$  = grid-leak resistance in ohms

$E$  = desired bias voltage

$I_g$  = d.c. grid current in milliamperes.

When two tubes are operated in push-pull or parallel and use a common cathode- or grid-leak resistor, the value of resistance becomes one-half what it would be for one tube. In push-pull Class-A circuits operating at audio frequencies, it is unnecessary to by-pass the cathode resistor to prevent negative feed-back. In this case the a.c. component of cathode current in one tube is out of phase with the a.c. component in the other, so that the two components cancel each other.

The choice of a biasing method depends upon the type of operation. Fixed bias generally is required where the d.c. plate current of the amplifier varies in operation, as in Class-B audio-frequency amplifiers. If cathode bias is used in such a case the bias voltage will vary with the plate current, which usually is undesirable. Since the plate current of a Class-A amplifier is constant with or without signal, such amplifiers almost invariably have cathode bias. Grid-leak bias cannot be used with amplifiers operated so that the grid is always negative with respect to the cathode, since in such

a case there is no grid current and hence no voltage drop in the grid leak. Grid-leak bias is chiefly used for r.f. power amplifiers and for certain types of detectors. In some types of power amplifiers, two or even all three types of bias may be used on one tube.

#### Cathode circuits; filament center tap—

When a filament-type cathode is heated by a.c., the hum introduced can be minimized by making the two ends of the filament have equal and opposite potentials with respect to a center point, usually grounded (§ 2-13), to which the grid and plate return circuits are connected. The filament transformer winding is frequently *center-tapped* for this purpose, as shown in Fig. 326-A. The same result can be secured with an untapped winding by substituting a center-tapped resistor of 10 to 50 ohms, as at B. The by-pass condensers,  $C_1$  and  $C_2$ , are used in radio-frequency circuits to avoid having the r.f. current flow through the transformer or resistor, either of which may have considerable reactance at r.f.

The filament supply for tubes with indirectly heated cathodes sometimes is center-tapped for the same purpose; although frequently one side of the filament supply, and hence one terminal of the heater, is grounded.

### § 3-7 Oscillators

**Self-oscillation**—The possibility of making an amplifier tube generate a sustained radio-frequency current already has been mentioned (§ 3-5). Self-oscillation is possible only because of the amplifying action of the tube, hence a triode or multi-element tube must be used. The ordinary diode does not amplify, and consequently cannot be made to oscillate.

In an amplifier circuit having positive feed-back, the total amplification is larger than it would be without feed-back (§ 3-3). In general the greater the feed-back the greater the total amplification, but the process of increasing feed-back for greater amplification cannot be carried on indefinitely. Because of the amplifying properties of the tube, more energy is developed in the plate circuit than is required in the grid circuit. If enough energy is fed back to the grid, the feed-back process becomes independent of any applied signal voltage and continuous oscillations are generated. That is, the tube supplies its own grid excitation. The actual energy required to overcome the grid losses is, in the end, taken from the d.c. plate supply.

It is sometimes helpful to look at oscillation from the standpoint of *negative resistance*. As previously described (§ 3-3), positive feed-back is equivalent to shunting a negative resistance across the input circuit of the tube. When the value of negative resistance becomes lower than the positive resistance of the circuit (if the circuit is parallel resonant the positive resistance will be the resonant impedance of the circuit) the net resistance is negative, indicating that the circuit can be looked upon as a *source of energy*. Such a source is capable of

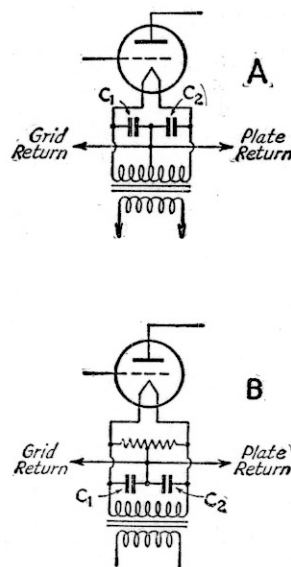


Fig. 326 — Filament center-tap connections.



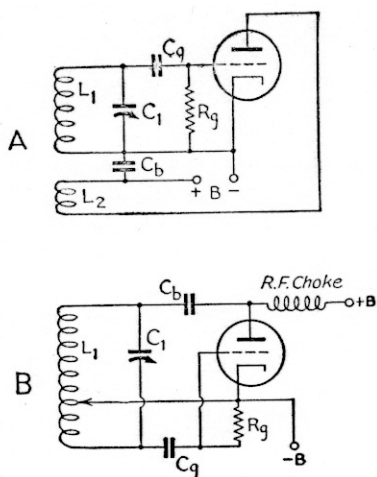


Fig. 327 — Two types of oscillator circuits with magnetic feed-back. A, tickler circuit; B, Hartley circuit.

maintaining a constant voltage which can be amplified by the tube. The actual energy, of course, comes from the plate circuit of the tube, so that the two viewpoints are equivalent.

A circuit having the property of generating continuous oscillations is called an *oscillator*. It is not necessary to apply external excitation to such a circuit, since any random variation in current will be amplified to cause oscillation. The frequency of oscillation will be that at which the feed-back voltage has the proper phase and amplitude. In the case of the resonant circuits usually associated with oscillators, it is very nearly the resonant frequency of the tuned circuit.

**Magnetic feed-back** — One form of feed-back is by electromagnetic coupling between plate (output) and grid (input) circuits. Two representative circuits of this type are shown in Fig. 327. That at A is called the *tickler* circuit. The amplified current flowing in the "tickler,"  $L_2$ , induces a voltage in  $L_1$  in the proper phase when the coils are wound in the same direction and are connected as shown in the diagram. The feed-back can be adjusted by adjusting the coupling between  $L_1$  and  $L_2$ .

The *Hartley* circuit, B, is similar in principle. There is only one coil, but it is divided so that part of it is in the plate circuit and part in the grid circuit. The magnetic coupling between the two sections of the coil provides the feed-back, which can be adjusted by moving the tap on the coil.

**Capacity feed-back** — The feed-back can also be obtained through capacity coupling, as shown in Fig. 328. In A, the *Colpitts* circuit, the voltage across the resonant circuit is divided, by means of the series condensers, into two parts. The instantaneous voltages at the ends of the circuit are opposite in polarity with respect to the cathode, hence in the right phase to sustain oscillation.

The tuned-grid tuned-plate circuit at B utilizes the grid-plate capacity of the tube

to provide feed-back coupling. There should be no magnetic coupling between the two tuned-circuit coils. Feed-back can be adjusted by varying the tuning of either the grid or plate circuit. The circuit with the higher  $Q$  (§ 2-10) determines the frequency of oscillation. The plate circuit must be tuned to a slightly higher frequency than the grid circuit, so that it will have inductive reactance and hence give positive feed-back (§ 3-3). The amount of detuning required is small, so it is customary to assume that the circuits are tuned to approximately the same frequency.

The *ultraudion* circuit at C is equivalent to the Colpitts, with the voltage division for oscillation brought about through the grid-to-filament and plate-to-filament capacities of the tube. In this and in the Colpitts circuit, the feed-back can be controlled by varying the ratio of the two capacities. In the ultraudion circuit, this can be done by connecting a small variable condenser between grid and cathode.

**Crystal oscillators** — Since a properly cut quartz crystal is equivalent to a high- $Q$  tuned circuit (§ 2-10), it may be substituted for a conventional tuned circuit in an oscillator to control the frequency of oscillation. A simple crystal oscillator circuit is shown in Fig. 329. It will be recognized as the tuned-plate tuned-grid circuit with the crystal substituted for the resonant circuit in the grid. Many variations of this fundamental circuit are used in practice.

**Series and parallel feed** — A circuit such as the tickler circuit of Fig. 327-A is said to be *series fed* because the source of plate voltage and the r.f. plate circuit (the tickler coil) are

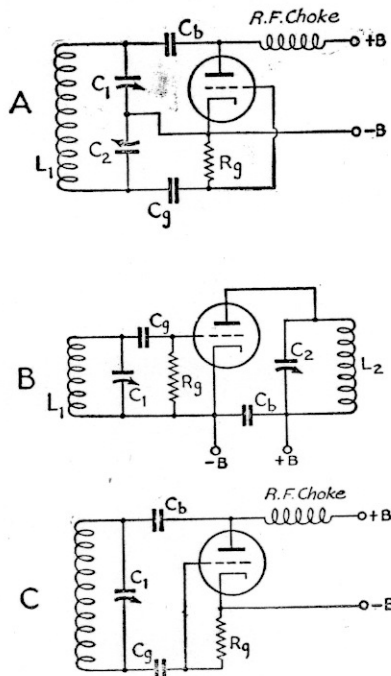


Fig. 328 — Oscillator circuits with capacity feed-back. A, Colpitts; B, tuned-plate tuned-grid; C, ultraudion.

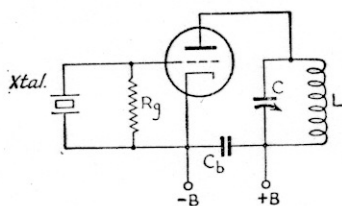


Fig. 329 — Simple crystal oscillator circuit.

connected in series, hence the d.c. plate current flows through the coil to the plate. A by-pass (§ 2-13) condenser,  $C_b$ , must be connected across the plate supply to shunt the radio-frequency current around the source of power. Other examples of series plate feed are shown in Figs. 328-B and 329.

In some cases the source of plate power must be connected in parallel with the tuned circuit in order to provide a path for direct current to the plate. This is illustrated by the Hartley circuit of Fig. 327-B, where it would be impossible to feed the plate current through the coil because there is a direct connection between the coil and cathode. Hence the voltage is applied to the plate through a radio-frequency choke, which prevents the r.f. current from flowing to the plate supply and thus short-circuiting the oscillator. The blocking condenser,  $C_b$ , provides a low-impedance path for radio-frequency current flow but is an open circuit for direct current (§ 2-13). Other examples of parallel feed are shown in Figs. 328-A and 328-C.

Values of chokes, by-pass and blocking condensers are determined by the considerations outlined in § 2-13.

**Excitation and bias** — The excitation voltage required depends upon the characteristics of the tube and the losses in the circuit, including the power consumed in the load. In practically all oscillators the grid is driven positive during part of the cycle, so that power is consumed in the grid circuit (§ 3-2). This power must be supplied by the plate circuit. With insufficient excitation, the tube will not oscillate; with too-high excitation, the *grid losses*, or power consumed in the grid circuit, will be excessive.

Oscillators are almost always grid-leak biased (§ 3-6). This not only takes advantage of the grid-current flow but also gives better operation, since the bias adjusts itself to the excitation voltage available.

**Tank circuit** — The resonant circuit associated with the oscillator generally is called the *tank circuit*. This name derives from the storage of energy associated with a resonant circuit of reasonably high  $Q$  (§ 2-10). It is applied to any resonant circuit in transmitting applications, whether used in an oscillator or in an amplifier.

**Power output** — The *power output* of an oscillator is the useful a.c. power consumed in a load connected to the oscillator. The load may be coupled as described in § 2-11.

**Plate efficiency** — The *plate efficiency* (§ 3-3) of an oscillator depends upon the load resistance, excitation and other operating conditions, and usually is in the vicinity of 50 per cent. It is not as high as in the case of an amplifier since the oscillator must supply its own grid losses, which usually are 10 per cent to 20 per cent of the output power.

**Frequency stability** — The frequency stability of an oscillator is its ability to maintain constant frequency in the presence of variable operating conditions. The more important factors which may cause a change in frequency are (1) plate voltage, (2) temperature, (3) loading, (4) mechanical variations of circuit elements. Plate-voltage variations will cause a corresponding instantaneous shift in frequency; this type of frequency shift is called *dynamic instability*. Temperature changes will cause tube elements to expand or contract slightly, thus causing variations in the interelectrode capacities (§ 3-2), and since these are unavoidably part of the tuned circuit the frequency will change correspondingly. Temperature changes in the coil or condenser will change the inductance and capacity slightly, again causing a shift in the resonant frequency. Both these temperature effects are relatively slow in operation, and the frequency change caused by them is called *drift*. Load variations act in much the same way as plate voltage variations except when there is a temperature change in the load, when drift also may be present. Mechanical variations, usually caused by vibration, cause changes in inductance and/or capacity which in turn cause the frequency to "wobble" in step with the vibration.

Dynamic instability can be reduced by using a tuned circuit of high effective  $Q$ , which means, since the tube and load represent a relatively low resistance in parallel with the circuit, that a low  $L/C$  ratio ("high- $C$ ") must be used (§ 2-10) and that the circuit should be lightly loaded. Dynamic stability also can be improved by using a high value of grid leak, which gives high grid bias and raises the effective resistance of the tube as seen by the tank circuit, and by using relatively high plate voltage and low plate current, which accomplishes the same result. Drift can be minimized by using low d.c. input (for the size of tube), by using coils of large wire to prevent undue temperature rise, and by providing good venti-

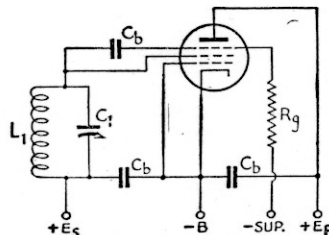


Fig. 330 — Negative-resistance oscillator. This circuit, known as the "transitron," requires that the screen be operated at a higher d.c. potential than the plate.

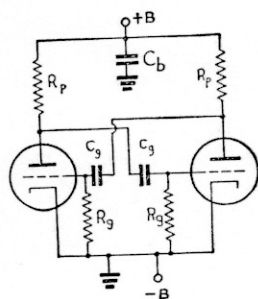


Fig. 331 — The multivibrator, or relaxation oscillator.

can be prevented by using well-designed components and insulating the oscillator from mechanical vibration.

**Negative-resistance oscillators** — If a resonant circuit were completely free from losses, a current once started would continue indefinitely; that is, sustained oscillations would occur. As previously explained, this condition can be simulated in practice by canceling the actual resistance in the circuit by inserting an equal or greater amount of *negative resistance*. Negative resistance is exhibited by any device showing an increase of current when the applied voltage is decreased, or vice versa.

In addition to negative resistance by feedback, the vacuum tube can be made to show negative resistance by a number of arrangements of electrode potentials. One such circuit is shown in Fig. 330. Negative resistance is produced by virtue of the fact that, as the suppressor grid of a pentode is given more negative bias, electrons normally passing through to the plate are turned back to the screen, thus increasing the screen current and reversing normal tube action (§ 3-2). The negative resistance so produced is sufficiently low so that ordinary tuned circuits will oscillate readily at frequencies up to 15 Mc. or so.

**The multivibrator** — The type of oscillator circuit shown in Fig. 331 is known as the *multivibrator*, or *relaxation oscillator*. Two tubes are used with resistance coupling, the output of one tube being fed to the input circuit of the other. The frequency of oscillation is determined by the time constants (§ 2-6) of the resistance-capacity combinations. The principle of oscillation is the same as in the feedback circuits already described, the second tube being necessary to obtain the proper phase relationship (§ 3-3) for oscillation when the energy is fed back.

The multivibrator is a very unstable oscillator, and for this reason its frequency readily can be controlled by a small signal of steady frequency introduced into the circuit. This phenomenon is called *locking*. The output waveshape of the multivibrator is highly distorted, hence has high harmonic content (§ 2-7). A useful feature is that the multivibrator can be locked at its fundamental frequency by a frequency corre-

sponding to one of its higher harmonics (the tenth harmonic is frequently used), and thus can be used as a *frequency divider*.

### 3-8 Cathode-Ray Tubes

**Principles** — The cathode-ray tube is a vacuum tube in which the electrons emitted from a hot cathode are first accelerated to give them considerable velocity, then formed into a beam, and finally allowed to strike a special translucent screen which *fluoresces*, or gives off light at the point where the beam strikes. A narrow beam of moving electrons is analogous to a wire carrying current (§ 2-4) and, like the wire, is accompanied by electrostatic and electromagnetic fields. Hence the beam can be moved laterally or deflected by electric or magnetic fields, since such fields will exert a force on the beam in the same way as on charged bodies or on wires carrying current (§ 2-3, 2-5). Since the cathode-ray beam consists only of moving electrons, its weight and inertia are negligibly small. For this reason, it can be made to follow instantly the variations in fields which are changing periodically, even at very high radio frequencies.

**Electron gun** — The electrode arrangement which forms the electrons into a beam is called the *electron gun*. In the simple tube structure shown in Fig. 332, the gun consists of the cathode, grid, and anodes Nos. 1 and 2. The intensity of the electron beam is regulated by the grid in the same way as in an ordinary tube (§ 3-2). Anode No. 1 is operated at a positive potential with respect to the cathode, thus accelerating the electrons which pass through the grid, and is provided with small apertures through which the electron stream passes. On emerging from the apertures the electrons are traveling in practically parallel straight-line paths. The electrostatic fields set up by the potentials on anode No. 1 and anode No. 2 form an *electron lens* system, comparable to an optical lens, which makes the electron paths converge to a point at the fluorescent screen in much the same way that a glass lens takes parallel rays of light and brings them to a point focus. Focusing of the electron beam is accomplished by varying the potentials on the anodes, the potential in turn determining the strength of the field. In practice the potential on anode No. 2 is usually fixed, while that on anode No. 1 is varied to bring the beam to focus. Anode No. 1 is, therefore, frequently called the *focusing electrode*.

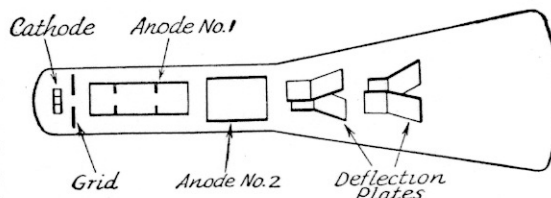


Fig. 332 — Arrangement of the elements in a cathode-ray tube of the type employing electrostatic beam deflection.



Sharpest focus is obtained when the electrons of the beam have high velocity, so that relatively high d.c. potentials are common with cathode-ray tubes. The current flowing to the anodes, however, is quite small (of the order of a few milliamperes at most), so that the power required is negligible. In some tubes a second grid is inserted between the control grid and anode No. 1, to provide additional acceleration of the electrons.

**Methods of deflection** — When focused, the beam from the gun simply produces a small spot on the screen, as just described. However, if after leaving the gun the beam is deflected by either magnetic or electrostatic fields, the spot will move across the screen in proportion to the force exerted on the beam. If the motion is sufficiently rapid, retentivity of vision makes the path of the moving spot (*trace*) appear as a continuous line.

Electrostatic deflection, generally used in the smaller tubes, is produced by *deflection plates*. Two sets of plates are placed at right angles to each other, as indicated in Fig. 332. The fields are created by applying suitable voltages between the two plates of each pair. Usually one plate of each pair is connected to anode No. 2, to establish the polarities (§ 2-3) of the fields with respect to the beam and to each other.

Tubes intended for magnetic deflection have the same type of gun, but have no deflection plates. Instead the deflecting fields are set up by means of coils, corresponding to the plates in tubes having electrostatic deflection. The coils are external to the tube but are mounted close to the glass envelope in the same relative positions occupied by the electrostatic deflection plates, as shown in Fig. 333. The coils marked  $A_1$  and  $A_2$  are connected so that their fields aid and have their axes on the same line through the tube. The coils marked  $B_1$  and  $B_2$  likewise are connected with fields aiding and also are aligned along the same axis through the tube, but this axis is perpendicular to the  $A_1$ - $A_2$  axis.

The beam deflection caused by a given change in the field intensity is called the *deflection sensitivity*. With electrostatic-deflection tubes it is usually expressed in millimeters per

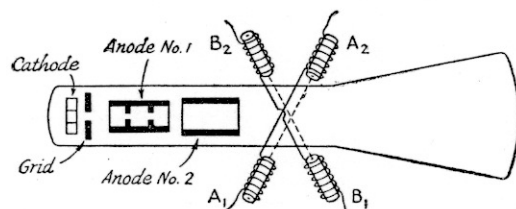


Fig. 333 — A cathode-ray tube with magnetic deflection. The gun represented here is the same as in the electrostatic-deflection tube shown in Fig. 332, but the beam is deflected by magnetic instead of electric fields. Actual deflection coils usually are formed to fit as closely as possible to the neck of the tube, so that the field will be as strong as possible for a given coil current.

volt, which gives the linear movement of the spot on the screen as a function of the voltage applied to a set of deflecting plates. Values range from about 0.1 to 0.6 mm/volt, depending upon the tube construction and gun electrode voltages. The sensitivity is decreased by an increase in anode No. 2 voltage because a higher voltage gives the electrons in the beam higher velocity, and hence they are less easily deflected by a field of given strength.

**Fluorescent screens** — The fluorescent screen materials used have varying characteristics, according to the type of work for which the tube is intended. The spot color is green, white, yellow or blue, depending upon the screen material. The *persistence* of the screen is the time duration of the after-glow which exists when the excitation of the electron beam is removed. Screens are classified as long-, medium- and short-persistence. Small tubes for oscilloscopic work usually are provided with medium-persistence screens of greenish fluorescence.

**Tube circuits** — A representative cathode-ray tube circuit with electrostatic deflection is shown in Fig. 334. One plate of each pair of deflecting plates is connected to anode No. 2. Since the voltages required normally are rather high, the positive terminal of the supply is usually grounded (§ 2-13) so that the common deflection plates will be at ground potential. This places the cathode and other elements at high potentials above ground, hence these elements must be well insulated. The various electrode voltages are obtained from a voltage divider (§ 2-6) across the high-voltage d.c. supply.  $R_3$  is a variable divider or "potentiometer" for adjusting the negative bias on the control grid and thereby varying the beam current; it is called the *intensity* or *brightness* control. The *focus*, or sharpness of the luminous spot formed on the screen by the beam, is controlled by  $R_4$ , which changes the ratio of the anode No. 2 and anode No. 1 voltages. The focusing and intensity controls interlock to some extent, and the sharpest focus is obtained by keeping the beam current low.

Deflecting voltages for the plates are applied to the terminals marked "input voltage,"  $R_1$  and  $R_2$  being high resistances (1 megohm or more) to drain off any accumulation of charge on the deflecting plates. Usually some provision is made to place an adjustable d.c. voltage on each set of plates, so that the spot can be "centered" when stray electrostatic or magnetic fields are present; the adjustable voltage simply neutralizes such fields.

The tube is mounted so that one set of plates produces a horizontal line when a varying voltage is applied to it, while the other set of plates produces a vertical line under similar conditions. They are called, respectively, the "horizontal" and "vertical" plates, but which set of actual plates produces which line is simply a matter of how the tube is mounted. It is usually necessary to provide a mounting which can be

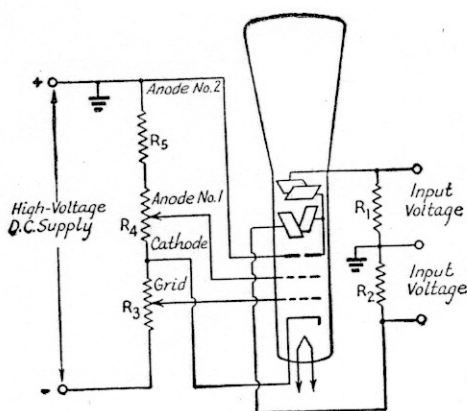


Fig. 334 — Cathode-ray tube circuit. Typical values for a 3-inch (screen-diameter) tube such as the 906:  
 $R_1, R_2$  — 1 to 10 megohms.  $R_4$  — 0.2 megohm.  
 $R_3$  — 20,000 ohms.  $R_5$  — 0.5 megohm.  
 The high-voltage supply should be about 1300 volts d.c.

rotated to some extent, so that the lines will actually be horizontal and vertical.

**Power supply** — The d.c. voltage required for operation of the tube may vary from 500 volts for the miniature type (1-inch diameter screen) to several thousand for the larger tubes. The current, however, is very small, so that the power required is likewise small. Because of the small current requirements, a rectified a.c. supply with half-wave rectification (§ 8-3) and a single 0.5 to 2- $\mu$ fd. condenser as a filter (§ 8-5) is satisfactory.

### § 3-9 The Oscilloscope

**Description** — An oscilloscope is essentially a cathode-ray tube in the basic circuit of Fig. 334, but with provision for supplying a suitable deflection voltage on one set of plates (ordinarily those giving horizontal deflection). The deflection voltage is called the *sweep*. Oscilloscopes frequently are also equipped with vacuum-tube amplifiers for increasing the amplitude of small a.c. voltages to values suitable for application to the deflecting plates. These amplifiers ordinarily are limited to operation in the audio-frequency range, and hence cannot be used at radio frequencies.

**Formation of patterns** — When periodically varying voltages are applied to the two sets of deflecting plates, the path traced by the fluorescent spot forms a *pattern* which is stationary so long as the amplitude and phase relationships of the voltages remain unchanged. Fig. 335 shows how such patterns are formed. The horizontal sweep voltage is assumed to have the "sawtooth" waveshape indicated; with no voltage applied to the vertical plates the trace simply sweeps from left to right across the screen along the horizontal axis  $X-X'$  until the instant H is reached, when it reverses direction and returns to the starting point. The sine-wave voltage applied to the vertical plates similarly would trace a line along the axis  $Y-Y'$  in the absence of any deflecting voltage on the horizontal plates. How-

ever, when both voltages are present the position of the spot at any instant depends upon the voltages on both sets of plates at that instant. Thus at time B the horizontal voltage has moved the spot a short distance to the right and the vertical voltage has similarly moved it upward, so that it reaches the actual position B' on the screen. The resulting trace is easily followed from the other indicated positions, which are taken at equal time intervals.

**Types of sweeps** — A horizontal sweep-voltage waveshape such as that shown in Fig. 335 is called a *linear sweep*, because the deflection in the horizontal direction is directly proportional to time. If the sweep were perfect the "fly-back" time, or time taken for the spot to return from the end (H) to the beginning (I or A) of the horizontal trace, would be zero, so that the line HI would be perpendicular to the axis  $Y-Y'$ . Although the fly-back time cannot be made zero in practicable sweep-voltage generators it can be made quite small in comparison to the time of the desired trace AH, at least at most frequencies within the audio range. The fly-back time is somewhat exaggerated in Fig. 335, to show its effect on the pattern. The line H'I' is called the *return trace*; with a linear sweep it is less brilliant than the pattern, because the spot is moving much more rapidly during the fly-back time than during the time of the main trace. If the fly-back time is short enough, the return trace will be invisible.

The linear sweep has the advantage that it shows the shape of the wave applied to the vertical plates in the same way in which it is usually represented graphically (§ 2-7). If the time of one cycle of the a.c. voltage applied to

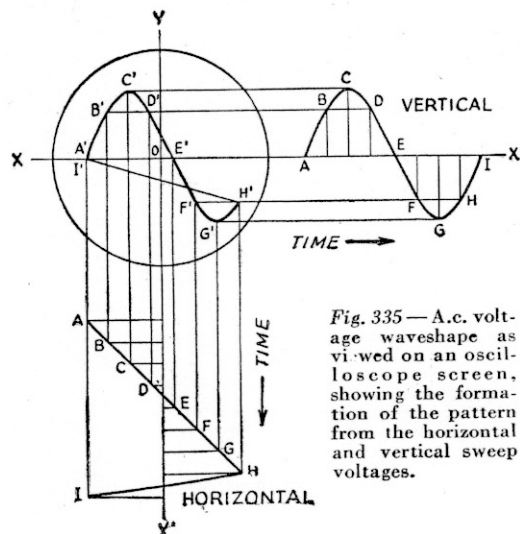


Fig. 335 — A.c. voltage waveshape as viewed on an oscilloscope screen, showing the formation of the pattern from the horizontal and vertical sweep voltages.

the vertical plates is a fraction of the time taken to sweep horizontally across the screen, several cycles of the vertical or signal voltage will appear in the pattern. The shape of only the last cycle (or the last few cycles, depending upon the number in the pattern and the

characteristics of the sweep) to appear will be affected by the fly-back in such a case.

Although the linear sweep generally is most useful, other sweep waveshapes may be desirable for certain purposes. The shape of the pattern obtained, with a given signal waveshape on the vertical plates, obviously will depend upon the shape of the horizontal sweep voltage. If the horizontal sweep is sinusoidal, the main and return sweeps each occupy the same time and the spot moves faster horizontally in the center of the pattern than it does at the ends. If two sinusoidal voltages of the same frequency are applied to both sets of plates the resulting pattern may be a straight line, an ellipse or a circle, depending upon the amplitude and phase relationships. If the frequencies are harmonically related (§ 2-7) a stationary pattern will result, but if one frequency is not an exact harmonic of the other the pattern will show continuous motion. This is also the case when a linear sweep circuit is used; the sweep frequency and the frequency under observation must be harmonically related or the pattern will not be stationary.

**Sweep circuits** — A sinusoidal sweep is easiest to obtain, since it is possible to apply a.c. voltage from the power line, either directly or through a suitable transformer, to the horizontal plates. A variable voltage divider or potentiometer can be used to regulate the width of the horizontal trace.

A typical circuit for a linear sweep is shown in Fig. 336. The tube is a *gas triode* or grid-control rectifier (§ 3-5). The breakdown voltage, or plate voltage at which the tube ionizes and starts conducting, is determined by the grid bias. When plate voltage is applied the voltage across  $C_1$  rises, as it acquires a charge through  $R_1$ , until the breakdown voltage is reached, when the condenser discharges rapidly through the comparatively low plate-cathode resistance of the tube. When the voltage drops to a value too low to maintain plate-current flow, the ionization is extinguished and  $C_1$

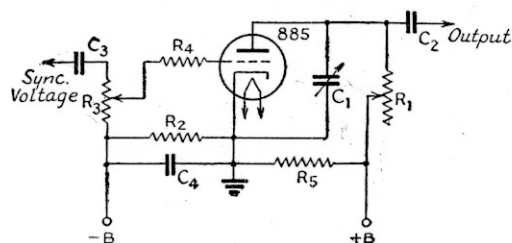


Fig. 336 — A linear sweep-oscillator using a gas triode.  
 $C_1$  — 0.001 to 0.25  $\mu$ fd.  $C_3$  — 0.1  $\mu$ fd.  
 $C_2$  — 0.5  $\mu$ fd.  $C_4$  — 25  $\mu$ fd., 25-volt electrolytic.  
 $R_1$  — 0.3 to 1.5 megohms.  
 $R_2$  — 2000 ohms.  $R_4$  — 25,000 ohms.  
 $R_3$  — 0.25 megohm.  $R_5$  — 0.1 megohm.  
 The "B" supply should deliver 300 volts.  $C_1$  and  $R_1$  are proportioned to give a suitable sweep frequency; the higher the time constant (§ 2-6), the lower the frequency.  $R_4$  limits grid-current flow during the de-ionizing period, when positive ions are attracted to the negative grid.

once more charges through  $R_1$ . If  $R_1$  is large enough, the voltage across  $C_1$  rises linearly with time up to the breakdown point. This voltage is used for the sweep, being coupled to the cathode-ray tube or to an amplifier through  $C_2$ . The fly-back is the time required for discharge through the tube, and to keep it small the resistance during discharge must be low.

To obtain a stationary pattern, the "sawtooth" frequency can be controlled by varying  $C_1$  and  $R_1$  and by introducing some of the voltage to be observed (on the vertical plates) into the grid circuit of the tube. This voltage "triggers" the tube into operation in synchronism with the signal frequency. Synchronization will occur even though the signal frequency is a multiple of the sweep frequency, provided the circuit constants and the amplitude of the synchronizing voltage are properly adjusted.

The voltage output of the type of circuit shown in Fig. 336 is limited, because the charging rate of the condenser is linear only on that portion of the logarithmic charging curve (§ 2-6) which is practically a straight line. A linear charging rate over a longer period of time can be secured by substituting a current-limiting device, such as a properly adjusted vacuum tube, for  $R_1$ .

**Amplifiers** — The usefulness of the oscilloscope is enhanced by providing amplifiers for both the horizontal and vertical sweep voltages, thereby insuring that sufficient voltage will be available at the deflection plates to give a pattern of suitable size. With small oscilloscope tubes (3-inch and smaller screens) the voltage required for a deflection of one inch varies from about 30 to 100 volts, depending upon the anode voltages, so that an amplifier tube capable of an undistorted peak output voltage of 100 or so is necessary. (With such an amplifier, the voltage difference, or total voltage "swing," between the positive and negative peaks is 200 volts.) A resistance-coupled voltage amplifier (§ 3-3) having a pentode tube is ordinarily used because of the high gain obtainable with this type of tube. The amplifier should be designed to have flat frequency response over as wide a range of audio frequencies as possible (§ 3-3, 5-9). Since a voltage gain of 100 to 150 or more is readily obtainable, full deflection of the beam can be secured with an input of one volt or less by the use of such an amplifier.

**Constructional considerations** — An oscilloscope should be housed in a metal cabinet, both to shield the tube from stray electromagnetic and electrostatic fields which might deflect the beam and also to protect the operator from the high voltages associated with the tube. It is good practice to provide an interlock switch which automatically disconnects the high-voltage supply when the cabinet is opened for servicing or other reasons.