5-1 The grid

The grid in a vacuum triode usually consists of a wire helix surrounding the cathode, as sketched in Fig. 5-1. If the grid potential is always negative, electrons are repelled and the grid current is negligible. This means that the power expended in the grid circuit to control the anode current is very small. It is desirable to minimize the area of the grid, so the number of electrons intercepted on their way to the anode is negligible. On the other hand, if the wires are spaced too widely, the grid's ability to control the anode current is reduced. Practical triodes are designed to strike a useful compromise between these conflicting requirements. The anode in vacuum tubes is commonly termed the *plate*, because of its shape in early tube designs. The conventional circuit symbol for a triode is shown in Fig. 5-2.

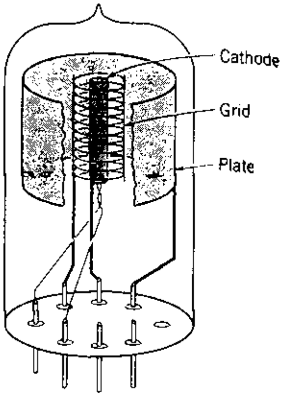


FIGURE 5-1 *Vacuum triode.*

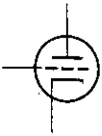


FIGURE 5-2 *Triode circuit symbol.*

The grid potential alters the electric-field configuration in the space between the cathode and plate from that corresponding to the vacuum diode discussed in the previous chapter. The manner in which this happens can be described in the following way. According to the derivation of Child's law, the plate voltage sets the current so that the electric field near the cathode is very small. The grid potential has a similar effect. Under the combined influence of the grid potential and the plate potential, the tube current is such that the electric field at the cathode remains small.

Since the grid is much closer to the cathode, its potential is relatively more effective in controlling the current than is the plate voltage. Therefore, using Child's law, the current in the tube may be written [1]

$$I_b = A(\mu V_c + V_b)^{3/2} \tag{5-1}$$

where A is a constant involving the tube geometry, V_c is the grid voltage, V_b is the plate voltage, and μ is a constant called the *amplification factor*. The amplification factor accounts for the greater effect of the grid voltage compared with the plate voltage. This equation agrees reasonably well with experimental current-voltage characteristics of practical triodes. It is difficult to evaluate A from first principles, however, and the exponent is often not exactly $3/2$. Therefore, it is common practice to display the characteristics of practical tubes graphically, rather than attempt an accurate mathematical representation.

The action of V_c in Eq. (5-1) opposes that of the plate voltage V_b since the grid potential is negative. An expression for the amplification factor is obtained by noting that these opposing actions cancel out if the electric charge induced on the cathode by the grid potential is equal and opposite to the charge produced by the plate voltage, or

$$-C_{gk}V_c + C_{pk}V_b = 0 \tag{5-2}$$

where C_{gk} is the capacitance between the grid and cathode. Solving for the amplification factor

$$\mu = \frac{V_b}{V_c} = \frac{C_{gk}}{C_{pk}} \tag{5-3}$$

According to Eq. (5-3) the amplification factor is increased if the grid is close to the cathode since the grid-cathode capacitance is increased. The plate is further away, and is shielded from the cathode by the grid, so that μ is always greater than unity. Actually, triodes with amplification factors ranging from 10 to 100 are commercially available.

5-2 Plate characteristics

Of the several graphical ways to represent the current-voltage characteristics of a triode, the most useful is a plot of the plate current as a function of plate voltage for fixed values of grid voltage. The curves for several grid potentials are called the *plate characteristics* of the tube. A typical set of plate characteristics, as provided by the tube manufacturer, is illustrated in Fig. 5-3. Note

[1] It has become commonly accepted to associate the subscripts p and b with the plate circuit and g and c with the grid circuit of a vacuum tube. Similarly, the subscript k refers to the cathode.

that each curve is similar to the current-voltage curve of a vacuum diode. Furthermore, the current at a given plate voltage is reduced as the grid is made increasingly negative. The plate cur-

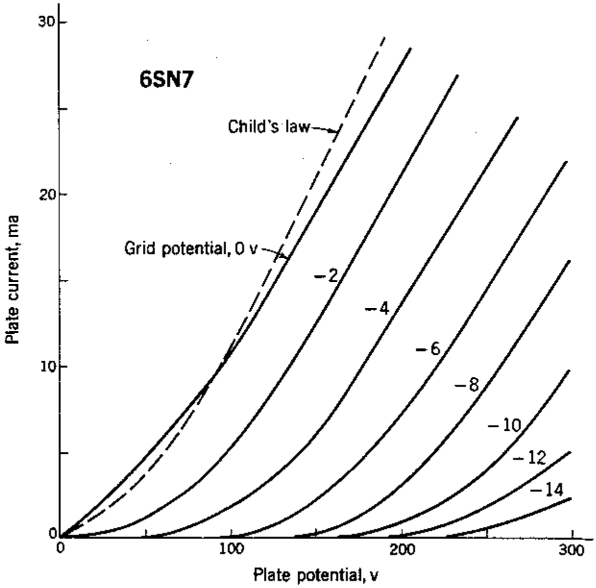


FIGURE 5-3 *Plate characteristics of type 6SN7 triode. Curve for zero grid voltage is in approximate agreement with Child's law.*

rent-voltage curves are displaced to the right with little change in shape for each negative increment in grid potential, in conformity with Eq. (5-1). Comparing Eq. (5-1) with the experimental curves shows why it is necessary to use graphical data: although Child's law represents the general behavior of the plate characteristics, it is not sufficiently accurate to yield satisfactory quantitative results (see Exercise 5-1).

According to Fig. 5-3, the plate current is essentially zero at sufficiently large negative grid potentials. The negative grid voltage necessary to put the tube in this *cutoff* condition depends upon the plate voltage. In effect, the tube is an open circuit when cut off. If the grid is at a positive potential, there is appreciable grid current. Then the grid is the anode of a diode biased in the forward direction and represents a much lower resistance than is the case for a negative grid voltage. In most circuits this effect prevents the grid from ever becoming positive. Therefore, at zero grid voltage the tube is said to be *saturated* since it is in its maximum conducting condition. The range between cutoff and saturation is the normal grid voltage range.

The plate characteristics for any triode are obtained experimentally with the aid of the circuit in Fig. 5-4, including suitable meters to measure the actual plate current and voltage. This circuit also illustrates how a triode is used as a simple amplifier. First it is necessary to plot the load line corresponding to the load resistance R_L on the plate characteristics. This is done just as for the vacuum diode considered in Chap. 4, by noting that the current is given by

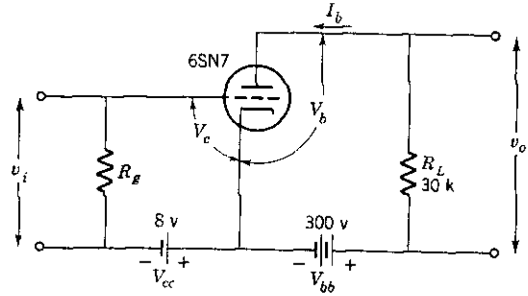


FIGURE 5-4 *Simple triode amplifier circuit.*

$$I_b = \frac{V_{bb} - V_b}{R_L} \tag{5-4}$$

As explained previously, this is the equation of a straight line with slope $-1/R_L$ with intercepts at ($V_b = 0$; $I_b = V_{bb}/R_L$) and ($V_b = V_{bb}$; $I_b = 0$), Fig. 5-5. The intersection of the load line with each curve of the plate characteristic gives the plate current for the given grid voltage.

The plate current and voltage corresponding to the dc grid bias V_{cc}, found by this procedure, is called the *operating point*. As the grid voltage varies in accordance with an applied ac input signal v_i, the plate-current excursions move back and forth along the load line, so Eq. (5-4) is satisfied at every instant. The corresponding changes in plate current give rise to an output signal across the load resistor. Suppose, for example, that the input signal is sinusoidal, as in Fig. 5-5. The output voltage is then also nearly sinusoidal but of much greater amplitude, indicating that the circuit amplifies the input signal.

Note that the input power is very small, because the grid current is negligible. In contrast, the output power, which is equal to the square of the ac plate current times the load resistance, may be appreciable. This power is derived from the plate voltage supply V_{bb} and is controlled by the valvelike action of the grid. The output voltage waveform is not an exact amplified replica of the input signal, because of curvature of the plate characteristics. This *distortion* is minimized by proper circuit design and by suitable choice of the operating point. Note also in Fig. 5-5 that as the grid voltage increases, the output voltage is reduced. This means that the triode amplifier introduces a 180° phase shift between the input and output signals. It is often convenient to account for this phase shift by writing the amplification factor as $-\mu$. The minus sign signifies that the output signal lags the input by a phase difference of 180°.

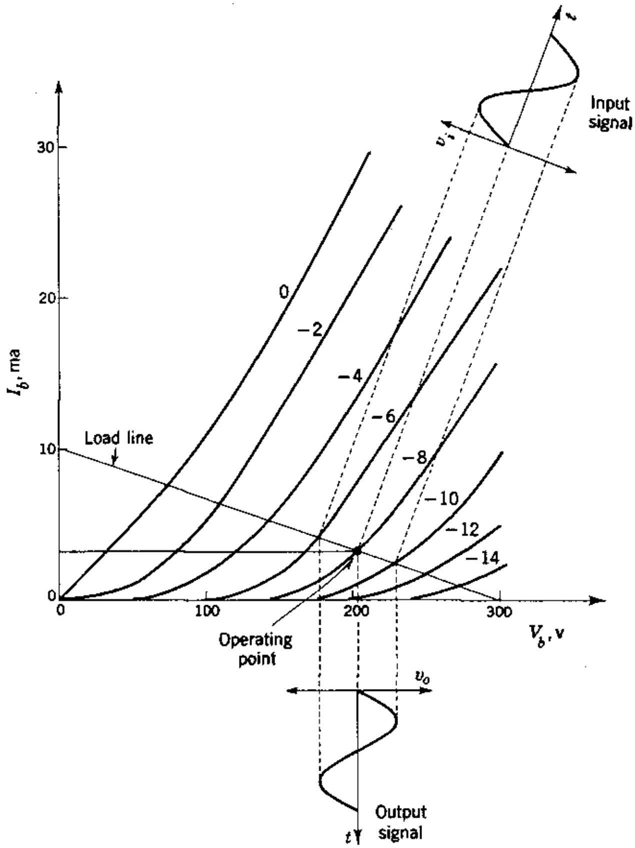


FIGURE 5-5 Analysis of triode amplifier of Fig. 5-4 using load line. Note 2-volt peak-to-peak input signal results in a 40-volt peak-to-peak output signal.

It is easier to determine the output waveform corresponding to a given input signal by using the *transfer characteristics* of a triode. These are curves of plate current as a function of grid voltage for fixed values of plate voltage, Fig. 5-6. Careful comparison of Figs. 5-5 and 5-6 reveals that the transfer characteristics contain the same basic information as the plate characteristics, so that one set of curves may be determined from the other. Actually, the dynamic transfer characteristic must be used to study the input-output properties because of the voltage drop across the load resistance. This is found by the same procedure developed for the vacuum diode in the previous chapter (see Exercises 5-2 and 5-3).

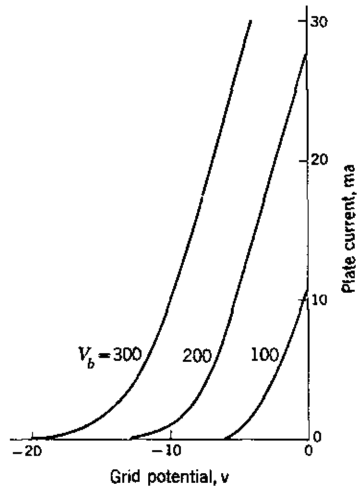


FIGURE 5-6 Transfer characteristics of type 6SN7 triode.

5-3 Small signal parameters

Very frequently the signal amplitudes applied to a vacuum tube are small compared with the full range of voltages covered by the plate characteristics. In this situation graphical analysis of tube performance is inaccurate because the plate characteristics are not given with sufficient precision. It is possible to represent the tube characteristics using an approximation to Child's law which is quite accurate for small signals. Once the operating point is established graphically, small departures about the operating point caused by small ac signals are treated by assuming the triode is linear. This approach may be illustrated in the following way. According to Child's law, Eq. (5-1), the plate current is a function of two variables, the plate voltage and the grid voltage,

$$I_b = f(V_c, V_b)$$

The change in plate current resulting from changes in grid voltage may be determined from the Taylor expansion of this equation about the operating point. Retaining only the first two terms, the change in plate current ΔI_b is written

$$\Delta I_b = \left(\frac{\partial I_b}{\partial V_c}\right)\Delta V_c + \left(\frac{\partial I_b}{\partial V_b}\right)\Delta V_b \qquad (5\text{-}5)$$

The first partial derivative in Eq. (5-5) is the slope of the transfer characteristic, Fig. 5-6, at the operating point and is called the *mutual transconductance* g_m. The meaning of this terminology is that g_m has the dimensions of conductance but relates the mutual changes between current in one circuit and voltage changes in another circuit. The second partial derivative in Eq. (5-5) is the slope of the plate characteristics, Fig. 5-3, at the operating point. The reciprocal of this slope is called the *plate resistance* r_p, since it represents the change in voltage associated with a change in current in the plate circuit. Introducing these definitions

$$g_m = \frac{\partial I_b}{\partial V_c}$$

and

$$\frac{1}{r_p} = \frac{\partial I_b}{\partial V_b} \tag{5-6}$$

Eq. (5-5) may be written

$$\Delta I_b = g_m \, \Delta V_c + \frac{1}{r_p} \, \Delta V_b \tag{5-7}$$

A useful relation between r_p and g_m is obtained by noting that if the net change in plate current is zero, Eq. (5-7) becomes

$$0 = g_m \, \Delta V_c + \frac{1}{r_p} \, \Delta V_b$$

or

$$g_m r_p = -\frac{\Delta V_b}{\Delta V_c} \tag{5-8}$$

The ratio $-\Delta V_b/\Delta V_c$ is just the definition of the amplification factor. The minus sign signifies that the plate voltage decreases when the grid potential increases, as discussed previously. Therefore, Eq. (5-8) is written

$$\mu = r_p g_m \tag{5-9}$$

This relation is useful in obtaining one of the three parameters if the other two are known.

If the variations ΔV_c and ΔV_b in Eq. (5-5) are sufficiently small, the partial derivatives may be regarded as constants and higher terms in the expansion safely ignored. The magnitudes of these *small signal parameters*, μ, r_p, and g_m, can be derived from the slopes of the characteristic curves at the operating point, as described above. So long as the quiescent operating point remains constant, the operation of the tube for small voltage signals around the operating point is adequately described by Eq. (5-7). Typical values of the small signal parameters for several triodes are given in Table 5-1.

The magnitudes of the small signal parameters depend upon the quiescent operating point. For this reason it is usually necessary

TABLE 5-1

TRIODE SMALL SIGNAL PARAMETERS

Type	μ	r_p, $10^3\ \Omega$	g_m, 10^{-3} *mho*
6C4	20	6.3	3.1
6CW4	68	5.4	12.5
6SL7	70	44	1.6
12AT7	55	5.5	10
12AU7	17	7.7	2.2
12AX7	100	62	1.6
7895	74	7.3	10.9

to evaluate μ, r_p, and g_m graphically at the point determined by the dc potentials and tube characteristics. To a first approximation, the amplification factor is independent of the operating point, since it depends only upon the ratio of the interelectrode capacitances, Eq. (5-3). The plate resistance depends upon the plate current, as may be shown with the aid of Child's law. Differentiating Eq. (5-1) with respect to V_b

$$\frac{1}{r_p} = \frac{\partial I_b}{\partial V_b} = {}^3\!/_2 A\,(\mu V_c + V_b)^{1/2} \tag{5-10}$$

Substituting for the quantity in parentheses from Eq. (5-1),

$$\frac{1}{r_p} = {}^3\!/_2 A \left(\frac{I_b}{A}\right)^{1/3} = {}^3\!/_2 A^{2/3} I_b^{\,1/3} \tag{5-11}$$

$$r_p = {}^2\!/_3 A^{-2/3} I_b^{\,-1/3} \tag{5-12}$$

According to Eq. (5-12), the plate resistance decreases slowly as the plate current increases. The variation of the mutual transconductance is also determined by differentiating Child's law with respect to V_c or, more simply, by using Eq. (5-9). Inserting Eq. (5-12) into Eq. (5-9) and solving for g_m,

$$g_m = {}^3\!/_2 A^{2/3} \mu I_b^{\,1/3} \tag{5-13}$$

which indicates that the mutual transconductance increases with plate current.

Since Child's law is not useful as a quantitative description of triode behavior, it is not expected that Eqs. (5-12) and (5-13) exactly represent the variation of the small signal parameters with tube current. Nevertheless, experimental data for a practical triode, Fig. 5-7, are in surprisingly good agreement with the analytical results. Note that the amplification factor is sensibly constant, except at the smallest plate currents, while g_m and r_p respectively increase and decrease with increasing plate current. According to Fig. 5-7, it is possible to obtain considerable variation in the small signal parameters by selecting different operating points. This is important in the design of vacuum-tube circuits for specific applications.

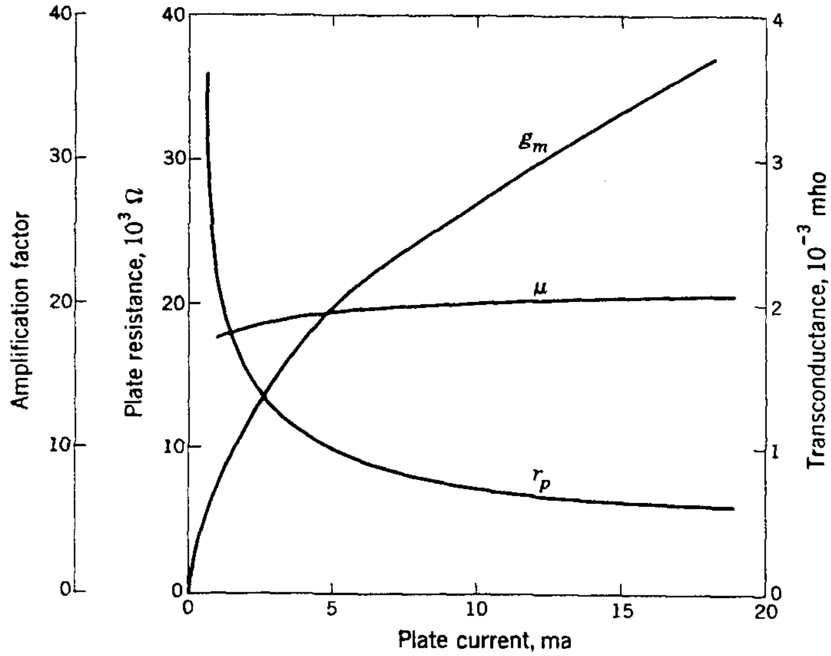


FIGURE 5-7 *Variation of triode small signal parameters with plate current.*

5-4 Triode equivalent circuit

The small signal parameters of a triode are used to calculate the performance of the tube in any circuit, so long as the signal voltages and currents are small compared with the quiescent dc values. According to Eq. (5-7), the ac component of the plate current is a function of the ac grid potential and the ac plate voltage so that

$$i_p = g_m v_g + \frac{1}{r_p} v_p \tag{5-14}$$

Henceforth the subscripts g and p signify the ac components of the grid and plate voltages (and currents), respectively. It must be kept in mind that the total electrode current or voltage has, in addition, a dc component corresponding to the operating point. After multiplying Eq. (5-14) by r_p and using Eq. (5-9), the ac plate voltage is given by

$$v_p = -\mu v_g + i_p r_p \tag{5-15}$$

Equation (5-15) may be interpreted as the series combination of a generator $-\mu v_g$ in series with a resistor r_p, as shown in Fig. 5-8. This configuration is reminiscent of the Thévenin equivalent circuit discussed in Chap. 1. Its validity in representing the performance of a triode rests on the concept of small signal parameters for a vacuum tube. Since Eq. (5-14) refers only to the ac components of the tube currents and voltages, Fig. 5-8 is called the *triode ac equivalent circuit.*

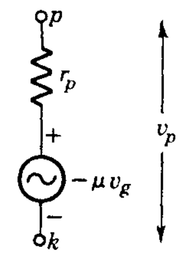


FIGURE 5-8 *Triode ac equivalent circuit.*

Consider the simple triode amplifier illustrated in Fig. 5-9*a*. According to Fig. 5-8, the equivalent circuit of the amplifier is obtained by replacing the triode with a generator and a resistor, as in Fig. 5-9*b*. Note that the dc battery supplies are omitted since the equivalent circuit refers only to ac quantities and the ac impedance of a battery is negligible. All other circuit components are included, however. According to Fig. 5-9*b*, there is no direct electrical connection between the input circuit and the output circuit. This illustrates the valve action of the grid in controlling the plate current with essentially zero power expenditure. Note that the minus sign associated with the generator accounts for the 180° phase difference between the grid voltage and the plate voltage.

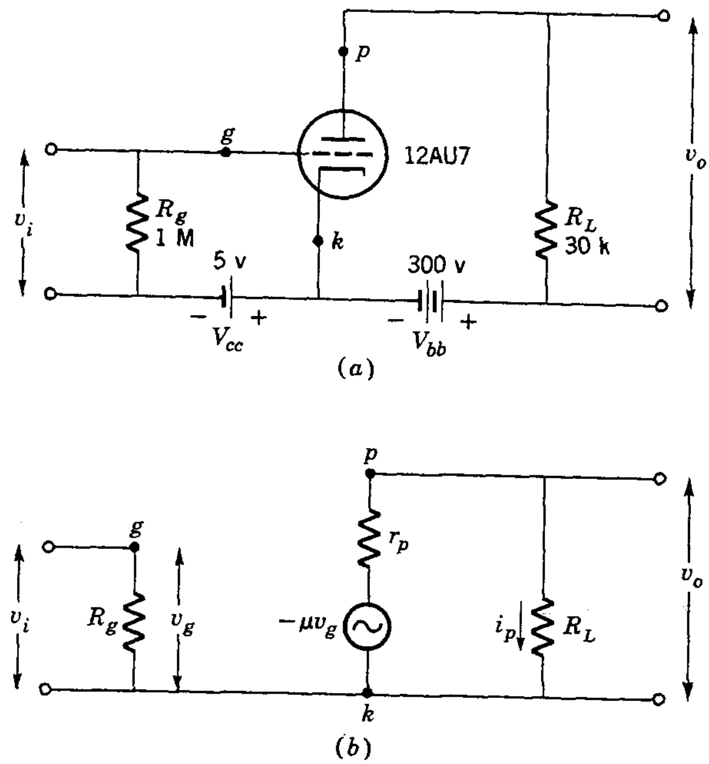


FIGURE 5-9 *(a) Triode amplifier and (b) its ac equivalent circuit.*

The output voltage of the amplifier circuit is calculated immediately from the equivalent circuit, Fig. 5-9*b*. The result is

$$v_o = i_p R_L = \frac{-\mu v_g}{r_p + R_L} R_L = \frac{-\mu v_g}{1 + r_p/R_L} \tag{5-16}$$

The ratio of the output signal to the input signal is called the *gain* of the amplifier. Suppressing the minus sign, since it represents only a 180° phase shift, and noticing that $v_g = v_i$, the gain of the amplifier is

$$a = \frac{v_o}{v_i} = \frac{\mu}{1 + r_p/R_L} \tag{5-17}$$

According to Eq. (5-17), the maximum gain of the circuit is equal to the amplification factor of the triode. This value is achieved when the load resistance is much greater than the plate resistance.

It is not always desirable to make the load resistance much larger than the triode plate resistance in a practical amplifier. A large load resistance introduces considerable dc power loss and requires a large plate supply voltage V_{bb} to put the tube at its optimum operating point. The amplification factor of most tubes is sufficiently large to yield appreciable gains with lower values of load resistance. It is also possible to use a transformer in the plate circuit. The impedance-matching properties of a transformer reflect a large ac impedance from the secondary, as explained in Chap. 2. In this case the dc resistance corresponds to the primary-winding resistance, which may be quite small. The expense and limited frequency range of transformers restrict their use to rather special applications.

The magnitude of the grid resistor R_g in this circuit is limited only by the voltage drop caused by residual grid current. The corresponding *IR* drop across R_g can change the grid bias from the value set by the grid bias battery V_{cc}. Since grid current is normally an uncontrolled quantity and varies considerably even between tubes of the same type, this is an undesirable condition. Grid resistances in the 0.5- to 10-MΩ range are satisfactory for most triodes. These values are large enough that the loading effect of the grid resistor on the input voltage source may be safely ignored in most applications.

PENTODES

5-5 Screen and suppressor grids

The capacitance between the grid and plate in a vacuum triode introduces serious difficulties when the tube is used as an amplifier at high frequencies. The ac plate signal introduced into the grid circuit through the grid-plate capacitance interferes with the proper operation of the circuit. Another grid is interposed in the space between the grid and plate to circumvent this difficulty. This *screen grid* is an effective electrostatic shield that reduces the grid-plate capacitance by a factor of 1000 or more. The screen grid is at a positive potential with respect to the cathode, and the current of electrons from cathode to plate is maintained. The helical grid winding is much more open than is the case for the control grid, so that the screen current is smaller than the plate current.

Two-grid four-electrode tubes called *tetrodes* are virtually obsolete except for certain special-purpose types. The reason for this is that electrons striking the plate dislodge other electrons. These may be attracted to the screen, particularly when the screen voltage is greater than the instantaneous plate potential. This introduces serious irregularities in the plate characteristics at low plate voltages. A *suppressor grid* is introduced between the screen and plate to eliminate this effect. The suppressor is held at cathode potential and effectively prevents all electrons dislodged from the plate from reaching the screen. The pitch of the suppressor grid helix is even larger than that of the screen grid. Therefore, the suppressor does not interfere with electrons passing from cathode to plate.

A tube with three grids is called a *pentode* because there are a total of five active electrodes. The conventional circuit symbol of a pentode is shown in Fig. 5-10. In normal operation the screen and

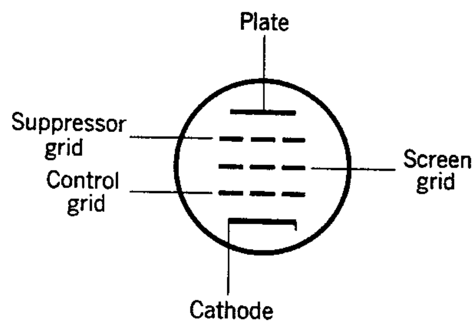


FIGURE 5-10 *Circuit symbol for pentode.*

suppressor grids are maintained at fixed dc potentials. Therefore the same small signal parameters used to describe the operation of a triode are suitable for pentodes as well. Addition of the screen and suppressor grids introduces major changes in the current-voltage characteristics, however, which are reflected in the magnitudes of the small signal parameters.

The influence of the plate potential on the electric field near the cathode is practically zero in pentodes, because of the shielding action of the screen and suppressor. This means that plate-voltage changes cause little or no change in the plate current, and, according to Eq. (5-6), the plate resistance is very large. Since the plate current is almost independent of the plate voltage, the plate characteristics are nearly straight lines parallel to the voltage axis. The action of the control grid is essentially the same as in a triode, however, so that their mutual transconductances are comparable. Therefore the amplification factor of a pentode is very large, according to Eq. (5-9). Typical values of plate resistance lie in the range 0.1 to 2 MΩ. Since g_m is of the order of 500 to 10,000 μmhos, the amplification factor may be as high as 10,000.

Typical plate characteristics of a pentode for a given positive screen potential and for the suppressor connected to the cathode are illustrated in Fig. 5-11. Note that the plate current is relatively independent of plate voltage, as anticipated above. The plate characteristics can be used to determine the operating point and circuit performance, much as in the case of a triode. Actually, however, the plate characteristics also depend upon the fixed screen potential. Higher screen voltages shift the curves in Fig. 5-11 upward to higher current values with little change in shape. It is common practice to specify pentode characteristics at two or three specific values of screen potential.

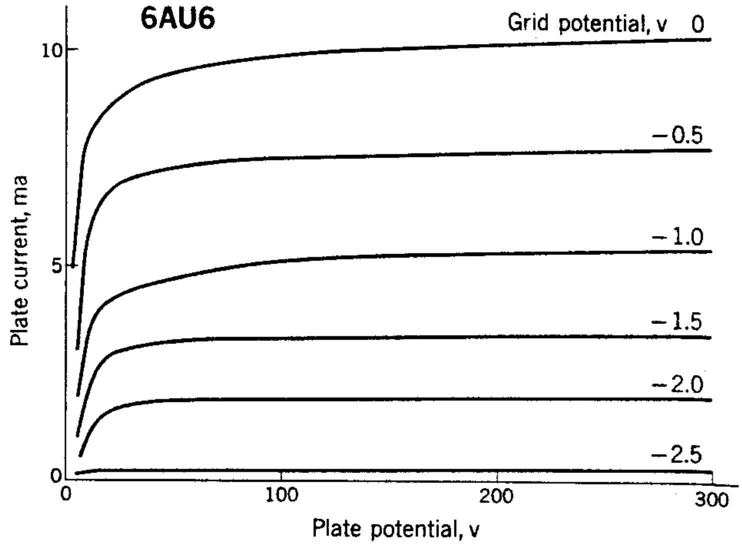


FIGURE 5-11 *Plate characteristics of type 6AU6 pentode.*

The screen voltage is maintained below the plate potential in most circuits. It turns out that the screen current is about 0.2 to 0.4 of the plate current at the recommended operating point. As mentioned above, it is almost universal to connect the suppressor grid to the cathode; in many tubes this connection is made internally.

The pentode is extensively used in amplifier circuits because of its very high amplification factor. It surpasses the triode as a high-frequency amplifier where small grid-plate capacitance is important. Plate-voltage excursions can be nearly as large as the plate supply voltage without introducing excessive distortion, so high-power operation is possible. Finally, the pentode is a useful constant-current source, because the plate current is essentially independent of the plate voltage.

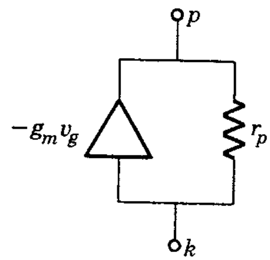
5-6 Norton equivalent circuit

Pentodes may be represented by the same equivalent circuit as triodes so long as appropriate values of the small signal parameters are used. These parameters depend upon the operating point and therefore vary with the screen and suppressor potentials, in addition to the grid bias and plate voltage. Because of the high plate resistance and constant-current properties of pentodes, it is generally most useful to use the Norton representation in preference to the Thévenin circuit. According to Eq. (1-85), the equivalent current generator is given by the ratio of the Thévenin equivalent voltage generator divided by the equivalent internal resistance. Therefore, using Fig. 5-8,

$$I_{eq} = \frac{-\mu v_g}{r_p} = -g_m v_g \tag{5-18}$$

The Norton equivalent circuit for a pentode is shown in Fig. 5-12.

FIGURE 5-12 Norton equivalent circuit of pentode.



A pentode amplifier stage, Fig. 5-13*a*, is represented by the equivalent circuit shown in Fig. 5-13*b*. The output voltage is simply the constant-current source times the parallel combination of the plate resistance and load resistance,

$$v_o = -g_m v_i \frac{r_p R_L}{r_p + R_L} \tag{5-19}$$

Neglecting the minus sign, the gain is

$$a = \frac{v_o}{v_i} = g_m \frac{R_L}{1 + R_L/r_p} \tag{5-20}$$

In most cases, the plate resistance is much greater than the load resistance so that a satisfactory approximation to Eq. (5-20) is just

$$a = g_m R_L \tag{5-21}$$

Plate load resistors much in excess of 0.1 MΩ or so are inconvenient, because the excessive dc-voltage drop caused by the plate current requires a very large plate-voltage source. Nevertheless, amplifications as great as $(10{,}000 \times 10^{-6}) \times (0.1 \times 10^{6}) = 1000$ are obtainable from a single pentode amplifier stage.

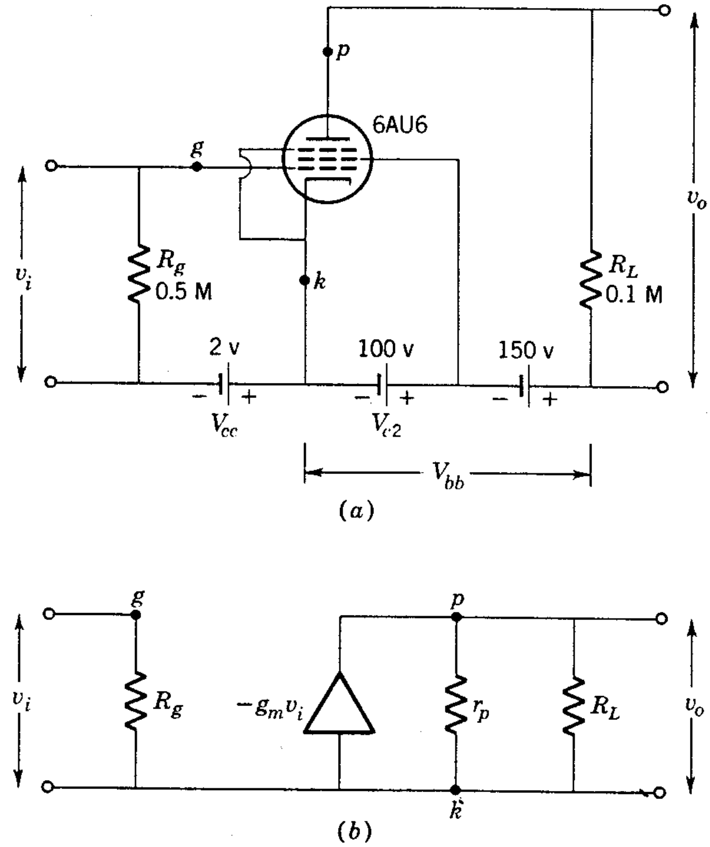


FIGURE 5-13 (*a*) *Elementary pentode amplifier.* (*b*) *its ac equivalent circuit.*

5-7 Other multigrid tubes

Many other vacuum-tube designs suitable for special circuit applications have been developed. A pentode having a control grid wound with a helix of varying pitch has an amplification factor that depends markedly upon the grid bias. This is so because electrons are controlled best in the region of the grid where the spacing is small. At sufficiently large values of negative grid bias the electron stream is cut off at this portion of the grid. Therefore, the amplification factor of the tube corresponds to that of a vacuum tube whose grid wires are widely spaced. At less negative biases the amplification factor is that of a tube with narrow grid spacing and the amplification factor is larger. These *variable-μ* tubes are used in automatic volume-control circuits where the amplification of the tube is automatically adjusted by controlling the grid bias. The bias is adjusted to maintain the output signal constant against variations in input signal. These designs are also called *remote-cutoff tubes*, since a very large negative grid voltage is required to reduce the plate current to a small value.

More than one electrode structure may be included within a single envelope when two tube types are often used together in circuits. An example of this is the dual vacuum diode for full-wave rectifier circuits discussed in the previous chapter. Other common structures are the dual triode and the dual diode-triode.

Many other combinations are possible and have been constructed. The symbol for a dual triode is indicated in Fig. 5-14*a*. This symbol also illustrates the method commonly employed to indi-

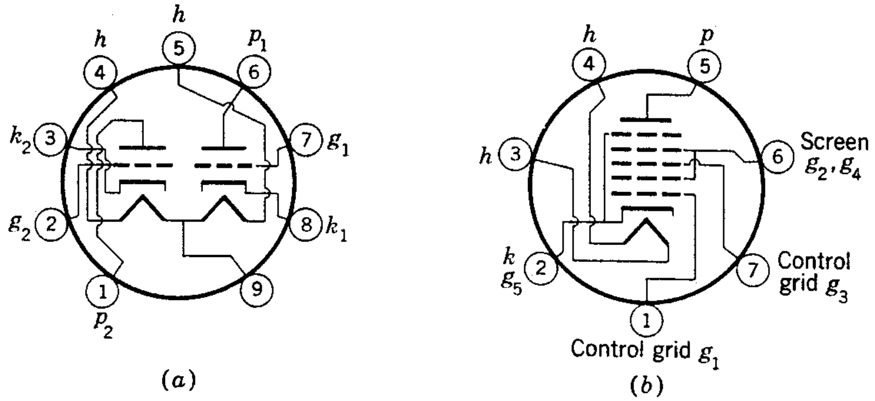


FIGURE 5-14 *(a) Base diagram of 12AX7 dual triode, (b) base diagram of 6BE6 pentagrid converter.*

cate the tube base pin connections to various electrodes. The base pins are numbered clockwise when viewed from the bottom. This convention facilitates identification of the various electrodes when the tube socket is examined in an actual circuit.

Vacuum tubes with more than three grids have been designed for special purposes. An example is the *pentagrid converter*, Fig. 5-14*b*. This tube has two control grids, g_1 and g_3, shielded from each other by two screen grids, g_2 and g_4. The fifth grid is the suppressor, g_5. This tube is used in frequency-converter circuits where two signals of different frequencies are applied to the two control grids. Nonlinearities of the tube characteristics result in sum and difference frequencies analogous to the diode first detector described in Chap. 4. Actually, the pentagrid converter can be used also to generate one of the signals within the tube itself, so only the input signal need be supplied externally.

In certain *beam power tubes*, most notably the type 6L6, the screen-grid wires are aligned with wires of the control grid. This forms the electron stream into sheets and reduces the screen current by a factor of five or so below that of conventional pentodes. There is no suppressor grid as such, but beam-forming plates at cathode potential further shape the electron stream. This specific electrode design causes the electron charges in the beam to produce an effective suppressor action. The result is that the plate characteristics are straight nearer to the $V_b = 0$ axis than is the case for a standard pentode. Accordingly, the beam power tube is useful as a power amplifier since the allowable plate-voltage range is nearly as large as the plate supply voltage. In addition, such tubes are often constructed with sturdy cathodes and anodes, so high-current operation is possible.

5-8 Cathode bias

A grid-bias battery is economically impractical in most circuits. Instead, negative grid bias is obtained by inserting a resistor in series with the cathode, Fig. 5-15. The IR drop across this re-

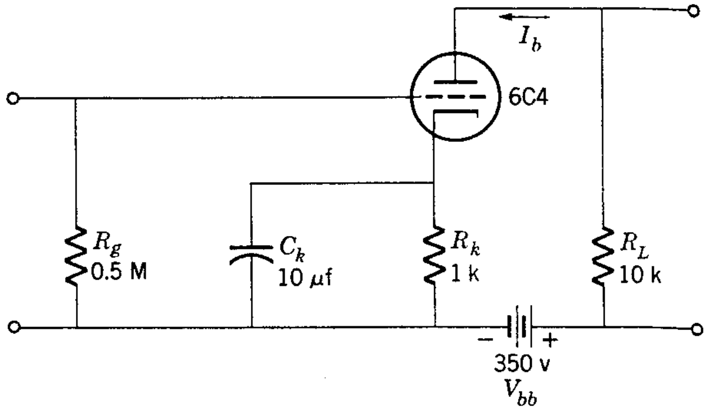


FIGURE 5-15 *Circuit diagram of a practical triode amplifier using cathode bias.*

sistor is $I_b \times R_k$, and the polarity makes the grid negative with respect to the cathode. The quiescent operating point may be found by first drawing the load line corresponding to

$$I_b = \frac{V_{bb} - V_b}{R_L + R_k} \tag{5-22}$$

According to Eq. (5-22) the intercepts of the load line are at V_{bb} and at $V_{bb}/(R_L + R_k)$, Fig. 5-16. By definition, the operating point must be located somewhere along the load line. Since the

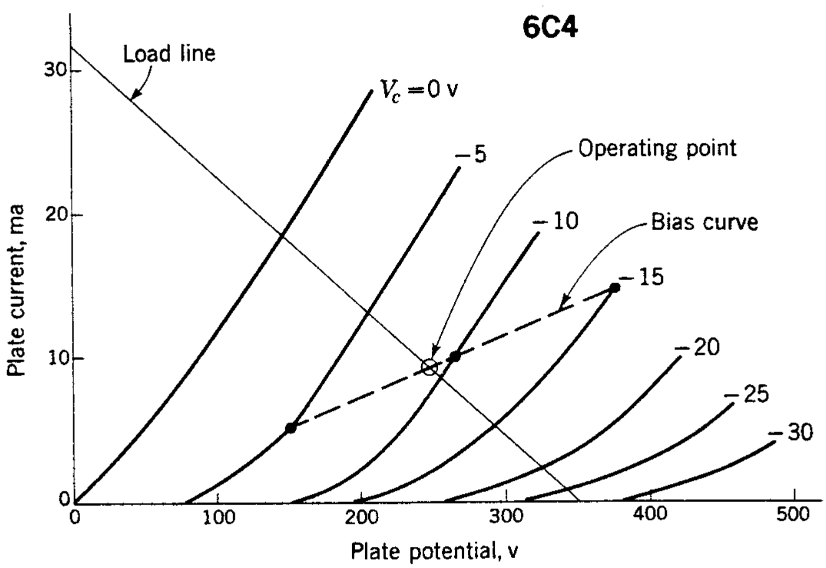
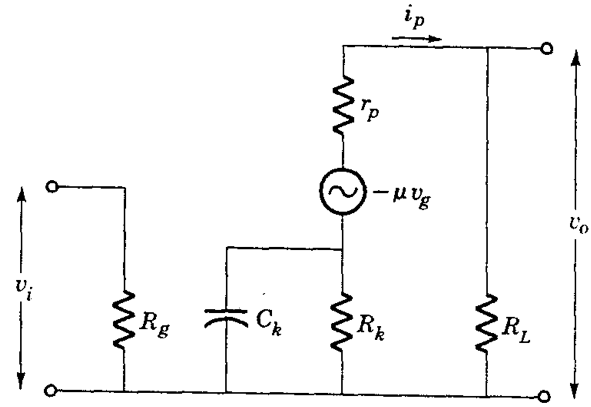


FIGURE 5-16 *Determination of operating point for 6C4 amplifier in Fig. 5-15.*

grid bias depends upon the plate current, it is necessary to draw a second line connecting the points $I_b = -V_c/R_k$ on every plate-characteristic curve. The intersection of this curve with the load line is the operating point.

Capacitor C_k shunting the cathode-bias resistor R_k in Fig. 5-15 prevents ac signals caused by the ac plate current in the cathode resistor from appearing in the grid circuit. This is illustrated

FIGURE 5-17 The ac equivalent circuit of cathode-bias amplifier.



with the aid of the ac equivalent circuit, Fig. 5-17. The impedance of R_k and C_k in parallel is

$$Z_k = \frac{R_k}{1 + jR_k\omega C_k} \tag{5-23}$$

The ac signal current is given by

$$i_p = \frac{-\mu v_g}{r_p + R_L + Z_k} \tag{5-24}$$

According to Fig. 5-15, the grid-cathode voltage is equal to the input voltage plus the ac voltage across Z_k, or

$$v_g = v_i + i_p Z_k \tag{5-25}$$

Inserting Eq. (5-25) into Eq. (5-24) and calculating the gain of the amplifier,

$$a = \mu \frac{R_L}{r_p + R_L + (1 + \mu)Z_k} \tag{5-26}$$

Suppose now the capacitor is omitted, so $Z_k = R_k$. Comparing Eq. (5-26) with Eq. (5-17) shows that the gain is reduced, because of the factor $(1 + \mu)R_k$ in the denominator. If, on the other hand, the capacitor is large enough that $(1 + \mu)Z_k$ is small compared with the plate resistance plus load resistance, the gain is restored to its original value. In effect the capacitor provides an ac path around R_k and, accordingly, it is called a *cathode bypass* capacitor. A convenient rule of thumb states that the capacitive reactance of the bypass capacitor should equal 1/5 of R_k at the lowest frequency of interest.

Determining the operating point for cathode-biased pentodes is slightly more involved than for triodes because the bias voltage depends upon the screen current as well as the plate current. It is usually satisfactory to assume the screen current is a fixed fraction of the plate current and proceed as in the case of the triode. The correct fraction to choose depends somewhat upon the tube type in question and may be estimated from the tube's screen-current characteristics. For most pentodes the total cathode current is approximately $1.3I_b$ at the operating point. This approximation usually yields a sufficiently accurate determination of the quiescent condition.

In many cases it is simpler to resort to the following "cut-and try" procedure for determining the operating point. Choose a point on the load line corresponding to an arbitrary grid-bias voltage and plate current. The screen current is then determined from the screen characteristics for these values of V_c and V_b. The product $-(I_b + I_s)R_k$ is compared with the chosen value of V_c. If these two values are equal, the original choice is satisfactory. If they are not, the process is repeated until the desired accuracy is obtained.

5-9 Screen bias

It is advantageous to eliminate the screen-grid-bias battery by deriving the screen potential from the plate supply voltage. This can be accomplished by means of a resistive voltage divider across the plate supply voltage. A simple series dropping resistor, Fig. 5-18, is even more convenient, however. The value of R_s is

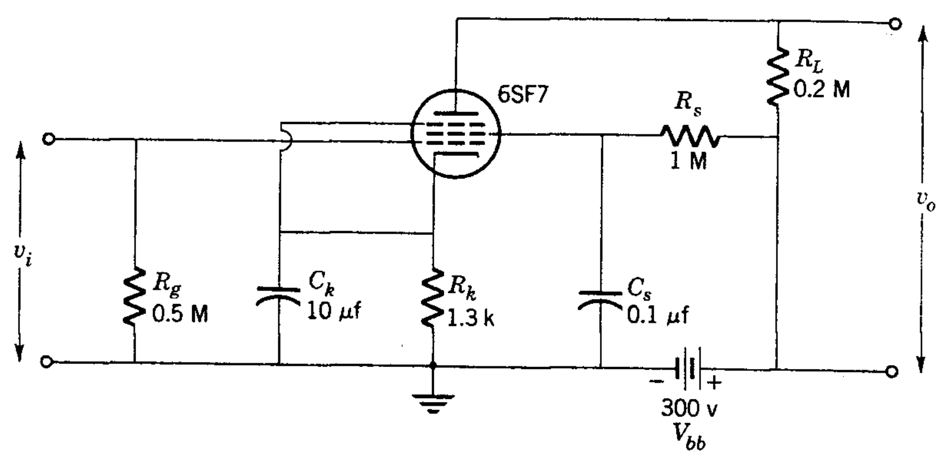


FIGURE 5-18 Practical pentode amplifier circuit.

selected to yield the desired screen voltage at the given screen current and plate supply potential. Values in the range from 0.05 to 1.0 MΩ are typical.

The screen resistor is bypassed with capacitor C_s to maintain the screen voltage constant independent of variations caused by signal voltages. This means that the reactance of C_s must be small compared with R_s at the lowest frequency of interest. Modest values of capacitance are sufficient because of the relatively large resistance of the screen dropping resistor.

Aside from the obvious economy achieved by providing grid, plate, and screen potentials from one voltage source, these bias techniques also result in more stable quiescent operation than does fixed bias. Suppose, for example, that the plate current tends to increase because of tube aging. This increases the negative grid bias and this, in turn, tends to lower the plate current. The net change in operating point is much less than is the case for fixed bias. The same situation exists with regard to the screen voltage.

It is inconvenient to measure electrode voltages with respect to the cathode in circuits employing a cathode-bias resistor. This is particularly true when more than one tube is used in a circuit. The usual practice is to refer all potentials to a common point called the *ground*. The ground point is considered to be electrically neutral so that, for example, the ground points of two different circuits may be connected with no influence upon the operation of either circuit. A typical use of the ground symbol, Fig. 5-19, is illustrated

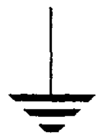


FIGURE 5-19 *Ground symbol.*

in the pentode-amplifier diagram of Fig. 5-18. Practical electronic circuits are often constructed on a metal base, or *chassis*, which serves as the ground.

SPECIAL CIRCUITS

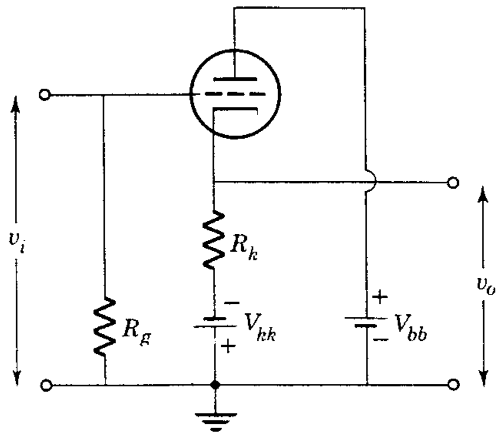
Many different vacuum-tube circuits are considered in subsequent chapters, but it is useful to analyze a few special circuits at this point. These circuits have important applications and the analysis illustrates the equivalent-circuit approach.

5-10 Cathode follower

The cathode is common to the input and output terminals in the simple amplifier circuit, insofar as ac signals are concerned. This configuration is used most often and is sometimes referred to as the *grounded-cathode connection.* Another configuration is the *grounded-plate* amplifier, Fig. 5-20. The plate resistor is omitted, and the output signal is developed across the cathode resistor.

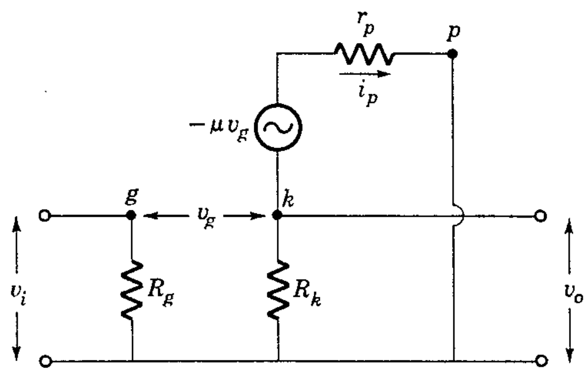
Note that in this circuit the plate is common to both input and output terminals and is at ground potential so far as ac signals are concerned. It is maintained at a high dc potential, however. The

FIGURE 5-20 *Elementary cathode-follower amplifier.*



battery V_{kk} in the cathode lead counteracts the large dc voltage across R_k caused by the quiescent tube current. The difference between the cathode potential and the grid potential results in the proper grid-bias value. This circuit is commonly called a *cathode follower* because the cathode potential follows that of the grid.

FIGURE 5-21 *Equivalent circuit of a cathode follower.*



The equivalent circuit of the cathode follower is given in Fig. 5-21. We proceed to find the output signal by first calculating the current

$$i_p = \frac{-\mu v_g}{r_p + R_k} \qquad (5\text{-}27)$$

The grid-cathode voltage is equal to the input voltage plus the voltage across the cathode resistor, or

$$v_g = v_i + i_p R_k \qquad (5\text{-}28)$$

Inserting Eq. (5-28) into Eq. (5-27), the current in the circuit is

$$i_p = \frac{-\mu v_i}{(1 + \mu)R_k + r_p} \qquad (5\text{-}29)$$

The drop across R_k caused by this current represents the output voltage. Note, however, that the output voltage is the negative of

i_pR_k, because current always enters the positive terminal of a load. Therefore

$$v_o = \frac{\mu v_i R_k}{(1+\mu)R_k + r_p} \tag{5-30}$$

The gain of the amplifier,

$$a = \frac{v_o}{v_i} = \frac{\mu}{(1+\mu) + r_p/R_k} \tag{5-31}$$

is always less than unity. In fact, if $R_k > r_p$, which is usually the case,

$$a = \frac{\mu}{\mu + 1} \approx 1 \tag{5-32}$$

The voltage gain of the cathode-follower circuit is essentially equal to unity, and, according to Eq. (5-30), the output voltage is in phase with the input signal. Therefore, the cathode voltage follows the input voltage very closely.

The virtue of the cathode follower is that the cathode voltage replicates the input signal in a much lower impedance circuit. Therefore, the internal impedance of the circuit as a power source is very low. This means the tube can deliver appreciable power to low-impedance loads. The equivalent internal impedance is determined using Thévenin's theorem. The theorem cannot be applied directly to Fig. 5-21, because the generator voltage $-\mu v_g$ depends upon the load current through R_k, according to Eq. (5-28). To find a more suitable circuit, Eq. (5-29) is put in the form

$$i_p = \frac{-v_i\mu/(1+\mu)}{R_k + r_p/(1+\mu)} \tag{5-33}$$

This expression is the ratio of an emf, $-v_i\mu/(1+\mu)$, divided by a resistance, $R_k + r_p/(1+\mu)$, which can be represented by the diagram of Fig. 5-22. Applying Thévenin's theorem to this circuit,

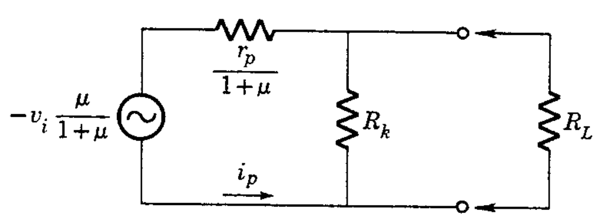


FIGURE 5-22

the equivalent internal impedance is the parallel combination of R_k and $r_p/(1+\mu)$,

$$R_o = \frac{R_k r_p/(1+\mu)}{R_k + r_p/(1+\mu)} = \frac{R_k r_p}{(1+\mu)R_k + r_p} \tag{5-34}$$

The *output impedance* of any circuit is the ratio of the output voltage divided by the output current when the input signal is zero. This is simply the internal impedance in the Thévenin equivalent representation. According to Eq. (5-34), the output impedance of the cathode follower is

$$R_o = \frac{r_p}{(1+\mu) + r_p/R_k} \approx \frac{r_p}{1+\mu} \approx \frac{r_p}{\mu} \tag{5-35}$$

This means that the output impedance is small. Note that the circuit results in an output impedance much smaller than R_k, since $R_k \gg r_p/\mu$.

It is inconvenient to employ two bias-voltage sources, so that a different bias arrangement, Fig. 5-23, is commonly used. The size

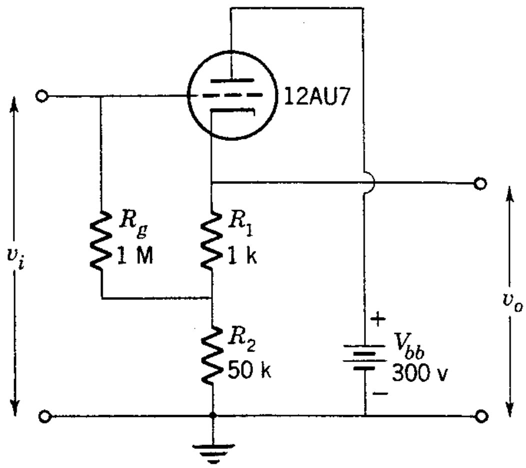


FIGURE 5-23 *Practical cathode-follower circuit.*

of R_1 is selected to yield the proper grid bias at the quiescent current, and the magnitude of R_2 is then determined by the desired value of $R_k = R_1 + R_2$. The operating point is determined by the same procedure used for the cathode-bias circuit, Fig. 5-16.

This circuit, Fig. 5-23, illustrates the second significant feature of the cathode follower: its large input impedance. The input impedance is the ratio of the input voltage to the current in the input circuit

$$R_i = \frac{v_i}{i_i} \tag{5-36}$$

Applying Kirchhoff's voltage rule to the input circuit, the input current is

$$i_i = \frac{v_i + i_p R_2}{R_g + R_2} \tag{5-37}$$

The current i_p is given by Eq. (5-29) with R_k replaced by $R_1 + R_2$. Substituting into Eq. (5-37),

$$i_i = \frac{v_i}{R_g + R_2}\left[1 - \frac{\mu R_2}{(1+\mu)(R_1+R_2) + r_p}\right]$$

$$= \frac{v_i}{R_g + R_2}\left[1 - \frac{\mu}{(1+\mu)(1+R_1/R_2) + r_p/R_2}\right] \tag{5-38}$$

Most often, $R_2 \gg R_1$ and $R_2 \gg r_p$, so that

$$i_i = \frac{v_i}{R_g + R_2}\left(1 - \frac{\mu}{1+\mu}\right) = \frac{v_i}{R_g + R_2}\frac{1}{1+\mu} \tag{5-39}$$

Comparing Eq. (5-39) with Eq. (5-36), the input impedance is

$$R_i = (1+\mu)(R_g + R_2) \tag{5-40}$$

which is quite large. This is an advantage since the cathode follower presents a very light load to preceding circuits. The reason for the high input impedance is, of course, the opposing voltage introduced into the grid circuit from the cathode resistor.

The cathode follower is an impedance-matching device with a very high input impedance and a very low output impedance. Although the voltage gain is less than unity, the power gain may be appreciable. This is so because the signal voltage is the same in both the high-impedance input circuit and the low-impedance output circuit. Since power is proportional to V^2/R, the power amplification is large. In addition, the circuit performance is stable and relatively independent of changes in component values. According to Eq. (5-32), the gain depends only on the amplification factor, which is the most stable of the small signal parameters.

5-11 Difference amplifier

The circuit diagramed in Fig. 5-24 is often used as the input stage of oscilloscope amplifiers and other laboratory instruments,

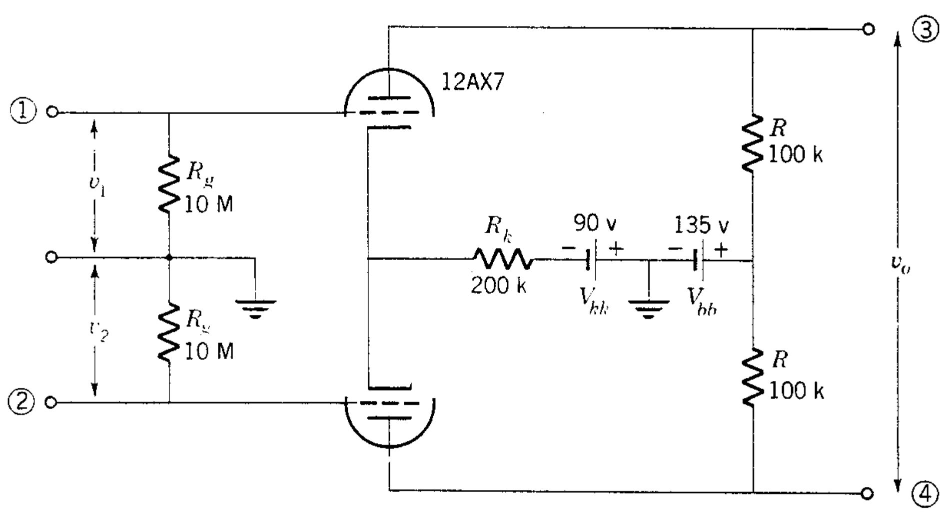


***FIGURE 5-24** Difference amplifier. Half-open tube symbol signifies a dual triode.*

because it yields a signal proportional to the difference between two input voltages. This useful property may be illustrated by analyz-

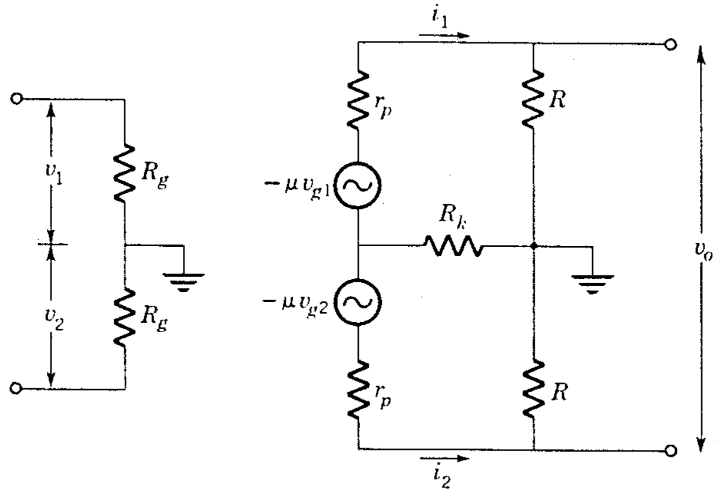


FIGURE 5-25 *Equivalent circuit of difference amplifier.*

ing the equivalent circuit, Fig. 5-25. Kirchhoff's voltage rule applied to both loops results in

$$
\begin{aligned}
-\mu v_{g_1} &= r_p i_1 + R i_1 + R_k(i_1 + i_2) \\
-\mu v_{g_2} &= r_p i_2 + R i_2 + R_k(i_1 + i_2)
\end{aligned}
\tag{5-41}
$$

Similarly, the grid-cathode voltages are

$$
\begin{aligned}
v_{g_1} &= v_1 + R_k(i_1 + i_2) \\
v_{g_2} &= v_2 + R_k(i_1 + i_2)
\end{aligned}
\tag{5-42}
$$

Equations (5-42) are substituted into (5-41) and the result solved for the two currents. The expression for the current in the upper loop is

$$i_1 = \mu \frac{v_2 - [1 + (r_p + R)/(1 + \mu)R_k]v_1}{\{[1 + (r_p + R)/(1 + \mu)R_k]^2 - 1\}(1 + \mu)R_k} \tag{5-43}$$

Because of the circuit symmetry, the result for i_2 has the same form with subscripts 1 and 2 interchanged. The plate-to-plate output voltage is

$$v_o = Ri_1 - Ri_2 = R(i_1 - i_2) \tag{5-44}$$

Substituting for i_1 and i_2 and simplifying,

$$v_o = \mu(v_2 - v_1)\frac{2 + (r_p + R)/(1 + \mu)R_k}{(1 + r_p/R)[2 + (r_p + R)/(1 + \mu)R_k]} \tag{5-45}$$

$$v_o = \frac{\mu}{1 + r_p/R}(v_2 - v_1) \tag{5-46}$$

which is similar to Eq. (5-17) for the amplification of a single triode. According to Eq. (5-46), the output voltage is a constant times the difference between the input signals. This result applies only if the two halves of the circuit are strictly identical. In practical circuits $(1 + \mu)R_k \gg r_p$, and this reduces the effects of any asymmetry.

The *difference amplifier* rejects any voltage signals that are common to both terminals, such that $v_1 = v_2$. At the same time, signals applied from terminal 1 to terminal 2 are amplified normally, since in this case

$$v_1 = \frac{v_i}{2} \qquad \text{and} \qquad v_2 = -\frac{v_i}{2} \tag{5-47}$$

The output voltage is

$$v_o = \frac{\mu}{1 + r_p/R}\left(\frac{v_i}{2} + \frac{v_i}{2}\right) = \frac{\mu}{(1 + r_p/R)}\, v_i \tag{5-48}$$

which means the circuit simply amplifies the input signal. The same result holds if the input signal is connected between ground and either grid, so that, for example, $v_1 = v_i$ and $v_2 = 0$. Since the circuit rejects *common-mode* signals, resulting from, say, stray electrical fields caused by the 60-cps power mains, it is useful as the input stage of a sensitive amplifier. In addition, the input may be connected to voltage sources that have neither terminal grounded, which is often very convenient.

The output of a difference amplifier is balanced with respect to ground. A single-ended output (one terminal grounded) is obtained by making one of the plate load resistors equal to zero, Fig. 5-26. The circuit has been drawn in this fashion to show that tube

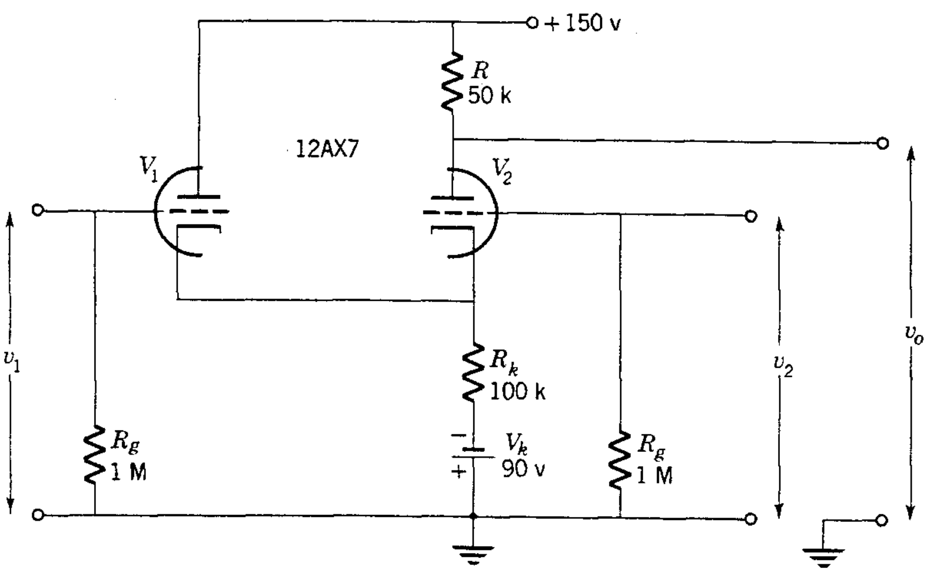


***FIGURE 5-26** Difference amplifier with single-ended output.*

V_1 may be considered as a cathode follower feeding the cathode of tube V_2. The output of V_2 is proportional to its cathode-to-grid voltage and hence approximately proportional to $v_2 - v_1$. The circuit can therefore be analyzed in terms of a simple amplifier preceded by a cathode follower. (See Exercise 5-18.)

Alternatively, the equivalent circuit of Fig. 5-25 can be used with the upper-plate load resistor shorted out. The output signal is

$$v_o = Ri_2 =$$

$$\mu \frac{v_1 - [1 + r_p/(1+\mu)R_k]v_2}{\{[1 + r_p/(1+\mu)R_k][1 + (r_p + R)/(1+\mu)R_k] - 1\}(1+\mu)R_k/R} \tag{5-49}$$

which may be simplified to

$$v_o = \mu \frac{v_2 - v_1 - v_2 r_p/(1+\mu)R_k}{1 + r_p/R[2 + (r_p + R)/(1+\mu)R_k]} \tag{5-50}$$

Introducing the approximation $(1+\mu)R_k \gg r_p + R$, this expression reduces to

$$v_o = \frac{\mu}{1 + 2r_p/R}(v_2 - v_1) \tag{5-51}$$

Comparing Eq. (5-51) with Eq. (5-46) shows that the single-ended difference amplifier is almost identical with the balanced-output circuit. Actually the approximations introduced in leading to Eqs. (5-46) and (5-51) are slightly more accurate in the case of the balanced circuit. Therefore, the balanced amplifier's ability to reject common-mode signals is superior.

5-12 VTVM

The voltage and power amplification of a vacuum triode results in a sensitive dc *vacuum-tube voltmeter* (*VTVM*) when used in conjunction with a standard d'Arsonval milliammeter. This is possible because of the very great input impedance of vacuum tubes. A common VTVM circuit, Fig. 5-27, is a cathode-follower difference

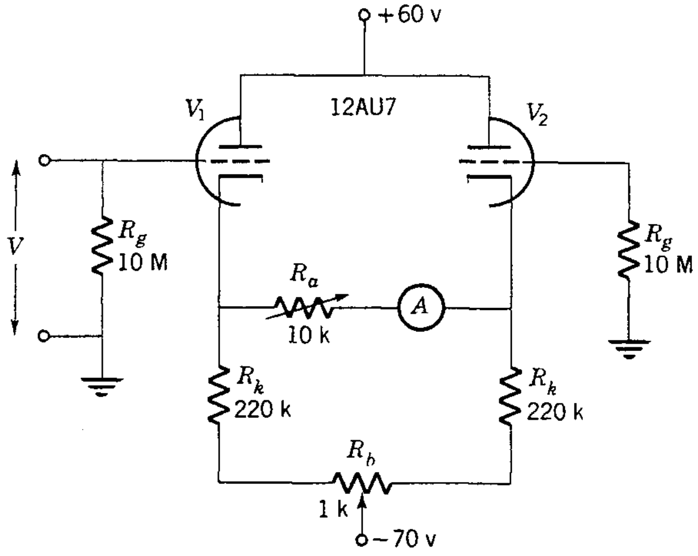


FIGURE 5-27 Simple VTVM.

amplifier with the meter connected between the cathodes. The unknown voltage is applied to the grid of one of the triodes. The grid of the other triode is unused and is returned to ground through a grid resistor. Since a cathode follower presents a high input impedance and a low output impedance, this circuit is particularly useful in the VTVM application.

The balanced circuit provides a convenient connection for the d'Arsonval meter which results in zero deflection with zero input signal, even though the quiescent current in each tube is nonzero. Furthermore, the symmetry of the circuit maintains performance stability against component changes caused by aging. Actually the circuit may be looked upon as a bridge comprising a triode in each of two arms together with the cathode resistors in the other two arms. A dc voltage applied to the grid of V_1 changes the tube's resistance and unbalances the bridge. The circuit may be analyzed using vacuum-tube equivalent circuits in the usual fashion (Exercise 5-20).

The adjustable resistor R_a in series with the meter is a calibration resistor in the diagram of Fig. 5-27. The potentiometer R_b is a balance adjustment which corrects for minor asymmetries in the triodes or other components. The circuit is balanced for zero current in the meter by adjusting R_b with zero voltage applied to the grid. It is necessary to readjust the balance control periodically as the tube warms up or as circuit components age.

The grid of V_1 is connected to multiplier resistors in commercial VTVM instruments to achieve multiple-range performance, much as in the case of the VOM circuit. The resistor values are greater in the vacuum-tube instrument, however, because of the much greater sensitivity. An additional feature of interest is that the VTVM may be designed so the maximum meter current, which occurs when one of the tubes is completely cut off, does not damage the meter. Therefore, the meter movement is unharmed, even if the VTVM is inadvertently connected to a voltage source much larger than the full scale value.

Standard VTVM instruments provide for ac measurements by using a diode rectifier circuit, as discussed in the previous chapter. The high input impedance of the cathode-follower difference amplifier is ideally suited to measure the output of the rectifier circuit. In addition to ac and dc voltages, most VTVM instruments also measure resistance with an ohmmeter circuit similar to those discussed in Chap. 1. Again, the difference amplifier is used as the indicator. This permits a very wide range of operation. For example, quite inexpensive instruments are capable of measuring unknown resistances from 1 Ω to 100 MΩ.

5-13 Class A, B, and C amplifiers

The grid signal never exceeds the cutoff voltage, and never becomes positive in all of the circuits examined thus far. Under such conditions, plate current exists at every instant of the input cycle. This is known as *class-A* operation and is the situation in most vacuum-tube applications. The transfer characteristics corresponding to this case, Fig. 5-28*a*, show that the output waveform is very similar to the input waveform. Some distortion may be introduced by curvature of the tube characteristics, however.

(*a*)

(*b*)

(*c*)

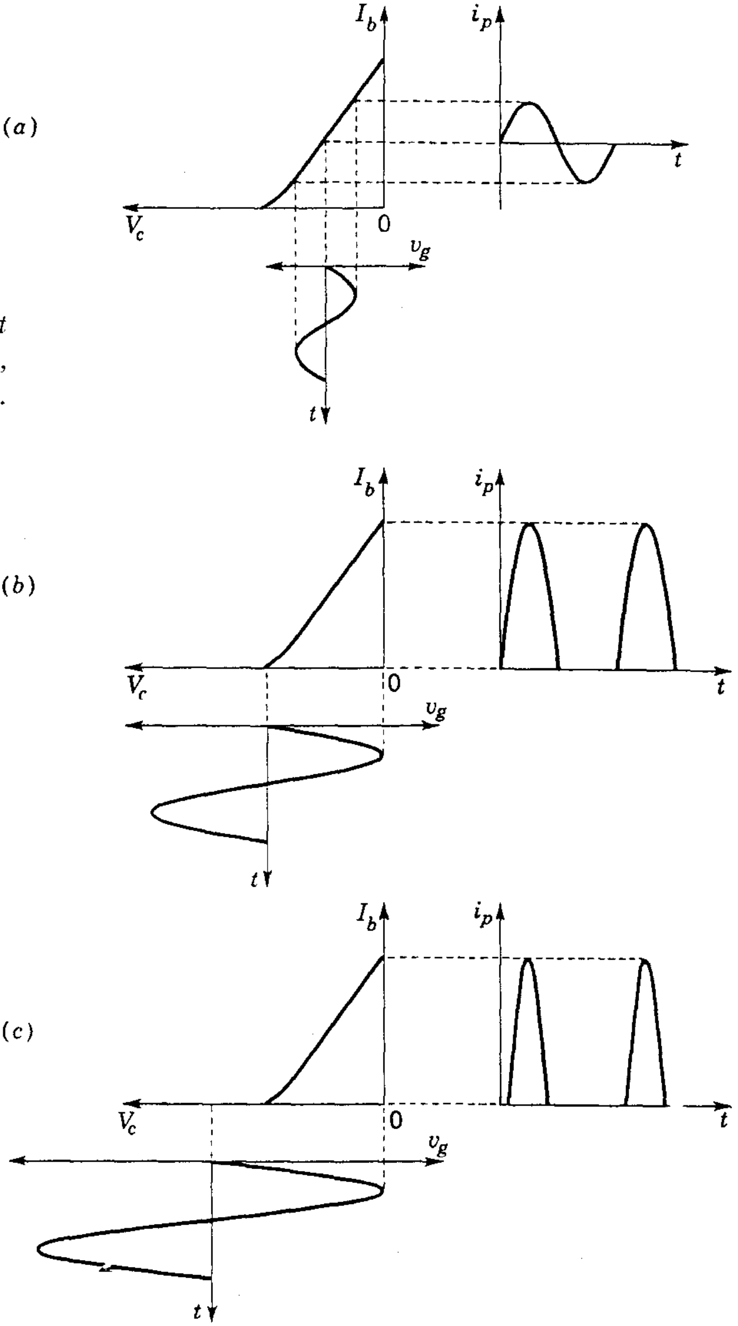


***FIGURE 5-28** Output current waveforms for (a) class-A, (b) class-B, and (c) class-C operation of amplifiers.*

If the dc bias equals the cutoff bias of the tube, plate current exists for only one-half of the input cycle, Fig. 5-28*b*. The input signal may be increased considerably without driving the grid positive, and this results in a greater power output. The increased power output of such *class-B* operation is achieved at the expense of the output waveform, for the plate current is a series of near-half-sine waves.

Clearly, class-B operation introduces very large distortions, since the output waveform is no longer a replica of the input signal. By connecting two tubes in a fashion somewhat analogous to the full-wave rectification circuit, it can be arranged that each tube supplies current on alternate half-cycles. Thus the output signal is restored to a replica of the input waveform and the magnitude of the amplified signal is much greater than is possible in class-A operation. This circuit is considered further in Chap. 7. An additional advantage of class-B amplifiers is that the quiescent current is zero, since the dc grid bias is at cutoff. This means that the quiescent power is zero. For this reason, as well as the large plate-current excursions, class-B circuits are very efficient power amplifiers.

Increasing the dc bias beyond cutoff is called *class-C* operation, Fig. 5-28*c*. In this case plate current exists for less than one-half of the input cycle and the input waveform cannot be recovered even with a two-tube circuit. Class-C amplifiers are used exclusively in connection with resonant circuits, where it is necessary to amplify only a single frequency. If the plate load of a class-C amplifier is a parallel resonant circuit having reasonable Q, it is only necessary to excite the resonant circuit once each cycle. The resonant circuit rings and supplies the remainder of the sine-wave signal in the output circuit. The current pulses of the class-C amplifier recur at the resonant frequency and keep the resonant circuit ringing. Because plate current exists for only a portion of the cycle, class-C amplifiers are even more efficient than the class-B circuits.

EXERCISES

5-1 Plot Child's law, Eq. (5-1), for a type 12AU7 triode and compare with experimental plate characteristics in Appendix 3. Do this by evaluating the constant A using the experimental curve for $V_c = 0$ and evaluating μ for the $V_c = -10$-volt curve.

Ans.: 1.1×10^{-5}; 17.2

5-2 Determine the dynamic transfer characteristic of the type 6SN7 triode amplifier of Fig. 5-4. Compare with the static transfer characteristics of Fig. 5-6.

5-3 Using the results of Exercise 5-2, plot the output-current waveform corresponding to a sinusoidal input signal of 2 volts. Repeat for a 6-volt signal, and note which output signal has greater distortion. Repeat for sawtooth input waveforms having the same peak-to-peak amplitude as the sinusoidal voltages.

5-4 Calculate the small signal parameters corresponding to Exercise 5-2 from the tube's characteristic curves at the operating point. Determine the variation in plate current using Eq. (5-7) for sinusoidal input signals of 2 and 6 volts. Compare with the graphical results obtained in Exercise 5-3.

Ans.: 1560 μmhos, 12.5 kΩ, 19.5; 7.6 ma, 25 ma

5-5 Using the triode equivalent circuit corresponding to Fig. 5-4 and the small signal parameters of Exercise 5-4, calculate the gain of the amplifier. Compare the output signal for 2 volts input with the results of Exercise 5-3. *Ans.*: 13.8; 27.6 volts

5-6 Plot the static transfer characteristics for a type 6AU6 pentode at plate voltages of 100, 200, and 300 volts. Do this with the aid of the plate characteristics given in Fig. 5-11.

5-7 Find the operating point of a type 12AX7 triode amplifier in the circuit of Fig. 5-15 if $R_L = 12{,}000\ \Omega$ and $R_k = 2000\ \Omega$. Use plate characteristics given in Appendix 3. *Ans.*: -3.1 volts, 1.6 ma

5-8 With the aid of Eq. (5-26) plot the gain of the type 6C4 triode amplifier, Fig. 5-15, as a function of frequency. Use a logarithmic frequency scale to cover the interval from 1 to 1000 cps. Assume $\mu = 100$ and $r_p = 60{,}000\ \Omega$.

5-9 Determine the operating point of a type 6SF7 pentode amplifier in the circuit of Fig. 5-18. Use the plate characteristics given in Appendix 3. *Ans.*: -6 volts, 1.8 ma

5-10 Determine the operating point of a type 12AU7 triode cathode-follower amplifier, Fig. 5-23. Calculate the input impedance, output impedance, and power gain using values of the small signal parameters determined from the plate characteristics.

Ans.: -3 volts, 3 ma; $2.3 \times 10^7\ \Omega$, 480 Ω, 4.8×10^4

5-11 Suppose a type 12AX7 triode is inserted into the circuit of Fig. 5-23 with no other changes. Repeat Exercise 5-10 and note that only minor changes result.

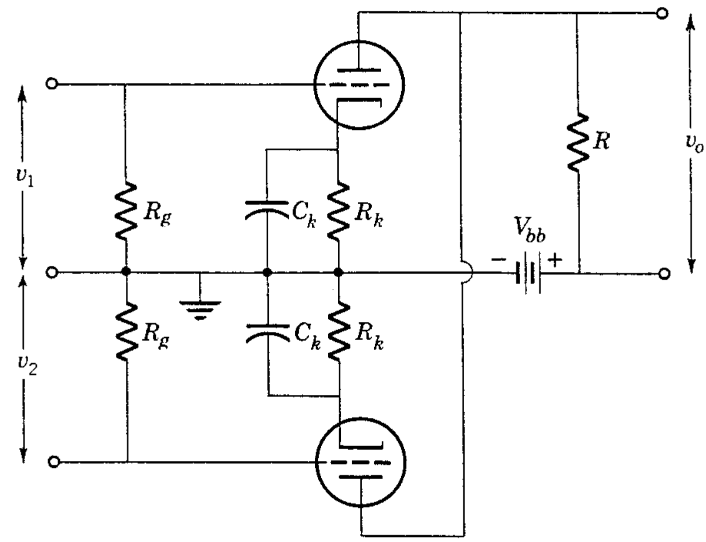
Ans.: -1.5 volts, 1.5 ma; 1650 μmhos, 55 kΩ, 96; $9.7 \times 10^7\ \Omega$, 566 Ω, 1.7×10^5

5-12 Explain why the gain of a difference amplifier, Fig. 5-24, is the same as that of a single triode, even though the cathode resistor is not bypassed. Do this by calculating the ac signal across R_k resulting from a sinusoidal input voltage applied to terminals 1 and 2. Repeat for a signal applied between terminal 1 and ground.

5-13 Analyze the circuit of Fig. 5-24 including a cathode bypass capacitor connected in parallel with R_k. Assume the impedance of the parallel combination is zero at the frequencies of interest. Compare the operation of this circuit with that of a difference amplifier.

5-14 Draw the ac equivalent circuit of the *summing* amplifier in Fig. 5-29. Show that the output voltage is the sum of the input signals.

FIGURE 5-29



5-15 Sketch the output waveforms between terminal 3 and ground and also between terminal 4 and ground of the difference amplifier, Fig. 5-24, resulting from a sinusoidal input signal applied between terminal 1 and ground. Pay particular attention to the phase of the output signals. In this application the circuit is called a *phase inverter.*

5-16 Determine the operating point of the type 12AX7 dual-triode difference amplifier, Fig. 5-24. Use plate characteristic curves given in Appendix 3. *Ans.:* −1.5 volts, 0.22 ma

5-17 Repeat Exercise 5-16 for the single-ended difference amplifier, Fig. 5-26. *Ans.:* −1.5 volts, 0.5 ma, 0.4 ma

5-18 Analyze the single-ended difference amplifier, Fig. 5-26, by considering the circuit to be a cathode-follower amplifier feeding a triode amplifier with an unbypassed cathode resistor. Do this by using the expressions for each stage found in the text. Compare the result with Eq. (5-51) when the same approximations are introduced.

5-19 With the aid of Eq. (5-46) calculate the output signal of the difference amplifier studied in Exercise 5-16. Use values of small signal parameters given in Table 5-1. Repeat for the single-ended difference amplifier, Fig. 5-26, and compare Eq. (5-50) with Eq. (5-51).

Ans.: 61.7; $28.5(v_2 - v_1) - 1.77 \times 10^{-3} v_2$; $29.7(v_2 - v_1)$

5-20 Analyze the VTVM circuit, Fig. 5-27, by deriving an expression for the meter current I as a function of the dc input voltage V. Insert numerical values given on the circuit diagram, assuming the meter resistance is negligible and the small signal parameters of the tube given in Table 5-1. What is the ohms/volt rating of this meter on the 1-volt scale? Compare with the sensitivity of a VOM using the same 100-μa d'Arsonval meter.

Ans.: $9.2 \times 10^{-5} v$; 10^4 Ω/volt; 10^7 Ω/volt