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ELECTRONIC CIRCUITS LECTURES

Robert Mozley
12/5/47

Fundamental Properties of Vacuum Tubes

The two-electrode vacuum tube, or diode, consists of an electron-emitting cathode surrounded by a positive anode (plate). A plot of plate current (i_b) vs plate voltage (e_b) is shown in Figure 1-1.

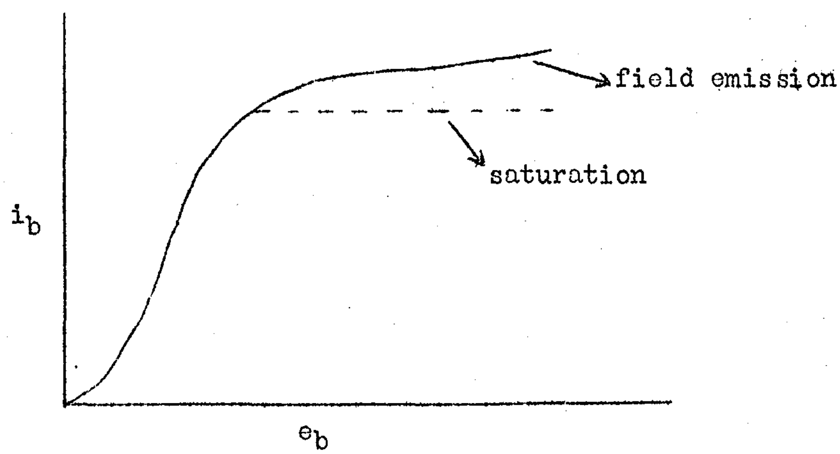


Figure 1-1

At low anode voltages, the anode current is limited by the repelling effect that the negative electrons already in the space have on the electrons just being emitted (space-charge effect). When a full space charge is present, the plate current depends upon the plate voltage according to Childs' law:

$$i_b \sim e_b^{3/2} \tag{1-1}$$

Increasing the plate voltage eventually results in an electron flow equal to total cathode emission, after which further increases in anode voltage will produce practically no additional current (voltage saturation). However, for high field stresses, additional electrons are pulled out of the cathode (field emission), increasing the current even further (see Figure 1-1).

The limitations upon current inside the tube may be considered as a resistance; i.e., the ratio of a change of plate voltage to the corresponding change in plate current,

$$r_p = \left(\frac{\partial e_b}{\partial i_b}\right)_{e_c} \tag{1-2}$$

is called the "plate resistance" of the tube. Note that r_p is the reciprocal of the slope of the curve in Figure 1-1, and is not equal to the ratio of the total plate voltage to the total plate current.

In ordinary vacuum tubes, large plate voltages are required in order to obtain large plate currents. However, by introducing a small amount of gas (1-30 microns pressure) into the tube, the plate current can be caused to jump from nearly zero to saturation current as the plate voltage exceeds the ionizing potential of the gas (about 15-20 volts).

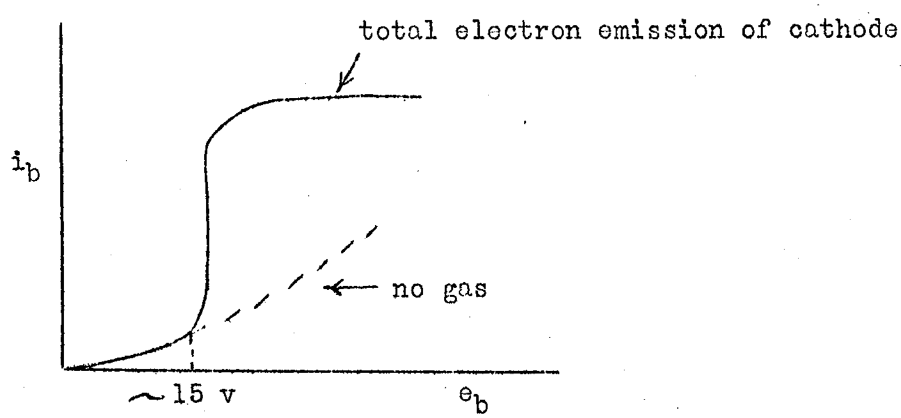


Figure 1-2

No space-charge effects are present in a gas tube, inasmuch as ionized positive ions are attracted toward the cathode and neutralize the space-charge.

Tube "characteristics" (plate characteristic curves, etc.) are plotted in tube handbooks and represent average values for a great number of tubes. As such, they should not be taken too seriously. Variations in manufacturing processes, heater temperatures, contact potentials, etc., will cause differences between tubes of the same type. Contact potential may be thought of as a battery in series with the tube element. The heater temperature determines the average velocity of emitted electrons; note that even at zero plate voltage in a diode, the electron flow may not be zero:

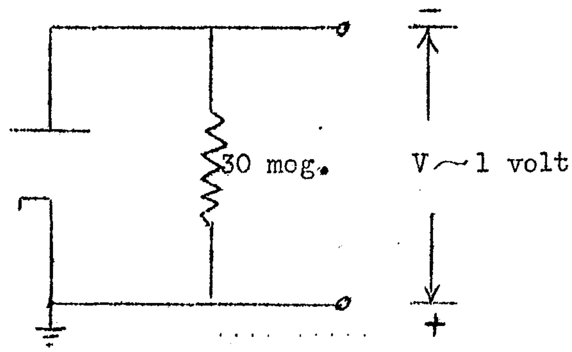


Figure 1-3

The introduction of a third electrode, or "grid", to electrostatically control the flow of electrons from cathode to plate forms a triode. The grid is normally operated at a negative potential (grid bias) with respect to the cathode and so attracts no electrons, but it affects the electrostatic field in the vicinity of the cathode. Plotting lines of electrostatic force:

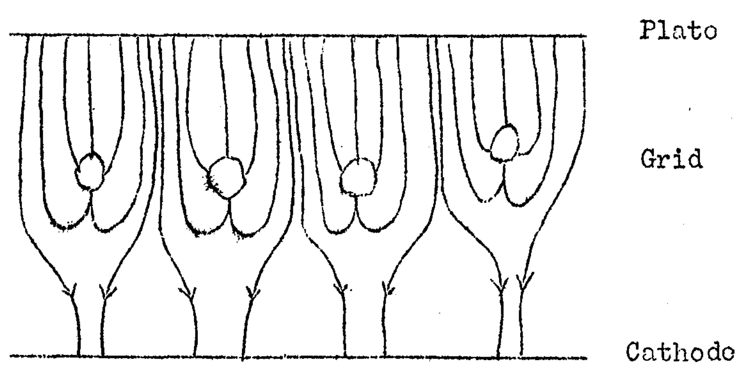


Figure 1-4

We see that the combined action of the grid and plate potentials determine the plate current in a triode. The relative effectiveness of a change in the grid potential to a change in plate potential in producing a given change in plate current is known as the amplification factor (μ). Thus,

$$\begin{pmatrix}\text{Field at}\\ \text{cathode}\end{pmatrix} \sim (e_b + \mu e_c) \qquad (1\text{-}3)$$

and since the plate current varies as the 3/2 power of the effective field,

$$i_b = K(e_b + \mu e_c)^{3/2} \qquad (1\text{-}4)$$

"Cut-off" is obtained when the fields produced by the cathode and anode exactly balance; i.e.,

$$e_b + \mu e_c = 0 \qquad (1\text{-}5)$$

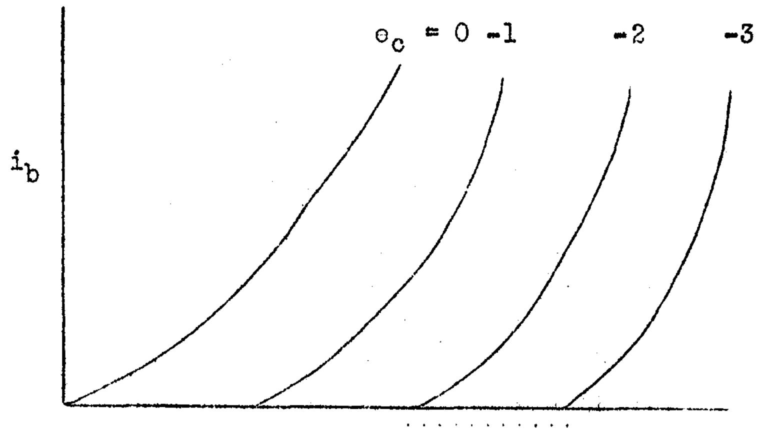
For example, a tube with 200 volts on the plate and an amplification factor of 10 will be cut off at $e_c = -20$ volts.

A continuous plot of the rlations between i_p, e_b, and e_c would require a 3-dimensional surface. The most important relationships are

(a) Plate current vs. plate voltage with constant grid voltage, and

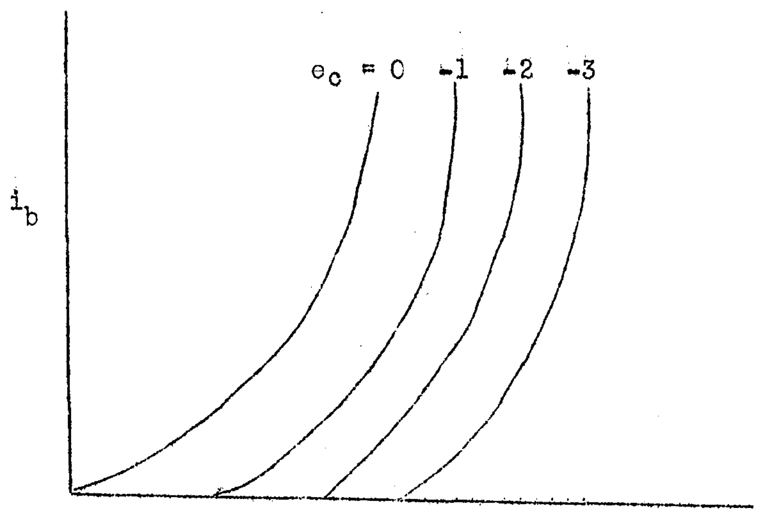
(b) Plate current vs. grid voltage with constant plate voltage.

Plots of (a) are most commonly available; representative triode curves are shown in Figure 1-5. A tube with uniform geometry (spacing of tube elements, etc.) would have regularly-spaced curves, as in Figure 1-5a. In practice, grid geometry varies within the tube such that the characteristic curves are parallel only at high plate currents.



Uniform Geometry

Figure 1-5a



Non-uniform Geometry

Figure 1-5b

For example, tube cut-off will be determined by that section of the tube most difficult to cut-off.

The important characteristics of a triode tube can be expressed in terms of three "constants" of the tube, which result from a mathematical expression for the plate current. Although the above-mentioned variations in tube characteristics make such a mathematical representation very approximate, it's use enables one to make quantitative estimates of tube performance without detailed use of the plotted curves. Let us adopt symbols distinguishing between <u>total</u>, <u>static</u> and <u>variation</u> in tube voltages and currents as follows

follows:

$$\left.\begin{aligned} i_b &= I_b + i_p = \text{plate current} \\ e_b &= E_b + e_p = \text{plate voltage} \\ e_c &= E_c + e_g = \text{grid voltage} \end{aligned}\right) \qquad (1\text{-}6)$$

where i_b = total instantaneous plate current,

I_b = static (no-signal) d.c. plate current,

i_p = variation (signal) in plate current,

etc. Then if we regard the plate current (i_b) as a function of e_b and e_c, we may expand $i_b(e_b, e_c)$ in a Taylor's series,

$$i_b = I_b \pm \left\{ \left(\frac{\partial i_b}{\partial e_c}\right)_{e_b} e_g + \left(\frac{\partial i_b}{\partial e_b}\right)_{e_c} e_p \right\}$$

$$+ 1/2 \left\{ \left(\frac{\partial^2 i_b}{\partial e_c^2}\right) e_g^2 + 2\left(\frac{\partial^2 i_b}{\partial e_c \partial e_b}\right) e_g e_p + \left(\frac{\partial^2 i_b}{\partial e_b^2}\right) e_b^2 \right\} \qquad (1\text{-}7)$$

+ terms of higher order.

Defining,

$$\left(\frac{\partial i_b}{\partial e_c}\right)_{e_b} = g_m = \text{transconductance} \qquad (1\text{-}8)$$

$$\left(\frac{\partial e_b}{\partial i_b}\right)_{ec} = r_p = \text{plate resistance} \qquad (1\text{-}9)$$

and assuming that g_m and r_p are <u>constant</u> for the operating region under consideration, so that second-order and higher-order terms in (1-7) vanish, then,

$$i_p = g_m e_g + e_p/r_p \qquad (1\text{-}10)$$

Similarly, expanding the plate voltage in a Taylor's series,

$$e_b = E_b + \left\{ \left(\frac{\partial e_b}{\partial e_c}\right)_{i_b} e_g + \left(\frac{\partial e_b}{\partial i_b}\right)_{e_c} i_p \right\} \qquad (1\text{-}11)$$

and defining

$$-\left(\frac{\partial e_b}{\partial e_c}\right)_{i_b} = +\mu = \text{amplification factor} \qquad (1\text{-}12)$$

we have

$$e_p = -\mu e_g + r_p i_p \qquad (1\text{-}13)$$

These approximations assume that the characteristic curves of the tube are all straight lines, parallel and evenly spaced. This is, of course, even approximately true only for small signals. Note the relation between the three constants:

$$r_p \cdot g_m = \left(\frac{\partial e_b}{\partial i_b}\right)_{e_c} \cdot \left(\frac{\partial i_b}{\partial e_c}\right)_{e_b} = -\left(\frac{\partial e_b}{\partial e_c}\right)_{i_b} = \mu \qquad (1\text{-}14)^*$$

The geometrical interpretation of r_p has already been given (note that r_p is the dynamic plate resistance). Similarly, g_m is the slope of curves of i_b vs. e_c (for various values of e_b).

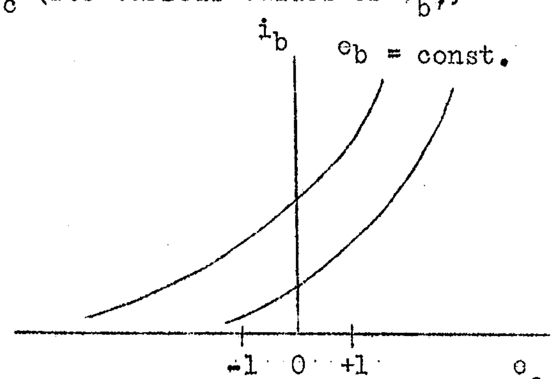


Figure 1-6

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*If $f(x, y, z) = 0$, then $dx = \left(\frac{\partial x}{\partial y}\right)_z dy + \left(\frac{\partial x}{\partial z}\right)_y dz$ and, holding x constant,

$$\left(\frac{\partial x}{\partial y}\right)_z \left(\frac{\partial y}{\partial z}\right)_x = -\left(\frac{\partial x}{\partial z}\right)_y$$

while u is the negative slope of lines of constant plate current plotted on an e_b - e_c graph:

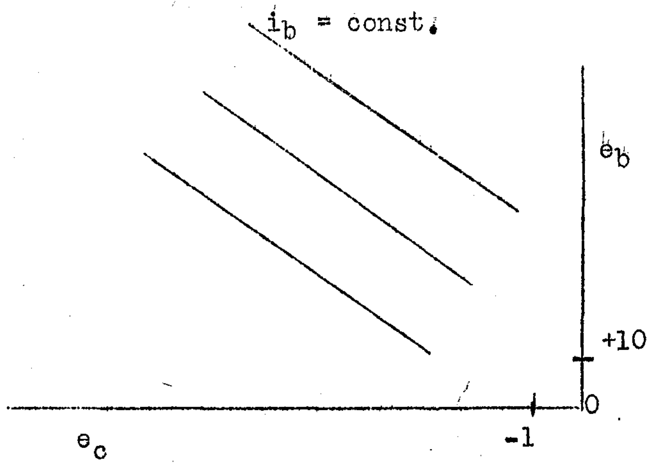


Figure 1-7

one can calculate μ and g_m from the ordinary "plate characteristic" curves by noting changes in i_b (or e_b) between adjacent lines of constant grid voltage; i.e.,

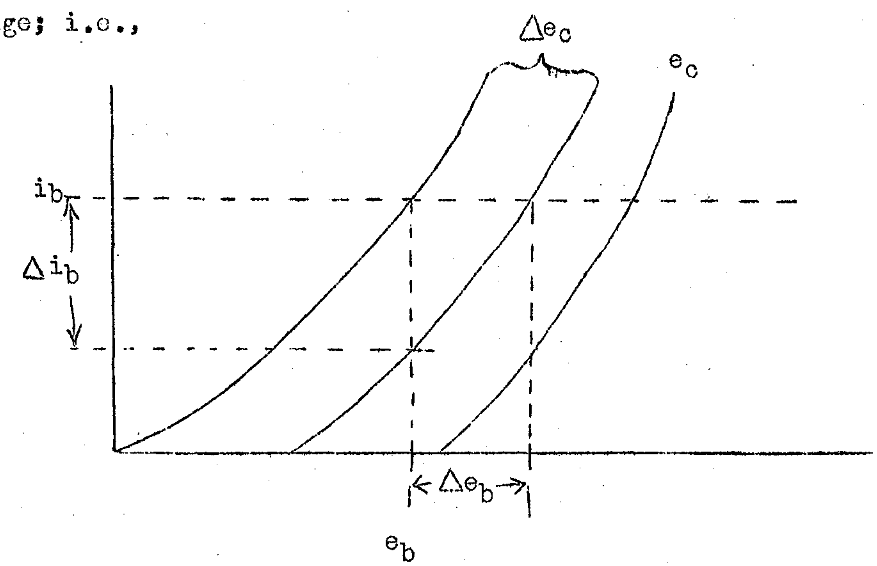


Figure 1-8

Then, the average values are:

$$\bar{\mu} \simeq -\left(\frac{\Delta e_b}{\Delta e_c}\right)_{i_b} \tag{1-14}$$

$$\bar{g}_m \simeq \left(\frac{\Delta i_b}{\Delta e_c}\right)_{e_p} \tag{1-15}$$

A fourth tube element, the screen grid, is introduced between the control grid and plate in the tetrode. The effect of a fixed positive screen-grid voltage is much the same as that of plate voltage (attract electrons leaving the cathode) but since the screen grid is only a "grid" of wires, most of the electrons go on past the screen toward the plate.

Tetrode

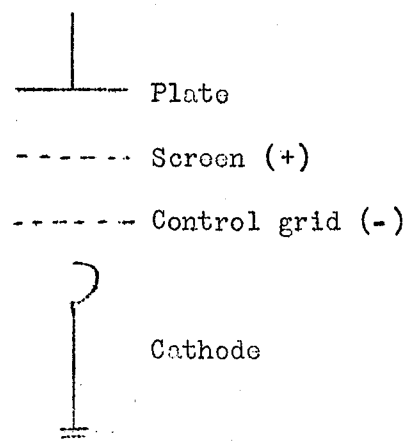
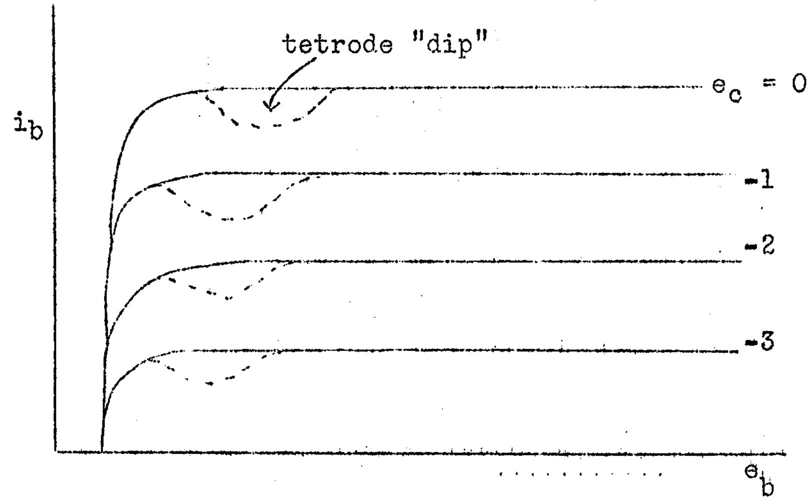


Figure 1-9

One value of the screen grid lies in its electrostatic shielding action between the plate and grid, reducing the capacitance between these two electrodes. In many applications, it is desirable to have very little coupling between the grid and plate circuits; the addition of a screen-grid may reduce c_{pg} from 10 $\mu\mu f$ to .01 $\mu\mu f$.

In a pentode a fifth (suppressor) grid is placed between screen and plate and is biased negatively with respect to plate. Secondary emission electrons which might otherwise be drawn to the screen are repelled back to the plate by the suppressor. This prevents the "dip" in plate current which normally occurs in tetrodes at plate voltages corresponding to initial secondary emission. (See Fig. 1-10).



Pentode plate characteristics

Figure 1-10

The action of the screen and suppressor grids is to make the plate current almost independent of plate voltage (above a certain critical value). Thus, from equations (1-9) and (1-12) one can see that the plate resistance of pentodes (and tetrodes) are very high compared to triodes, while the amplification factor is almost infinite.

References:

Terman, F. E. - Radio Engineering, Chap. IV.

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ELECTRONIC CIRCUITS LECTURES

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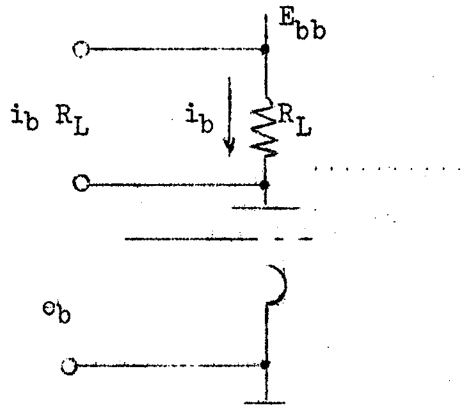
12/12/47

Load Line

We shall consider primarily circuits in which the load will be a pure resistance, or may be considered as equivalent to a resistance:



Resistive load in plate circuit.

E_{bb} = plate supply voltage
R_L = load resistance

Figure 2-1

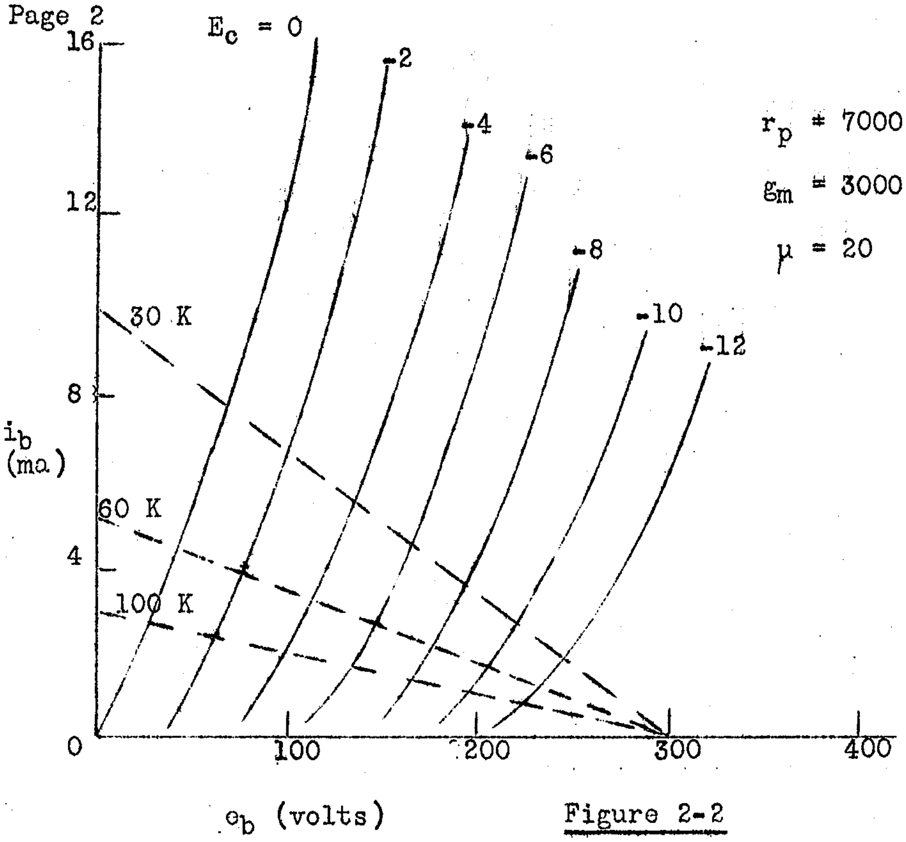
For a given E_{bb} and R_L, the values which the plate current (i_b) can assume are directly related to the (instantaneous) plate voltage (e_b) by the relation:

$$i_b R_L + e_b = E_{bb} \qquad \text{or} \qquad i_b = \frac{E_{bb} - e_b}{R_L} \qquad (2\text{-}1)$$

Since equation (2-1) is that of a straight line on the i_b - e_b diagram and has a slope determined by the load resistance, it is often called the "load-line equation." The line is determined readily by it's two limiting values:

$$\left.\begin{aligned} i_b &= 0 \quad \text{at} \quad e_b = E_{bb} \\ i_b &= \frac{E_{bb}}{R_L} \quad \text{at} \quad e_b = 0 \end{aligned}\right) \qquad (2\text{-}2)$$

(This of course assumes that the control grid does not draw grid current.)



r_p = 7000 ohms

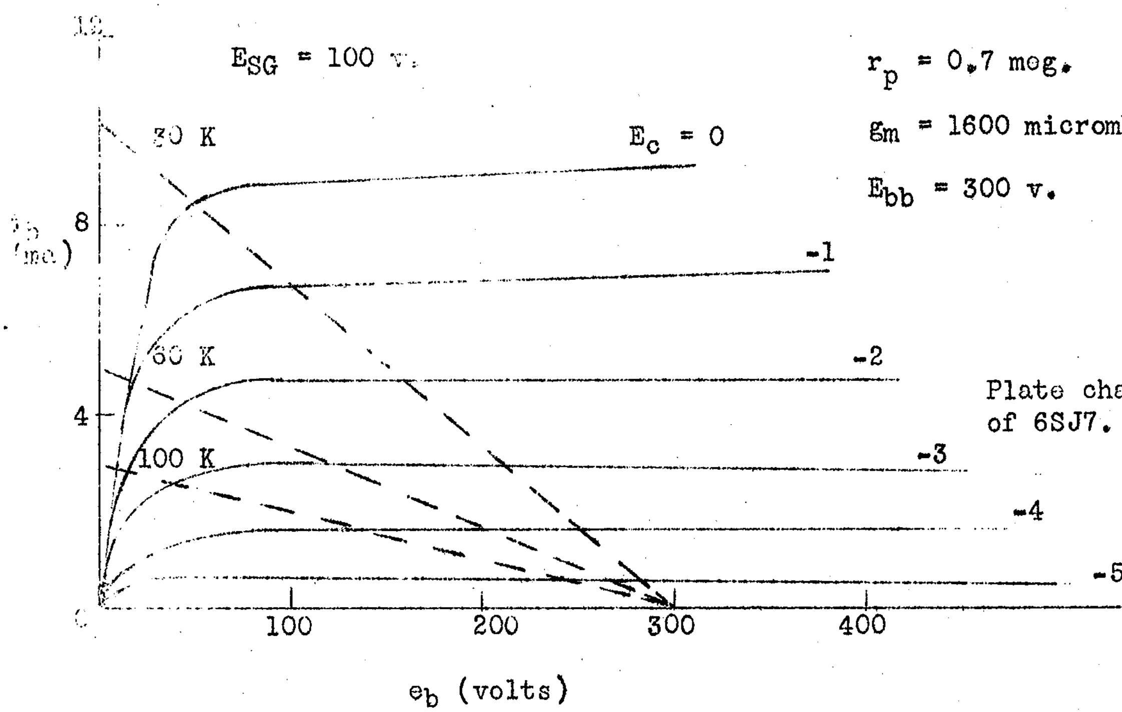
g_m = 3000 micromhos

μ = 20

E_{bb} = 300 v.

Plate characteristics of 6SN7.

Figure 2-2



r_p = 0.7 meg.

g_m = 1600 micromhos

E_{bb} = 300 v.

Plate characteristics of 6SJ7.

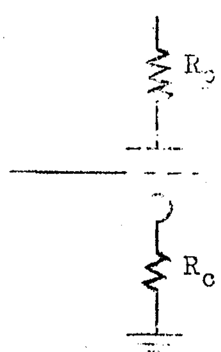
. . . .

Figure 2-3

Load lines for R_L = 30 K, 60 K, and 100 K are drawn in Figures 2-2 and 2-3 for a commonly used triode (6SN7) and pentode (6SJ7).

The load line defined by equation (2-1) is called the static load line, since it represents the locus of corresponding values of plate current and plate voltage as the grid voltage is varied under static conditions. If the load is reactive, the dynamic "path of operation" will not be a straight line; rather, it will be an ellipse or some more complicated curve, depending upon the type of grid excitation and previous history of the circuit. If the load may be treated as a pure resistance, however, the dynamic path of operation is a straight line and coincides with the static load line. We will make this assumption in our further considerations.

If we also assume that the control grid does not draw current, equation (2-1) will hold for triodes even if the load resistance is divided between plate and cathode circuits:



$$R_L = R_p + R_c$$

Figure 2-4

However, in tetrodes and pentodes the screen grid draws some of the cathode electron current and this must be taken into account in using the load line equation.

The load line is a useful tool in estimating the linearity of the tube in amplifying signals. Assuming a "middle point" or average grid bias (E_c), plate supply voltage (E_{bb}) and load resistance (R_L), one can determine how symmetrical the variations in instantaneous plate voltage will be in response to a given sinusoidal input grid voltage. For example, for the 6SN7 (Figure 2-2) with the following conditions:

$$E_{bb} = 300 \text{ v.}$$
$$E_c = -3 \text{ v.}$$
$$R_b = 30 \text{ k.}$$

and a sinusoidal signal voltage of $e_g = 3 \sin \omega t$ (v). Then, for

e_c = -6 v.	e_b = 170 v.
-3 v.	125 v.
0 v.	75 v.

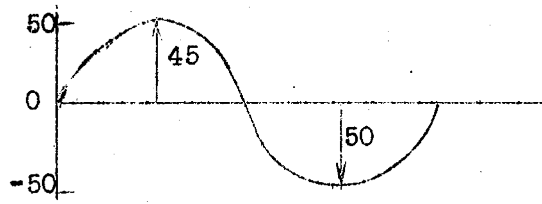


Figure 2-5

The plate current is thus roughly sinusoidal. However, for a 100 K load, E_c = -6 v., and a signal voltage $e_g = 6 \sin \omega t$. The distortion is appreciable:

e_c = -12 v.	e_b = 230 v.
- 6 v.	140 v.
0 v.	35 v.

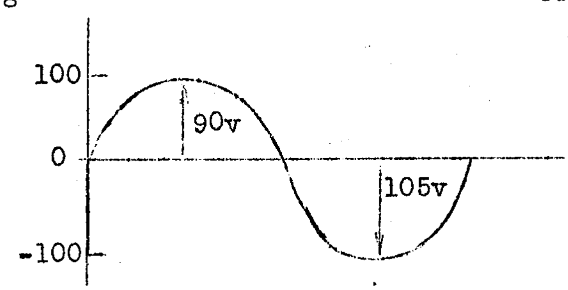


Figure 2-6

Loads of over 1 megohm are seldom used since tube current variations are sufficient to completely shift the "operating region" of voltages if high resistances are used.

The plate characteristics of a 6SJ7 tube are given in Figure 2-2 for E_{SG} = 100 v. To estimate the distortion in a pentode as compared to a triode, let us use the 30 K load line and find the plate current swing, for

$E_c = -3$ v.

$e_g = 2 \sin \omega t$

then, for

$e_c = -5$ v.	$e_b = 285$ v.
-3 v.	210 v.
-1 v.	100 v.

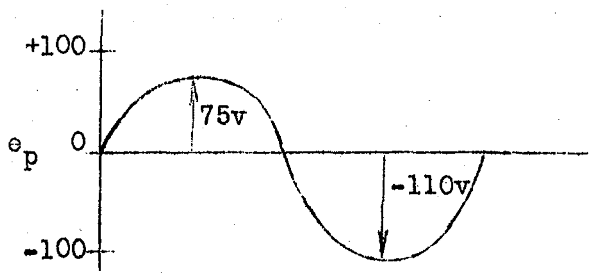


Figure 2-7

In general, a pentode gives more distortion of large signal voltages than a triode, but for small signals the distortion can be neglected in both types of tubes. To avoid distortion, the load line should not pass below the "knee" of the saturation curve. As a "rule of thumb" the load line should pass through the knee in order to conserve power.

We have already noted that if the load is not a pure resistance, the dynamic path of operation differs from the static load line. Graphical analysis of the behavior is, in general, complicated.

In certain cases in which the reactive component of the load is negligible, the dynamic load line is chosen so that it passes through the static operating point and has a slope equal to the reciprocal of the a-c load resistance. For example, if the a-c load resistance is less than the d-c resistance,

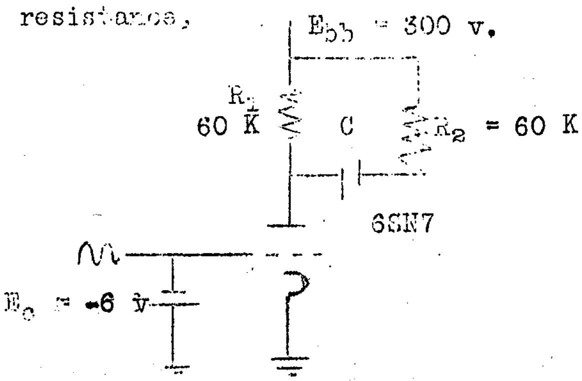


Figure 2-8

Static conditions:

$E_c = -6$ v, $E_{bb} = 300$ v.

$R_b = R_1 = 60$ K.

Dynamic conditions:

Assume $X_c \ll R_2$

$r_b = \dfrac{R_1 R_2}{R_1 + R_2} = 30$ K

Thus,

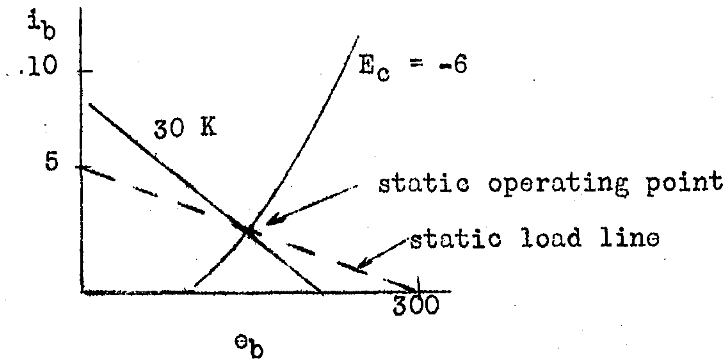


Figure 2-9

Another example, for which the a-c load resistance is greater than the d-c load resistance: (assume coils with no resistance, and unity coupling)

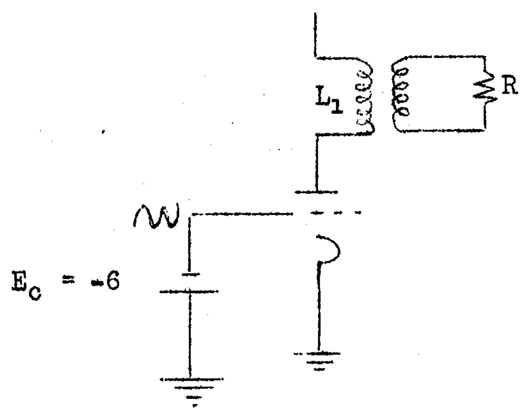
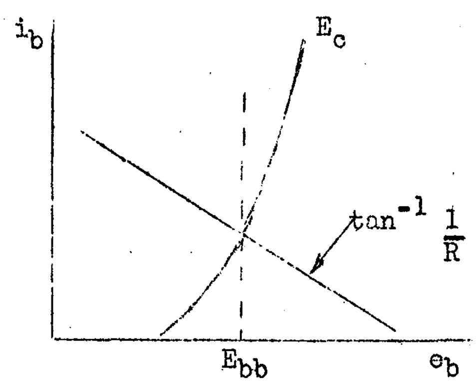


Figure 2-10

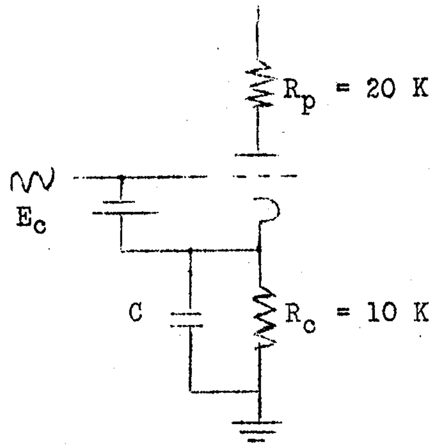


0 $\simeq$ d-c resistance of coil L_1

R = a-c resistance in plate circuit.

Figure 2-11

Finally, if a bypass condenser is used in the cathode, with $X_c \ll R_c$ at the signal frequencies:

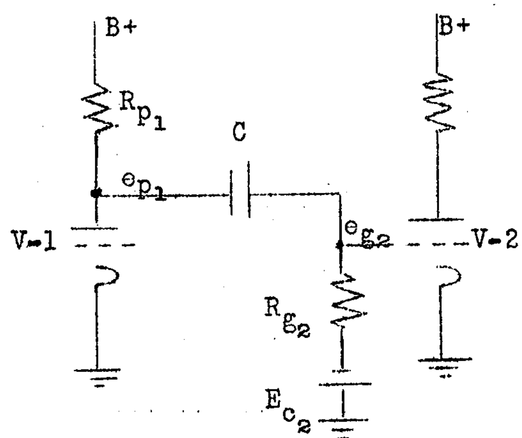


Use static 30 K load line.

Figure 2-12

Coupling Between Stages

The first consideration in coupling two stages together is to block the d-c plate voltage of the first tube from the grid of the second tube. Furthermore, the impedance of the blocking condenser, X_c, and the grid resistor, R_{g_2}, form a dividing network determining the fraction of the a-c plate voltage of V-1 appearing on the grid of the second tube.



$$e_{g_2} = \frac{R_{g_2}}{R_{g_2} + jX_c}\, e_{p_1}$$

Figure 2-13

In practice, $R_{g_2} \gg X_c$ or R_{p_1} so that the load impedance of V-1 is essentially its plate resistor and the entire a-c plate voltage appears on the grid of V-2. The upper value of R_{g_2} is limited by tube socket leakage resistance. Furthermore, in some tubes a very high grid resistance may cause the grid to become positive (due to secondary emission grid current) and "run away", destroying the tube. These tubes are usually pentodes (6AC7, etc.) and the handbooks give limiting values for R_g.

References:

Reich, Theory and Applications of Electron Tubes, Chap. IV.

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ELECTRONIC CIRCUITS LECTURES

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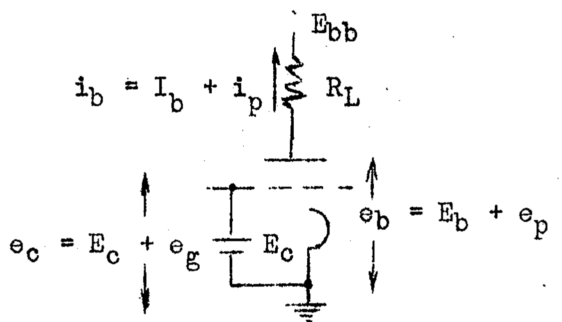
12/19/47

Vacuum Tube Amplifiers

Equivalent-Circuit Theorems

Consider the variations in plate current (i_p) produced by the application of a signal voltage (e_g) to the control grid of a vacuum-tube with a resistive load (R_L):



$$E_{bb} = e_b + i_b R_L \text{ (dynamic)}$$
$$= E_b + I_b R_L \text{ (static)}$$

$$\therefore e_p = -i_p R_L \qquad (3\text{-}1)$$

Substituting (3-1) in the load line equation

$$i_p = e_g g_m + e_p/r_p$$

we obtain

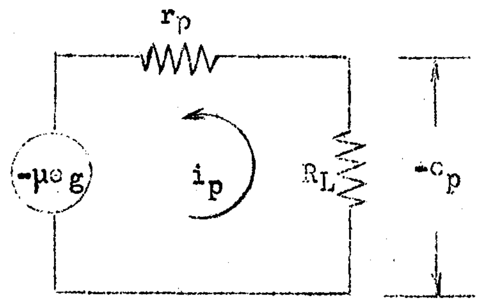
$$i_p = e_g g_m - i_p R_L/r_p$$

$$\therefore i_p = \frac{e_g g_m}{1 + R_L/r_p} = \frac{e_g g_m r_p}{r_p + R_L}$$

or, since $g_m r_p = \mu$ = amplification factor,

$$i_p = \frac{\mu e_g}{r_p + R_L} \qquad (3\text{-}2)$$

Thus the effect on the plate current is exactly as though the plate-cathode circuit were a generator developing a voltage $-\mu e_g$ and having an internal resistance equal to the plate resistance of the tube; i.e.,



Constant-voltage generator form of equivalent circuit.

Figure 3-2

(The generator voltage is negative to agree with the direction of flow of conventional current.) The constant-voltage form of equivalent circuit is particularly useful in calculating the gain of the tube:

$$\text{Gain} = \frac{-e_p}{e_g} = \mu \frac{R_L}{r_p + R_L} \tag{3-3}$$

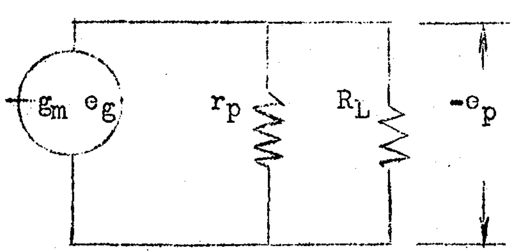
It is sometimes more convenient to analyze the plate-cathode circuit in terms of a constant-current source instead of a constant-voltage source. Substituting equation (3-2) in (3-1),

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

and using $\mu = g_m r_p$,

$$e_p = -g_m\, e_g \frac{r_p R_L}{r_p + R_L} \tag{3-4}$$

The equivalent circuit:



Constant-current generator form of equivalent circuit.

Figure 3-3

This form is particularly useful when the plate resistance is high compared to the load resistance (as in pentodes) in which case

$$e_p \simeq -g_m e_g$$

Note that both forms of equivalent circuit are physically identical though mathematically different. The exactness of either relation depends upon the assumption that r_p, g_m, and μ are constants (which is approximately true only for small signals).

The Cathode-Follower

A circuit widely used in voltage amplifiers is the cathode-follower in which the input signal is applied between grid and ground, and the output voltage is taken from the cathode resistor. Considering only the changes in voltages (neglecting d-c components of voltages),

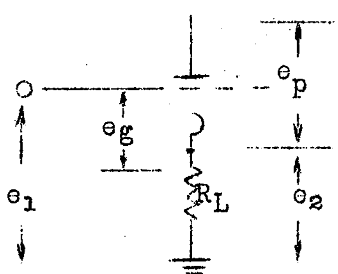


Figure 3-4

$$e_g = e_1 - e_2$$

$$e_p = -e_2$$

$$\therefore e_1 = e_g - e_p \tag{3-5}$$

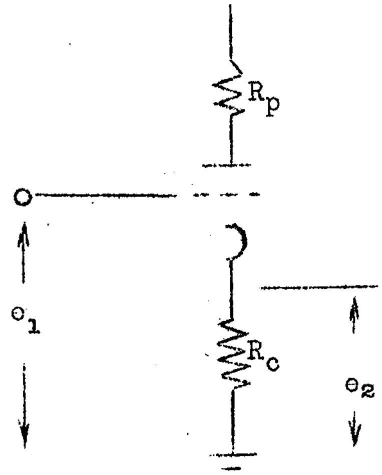
The voltage gain of the cathode-follower is:

$$\text{Gain} = \frac{e_2}{e_1} = -\frac{e_p}{e_1} = 1 - \frac{e_g}{e_1}$$

i.e., the gain is always less than unity. In terms of tube characteristics, using equation (3-3)

$$\text{Gain} = -\frac{e_p}{e_g - e_p} = \frac{\mu R_L}{r_p + R_L + \mu R_L} = \frac{R_L}{\left(\frac{r_p + R_L}{\mu}\right) + R_L} \tag{3-6}$$

Where there is resistance in the plate circuit,



$$R = R_c + R_p$$

$$R_L = R_c$$

$$e_2 = -e_p = \mu e_g \frac{R_c}{r_p + R}$$

$$\therefore \text{Gain} = \frac{R_c}{\left(\frac{r_p + R}{\mu}\right) + R_c} \quad \text{in cathode circuit} \tag{3-7}$$

Figure 3-5

In this case it can be seen that if μ is large, the first term in the denominator affects the gain only slightly. Thus, small variations in μ and r_p, due to the curved tube characteristics and to changes in the tube, do not affect gain, and a "flat" response results. The gain in the plate circuit may be greater than unity,

$$\text{Plate gain} = \frac{R_p}{R_c} \cdot \frac{e_2}{e_1}$$

and is also stabilized by the presence of an unbypassed R_c and may also be greater than unity.

The chief advantage of the ordinary cathode-follower is its ability to provide low output impedance from a relatively high input impedance. To determine the output impedance, consider the increased current required from an impedance measuring device (such as a battery and voltmeter) in order to produce an increase of 1 volt (say) in e_2. If the tube were <u>not</u> present and R_c = 1000 ohms, the output impedance would be

$$R = \frac{\Delta E}{\Delta I} = \frac{1 \text{ v.}}{1 \text{ ma.}} = 1000 \text{ ohms.}$$

<u>With</u> the tube present, an increase in e_2 produces corresponding <u>decreases</u>

in e_g and e_p which in turn reduce the tube current flowing in R_c. Increased battery current is required to maintain the voltage increase ΔE; thus the output impedance is effectively lowered by inserting the tube. The total increase in battery current is made up of:

$\Delta I_1 = \dfrac{\Delta e_2}{R_c}$ = current to produce voltage increase <u>without</u> tube

$\Delta I_2 = -\Delta e_g \cdot g_m$ = increase in battery current to compensate for drop in grid voltage

$\Delta I_3 = -\dfrac{\Delta e_p}{r_p}$ = increase in battery current to compensate for drop in plate voltage

Since $\Delta E = \Delta e_2 = -\Delta e_g = -\Delta e_p$, the output impedance is

$$R = \frac{\Delta E}{\Delta I} = \frac{1}{1/R_c + g_m + 1/r_p} \quad (3\text{-}8)$$

or, the output impedance of a cathode-follower looks like:

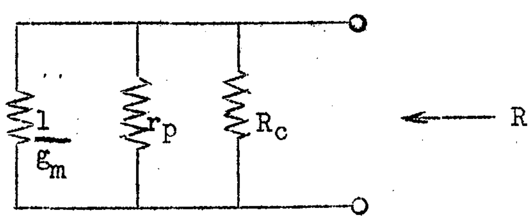


Figure 3-6

In case $\mu \gg 1$, then $r_p \gg \dfrac{1}{g_m}$ and for small R_c, we have

$$R \simeq \frac{1}{g_m}$$

As an example, consider a 6SN7 tube with R_c = 1000 ohms. Since g_m = 3000 μmhos, and r_p = 7000 ohms, we have for ΔE = 1v.,

$\Delta I_1 = +1/1000 \cdot 10^3 = 1.0$ ma.

$\Delta I_2 = -(-1)(3000) = 3.0$ ma.

$\Delta I_3 = -(-1)/(7000) \cdot 10^3 = 0.14$ ma.

$\Delta I = \quad = 4.14$ ma.

Thus,

$$R = \frac{\Delta E}{\Delta I} = \frac{1 \text{ v.}}{4.14 \text{ ma.}} \simeq 250 \text{ ohms.}$$

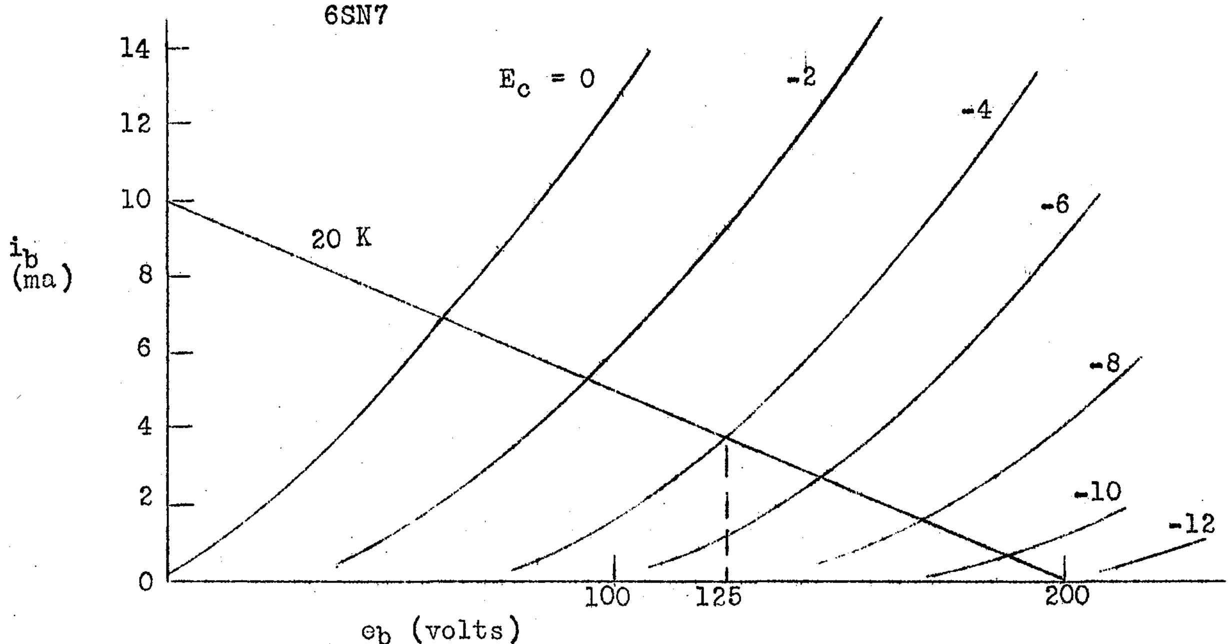


Figure 3-7

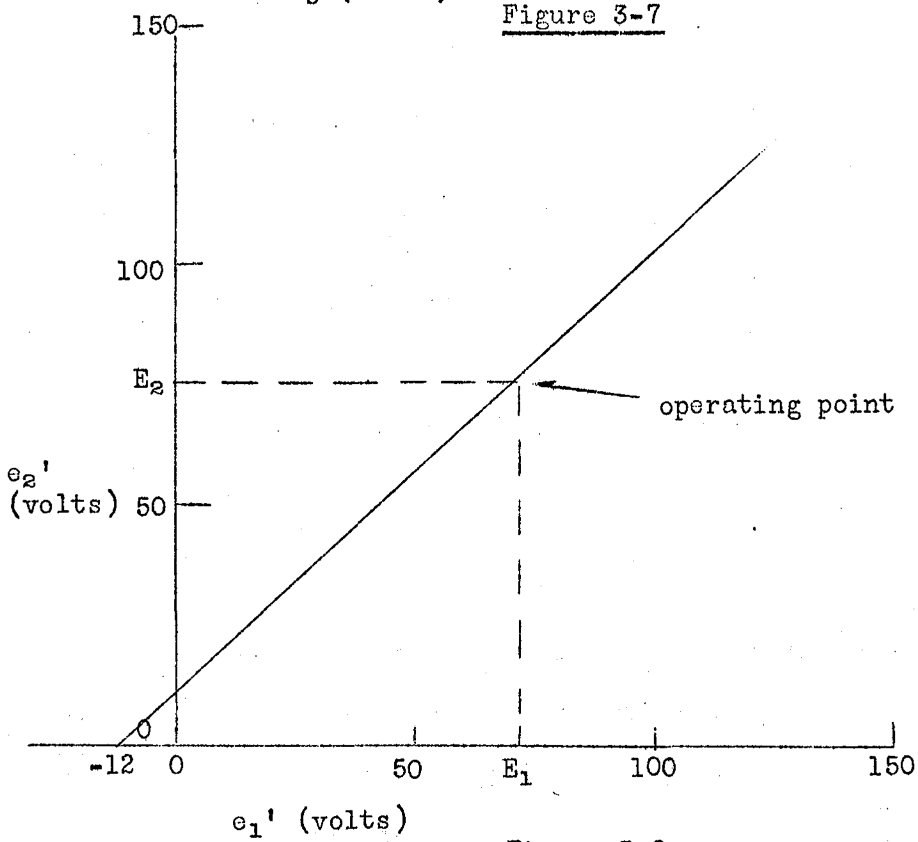


Figure 3-8

Although the cathode-follower provides practically distortionless output for normal input signal voltages, it should be borne in mind that it will distort very large input signals. Consider a 6SN7 with E_{bb} = 200 v., and R_c = 20 K;

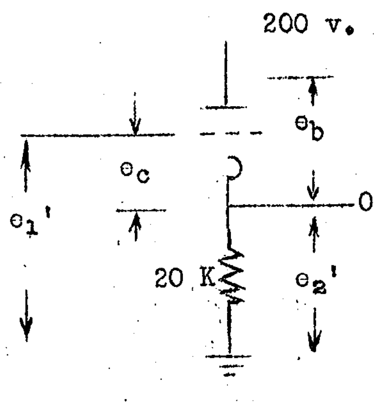


Figure 3-9

For convenience, define the d-c (static operating) voltages E_1, E_c, E_2 so that the total instantaneous voltages shown are:

$$\left.\begin{aligned} e_1' &= E_1 + e_1 \\ e_2' &= E_2 + e_2 \\ e_c &= E_c + e_g \end{aligned}\right) e_1' = e_c + e_2'$$

The limits upon signal amplitude are set by the instantaneous grid bias ($0 > e_c > \text{cutoff}$). For example, assume an operating bias of E_c = -4 v. Then (see Figure 3-7),

$$e_b = 125 \text{ v.} \qquad E_2 = 200 - 125 = 75 \text{ v.}$$
$$E_1 = 75 - 4 = 71 \text{ v.}$$

Now if e_c can vary from 0 to -11 v., we can plot the corresponding values of e_1' vs. e_2' (see Figure 3-8). This plot illustrates not only the linearity of the cathode-follower and the gain (slope of curve), but also the limits on input. For if the input signal e_1 swings more than 130 - 71 = 59 volts positive the grid is driven positive, and if $e_1 > (71 + 12) = 83$ volts negative the tube is cutoff. To allow maximum voltage swing, a grid bias of $E_c \simeq -3$ v., is best.

References:

(1) Terman, Radio Engineering, Chap. V.

(2) Chaffee, Theory of Thermionic Vacuum Tubes, Chap. VIII.

(3) Rider, Inside the Vacuum Tube, pp. 332-338.

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