The Determination of Quiescent Voltages and Currents in Pentode Amplifiers

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VERY often designers of electronic equipment are confronted with the problem of determining the quiescent electrode voltages and currents for a given amplifier circuit, particularly when an existing design is being checked.

If a triode is used, the solution presents little difficulty, but for pentode amplifiers greater difficulty is experienced mainly because the screen grid voltage is unknown. Although values of anode and control grid voltages can be found for a known screen voltage, this voltage in a particular circuit depends on the parameters of the circuit so that the bias on the tube, and the anode and screen voltages are interdependent. The following is an approximate method of obtaining the quiescent values of anode, screen grid and control grid voltages and currents when the circuit parameters and supply voltage to the amplifier are known.

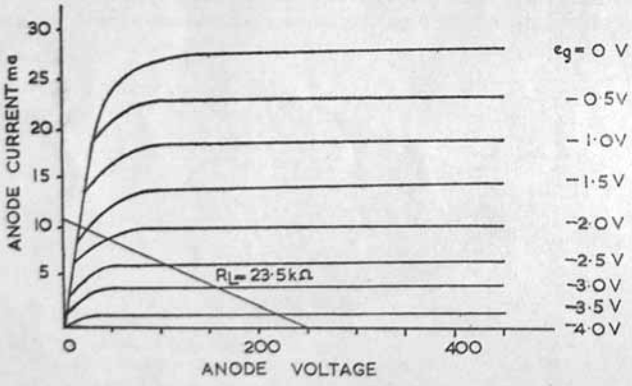

Fig. 1.
Anode characteristic of EF91 pentode
$e_g = 250$ volts

Dynamic Characteristics of Pentodes

Manufacturers of valves usually give anode characteristics for one particular screen voltage (usually 250 or 100 volts). Typical anode characteristics are shown in Fig. 1. On these characteristics a loadline can be drawn and a dynamic characteristic relating anode current and grid voltage added. It should be noted that this is drawn for the particular screen voltage at which the anode characteristics are given. If the screen voltage is changed to another value, another set of anode characteristics is obtained.

An examination of experimentally obtained dynamic characteristics* for pentodes at various fixed screen voltages shows that they are a family of curves approximately parallel to each other (particularly the lower portions), i.e., are practically the same shape, and equally spaced for equal increments or decrements in screen voltage, except when the screen voltage is very low, say below 10 volts. One interesting point is that as the screen voltage decreases the dynamic characteristics have slightly longer linear portions and slightly higher slopes for reasons discussed in section 3 below.

The spacing between the various dynamic characteristics can be determined (for any given control grid voltage) by making use of the fact that when the valve is connected as a triode we have:

$$\mu_T = \left.\frac{\triangle e_a}{\triangle e_g}\right|_{i_a \text{ constant}} = \left.\frac{\triangle e_s}{\triangle e_g}\right|_{i_a \text{ constant}}$$

or for any fixed anode current a change in screen voltage $\triangle e_s$ is equivalent to a change in control grid

$$\text{voltage of } \triangle e_g = \frac{\triangle e_s}{\mu_T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Thus if μ_T is known, the spacing between the dynamic characteristics can be calculated and a family of dynamic characteristics can be drawn, without recourse to the anode characteristics at various screen voltages.

A typical family is shown in Fig. 2; the curve for zero screen voltage is similar in shape to the others but is further spaced and of lower slope.

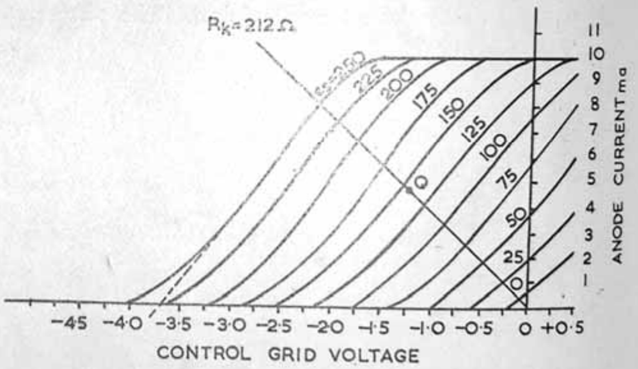

Fig. 2.
Family of dynamic characteristics, EF91
$R_L = 23.5$ kΩ, $E_B = 250$ volts

Relationships between Anode Current and Screen Voltage

For any given amplifier, if the screen voltage is known, the quiescent conditions are readily determined.

For an amplifier with cathode resistor R_k, there is a relationship between quiescent anode current and screen voltage which can be determined as follows.

The grid voltage and anode current are related by:

$$e_g = -(i_a + i_s)R_K$$

where i_s is the screen current. In the absence of more accurate information this screen current can be taken as a constant proportion of the anode current; $i_s = ki_a$, where k is a constant between 0.33 and 0.25 provided the anode voltage does not fall below about 15 to 20 per cent of the screen voltage, below which the screen takes a rapidly increasing proportion of the cathode current. The constant k can be determined from figures published by the valve manufacturer. The value of k begins to increase rapidly as the anode current approaches the limiting value just below E_B/R_L, where E_B is the D.C. supply voltage

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* See "Radiotron Designers Handbook" 3rd Edition, p.273. Also "Dynamic Characteristics of Pentodes" *Communications*, July 1946. p.14.

and R_L the load resistor. At any one particular screen voltage e_s, the dynamic characteristics will be straight until the anode current is about 20 e_s/E_B per cent from the limiting value, because for higher anode currents the anode voltage is below 20 per cent of the screen voltage and therefore the screen current is rising rapidly and the anode current is becoming asymptotic to its limiting value. Thus we have

$$= -(k+1)i_a R_K \quad \text{.................} \quad (2)$$

This can be represented by a straight line on the same graph as the family of dynamic characteristics, the intersection of the cathode line and the particular dynamic characteristics giving the anode current for the particular screen voltage. From a graph such as is shown in Fig. 2 anode current versus screen voltage can be plotted, the shape of the curve being as shown in Fig. 3.

This curve is practically a straight line which bends rapidly and is asymptotic to a current slightly below E_B/R_L, the limiting value of anode current.

A second relationship between anode current and screen voltage is furnished from the conditions existing in the screen circuit. With a screen resistor R_s and screen supply voltage E_s we have

$$e_s = E_s - i_s R_s$$
$$i_s = k i_a$$
$$e_s = E_s - k i_a R_s \quad \text{.......................} \quad (3)$$

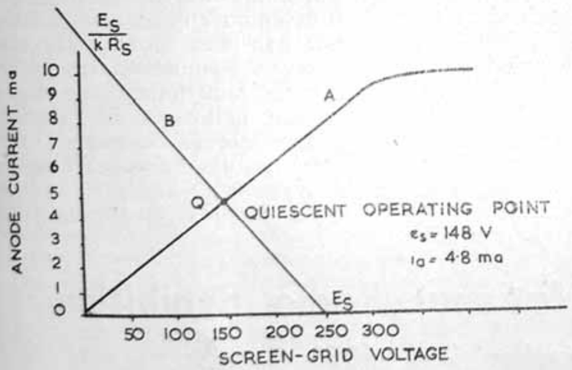

Fig. 3.
Anode current versus screen voltage

which is the second relationship needed to determine e_s and i_a for the particular amplifier. This relationship is a straight line. It should be noted that E_s and R_s are the effective values of screen supply voltage and screen resistor respectively. If a simple series dropping resistor is used, E_s is equal to E_B, the supply voltage, and R_s is the value of the series resistor, but if a voltage dividing network is used, Thèvenin's Theorem must be applied to find E_s and R_s.

The intersection of the two lines gives the quiescent screen voltage and anode current.

A Typical Example

To illustrate this graphical approach, consider an amplifier using an EF91 valve, connected as shown in Fig. 4.

The anode characteristics and dynamic characteristics for e_s = 250 volts are shown in Figs. 1 and 2 respectively. The value of μ_T for this valve is about 68 and k is 0.255. The calculated family of dynamic characteristics is shown in Fig. 2, together with the cathode loadline for R_K = 212 ohm (from Equation 2) and the anode current screen voltage relationships are shown in Fig. 3, curve A being that determined from Fig. 2 and line B being that of the screen loadline (Equation 3). The equilibrium screen voltage is given by the intersection of lines A and B.

The quiescent conditions thus determined are given in Table 1, together with the measured values for the particular circuit. It can be seen that there is fairly close agreement between the results.

TABLE I.
EF91 Pentode : R_L = 23.5 k ohm. R_S = 82 k ohm. R_K = 212 ohm.
E_B = 250 volt.

Quiescent Value	Graphical Results	Measured Values
Screen Voltage	148 V	152 V
Anode Voltage	137 V	143 V
Anode Current	4.8 mA.	4.65 mA.
Screen Current	1.22 mA.	1.20 mA.
Grid Bias	1.27 V	1.31 V

6J7G Pentode : R_L = 250 k ohm. R_S = 1.2 Megohm. R_K = 1200 ohm.

E_B = 300 V.

	Graphical Result	Measured Value
Screen Voltage	47 V	43 V
Anode Voltage	88 V	85 V
Anode Current	0.85 mA.	0.86 mA.
Screen Current	0.21 mA.	0.21 mA.
Grid Bias	1.28 V	1.30 V

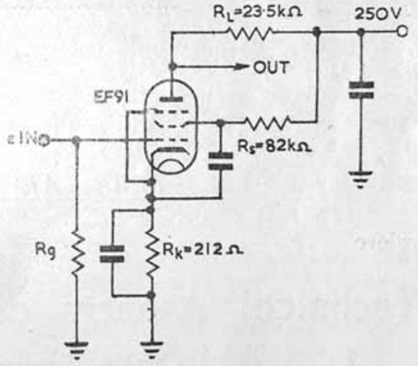

Fig. 4.
Typical pentode amplifier

In Table 1 results are also given for a pentode amplifier using a type 6J7G valve. It is thought that in the majority of cases the calculated results will be within 10 per cent of their actual values, but it must be remembered that individual valve characteristics can vary greatly from the published values, particularly if the anode current is well below the normal operating value. Also, consideration must be given to variation of resistors from their nominal values. The changes in operating conditions due to variations in resistor value can be easily determined by making the calculations outlined above for the upper and lower limits of the resistor concerned.

Analytical Treatment

The equation to a family of dynamic characteristics as shown in Fig. 2 is given by

$$i_a = a + b(e_g + \overline{e_s - A}/\mu_T) \quad \text{...........} \quad (4)$$

where i_a = anode current,
a = a constant equal to the projected value of i_a for $e_g = O$ at screen voltage $e_s = A$,
b = a constant equal to the slope of the dynamic characteristics at $e_s = A$,

e_g = control grid voltage, polarity being considered with respect to cathode,
e_s = screen voltage,
A = screen voltage for which constants a and b are determined, and for which the original anode characteristics are given,
$\mu_T = \partial e_s / \partial e_g$ = amplification factor of valve connected as a triode,

with the limitation that i_a does not exceed E_B / R_L.

This gives only the straight portion of the curves and does not consider curvatures near cutoff and near the limiting value of anode current.

The equation to the cathode loadline is

$$e_g = -(1 + k) i_a R_K$$

The intersection of this line and the dynamic characteristic gives

$$i_a = a + b\left\{ -(1 + k) i_a R_K \overline{+\ e_s -} A / \mu_T \right\}$$

$$\text{or } i_a = \frac{a / b + e_s - A / \mu_T}{1 / b + (1 + k) R_K}$$

$$= \frac{(E_g - A / \mu\ ) + e_s / \mu_T}{1 / b + (1 + k) R_K} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

where $E_g = a / b$ is the projected grid base at $e_s = A$. This is the equation to line A in Fig. 3.

The equation to the screen line is

$$i_a = \frac{E_s - e_s}{k R_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where E_s = effective screen supply voltage,
$k = i_s / i_a$,
R_s = effective screen resistor.

Combining Equations (5) and (6) we have that the quiescent screen voltage is given by

$$e_s = \frac{E_s (1 / b + \overline{1 + k}\ R_K) - k R_s (E_g - A / \mu_T)}{1 / b + (1 + k) R_K + k R_s / \mu_T} \quad \ldots (7)$$

and therefore

$$i_a = \frac{E_g - A / \mu_T + b\ E_s / \mu_T}{1 / b + (1 + k) R_K + k R_s / \mu_T} \quad \ldots\ldots\ldots\ldots (8)$$

Since E_g is approximately equal to A / μ_T, we have

$$e_s \approx \frac{E_s}{1 + \dfrac{k\ R_s}{\mu_T \left\{ 1 / b + (1 + k) R_K \right\}}} \quad \ldots\ldots\ldots\ldots (9)$$

This gives the quiescent screen voltage, from which all other quiescent conditions are readily determined.

For the circuit shown in Fig. 4, the value of E_g is -3.65 V and $1 / b = 185$ (from Fig. 2). Substituting in the Equation (7) we have

$$e_s = \frac{250}{1 + \dfrac{.255\ .\ 82}{68 \left\{ .185 + .266 \right\}}} = \frac{250}{1 + .681} = 149 \text{ V.}$$

This is close to the measured value.

Conclusion

A method has been presented which enables approximate values of the quiescent electrode values of voltages and currents in a pentode amplifier to be determined, either graphically or by calculation from a dynamic characteristic for a particular screen voltage. The graphical method is more accurate and should be used in preference to calculation since a much clearer picture of operating conditions can be obtained. The method gives an approximate solution only, but in practice it has been found to be close enough for design purposes. It must be remembered that individual valves vary from the average characteristics as given by the manufacturer, so more accurate calculations are seldom warranted. The approach is particularly useful in determining the effect of changes in circuit parameters, such as cathode resistor or screen resistor, on the operation of the amplifier.