thermoelectrons, many of them have sufficient energy to arrive at the grid even if it is at a considerable negative potential with respect to the cathode. Thus, this positive grid current becomes as great as the negative (positive-ion) grid current, making the net current zero at some negative grid potential, usually about -1.0 to -1.8 volt for oxide-coated unipotential cathodes at temperatures of 1000° to 1100° K. This is the "floating-grid" potential, which the grid assumes if disconnected. It is largely independent of plate voltage but tends to be slightly more negative at the lower values.

Because of the distribution of electron initial velocities, the grid current increases exponentially with respect to grid potential, increasing itself by a factor of 10 for every 0.2- or 0.3-volt increase of potential. (The fact that the grid potential moves as the logarithm of the grid current is used in certain computing devices.) This exponential type of increase ends at from 10 to 100 μa; thereafter the nature of the increase depends on the tube type and is also considerably affected by plate voltage—the lower the plate voltage the more the grid current.

The logarithmic portion of the grid-current curve is shown in Fig. 11·4. This part of the curve shows much less variation from tube to tube than the negative portion. A reduction of cathode temperature reduces the grid current at a given bias, but it also increases the plate potential at a given plate current. The result is that if the grid current is not to exceed some predetermined magnitude, for a certain plate current the minimum allowable plate potential is not affected by cathode temperature.

Minimum allowable plate potential is of great importance in d-c amplifier design. It depends primarily on the maximum allowable positive grid current, which depends on input resistance, and on the permissible voltage error resulting from their product. For example, a grid current of 0.02 μa in a series input resistance of 1 megohm causes the actual grid voltage to be 20 mv lower than the input potential. In the case of Fig. 11·4, with a plate current of 0.1 ma, this would occur at $e_p =$ about 50 volts, regardless of cathode temperature. In this same example, a reduction of plate current by a factor of 10 (to 0.01 ma) would lower the plate potential by only 15 or 20 volts.

The higher the μ of a triode the higher will be the minimum allowable plate potential (assuming a given allowable grid current and a given plate current), the latter being roughly proportional to the former.

In a pentode, the plate can operate at much lower potentials than in a triode, provided that the screen is at a sufficiently high potential to permit ample negative bias on the control grid. The only requirement on the pentode-plate potential is that it be high enough to keep the screen from taking all of the current; most low-power pentodes will

operate satisfactorily as voltage amplifiers with plate potentials in the neighborhood of 10 volts.

11·6. The Effect of Heater-voltage Variation.—Variation of the cathode temperature of a vacuum tube in which the current is limited by electrode potentials and space charge rather than by cathode emission has the effect of varying the average initial electron velocity and therefore also the electrode voltages required to obtain a given electron flow.[1] When the plate current is very small compared with cathode emission, as is often the case in the first stage of a d-c amplifier, this effect is fairly independent of plate current. It may be expressed in terms of the amount by which the cathode voltage must be changed relative to the other electrode voltages in order to hold the current constant as the cathode temperature is varied.

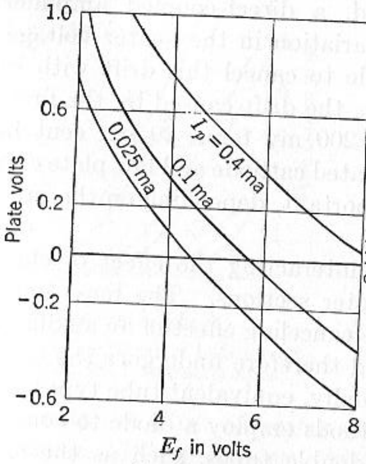

Fig. 11·5

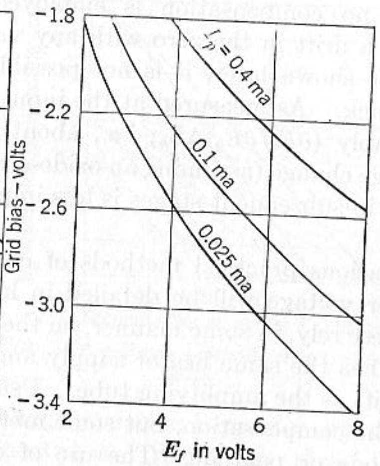

Fig. 11·6

Fig. 11·5.—Diode heater-voltage characteristics (6SL7 as diode).
Fig. 11·6.—Triode heater-voltage characteristics (6SL7, $E_p = 150$ volts).

For oxide-coated unipotential cathodes, this amount is approximately 0.2 volt for a 20 per cent change of heater voltage about the normal value, whether the tube is a diode, a triode, or a multigrid tube. Figure 11·5 illustrates the relationship for a diode. (A 6SL7 triode with grid connected to plate was used as a diode in this test, for comparison with Fig. 11·6. An ordinary diode gives the same result, however.) It is seen that the slope $\partial E_p/\partial E_h$ at a given value of heater voltage is not greatly affected by current at the low-current values employed.

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[1] L. R. Koller, *The Physics of Electron Tubes*, 2d ed., McGraw-Hill, New York, 1937; W. G. Dow, *Fundamentals of Engineering Electronics*, Wiley, New York, 1937; J. Millman and S. Seely, *Electronics*, McGraw-Hill, New York, 1941. See also Appendix C for a discussion of the drift of vacuum-tube characteristics under constant applied potentials.

Figure 11·6 gives the same sort of information for the same tube used as a triode. Here the plate-to-cathode voltage was fixed; and as the cathode temperature varied, the current was held constant by adjustment of the grid potential. To have been completely comparable with the diode characteristics, the plate-to-grid potential should have been held constant; however, the results differ only by $1/\mu$. It is seen that the slope $\partial E_c/\partial E_h$ is about the same as was the slope $\partial E_p/\partial E_h$ for the diode and that in this case, too, it remains fairly constant with changes in plate current.

If no compensation is employed, a direct-coupled amplifier will suffer a drift in the zero with any variation in the heater voltage. As will be shown later, it is not possible to cancel this drift with inverse feedback. As measured at the input, the drift caused by the first stage is simply $(\partial E_c/\partial E_h)\Delta E_h$; i.e., about 200 mv for a 20 per cent heater-voltage change (assuming an oxide-coated cathode and low plate current). Drift in subsequent stages is less important, depending on the preceding gain.

Various practical methods of counteracting the effect of change in heater voltage will be detailed in later sections. The most important of these rely, in some manner, on the canceling effect of an auxiliary tube that has the same heater supply and therefore undergoes the same sort of drift as the amplifying tube. Usually, equivalent tube types are used for the compensation, but some methods employ a diode to compensate a triode or pentode. The use of double tubes, such as the 6SL7, is preferable, since the cathode characteristics of a pair of triodes in the same envelope, made on the same day by the same manufacturer, are likely to be more alike than the characteristics of a random pair. To check this, the characteristics of 18 6SL7 double triodes (36 triodes) were measured. For each triode was recorded the change in grid bias that was needed to hold constant a plate current of 0.2 ma at a plate voltage of 150 volts while the heater voltage was changed from 10 per cent below normal to 10 per cent above normal. The tubes were of various ages and makes. The average value of ΔE_h for the 20 per cent change was 210 mv, and 90 per cent of the values lay between 191 and 210 mv. Pairing the triodes at random without regard to envelopes, the average difference in ΔE_h between pairs[1] would be 14 mv, whereas the average difference between the two triodes in each envelope was only 8 mv.

A set of mutual characteristics for a 6SL7 is given in Fig. 11·7 for two different heater voltages. For a given current, $\partial E_c/\partial E_h$ is not affected by the value of E_p; nor is $\partial E_c/\partial E_h$ appreciably affected by the value of I_p for currents less than 1 ma, such as are employed in most voltage amplifiers. For higher currents, no longer negligible compared with cathode emission, $\partial E_c/\partial E_h$ changes somewhat more with change in current and is also subject to much more variation from tube to tube.

Table 11·1 gives the average characteristic (in terms of ΔE_c required by a 20 per cent change of E_h about normal) and dispersion of the characteristic for rather limited samples of certain tube types. Both high and low values of current were applied, and the results show that for high currents the effect of heater-voltage variation is greater and much more erratic. Pentodes were connected as triodes for these tests; this type of operation is legitimate, because it is found that the ratio between plate and screen currents is not affected by this connection.

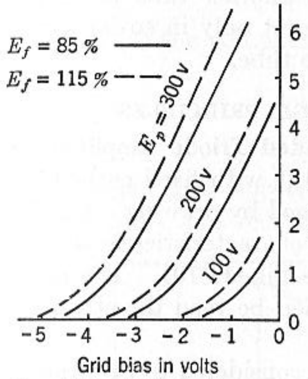

FIG. 11·7.—Effect of heater voltage on 6SL7 characteristics.

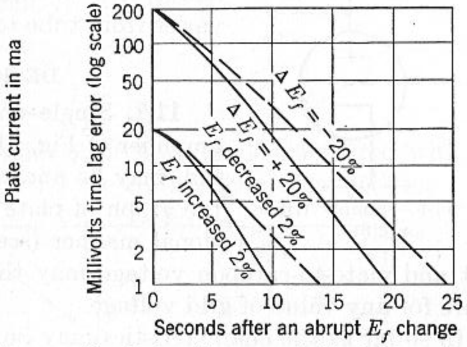

FIG. 11·8.—Heater-cathode time lag of a 6SL7.

TABLE 11·1.—EFFECT OF ELECTRODE VOLTAGES AND CURRENTS ON THE AVERAGE DRIFT RESULTING FROM HEATER-VOLTAGE VARIATION AND ON THE DEVIATION FROM THIS AVERAGE, AND THE GRID BIAS AND DEVIATION THEREFROM

Tube type	No. of tubes in sample	Plate (and screen) potential, volts	Plate (and screen) current, ma	Average grid bias (E_h = 63v), volts	Probable deviation of grid bias, volts	Average bias shift required for ΔE_h = 20 %, mv	Probable deviation of bias shift, mv
6SN7	10(20 sec.)	60	2.0	−1.65	±0.15	210	± 15
		240	10.9	−6.70	±0.40	425	± 90
6SJ7	10	60	2.5	−1.60	±0.10	215	± 15
		240	10.0	−7.20	±0.35	400	±110
6AC7	10	60	2.0	−1.30	±0.25	210	± 15
		240	8.0	−5.10	±0.60	290	± 40
6AG7	10	60	10.0	−3.20	±0.20	220	± 20
		240	40.0	−7.90	±0.25	325	± 50

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[1] In a gaussian distribution of values, the average difference between pairs of values is $2\sigma/\sqrt{\pi}$, where σ is the standard deviation of the distribution.

There is a certain amount of thermal lag between a change of heater voltage and the resulting change of emission. Its magnitude, for a sudden increase or decrease of heater voltage on a 6SL7, is shown in Fig. 11·8 in terms of the lag in bias for a given current. This lag is of particular interest where the method of compensation involves the direct application of heater voltage as a circuit parameter. Where the compensation employs another tube as mentioned above, it is of interest only in so far as the lag varies from tube to tube.

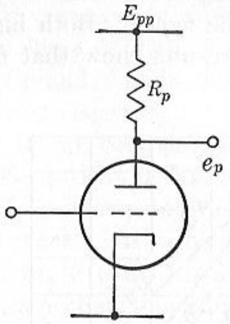

FIG. 11·9.—Simple triode amplifier.

DESIGN PRINCIPLES

11·7. Single-ended Triode Amplifiers.—The amplifier of Fig. 11·9, with fixed cathode potential, may be analyzed by drawing a load line on the graph of plate characteristics in the conventional manner (see Fig. 11·10). The plate current and plate-to-cathode voltage may then be read directly from the figure for any value of grid voltage.

In so far as the characteristics may be considered to be straight and parallel and to start from zero plate current at zero plate and grid voltage, the operation of the amplifier may be analyzed mathematically from the formula for plate current:

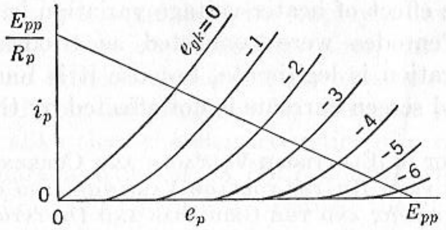

FIG. 11·10.—Plate characteristics with load line.

$$i_p = \frac{e_{pk} + \mu e_{gk}}{r_p}, \tag{1}$$

where μ is $\left.\frac{\partial e_{pk}}{\partial e_{gk}}\right|_{i_p}$ and r_p is $\left.\frac{\partial e_{pk}}{\partial i_p}\right|_{e_{gk}}$. Substituting $E_{pp} - R_p i_p$ for e_{pk}, the plate current is found to be

$$i_p = \frac{E_{pp} + \mu e_{gk}}{r_p + R_p}, \tag{2}$$

and the plate voltage is

$$e_p = E_{pp} - R_p i_p = \frac{\frac{r_p}{R_p} E_{pp} - \mu e_{gk}}{1 + \frac{r_p}{R_p}}. \tag{3}$$

From Eq. (2) the current gain (considering R_p as the load) is

$$\frac{\partial i_p}{\partial e_{gk}} = \frac{\mu}{r_p + R_p}, \tag{4}$$

and from Eq. (3) the voltage gain is

$$\frac{\partial e_p}{\partial e_{gk}} = \frac{-\mu}{1 + \frac{r_p}{R_p}}. \tag{5}$$

Thus the current gain approaches g_m if R_p is small compared with r_p; and if R_p is large compared with r_p, the voltage gain approaches μ.

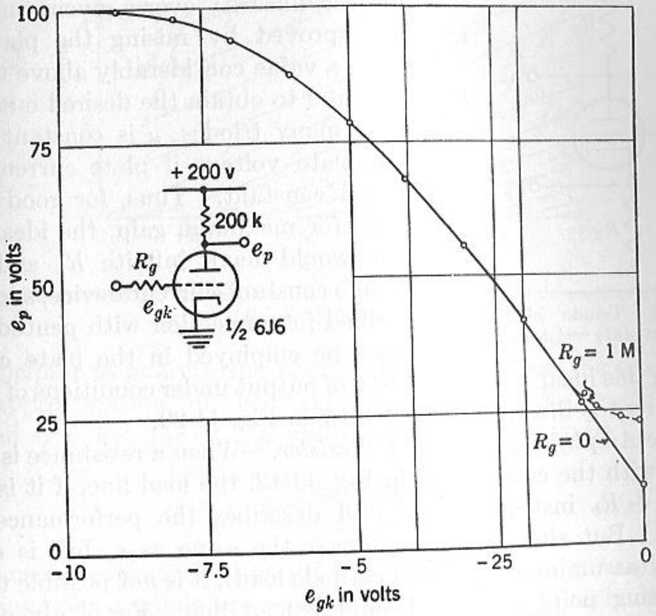

FIG. 11·11.—Typical triode amplifier characteristics.

This relation would indicate that a very high resistance should be employed for R_p if a voltage amplifier is to realize the maximum gain. Actually, r_p is approximately inversely proportional to plate current for small values of i_p, and μ drops slightly as plate current is decreased. Therefore, for a given E_{pp}, the gain ceases to increase as R_p is increased beyond a finite multiple of r_p. For instance, in a 6J6 triode, by measuring the increment of plate voltage obtained between $e_g = -2.5$ and -5

directions is achieved with $E = E_{pp}/2$ and $R = 1/g_m$, but the maximum gain occurs with an R of several times $1/g_m$.

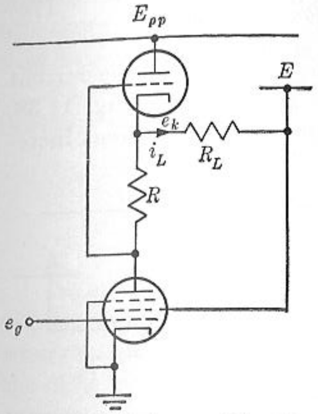

FIG. 11·39.—Series amplifier using pentode.

If a pentode is used in the lower position, as in Fig. 11·39, the formulas are simpler. In this case, Eq. (74), the voltage gain with $R_L = \infty$, becomes

$$\frac{\Delta e_k}{\Delta e_g} = -g_m(r_p + \mu R), \tag{79}$$

where g_m refers to the pentode and μ and r_p to the triode. The output impedance is simply

$$Z_0 = r_p, \tag{80}$$

because the pentode current is independent of its plate voltage, so that if e_k is moved by external means, the triode bias will remain constant and its current will vary according to plate resistance. From Eqs. (79) and (80) the voltage gain with load is found to be

$$\mathcal{G} = -g_m \frac{r_p + \mu R}{1 + \dfrac{r_p}{R_L}}, \tag{81}$$

and the current gain is

$$\frac{\Delta i_L}{\Delta e_g} = -g_m \frac{r_p + \mu R}{r_p + R_L}. \tag{82}$$

A practical example of this output circuit is given in Fig. 11·42. Both tubes are pentodes, but the upper tube behaves like a triode because its plate and screen both are fixed.

A comparison of this circuit with the differential amplifier shows that for tubes of the same capabilities, the former has at least four times the gain and twice the maximum output current in both directions as the latter. On the other hand, this circuit requires a low-impedance intermediate voltage source, and, for a given available $B+$ voltage, the input voltage level must be considerably lower than that for a differential amplifier.

11·12. Cancellation of Effect of Heater-voltage Variation.—The fundamental effect of heater-voltage variation was explained in Sec. 11·6: A definite change of heater voltage is the equivalent of a definite change of the cathode potential relative to the other electrode potentials. For oxide-coated cathodes, a 10 per cent increase of heater voltage is the same as a cathode-potential decrease of about 100 mv, although this

figure is subject to some variation from tube to tube and is larger and more erratic if the cathode current is very great. Thus the effect can be canceled either by an equal displacement in the opposite direction of the cathode potential or by approximately the same grid potential displacement in the same direction. If such a cancellation is not applied, the output of the amplifier will shift by its gain times this equivalent cathode-potential decrease. If more than one stage is involved, each will contribute to the heater effect by an amount that depends on the gain of the following stages, but, in general, the gain of the first stage will be great enough so that the heater effect in following stages is negligible in comparison.

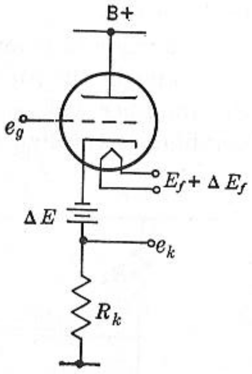

FIG. 11·40.—Heater-voltage variation effect on a cathode follower.

Negative feedback cannot reduce the amount of adjustment required at the input to cancel this effect. This fact is obvious in the case of a cathode follower. The effect of an increase of E_f is the same as the insertion of a low-voltage battery of zero resistance in series with the cathode, as shown in Fig. 11·40. If this were done, with no change in e_g, e_k would change by an amount almost equal to the battery voltage ΔE. To cancel this change, e_g must be lowered by just ΔE.

In a majority of applications, some method of canceling the effect of variations of heater voltage is necessary or advisable. (Of course, if the heater supply is well regulated, or if the resulting error is within allowable limits in a specific application, no cancellation will be needed.)

Diode Cancellation.—A comparison of Figs. 11·5 and 11·6 shows that the slopes of these curves for the diode are substantially the same as those for the triode. (At extremely low currents the triode curves become a little steeper, because incomplete grid control over the electrons is more noticeable with increasing temperature.) Thus the variation in a diode, whose heater is connected to the same source as that of the triode, may be used to offset the variation in the amplifying tubes.

One method of diode cancellation is shown by Fig. 11·41. The negative B voltage is large compared with the expected fluctuation at the cathode, so that the current in R may be considered constant (R is required to be large compared with the diode's variational resistance). It is desired that, with no change in e_g, i_p (and thus e_p) will remain constant. To permit this, a certain increase of E_f must be compensated for by a certain rise Δe_k at the cathode of the amplifier. But if the diode has the same cathode characteristic, this same increase Δe_k will occur at the diode, since the diode current is constant. If the two cathodes have different heater-voltage characteristics, the compensation will suffer accordingly. But generally the error will be less than one-tenth of that with no correction; e.g., the error due to a 10 per cent change of E_f, measured at e_g, will be less than 10 mv.

The error due to the fact that R is finite is not noticeable in comparison with that due to tube differences unless the voltage across R is less than about 10 volts. It can be shown that this error is only $r_d/(R + r_d)$ of the error with no compensation, where r_d is the diode variational resistance.

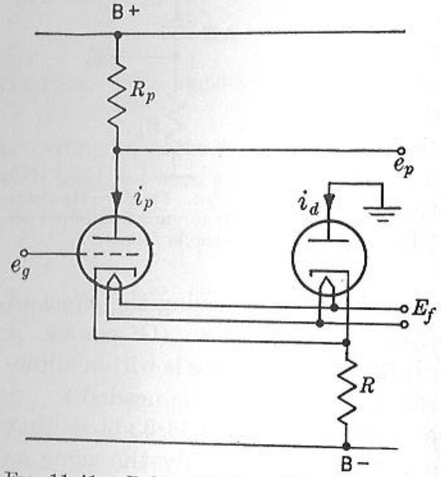

FIG. 11·41.—Balancing E_f variator by means of a diode.

The value of R must be such that its current will be greater than the maximum in the amplifying tube; otherwise the diode will cut off, and the amplifier will cease to function as such. The cathode return of the amplifier is through the variational diode resistance r_d (in parallel with R, which should be large enough to be negligible in comparison). A loss of gain [Eq. (9)] results unless μr_d [or $(\partial e_{g_2}/\partial e_g)r_d$ if a pentode is used] is very small compared with R_p. It must be remembered, in selecting R, that r_d is a function of the diode current and may be determined from the slope of the diode current-voltage curve. At very low currents (e.g., below 0.2 or 0.3 ma, for a 6AL5) r_d becomes inversely proportional to the current, with a multiplier that is not a function of the diode type or even of the number of diodes in parallel (since increasing the number would decrease the current and increase the variational resistance of each). Thus, for all diodes with unipotential oxide-coated cathodes, the variational resistance at very low current approximates

$$r_d \approx \frac{0.09}{i_d} \text{ kilohms} \tag{83}$$

if i_d is in milliamperes.[1] This variation of the diode impedance might conceivably be used to linearize a portion of the amplifier output curve by varying the gain in a direction opposite to its natural curvature.

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[1] This equation derives from the fact that the current at small values is exponential with respect to voltage: $i_d \approx i_0 e^{11,600 e_{pk}/T}$, where T is the absolute temperature of the cathode and is 1000° to 1100°K in this instance.

Tubes with diodes using the same cathode as the triode or pentode are especially useful in the circuit shown in Fig. 11·41, since the heater-voltage characteristics are bound to be nearly identical. For example, a sample of six 6SQ7 double-diode triodes was tested in the circuit of Fig. 11·41, with the diode plates in parallel (e_p = 150 volts; i_p = 0.1 ma; i_d = 0.08 ma). The adjustments required at the grid by a 20 per cent heater-voltage change were −10, −5, 0, +2, +3, and +6 mv, whereas the adjustments required with the cathode grounded ranged from 195 to 212 mw. The drift due to aging of the heater or cathode may also be fairly well canceled in this way.

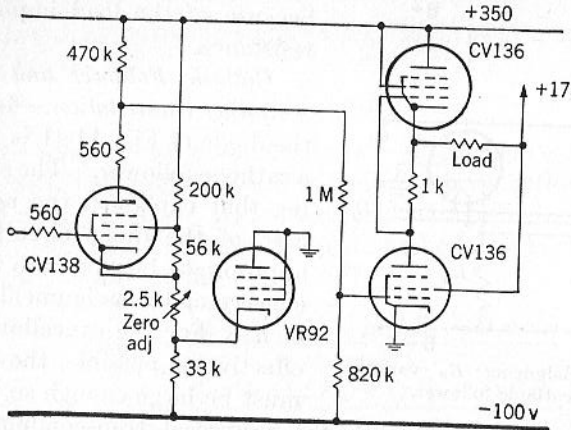

FIG. 11·42.—D-c servo amplifier.

Figure 11·42 is the circuit diagram of a direct-coupled velocity servo amplifier,[1,2] which furnishes field excitation for a d-c servo motor. The input stage of this amplifier uses diode cancellation of heater-voltage variation. The zero-adjustment resistance and screen-grid bleeder do not impair this function because the currents here are substantially constant. The diode current is two or three times the cathode current or the pentode.

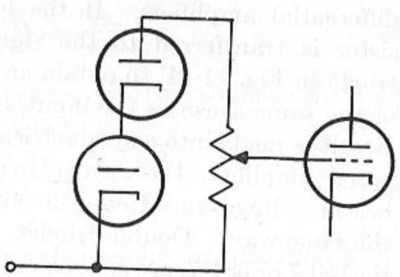

FIG. 11·43.—Diode heater-voltage cancellation at amplifier grid.

A method that requires two diodes but needs no negative supply and permits manual adjustment for differences in cathode characteristics is illustrated by Fig. 11·43. The circulating current due to initial electron

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[1] Telecommunications Research Establishment Report.

[2] Cf also Sec. 11·14 for further discussion of this circuit.

velocity (Edison effect) in the diodes inserts a negative voltage in series with the grid. This voltage increases with increasing heater voltage, and its slope factor may be adjusted with the potentiometer. The resistance employed may be anywhere from 10,000 ohms to 1 megohm. A single diode is not potent enough because of the load imposed by the resistance.

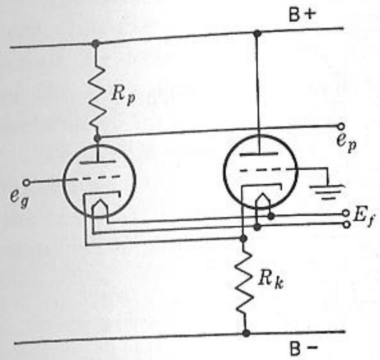

FIG. 11·44.—Balancing E_p variation with a cathode follower.

Cathode Follower and Differential Amplifier Cancellation.—In Fig. 11·44 the diode of Fig. 11·41 is replaced by a cathode follower. The same reasoning that explained the action in the case of the diode circuit is equally appropriate here, as are the remarks concerning the assignment of the value of R_k. For the cancellation to be as effective as possible, the $B-$ voltage must be large enough so that R_k may be very large compared with the reciprocal transconductance of the cathode follower. In the comparison with the diode circuit, this latter quantity corresponds to the diode variational resistance.

The grid of the cathode follower provides a convenient high-impedance point for zero adjustment for the amplifier. This and other features of the circuit have been discussed under differential amplifiers. If the load resistor is transferred to the right-hand triode in Fig. 11·44, to obtain an output of the same sense as the input, or if the circuit is made into a symmetrical differential amplifier, the cancellation of heater-voltage variation still obtains in the same way. Double triodes, such as the 6SL7 or 6SU7, are convenient for this type of application and give reasonable assurance of similar cathode characteristics. (The 6J6 should be very appropriate, since the same cathode is used for both triodes; but it seems subject to considerable drift because of its type of construction.)

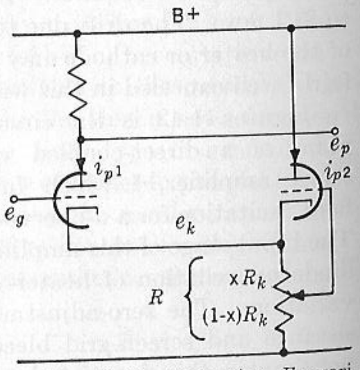

FIG. 11·45.—Balancing E_f variation with a self-biased cathode follower.

The circuit of Fig. 11·45, which employs a self-biasing cathode follower as a cathode return for the amplifier tube, permits adjustment for the inequality that may exist between the cathode characteristics of the two tubes. If i_{p1} is to be held constant in spite of any given change of heater voltage, e_k must be changed by some amount ΔE_1. Since i_{p1} is constant, the resulting change of current in R_k all occurs in the cathode-follower tube.

$$\Delta i_{p2} = \frac{\Delta E_1}{R_k}. \tag{84}$$

If x is the portion of R_k between the cathode and the grid tap, the change of grid bias is

$$\Delta e_{gk} = -x\,\Delta E_1 \tag{85}$$

But this tube behaves as if a small voltage $-\Delta E_2$ (which is approximately equal to $-\Delta E_1$) had been inserted in series with its cathode (as in Fig. 11·40). Thus the effective grid-to-cathode voltage has changed by the amount $\Delta E_2 - x\,\Delta E_1$, and effective plate-cathode voltage has changed by $\Delta E_2 - \Delta E_1$. So from Eq. (1),

$$\begin{aligned} \Delta i_{p2} &= \frac{\Delta E_2 - \Delta E_1 + \mu_2(\Delta E_2 - x\,\Delta E_1)}{r_{p2}} \\ &= \frac{(\mu_2 + 1)\,\Delta E_2 - (x\mu_2 + 1)\,\Delta E_1}{r_{p2}}. \end{aligned} \tag{86}$$

Combining (86) and (84),

$$R_k = \frac{r_{p2}}{\mu_2\left(\dfrac{\Delta E_2}{\Delta E_1} - x\right) + \dfrac{\Delta E_2}{\Delta E_1} - 1}. \tag{87}$$

Or, approximately,

$$\left(\frac{\Delta E_2}{\Delta E_1} - x\right) R_k \approx \frac{r_{p2}}{\mu_2}. \tag{88}$$

If the two cathodes have exactly equal characteristics, so that $\Delta E_1 = \Delta E_2$, the portion of R_k below the grid tap is simply

$$(1 - x)R_k = \frac{r_{p2}}{\mu_2}, \tag{89}$$

where r_{p2} is the plate resistance of the cathode-follower tube, and if there is a resistor inserted in series with this plate, it is included in r_{p2}.

The amplifier tube cathode is, in effect, connected to a voltage $E_{pp}/(\mu + 1)$ through a resistance $r_{p2}/(\mu + 1)$, regardless of the value of the portion of R_k above the grid tap (although this value does determine the cathode-follower plate current, which in turn affects r_{p2}). Thus the amplifier tube will be just about cut off at zero grid voltage, and it will have a gain [Eq. (9)] of $\mu R_p/(R_p + 2r_p)$. The value of R_k is not critical but should be between two and eight times r_p/μ. The triodes should be aged for a while and cycled several times through the extremes of heater voltage before the adjustment is made.

Cancellation by a Series Triode.—In the circuit of Fig. 11·46, the plate resistor for the amplifier (lower) tube comprises a circuit resembling the constant-current device of Fig. 11·18 except that the voltage E is omitted. Thus this is not a constant-current device but is simply the equivalent of a resistor whose upper end is attached to E_{pp} and whose value is $r_p + (\mu + 1)R$ [Eq. (23)]. Thus from Eq. (7), if the two triodes are similar,

$$e_p = \frac{\dfrac{r_p + (\mu + 1)R_k}{r_p + (\mu + 1)R} E_{pp} - \mu e_g}{1 + \dfrac{r_p + (\mu + 1)R_k}{r_p + (\mu + 1)R}}. \tag{90}$$

If the two cathodes respond equally to a change of heater voltage, R should equal R_k for cancellation of the effect.[1] With e_g fixed, a given increase of E_h causes a certain small increase of current; but since this increase is the same in both tubes, the grid biases change identically. Therefore, the two plate-to-cathode voltages suffer no change, and e_p remains constant. If $R_k = R$, Eq. (90) becomes

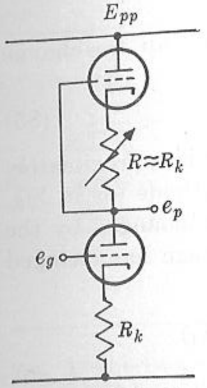

FIG. 11·46.—Cancellation of E_f variation with a series triode.

$$e_p = \frac{E_{pp}}{2} - \frac{\mu e_g}{2}. \tag{91}$$

Thus, when e_g is zero, the output voltage is half the plate-supply potential (as is already apparent by symmetry), and the gain is $\mu/2$. The output voltage is linear with respect to e_g because r_p does not appear in Eq. (91). Of course, the two r_p's were assumed equal, but this assumption is not far in error, as the currents in the two tubes are equal.

The output impedance, from Eq. (11), is (if $R_k = R$)

$$Z_p = \frac{r_p + (\mu + 1)R_k}{2}. \tag{92}$$

If the two cathodes have different heater-voltage characteristics, either R or R_k may be adjusted until cancellation is obtained. This adjustment will not usually change the gain from $\mu/2$ by more than 5 per cent.

Cancellation by Means of a D-c Potential Proportional to Heater Voltage. If the d-c load on the power supply is fairly constant, its unregulated output will vary in proportion with the a-c line voltage and therefore with E_h. Thus this output may be employed in some way to offset the effect on the cathode of the variations of E_h. For example, in Fig. 11·47, if E_h increases, e_k will rise a small amount, which, if the adjustment is right, will keep the plate current constant with no change of e_g. If the cathode is on the bleeder at a point 1 volt from ground, then regardless of the total voltage on the bleeder, e_k will rise 0.1 volt with a 10 per cent rise in the unregulated source. This rise is just about the required amount. Another resistor, inserted in series with the cathode for degeneration or zero adjustment, will not affect the cancellation.

If the source is not well filtered, filtering may be done at the cathode. But a condenser of a given capacity is more effective if placed as shown, about midway on the bleeder.

Rapid line fluctuations will produce errors whose nature and duration is revealed by Fig. 11·8. Another disadvantage of this method is that the correction is linear with respect to E_h whereas the effect itself is curved (Fig. 11·6); therefore, the cancellation is of limited range.

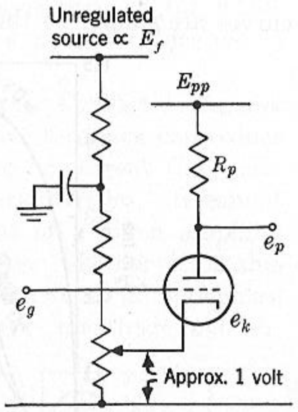

FIG. 11·47.—Variation of e_k with e_p.

Cancellation by Special Connections of Multigrid Tubes.—The circuit of Fig. 11·48, wherein the second grid of a tetrode or pentode is used as the control grid for the plate current, is actually very much like the circuit of Fig. 11·41. Here the first grid instead of a separate diode plate is grounded (or otherwise fixed) and acts as a diode plate to furnish a large part of the cathode current. If the cathode temperature is increased, its potential will rise; and since i_g is practically constant (e_p is assumed to be held constant, and the variation of e_k is small compared with the drop across R_k), its rise will be just enough to neutralize the effect on the other electrodes in the tube. The advantage over the diode-cancellation method of Fig. 11·41 is that the same cathode area is used in the cancellation as in the amplification. The drift that is caused by change of average initial electron velocity with time is also canceled in the same way as that due to temperature change.

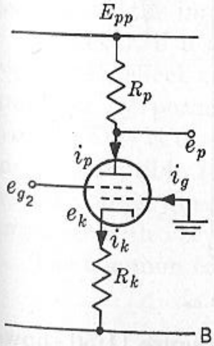

FIG. 11·48.—First grid as diode plate.

Ordinary pentodes are generally unsatisfactory in this circuit because the screen grid has so much control over the plate current that the latter is completely cut off (except of extremely high plate voltage) when the screen-grid potential is lowered far enough so that its own current is

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[1] Maurice Artzt, "Survey of D-c Amplifiers," *Electronics*, August, 1945.

negligible. The suppressor grid, on the other hand, has very little control. In a tetrode like the 6V6, however, the effect of the screen grid is between these two extremes. Figure 11·49 shows the plate characteristics of a 6V6 in the circuit of Fig. 11·48, with a negative supply of 45 volts, and $R_k = 90{,}000$ ohms, so that i_k is just about $\frac{1}{2}$ ma. The curves are similar to those of an ordinary triode with a μ of about 40, except that the current has an upper limit of $\frac{1}{2}$ ma. Figure 11·50 shows the effect of heater voltage on e_k and e_{g2}, the latter being adjusted so as to maintain constant plate current. When i_p and i_g are about the same, e_{g2} is fairly constant over a large temperature range.

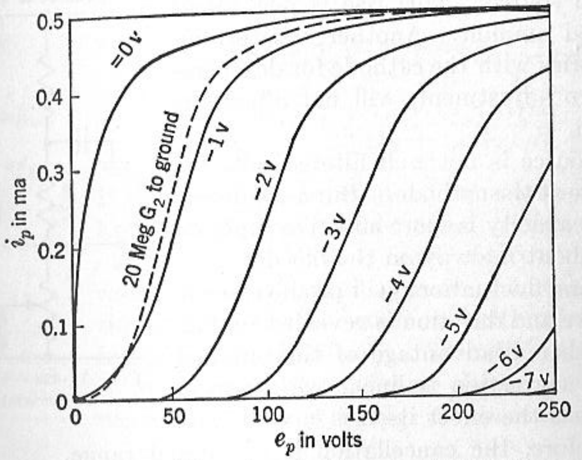

FIG. 11·49.—Plate characteristics of a 6V6 triode.

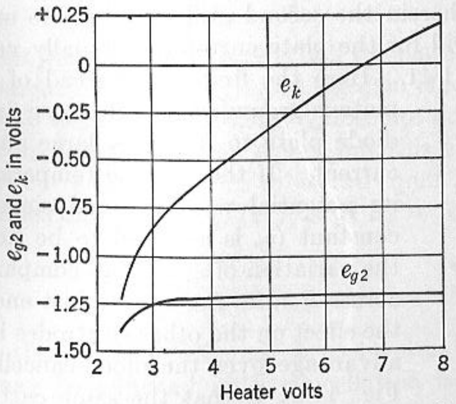

FIG. 11·50.—Effect of heater voltage on e_{g2} and e_k.

The 6AS6 miniature pentode has a specially designed suppressor grid that has unusually effective control over the plate current. This tube may be used in a manner similar to the one in the circuit of Fig. 11·48, but with the suppressor as the control grid and the screen grid at some positive potential. This method of operation has the advantage of producing plate characteristics more like those of a pentode, but the cancellation of heater-voltage effect seems to be less effective over a wide operating range than in the case of the tetrode. A pentagrid converter tube might also be applicable in the same way as the 6AS6. More research is indicated in this field, with a possible objective of developing a suitable tube for the purpose.

11·13. The Use of Feedback in D-c Amplifiers. *Conductive Negative Feedback.*—Conductive, or direct-coupled, negative feedback can reduce the dependence of gain upon output d-c voltage or current (i.e., nonlinearity or amplitude distortion) and tube characteristics. It cannot reduce the effect of zero drift or displacement of a given amplifier (as referred to the input terminals) no matter whether it is due to heater-voltage variation, tube aging or replacement, or microphonics. This fact was illustrated in Sec. 11·12 for the case of a cathode follower, in which the zero drift referred to the input terminals was found to equal the tube drift in terms of the shift of grid-to-cathode potential required to maintain constant current. In some instances, as in the arrangement of Fig. 11·51, negative feedback can actually increase the effect of drift as seen at the input terminals. In Fig. 11·51, if the amplifier drifts so that a given change Δe_g is required to hold e_0 constant, the change required at the input terminals is $\Delta e_1 = \Delta e_g(R_1 + R_2)/R_2$.

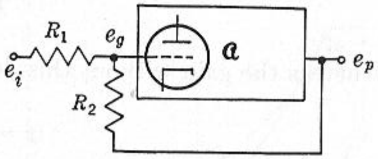

FIG. 11·51.—Direct feedback using resistance adding.

However, if a given over-all gain is required, negative feedback can reduce the effect on zero displacement of changes in certain parts of an amplifier by permitting the use of more amplification ahead of these parts. This is often of great value, since a power-output stage is much more susceptible to shifts caused by variations of load, supply voltage, heater voltage (because of greater tube currents), etc., than is a voltage amplifier with very low power output.

The common form of the feedback equation is

$$\mathcal{G} = \frac{\mathcal{A}}{1 - \mathcal{A}\beta}. \tag{93}$$

where $\mathcal{A}$ is the gain without feedback, $\mathcal{G}$ is the gain with feedback, and β is the fraction of output voltage that is added to the input voltage. This equation is based on the assumption of simple addition involving no attenuation of the input voltage and no disturbance of the amplifier parameters by the feedback action. In Fig. 11·51 the resistance addition