LOW-DISTORTION POWER VALVES

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SUMMARY.—A survey is given of various low-distortion valve constructions. Two new constructions are described by means of which the second harmonic of a single-stage class-A pentode amplifier can be considerably reduced, resulting in a reduction of the total distortion by a factor of 2 up to an output of about 25% of the static anode dissipation. For large outputs (up to 50% of the static anode dissipation) the distortion is the same as that of a normal valve. The new valves have an I_a–V_g characteristic that is practically linear in the neighbourhood of the normal operating point.

1. Introduction

IN the course of valve development many attempts have been made to lower the distortion which is especially liable to arise in the last stage of audio-frequency amplifiers.

In 1937 Kleen[1] gave a survey of the results that had been obtained up to that date by various methods. The aim of this article is to give a somewhat more extensive survey including some new results obtained since 1937, while two different methods that have been studied in more detail by the present authors will be discussed.

Negative feedback is one well-known measure for reducing distortion, but negative feedback causes a serious decrease of the effective mutual conductance. In the following we shall confine ourselves, therefore, to special valve constructions which give low distortion in the valve itself. We, therefore, start with an analysis of the different causes contributing to the non-linearity of the valve characteristic. Only tetrodes and pentodes will be dealt with because these valves have the highest efficiency.

Fig. 1. *The I_a–V_g characteristic of a pentode or tetrode; Curve A, 3/2-power law according to Langmuir; Curve B, Exponential tail due to the Maxwellian velocity distribution of the electrons; Curve C, Tail due to diode effect; Curve, D Decrease of slope due to space charge between control and screen grids; Curve E, Further decrease of the dynamic slope caused by returning electrons at low anode voltages.*

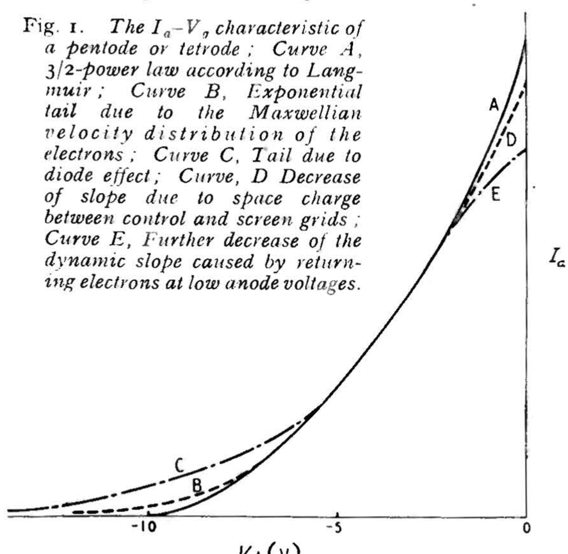

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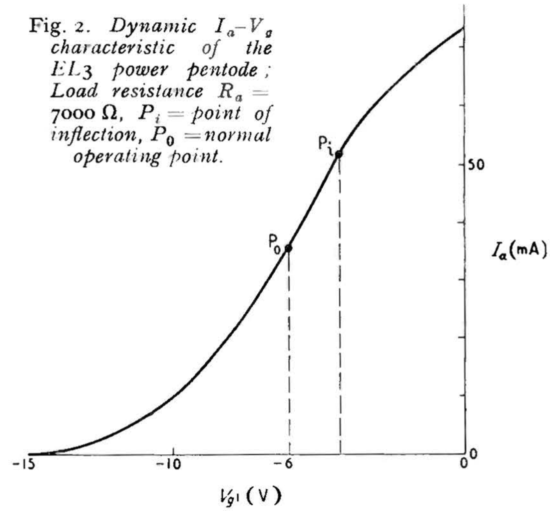
Fig. 2. *Dynamic I_a–V_g characteristic of the EL3 power pentode; Load resistance R_a = 7000 Ω, P_i = point of inflection, P_0 = normal operating point.*



2. The I_a-V_g Characteristic

The I_a–V_g characteristic of a tetrode or a pentode is governed mainly by Langmuir's 3/2-power law (curve A in Fig. 1). This law is valid when

1. The initial velocities of the electrons are negligible.

2. The electric field at the cathode surface is homogeneous.

3. Space charge between the control grid and the screen grid plays no important part, and

4. The ratio of screen-grid current to anode current is independent of the anode current.

Since these four conditions are not fulfilled in practice, deviations from the 3/2-power law occur due to the following causes:

1. Because of the Maxwellian velocity distribution of the emitted electrons, for small values of I_a the I_a–V_g characteristic is exponential (curve B).

2. In high-slope power valves the latter deviation, however, is negligible in comparison to that caused by the inhomogeneity of the field strength at the cathode surface (i.e., the so-called diode effect, curve C). To get a high value of the anode

current as well as of the mutual conductance the distance between the cathode and the control grid is made equal to the pitch of that grid or even smaller. For such dimensions the electron emission in the region between the wires of the grid can only be suppressed by very large negative grid voltages.

3. In some cases, especially with large values of anode current and distance between control and screen grids the space charge in this region causes a decrease of the slope (curve D).

(b) The influence of the space charge between the screen grid and the anode may result in a deviation similar to curve E.

(c) Valves in which the control grid and screen grid are ' lined up ' may show a variation in the relative number of electrons intercepted by the screen grid, because of the variation in electron focusing by the control grid.[13] This effect will be discussed in detail in Section 4, as it has provided us with a possibility of reducing the distortion.

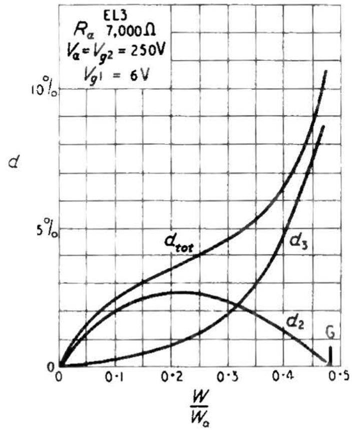


Fig. 3 (left). Distortion of the EL3 as a function of the efficiency W/W_0: W = dynamic output, $W_0 = I_a V_a$ = static anode dissipation, d_2 = second harmonic distortion, d_3 = third-harmonic distortion, d_{tot} = total harmonic distortion, G = limit set by grid current.

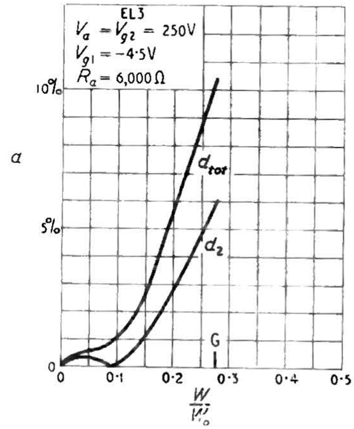


Fig. 4 (right). *Distortion of the EL3 at $V_{g1} = -4.5$ V; load resistance R_a = 6000 Ω, G = limit set by grid current.*

4. The ratio of screen-grid current to anode current may vary with varying I_a due to three causes :

(a) The anode circuit of the valve usually contains a load resistance, and at low anode voltages many of the electrons deflected by the grid wires cannot reach the anode and return to the screen grid, so that another deviation from the dynamic characteristic occurs (curve E).

It is not our aim to give a full list of all the effects contributing to valve distortion, and we have only mentioned the phenomena that are important in our investigations. The influence of secondary emission at the anode has already

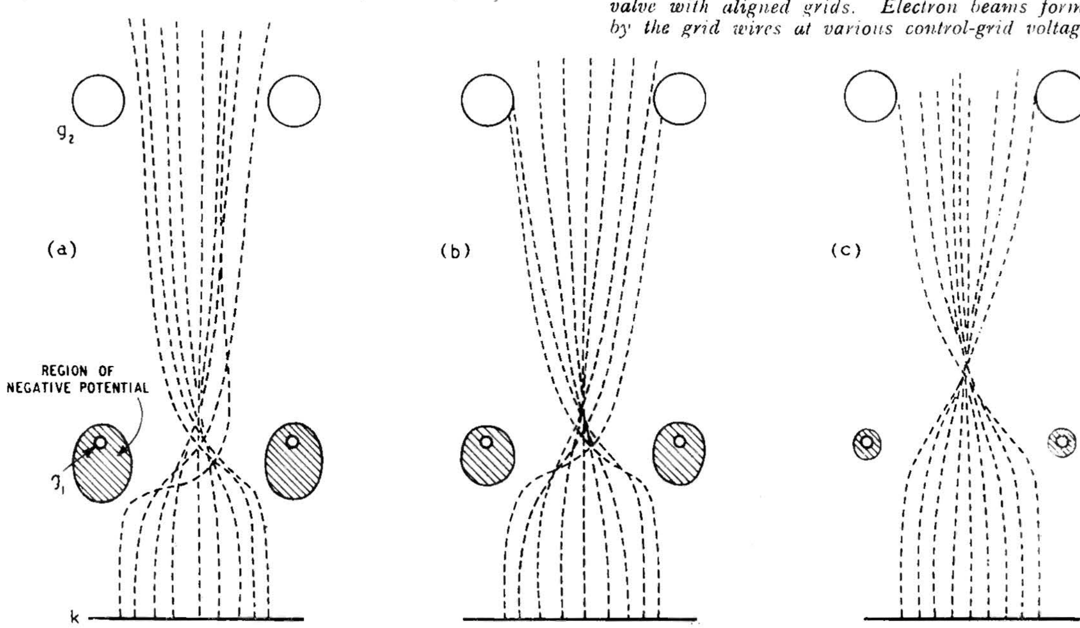
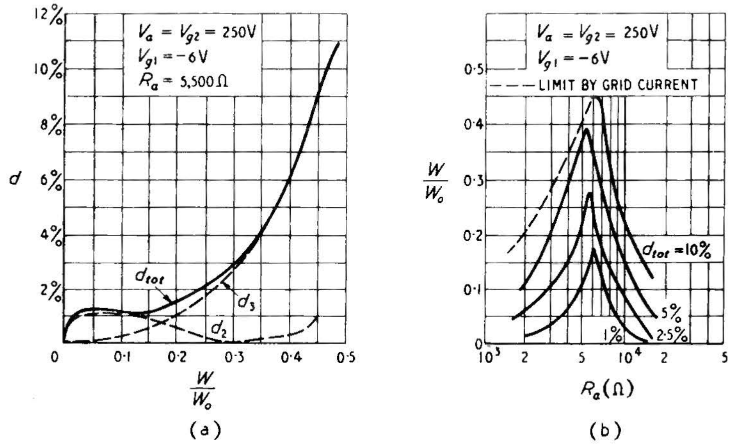


Fig. 5. *Cross section of a low-distortion power valve with aligned grids. Electron beams formed by the grid wires at various control-grid voltages.*

been discussed in detail by Jonker and Heins van der Ven,[2,14] so it will not be discussed here.

As an example of a normal dynamic pentode characteristic, in which most of the effects mentioned above are present, Fig. 2 shows the dynamic I_a–V_g characteristic of the EL3 pentode. As may be seen, the point of inflection caused by the load resistance lies at about $V_{g1} = -4.5$ V, while the normal grid bias for this valve is $V_{g1} = -6$ V. Thus for normal grid bias we shall have, when the signal voltages are not too large, a dynamic characteristic showing on the average a curvature which results in considerable second-harmonic distortion in the output.* This may also be seen from Fig. 3, where for the EL3 the distortion is given as a function of the efficiency W/W_0 under normal operating conditions (W = output of the valve, $W_0 = I_aV_a$ = static anode dissipation). With strong signals ($W/W_0 \approx 0.5$) the third harmonic begins to play the most



important part, because of the S-shape of the characteristic due to the load resistance.

Now it is obvious that when signals are not too strong the distortion caused by the second harmonic can be reduced by adjusting the grid bias to the point of inflection or by using a suitably chosen value of the load resistance. Adjusting both the grid bias and the load resistance to their optimum values with regard to low second-harmonic distortion for the EL3 gives a distortion curve as illustrated in Fig. 4. We see that up to an efficiency of 15% the distortion is indeed improved, but the maximum output is limited by the point where grid-current distortion appears; for this pentode the maximum efficiency has thus been reduced from 50% to 25%.

3. Older Low-Distortion Valve Constructions

In the course of time many proposals have been made for reducing the distortion by special electrode constructions. Attempts have been made to improve the tail of the characteristic by the electron-optical focusing of surplus current on an auxiliary electrode.[3] It has been proposed to reduce the curvature for large values of I_a by using simultaneously two different control grids,[1,4] by using a deflection electrode together with a special form of the output anode,[5] by using the partition of the cathode current by a specially shaped grid and a plate[6] or by the influence of space charge.[7] Recently

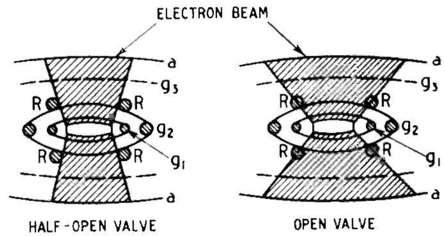
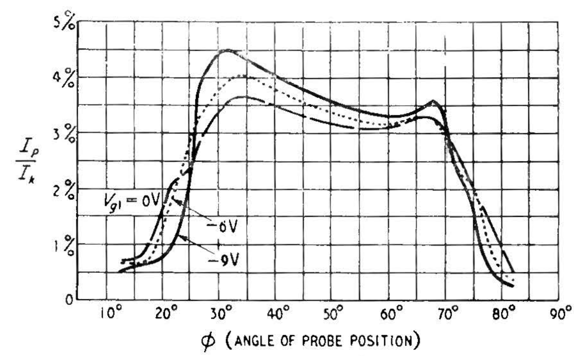


Fig. 6 (left). *Distortion of a valve having an electrode arrangement like that of Fig. 5. (a) Distortion as a function of efficiency; (b) Efficiency W/W_0 as a function of R_a at various constant values of d_{tot}.*

Fig. 7 (above). *Electron beams formed by the rods of the control grid at different values of the control-grid voltage.*

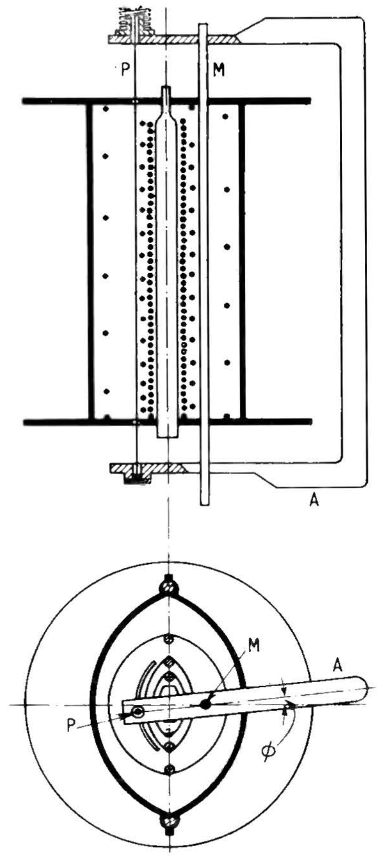
Fig. 8 (below). *Width of the electron beams shown in Fig. 7, as measured by means of a movable probe (see Fig. 9).*



Brian[8] and Pickering[9] have published results obtained when using a tetrode with a positive first grid (space-charge grid). Although their

* For a good comparison we used experimental EL3 pentodes that were made at the same time as the low-distortion pentodes to be discussed in Section 4. The EL3 characteristics given here, therefore, show small deviations from the EL3 characteristics normally published.

construction seems to us the most useful hitherto published, we wish to make the following remark. The maximum efficiency of their valve is much lower than that of a pentode, especially when the



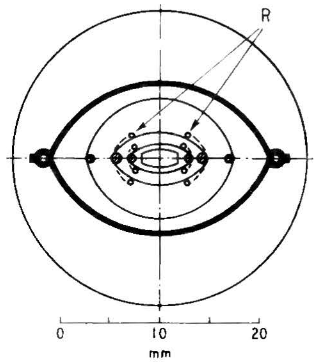


Fig. 9 (left). *Construction of an experimental valve containing a movable probe P for measuring the width of the electron beam.*

Fig. 10 (right). *Electrode arrangement of a low-distortion power valve using additional focusing rods.*

valves are not used in push-pull (for many applications one prefers to use a class-A amplifier with one single valve). Now, as was shown in Section 2, it is also possible to reduce the distortion of a pentode by adjusting R_a and V_{g1} to a suitable value. In this case the maximum efficiency for the pentode is even higher than that of the space-charge-grid valve.

However, none of the special valve constructions have up to now been produced on a large scale. The reasons for this may be :

1. Some of the constructions are too expensive, because they are rather intricate.

2. The other properties of the valve (e.g. maximum efficiency, mutual conductance, internal resistance) are sometimes worse than those of the normal valve.

3. In some cases the decrease of distortion depends too much upon the value and phase angle of the load impedance.

Still a low-distortion power valve with other characteristics normal is always attractive, because a smaller amount of feedback is required, resulting in a higher value of the mutual conductance, and difficulties resulting from the frequency-dependence of the feedback are less serious.

We have, therefore, investigated the problem from a different angle, trying only to avoid curvature of the dynamic characteristic in the neighbourhood of the normal operating point leaving the tail, caused by diode effect, and the upper curvature, caused by the presence of the load resistance, as they are. It is our conviction that it is not possible to improve the latter appreciably when only simple electrode constructions are used.

We have succeeded in making the region of the I_a–V_g characteristic around the normal operating point fairly linear by two different methods, in both of which use is made of the variation in screen current with varying control-grid voltage, namely by

1. Lining up the first and second grids of the pentode, and

2. Using the influence that the rods of the control grid have upon the electron flow.

These two methods were already indicated by Kleen,[1] but as far as we know they have not been studied extensively before. The results of our experiments are given in Section 4.

4. Low-Distortion Power Pentodes

It is well known that the wires of the control grid in a normal valve divide the electron current into several flat beams which cross over somewhere beyond the grid plane (see e.g., Knoll and others[10, 11], and Jonker [2, 12]).

In Fig. 5 a cross-section is given of a valve in which the wires of the control and screen grids are lined up. The shape of the electron beams formed by the wires of the control grid, as photographed from large-scale models on a rubber sheet, are also drawn for three different control-grid voltages ; viz, strongly negative, near the operating point, and slightly negative. From extensive experiments on the rubber sheet with various grid dimensions we concluded that for suitable dimensions of the screen grid it is possible to intercept a varying part of the beams by the combined action of the focus displacement and the variation in aperture of the electron beams at different control-grid voltages.

For our purpose the dimensions were chosen so that the interception was the maximum at a grid voltage somewhat less negative than the normal operating point.

These experiments with the help of models on the rubber sheet have led to a pentode construction very closely resembling the EL3, and showing much less distortion than the corre-

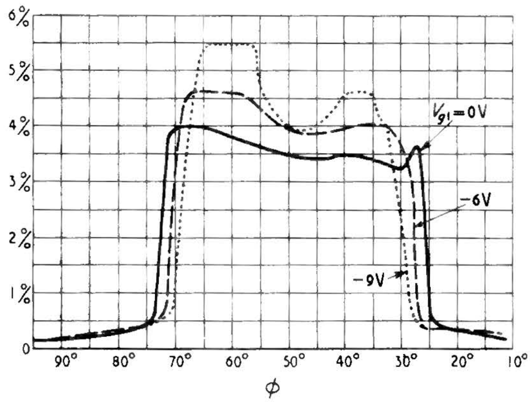
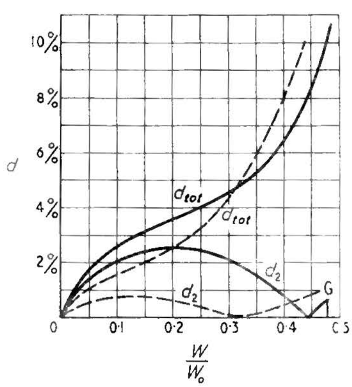


Fig. 11. *The same as Fig. 8, but using additional focusing rods connected to the control grid.*

sponding normal valve (see Fig. 6). Of course with this method there are limits in the dimensioning of the valve, because the grids have to be lined up, and for a given construction of the control grid and a given distance between the control and screen grids the diameter of the screen-grid wires is fixed, on account of the conditions set by the interception effect.

The experiments indicated that good results can be obtained with various distances between the two grids provided the wire diameters are suitably chosen.



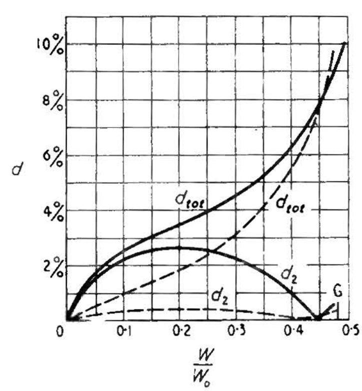


Fig. 12 (left). *Distortion with a valve construction like that of Fig. 7 as a function of the efficiency W/W_0; G = limit set by grid current. Solid line curves for EL3, dotted for low-distortion valve of Fig. 10;* $V_a = V_{g2} = 250$ V, $V_{g1} = -6$ V, $R_a = 7{,}000\ \Omega$.

Fig. 13 (right). *The same as Fig. 12 but with additional focusing rods.*

The second method we developed, which makes use of the variation in aperture of the electron beams, seems, however, much more attractive, because it can be applied to any normal valve without any variation of grid dimensioning and with only a slight variation of the valve characteristics. The idea may be easily understood from Fig. 7. The electron stream is divided by the negatively-charged rods of the control grid into two beams, the width of which decrease as a function of the control-grid voltage.

Fig. 8 shows the intensity of the beam at various places as measured by means of a probe (experimental valve, see Fig. 9). Now a variable amount of the anode current can be intercepted by placing auxiliary positive electrodes of a suitable form near the edge of the electron beams. For our purpose it proved to be sufficient to use cylindrical rods (R) of 0.3 mm diameter (see Fig. 7). The best position for these rods was determined from the measurements with the probe valves.

The edges of the beams can be made better defined by using additional focusing rods connected to the control grid (see Figs. 10 and 11).

Figs. 12 and 13 give the results of the output measurements taken on the latter valves (Fig. 13 with additional focusing rods). The best results were obtained with the valves fitted with additional rods; the curves give the mean values for five valves. The spread in the distortion of the individual valves was not very great (of the order of 20%). The tolerances in the positions and the shape of the intercepting rods are of the same order of magnitude as the tolerances in normal cathode-grid constructions of power pentodes. We see that for an output up to about half of the maximum useful output the distortion is reduced by about a factor of 2 this improvement being due to the absence of the second harmonic. This is more than was obtained by varying the grid bias of a normal EL3 valve (see Fig. 4). Moreover, the new valves have the same maximum output as that of the normal valve under normal operating conditions ($W/W_0 \approx 50\%$). This elimination of the second harmonic again proved to be not very sensitive to variation of the load resistance R_a, just as was the case with the valves having lined-up grids.

Finally Fig. 14 gives the slope of the dynamic

I_a–V_g characteristic for a normal pentode EL3 and for a low-distortion valve according to Fig. 10. We see that for the low-distortion valve the slope is almost constant within a large voltage region around the normal operating point. The same may be concluded from Fig. 15, where the second-and third-harmonic distortion for small signal ($V \approx 0.2$Vr.m.s.) as a function of grid bias are given for the same valves. From these measurements we may also safely conclude that as long as the signal is not too large the *intermodulation* of the new valves will be considerably smaller than that of the non-corrected pentode. The characteristics given in Figs. 14 and 15 provide us with a measure for the quality with regard to both distortion and intermodulation independently of the frequencies for which the valve may be used.

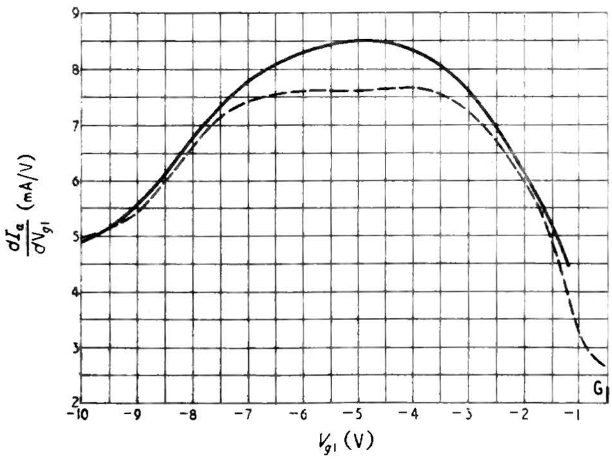


Fig. 14. *Slope of the dynamic I_a–V_g characteristic as a function of V_{g1} for a normal pentode EL3 and for a low-distortion pentode like that of Fig. 10. G = limit set by grid current. Solid line curves for EL3, dotted for low-distortion valve of Fig. 10;* $V_a = V_{g2} = 250$ V, $V_{g1} = -6$ V, $R_a = 7{,}000\ \Omega$.

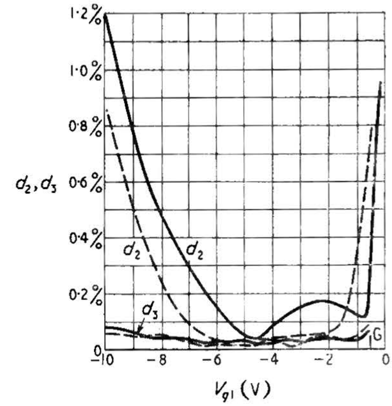


Fig. 15. *Second harmonic for small input voltage ($V \approx 0.2$ V r.m.s.) as a function of V_{g1} for the EL3 and for a low-distortion pentode. Solid line curves for EL3, dotted for low-distortion valve of Fig. 10;* $V_a = V_{g2} = 250$ V, $V_{g1} = -6$ V, $R_a = 7.000\ \Omega$.

REFERENCES

1 W. Kleen, *Telefunkenröhre*, Vol. 10, pp. 147–156, 1937.
2 J. L. H. Jonker, *Wireless Engineer*, Vol. 16, pp. 274–286, 1939; A. J. Heins van der Ven, *Wireless Engineer*, Vol. 16, pp. 383–390, 1939.
3 German patent 732727, French patents 923791 and 808004.
4 French patent 824521.
5 French patent 774703.
6 British patent 451662.
7 Dutch patent 53142, French patent 819632.
8 W. S. Brian, *Electronics*, Vol. 20, pp. 121–123, Aug. 1947.
9 N. Pickering, *Electronics*, Vol. 21, pp. 96–100, March 1948.
10 M. Knoll. *Z. techn. Physik*, Vol. 15, pp. 584-591, 1934.
11 M. Knoll, and J. Schloemilch, *Arch. f. Elektrotechnik*, Vol. 28, pp. 507-516, 1934.
12 J. L. H. Jonker, *Thesis Delft*, 1942.
13 J. L. H. Jonker, *Philips Res. Rep*, Vol. 4, pp. 355 365, 1949.
14 J. L. H. Jonker, *Philips tech. Rev.*, Vol. 10, pp. 346-351, 1949.