Grid-circuit distortion in low-bias audio-frequency vacuum-tube amplifiers.

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CONTENTS.

Page No.

1.0 SUMMARY.

INADEQUATE CONSIDERATION OF THE EFFECT OF CONTROL-GRID CURRENTS FLOWING IN COUPLING IMPEDANCES IN LOW-LEVEL AUDIO-FREQUENCY VACUUM-TUBE AMPLIFIERS HAS LED MAJOR VACUUM-TUBE MANUFACTURERS TO RECOMMEND OPERATING CONDITIONS WHICH RESULT IN SERIOUS GRID-CIRCUIT DISTORTION.

THE INVESTIGATION OF GRID-CIRCUIT OPERATION WHICH FOLLOWS LEADS TO DESIGN RECOMMENDATIONS WHICH ENSURE THAT DISTORTION WILL NOT EXCEED A PRE-DETERMINED PERCENTAGE.

Conventional analyses of vacuum tube (valve) performance have established the dichotomy of negative control-grid operation without grid current and positive control-grid operation with grid current. This convention is satisfactory for most valve applications, but requires modification for some low-bias operating conditions.

Positive control-grid currents are known to approach zero exponentially with increasing negative bias (1) (2) and valves are frequently operated under conditions which lead to control-grid currents between 10^{-6} and 10^{-9} amp. The effects of currents of this order, modulated by a signal and flowing in an impedance in the control-grid circuit, are investigated.

The analysis proceeds from a review of the theory of retarding-field control-grid current to a practical investigation of the factors affecting the magnitude and slope of this characteristic. It is determined that for typical modern AC-operated vacuum tubes an effective cathode temperature of approximately 1160°K can be assumed. From existing theory and this one empirical factor the grid-circuit distortion caused by the flow of retarding-field grid current in typical audio-frequency amplifiers is calculated. Approximate experimental confirmation of the calculated distortion is obtained.

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2.0 SYMBOLS.

The more important of the symbols to be used are presented below.

I_R = general symbol for retarding-field grid current (amps).

I_{DC} = DC component of I_R (amps).

I_{AC} = AC component of I_R (amps).

I_s = total emission from cathode at temperature T (amps).

I_o = modified Bessel function of the first kind of zero order.

e = electronic charge (coulombs).

E = applied grid potential (including contact potential differences) (volts).

k = Boltzmann's constant (joules per degree Kelvin).

T = cathode temperature (degrees Kelvin).

F = a grid current multiplying factor, usually less than unity and dependent upon the voltages applied to electrodes other than the control grid in a multi-electrode valve.

R_{AC} = effective series resistance between generator and control grid (ohms).

R_1 = physical series resistance between generator and control grid (ohms).

R_{DC} = resistance between control grid and cathode (ohms).

R_i = control-grid input resistance (ohms).

D' = ratio of mean grid current with signal applied to mean current without signal when R_{AC} is negligibly small, and R_{DC} is negligibly small.

B = ratio of mean grid current with signal applied to mean current without signal when R_{AC} is of significant size.

C = $\frac{B}{D}$

P = grid-current multiplying factor caused by application of voltage $+\Delta E$ to control grid.

Q = grid-current multiplying factor caused by application of voltage $-\Delta E$ to control grid.

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3.0 INTRODUCTION.

Probably one of the most authoritative statements on the importance of control-grid currents in equipment design is to be found in (3). Published by the Advisory Group on Electron Tubes, from the Office of the Assistant Secretary of (American) Defence Research and Development, its opening paragraphs are:-

> "To the equipment designer grid currents are probably the most vicious of detrimental properties of electron tubes. It is not unusual to have a two year interval between the original bread-board of a circuit and the time when a serious grid current hazard is recognized. The frequent lack of recognition of grid current hazards has no doubt been fostered by the over-simplified description of an electron tube as a device which operates with a negative grid voltage and draws no current from the signal source.
>
> "There are at least eight distinct forms of grid current, which might be given the following arbitrary titles:-
>
> 1. Inter-electrode leakage
> 2. Gas ionization current
> 3. Grid emission current
> 4. Positive grid electron current
> 5. Secondary grid emission current
> 6. Negative grid electron current
> 7. Grid photo-emission current
> 8. UHF input admittance characteristic associated with transit time and lead inductance."

Of these currents, the one most familiar to equipment designers is the "Positive Grid Electron Current". However ignorance on the part of design engineers of the characteristics of "Positive Grid Electron Current" is one of the most frequent causes of trouble in electronic equipment.

That this current also causes distortion in audio-frequency amplifiers had received no serious mention in engineering literature prior to the publication of (4)* although, as shown below, currents even as small as 10^{-9} amp. may be significant in this respect.

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* See, however, (5), (6) and Sect. 8.2 "Comparative Results."

4.0 CONTROL-GRID CHARACTERISTICS.

In an investigation of the effects of small values of control-grid current, both the slope of the current-voltage characteristic and the magnitude of the current are important. Many factors affect these characteristics, but investigation shows that none of them leads to any appreciable divergence from the slope of the classical retarding-field diode characteristic. The magnitude of the grid current, however, is affedted.

4.1 Diode Characteristic.

When, in a multi-electrode valve, voltages are applied only to the control-grid-cathode system, current flows to the grid under saturated, space-charge-limited or retarding-field diode conditions according to the magnitude and polarity of the applied voltage (7) (8).

With a control-grid voltage sufficiently negative to bring about retarding-field conditions the grid current is approximately *

$$I_R = I_s \exp \frac{(Ee)}{(kT)} \text{ amp} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (1)$$

where I_s = total emission from cathode at temperature T,

E = applied potential (including contact potential difference),

e = electronic charge,

k = Boltzmann's constant,

and T = cathode temperature (degrees Kelvin).

* eqn. (1) applies strictly to infinite parallel plane electrodes. Schottky (9) has shown that the retarding-field current is slightly modified for cylindrical electrodes, which more closely approximate the construction of valve types subseqiently investigated.

Taking the logarithm of both sides and differentiating:

$$\frac{d(\ln I_R)}{dE} = \frac{e}{kT} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

$$\text{Since } \frac{e}{k} = 11606 \text{ degrees/volt}$$

$$\frac{d(\ln I_R)}{dE} = \frac{11606}{T} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

i.e. the slope of the grid characteristic is inversely proportional to the cathode temperature, T. It should be noted, however, that many effects combine to modify this slope (7) (10).

Thus the retarding-field diode (control-grid) current in a valve having a cathode temperature of 1161°K decreases to $\frac{1}{\varepsilon}$, i.e. approximately 0.37 of its original value for each additional 0.1 volt of negative bias applied.

That the effective cathode temperature of typical modern valves is in fact approximately 1161°K is demonstrated in Fig. 1, the control-grid characteristic of a 6AU6 radio-frequency and audio-frequency pentode. Curve A is the diode curve (grids 2 and 3 and anode earthed) with 6.3 volts applied to the heater, and it will be noted that the grid current increases 2.7 times for each 0.1 volt reduction of negative bias.

The method of plotting control-grid characteristics as shown in Fig. 1 is described in Appendix 1, "The Measurement of Retarding-Field Control-Grid Current."

4.2 <u>Grid Characteristic of Multi-Electrode Valves.</u>

Fig. 1 also shows, in curves B and C, the control-grid characteristic of the same 6AU6 valve with 50 and 100 volts positive applied to grid 2 and to the anode, with grid 3 earthed. The tendency towards non-linearity at currents approaching 10 microamps is due to the transition from retarding-field to space-charge-limited conditions.

Curves A, B and C show that by modifying the electrostatic field between control grid and cathode, the positive grid 2 plus anode potential has reduced the control-grid current. The slope of the linear section of the characteristic however is virtually unchanged.

This effect can be expressed:

$$I_R = F \; I_s \exp \frac{(Ee)}{(kT)} \text{ amp} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (4)$$

where F = a factor usually less than unity, dependent upon the voltages applied to electrodes other than the control grid in a multi-electrode valve.

4.2.1. Triodes.

Since plate voltage variations in a triode valve modify the retarding-field grid current, in a normal triode amplifier the variations in plate voltage produced by the application of a signal to the control grid result in a modification of the grid-current characteristic.

It can be demonstrated however from Fig. 1 that the magnitude of this effect is small. An increase of triode plate voltage in this figure from 50 volts to 100 volts has an effect on control-grid current equivalent to a decrease of negative control-grid bias of 0.08 volt.

As the impedance in the control-grid circuit is negligible, this effect can be expressed as an amplification factor from plate to control-grid of $\frac{0.08}{50}$, i.e. $\frac{1}{625}$ times, in terms of the effect of these voltages on the control-grid current, over the range of plate voltage from 50 to 100 volts. In typical resistance-coupled audio-frequency amplifiers the operating plate voltage falls within this range.

Since the normal control-grid-to-plate amplification factor of a triode-connected 6AU6 is 30, a typical maximum grid-to-plate gain can be taken as 25 times.

Thus the maximum effect of a varying triode plate voltage in modifying the slope of a 6AU6 control-grid current characteristic can be expressed as the product of the two amplifications, viz. approximately $25 \times \frac{1}{625}$, or 4%.

Similar or smaller factors apply to other triode amplifiers and it is thus evident that the modification of slope of grid characteristics likely to be caused by plate voltage variations in a triode amplifier are not greater than variations that may be caused by other factors, e.g. cathode temperature in different valve designs.

4.2.2 <u>Pentodes</u>.

In pentode applications in which the screen voltage has no AC component, investigation shows that fluctuations in the plate voltage, at least over a linear excursion of the plate characteristic of the 6AU6 and other pentode audio-frequency amplifiers, do not significantly affect the control-grid characteristic.

4.3 <u>Grid-Cathode Spacing</u>.

An investigation of valves covering the range of differences in spacing between cathode and control grid that is likely to be met in modern audio-frequency amplifiers shows that this factor has a negligible effect on the slope of the characteristic.

This is demonstrated in Fig. 2 in which Curve A is the control-grid characteristic of a 6SJ7GT with spacing between adjacent surfaces of grid and cathode of 0.015 inch, Curve B of a 6AU6 with spacing of 0.008 inch and Curve C of a 6BQ7A with 0.002 inch. The valves were chosen at random, the pentodes were triode-connected and in each case the characteristics were plotted with heater and plate voltages of 6.3 and 50 volts respectively.

The slope of each grid characteristic closely approximates that of an ideal planar diode with cathode temperature of 1161°K and in spite of the difference in grid-cathode spacing the magnitudes of the grid currents differ no more than do those of different valves of the same type.

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5.0 GRAPHICAL REPRESENTATION OF DISTORTION.

In many audio-frequency amplifier applications of valves the signal is applied to the grid through a series impedance, for example an impedance due to the diode load in the case of the first audio-frequency amplifier in a radio receiver or due to the impedance of a previous resistance-coupled stage in a conventional amplifier.

The flow of grid current modulated by signal voltages in such an impedance results in distortion of the signal applied to the grid of the valve. A graphical construction to demonstrate this is shown in Fig. 3.

Although the grid characteristics of Fig. 1 and 2 have been presented in logarithmic form to show their exponential nature, a linear grid-current plot is more suitable to demonstrate the generation of distortion. Curve A of Fig. 3 is a control-grid characteristic plotted in this way with the bias needed to give 0.1 micro-amp of grid current when applied through a 0.1 megohm grid resistor used as the grid-voltage reference point.

A sinusoidal signal, B, with a peak-to-peak amplitude of 0.4 volt is shown at the bottom of Fig. 3. Each point on B is considered to be projected from the base line to the grid characteristic by a line parallel to G. The slope of G represents the slope of the impedance between the signal generator and the grid of the valve in accordance with the voltage and current scales used. In the figure the slope is that of a series impedance of 0.1 megohm.

Waveform C in Fig. 3 is the distorted signal voltage applied to the grid of the valve. The voltage drop across the series impedance at any point in the excitation cycle is the voltage, as read from the control-grid voltage scale, traversed by the lines parallel to G.

Thus Curve C of Fig. 3 represents the distorted signal produced by applying a 0.4 volt peak-to-peak sinusoidal input through a 0.1 megohm series impedance to the control grid of a valve drawing 0.1 microamp of positive grid current in the absence of a signal

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6.0 GRID-CURRENT EQUATION.

To obtain an equation representing the grid current in a typical audio-frequency amplifier, consider the circuit of Fig. 4.

Let the effective series resistance between generator and control grid be R_{AC}, i.e. C_1 is very large and $\frac{1}{R_{AC}} = \frac{1}{R_1} + \frac{1}{R_{DC}}$, and let the valve be biased into the retarding-field region of its grid characteristic by E_{DC}, which includes the effect of contact-potential differences within the valve.

Further, let the generator output voltage be $\frac{R_1 + R_{DC}}{R_{DC}}$ (E_{AC} sin wt) so that whatever the values of R_1 and R_{DC} the alternating voltage applied to the grid of the valve in the absence of grid current is E_{AC} sin wt.

It has been shown that, to a close approximation, when $E_{AC} = 0$ and $R_{DC} = 0$, the grid current under these conditions, that is

$$I'_{DC} = F\, I_s \exp\,(10E_{DC}) \text{ amp} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (5)$$

If now the bias voltage be applied to the grid through R_{DC} the voltage drop across the resistor increases the negative bias on the valve and this reduces the current. Let the current in the presence of R_{DC} be I_{DC}, then

$$I_{DC} = F\, I_s \exp\left[-10(E_{DC} + I_{DC} R_{DC})\right] \text{ amp} \quad \ldots \quad \ldots \qquad (6)$$

Let E_{AC} have a finite value so small that it does not affect the average value of current. Then the current flowing in the grid circuit of the valve is

$$I_{DC} + I_{AC} = F\, I_s \exp\left[-10\,(E_{DC} + I_{DC}\;R_{DC} + E_{AC} \sin wt)\right] \text{ amp} \quad \ldots \qquad (7)$$

In general, however, the applied sinusoidal signal will increase the average value of grid current.

With R_{DC} and R_{AC} negligibly small let the ratio of mean current with applied signal to mean current without signal be D'. Then

$$D' = \frac{1}{2\pi}\int_0^{2\pi} \exp\,(10\ E_{AC}\ \sin wt)\ dt \qquad \ldots \quad \ldots \qquad (8)$$
$$= I_o\ (10E_{AC})$$

where I_o is the modified Bessel function of the first kind of zero order (see for example [11] p. 103).

Similarly when R_{AC} is not negligibly small, and assuming temporarily that the increase in current does not flow in R_{DC}, let the ratio as above be D. Then

$$D = I_o \left\{10\ (E_{AC} - I_{AC}\ R_{AC})\right\} \qquad \ldots \quad \ldots \quad \ldots \qquad (9)$$

since the voltage drop across R_{AC} reduces the signal applied to the grid.

B ut because R_{DC} is also of significant size the increase in current due to the applied signal results in a greater negative voltage being developed across R_{DC} and thus in a smaller increase in current than the ratio D.

Let B be the actual ratio of mean grid current with signal applied to mean current without signal when R_{AC} is of significant size. Then

$$B = D \exp \left\{-10\ I_{DC}\ R_{DC}\ (B-1)\right\} \qquad \ldots \quad \ldots \quad \ldots \qquad (10)$$

Since the excursions of a signal applied to the grid result of necessity in an increase of average direct current by the ratio D as compared with the current at the point of zero excitation in the operating cycle, and since the actual increase in current under the operating conditions being considered is the smaller ratio B, the grid current equation becomes

$$I_{DC} + I_{AC} = C\,F\,I_s \exp\left\{-10\left[E_{DC} + I_{DC}R_{DC} + (E_{AC} - I_{AC}R_{AC})\sin wt\right]\right\} \text{ amp} \ldots \quad (11)$$

$$\text{where } C = \frac{B}{D} = \exp\left\{-10\,I_{DC}R_{DC}(B-1)\right\} \quad \ldots \quad \ldots \quad \ldots \quad (12)$$

6.1 Graphical Representation

The direct current and voltage effects are as shown in Fig. 5 with the curve $D\,F\,I_s \exp(-10\,E_{DC})$ drawn for a particular value of applied alternating voltage.

Fig. 5 shows in particular the relationship between I_{DC}, the standing current in the grid resistor in the absence of a signal, BI_{DC}, the actual grid current flowing in the presence of a signal, and CI_{DC}, the grid current which when multiplied D times by the application of a signal, becomes equal to BI_{DC}.

Curves similar to those of $F\,I_s \exp(-10\,E_{DC})$ are published in valve data handbooks as diode detection characteristics for various signal levels.

6.2 Generation of Distortion.

Equation 11 evaluates the direct and alternating currents flowing in the grid circuit of the valve in Fig. 4 and although the signal applied to the circuit is sinusoidal the harmonic components of the retarding-field current develop harmonic voltages across R_{AC} which must also appear between grid and cathode of the valve. Thus a solution of eqn. 11 would give the distortion of the signal applied to the valve.

However a solution of eqn. 11 cannot be obtained. Distortion has nevertheless been evaluated by determining the effect of applied signals on the operating condition, i.e. the factor C in eqn. 11, and then by a point-by-point investigation of the excursion of the signal voltage.

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7.0 DISTORTION ANALYSIS.

The construction of Fig. 3 demonstrates the distortion introduced into a 0.2 volt peak signal when applied through a 0.1 megohm resistor to the grid of a valve drawing a standing grid current of 0.1 microamp.

The distortion, however, is a function of the geometry of the figure rather than of the particular values of the scales used. If, for example, the current values of the grid characteristic were doubled and at the same time the series resistance were halved, the figure, and hence the distortion, would be unchanged.

Thus, for a given input voltage the distortion is constant so long as the product of standing current and series resistance is a constant.

By plotting input voltage against distortion for a limited range of I_{DC} R_{AC} products it is therefore possible to present a wide range of possible operating conditions. The range chosen for subsequent investigation is I_{DC} R_{AC} = 10^{-2}, 10^{-3} and 10^{-4} volt, the 10^{-2} volt condition representing for example "grid-leak bias" conditions with 0.1 microamp of grid current and an AC series resistance of 0.1 megohm, and the 10^{-4} volt condition representing perhaps 0.1 microamp of grid current with a series resistance of 1000 ohms or other conditions such as 0.001 microamp of grid current and 0.1 megohm series resistance.

It was shown in Fig. 3 that for a given set of conditions the waveform at the grid of the valve can be obtained graphically, and from the waveform the distortion can of course be derived.

Without reconstructing the whole waveform however, well-known techniques can be used to determine the magnitude of any number of distortion products for any set of conditions. For example, the magnitude of the first four harmonics (including the fundamental) and the DC component can be obtained from a knowledge of the voltage at five particular equally spaced points on the grid swing, see (12) and Appendix 4 - "The Calculation of Distortion".

To determine the change in voltage at the grid of the valve due to a given voltage increment at the generator end of the series resistance, assume that in Fig. 4 the input resistance of the valve is much greater than R_{DC} and that the time constant $C_1 (R_1 + R_{DC})$ is sufficiently large that the charge on capacitor C_1 does not change appreciably during an audio-frequency cycle. These conditions are those normally encountered.

Now let a small alternating voltage, such that in the absence of grid current the signal at the grid of the valve would be ΔE volt peak, be applied from the generator. The alternating retarding-field grid current will set up a voltage across R_{AC} and thus reduce the signal applied to the grid.

Initially $I_R = F\,I_s \exp\left\{-10\,(E_{DC} + I_R R_{AC})\right\}$ amp.

At the instant when the maximum positive voltage is applied from the generator, suppose the current to have increased by a factor P. Then

$$P\,I_R = F\,I_s \exp\left\{-10\,(E_{DC} - \Delta E + P\,I_R R_{AC})\right\} \text{ amp.} \quad (13)$$

$$\therefore P = \exp\left\{10\left[\Delta E - I_R R_{AC}(P-1)\right]\right\} \quad \ldots \quad \ldots \quad \ldots \quad (14)$$

Similarly, when $-\Delta E$ volt is applied, let the current decrease by a factor Q. Then

$$Q\, I_R = F \quad I_s \exp\left\{-10\ (E_{DC} + \Delta E + Q\, I_R\, R_{AC})\right\} \text{ amp.. } \quad (15)$$

$$\therefore Q = \exp\left\{-10\left[\Delta E - I_R\, R_{AC}\ (1-Q)\right]\right\} \ \ldots \ \ldots \ \ldots \ (16)$$

Eqn. (13) and (15) give the current flowing in the grid circuit at the maximum and minimum peaks of an applied alternating voltage of peak magnitude ΔE volt. Eqn. (14) and (16) also contain the peak voltages actually applied to grid, these being one tenth of the argument of the exponential function.

Thus a small alternating voltage of peak magnitude ΔE volt in the absence of grid current, applied to the grid through a series resistance R_{AC} results, in the presence of a standing retarding-field current I_R, in positive and negative peaks of $\Delta E - I_R\, R_{AC}\ (P-1)$ volt and $-\Delta E + I_R\, R_{AC}(1-Q)$ volt respectively at the control grid of the valve.

The evaluation of P and Q has been effected by plotting $I_R\, R_{AC}$ against P and Q with ΔE as a parameter, for a convenient range of values of ΔE and $I_R\ \ R_{AC}$, as shown in Fig. 6 to be described below.

7.1 <u>Variation of Current with Applied Signal</u>.

No account has been taken in this section of the effect of the applied signal on the magnitude of the average value of grid current, i.e. the factor C in eqn. (11). This can be evaluated however by plotting D against C with values of $I_{DC}\ R_{AC}$ as a parameter.

To simplify this calculation eqn. (9) has been reduced to

$$D = I_o \quad (10\ E_{AC})$$

the justification for the omission of the $I_{AC}\ R_{AC}$ term being that in practical cases valves are not used under conditions in which the loss of signal due to valve input conductance is more than a small fraction of the signal. (Subsequent calculations show that a maximum reduction of signal of less than 1db occurs under the conditions considered.)

In selecting suitable values of $I_{DC}\ R_{AC}$ the following considerations apply. As already suggested, the plotting of distortion for a limited range of $I_{DC}\ R_{AC}$ values can cover typical operating conditions. A complication is introduced however by the fact that the increase in mean current due to applied signals flows not in R_{AC}, but in R_{DC}, the value of which bears no direct relationship to the value of R_{AC}, the distortion-producing resistor

This difficulty can be overcome however by the same technique of taking a limited number of values to cover the usual range of operating conditions. For example, two ratios of R_{DC}/R_{AC} of 2 to 1 and 20 to 1 have been selected, the former to represent the condition of equal plate load and following grid leak and the latter the other extreme of approximately a 0.1 megohm plate load with 2 megohm following grid leak or a 0.25 megohm series resistor and a grid-leak-biased following stage with 5 megohm grid leak.

Thus eqn. (14) and (16) are to be solved not only for cases in which the applied signal has no effect on the average grid current but also with larger inputs, for a range of values of C dependent upon the applied input voltage and for R_{DC}/R_{AC} values of 2 and 20. The solutions are obtained by means of Fig. 6.

7.2 Use of Nomogram.

In using Fig. 6 to evaluate P and Q there are two operations, firstly the determination of $C\ I_{DC}\ R_{AC}$ from a knowledge of $I_{DC}\ R_{AC}$, of the value of the applied signal and of the ratio R_{DC}/R_{AC}, and secondly the evaluation of P and Q after the operating condition $C\ I_{DC}\ R_{AC}$ has been determined.

To simplify the use of the nomogram, suitable "Applied Voltages" are marked at the left-hand side. These points are the plot of $I_o\ (10\ E_{AC})$, as derived from eqn. 9, on the two-decade logarithmic scale 1 to 10^2 from bottom to top of the figure.

To determine for example $C\ I_{DC}\ R_{AC}$ when $I_{DC}\ R_{AC} = 10^{-2}$ volt, the applied signal = 0.36 volt peak and $R_{DC}/R_{AC} = 20$, pass horizontally from "Applied Voltage" = 0.36 volt to the $R_{DC}/R_{AC} = 20$ line originating at $I_{DC}\ R_{AC} = 10^{-2}$ volt. It will be found that $C\ I_{DC}\ R_{AC} = 2.21 \times 10^{-3}$ volt, which is the operating condition.

P can now be determined by following the $C\ I_{DC}\ R_{AC}$ value vertically upwards to the "P-line" corresponding to the applied voltage ($\Delta E = 0.36$ volt peak) and reading P from the logarithmic scale at the right-hand side of the figure. For the example chosen, the "P-line" for 0.36 volt intersects the value of $C\ I_{DC}\ R_{AC} = 2.21 \times 10^{-3}$ volt at P = 22.5. The positive peak of the voltage applied to the grid of the valve under these conditions can now be calculated from eqn. 14 as $0.36 - 2.21 \times 10^{-3} \times 21.5$ volt, i.e. 0.3125 volt.

The negative peak can be calculated separately in a similar manner using the "Q lines" and the distortion can be determined from these values. Intermediate points on the grid swing necessary for the calculation of higher-order distortion can also be calculated in a similar manner.*

For reasons set out in Appendix 3, "Construction of Nomogram," it is necessary only to plot a limited section of the Q lines. They are used in conjunction with the "Values of Q" at the left-hand side of the nomogram in a manner similar to that described for the "P lines."

An interesting aspect of Fig. 6 is that the R_{DC}/R_{AC} lines demonstrate the amount of 'biasing-back' of the valve that occurs with signal for the three initial I_{DC} R_{AC} conditions of 10^{-2}, 10^{-3} and 10^{-4} volt.

Thus for a static I_{DC} R_{AC} value of 10^{-2} volt and $R_{DC}/R_{AC} = 20$, i.e. a grid-leak resistance value twenty times greater than the effective series resistance, the operating condition in the presence of an input signal of 0.48 volt is C I_{DC} $R_{AC} = 9.5 \times 10^{-4}$ volt, more than a ten times reduction in I_{DC} (since R_{AC} is unchanged).

With a smaller grid leak and with smaller initial values of I_{DC} R_{AC} the 'biasing-back' is reduced, until with I_{DC} $R_{AC} = 10^{-4}$ volt and $R_{DC}/R_{AC} = 2$ it is negligible for signals up to 0.48 volt peak.

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* See Appendix 4 - "The Calculation of Distortion."

8.0 CONFIRMATION.

The circuit of Fig. 7 was used to obtain experimental confirmation of the calculated results. A problem in devising a test circuit was the obtaining of accurate I_{DC} R_{AC} values of 10^{-2}, 10^{-3} and 10^{-4} volt with R_{DC}/R_{AC} ratios of 2 and 20, without using unduly large values of grid-circuit resistance, without exceeding some few microamps of grid current (in order to maintain operation on the exponential part of the grid characteristic) and without introducing unwanted signals into the grid circuit, as several electronic microammeters, when used in conjunction with the necessary biasing circuits, were found to do.

This problem was overcome by using the valve under test, in conjunction with appropriate grid-circuit resistors, to measure grid currents of 10^{-6}, 10^{-7} and 10^{-8} amp, while the parallel resistance of R_1, R_{DC} and the 1 megohm input resistance of the wave analyser was adjusted to 10^4 ohms. Different combinations of R_1 and R_{DC} were used to give R_{DC}/R_{AC} ratios of 2 and 20, the values being:-

	R_1	R_{DC}
R_{DC}/R_{AC} = 2	20,410 ohms	20,000 ohms
R_{DC}/R_{AC} = 20	10,640 ohms	200,000 ohms

To obtain a distortion reading with a grid current of, for example, 10^{-7} amp, the switch S_1 was opened, the switch S_2 set to the 1 megohm resistor, the appropriate bias applied, as determined from the grid characteristic, and the plate current meter set to zero by means of the shunting circuit. (A 100 microamp centre-zero meter was used in this shunting circuit thereby greatly increasing the accuracy of plate-current indication over a direct measurement of plate current). Switch S_1 was then closed and the plate current meter re-adjusted to zero by means of the grid-bias control. If the required change in bias was 0.1 volt the grid current flowing after this adjustment was 10^{-7} amp. If the initial bias setting was incorrect, modifications were made and the procedure repeated. The 400 c/s signal was then applied to the grid and the distortion was measured.

After each distortion reading had been carried out the grid current was re-checked to ensure that it had not drifted during the measurements. This precaution was necessary because the grid current could not be observed continuously.

As distortion was to be measured for particular levels of signal applied through a series resistor to the grid of the valve, the signal could not be measured at the grid, but rather the generator output was adjusted to suitable values such that, when voltage-divider effects were taken into account, the signal at the grid would be of the required magnitude in the absence of signal damping.

For example, when $R_{DC}/R_{AC} = 2$, it has been stated above that $R_1 = 20,410$ ohms and $R_{DC} = 20,000$ ohms. As the 1 megohm input impedance of the wave analyser was in parallel with R_{DC} between the control grid of the valve and ground, the effective resistance from grid to ground was 19,610 ohms. Thus of the signal generator output $\frac{19,610}{20410 + 19610}$ i.e. 0.490 was applied to the grid of the valve.

Similarly when $R_{DC}/R_{AC} = 20$, $R_1 = 10,640$ ohms and $R_{DC} = 200,000$ ohms, the signal applied to the grid of the valve was 0.940 of the generator output. The output was adjusted to provide the required signal at the grid in the absence of grid current allowing for this effect.

8.1 Experimental Results.

Calculated and measured results are set out in Fig. 8 and in Table 1 (page 31). Correlation is not perfect, but in view of the difficulties of the experimental technique, it is felt that verification of the analysis has been obtained.

Factors which militated against complete correlation of results are -

(i) the output of the signal generator contained distortion products of the same order of magnitude as some of the lowest distortion readings, viz.:-

Harmonic order	2	3	4
Distortion percentage	0.10	0.06	0.02

These readings were obtained by connecting the output of the signal generator directly to the wave analyser and it is possible that some of the measured distortion was due to effects described in (ii) below:

(ii) as shown in [13] small distortion percentages can be due to distortion generated internally in a wave analyser.

As the method of combination of these spurious harmonics with those it is desired to measure is unknown, it is realised that the accuracy of the results is less than that implied by the figures in Table 1.

TABLE 1.

MEASURED AND CALCULATED VALUES OF GRID-CIRCUIT DISTORTION

$I_{DC} R_{AC} = 10^{-2}$ VOLT

$R_{DC}/R_{AC} = 2$

Signal Voltage (Peak Volts)	Second Harmonic (%)		Third Harmonic (%)		Fourth Harmonic (%)		Total Harmonic Distortion (%)	
	M*	C*	M	C	M	C	M	C
0.06	1.0	1.2	0.05	NC *	0.05	NC	1.0	1.2
0.12	1.9	2.3	0.2	0.4	0.05	0.1	1.9	2.4
0.18	NM*	3.6	NM	NC	NM	NC	NM	3.6
0.24	3.7	4.5	0.7	0.9	0.05	0.1	3.8	4.6
0.32	5.3	NC	1.1	NC	0.05	NC	5.4	NC
0.36	NM	5.8	NM	1.7	NM	0.3	NM	6.1

$R_{DC}/R_{AC} = 20$

Signal Voltage (Peak Volts)	Second Harmonic (%)		Third Harmonic (%)		Fourth Harmonic (%)		Total Harmonic Distortion (%)	
	M	C	M	C	M	C	M	C
0.06	1.0	1.2	- *	NC	-	NC	1.0	1.2
0.12	1.9	2.2	0.2	0.1	-	0.07	1.9	2.2
0.18	NM	2.8	NM	NC	NM	NC	NM	2.8
0.24	3.2	3.1	0.7	0.9	-	0.2	3.3	3.2
0.32	3.4	NC	1.0	NC	0.1	NC	3.5	NC
0.36	NM	3.3	NM	1.3	NM	0.3	NM	3.6
0.40	3.7	NC	1.2	NC	0.2	NC	3.9	NC
0.48	3.7	3.3	1.5	1.7	0.3	0.5	4.0	3.7

* M = Measured; NM = Not Measured.
* C = Calculated: NC = Not Calculated.
* - = < 0.05

$I_{DC}\ R_{AC} = 10^{-3}$ VOLT.

$R_{DC}/R_{AC} = 2$

Signal Voltage (Peak Volts)	Second Harmonic (%)		Third Harmonic (%)		Fourth Harmonic (%)		Total Harmonic Distortion (%)	
	M*	C*	M	C	M	C	M	C
0.06	NM*	0.2	NM	NC*	NM	NC	NM	0.2
0.12	0.2	0.4	0.05	NC	0.05	NC	0.2	0.4
0.18	NM	0.6	NM	NC	NM	NC	NM	0.6
0.24	0.6	0.8	0.05	0.3	0.05	0.01	0.6	0.9
0.32	0.9	NC	0.3	NC	0.05	NC	0.9	NC
0.36	NM	1.8	NM	0.8	NM	0.2	NM	1.9
0.40	1.3	NC	0.5	NC	0.2	NC	1.4	NC
0.48	1.8	2.7	0.8	1.4	0.3	0.4	2.0	3.1

$R_{DC}/R_{AC} = 20$

Signal Voltage (Peak Volts)	Second Harmonic (%)		Third Harmonic (%)		Fourth Harmonic (%)		Total Harmonic Distortion (%)	
	M	C	M	C	M	C	M	C
0.06	NM	0.2	NM	NC	NM	NC	NM	0.2
0.12	0.3	0.3	0.05	NC	-*	NC	0.3	0.3
0.18	NM	0.5	NM	NC	NM	NC	NM	0.5
0.24	0.6	0.7	0.3	0.2	0.05	0.05	0.6	0.7
0.32	0.8	NC	0.3	NC	0.1	NC	0.8	NC
0.36	NM	1.1	NM	0.5	NM	0.16	NM	1.2
0.40	1.0	NC	0.4	NC	0.2	NC	1.1	NC
0.48	1.2	1.5	0.6	0.8	0.2	0.3	1.4	1.7

* M = Measured; NM = Not Measured.
* C = Calculated; NC = Not Calculated.
* - = < 0.05.

$I_{DC}\ R_{AC} = 10^{-4}$ VOLT

$R_{DC}/R_{AC} = 2$

Signal Voltage (Peak Volts)	Second Harmonic (%)		Third Harmonic (%)		Fourth Harmonic (%)		Total Harmonic Distortion (%)	
	M ✯	C ✯	M	C	M	C	M	C
0.06	NM✯	0.01	NM	NC ✯	NM	NC	NM	0.01
0.12	0.1	0.04	0.05	NC	0.05	NC	0.1	0.04
0.18	NM	0.08	NM	NC	NM	NC	NM	0.08
0.24	0.1	0.1	0.05	NC	0.05	NC	0.1	0.1
0.32	0.15	NC	0.05	NC	0.05	NC	0.15	NC
0.36	NM	0.2	NM	NC	NM	NC	NM	0.2
0.40	0.2	NC	0.1	NC	0.05	NC	0.25	NC
0.48	0.4	0.54	0.2	0.36	0.1	0.1	0.4	0.6

$R_{DC}/R_{AC} = 20$

Signal Voltage (Peak Volts)	Second Harmonic (%)		Third Harmonic (%)		Fourth Harmonic (%)		Total Harmonic Distortion (%)	
	M	C	M	C	M	C	M	C
0.06	NM	0.01	NM	NC	NM	NC	NM	0.01
0.12	0.1	0.04	- *	NC	-	NC	0.1	0.04
0.18	NM	0.08	NM	NC	NM	NC	NM	0.08
0.24	0.1	0.1	0.05	NC	-	NC	0.1	0.1
0.32	0.15	NC	0.06	NC	-	NC	0.15	NC
0.36	NM	0.2	NM	NC	NM	NC	NM	0.2
0.40	0.2	NC	0.1	NC	0.05	NC	0.25	NC
0.48	0.3	0.4	0.2	0.2	0.06	0.09	0.4	0.5

✯ M = Measured; NM = Not Measured.
✯ C = Calculated; NC = Not Calculated.
✯ - = < 0.05

8.1.1 Discussion. Considering Fig. 8, the shape of the distortion curves is of interest, and is due to the following factors. In the absence of 'biasing-back' with signal, due to additional negative bias being developed across the grid resistor in the presence of a signal (see Fig. 5), the distortion curves tend to increase sharply as the signal increases. This curvature is offset in varying degrees however by the reduction in distortion due to the signal-generated bias for high values of I_{DC} R_{AC} and R_{DC}/R_{AC}. For the curve I_{DC} $R_{AC} = 10^{-2}$ volt and $R_{DC}/R_{AC} = 20$ the increase of bias with signal compensates at high inputs for the tendency for distortion to increase with increasing signal voltage.

This reduction in distortion is however applicable only to steady-state conditions. In normal amplifier usage instantaneous distortion will vary with the charge on the grid-coupling capacitor between the limits of the distortion applicable to the R_{DC}/R_{AC} ratio in use and a maximum which would occur with R_{DC} equal to R_{AC}. The variation of instantaneous bias with signal will in fact add to the signal a secondary type of distortion particularly noticeable on square waves.

Under practical conditions however the variation in distortion between R_{DC}/R_{AC} ratios of 2 and 20 is of minor significance since operating conditions should always be such as to allow at most a very small value of grid-circuit distortion, for example not more than $\frac{1}{2}$%. Under these conditions distortion is little affected by variation of the R_{DC}/R_{AC} ratio.

To interpret the curves of Fig. 8 in terms of practical circuits, a "grid-leak biased" audio-frequency amplifier with grid current of 0.1 microamp and series grid resistance of 0.1 megohm ($I_{DC} R_{AC} = 10^{-2}$ volt) could be expected to develop about 2% distortion in its grid circuit for an applied signal as small as 0.1 volt peak.

Alternatively if high fidelity were required from a resistance-capacitance coupled stage at 0.5 volt peak input with a 0.5 megohm plate load in the preceding stage and with a 1 megohm grid leak, then the control-grid current would need to be smaller than 3.10^{-4} microamp, since at this value of grid current the grid-circuit distortion for this stage alone would be about 0.5%

8.2 Comparative Results.

It is possible to make some comparison between the experimental results described and figures produced by other workers, at least insofar as the order of magnitude of distortion is concerned.

In Ref. (5), "The Influence of the A.F. Input Stages on Quality of Reproduction," grid-circuit distortion is plotted against variation of input impedance for a "grid-leak biased" single-stage audio-frequency amplifier. As would be expected from the preceding analysis, maximum distortion occurs when input impedance is a maximum but unfortunately the control-grid current is not stated.

However the following information is available:-

R_{DC} = 10 megohms

R_{AC} = 0.25 megohm maximum

Stage gain = 50

Output voltage = 5 volts r.m.s.

Stage Distortion (for R_{AC} = 0.25 megohm) = 3.5%

Valve input resistance = 1 to 3 megohms.

The following assumptions seem justified:-

(i) As valve input resistance lies between 1 and 3 megohms the grid current is between approximately 0.1 and 0.03 microamp (See Sect. 9.0 "Input Impedance" below).

(ii) The stage distortion with $R_{AC} = 0$ is less than 0.5% so that the grid-circuit distortion will be approximately equal to the total stage distortion of 3.5%.

(iii) Input voltage = $\dfrac{\text{Output voltage}}{\text{Stage gain}}$ = 0.1 volt r.m.s.

(iv) $R_{DC}/R_{AC} = 40$.

Taking I_{DC} as 0.04 microamp, which lies in the range stated, and $I_{DC}\ R_{AC} = 10^{-2}$ volt, a check against calculated distortion in Fig. 8 with $R_{DC}/R_{AC} = 20$ shows that for a peak input voltage of 0.14 volt (0.1 volt r.m.s.) a distortion of 2.4% can be expected.

The agreement between the 3.5% distortion measured in [5] and the 2.4% obtained from calculation is good, and a much larger variation could be accounted for by the 3 to 1 range within which the control-grid current may lie. Examination of Fig. 8 shows that under the conditions detailed, no great variation in distortion would be expected from the fact that the calculation was carried out with $R_{DC}/R_{AC} = 20$ whereas in (5) $R_{DC}/R_{AC} = 40$.

Ref. (6), "Low Distortion Operation of Some Miniature Dual Triodes," describes experiments in which grid-circuit distortion is produced by variation of signal-source impedance and of bias voltage (and thus of control-grid current). This distortion is not measured directly but instead the total distortion (including the plate-circuit distortion) of a single triode audio-frequency amplifier stage is measured and variations produced by modifications to the source impedance and the bias voltage are plotted.

Since the second harmonic distortion generated in the grid circuit is out of phase with the plate-circuit second harmonic distortion, cancellation occurs and second harmonic minima appear in the results.

The following data are supplied or can be calculated:-

Input Voltage = 0.04 volt (probably r.m.s.)

I_{DC} = 1.56 microamp

R_{DC} = 0.5 megohm

Conditions		A	B	C	D
R_{AC} (megohm)	=	0.005	0.045	0.084	0.25
R_{DC}/R_{AC}	=	100	11.1	5.95	2
I_{DC} R_{AC} (volt)	=	0.0078	0.07	0.13	0.39
Stage Distortion (%)	=	0.44	3.9	5.6	8

In each condition, stage distortion is 0.6% in the absence of grid-circuit distortion, so that for conditions B, C and

D the grid-circuit distortion will closely approximate the total stage distortion. Whilst no close check can be made in these cases it can be said that the order of distortion is not unexpected.

For condition A, I_{DC} R_{AC} = 0.0078 volt and it is not possible to check distortion from Fig. 8 at this level. However at a slightly increased I_{DC} R_{AC} value of 0.01 volt, a distortion of 1.0% would be anticipated for the 0.05 volt input signal. Since this distortion is out of phase with the constant 0.6% distortion in the plate circuit a resultant of 0.4% distortion can be expected. This can be compared with the 0.44% tabulated above. The closeness of this correlation is probably fortuitous but at least it can be said that the order of the results calculated above has received confirmation.

8.3 Graphical Confirmation.

Whilst the complications of a full graphical representation of control-grid circuit operation (including the factor C) are considerable, the distortion shown in Fig. 3 can be readily obtained and a comparison with calculated results is of interest.

Fig 3 is constructed for conditions in which the signal is applied to the control-grid through a series 0.1 megohm resistor without an isolating capacitor and grid leak. The R_{DC}/R_{AC} ratio is therefore unity.

Examination of the calculated results in Table 1 (or Fig. 8) shows that for I_{DC} R_{AC} = 10^{-2} volt and with a 0.24 volt peak signal a decrease in the R_{DC}/R_{AC} ratio from 20 to 2 increases the total r.m.s. distortion from 3.2% to 4.6% but a smaller increase in distortion above 4.6% would be anticipated from a decrease of R_{DC}/R_{AC} from 2 to 1.

It can be expected therefore that for Fig. 3 with $I_{DC}\ R_{AC} = 10^{-2}$, $R_{DC}/R_{AC} = 1$ and a signal of 0.2 volt peak (Condition 1 below) the distortion would be similar to but perhaps less than that for $I_{DC}\ R_{AC} = 10^{-2}$, $R_{DC}/R_{AC} = 2$ and a 0.24 volt signal (Condition 2).

The actual distortion in Fig. 3 can be readily determined by the methods already used and the comparison is set out below:-

	2nd Harmonic	3rd Harmonic	4th Harmonic
Condition 1 ..	4.4%	0.8%	0.06%
Condition 2 ..	4.5%	0.9%	0.1%

The closeness of the result of this comparison with that anticipated is an indication of the validity of the preceding analysis (excluding the effects of the factor C).

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9.0 INPUT RESISTANCE.

An interesting aspect of the constancy of slope of the grid characteristic of modern AC-operated valves, as demonstrated in Section 4, is the fact that the approximate input resistance of any valve of this type, biased into the retarding-field region of its grid characteristic but without an applied signal, can be readily approximated from a knowledge of the magnitude of its grid current.

Since, from Eqn. (4), $I_{DC} = F\, I_s \exp\frac{(Ee)}{(kT)}$ amp.

$$\frac{d\, I_{DC}}{dE} = \frac{e}{kT}\, F\, I_s \exp\frac{(Ee)}{(kT)} \text{ amp/volt.. (17)}$$

Thus, since $\frac{e}{kT} \approx 10$ volt $^{-1}$

the magnitude of the valve input resistance, $R_i = \dfrac{1}{10F\; I_s \exp\frac{(Ee)}{(kT)}}$

i.e., small-signal valve input resistance in megohms is the reciprocal of ten times the grid current in microamps.

Thus if an input resistance only as low as 10 megohms is required, bias must be sufficient to reduce retarding-field grid current to not more than 10^{-2} microamp.

9.1 Experimental Confirmation.

Confirmation of this statement is shown in Fig. 9 in which the control-grid current and measured control-grid input resistance of a 6AU6 with heater voltage of 6.3 volts and triode plate voltage of 50 volts are plotted against control-grid voltage. It will be seen that the grid-input resistance follows the rule above within the limits of experimental error.

9.2 Signal Damping.

From eqn. 18 it is evident that valve input resistance, R_i, is inversely proportional to retarding-field grid current. Thus for any particular $I_{DC}\ R_{AC}$ product, R_{AC}/R_i is a constant and when a small signal is applied to the control grid through R_{AC} the circuit can be considered as a voltage divider with a constant fraction of the signal applied to the grid.

$$\begin{aligned}
\text{From eqn. 18, when } I_{DC}\ R_{AC} &= 10^{-2} \text{ volt,} \\
10\ R_{AC} &= R_i, \\
\therefore \text{damping} &= \frac{1}{11} \\
&= 0{,}828 \text{ db.} \\
\text{Similarly for } I_{DC}\ R_{AC} &= 10^{-3} \text{ volt} \\
\text{damping} &= 0.088 \text{ db.} \\
\text{and for } I_{DC}\ R_{AC} &= 10^{-4} \text{ volt,} \\
\text{damping} &= 0.008 \text{ db.}
\end{aligned}$$

For larger signals, however, the degree of damping is affected by the variation of valve input resistance over a cycle and it is necessary to calculate the fundamental component of the distorted waveform.

A sample calculation is presented in Appendix 4 and Fig. 10 shows the variation of damping with input signal for $I_{DC}\ R_{AC}$ values of 10^{-2}, 10^{-3} and 10^{-4} volt and for R_{DC}/R_{AC} ratios of 2 and 20.

It will be noted that in general damping increases with signal input, but with $I_{DC}\ R_{AC} = 10^{-2}$ volt and $R_{DC}/R_{AC} = 20$, the "biasing back" that occurs with increase of signal input more than offsets this effect.

As the loss due to signal damping with $I_{DC} R_{AC} = 10^{-2}$ volt approaches 1 db., it is evident that larger values of $I_{DC} R_{AC}$ should not be permitted in designs. Unless this precaution is observed the gain of the equipment (in the absence of feedback) will be variable by the amount of the possible damping, and will depend upon the actual amount of control-grid current flowing, which will vary from valve to valve, with any one valve as it ages, and with variations of voltages applied to the valve (especially the heater voltage).

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10.0 RELATIONSHIP BETWEEN CONTROL-GRID BIAS AND CURRENT.

Whilst this analysis has been of necessity carried out with reference to values of control-grid current, valve operating conditions are invariably set up for particular values of control-grid bias.

The relationship between bias and current is, however, dependent on many factors, such as valve type and construction, valve processing schedules, age of valve and type of service, applied voltages, factors causing reverse grid current, and other less important considerations.

Nevertheless, since recommendations are to be made for the avoidance of grid-circuit distortion, investigation is necessary only into conditions likely to lead to maximum grid current.

10.1 Variation of Control-Grid Current with Use.

The effect of operating life on the control-grid current of a valve is generally acknowledged amongst valve engineers to be a smoothing-out of variations due to initial valve processing. Thus valves of similar type and design with high and low grid current, if operated under the same conditions, should tend towards an average value determined by the state of the cathode and by cathode-material deposits on the surface of the grid. In valves with higher than usual control-grid current the effect of operation should therefore be a reduction of this current.

To test this hypothesis thirty valves were placed on extended life test under two sets of operating conditions. In the initial test twenty 6AU6 valves ran with plate and screen voltages of 150 volts, heater voltage of 6.3 volts and a cathode bias resistor of 250 ohms. This resulted in an average cathode current of about 7 milliamps and a bias of 1.7 volts.

After this test had been running for some months other tests raised the possibility that the lower cathode current experienced under resistance-coupled conditions might lead to higher grid currents during operation, and a second life test was organised under resistance-coupled conditions with a heater voltage of 6.3 volts and a B supply of 250 volts. Plate and screen resistors of 0.27 and 0.47 megohm were used and a 2200 ohm cathode resistor gave an average bias of 2.2 volts and a cathode current of 1 milliamp.

These tests were continued for 27,000 hours and 20,000 hours respectively (i.e. over 3 years and approaching 2½ years of continuous operation) with results as shown in Fig. 11.

Although the original hypothesis does not seem to be completely verified, at least in the first year of continuous operation the average value of grid current fell, and the subsequent increase, although unexpected, had not resulted at 27,000 hours in any values of grid-current higher than the initial values. No significant variation in the behaviour of the valves operated under the different conditions could be observed.

The failures that occurred during the test, although at first sight high, are in fact very good, since 60% of a random selection of commercial valves is still operating satisfactorily after 27,000 hours of use.

On the basis of this test and the commonly accepted theory of the behaviour of so-called "contact potential" it was decided that conditions which would give satisfactory control-grid current in new valves would also be satisfactory throughout the life of the valve.

10.2 Grid-Current Cut-Off Bias.

An analysis was therefore carried out on the "grid-current cut-off" bias of more than one thousand unused valves of different types. The "grid-current cut-off" bias is the bias required to reduce grid current to 0.2 microamp, a value in the retarding-field region, and measured in the Amalgamated Wireless Valve Company at nominal heater voltage and without potentials applied to other electrodes. Valves are "preheated", before the measurement is made, for a period of time sufficient to allow the control-grid current to reach its maximum value, i.e. for at least several minutes.

Under these conditions 500 type 6AU6 valves showed a mean "grid-current cut-off" bias of -0.97 volt with a standard deviation of 0.17 volt. Corresponding figures for 337 type 6AV6 high-mu triodes were -0.72 volt and 0.28 volt, for 100 type 6SJ7GT valves -0.81 volt and 0.17 volt and for 72 type 6BQ7A triodes -0.85 volt and 0.14 volt.

It is realised that valves of the same type made to a different mechanical design by another manufacturer would not necessarily have the same "grid-current cut-off" bias or standard deviation. Experience has shown however that in general variations of this characteristic between valves from different manufacturers are no greater than those amongst valves from the same manufacturer.

10.3 Influence of Other Electrodes.

The influence of potentials applied to other electrodes varies considerably with individual valve types. The retarding-field grid current of a 6SJ7GT may be decreased fifty times by increasing the grid 2 and anode voltage from 0 to 100 volts.

On the other hand, with the close-spaced 6BQ7A an increase of anode voltage from zero may result in an initial two or three times increase in control-grid current, followed by a decrease to the original value when the anode voltage has reached approximately 100 volts.

With the 6AU6 and 6AV6 an increase in triode-anode voltage from 0 to 100 volts may result in retarding-field grid current reductions of the order of twenty times and four times respectively.

Accordingly, the value of "grid-current cut-off" bias determined as above without potentials applied to outer electrodes can be used conservatively as the bias required to reduce control-grid current to 0.2 microamp in the majority of valves operating with normal voltages applied to other electrodes.

10.4 General Recommendation for Minimum Control-Grid Bias.

On the assumption that a standing grid current of 10^{-9} amp will be satisfactory for general purpose audio-frequency amplifiers, a minimum bias figure of -1.8 volt can now be recommended. This value is the sum of -0.5 volt, to reduce the current from 0.2 to approximately 0.001 microamp, and -1.3 volt* to allow for "grid-current

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* It is of interest that in the "Electronic Tube Handbook" and other publications of N.V. Philips Gloeilampenfabrieken the grid-current cut-off bias (0.3 microamp in this case) for all valve types for which it is quoted (e.g. EBF32 in the handbook mentioned) is given as -1.3 volt maximum.

cut-off" bias plus twice the standard deviation. Under these conditions not more than one valve in fifty should exceed the desired maximum grid current.

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11.0 REVERSE GRID CURRENTS.

The effect of reverse grid currents on the value of bias required to avoid grid-circuit distortion has been ignored for the reasons below.

11.1 Proportion of Valves with Reverse Grid Current.

Of 1,009 valves examined, only eight - three of these from one day's production - had reverse grid currents of 0.2 microamp or more when operated at maximum ratings.

11.2 Effect of Operating Conditions on Reverse Grid Current.

Audio-frequency amplifier valves operated under low-bias conditions are almost invariably resistance coupled. Since gas current is approximately proportional to plate current and to the square of the plate voltage, this low-current, low-voltage operating condition greatly reduces the tendency for reverse grid current to flow.

11.3 Effect of Reverse Grid Current on Distortion.

Since gas current increases with increasing plate current, i.e. with decreasing negative bias, any values of gas current likely to be present in a valve minimize the curvature of the positive grid-current characteristic and thus reduce the grid-circuit distortion. The condition for maximum distortion is thus a valve with minimum reverse grid current.

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12.0 RECOMMENDATIONS.

With low-level audio-frequency amplifiers, negative grid bias is usually kept as small as possible because maximum gain is obtained from resistance-coupled pentodes in this condition and because high-mu triodes cut-off rapidly as bias is increased.

For these reasons existing valve manufacturers' recommendations (see Appendix 2) usually specify bias values which are inadequate in the light of the preceding analysis. It is realised that these recommendations are accompanied by satisfactory values of measured distortion, but the reason for this, it is suggested, is that the measurements are made with zero driving-source impedance and thus do not include the grid-circuit distortion that would occur in more practical conditions.

To restrict grid-circuit distortion to a maximum of 0.1% the following recommendations are made.

12.1 Resistance-Coupled Pentodes.

For valve types in which it is not essential to use the smallest possible bias, e.g. normal resistance-coupled pentodes:-

For signals up to 0.25 volt peak and for driving-source impedance not greater than 0.1 megohm the recommended bias is -1.8 volt.

12.2 Recommendations where Minimum Bias is Required.

Where negative bias must be kept to a minimum, e.g. with high-mu triode amplifiers, the following more detailed recommendations apply.

12.2.1. For signals not greater than 5 millivolts peak the $I_{DC} R_{AC}$ product should not exceed 10 millivolts;

12.2.2 For signals between 5 and 50 millivolts

peak the I_{DC} R_{AC} product should not exceed 1 millivolt;

12.2.3 For signals between 50 and 250 millivolts

peak the I_{DC} R_{AC} product should not exceed 100 microvolts.

12.3 Determination of Grid Current.

To determine I_{DC}, allow -1.3 volt of bias to reduce the grid current to 0.2 microamp. Each additional 0.1 volt of negative bias will reduce I_{DC} to 0.37 of the original figure.

12.4 Conditions with Increased Distortion.

For applications in which greater distortion can be tolerated, larger I_{DC} R_{AC} products and thus smaller values of negative bias can be used in accordance with the results set out in Fig. 8.

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13.0 EVALUATION.

In vacuum-tube operated audio-frequency electronic equipment not containing semi-conductors only two sources of harmonic distortion have in the past been taken into consideration in distortion calculations, firstly the non-linear transfer characteristic of the vacuum-tubes and secondly non-linearities due to the presence of magnetic materials used in other components.

In analysing and evaluating grid-circuit distortion as a third non-linearity it has been necessary in the preceding sections to isolate the effect and to examine it in the absence of other forms of distortion. It is then possible to carry out designs in such a way that grid-circuit distortion does not exceed a calculable probable maximum and if desirable to use known methods of distortion reduction, i.e. various feedback circuits, to minimize all typesof distortion arising from the various sources in an amplifier.

Moreover with the design criteria for grid-circuit distortion established, it becomes the responsibility of equipment designers to avoid this type of distortion (where necessary) equally with other types, while realising that variations between valves with respect to their liability to introduce distortion of this type are many times greater than their variation with respect to transfer-characteristic distortion. As shown in Sections 13.1 and 13.2 it is possible to reduce grid-circuit distortion to any desired level while still controlling other forms of distortion as required.

In the following sub-sections the inter-relationship between the design requirements for low grid-circuit distortion and the overall requirements for low-level audio-frequency input stages and for a complete low-distortion fifty-watt audio-frequency amplifier are considered.

13.1 Prevention of Grid-Circuit Distortion.

It is usually when valves are operated as low-level audio-frequency amplifiers that circuit conditions are such as to lead to grid-circuit distortion.

An example is Ref. 16, a design for a pre-amplifier for use with high-fidelity power amplifiers in which the input stage is grid-leak biased. The specified 0.05 percent intermodulation distortion at 1.5 volts output could probably be met only with a low-impedance signal source.

However, it is not only when grid-leak bias is used that grid-circuit distortion is likely to be encountered. Any of the ten sets of operating conditions set out in Appendix 2 would lead to grid-circuit distortion with a significant percentage of valves (with input signals of the order of 0.1 volt or more) and only one of these sets of conditions is grid-leak biased.

With either triodes or pentodes grid-circuit distortion can be avoided by an increase in bias. A low-level audio-frequency amplifier stage is usually resistance coupled and as the effect of increasing bias on resistance-coupled triodes and pentodes is different, the two valve types are considered separately below, after a brief review of the main aspects of resistance-coupled operating conditions.

13.2 Resistance Coupling.

Amongst the better discussions on resistance coupling is Ref. 17, in which is demonstrated the significance of the ratio of the plate current flowing in the load circuit of a resistance-coupled stage to the current that would flow if the plate of the valve were short-circuited to cathode. This ratio is designated K, and the design of a resistance-coupled stage is best carried out by adjusting K to a suitable value.

The dynamic characteristic of a resistance-coupled triode or pentode is approximately S-shaped (Ref. 14 p. 509) the lower section of the curve being primarily the three-halves power law of the valve's transfer characteristic and the upper section being curved in the opposite direction due to the decreasing plate voltage as the plate current increases.

The gain of a resistance-coupled stage is proportional to the slope of the dynamic characteristic and because of the reverse slope at higher current values there is a region of reasonably constant slope between approximately K = 0.5 and K = 0.8. Although it is desirable, when large output voltages are required, to restrict K to values less than 0.7, nevertheless moderate variations in K, and equivalent variations of bias voltage, can be made with little effect on the gain or distortion of the stage.

13.2.1 Resistance-Coupled Triodes.

In Ref. 17 are presented a large number of graphs of intermodulation distortion vs. K for different values of output voltage and following grid leak and for different valve types.

Fig. 9 of this reference consists of graphs for a triode-connected 6SJ7, and, especially with high values of following grid leak, as commonly used, and small out-put voltages, e.g. 10 volts, as might be expected from a first stage, intermodulation distortion is practically constant between K values of 0.56 and 0.80 corresponding to a plate-current variation from 1.4 to 2.0 mA.

In this case at least, appreciable variation in bias voltage, such as might be required in order to avoid grid-circuit distortion, could be tolerated without increasing plate-circuit distortion unduly.

Furthermore the factors which contribute to the flexibility of the stage in this respect, e.g. low output voltage and high value of following grid leak, are those most likely to be met in a low-level audio-frequency stage in which an increase of bias in order to avoid grid-circuit distortion may be necessary.

Nevertheless it must also be recognised that conditions may arise in which an increase of bias in a triode resistance-coupled stage increases the plate-circuit distortion of the stage more than it reduces the possible grid-circuit distortion.

If this should occur, an increase of plate supply voltage will allow plate-circuit distortion to be reduced to the original value in spite of increased bias voltage. As an example of this effect see Table 2 in Section 13.3 below.

However if an increase in plate supply voltage, or other means of reducing the distortion, cannot be applied in any particular case, then, if it is a design requirement that distortion must not exceed a specified maximum, it becomes necessary to modify the design, perhaps by using a pentode to replace the triode input stage (see Section 13.2.2 below) or by using a triode with a lower amplification factor which could therefore tolerate a higher value of bias for a given plate supply voltage (See Section 13.3.3 below). If the latter alternative resulted in too great a gain reduction, it might be necessary to add another triode stage.

13.2.2 Resistance-Coupled Pentodes.

With a pentode stage which is liable to grid-circuit distortion, all of the comments of Section 13.2.1. are relevant, but one further feature of the performance of the stage must be considered; the factor K has exactly the same significence as with triodes but in addition to being a function of control-grid bias it is also a function of the screen-grid voltage of the stage.

Thus if an increase in bias is necessary in order to avoid grid-circuit distortion, similar performance can be obtained from the stage by increasing the screen voltage until K returns to its original value, see Ref. 18, page 115, "The distortion of any (pentode) valve is however only slightly affected by small changes in grid bias provided that the screen voltage is adjusted to keep the value of K constant."

The reason for this effect is made clear in Fig. 12.14A page 504 of Ref. 14. In this figure the dynamic characteristics of a resistance-coupled 6J7 pentode valve are presented for eleven values of screen voltage from 0 to 100 volts. The characteristics for screen voltages of from 20 volts to 100 volts are similar in shape and slope, being merely displaced to higher negative control-grid bias voltages as the positive screen voltage is increased.

Thus with a pentode resistance-coupled input stage there should be no difficulty in applying sufficient control-grid bias to avoid grid-circuit distortion.

13.3 Measurements on Fifty-Watt Amplifier.

To demonstrate the incidence of grid-circuit distortion in a complete piece of equipment, measurements were carried out on the 50 watt amplifier described in Ref. 17. The circuit constants of the first stage are (see Appendix 2) those recommended by a valve manufacturer for the valve in question (12AX7, B339 and ECC83 are different numbers for the same valve type) but in the amplifier the plate voltage of the stage, and hence the bias voltage, is much greater than that in the valve manufacturer's recommendation, 380 volts instead of 200 volts.

In the form in which it is described in Ref. 19 the amplifier should always be free of grid-circuit distortion, since the bias on the first stage is, as indicated on the circuit, -2.3 volts. Had the 12AX7 operating conditions of Appendix 2 been adopted by the equipment designer however, the measurements show that the performance of the amplifier would have been impaired with a significant percentage of input valves whenever a high-impedance driving source, e.g. a crystal pick-up, was used with the amplifier.

The experiment was planned in the following way. Since it is contended that the recommendations of Appendix 2 are unsatisfactory, it should be possible to demonstrate grid-circuit distortion in the amplifier when driven from a high-impedance signal source merely by reducing the plate-supply voltage of the first-stage 12AX7, which has circuit constants as in Appendix 2, until the control-grid bias is the recommended -1.2 volts. Under these conditions the distortion should be apparent with valves with grid-current cut-off voltages near the top limit (see Section 10.4) of -1.3 volts.

Furthermore, when grid-circuit distortion is evident in the input half of the 12AX7 it could also appear in the other half because this operates at the same signal level and from a high-impedance source.

In order that the distortion could be demonstrated to be a function of driving-source impedance however, a 12AX7 was selected with a grid-current cut-off voltage of -1.2 volts on the input triode and -0.8 volt on the other triode. The second triode thus did not at any time introduce grid-circuit distortion and a comparison of measurements made with signals applied from high-impedance and low-impedance sources demonstrated the incidence of grid-circuit distortion in the first triode.

In addition this procedure had the advantage of showing the effect of negative feedback applied to the cathode of a valve in which grid current was causing grid-circuit distortion. The usual proof of the effect of negative feedback in reducing distortion shows that a feedback loop completely containing a valve and its grid-circuit would reduce grid-circuit or any other type of distortion by a factor equal to the amplifier gain reduction. The same conditions, however, do not necessarily apply when the grid-circuit in which the distortion is generated is not contained within the feedback loop, as is the case in the amplifier of Fig. 13.

Using a distortion-factor meter, distortion measurements at the nominal amplifier output of 50 watts were carried out at the output of the first stage without feedback and at the output of the amplifier both with and without feedback. A preliminary test showed that first stage distortion was not affected by the push-pull operation of the second 12AX7 triode. The measurements were made over a range of plate supply and bias voltages and with high and low driving-source impedances.

The results of the measurements are set out in Table 2.

TABLE 2.

Signal Source Impedance = 600 ohms

Plate Supply Voltage (i) (Volts)	Control-Grid Voltage (Volts)	1st Stage Distortion (ii) (%)	Total Amplifier Distortion	
			(No Feedback) (%)	(With Feedback) (%)
380	-2.30	0.28	2.9	0.30
270	-1.67	0.32	2.9	0.30
200	-1.33	0.35	3.0	0.32
180	-1.18	0.38	3.1	0.32
160	-1.08	0.37	3.0	0.31
140	-0.95	0.32	2.9	0.30

Signal Source Impedance = 100,000 ohms

Plate Supply Voltage (i) (Volts)	Control-Grid Voltage (Volts)	1st Stage Distortion (ii) (%)	Total Amplifier Distortion	
			(No Feedback) (%)	(With Feedback) (%)
380	-2.30	0.28	2.9	0.30
270	-1.67	0.32	3.0	0.30
200	-1.33	1.0	3.2	0.33
180	-1.18	3.8	4.0	0.8
160	-1.08	7.4	7.7	1.8
140	-0.95	11.0	12.0	3.8

(i) Measured at junction of R_5, R_6 and R_7

(ii) Measured with distortion meter in series with R16, the second stage grid leak.

Signal input for 50 watts output, amplifier as described, = 0.53 volts r.m.s.

Signal input for 50 watts output, amplifier as described, but without feedback, = 0.056 volt r.m.s.

Signal source distortion = 0.23%

13.3.1 Analysis of Measurements.

The following points are of interest.

(i) Plate Supply Variation. With the amplifier driven from a low-impedance signal source an increase in control-grid bias from -0.95 to -2.3 volts, when accompanied by a plate supply voltage increase from 140 to 380 volts, with circuit constants unchanged, did not result in any marked variation in distortion in the first stage of the amplifier. This is not unexpected because of the low output voltage of the amplifier stage, i.e. slightly less than five volts peak.

(ii) Feedback Factor. The increase in input voltage with feedback for 50 watts output represents a feedback gain reduction factor of 19.5 db. This compares with 22 db nominated in Ref. 19.

(iii) Grid-Circuit Distortion. In ref. 19 the bias developed by the input 12AX7 triode in the amplifier as given is -2.3 volts, which agrees with the measurements in Table 2. Unfortunately the bias voltage developed with a 200 volt plate supply voltage is greater than that stated in the recommended conditions of Appendix 2, and this minimizes the effect of control-grid current. The bias developed with a 180 volt plate supply is however identical in the valve used with that stated in the Appendix 2 conditions with a 200 volt supply.

Nevertheless even with a bias of -1.33 volts, representing a control-grid current of less than 0.06 microamp, grid-circuit distortion is marked in the first stage measurements, and detectable in the total amplifier distortion without feedback.

With -1.2 volts bias as recommended in Appendix 2 and with a high-impedance signal source, grid-circuit distortion is ten times greater than the plate circuit distortion in the first 12AX7 triode and has increased total amplifier distortion with feedback applied almost threefold.

Moreover the design of the amplifier is such that the first stage grid-to-cathode signal voltage of 56 millivolts required to drive the amplifier to full output is lower than commonly experienced in such applications. With a less sensitive amplifier grid-circuit distortion would increase by very approximately the same proportion as the increase in signal required to drive the amplifier to full output (see Fig. 8).

The 0.1 megohm signal-source resistance used in the grid-circuit distortion measurements is felt to be a not unduly high value since at 1000 c/s the impedance of many typical crystal pick-ups (such as might be used with an amplifier of this sensitivity) is about 0.5 megohm (Ref. 14, p.720) and of ceramic pick-ups about 0.15 megohm (Ref.14, p.721.) The impedance between slider and ground of the commonly used 0.5 megohm volume control also rises to 0.125 megohm in the mid-position of the control.

Further, of the ten sets of valve operating conditions recommended by valve manufacturers in Appendix 2, six and perhaps seven would cause the valve to be operated with lower negative bias than that for the 12AX7 as measured.

13.3.2. Effect of Negative Feedback on Distortion.

Examination of Table 2 shows that for conditions under which there is no grid-circuit distortion, the application of feedback gives a reduction of distortion approximately equal to the reduction of gain, i.e. almost ten times. This is in accordance with existing theory.

However, with high values of grid-circuit distortion the feedback is less effective in reducing overall distortion and this is because the grid-circuit in which the distortion is produced is not completely contained within the feedback loop. The effect can be explained as follows.

In Fig. 13 let the input impedance, grid to ground, of the input 12AX7 triode V_1, without feedback, be R_i and the input impedance with feedback be R_i'. Also let the gain of the amplifier from input grid to output be A and let a fraction β of the output be fed back to the cathode of V_1. Ignoring the effect of the unbypassed 100 ohms in the cathode circuit of V_1 as having only a second-order effect, this negative feedback will reduce the gain to $\frac{1}{1+A\beta}$ of the original in accordance with well-known theory.

In the absence of feedback apply a signal E_i between the grid of V_1 and ground and let a current I_i flow in the grid circuit.

Then $R_i = \frac{E_i}{I_i}$

Now apply negative feedback and let the input signal to produce the same amplifier output be E_i' and the input current with this signal applied be I_i'.

Then $R_i' = \dfrac{E_i'}{I_i'}$.

But since the grid-to-cathode voltage of V_1 with feedback is unchanged to produce a given amplifier output voltage,

$$E_i' = E_i(1 + A\beta),$$

and since a given grid-to-cathode voltage will result in the same input grid current (ignoring cathode-to-ground impedance as being very much less than grid-circuit impedance)

$$I_i' = I_i .$$

Therefore $R_i' = \dfrac{E_i(1 + A\beta)}{I_i}$

$$= R_i(1 + A\beta).$$

The input impedance of the input stage in Fig. 13 is therefore increased by negative feedback by the gain reduction factor of the feedback. The effective current-voltage characteristic of the input circuit is consequently altered and the reduced slope of the characteristic reduces the distortion. The following reasoning however allows the grid-circuit distortion in the presence of negative feedback, applied as in Fig. 13, to be evaluated without a fresh calculation of distortion for each value of feedback.

Suppose that in a particular case negative feedback giving a tenfold gain reduction is applied to an input stage as in Fig. 13. This will result in a tenfold increase in input impedance and also necessitate a ten times larger signal input to give the same output.

Now if the resistance of the signal source were also increased ten times, each static and dynamic impedance in the input circuit would be ten times larger with feedback than without feedback and the signal voltage for a given amplifier output would also be ten times larger with feedback. Under these conditions the input current at each point on the excitation cycle would be the same either with or without feedback. The grid-circuit distortion would therefore not be affected by the feedback.

In a practical application of feedback however the resistance of the signal source would not be altered and would in fact be ten times less than the value which would give identical distortion for the same amplifier output with feedback. This results in an I_{DC} R_{AC} value ten times smaller than the value without feedback and also in distortion in accordance with this figure when determined for the original signal input i.e. for the actual grid-to-cathode first-stage input.

The measurements in Table 2 allow a comparison to be made between the effect on grid-circuit distortion of the application of tenfold negative feedback and of a tenfold reduction of grid current.

From Section 9.0 it can be assumed that a tenfold reduction of static control-grid current will be produced by an increase of negative bias of 0.23 volt. The total amplifier distortion at -0.95 volt bias with negative feedback and a signal source resistance of 0.1 megohm is 3.8% and this is almost entirely grid-circuit distortion, since the distortion under similar conditions but with low signal-source resistance is only 0.3%.

A comparison with either the first stage distortion (3.8%) without feedback but with an additional 0.23 volt of negative bias, or with the total amplifier distortion (4.0%) under the same conditions, shows that very close correlation of distortion at full amplifier output is obtained between a ten-fold decrease in the I_{DC} R_{AC} product and the use of tenfold feedback.

A similar check can be made with -1.08 volts bias and tenfold negative feedback (1.8% distortion) and -1.33 volts bias without feedback (1.0% first stage distortion, 3.2% total distortion). The correlation is not so good in this case but the bias increase is -0.25 volt, which accounts for some decrease in the no-feedback first stage distortion. Moreover the total distortion is obviously increased by components from stages other than the input 12AX7 triode.

The effect on grid-circuit distortion of negative feedback applied to the cathode of the valve causing the distortion can therefore be expressed as a reduction of I_{DC} R_{AC} by a factor equal to the gain reduction of the negative feedback.

The grid-circuit distortion of a valve with negative feedback applied to its cathode can therefore be calculated as previously described by assuming both I_{DC} R_{AC} and the actual signal input to be reduced by a factor equal to the gain-reduction factor of the feedback.

13.3.3 Conclusions.

The plate current of a triode valve can be expressed as

$$I_p = p(E + E_b/\mu)$$

where I_p = plate current,

p = perveance, a constant,

E = grid potential,

E_b = plate voltage,

and μ = amplification factor.

From this equation can be obtained an approximation of the negative grid voltage required to reduce to zero the plate current of a valve, viz. $\frac{E_b}{\mu}$ volts. Thus the higher the amplification factor of a triode valve, the smaller the value of negative bias required to cut-off its plate current with a given plate voltage.

Where therefore it is considered necessary to use a higher than usual value of negative bias on a valve, plate-circuit distortion is most likely to be experienced in valves with a high amplification factor.

The 12AX7 valve used in the input stage of the amplifier of Fig. 13 is in fact the valve type with the highest effective triode amplification factor of any commonly used valve. This statement applies not only to triodes but also to pentodes, in which the amplification factor between grid 1 and grid 2 has a similar significance to the grid-to-plate amplification factor of a triode.

Thus difficulties brought about by increasing of bias in order to avoid grid-circuit distortion are at their greatest in the amplifier tested. Where it is necessary to accommodate an input signal as large as 0.25 volt peak, the bias of -1.8 volts recommended in Section 12.1 should be used, and from Table 2 it can be seen that this would necessitate a plate supply voltage of approximately 300 volts under the conditions used i.e. with a plate load of 0.22 megohm. The actual voltage on the plate of the valve under these conditions would be approximately 200 volts (the maximum plate voltage permitted by the valve manufacturers is 300 volts).

In most low-distortion amplifiers plate supply voltages of this order are available, so that the special design procedures mentioned in Section 13.2.1. as methods of overcoming grid-circuit distortion in difficult cases should very rarely be necessary.

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APPENDIX 1.

THE MEASUREMENT OF RETARDING-FIELD CONTROL-GRID CURRENT.

A simple method of measurement of control-grid current in the range from 10 to 10^{-3} microamp is described in [15]. The circuit used is shown in Fig. 12 and the principle of operation is that the plate current of the valve under test is used as an indicator of its grid voltage, the grid voltage in turn being established by the flow of control-grid current in a resistor, R, of known and adjustable size.

The value of the voltage developed across the grid resistor is determined by noting the plate current of the valve at zero bias, short-circuiting the grid resistor and increasing the negative bias until the plate current returns to its original value.

The applied bias is then equal to the voltage developed across the grid resistor and as the value of the resistor is known, the grid current can be determined. By substituting progressively larger values of grid resistor a continuous plot of control-grid current vs. voltage can be obtained.

The "bucking" circuit connected across the plate-current meter allows a centre-zero microammeter to be used for the current measurement and thus increases the accuracy with which the grid voltage can be adjusted after substitution of a variable voltage for the "grid-leak bias".

In the unit built for grid-current measurements in the present investigation, the resistor R consisted of thirteen resistors selected for accurate values of 0.1, 1.0, 10 and 50 megohms, there being ten resistors of the last value. These resistors were wired in series on a ceramic terminal block and baked and vacuum impregnated with moisture-resisting varnish. Connection was made to appropriate junctions in the series-string by means of clip leads in order to avoid any leakage in switches.

A typical set of readings in the plotting of a control-grid characteristic is reproduced below:-

RESISTOR VALUE (Megohms)	EQUIVALENT BIAS (Volts)	CONTROL-GRID CURRENT (CALCULATED) (Microamps)
1	-0.69	0.69
10	-0.90	0.090
50	-1.04	0.021
100	-1.10	0.011
150	-1.14	0.0076
200	-1.16	0.0058
300	-1.20	0.0040
500	-1.25	0.0025

To obtain readings of smaller values of grid current, e.g. 0.001 microamp, larger values of grid resistor could have been used but the alternative of taking measurements with an initial bias applied through 500 megohms was used in order to avoid the mechanical complication of a large number of 50 megohm resistors (the largest value readily obtainable).

For example:-

RESISTOR VALUE (Megohms)	INITIAL BIAS (Volts)	FINAL BIAS (Volts)	DIFFERENCE (Volts)	CONTROL-GRID CURRENT (Microamps)
500	0.84	-1.34	0.50	0.001

It was found desirable to operate the valve under test for at least fifteen minutes before commencing measurements in order to allow the control-grid current to stabilize. Under these conditions and with controlled electrode voltages, readings were repeatable for at least the length of time required to take a set of measurements.

Readings approaching 10 microamps of control-grid current resulted from the use of the smallest (0.1 megohm) resistor but with some valve types non-linearity due to the beginning of space-charge-limited conditions was evident with currents of this order. Accordingly most sets of readings were restricted to values not greater than 1 microamp.

A disadvantage of the method of grid-current measurement described above is that it requires a voltage to be applied to the anode of the valve under test. When a simple diode characteristic is required however (e.g. Fig. 1, Curve A) a sufficient number of readings can be obtained with a moving-coil meter. Composite characteristics drawn with moving-coil meter and by the method described above give good agreement of readings within the range of overlap of the two methods provided that the separate sections of each curve are measured without delay. This is evidenced in Fig. 1 in which moving-coil meter readings are shown with a dot whereas readings obtained by the method described are represented by a circle.

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APPENDIX 2.

VALVE MANUFACTURERS' RECOMMENDATIONS.

Examples of valve manufacturers' recommended operating conditions in which it is considered that the control-grid bias voltage is too low:-

MULLARD:-

Source:- "Technical Handbook"

Valve type	ECC83	EF86
Plate Supply Voltage (volts)	200	150
Plate Load Resistor (megohms)	0.22	0.22
Screen Resistor (megohms)	-	1.0
Cathode Resistor (ohms)	3300	2700
Cathode Current (milliamps)	0.36	0.55
Control-Grid Bias* (volts)	-1.19	-1.49
Following Grid Resistor (megohms)	0.68	0.68
Gain	56	150
Output Voltage (r.m.s. volts)	24	24.5
Total Distortion Percentage +	4.6	5.0
+Output voltage and distortion at start of grid current.		

* Calculated from other data.

N.V. PHILIPS GLOEILAMPENFABRIEKEN:-

Source:- "Electronic Tube Handbook"

Valve Type	ECC82	EF12
Plate Supply Voltage (volts)	100	100
Plate Load Resistor (megohms)	0.22	0.20
Screen Resistor (megohms)	-	0.50
Cathode Resistor (ohms)	3900	2200
Cathode Current (milliamps)	0.33	0.46
Control-Grid Bias* (volts)	-1.3	-1.0
Gain	14.5	128
Output Voltage (1) (volts)	8	5
Total Distortion Percentage	4.0	0.7
(1) I_g = +0.3 uA		

* Calculated from other data.

R.C.A.:-

Source:- "R.C.A. Tube Handbook HB3"

Typical Operation and Characteristics -		
Valve Type	6AU6	6AV6
Plate Voltage (volts)	250	100
Screen Voltage (volts)	150	-
Cathode Resistor (ohms)	68	-
Cathode Current (milliamps)	14.9	0.5
Control-Grid Bias (volts)	-1.0	-1.0
Mutual Conductance (microamps per volt)	5200	1250
Plate Resistance (megohms)	1.0	0.08

R.C.A. information from other sources is to the effect that resistance-capitance coupled conditions are adjusted so that the maximum output voltage is obtained for a control-grid current of 0.1 microamp.

STANDARD TELEPHONES & CABLES LTD.

Source:- Brimar Valve and Teletube Manual No. 6

Valve Type 6AT6	A	B
Anode Supply Voltage (volts)	250	250
Anode Load Resistor (megohms)	0.25	0.25
Grid Resistor (megohms)	1.0	1.0
Cathode Bias Resistor (ohms)	3000	0
Control-Grid Bias* (volt)	-	0
Peak Output (volts)	43	40
ϕ Stage gain	42	42
ϕ Harmonic Distortion Percentage	1	5
ϕ Figures are for 12 volts peak output.		

* Calculated from other data.

Note that condition B is "grid-leak biased" with only a 1 megohm grid leak, so that I_{DC} would probably be at least 0.5 micro-amp, giving $I_{DC}\ R_{AC} = 10^{-2}$ volt for a series impedance as low as 0.02 megohm.

Further, from the stage gain and peak output figures it is apparently intended that an input voltage of approximately one volt (presumably r.m.s.) can be handled, although the grid-circuit distortion (deduced from comparison with condition A) is already about 5% with an input voltage of about 0.3 volt. The series impedance, R_{AC}, for the conditions of measurement is not stated.

SYLVANIA.

Source:- "TECHNICAL MANUAL: Sylvania Electronic Products."

Valve Type.	6J7GT	6SQ7GT
Plate Supply Voltage (volts)	100	100
Plate Load Resistor (megohms)	0.47	0.27
Screen Resistor (megohms)	1.8	-
Cathode Resistor (ohms)	3900	5600
Plate Current (milliamps)	0.168	0.138
Screen Current (milliamps)	0.465	-
Control Grid Bias (volts)	-0.622	-0.774
Screen Voltage (volts)	16.3	-
Plate Voltage (volts)	21	62.8
Following Grid Resistor (megohms)	1.0	0.27
Signal Voltage (1) (peak volts)	0.14	0.1
Output Voltage (peak volts)	17.0	4.1
Gain	121.5	41.0
Total Distortion Percentage	5.0	3.2

Note (1). For self-bias operation this is taken at the grid-current point with less than 1/8 microamp of grid current.

Three points emerge from these tables. Firstly, there is a lack of uniformity in the minimum values of bias recommended by the different manufacturers, both from manufacturer to manufacturer, and with individual manufacturers for different valve types (the two recommendations quoted for each manufacturer are the two lowest-bias conditions noted in the sources specified.)

Secondly, it seems that the valve manufacturers in question - and they include a sample of the world's major receiving valve manufacturers - consider control-grid currents of some few tenths of a microamp to be negligible, whereas in fact currents of one thousandth of a microamp can cause undesirable distortion under practical conditions.

Thirdly, the significance of the combination of source impedance and control-grid current is not recognised. If the 6J7GT for which recommendations are published by Sylvania be assumed to be driven by another 6J7GT with similar operating conditions, the source impedance of the signal is about 0.3 megohm (assuming the anode impedance of the driving valve to be very much greater) and with 0.1 microamp of control-grid current - less than the nominated maximum - the I_{DC} R_{AC} product would be 0.03 volt. This would lead to grid-circuit distortion more severe than the tabulated 5% transfer-characteristic distortion with the signal voltages specified.

APPENDIX 3.

CONSTRUCTION OF NOMOGRAM

The calculations for the construction of the nomogram of Fig. 6 were carried out in the following manner:

VALUE OF C.

(1) Since from the simplification of eqn. (9)

$$D = I_o \ (10\ E_{AC}),$$

values of D for required * values of E_{AC} are available from a table of Bessel functions, and these, although plotted on the two-decade vertical logarithmic scale marked "Applied Voltage" as values of D, are identified as the corresponding value of E_{AC}.

(2) From the relationship

$$D = B \exp \left[10\ I_{DC}\ R_{DC}\ (B-1)\right]$$

values of D over the required range are plotted against empirically chosen values of B. For the maximum value of E_{AC} chosen, 0.48 volt,

$$D = I_o\ (10\ E_{AC}) = 22.79$$

and values of B must therefore be chosen to provide a smooth plot between D = 1 and, say, D = 23.

(3) During the calculation of step (2) the value of C,

$$C = \exp-\left[10\ I_{DC}\ R_{DC}\ (B-1)\right],$$

is noted and plotted.

Thus to calculate a particular case, take

$$I_{DC}\ R_{DC} = 2 \times 10^{-2} \text{ and } R_{DC}/R_{AC} = 2$$

For B = 2,

$$D = B \exp \left[10\ I_{DC}\ R_{DC}\ (B-1)\right] = 2.442$$

and C = 0.818

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* For the factors involved in choosing values of E_{AC} for subsequent calculation, see Apendix 4.

Note that this calculation provides values for $I_{DC}\ R_{AC} = 10^{-2}$ with $R_{DC}/R_{AC} = 2$ as well as for $I_{DC}\ R_{AC} = 10^{-3}$ with $R_{DC}/R_{AC} = 20$.

When a suitable range has been calculated, the values of D are plotted on the two-decade, 1 to 10^2, vertical logarithmic scale of the nomogram, against the values of C which are plotted on the three-decade horizontal logarithmic scale.

VALUE OF P.

From eqn. 14

$$P = \exp\left\{10\left[\Delta E - I_{DC}\ R_{AC}\ (P - 1)\right]\right\}$$

To plot values of P against values of $I_{DC}\ R_{AC}$ with values of ΔE as a parameter, this equation was rearranged to

$$\frac{\exp\ (10\Delta E)}{P} = \exp\ 10\left[I_{DC}\ R_{AC}\ (P-1)\right]$$

For particular values of ΔE and P the value of $I_{DC}\ R_{AC}$ can now be determined. For example, take $\Delta E = 0.24$ volt, then $\frac{\exp\ (2.4)}{P} = \exp\left[10\ I_{DC}\ R_{AC}\ (P-1)\right]$.

However, since $\exp\left[10\ I_{DC}\ R_{AC}\ (P-1)\right] \nless 1$,

$$P \ngtr 11.023$$

Assume P = 10,

then $\frac{11.023}{10} = \exp\ (10\ I_{DC}\ R_{AC} \times 9)$

but $1.1023 = \exp\ (0.0974)$.

$\therefore\ I_{DC}\ R_{AC} = 0.00108$ volt.

By suitable selection of values of P it is thus possible to plot P against the required range of values of $I_{DC}\ R_{AC}$ for selected values of ΔE.

VALUE OF Q.

From eqn. 16

$$Q = \exp \left(-10 \left(\Delta E - I_{DC} R_{AC} (1 - Q) \right) \right)$$

By a technique similar to that described for the plotting of P, Q can be plotted against I_{DC} R_{AC} with values of ΔE as a parameter.

Because of the form of the equation, however, and because Q tends towards zero with large values of ΔE, it is not necessary to continue the plotting of Q over the range required for P, and this plotting has been kept to a minimum in order to avoid undue complexity in the nomogram. Values of Q not covered by Fig. 6 are readily obtainable by interpolation from the calculations used for the partial plot of Q lines.

For example, when $\Delta E = 0.06$ volt, the variation in Q values for the range of I_{DC} R_{AC} from 10^{-2} volt to 10^{-4} volt is only from approximately Q = 0.57 to Q = 0.55. The somewhat larger percentage variations in the smaller values of Q for larger values of ΔE are in fact even less significant because Q in eqn. 16 is subtracted from unity and because a small Q value is always used in conjunction with a large P value in the calculation of harmonics (See Appendix 4.)

PLOTTING OF RESULTS TO CONSTRUCT NOMOGRAM.

Since the values of P for the relevant ranges of ΔE and of I_{DC} R_{AC} fall only just outside the range 1 to 10^2, these can be plotted on the same vertical two-decade logarithmic scale as was used for plotting C versus D.

Similarly the values of Q fall in the range 1 to 10^{-2} and by starting from the top of the figure, values of Q can also be plotted using the same scales.

It is now possible to see that by entering the "Applied Voltage" scale at the left-hand side of the figure at, for example, 0.36 volt, this action has selected the appropriate value of D, viz. 8.028.

By passing horizontally to the curve $R_{DC}/R_{AC} = 20$ which originates at $I_{DC}\,R_{AC} = 10^{-2}$ volt, the value of $C\,I_{DC}\,R_{AC}$ is obtained, viz. 2.21×10^{-3} volt.

Passing vertically to the "P line" for $\Delta E = 0.36$ now solves the equation for the value of P, i.e. P = 22.5, from which the peak value of the signal is available as shown in Section 8.2.

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APPENDIX 4.

THE CALCULATION OF DISTORTION.

On the basis of preliminary distortion measurements it was decided that the calculation of four harmonics (including the fundamental) would be sufficient.

Amongst a number of approximate methods of obtaining Fourier coefficients is one by Espley [12] who describes a method of calculating four harmonics of a waveform when the values of five particular equally spaced points on the excursion are known.

Transposing Espley's formulae,

$$\text{Fundamental (peak volts)} = 1/3\,(E_{1.0} + E_{0.5} - E_{-0.5} - E_{-1.0})$$

$$\text{Second harmonic } (\%) = 75\,\frac{E_{1.0} + E_{-1.0}}{E_{1.0} + E_{0.5} - E_{-0.5} - E_{-1.0}}$$

$$\text{Third harmonic } (\%) = 50\,\frac{E_{1.0} - 2E_{0.5} + 2E_{-0.5} - E_{-1.0}}{E_{1.0} + E_{0.5} - E_{-0.5} - E_{1.0}}$$

$$\text{Fourth harmonic } (\%) = 25\,\frac{E_{1.0} - 4E_{0.5} - 4E_{-0.5} + E_{-1.0}}{E_{1.0} + E_{0.5} - E_{-0.5} - E_{-1.0}}$$

Where $E_{1.0}$ = maximum positive excursion of grid voltage,

$E_{0.5}$ = positive grid voltage when positive excitation is one half of maximum,

$E_{-0.5}$ = negative grid voltage when negative excitation is one half of maximum,

and $E_{-1.0}$ = maximum negative excursion of grid voltage.

Results are exact when harmonics above the fourth are zero and as it will be seen from calculations that there is a sharp reduction in harmonic amplitude as the order of the harmonic increases, errors due to the omission of harmonics of higher order than the fourth are felt to be insignificant.

Each of the voltages $E_{1.0}$, $E_{0.5}$, $E_{-0.5}$ and $E_{-1.0}$ consists of an applied-voltage term and a difference term, and examination of Espley's formulae shows that a re-arrangement is possible which, after the determination of the amplitude of the fundamental, allows the harmonics to be evaluated using only the difference terms. This has the advantage of minimizing calculation and, which is more important, increasing the accuracy of the calculated results for the use of a given number of significant figures.

Thus for any particular set of conditions

$$E_{1.0} = \Delta E - I_{DC} R_{AC} (P_{1.0} - 1),$$

$$E_{0.5} = \frac{\Delta E}{2} - I_{DC} R_{AC} (P_{0.5} - 1),$$

$$E_{-0.5} = \frac{-\Delta E}{2} + I_{DC} R_{AC} (1 - Q_{-0.5}) \text{ and}$$

$$E_{-1.0} = -\Delta E + I_{DC} R_{AC} (1 - Q_{-1.0})$$

Where $P_{1.0}$, $P_{0.5}$, $Q_{-0.5}$ and $Q_{-1.0}$ are the values of P and Q determined for the values of $E_{1.0}$, $E_{0.5}$, $E_{-0.5}$ and $E_{-1.0}$ respectively.

Espley's formulae can therefore be expressed:-

Fundamental (peak volts) =

$$\Delta E - \frac{I_{DC} R_{AC}}{3} \left\{ (P_{1.0} - 1) + (P_{0.5} - 1) + (1 - Q_{-0.5}) + (1 - Q_{-1.0}) \right\}$$

Second Harmonic (%) = $\dfrac{25\, I_{DC} R_{AC} \left\{ (1 - Q_{-1.0}) - (P_{1.0} - 1) \right\}}{\text{Fundamental}}$

Third Harmonic (%) =

$$\frac{\frac{50}{3} I_{DC} R_{AC} \left\{ 2(P_{0.5} - 1) + 2(1 - Q_{-0.5}) - (P_{1.0} - 1) - (1 - Q_{-1.0}) \right\}}{\text{Fundamental}}$$

Fourth Harmonic (%) =

$$\frac{\frac{25}{3} I_{DC} R_{AC} \left\{ 4(P_{0.5} - 1) + (1 - Q_{-1.0}) - 4(1 - Q_{-0.5}) - (P_{1.0} - 1) \right\}}{\text{Fundamental}}$$

In order to minimize calculation, a succession of excitation voltages each twice as large as the previous one was initially selected. In this way the maximum for one excitation voltage became the mid-point for the succeeding one.

It was found, however, that insufficient points were obtained in this manner and two additional excitation voltages were calculated, the values eventually used being 0.06, 0.12, 0.18, 0.24, 0.36, and 0.48 peak volts.

To demonstrate a distortion calculation, take $I_{DC}\ R_{AC} = 10^{-2}$ volt, $R_{DC}/R_{AC} = 20$ and applied voltage = 0.36 volt peak. From Fig. 6,

$$C\ I_{DC}\ R_{AC} = 0.00221 \text{ volt}$$

$$P = 22.5$$

and $$Q = 0.03$$ (from calculations used for plotting Q lines.)

In the plotting of the half-excitation points, i.e. $\Delta E = 0.18$ volt, the value of $C\ I_{DC}\ R_{AC}$ remains unchanged at the value determined for $\Delta E = 0.36$ volt since the integrated biasing effect due to the whole waveform of the applied signal, i.e. the factor C, is the same. This requirement to calculate P and Q for one value of applied signal, from a value of $C\ I_{DC}\ R_{AC}$ determined from a different value of signal was one of the requirements in the designing of the nomogram, Fig. 6.

Thus for the half-excitation points $C\ I_{DC}\ R_{AC} = 0.00221$ volt,

$$P = 5.47$$

and $$Q = 0.17$$

Therefore,

Fundamental (peak volts)

$$= 0.36 - \frac{0.00221}{3}(21.5 + 4.47 + 0.83 + 0.97)$$

$$= 0.3395$$

Second Harmonic (%)

$$= \frac{25 \times 0.00221}{0.3395} \quad (21.5 - 0.97) *$$

$$= 3.34$$

Third Harmonic (%)

$$= \frac{50 \times 0.00221}{3 \times 0.3395} \quad (8.94 + 1.66 - 0.97 - 21.5) *$$

$$= 1.29$$

Fourth Harmonic (%)

$$= \frac{25 \times 0.00221}{3 \times 0.3395} \quad (17.88 + 0.97 - 21.5 - 3.32) *$$

$$= 0.32$$

Total rms Distortion (%) $= \sqrt{3.34^2 + 1.29^2 + 0.32^2}$

$$= 3.6$$

Since the applied voltage is 0.36 volt peak and the signal at the grid is 0.36 - 0.0205 volt peak

$$\text{damping} = \frac{0.0205}{0.360}$$

$$= 0.48 \text{ db.}$$

* = Phase neglected.

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GRID CIRCUIT DISTORTION

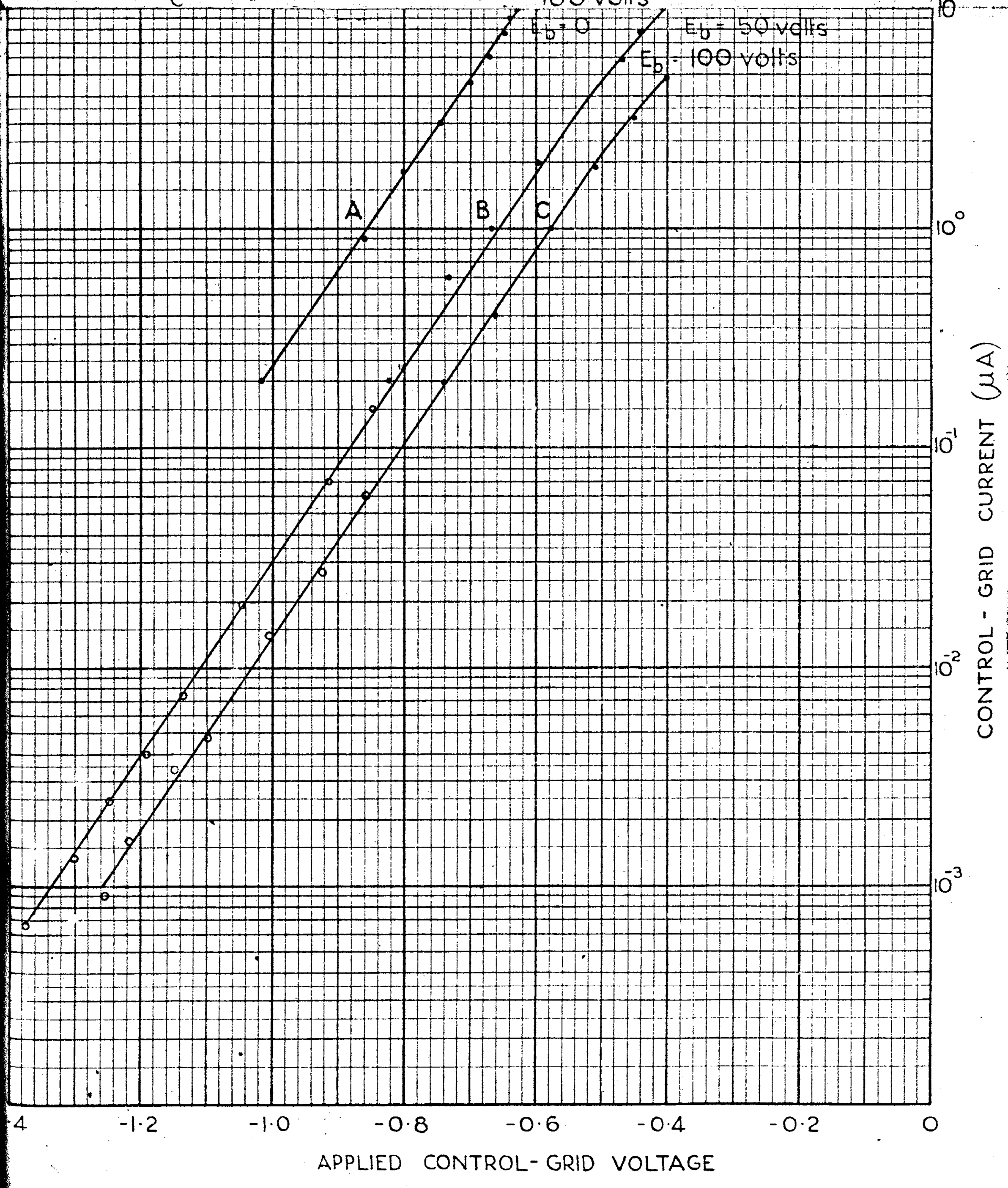
Fig. 1

6AU6 Grid characteristic E_f = 6·3 volts

A : Plate & screen voltage = 0

B : " " " = 50 volts

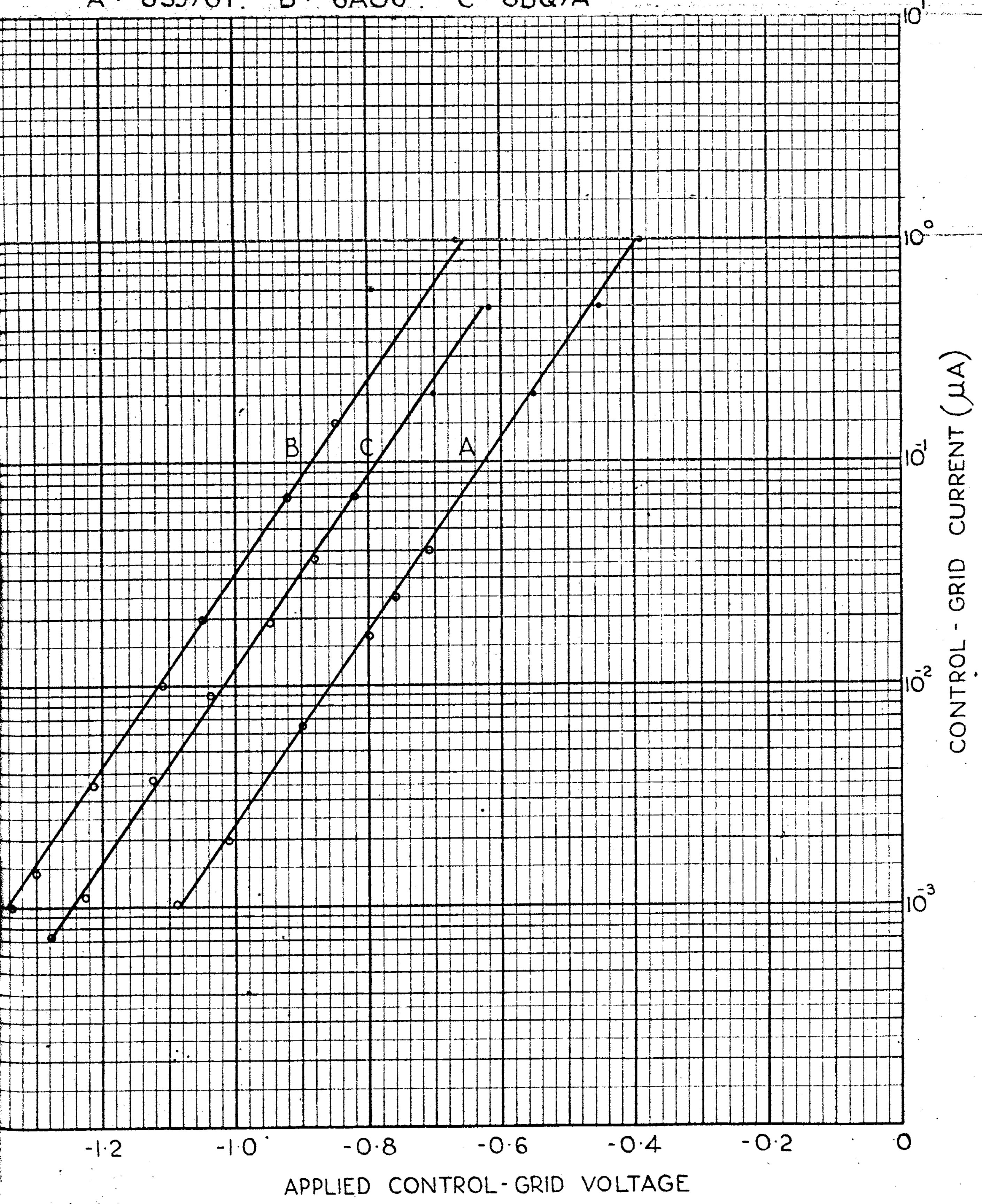
C : " " " = 100 volts



GRID CIRCUIT DISTORTION

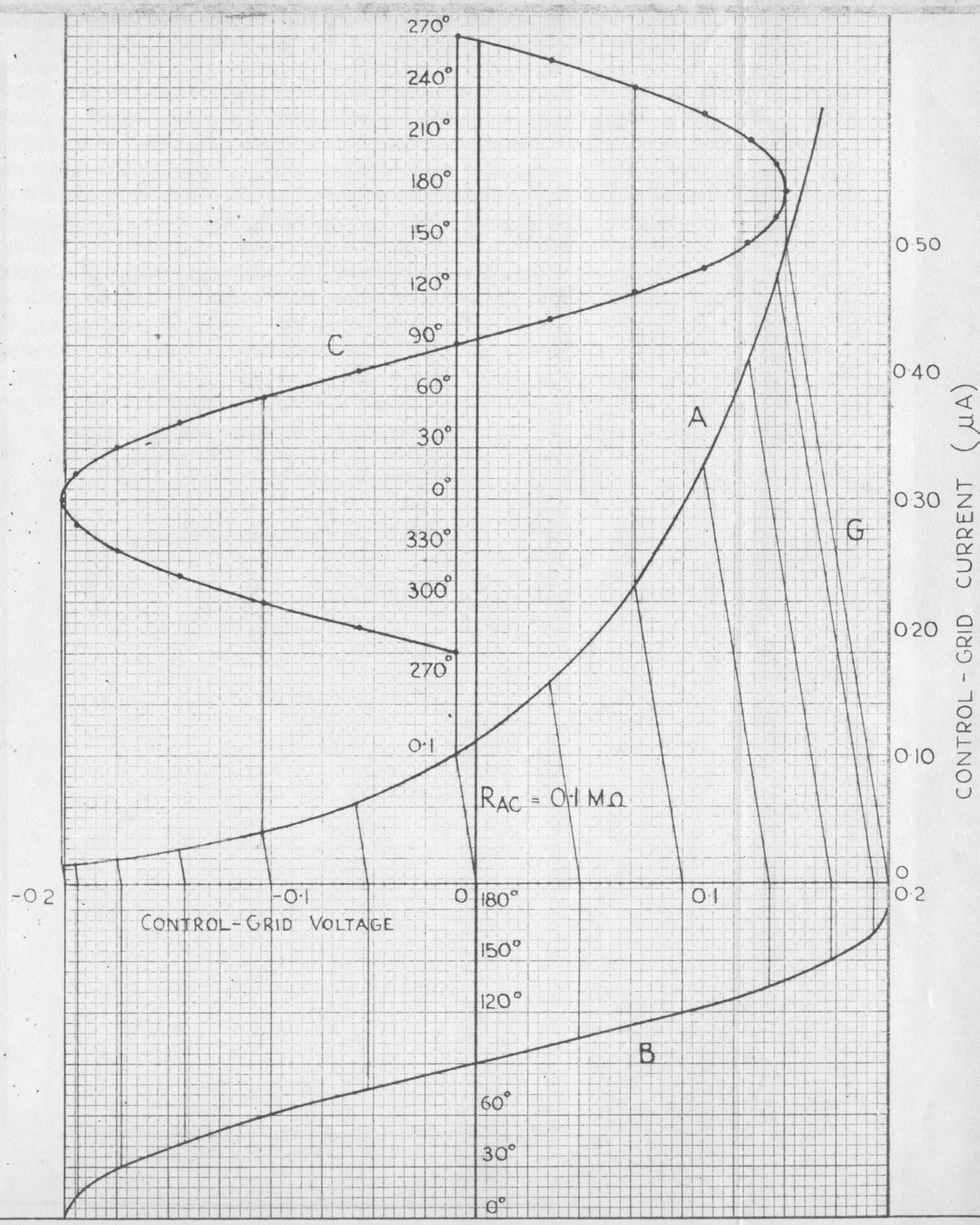
Fig 2.

Control Grid characteristics of triode-connected valves with Ef = 6·3 volts, Eplate = 50 volts
A : 6SJ7GT. B : 6AU6. C : 6BQ7A



GRID CIRCUIT DISTORTION Fig. 3

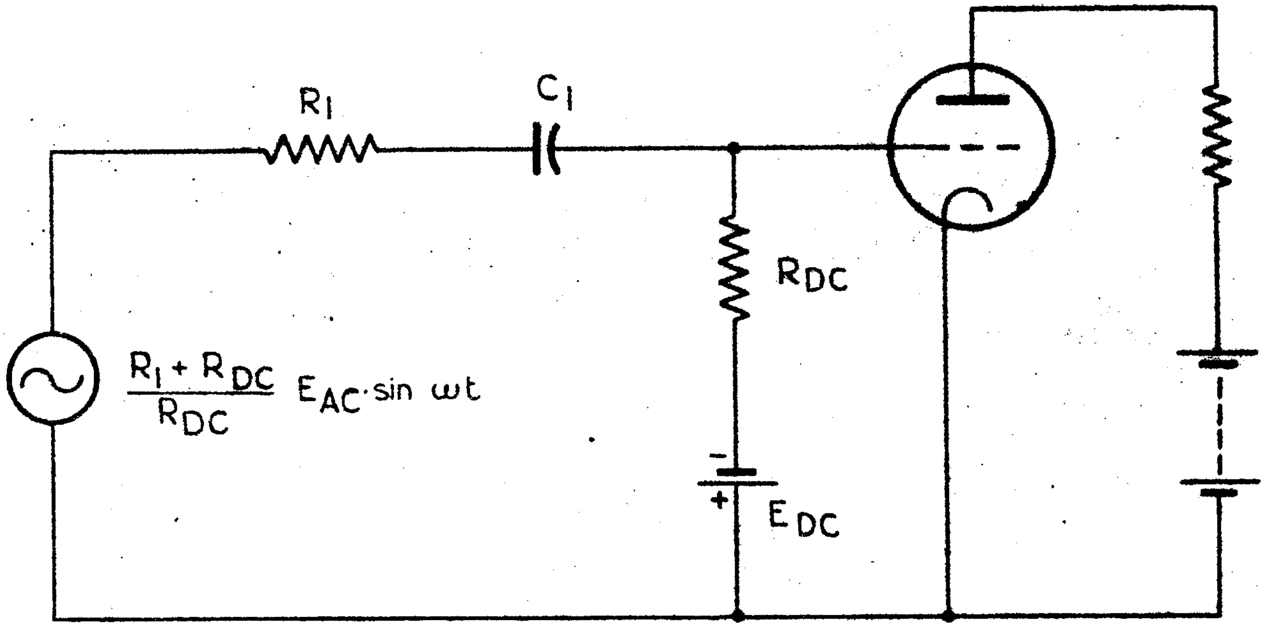
GRAPHICAL ILLUSTRATION OF GENERATION OF GRID - CIRCUIT DISTORTION



GRID - CIRCUIT DISTORTION

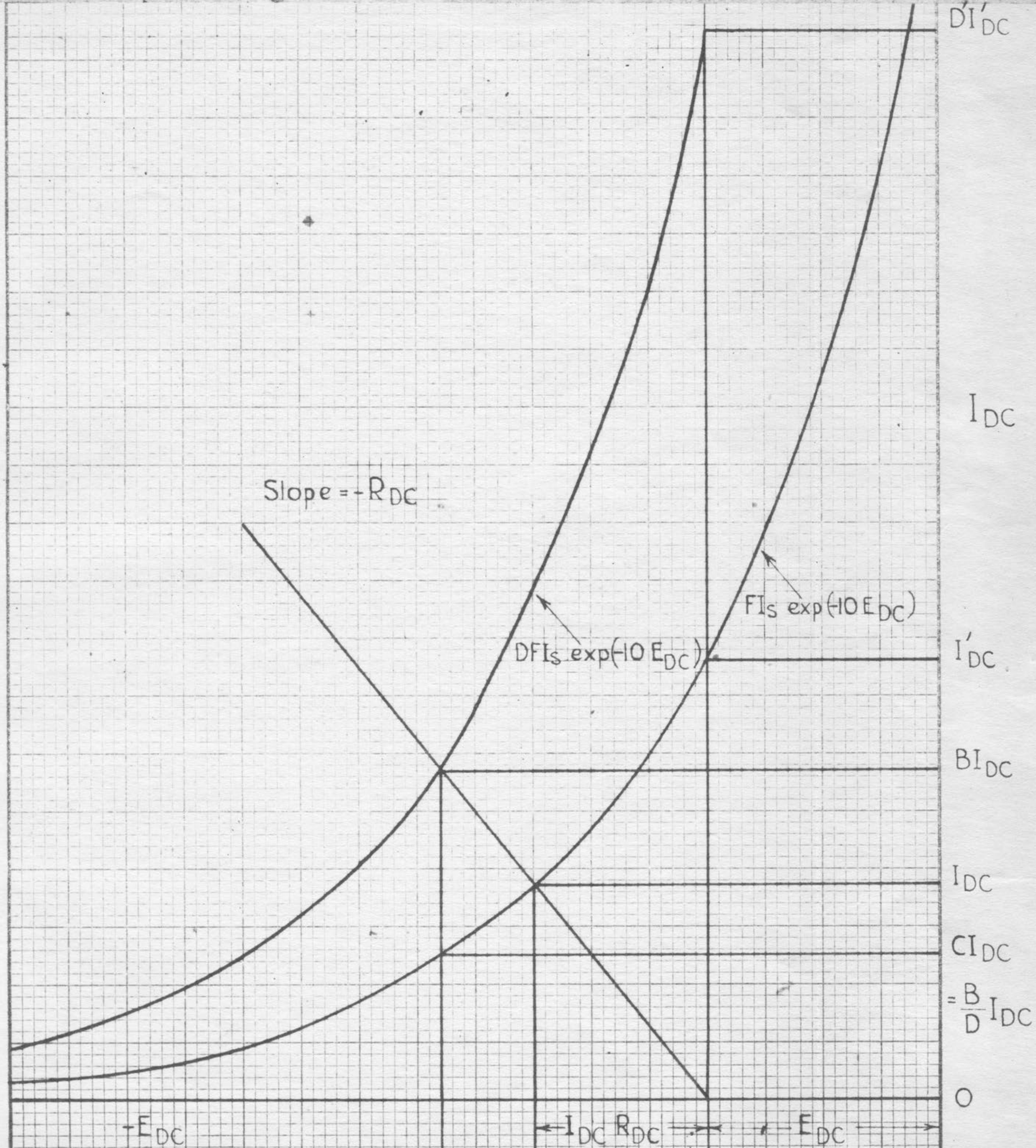
Fig. 4.

CIRCUIT OF AUDIO - FREQUENCY AMPLIFIER



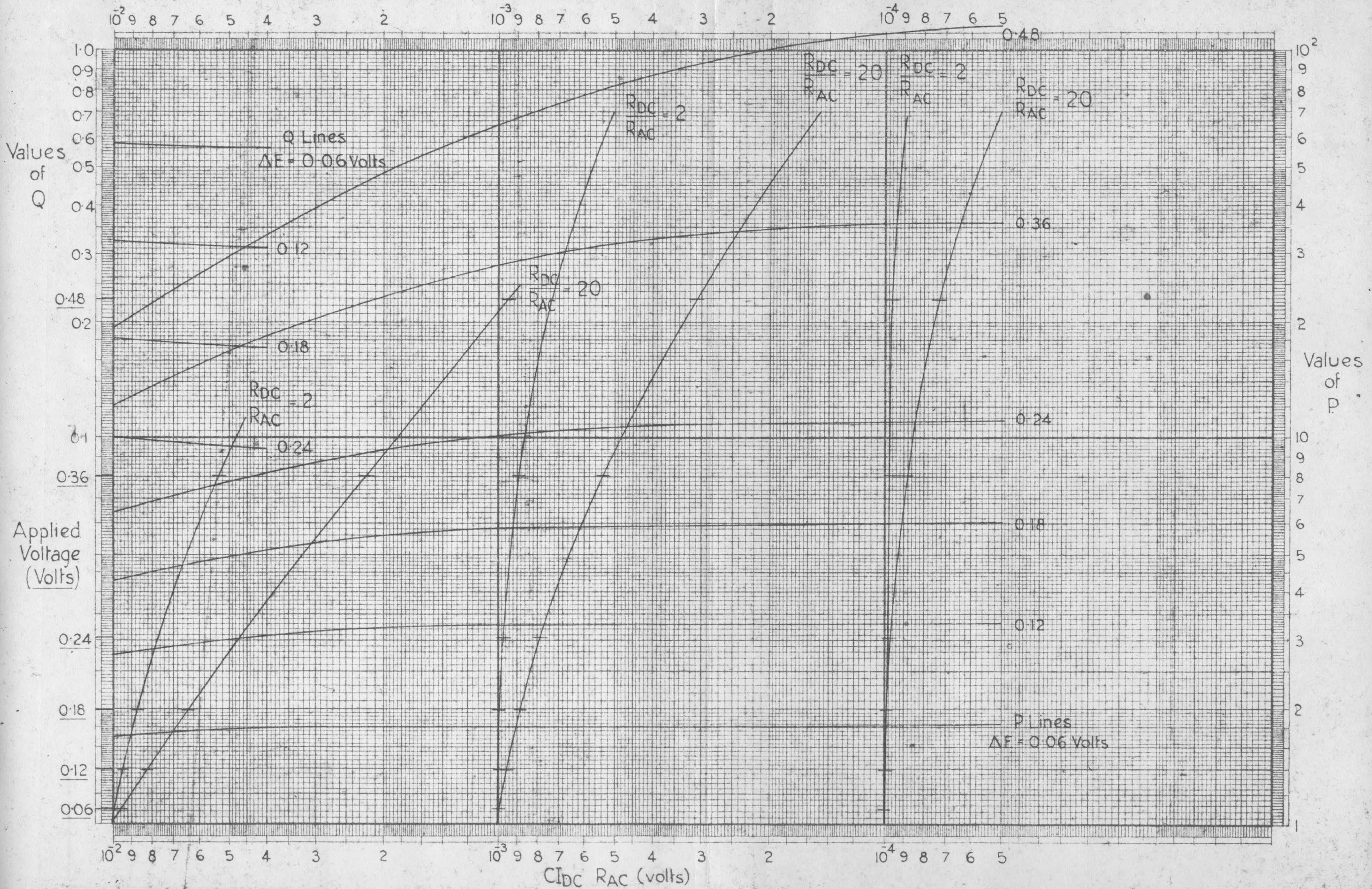
GRID CIRCUIT DISTORTION   Fig. 5.

GRAPHICAL REPRESENTATION OF CONTROL GRID - VOLTAGES AND CURRENTS



GRID CIRCUIT DISTORTION   Fig. 6.

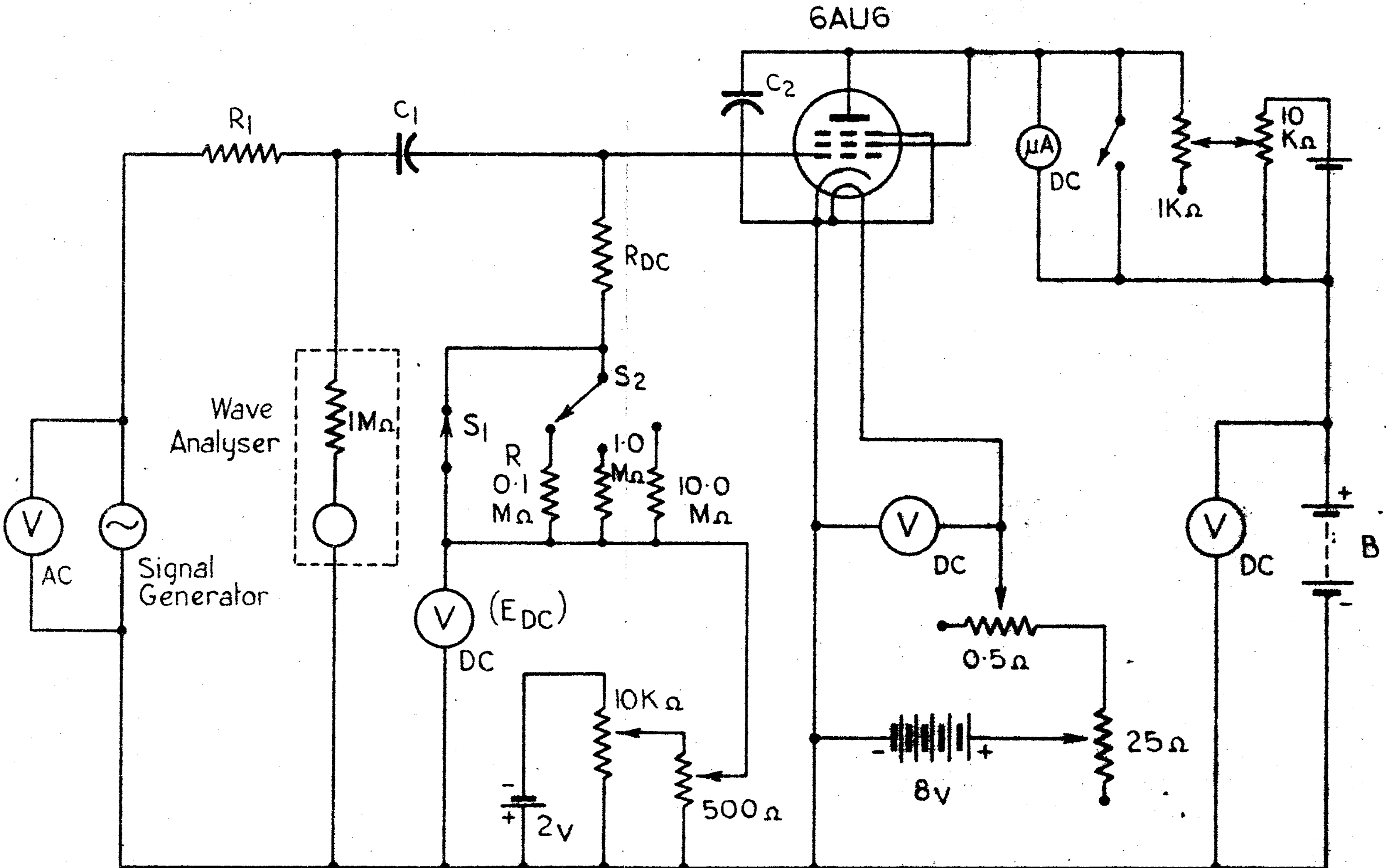
NOMOGRAM FOR EVALUATION OF FACTORS C, P & Q



GRID CIRCUIT DISTORTION

Fig. 7

CIRCUIT FOR MEASUREMENT OF GRID-CIRCUIT DISTORTION



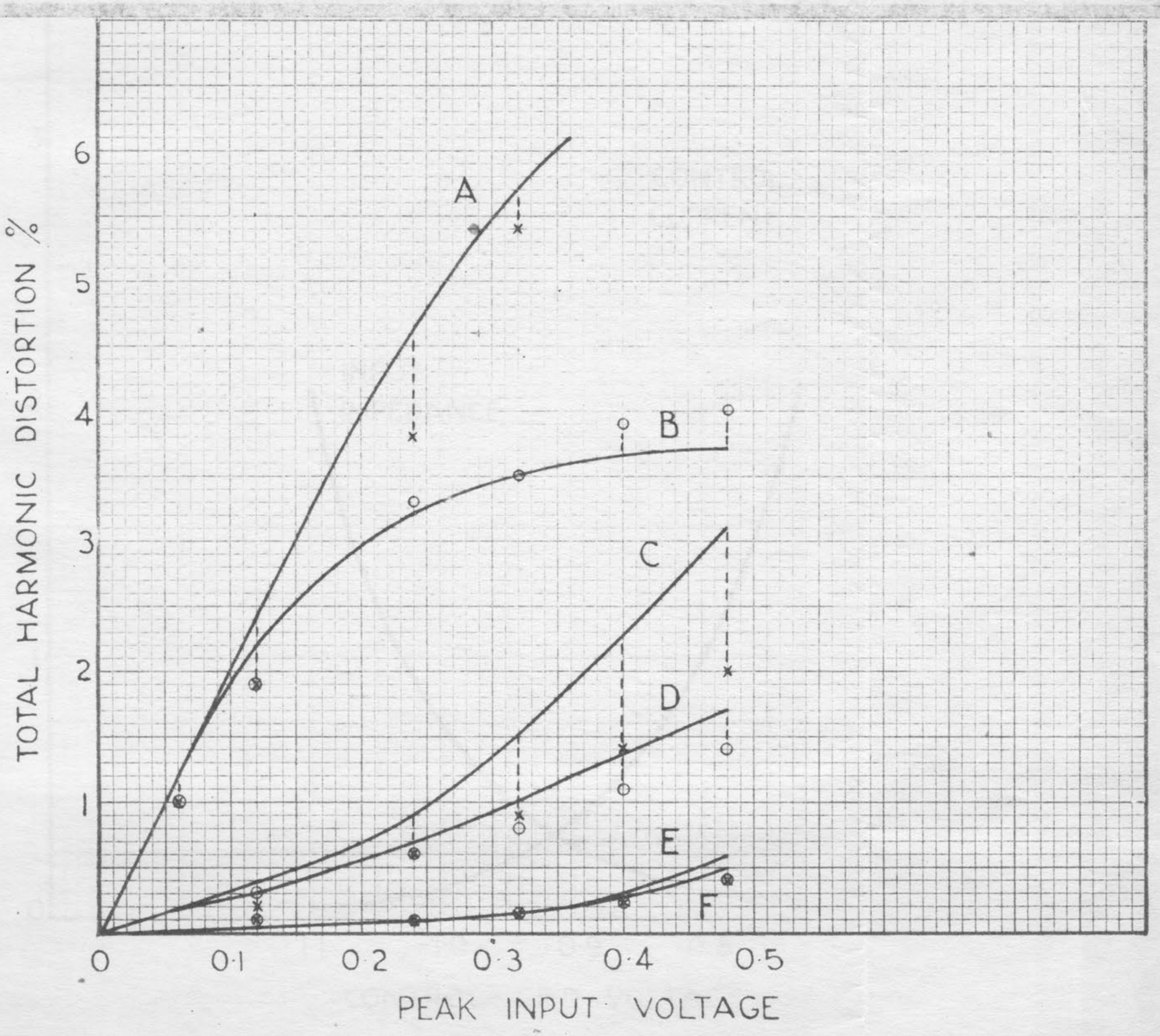
GRID CIRCUIT DISTORTION

Fig. 8

CALCULATED & MEASURED VALUES OF TOTAL GRID-CIRCUIT HARMONIC DISTORTION

(MEASURED VALUES SHOWN × AND ○)

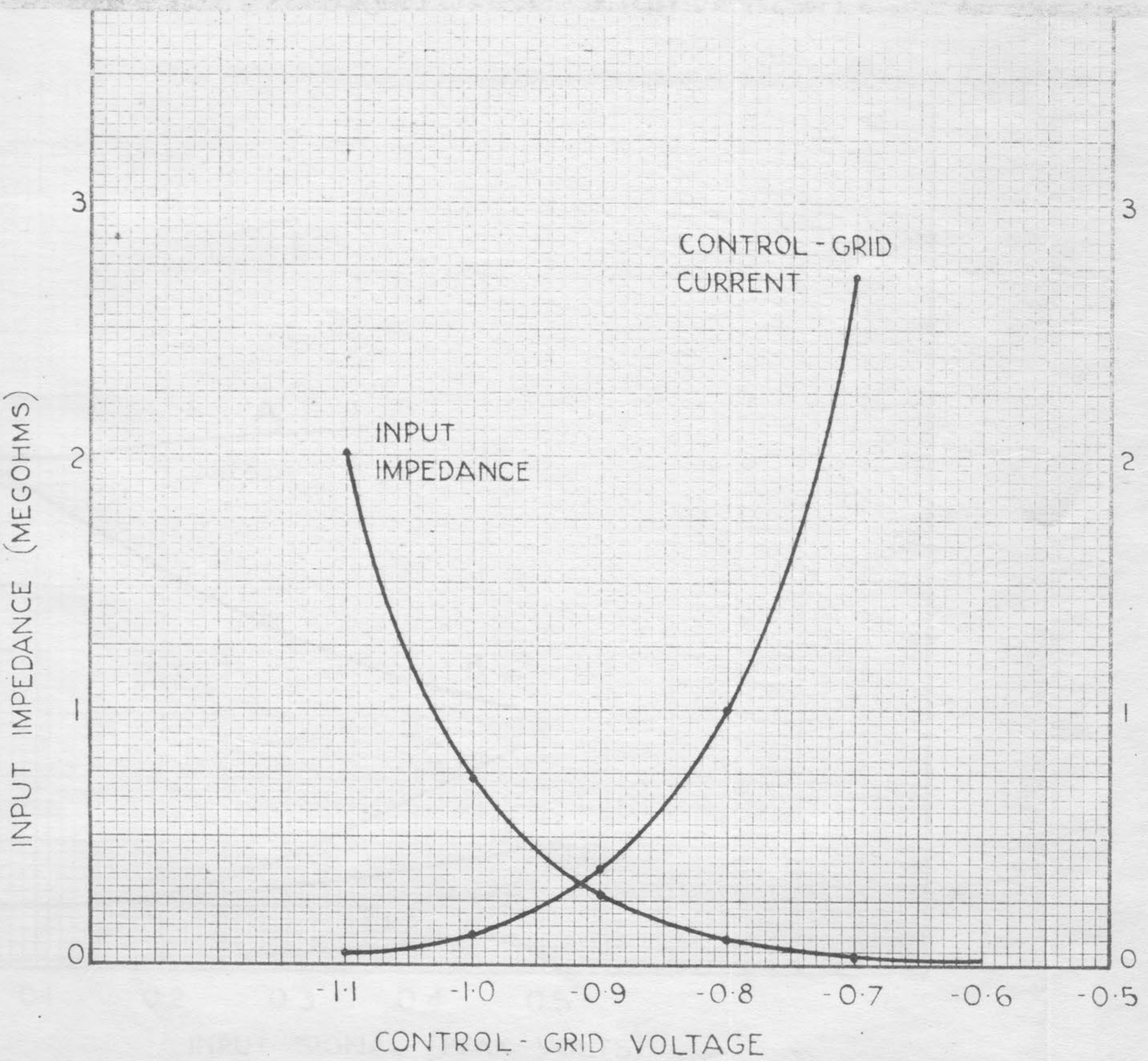
CURVE	R_{DC}/R_{AC}	$I_{DC}\,R_{AC}$ (VOLT)
A	2	10^{-2}
B	20	10^{-2}
C	2	10^{-3}
D	20	10^{-3}
E	2	10^{-4}
F	20	10^{-4}



GRID - CIRCUIT DISTORTION

Fig. 9.

MEASURED INPUT IMPEDANCE AND CONTROL-GRID CURRENT PLOTTED AGAINST CONTROL-GRID VOLTAGE

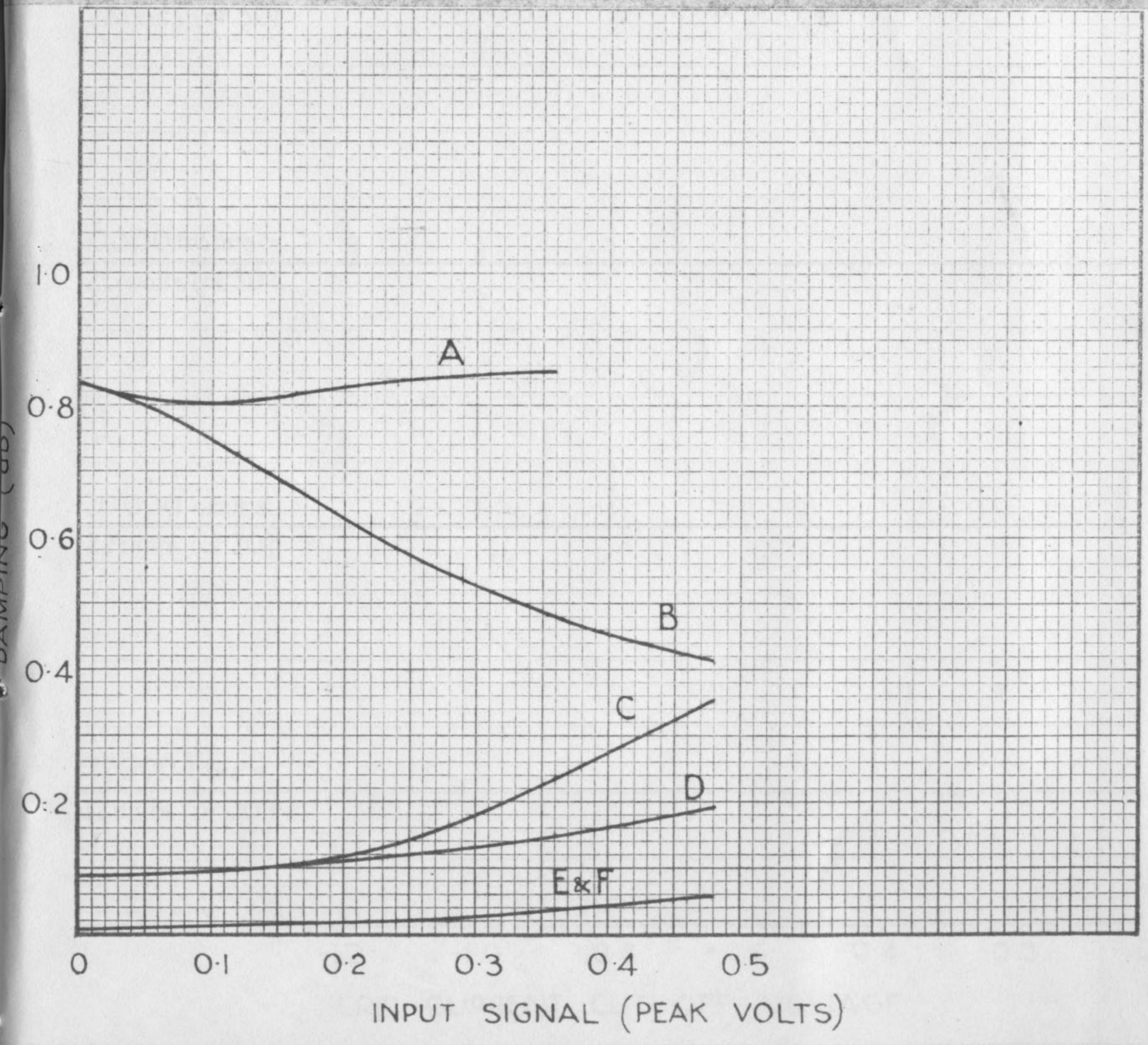


GRID CIRCUIT DISTORTION

Fig. 10

CALCULATED VALUES OF SIGNAL DAMPING

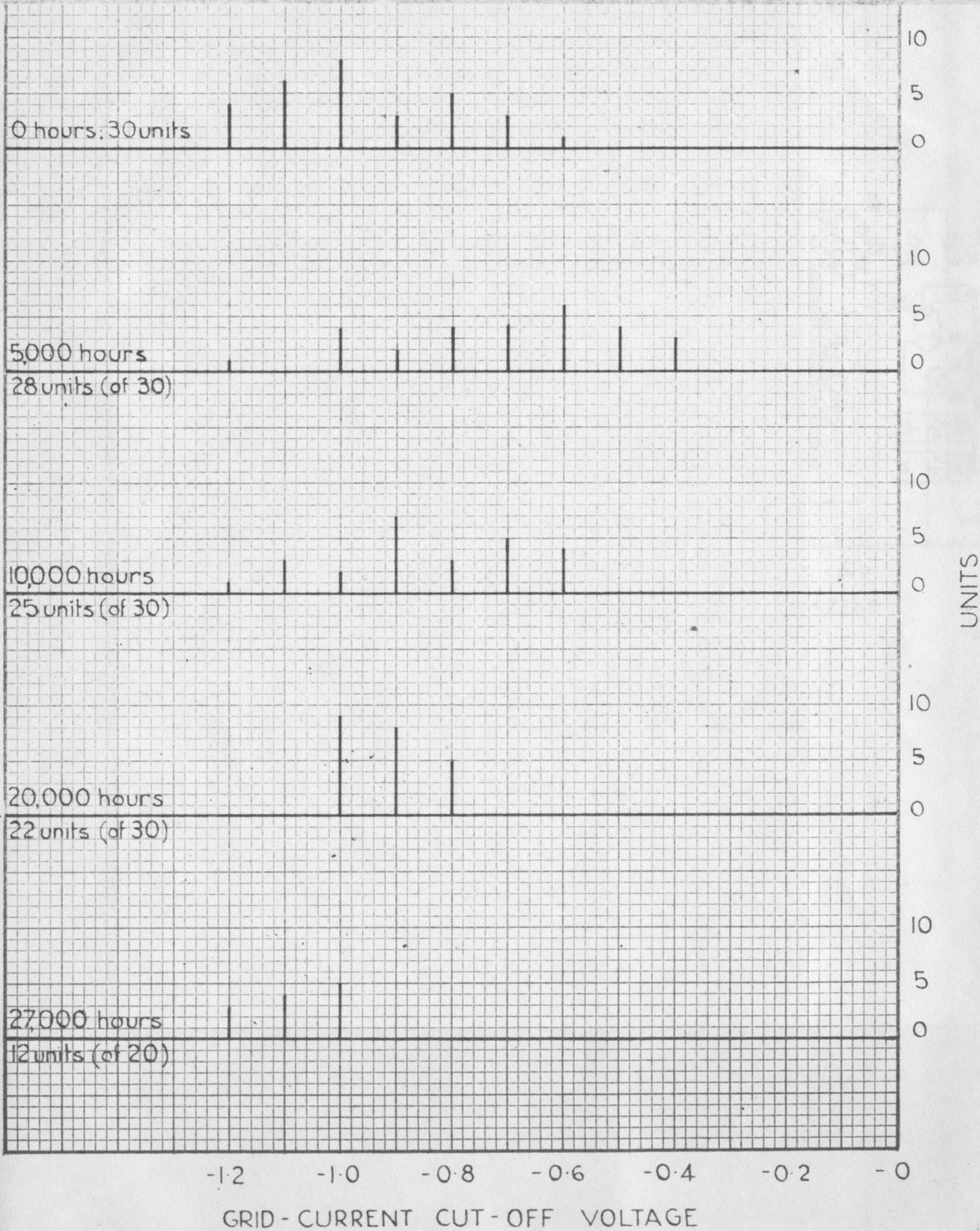
CURVE	R_{DC}/R_{AC}	$I_{DC}\,R_{AC}$ (VOLT)
A	2	10^{-2}
B	20	10^{-2}
C	2	10^{-3}
D	20	10^{-3}
E	2	10^{-4}
F	20	10^{-4}



GRID CIRCUIT DISTORTION

Fig. 11.

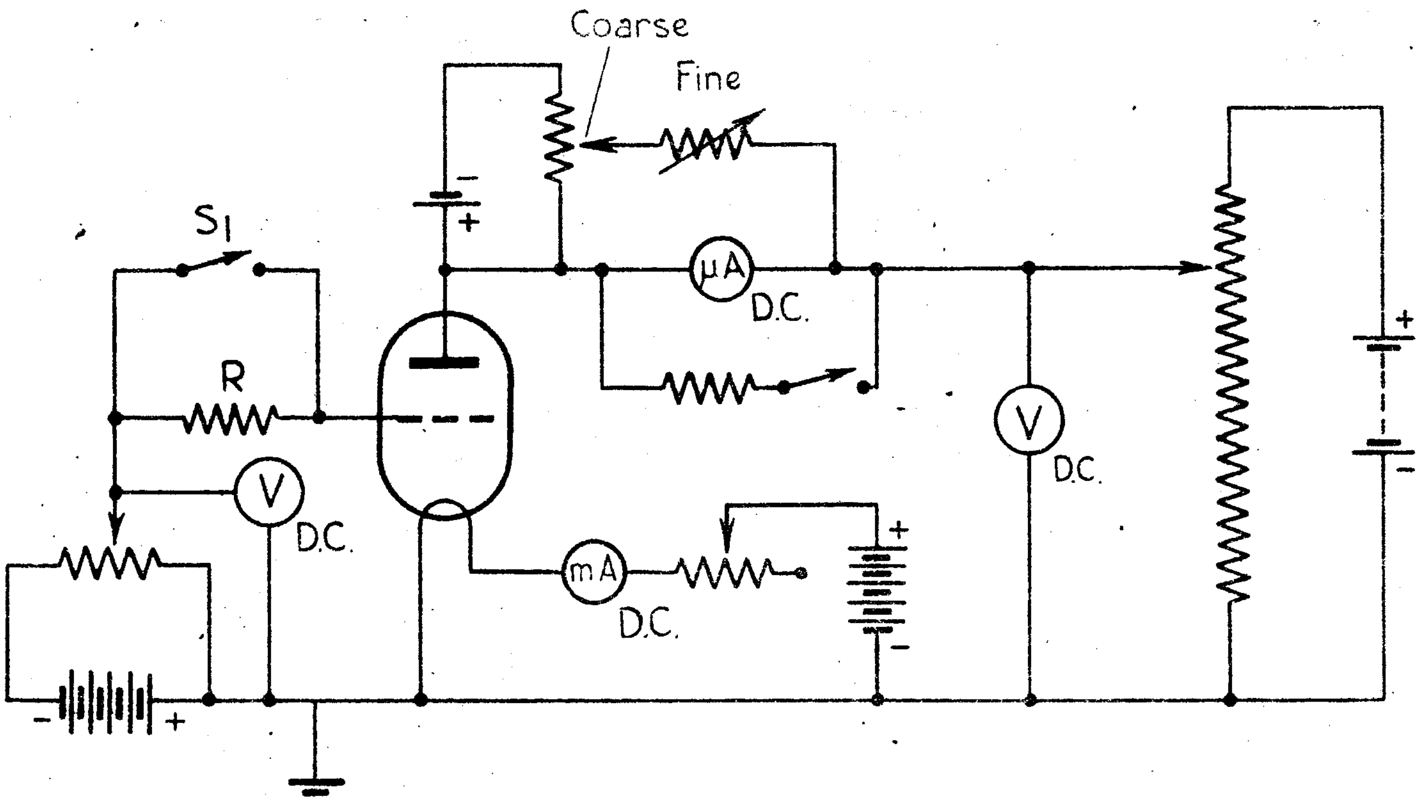
VARIATION OF GRID-CURRENT CUT-OFF VOLTAGE DURING LIFE-TEST



GRID CIRCUIT DISTORTION

Fig. 12.

CIRCUIT FOR MEASUREMENT. OF RETARDING-FIELD
CONTROL-GRID CURRENT



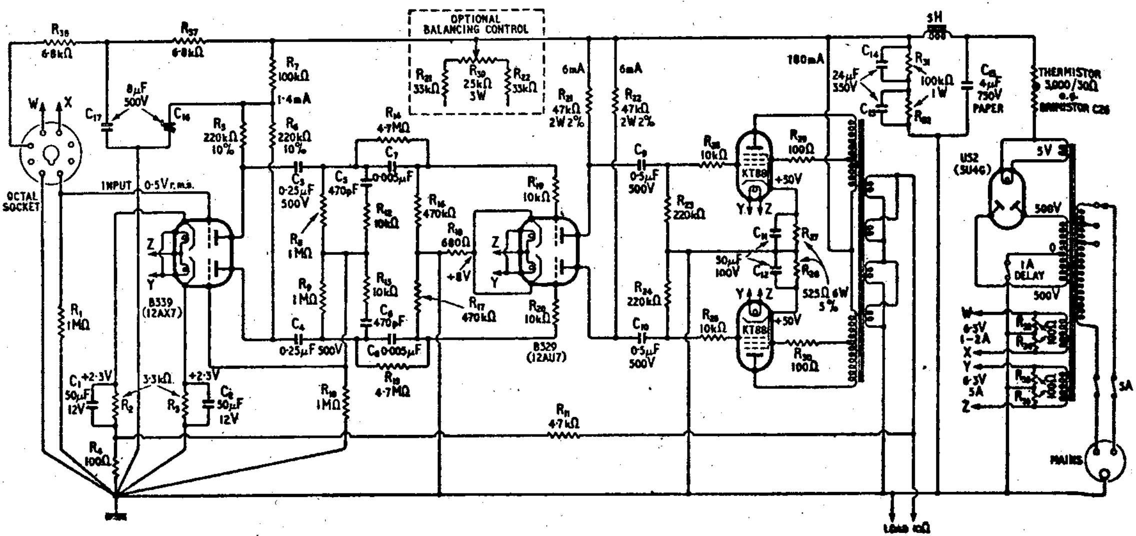


Fig. 13 Circuit of Fifty-Watt Amplifier