A METHOD OF REDUCING THE HARMONIC DISTORTION IN AUDIO AMPLIFIERS

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S U M M A R Y

A method of introducing harmonic distortion into an audio amplifier, by means of a non-linear device, of such nature as to compensate for the harmonic distortion, intrinsic to certain types of power output tubes, is described. Details of the design of a model, which was constructed to enable experimental testing of the theory and the results of this testing are also given.

CONTENTS

SECTION I

I N T R O D U C T I O N

Towards the end of 1946 the author was employed on the development of a series of high fidelity theatre amplifiers in the laboratories of the Electronics Division of the Northern Electric Co. These amplifiers were required to meet the new Academy of Motion Picture Arts and Sciences' standard of less than 2% harmonic distortion at rated power output over the frequency range 50-5000 c.p.s. in production and it had been decided that laboratory models would have to have less than 1% over this range in order to provide a safe margin for the shop.

Considerable difficulty was encountered before the 1% figure was achieved and one of the obstacles to running down the sources of distortion was found to lie in the fact that distortion cancellation between stages takes place in much the same fashion as hum cancellation occurs. It was at this time that the idea of making use of distortion cancellation to improve the performance of amplifiers suggested itself.

A method of doing this was devised, a model was built and experimental verification was obtained. The circuit was made the subject of a patent application which, however, was turned down on the grounds that there was "no patentable novelty". This was probably due to the circuit, patented by G. C. Crisson and outlined as item (3) of Sect.II of this paper, which uses the same principle.

Since Mr. Crisson had an entirely different purpose in mind and since the work described in the following was carried out before the author was aware of Mr. Crisson's patent, it is felt that sufficient originality exists to justify submission of this paper as thesis material.

SECTION II

H I S T O R I C A L   O U T L I N E

While it is well know that harmonic distortion in audio amplifiers can be reduced, e.g. cancellation of even harmonics is one of the advantages of the push-pull amplifier, a search of the published literature has failed to reveal any papers dealing with this subject. However, a number of U.S. patents have been granted to the inventors of circuits designed for this and similar purposes and a review of these in chronological order follows by way of historical outline.

(1) U.S. pat. 1,464,111, 7 Aug 23 Harry S. Read

Fig. (1) shows two identical amplifiers V1 and V2. Potentiometer P1 is adjusted so that the signal voltage applied to the grid of V2 is equal to that applied to the grid of V1 in magnitude. Under these conditions even harmonics generated in V2 will be 180° out of place with those appearing at the plate of V2 from amplification of those generated in V1 and equal in magnitude to them. Thus complete cancellation of even harmonics occurs. Odd harmonics, however, will be additive.

(2) U.S. pat. 1, 613,927, 11 Jan 27, O.E. Buckley

Two identical vacuum tube amplifiers have their grids connected in parallel and their plates connected in push-pull. The grid bias of one is made greater than that of the other, so that its Eg-Ip characteristic is displaced to the left as shown in Fig.(2). Since the grids of the tubes are connected in parallel, the combined Eg-Ip characteristic is the difference between the two and thus the curvature is to some extent rectified and harmonic reduction is therefore effected.

(3) U.S. pat. 1,737,830, 3 Dec 29, G.C. Crisson.

The non-linearity of the diode is used to achieve volume compression by by driving D1 and D2 shown on Fig.(3) with an undistorted current, obtained by applying the signal through a large resistance to these diodes. The compressed signal is then transmitted through the system to the receiving end where it is applied to D3 and D4 through a low resistance so that volume expansion is obtained across the low resistance and an undistorted output results. This arrangement was said to be of value in that it will enable transmission at a higher mean level, without overloading the system and would thus reduce the effects of noise.

(4) U.S. pat. 1,864, 670, 28 Jun 32, F.W. Reynolds.

Fig.(4) shows a photo-cell coupled to the grid of a vacuum tube amplifier. The photo-cell output Eg, appearing across Rg, will not, it is stated, increase linearly with increase of light intensity. However, since Ip increases at more than linear rate with increase of Eg, Ip will approximate linear increase with increase of light intensity.

(5) U.S. pat. 1,990,062, 5 Feb 35, R. A. Braden.

There is stated to be a minimum of second harmonic distortion in pentodes and a minimum of third harmonic distortion in triodes as their grid bias is varied. As the bias is shifted from one side to the other of this point the phase of the harmonic is reversed. If two tubes are connected in parallel, biased to each side of the minimum, substantial reduction of these harmonics is claimed.

(6) U.S. pat. 2,070,407, 16 Mar 37, F.L. Dechant.

Refer to Fig.(5). Vacuum tubes Y,Y are connected in a conventional class B amplifier circuit. Flat-topping occurs because of the effect of grid current drawn by the grids of tubes Y,Y. Tubes X,X are operated with a relatively greater bias than tubes Y,Y and therefore only conduct during the periods when grid current is being drawn by tubes Y,Y. The additional current drawn by tubes X,X during this period compensates for the flat-topping referred to above.

(7) U.S.pat.2,379,699, 3 Jul 45, John R. Ford.

Refer to Fig. (6). Resistances R1 and R 2 together with amplifier V1 complete a bridge and are adjusted so that the point A is at ground potential for the signal. This bridge is not balanced, however, for the harmonics generated by V1 and consequently they appear between A and ground. If they are fed to V2, in proper magnitude, it is claimed that the phase reversal, which occurs in V2 will lead to complete harmonic cancellation across the load resister R_L.

SECTION III

T H E O R Y

Fig.(7) shows the operating line of a non-linear resistive device. If an operating point Eo, Io is chosen and the device is excited by a constant current generator of sinusoidal current, the voltage appearing across the device will be non-sinusoidal. If this voltage is applied to another non-linear device with the same characteristic it is clear that the current produced in the second device will be sinusoidal.

This statement can easily be proved analytically. Let I_1 (sin wt) be the current applied to the non-linear device and let Z_1 (Io,I1) be the impedance of the device: Then a voltage will be produced across the device as

$$E_1 = I_1 Z_1$$

If this voltage is now applied to a second device of similar characteristic that is to say of impedance $Z_2 = K.Z_1$, where K is any constant, then a current will be produced in the second device as

$$I_2 = \frac{E_1}{Z2} = \frac{I_1 Z_1}{K Z_1} = \frac{I_1}{K}$$

Therefore I_2 will be sinusoidal.

This principle can be used to effect cancellation of harmonic distortion, introduced in a vacuum tube amplifier as a result of non-linearity of its operating line. Fig. (11) shows the Eg - Ip characteristic of the 6L6G, used in the experimental part of this work. If this tube is driven by a sinusoidal signal, its non-linearity will produce the output waveform shown on Fig. (13). However, if the tube is driven by a non-sinusoidal voltage of the type shown on Fig. (15), it is clear that the enlarged and peaked negative half cycle will compensate for the flattened negative half cycle of Fig. (13). Such a pre-distorted waveform of exactly the right shape to effect complete cancellation of the distortion introduced by the 6L6G can be obtained by driving a diode, with exactly the same shape of operating line as that of the 6L6G, with a sinusoidal current.

Fig.(8) shows a simplified schematic of a circuit which provides a suitable arrangement of the diode connected into the grid circuit of the power output tube. R1 must be large compared to the dynamic resistance of the diode D1 to ensure that the current produced by the signal source Es will remain sinusoidal. C1 is required to prevent the polarizing D.C. applied to D1 from the battery B1 from entering the signal source and C2 is required to perform the same function in respect of the grid of the power output tube V1. Should the integrals of the two half cycles of voltage appearing across D1 differ, the output voltage of D1 would assume a different axis after passing through C2. This could be compensated for, however, at full output by a change in the grid bias of V1. This compensating change in grid bias would be too large at smaller signal voltages,but this would probably not be too serious, since the operation of both D1 and V1 becomes more linear as the signal voltage is decreased.

The problem is thus reduced to finding a diode with the desired shape of operating line. This problem can be simplified by foregoing the use of the portion of the 6L6G characteristic above its top bend, without appreciably decreasing the available power output. This is so , since the full current range of the tube yields a peak to peak output current of 135 ma., which does not appreciably exceed the peak to peak output current of 125 ma., which is obtained if the tube is operated over the range 5-130 ma. A second reason for restricting the operating range lies in the difficulty, which would be encountered in trying to obtain stable compensation in regions where a minute change in input current to the diode must produce an appreciable change in its output voltage.

SECTION IV

CIRCUIT DESIGN AND ADJUSTMENT

While the desirability of obtaining the diode characteristic to the same scale as the grid voltage scale of the 6L6G characteristic was appreciated, it was decided, since it was not possible to attempt the design of a suitable diode, to be content with obtaining the desired characteristic at low voltage and to make use of a two stage amplifier (so as not to invert the diode output) to adjust the output voltage to the value required to drive the 6L6G.

It was further decided to employ a type 6Sk7 as the diode, making use of its remote cut-off characteristic and its grid and screen voltages as variables that might enable adjustment of its characteristic to match that of the 6L6G.

Fig. (9) shows a schematic diagram of the test amplifier, which was constructed for the experimental part of their work. Fig. (10) shows a photograph of it, together with the test equipment, used.

V1 is the 6Sk7, operated as a diode with screen and plate voltages and cathode resistor variable. The by-pass condenser on the screen prevents change in its voltage as the input signal goes through its cycle. The cathode resistor was left un-bypassed, since its voltage was free to change during static measurements of the diode operating characteristic and therefore required the same freedom when the diode was under the influence of a signal. Condenser C1 blocks D.C. from the signal source. Resistor R1 is large compared to the dynamic resistance of V1, which is about 2000 ohms and therefore ensures that V1 will be driven from a constant current generator and will therefore have a sinusoidal current passed through it. R3 prevents the impedance of the power supply from shunting the diode and also is large enough to ensure stability of the polarizing current, passed through V1. S1 is provided to permit switching of the diode out of circuit, thereby permitting operation of the amplifier in conventional fashion. V2 and V3 comprise a conventional two stage voltage amplifier, provided with a volume control P3. V4 is the 6L6G output tube, provided with variable grid bias by means of P4. It was decided to use a direct resistive load with the plate current passing through it, since this eliminated possibilities of error, which a conventional output transformer would have introduced as a result of its losses and variation with frequency of the impedance presented to the tube. The type of operation chosen for the 6L6G was class A1 with fixed bias of - 18 volts, screen voltageof 250 volts, plate voltage of 350 volts and load resistance of 4200 ohms. The plate supply voltage, required to provide for the drop in the load resistance was 600 volts. Switch S2 was provided to enable a multi-range Weston model 322 D.C milliameter to be switched into the plate circuit of V1 and the screen and plate circuits of V4. Voltage measurements were made by means of a Weston model 772 analyzer.

The procedure used to set up the circuit will now be detailed.

First, the Eg-Ip characteristic of the 6L6G was obtained by varying its grid voltage and keeping its screen and plate supply voltages constant at 250 volts and 600 volts respectively. This curve is plotted as Fig.(11). As explained above the plate current range was chosen as 5 ma. to 130 ma. Assuming sinusoidal output current, this would require an operating point midway between these extremes or at 67.5 ma. of plate current, corresponding to a grid bias of 16.3 volts. The ratio of the negative grid voltage departure, required to swing to 5 ma. of plate current, to the positive grid voltage departure, required to swing to 130 ma. of plate current, was then obtained from Fig. (11) as $\frac{37.0 - 16.3}{16.3 - 6.0} = \frac{20.7}{10.3} = 2.01$

A number of static curves were then run for the 6SK7 diode, plots of which are shown on Fig.(12). First, with the cathode resistor R2 set at 0 ohms, curves were obtained for different values of screen voltage by varying the plate supply voltage applied to the diode by means of P2, thereby varying the current passing through the diode, and reading the values of voltage obtained across the diode. In each case the screen voltage was maintained constant at the chosen value by means of P1. Second, the same procedure was followed with the screen voltage maintained at 50 volts and with different values of the cathode resistor R2.

The extent to which these curves matched the Eg-Ip curve of the 6L6G was then tested on a trial and error basis as follows. First their general shape was considered, which led to rejection of those with R2 set at 500 and 1000 ohms because of the comparatively abrupt manner in which their slopes changed from that of the mid-range to that of the tail. The curve with the screen voltage set at 25 volts was also rejected because of its lack of curvature. Then, choosing different operating points and different amplitudes of input of sinusoidal current, the peak values of the resulting positive and negative half cycles of voltage appearing across the diode were taken off the remaining curves. The ratios of these peak values were then taken and compared to the figure of 2.01 obtained from the 6L6G curve. This led to the conclusion that the best curve would be obtained with the cathode resistor R2 set to 0 ohms and with the screen voltage at some value between 50 and 75 volts. However, since increase of the screen voltage much above 50 volts caused the screen dissipation to rise above its rated maximum, in view of the low plate voltage, and since the curve with screen voltage of 50 volts yielded a ratio of 1.90, when the operating point was set at 0.75 ma. with a peak value of applied current of 0.75 ma., it was decided to proceed with this curve.

It was now necessary to determine the D.C. component of the output waveform of thediode, so as to enable an adjustment to the grid bias of the 6L6G to restore it, since it would otherwise be lost through the coupling condensers between the diode and the 6L6G. This was done by developing the diode's output waveform, shown on Fig. (14) by applying a sinusoidal current of 0.75 ma. peak to the chosen diode characteristic and establishing the D.C. component by averaging over a cycle one half the difference between the number of squares in the positive and negative half cycles. The value so obtained was -0.12 volts, which, when multiplied by the ratio of the positive swing required at the grid of the 6L6G to the positive swing appearing across the diode gave a required correction of $-0.12 \times \frac{10.3}{1.25} \doteq 0.98$ volts.

The two stage voltage amplifier was next tested to ensure that it was free from distortion. Its frequency response was found to be within 0.5 db. down at 50 c.p.s. and 20,000 c.p.s., with respect to 1000 c.p.s. and its harmonic distortion less than 1% from 50 c.p.s. to 10,000 c.p.s. with an output voltage of 16 volts R.M.S. These measurements were made with a Hewlett Packard model 205AG audio oscillator, a Hewlett Packard model 330B distortion analyzer and a Ballantyne model 300 vacuum tube voltmeter.

The circuit was then considered ready for setting up, which was carried out as follows. First, the plate supply, screen and grid voltages of the 6L6G were set to 600,250 and -17.3 volts respectively, the grid voltage of -17.3 volts being required rather than the chosen figure of -16.3 volts in order to restore the D.C. component of the input waveform. Next, the diode cathode resistance R2 was set to 0 ohms, its screen voltage to 50 volts by means of P1 and its operating current to 0.75 ma., by means of P2. The input signal required from the oscillator to drive the diode with a signal of 0.75 ma. peak was then calculated as follows.

The dynamic resistance of the diode at its operating point was obtained from Fig.(12) as $\frac{\Delta E}{\Delta I} = \frac{2.25-1.8}{0.25} \times 1000 = 2000$ ohms

The total input resistance was therefore 49,000+2,000 = 51,000 ohms and the required input voltage was therefore

$$\frac{0.75 \times 51{,}000}{1.41 \times 1{,}000} = 27.2 \text{ volts, R.M.S.}$$

The oscillator was then connected to the input of the amplifier and its output adjusted to 27.2 volts at 1000 c.p.s.

It was then necessary to adjust the gain of the two stage voltage amplifier so as to ensure application of the correct amplitude of signal to the grid of the 6L6G. Since this signal was non-linear, it was necessary to do this on a peak to peak basis by using a calibrated oscilloscope. The oscilloscope used was a R.C.A. model 155A. The procedure was as follows. First the loading effect of the oscilloscope on the 6L6G grid was determined by observing that it reduced the output voltage in the ratio of 48.5 to 50.0 or 0.95. Then the peak to peak value of voltage required at the grid of the 6L6G was obtained from Fig.(11) as 31 volts. This voltage would be reduced to 0.95 x 31 or 29.5 volts with the oscilloscope connected to the 6L6G grid. The R.M.S. value of a sinusoidal voltage with peak to peak value of 29.5 volts is $\frac{29.5}{2 \times 1.41} = 10.4$ volts R.M.S. . Accordingly the oscillator was connected to the oscilloscope and, with its output voltage adjusted to 10.4 volts at 1000 c.p.s., the gain of the oscilloscope amplifier was adjusted so that the peak to peak magnitude of the trace on the oscilloscope screen was 20 divisions. The oscillator was then returned to the input of the amplifier and with the oscilloscope connected to the grid of the 6L6G, the gain control P3 was adjusted to give an amplitude of waveform on the oscilloscope screen of 20 divisions.

The output of the 6L6G was then measured by means of the Ballantyne vacuum tube voltmeter (which had been fitted with an external 3 to 1 multiplier) and was found to be 186 volts. The output harmonic distortion was measured by means of the Hewlett Packard distortion analyzer and was found to be 1.9%, while a similar measurement of the signal applied to the grid of the 6L6G yielded a figure of 13.5%.

The output voltage of 186 volts represents a power output of

$$\frac{186 \times 186}{4200} = 8.25 \text{ watts}$$

The expected output based on the chosen plate current swing 5 ma. to 130 ma. was

$$\left(\frac{125}{2 \times 1.41}\right)^2 \times \frac{4200}{10^6} = 8.19 \text{ watts}$$

SECTION V

T E S T S   A N D   M E A S U R E M E N T S

A number of tests and measurements and harmonic analysis of the more important waveforms were carried out. The results of these are given in this section.

(1) Performance of the amplifier with the diode switched out of circuit.

a) Voltages on 6L6G - E_{bb} - 600 volts
E_p - 350 volts
E_{sg} - 250 volts
E_g - -18 volts

b) P3 on full

c) Input to the amplifier adjusted to give $\frac{18}{1.44}$ = 12.7 volts R.M.S on the grid of the 6L6G at 1000 c.p.s.. On this basis the input voltage to the amplifier was found to be 0.087 volts.

d) A frequency response run was then made, keeping the input voltage at 0.087 volts and reading the output voltage across R12, with results as follows.

Frequ.c.p.s.	50	100	200	500	1000	2000	5000	10,000	20,000
o/p voltage	219	225	228	228	228	228	222	204	185
Relative db.	-0.3	-0.1	0	0	0	0	-0.2	-1.0	-1.8

e) The power output at 1000 c.p.s. was then calculated as

$$\frac{228 \times 228}{4200} = 12.4 \text{ watts}$$

f) The total harmonic distortion was then obtained at the frequencies shown below by means of the Hewlett Packard distortion analyzer.

Frequ.c.p.s	50	1000	5000	10,000
Distortion db Below sig.	17.5	17.5	16.5	15.0
Distortion %	13.5	13.5	15.5	18.0

g) The output waveform was then plotted from the calibrated oscilloscope and is reproduced on Fig.(13).

h) The distortion at 1000 c.p.s. was then measured by means of a G.R. wave analyzer with the following relative amplitudes being obtained.

Frequ. c.p.s.	Rel. Amplitude
1000	100.0
2000	11.6
3000	7.3
4000	4.0
5000	1.5
6000	0.8
7000	0.4
8000	0.0
9000	0.3
10,000	0.3

This gives a total percentage harmonic distortion, neglecting the 5th and higher harmonics of:

$$\frac{\sqrt{11.6^2 + 7.3^2 + 4.0^2}}{100} = 14.3\%$$

i) The theoretically expected waveform was then obtained from the Eg-Ip characteristic of the 6L6G, shown as Fig.(11), by applying a sinusoidal voltage with peak value of 18 volts to it. The curve, so obtained, is reproduced in Fig. (13).

j) Harmonic analysis of the waveform, referred to in (i) above, was then carried out for the D.C., 1st, 2nd, 3rd, and 4th harmonics, with amplitudes and phase angles as indicated below being obtained.

Frequ. c.p.s.	Amplitude Ma.Peak	Phase Angle	%Amplitude
D.C.	9.1	Positive	12.3
1000	74.0	0°	100
2000	4.7	0°	6.7
3000	-9.5	180°	12.8
4000	-4.4	180°	6.0

These components together with their sum are shown plotted on Fig.(17). The percentage harmonic distortion, represented by these components, was then calculated as

$$\frac{\sqrt{4.7^2 + 9.3^2 + 4.4^2}}{74} \times 100 = \frac{11.5 \times 100}{74} = 15.5\%$$

k) The theoretical power output represented by the components in (j) above was then obtained, by first calculating the R.M.S. current as.

$$\sqrt{\frac{74^2+4.7^2+9.5^2+4.4^2}{1.41}} = 52.8 \text{ ma. R.M.S.}$$

The expected power output was therefore

$$\frac{52.8 \times 52.8 \times 4200}{10^6} = 11.8 \text{ watts}$$

(2) Performance of the amplifier with the diode in circuit

a) All voltages, currents and adjustments as in Section IV above; frequency 1000 c.p.s. unless otherwise specified.

b) The voltage waveform across the diode was plotted from the calibrated oscilloscope and is reproduced on Fig. (14).

c) The voltage waveform applied to the grid of the 6L6G was plotted from the calibrated oscilloscope and is reproduced on Fig. (15).

d) The output voltage waveform of the 6L6G was plotted from the calibrated oscilloscope. The output current waveform, obtained by dividing the voltage values by 4200 ohms, the value of the load resistor R12, is reproduced on Fig. (16).

e) The theoretically expected output current waveform, was obtained by multiplying up the values of the diode output waveform, obtained in Sect. IV in the ratio of $\frac{10.3}{1.25}$ (this curve is plotted on Fig.(14) and applying the waveform so obtained to the Eg-Ip characteristic of the 6L6G.

f) The harmonic content of the waveform across the diode, the grid of the 6L6G and the output of the 6L6G were then measured by means of the Hewlett Packard distortion analyzer with the following results.

	Diode	Grid 6L6G	Plate 6L6G
Distortion db Below sig.	17.5	17.5	34.5
Distortion %	13.5	13.5	1.9

g) The waveforms covered in (f) above were then analyzed by means of the G.R. wave analyzer with the following results.

Frequ.c.p.s.	Diode	Grid 6L6G	Plate 6L6G
1000	100	100	100
2000	14.0	14.7	1.8
3000	5.2	5.4	1.3
4000	1.6	1.5	0.3
5000	0.8	0.5	0.3
6000	0.6	0.4	0.7
7000	0.3	0.2	0.3
8000	0.08	0.04	0.03
9000	0.05	0.04	0
10,000	0.1	0.1	0.14

These gave percent harmonic distortions, neglecting 5th and higher harmonics, as follows:

Diode

$$\sqrt{\frac{14^2 + 5.2^2 + 1.6^2}{100}} \times 100 = 15.1\%$$

Grid 6L6G

$$\sqrt{\frac{14.7^2 + 5.4^2 + 1.5^2}{100}} \times 100 = 15.7\%$$

Plate 6L6G

$$\sqrt{\frac{1.8^2 + 1.3^2 + 0.3^2}{100}} \times 100 = 2.2\%$$

h) The theoretical waveform across the diode, obtained from the diode characteristic (shown on Fig.(14)) was then subjected to harmonic analysis for the D.C. component, 1st, 2nd, 3rd and 4th harmonics with results as follows

Frequ.c.p.s.	Amplitude-Volts Peak	Phase	% Amplitude
D.C.	0.25	negative	15.0
1000	1.67	0°	100
2000	-0.28	180°	16.7
3000	0.14	0°	8.3
4000	-0.035	180°	2.1

These components together with their sum are down plotted on Fig.(18).

These give a total percentage harmonic distortion of:

$$\sqrt{\frac{16.7^2 + 8.3^2 + 2.1^2}{100}} \times 100 = 18.5\%$$

i) The distortion was then measured at reduced output levels to check that compensation was not critical as to input signal level with results as follows

Output Volts	Relative db	Distortion db below Signal	Distortion %
186	0	34.5	1.9
132	- 3	39.0	1.1
93	- 6	40.0	1.0

j) The frequency response was the measured at an output level 12 db down from the maximum output, by reducing the input voltage to 6.8 volts, holding the input voltage constant at all frequencies and measuring the output voltage, with results as follows:

Frequ.c.p.s.	50	100	200	500	1000	2000	5000	10,000	20,000
o/p volts	44	45	46	46	46	46	44	39	34
Relative db	-0.4	-0.2	0	0	0	0	-0.4	-1.2	-2.0

k) The distortion at the full output of 186 volts was then measured at different frequencies with the Hewlett Packard distortion analyzer with results as follows:

Frequ.c.p.s.	50	100	1000	5000	10,000
Distortion db Below sig.	25	30	34.5	31	18
Distortion %	5.6	3.2	1.9	2.8	12

SECTION VI

C O N C L U S I O N

With the exception of the theoretical harmonic analysis of the output waveform of the 6L6G, with the diode switched out of circuit, the theoretical results agree with the experimental results as well as may be expected.

In the case of the above descrepancy it is felt that the theoretical hafmonic analysis is more likely to be in error, since the method used was essentially approximate and since the normal ouput of the 6L6G includes a higher percentage of 2nd than of 3rd harmonic.

The measured harmonic analysis of the 6L6G output, with the diode switched out of circuit, shows approximately the same harmonic content as that of the waveform applied to the grid of the 6L6G with the diode in circuit, indicating that components, of the correct magnitude to cancel the harmonic components generated in the 6L6G, are included in the signal applied to its grid. Since the operating range of the 6L6G is different under the two conditions, the equivalence of the two harmonic contents could only be expected to be approximate. It is of course clear that nearly complete cancellation is taking place from a comparison of the measured harmonic contents of the input and output waveforms of the 6L6G.

It is regretted that a theoretical harmonic analysis of the 6L6G output waveform, with the diode in circuit was not feasible, owing to the difficulty of obtaining results of sufficient accuracy to have meaning when the harmonic content is small, without resorting to elaborate methods.

The frequency response of the amplifier with the diode in circuit is reasonably flat showing, as was to be expected, that there is no difficulty with the circuit in this respect. The fact that the distortion at 1000 c.p.s. decreased as the amplifier input was reduced shows that compensation remains adequate at all signal levels up to the maximum value. This was expected, although the adjustment to the grid bias of the 6L6G to restore the D.C. component was too great except at maximum output, since the characteristics of both diode and 6L6G become increasingly linear as the excursions from their operating points are reduced. The performance as regards harmonic distortion with variation of signal frequency was not too satisfactory in terms of high fidelity performance in that the distortion rose to 5.6% at 50 c.p.s. and 12% at 10,000 c.p.s. . This can be explained however by the fact that the falling off of the amplifier gain at these frequencies upset the balance of the circuit, which had had its input voltage and gain adjusted at 1000 c.p.s.. In a practical application of the circuit, as outlined below, the diode would operate at high level directly in the grid circuit of the 6L6G and under these circumstances it is believed that the problem would not arise.

The improvement in performance of the 6L6G over the normal method of operating it with sinusoidal input is quite marked as regards harmonic distortion, the distortion at full output being reduced from 13.5% to 1.9%. Although the power output is less, the difference is seen to be of not too great significance when the ratio of the outputs of fundamental, as distinct from the total outputs, is expressed in db. as

$$10 \log \frac{12.4\,(1-0.135^2)}{8.25(1-0.019^2)} = 1.69 \text{ db.}$$

This difference in power output of fundamental or desired signal is unavoidable since a sinusoidal output current, occupying the full current range of the tube represents a power output of only

$$\frac{67.5 \times 67.5}{2 \times 10^6} \times 4200 = 9.5 \text{ watts}$$

As may be seen from Fig. (17) the greater amplitude of fundamental, obtained with normal operation, is only made possible by the presence of the harmonics, which subtract from the fundamental at those points where the output of fundamental would otherwise exceed the available current range.

The question as to whether this circuit is suitable for use in practical applications has notbeen made a part of this work. It must be appreciated that the circuit relies on a form of balancing action and is therefore critical in the sense that a bridge balance is critical. Thus variation from tube to tube might very well impair its performance. In the case of the diode used in this experiment, the bottom end of its characteristic is negative, due to contact potential, which is quite variable from tube to tube and would therefore cause trouble. However, a diode might very well be designed to match the 6L6G characteristic at a much higher voltage level thus rendering the effectof contact potential negligible.

As regards uses for the circuit, provided the above requirement could be met, it must first be made clear that it offers little or no improvement over the performance of push-pull amplifiers,since in the latter the combined characteristic is made very nearly linear. This would appear to limit its use to domestic radio receivers of low power output, where the cost of a push-pull output stage would be prohibitive. The importance of reducing the harmonic distortion in the output of such receivers has increased with the advent of frequency modulation and the corresponding need of improvement in the performance of such receivers if really high fidelity reproduction is to be achieved. It is felt that the circuit could be incorporated into such receivers with little increase in cost, since the diode could be built into the envelope of the power output tube and could be used as the plate load for the driver stage, which would probably have to be a pentode rather than the conventional high-mu triode, so as to ensure that the diode would be driven by a constant current generator.

It is regretted that there was no time to attempt the design of a suitable diode and to make further tests of the circuit, such as investigating the effect of variations from tube to tube and attempting to find a better operating characteristic for the 6L6G, owing to transfer of the author from the Northern Electric Co. at the end of August, 1947. Investigation of the latter point may well have resulted in increased power output, since the operating line used was chosen by the tube designers on the basis of a compromise between power output and harmonic distortion.

It is wished to express sincere thanks to the Electronics Division of the Northern Electric Co., for having made available the laboratory facilities and material required for this work.

SECTION VII

TABULATION OF READINGS AND CALCULATIONS

With a view to presenting as complete information as possible, following are all readings and calcuations not given in the preceding sections.

(a) Readings from which the Eg-Ip characteristic of the 6L6G, plotted as Fig.(11) were obtained.

Eg-volts	0	-3	-6	-9	-12	-15	-18	-21	-24
Ip-ma.	135	134	130	114	96	76	60	44	33

Eg-volts	-27	-30	-33	-36	-39	-42	-45
Ip-ma.	24	16	10	6.5	3.9	1.9	1.1

b) Readings from which the Ep-Ip characteristics of the 6SK7 diode, plotted on Fig. (12), were obtained.

Esg - 50 volts R2 - 0 ohms

Ip-ma.	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25	0.015
Ep-volts	3.87	3.42	3.05	2.65	2.25	1.80	1.27	0.62	-0.57

Esg - 50 volts R2 - 500 ohms

Ip-ma.	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25	0.032	0
Ep-volts	5.51	4.62	3.99	3.65	3.20	2.75	2.21	1.75	1.0	0

Esg - 50 volts R2 - 1000 ohms

Ip-ma.	2.00	1.75	1.74	1.50	1.25	0.75	0.50	0.25	0.008	0.003	0
Ep-volts	27.2	8.71	7.04	5.35	4.51	3.42	2.89	2.35	1.75	1.02	0

Esg - 25 volts R2 - 0 ohms

Ip-ma.	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25	0.16	0
Ep-volts	7.69	5.57	4.41	3.55	2.82	2.21	1.62	0.81	0.53	-0.54

Esg - 75 volts R2 - 0 ohms

Ip-ma.	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25	0
Ep-volts	2.91	2.52	2.20	1.95	1.65	1.20	0.85	0.21	-0.69

c) Determination of optimum diode curve and operating point.

Esg - 50 volts R2 - 0 ohms

Ip range	Ep range	Ep swings	Ratio
1.75 0.875 0	3.42 2.00 -0.57	1.42 0 2.57	1.81

Ip range	Ep range	Ep swings	Ratio
1.5 0.75 0	3.05 1.80 -0.57	1.25 0 2.37	1.89

Ip range	Ep range	Ep swings	Ratio
1.0 0.5 0	2.25 1.27 -0.57	0.98 0 1.85	1.88

Esg - 75 volts   R2 - 0 ohms

Ip range	Ep range	Ep swings	Ratio
1.0	1.65	0.75	
0.5	0.85	0	1.92
0	-0.69	1.44	

Ip-range	Ep range	Ep swings	Ratio
0.9	1.47	0.62	
0.5	0.85	0	1.4
0.1	-0.4	0.89	

Ip range	Ep range	Ep swings	Ratio
0.985	1.575	0.725	
0.5	0.85	0	2.12
0.015	-0.69	1.54	

d) Performance of the 2 stage voltage amplifier

(1) With P3 on full and 0.125 volts R.M.S. applied to the grid of the first 6J5, the voltage appearing on the grid of the 6L6G was measured with the following results.

Frequ.c.p.s	50	100	200	500	1000	2000	5,000	10,000	20,000
o/p voltage	15.9	16	16	16	16	16	16	15.9	15.1
Relative db.	-0.1	0	0	0	0	0	0	-0.1	-0.5

(2) With the output kept constant at 16 volts R.M.S. the total harmonic distortion was measured by means of the Hewlett Packard distortion analyzer with the following results.

Frequ.c.p.s.	50	1000	5000	10,000
Distortion-db. below sig.	41	42	45	41
Distortion %	0.9	0.8	0.6	0.9

e) Readings from which the waveform, of the output of 6L6G, with the diode switched out of circuit, shown on Fig.(13), was plotted from the oscilloscope.

Oscilloscope time base scale divs.	10	9	8	7	6	5	4	3	2	1	0
Oscilloscope amplitude scale divs.	0	4	7	9	9	9	9	8		←linear→	
Waveform voltages-volts	0	144	252	324	324	324	324	288		←linear→	
Waveform currents-ma.	0	34	61	77	77	77	77	68		←linear→	

Oscilloscope time base scale divs.	1	2	3	4	5	6	7	8	9	10
Oscilloscope amplitude scale divs.	-2.5	-4	-5.2	-5.9	-6.1	-6	-5.8	-5.0	-3.3	0
Waveform voltages-volts	-90	-144	-187	-213	-220	-216	-209	-180	-119	0
Waveform currents-ma.	-21	-34	-45	-51	-52	-51.5	-50	-43	-28	0

The waveform voltages were obtained by determing the oscilloscope sensitivity by means of the oscillator and the Ballantyne voltmeter. This gave a sensitivity of 1 scale div. = 36 volts. The waveform currents were obtained by dividing the waveform voltages by the 6L6G load resistance of 4200 ohms.

f) Development of the output waveform of the 6L6G, with the diode out of circuit, shown on Fig. (13), by applying a sinusoidal voltage of 18 volts peak with a grid bias of -18 volts to the Eg-Ip characteristic shown on Fig. (11)

Phase angle	0	22.5°	45°	90°	135°	157.5°
Input volts	0	6.9	12.7	18	12.7	6.9
Eg-volts	-18	-11.1	-5.3	0	-5.3	-11.1
Ip-ma.	60	100	132	135	132	100
o/p-ma.	0	40	72	75	72	40

Phase angle	180°	202.5°	225°	270°	315°	337.5°
Input volts	0	-6.9	-12.7	-18	-12.7	-6.9
Eg-volts	-18	-24.9	-30.7	-36	-30.7	-24.9
Ip-ma.	60	29	14	6.5	14	29
o/p-ma.	0	-31	-46	-53.5	-46	-31

g) Harmonic analysis of waveform, obtained in (f) above.

This was done by choosing the axis XX, on Fig. (13), as origin so as to eliminate sine terms, and using the value of the ordinate at the points 0°, 45°, 90°, 135°, 180° to obtain the five following equations from the expression

$$I = I_o + I_1 \cos\theta + I_2 \cos 2\theta + I_3 \cos 3\theta + I_4 \cos 4\theta$$

$$74 = I_o + I_1 + I_2 + I_3 + I_4$$
$$72 = I_o + 0.7I_1 + 0 \quad -0.7I_3 \quad -I_4$$
$$0 = I_o + 0 \quad -I_2 + 0 + I_4$$
$$-45 = I_o \quad -0.7I_1 + 0. + 0.7I_3 \quad -I_4$$
$$-55 = I_o - I_1 + I_2 \quad -I_3 + I_4$$

Solution of these gave

I_o = 9.1 ma.

I_1 = 74 ma.

I_2 = 4.75 ma.

I_3 = -9.5 ma.

I_4 = -4.4 ma.

h) Readings from which the oscilloscope waveform of the output of the diode, shown on Fig. (14), was plotted.

Oscilloscope time base scale divs.	10	9	8	7	6	5
Oscilloscope amplitude scale divs.	0	1.4	2.6	3.5	4.4	4.6
Waveform voltage-volts	0	0.4	0.7	1.0	1.2	1.3

Oscilloscope time base scale divs.	4	3	2	1	0
Oscilloscope amplitude scale divs.	4.5	4.0	3.0	1.8	0
Waveform voltage-volts	1.25	1.1	0.8	0.5	0

Oscilloscope time base scale divs.	1	2	3	4	5
Oscilloscope amplitude scale divs.	-1.8	-3.8	-6.0	-8.0	-8.7
Waveform voltage-volts	-0.5	-1.1	-1.7	-2.3	-2.5

Oscilloscope time base scale divs.	6	7	8	9	10
Oscilloscope amplitude scale divs.	-7.5	-5.5	-3.8	-1.8	0
Waveform voltage-volts.	-2.1	-1.6	-1.1	-0.5	0

The waveform voltages were obtained by determing the oscilloscope sensitivity by means of the oscillator and Ballantyne voltmeter. This gave a sensitivity of 1 scale div. = 0.283 volts

(I) Readings from which the oscilloscope waveform of the signal applied to the grid of the 6L6G, shown on Fig. (15), was plotted.

Oscilloscope time base scale divs.	10	9	8	7	6	5
Oscilloscope amplitude scale divs.	0	1.4	2.5	3.5	4.4	4.5
Waveform voltage-volts.	0	3.3	5.9	8.2	10.3	10.6

Oscilloscope time base scale divs.	4	3	2	1	0
Oscilloscope amplitude scale divs.	4.4	3.8	3.0	1.6	0
Waveform voltage-volts	10.3	8.9	7.0	3.8	0

Oscilloscope time base scale divs.	1	2	3	4	5
Oscilloscope amplitude scale divs.	-1.8	-3.6	-6.0	-8	-8.6
Waveform voltage-volts.	-4.2	-8.5	-14.1	-19.8	-20.2

Oscilloscope time base scale divs.	6	7	8	9	10
Oscilloscope amplitude scale divs.	-7.5	-5.5	-3.6	-1.8	0
Waveform voltage-volts	-17.6	-12.9	-8.5	-4.2	0

The waveform voltages were obtained by determing the oscilloscope sensitivity by means of the oscillator and Ballantyne voltmeter, taking into account the reduction of 6L6G output voltage in the ratio of 0.95 owing to the loading effect of the oscilloscope. This gave a sensitivity of 1 scale div. = 2.35 volts.

(j)Readings from which the oscilloscope waveform of the output of the

6L6G, shown on Fig. (16) was plotted.

Oscilloscope time base scale divs.	10	9	8	7	6	5
Oscilloscope amplitude scale divs.	0	3.0	5.1	7.0	8.7	9.0
Waveform voltage-volts	0	87	147	202	252	260
Waveform current-ma.	0	20.7	35.0	48.2	60.0	61.0

Oscilloscope time base scale divs.	4	3	2	1	0
Oscilloscope amplitude scale divs.	8.9	7.5	6.1	3.2	0
Waveform voltage-volts	257	218	176	92	0
Waveform current-ma.	61.3	52	41.9	21.9	0

Oscilloscope time base scale divs.	1	2	3	4	5
Oscilloscope amplitude scale divs.	-3.0	-6.0	-7.8	-9.0	-9.1
Waveform voltage-volts	-87	-173	-225	-260	-263
Waveform-current-ma.	-20.7	-41.2	-53.5	-61.9	-62.7

Oscilloscope time base scale divs.	6	7	8	9	10
Oscilloscope amplitude scale divs.	-8.6	-7.0	-5.1	-2.4	0
Waveform voltage-volts	-248	-202	-147	-69	0
Waveform current-ma.	-59.0	-48.2	-35.0	-16.4	0

The waveform voltages were obtained by determing the sensitivity of the oscilloscope by means of the oscillator and Ballantyne voltmeter. This gave a sensitivity of 1 scale/div = 28.9 volts. The waveform currents were obtained by dividing the voltage values by 4200 ohms, the value of the load resistance R 12.

k) Development of the output waveform of the diode from its Ep-Ip characteristic by applying a sinusoidal current of 0.75 ma. peak and of the output waveform of the 6L6G, by applying the diode waveform, multiplied up in the ratio $\frac{10.3}{1.25}$ to the Eg-Ip characteristic of the 6L6G.

Phase angle	0°	22.5°	45°	90°	135°	157.5°
Diode input-ma.	0	0.28	0.53	0.75	0.53	0.28
Diode Ip-ma.	0.75	1.03	1.28	1.50	1.28	1.03
Diode Ep-volts	1.80	2.25	2.68	3.05	2.68	2.25
Diode o/p-volts	0	0.45	0.87	1.25	0.87	0.45
6L6G input-volts	0	3.7	7.2	10.3	7.2	3.7
6L6G Eg-volts	-16.3	-12.6	-9.1	-6.0	-9.1	-12.6
6L6G Ip-ma.	68	92	113	130	113	92
6L6G o/p-ma.	0	24	45	62	45	24

Phase angle	180°	202.5°	225°	270°	315°	337.5°
Diode input-ma.	0	-0.28	-0.53	-0.75	-0.53	-0.28
Diode Ip-ma.	0.75	0.47	0.22	0	0.22	0.47
Diode Ep-volts	1.80	1.20	-0.55	-0.57	-0.55	1.20
Diode o/p-volts	0	-0.60	-1.30	-2.37	-1.30	-0.60
6L6G input-volts	0	-4.9	-10.7	-19.5	-10.7	-4.9
6L6G Eg-volts	-16.3	-21.2	-27.0	-35.8	-27.0	-21.2
6L6G Ip-ma.	68	43	23	7	23	43
6L6G o/p-ma.	0	-25	-45	-61	-45	-25

l) Development of the harmonic analysis of the voltage waveform across the diode, obtained in (k) above, using the method outlined in (g) above, taking the axis XX on Fig.(14) as origin.

$$1.25 = E_o + E_1 + E_2 + E_3 + E_4$$
$$0.87 = E_o + 0.7E_1 + 0 - 0.7E_3 - E_4$$
$$0 = E_o + 0 - E_2 + 0 + E_4$$
$$-1.3 = E_o - 0.7E_1 + 0 + 0.7E_3 - E_4$$
$$-2.37 = E_o - E_1 + E_2 - E_3 + E_4$$

Solution of these gave:

E_o = -0.25 volts

E_1 = 1.67 "

E_2 = -0.28 "

E_3 = 0.14 "

E_4 = -0.035 "

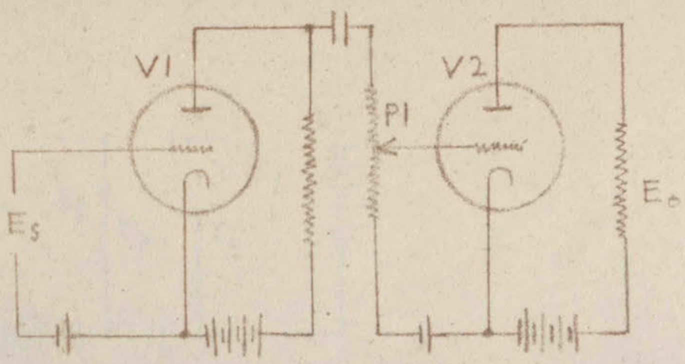


FIG.(1)

FIG.(2)

FIG.(3)

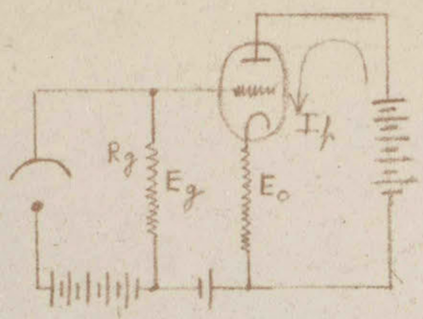


FIG. (4)

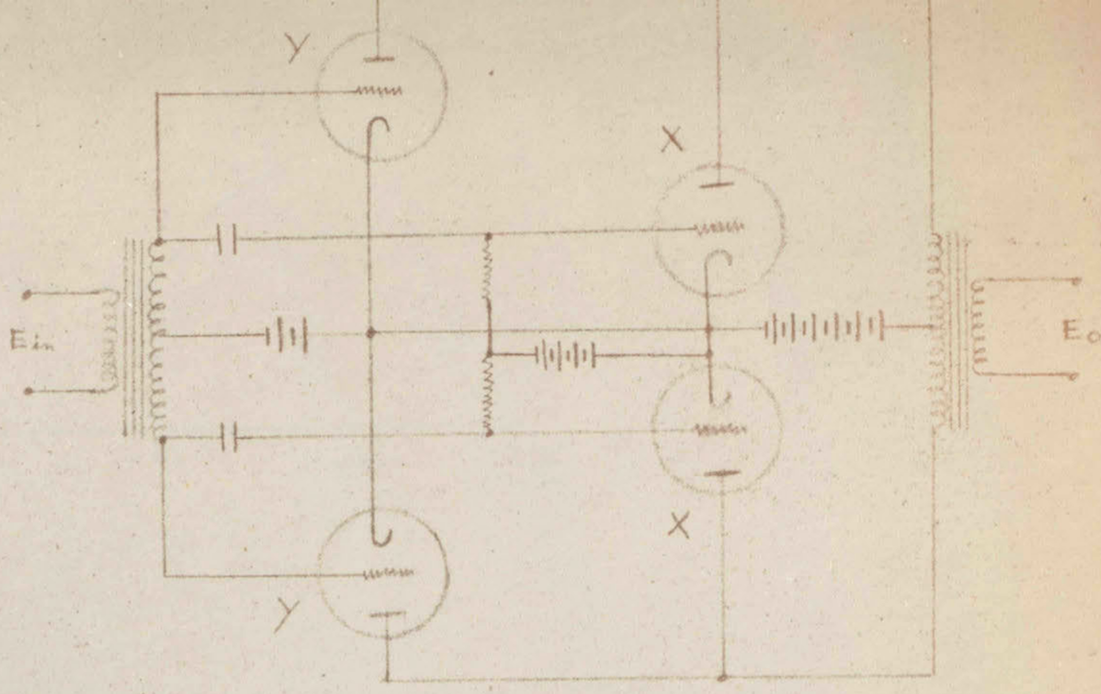


FIG. (5)

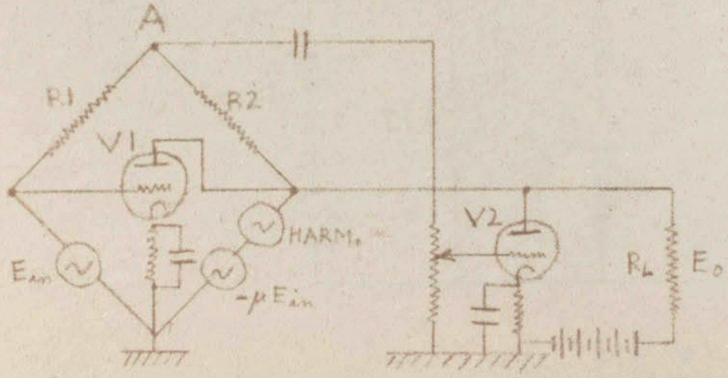
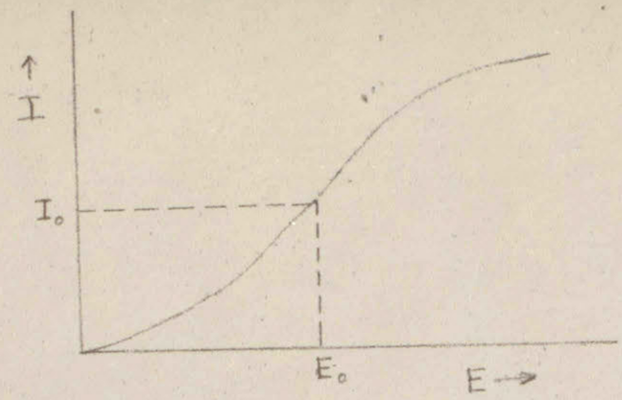


FIG. (6)

FIG.(7)



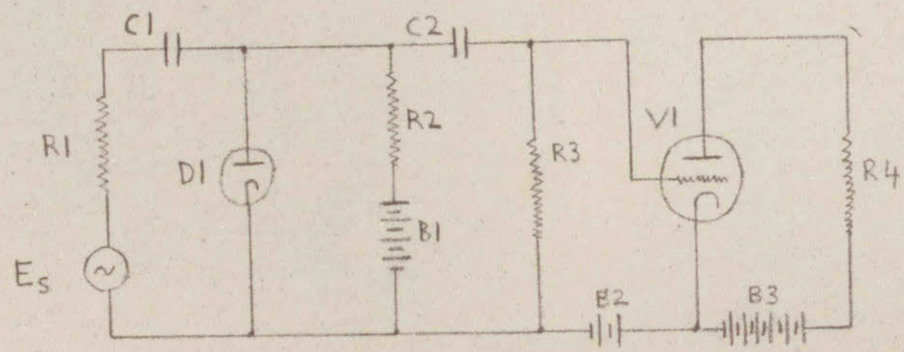


FIG.(8)

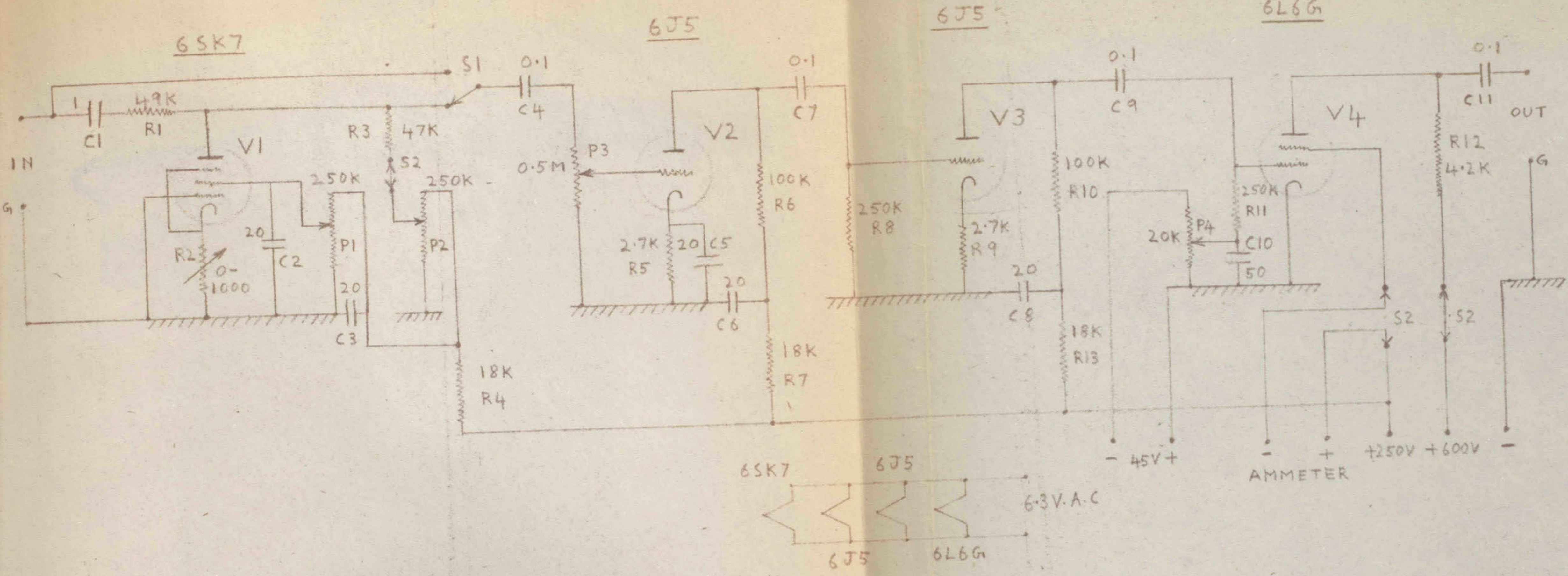

6SK7
6J5
6J5
6L6G
S1
0·1
C4
0·1
C7
0·1
C9
0·1
C11
OUT
IN
G
1
C1
49K
R1
V1
R3
47K
S2
250K
250K
0·5M
P3
V2
V3
V4
100K
R6
250K
R8
100K
R10
R12
4·2K
G
R2
0-1000
20
C2
P1
P2
20
C3
2·7K
R5
20
C5
20
C6
18K
R4
18K
R7
2·7K
R9
20
C8
18K
R13
20K
P4
250K
R11
C10
50
S2
S2
− 45V +
− + AMMETER
+250V
+600V
−
6SK7
6J5
6J5
6L6G
6·3V·A·C

FIG. (9)

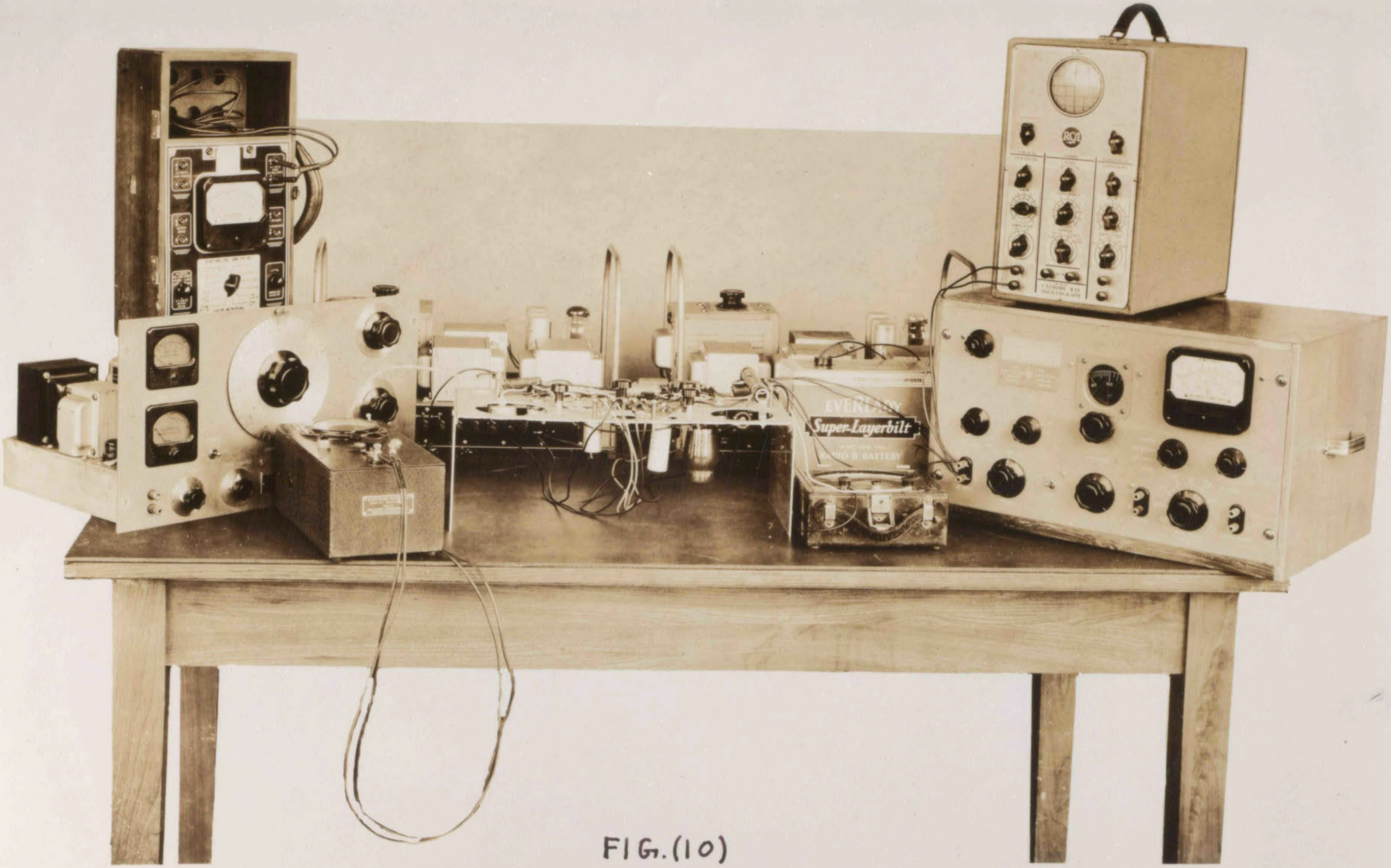


FIG. (10)

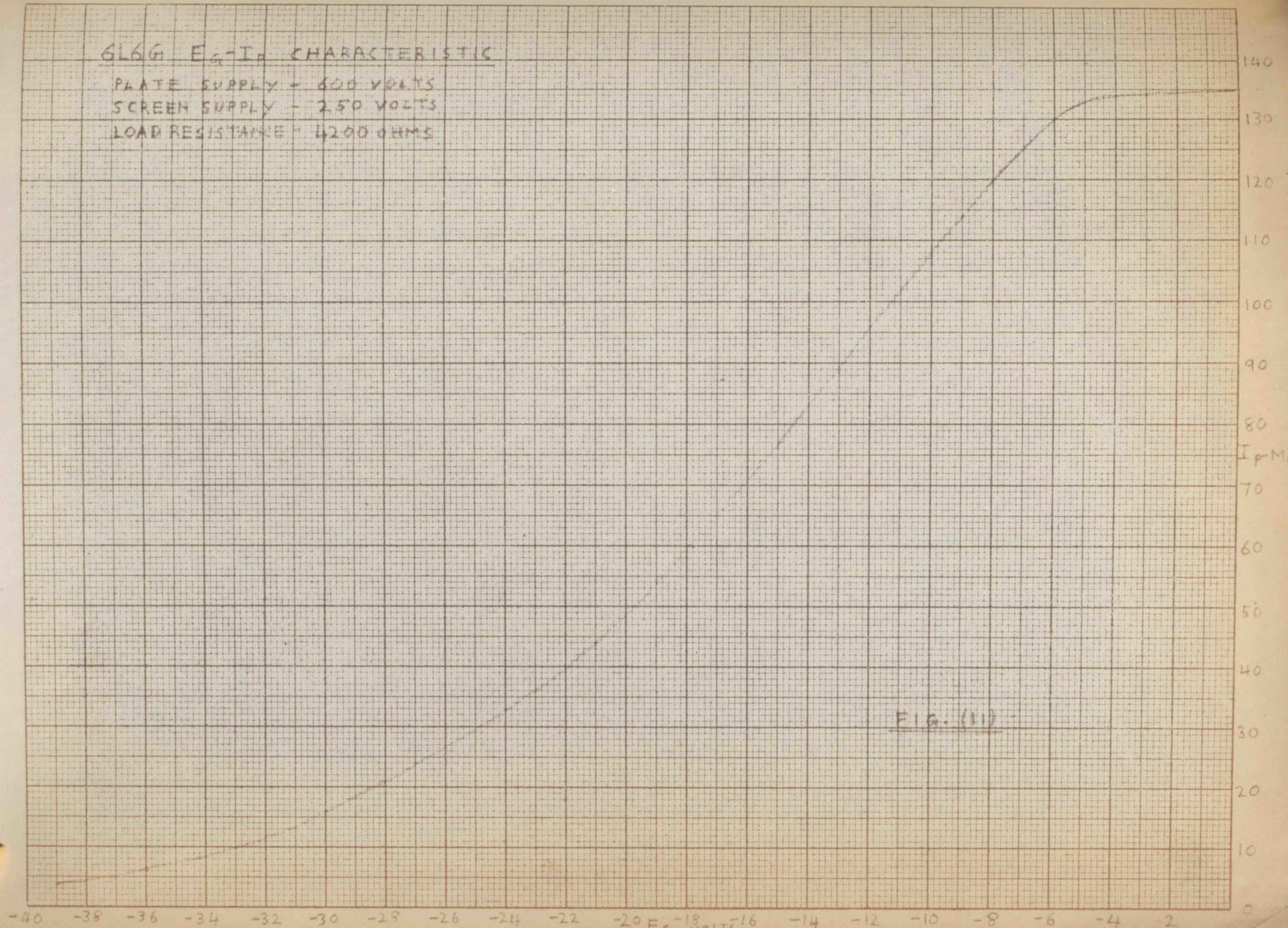

6L6G E_G-I_P CHARACTERISTIC
PLATE SUPPLY - 600 VOLTS
SCREEN SUPPLY - 250 VOLTS
LOAD RESISTANCE - 4200 OHMS
I_p-MA
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-40
-38
-36
-34
-32
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2

FIG. (11)

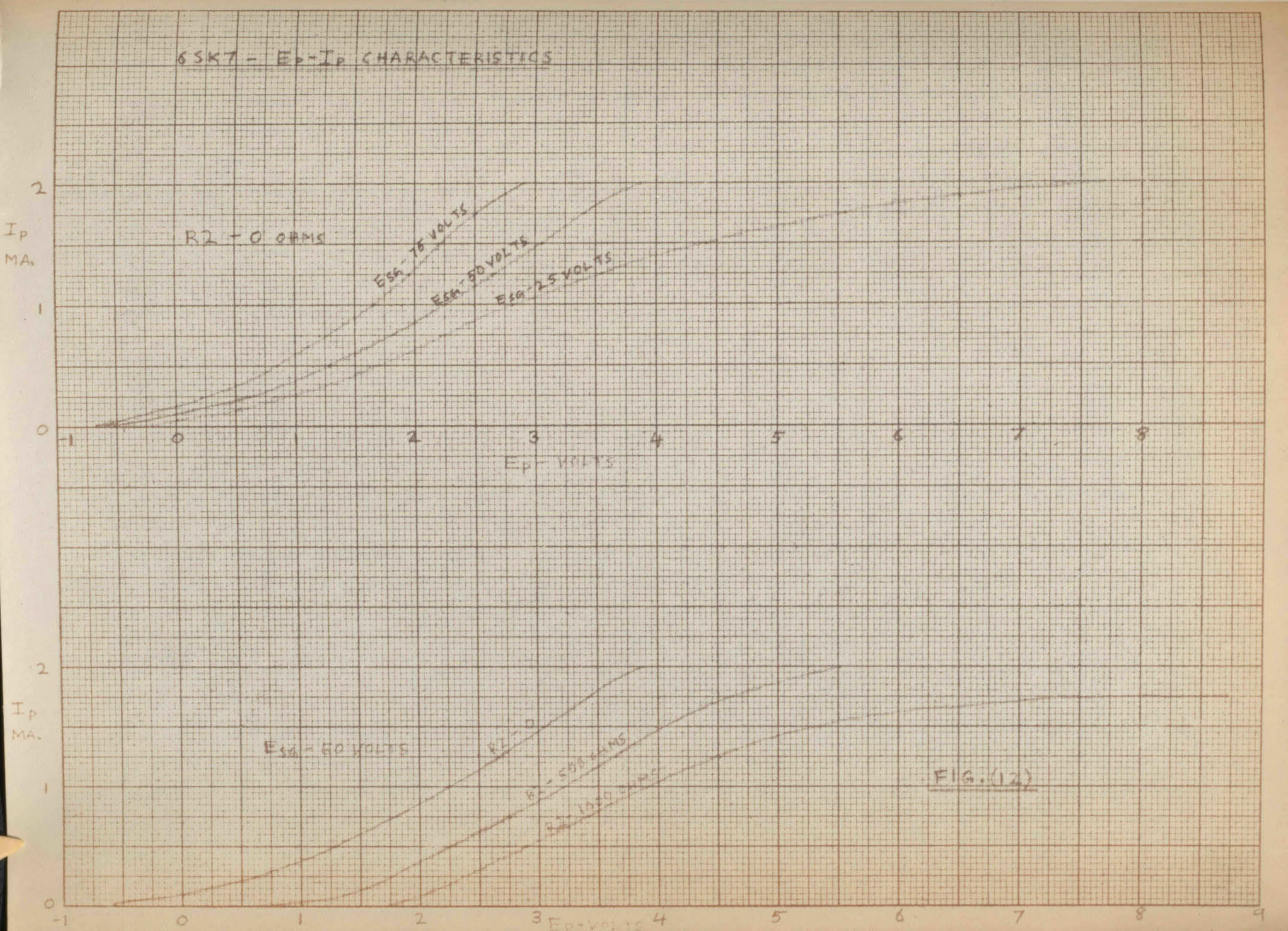

6SK7 - Ep-Ip CHARACTERISTICS
R2 - 0 OHMS
Esg - 75 VOLTS
Esg - 50 VOLTS
Esg - 25 VOLTS
Ip MA.
Ep - VOLTS
Esg - 50 VOLTS
R2 - 0
R2 - 500 OHMS
R2 - 1000 OHMS
Ip MA.
Ep - VOLTS

FIG. (12)

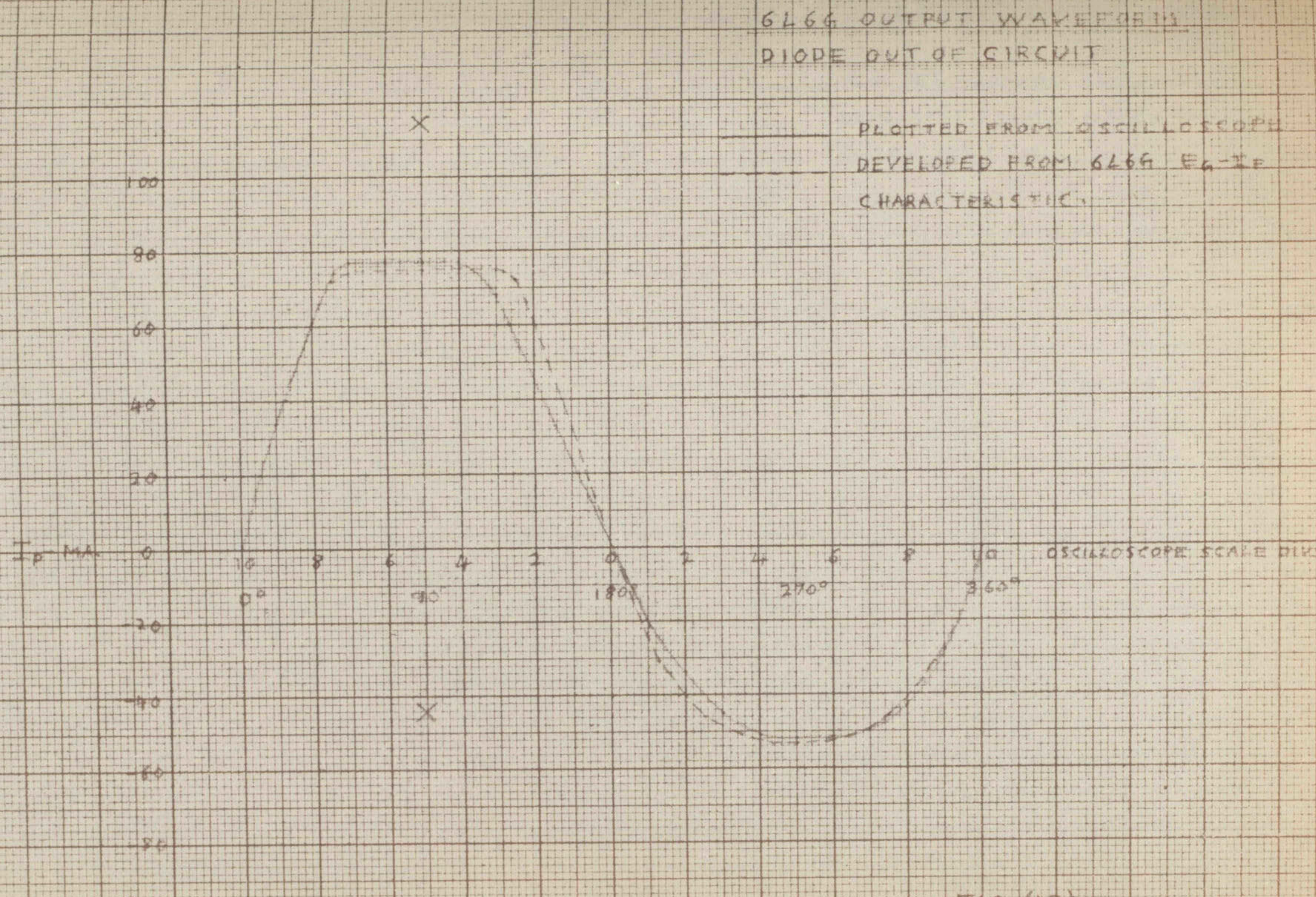

6L6G OUTPUT WAVEFORM
DIODE OUT OF CIRCUIT
PLOTTED FROM OSCILLOSCOPE
DEVELOPED FROM 6L6G Eg-Ip
CHARACTERISTIC.
Ip MA
100
80
60
40
20
0
-20
-40
-60
-80
-100
10
8
6
4
2
0
2
4
6
8
10
OSCILLOSCOPE SCALE DIVS.
0°
90°
180°
270°
360°

FIG.(13)

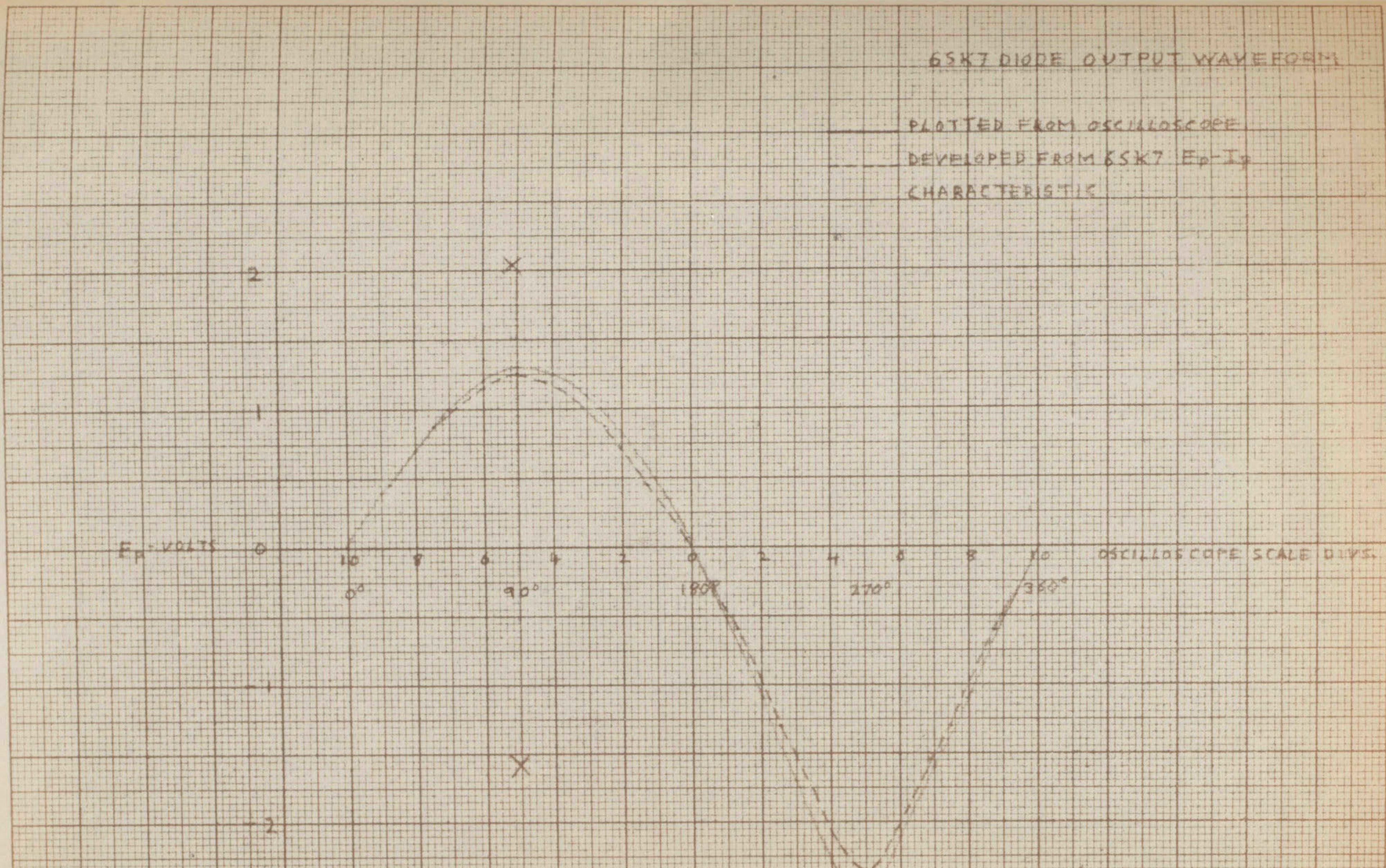

6SK7 DIODE OUTPUT WAVEFORM
PLOTTED FROM OSCILLOSCOPE
DEVELOPED FROM 6SK7 E_p-I_p
CHARACTERISTIC
E_p - VOLTS
2
1
0
-1
-2
-3
10
8
6
4
2
0
2
4
6
8
10
OSCILLOSCOPE SCALE DIVS.
0°
90°
180°
270°
360°

FIG-(14)

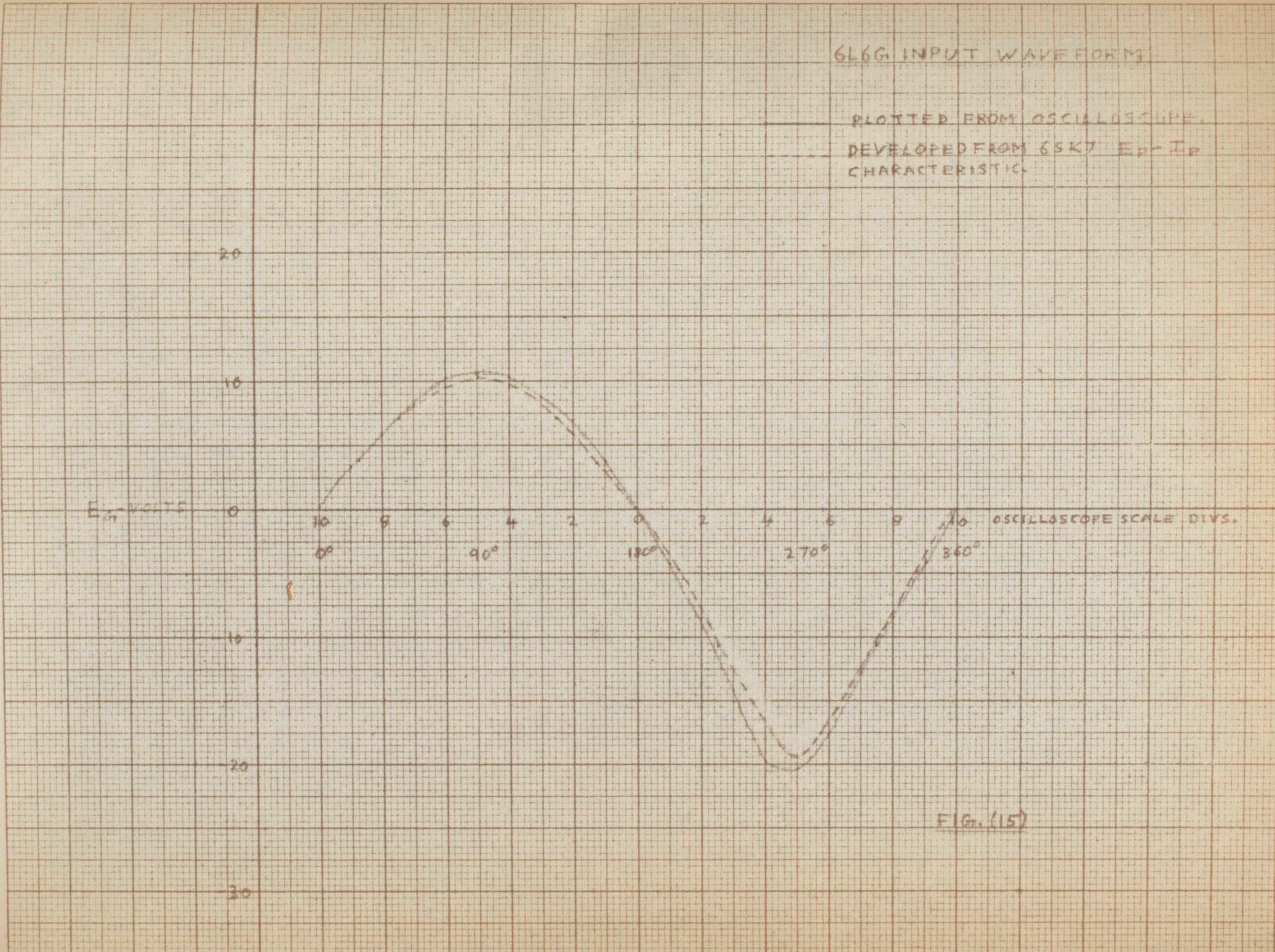

6L6G INPUT WAVEFORM
PLOTTED FROM OSCILLOSCOPE.
DEVELOPED FROM 6SK7 Ep-Ip CHARACTERISTIC.
Eg-VOLTS
20
10
0
10
20
30
10
8
6
4
2
0
2
4
6
8
10
OSCILLOSCOPE SCALE DIVS.
0°
90°
180°
270°
360°

FIG. (15)

6466 OUTPUT WAVEFORM

DIODE IN CIRCUIT

PLOTTED FROM OSCILLOSCOPE

DEVELOPED FROM 6SK7 E_p-I_p AND 6466 E_G-I_p CHARACTERISTICS.

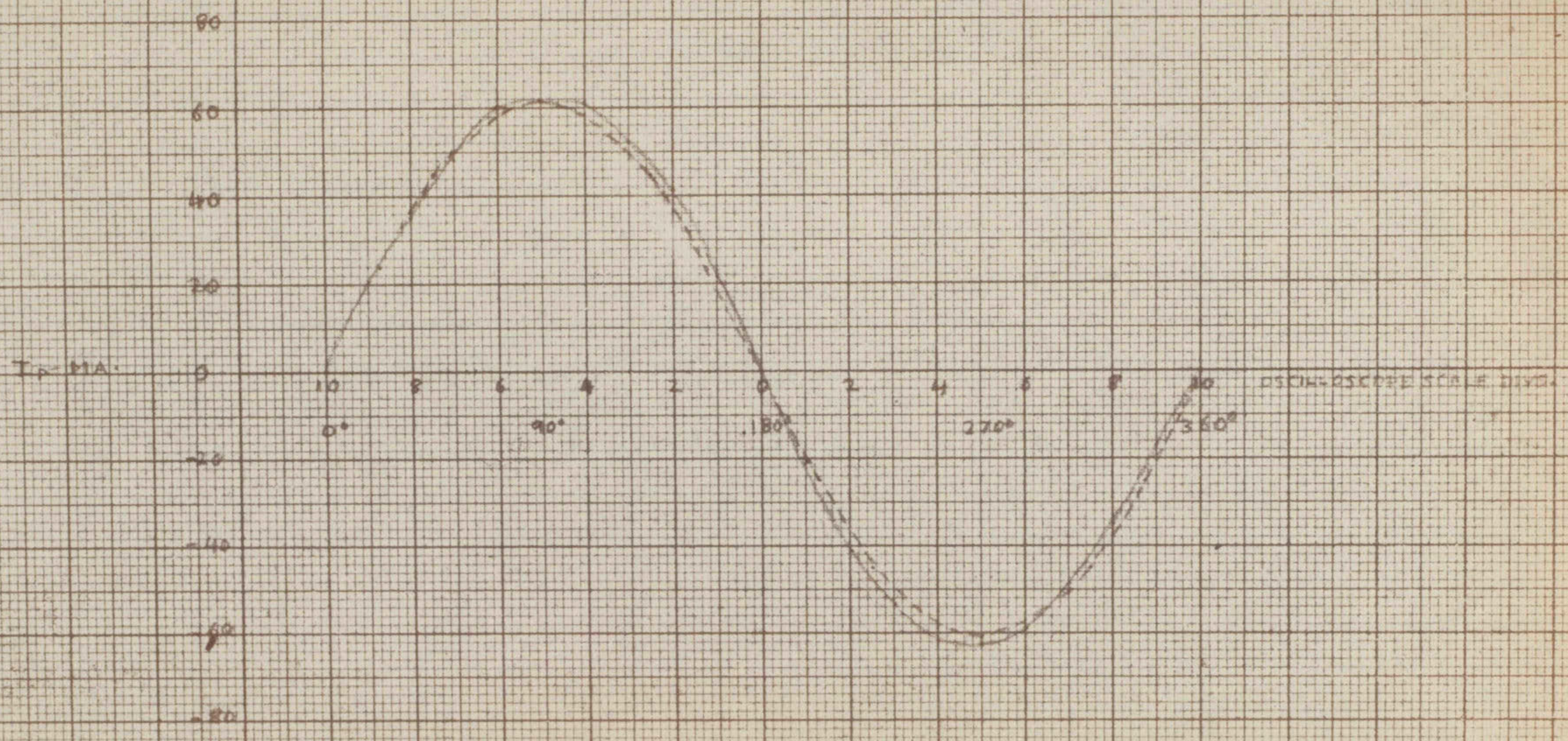


FIG.(16)

HARMONIC ANALYSIS OF 6L6G OUTPUT WAVEFORM - DIODE OUT OF CIRCUIT.

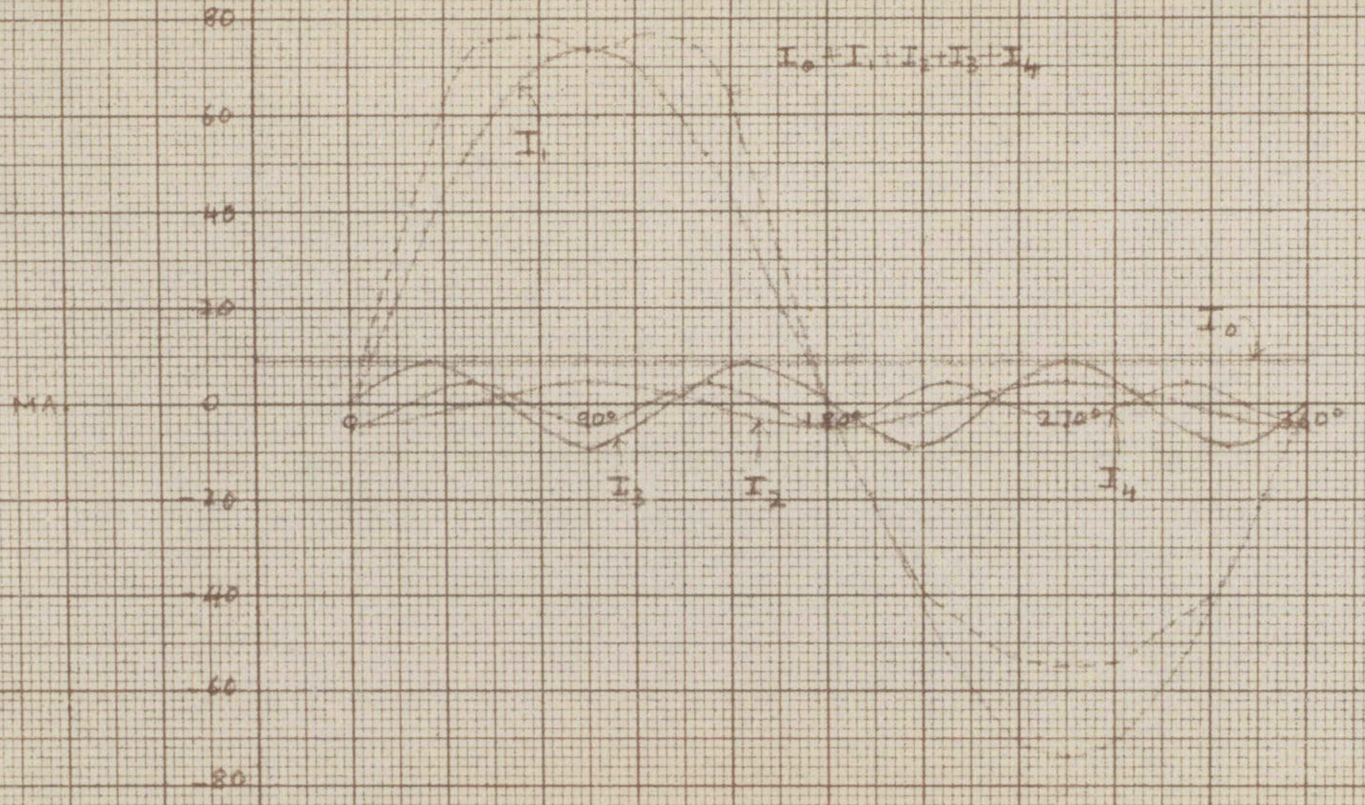


FIG. (17)

HARMONIC ANALYSIS OF
6SK7 OUTPUT WAVEFORM

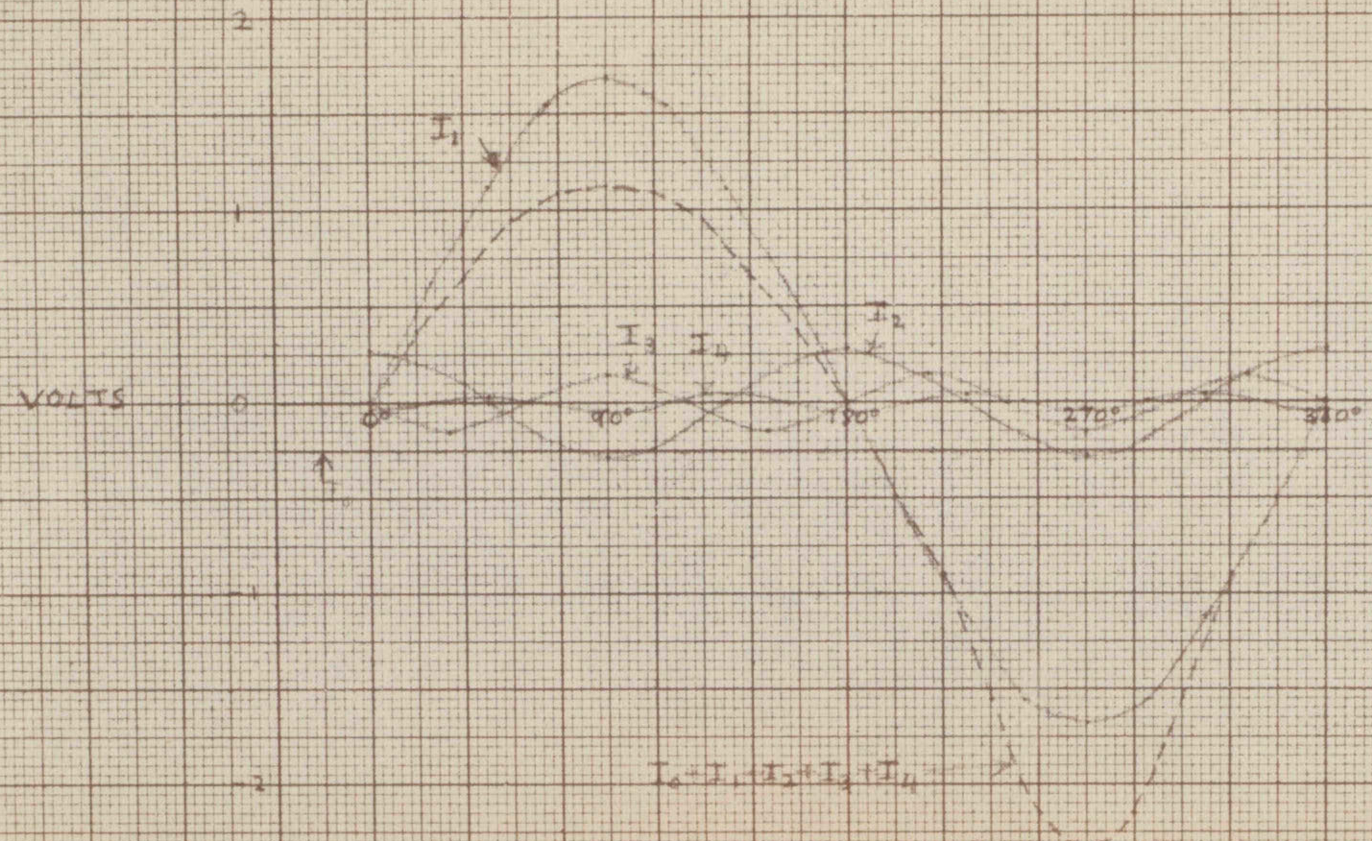


FIG.(18)