ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

GROUNDED GRID SWEPT POWER AMPLIFIER

Technical Memorandum No. 40

Department of Electrical Engineering
Electronic Defense Group

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This is not a final report. Further investigation may make it desirable to have this report revised, superseded or withdrawn.

Project 2262

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ABSTRACT

A model of the Swept Power Amplifier has been constructed and demonstrates the following desirable characteristics: (1) useful power output, gain and efficiency; (2) wide tuning range; (3) simplicity; (4) uncomplicated tuning. A method of analysis is presented such that one can predict the power output, gain and efficiency. The experimental and theoretical results are compared.

GROUNDED GRID SWEPT POWER AMPLIFIER

1. INTRODUCTION

Many important applications of wide-band power amplifiers to the UHF and VHF ranges have recently been achieved. One solution to the problem of wide-band amplification in this range is the distributed amplifier. However, distributed amplifiers using pentodes suffer at high frequencies from cathode and grid lead difficulties. In general, the difficulties involved in narrow band amplification are less severe than those associated with wide-band amplification. Over narrow bandwidths grounded-grid power triodes with excellent high-frequency characteristics (because of disc-seal construction) can be used with good efficiencies. For some applications only instantaneous narrow band coverage with wide frequency range tunability is required. Thus it has been suggested that it may be possible to design a power amplifier that amplifies instantaneously over a narrow band but with provision for sweeping the narrow band "window" over a wide band.

This memorandum describes the design, predicted results and power measurements of a grounded-grid swept power amplifier built by EDG Task 1.

2. THEORETICAL CONSIDERATIONS

The first step in designing the swept power amplifier is to determine the input impedance of the tube and then design a network to place at the input of the tube which will match the impedance of the tube to the 50 ohm cable. Next a plate circuit must be designed which will permit power amplification over a narrow band and which is sufficiently simple that the narrow band may be swept over a wide-band.

2.1 Input Matching Network and Analysis of Input Impedance

In order to achieve good gain characteristics with a grounded-grid triode it is desirable to match the tube to both the source and load impedances. It was decided to use a minimum-loss Tschebycheff two-pole matching network to match the triode to the 50-ohm cable used to transmit the power into the amplifier. The two-pole network was chosen because it is capable of providing an impedance match over a 300 mc band with less than 0.7 db mismatch, and also because it has relatively few elements. This means that the problem of adjusting the values of the elements should be minor.

It is necessary to know the equivalent input circuit of the tube with the plate circuit connected in order to match the tube to the line using this network. It is possible to analyze the circuit of a grounded-grid triode to find the equivalent input circuit.

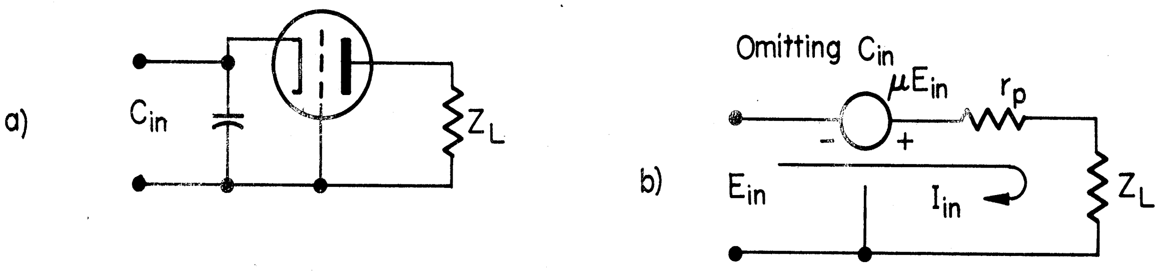


FIG. I. GROUNDED - GRID AMPLIFIER

From Figure 1, neglecting input capacity, the analysis is as follows:

$$E_{in} + \mu E_{in} = I_{in} (r_p + Z_L)$$

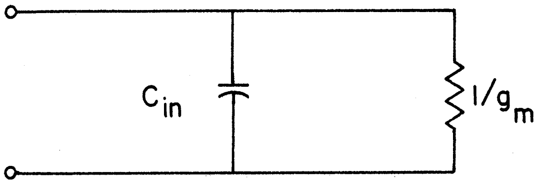
$$Z_{in} = \frac{E_{in}}{I_{in}} = \frac{r_p + Z_L}{1 + \mu}$$

for $Z_L << r_p$

$1 << \mu$,

$$Z_{in} = \frac{r_p}{\mu} = \frac{1}{g_m}$$

The equivalent input circuit then becomes:



The 2C39-A triode was chosen for this amplifier because of its disc-seal construction. The g_m of this tube is nominally 20,000 μmho. Thus the input resistance is known (i.e., 1/.02 = 50 ohm). The input capacitance is difficult to measure because of the loading of the capacitance by the input resistance created by the hot tube.

It is possible to obtain a fairly good impedance match between the tube and the line by assuming a value for C_{in}, **building the network designed on the basis** of the assumed value for C_{in}, and then measuring the impedance seen looking into the network. After doing this three or four times one is able to intelligently design a fairly good network. This was done, and, with an assumed value of 20 μμf for this capacitance, the best match was achieved. The resulting network is shown in Fig. 2.

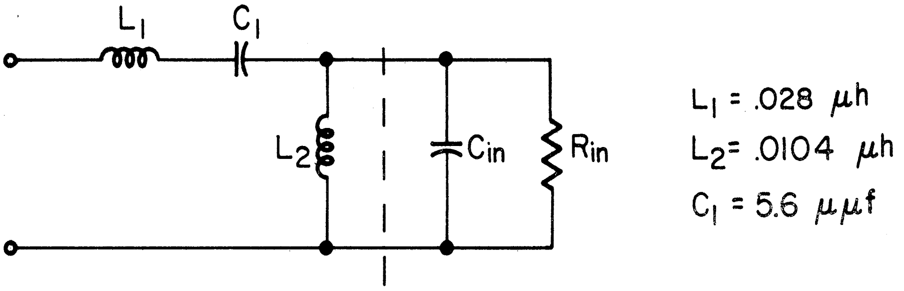
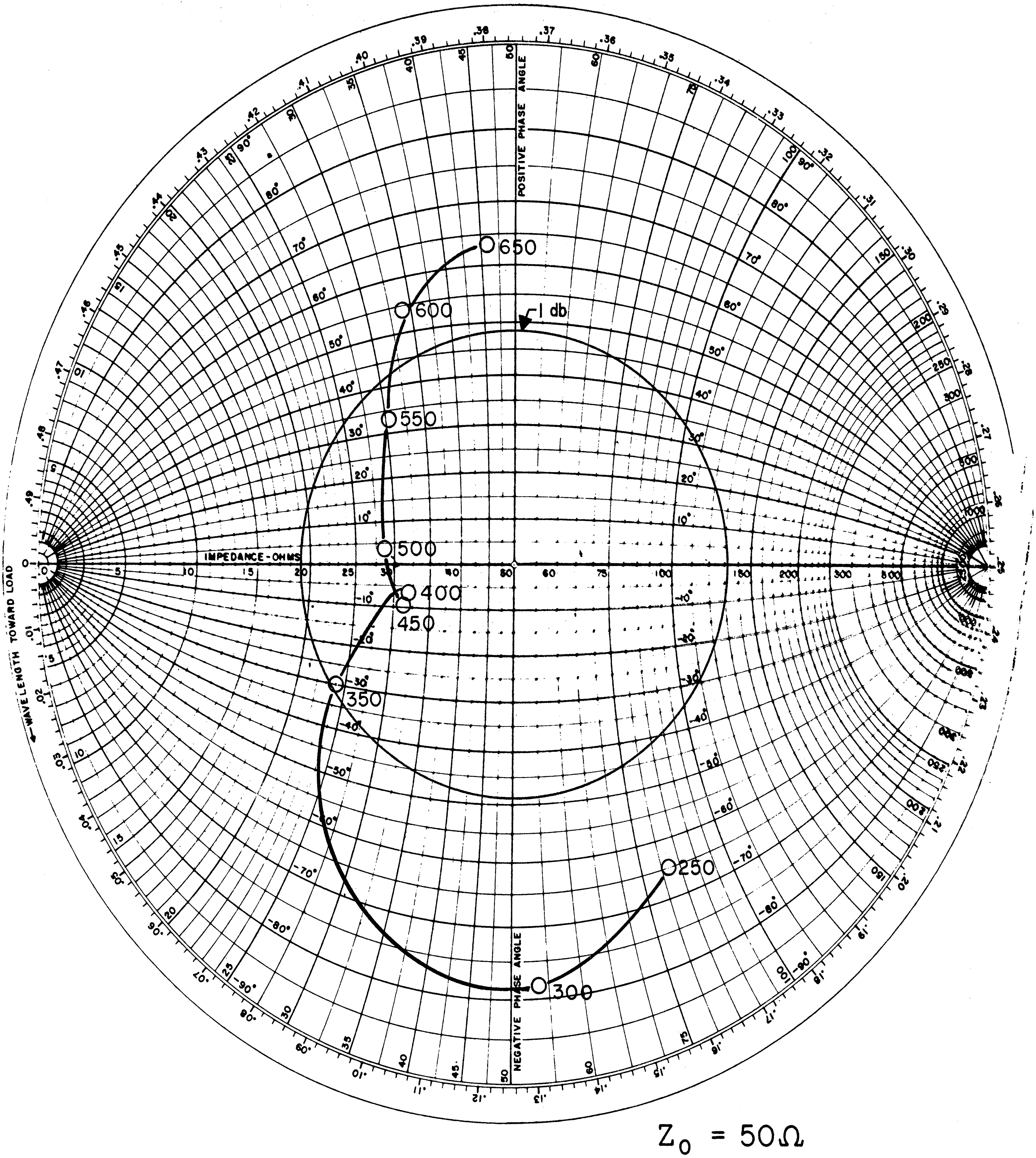


FIG. 2. NETWORK EQUIVALENT OF FIG. 1.

The impedance seen looking into the network was measured using the General Radio Type 1602-B Admittance Meter. A plot of this impedance is shown in Fig. 3. It can be seen that the match achieved was not as good as the theoretical limit. This is the result of several causes, the most important of which are:



$Z_0 = 50\Omega$

Z-θ CHART

MODEL 803A VHF BRIDGE

HEWLETT-PACKARD COMPANY
PALO ALTO, CALIFORNIA

FIG. 3. INPUT IMPEDANCE OF SWEPT POWER AMPLIFIER

1. The value of C_{in} was not known exactly.
2. The inductances L_1 and L_2 degenerate to pieces of wire of the order of 2 inches long, making it difficult to get the correct value for the inductances in the network. (It would be possible using more precise methods to obtain a better match).

However, it can be seen that over most of the band the match is within 1 db, and it was felt that for the purpose of demonstrating the feasibility of building the swept power amplifier, this network was acceptable.

2.2 The Plate Circuit

In designing a swept amplifier, it is desirable to keep the plate circuitry simple so that the frequency is controlled by as few elements as possible. This makes it feasible to sweep the amplifier quite easily. A plate circuit described by Christopherson[1] lends itself very nicely to this application for the following reasons:

1. The frequency can be controlled by one element;
2. The network raises the low output impedance (50 ohm cable) to a much higher impedance as seen by the tube;
3. The output capacitance of the tube and the other stray capacities are included in the network.

This network is the so-called "pi-coupling" network. It has the structure as shown in Fig. 4.

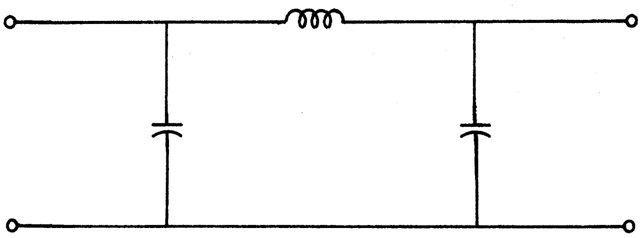


FIG. 4 "PI-COUPLING" NETWORK

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[1] W. A. Christopherson, "The Analysis and Synthesis of Grounded-Grid Amplifier Transfer Functions," Technical Report No. 46, Stanford University.

The complete circuit of the swept power amplifier is shown in Fig. 5.

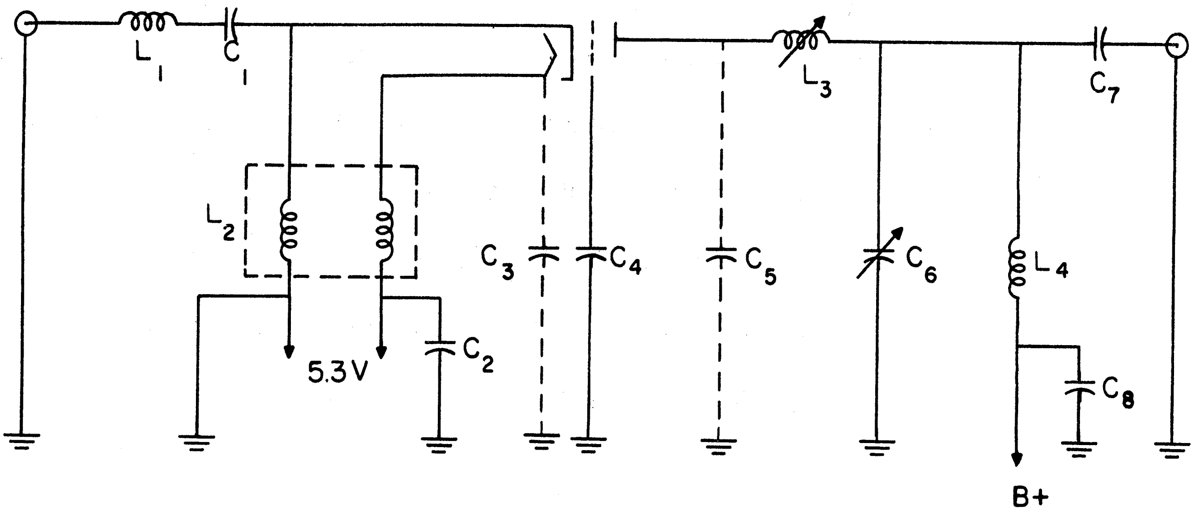

FIG.5 CIRCUIT OF SWEPT POWER AMPLIFIER

L_1 = .028 μh
L_2 = .0104 μh
L_3 = tuning inductor
L_4 = RF Choke, self resonant at 450 mc/s.
C_1 = 5.6 μμf
C_2 = 1000 μμf
C_3 = Input Capacitance
C_4 = 68 μμf
C_5 = Output Capacity of tube plus stray capacitance
C_6 = 1-35 μμf air capacitor
C_7 = 100 μμf
C_8 = 750 μμf

It was desired to choose the elements in the pi-coupling network to amplify at frequencies as high as possible and still give as large a swept band of frequencies as possible. One method of doing this is to choose various geometries for the inductance and make C_6 (Fig. 5) an adjustable capacitance, adjusting for maximum response with any one inductance in the circuit. Using this circuit it was possible to tune the amplifier from 445 mc to 522 mc with a 3 db instantaneous bandwidth varying from 9 to 12 mc respectively. A photograph of the response is shown in Fig. 6. The photograph is composed of two exposures, one taken with the amplifier tuned to the lowest frequency, the second taken with the amplifier tuned to the highest frequency. The 3 db points and the center frequency are indicated on each curve. Figure 7 is a photograph of the inductor used and

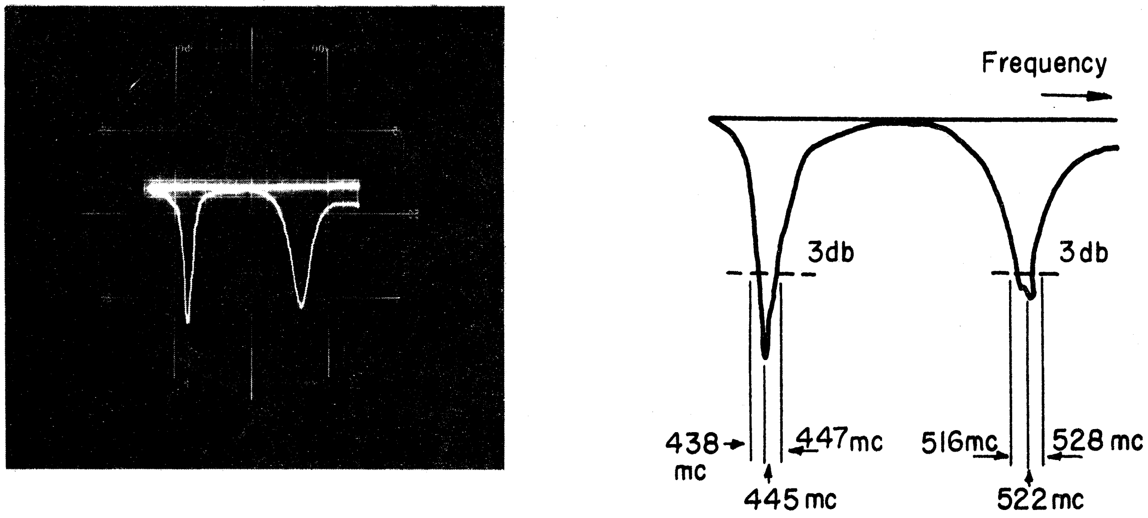

FIG. 6. PHOTOGRAPH OF AMPLIFIER GAIN CHARACTERISTIC (TWO EXPOSURES).

the housing for the inductor. The sweeping of the center frequency is accomplished by changing the inductance, L_3, as indicated in Fig. 5. The inductance is changed by moving a concentric slug of brass, which is essentially a shorted ring, from the center of the outside brass ring to a point "infinitely far removed" from the outer ring. In practice it was found necessary to move the slug only 11/16 inch from the center of the outer ring to obtain the sweep range.

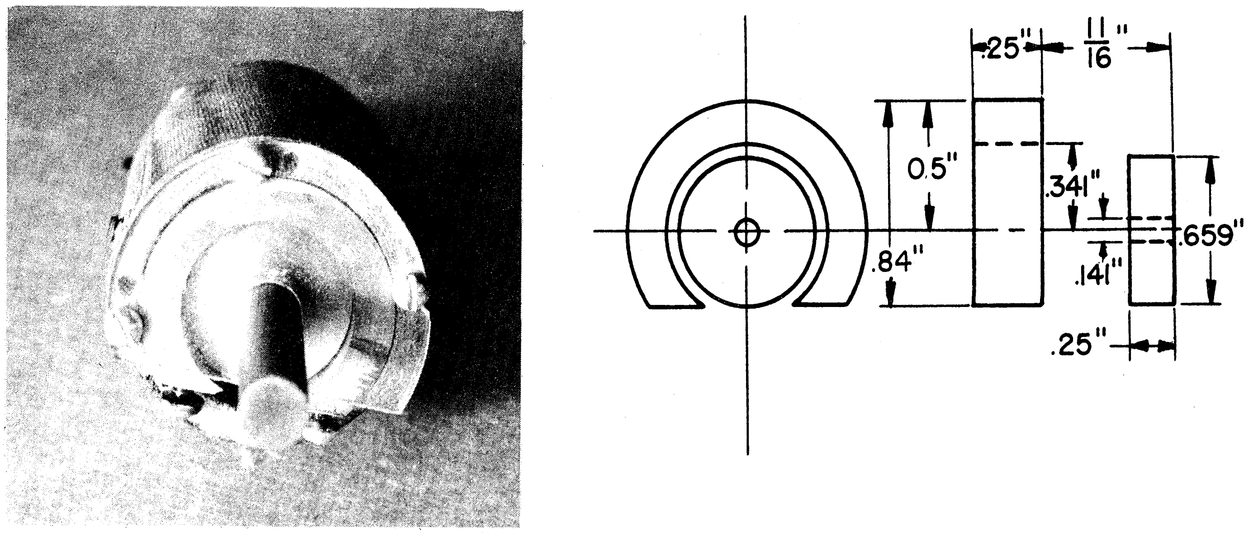

FIG. 7. PHOTOGRAPH OF TUNING INDUCTANCE MOUNTED IN HOUSING.

2.3 Theoretical Power Output

After picking the operating point (plate voltage = 600 v and cathode bias = -3 v) it is possible to predict the power output, power gain and efficiency for various power inputs to the amplifier. The first step is to analyze the plate circuit to determine the impedance presented to the tube by the plate circuit (Z_{11}), and the transfer impedance of the plate circuit (Z_{12}) (see Appendix A).

Christopherson[1] shows that for this circuit

$$C_2 = \sqrt{\frac{C_1}{2\pi BWR_2}} \quad ;$$

$$C_s = \frac{C_1C_2}{C_1+C_2} \quad ;$$

$$L = \frac{1}{4\pi^2 f_o^{\,2} C_s} \quad .$$

where BW = bandwidth in cycles per second, and

f_o = center frequency in cycles per second.

These equations hold for $\gamma < 0.3$, where γ is defined as:

$$\gamma = \frac{1}{2\pi f_o R_2 (C_1+C_2)}$$

Assuming the center frequency is 450 mc, the bandwidth is 12 mc, C_1 is 6 μμf, and R_2, the impedance of the coaxial line, is 50 ohms, we get the following values for the network elements.

$$C_2 = \sqrt{\frac{6 \times 10^{-12}}{2\pi(12 \times 10^6)(50)}} = 39.9 \ \mu\mu f$$

$$C_s = \frac{(6)\ (39.9)}{(6) + (39.9)} \times 10^{-12} = 5.34 \ \mu\mu f.$$

$$L = \frac{1}{4\pi^2(450 \times 10^6)^2(5.34 \times 10^{-12})} = 0.0234 \ \mu h.$$

$$\gamma = \frac{1}{2\pi(450 \times 10^6)(50)(46 \times 10^{-12})} = 0.154$$

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[1] Christopherson, op.cit.

$$\lambda = 0.154 < 0.3 \text{ so the above equations are valid.}$$

$$\omega_o = 2\pi(450 \times 10^6) = 2.83 \times 10^9$$

It remains now to calculate Z_{11} and Z_{12} as defined in Appendix A. These relations are:

$$|Z_{11}(j\omega)|^2 = \frac{(R-\omega^2LC_2R)^2 + (\omega L)^2}{(1-\omega^2LC_1)^2 + \left[\omega R(C_1+C_2)-\omega^3LRC_1C_2\right]^2}$$

$$|Z_{12}(j\omega)|^2 = \frac{R^2}{(1-\omega^2LC_1)^2 + \left[\omega R(C_1+C_2)-\omega^3LRC_1C_2)\right]^2}$$

Substituting into these equations the element values obtained above, numerical values of $Z_{11}(j\omega)$ znd $Z_{12}(j\omega)$ at the center frequency f_o are calculated.

$$|Z_{11}(j\omega)| = 2,080 \text{ ohms}$$

$$|Z_{12}(j\omega)| = 312 \text{ ohms}$$

The amplifier can now be reduced to the equivalent circuit shown in Fig. 8.

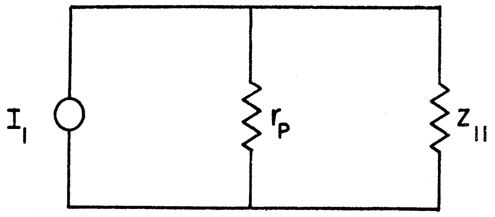

FIG. 8 EQUIVALENT CIRCUIT OF AMPLIFIER

I_1 = Fundamental component of plate current.
r_p = Plate resistance of the vacuum tube.
Z_{11} = Driving point impedance of the plate circuit.

r_p can be found from a plot of plate current vs the plate voltage. It is the negative of the slope of this curve at the operating point. For plate voltage = 600 v and cathode bias = -3v we get

$$r_p = 3130 \text{ ohms}$$

From Appendix B for 3 watts drive, I_1 can be seen to be 109.5 ma **rms.** Thus, the current into the plate circuit $I_{Z_{11}}$ is found by the relation

$$I_{Z_{11}} = \frac{r_p}{r_p + Z_{11}} I_1$$

for this case,

$$I_{Z_{11}} = \frac{3130}{3130 + 2080} (109.5) = 65.7 \text{ ma.}$$

The output voltage is found by the relation

$$E_{out} = I_{Z_{11}} Z_{12} .$$

For this case,

$$E_{out} = (65.7 \times 10^{-3})(312) = 20.5 \text{ v.}$$

The output voltage is the voltage across the 50 ohm resistor which represents the coaxial cable leading from the amplifier. The output power is the power dissipated in this representative resistor, or:

$$P_{out} = \frac{(E_{out})^2}{R} = \frac{(20.5)^2}{50} = 8.4 \text{ watts.}$$

The input DC power is found by:

$$P_{in} = E_{bb} I_o ,$$

where E_{bb} = plate voltage, and

I_o = DC component of output current.

For this case, the power in is given by:

$$P_{in} = (600)(102 \times 10^{-3}) = 61.6 \text{ watts.}$$

The plate circuit efficiency is defined by:

$$\eta = \frac{P_{out}}{P_{in\ DC}} \times 100 .$$

For this case the efficiency is

$$\eta = \frac{8.4}{61.6} \times 10 = 13.6\%$$

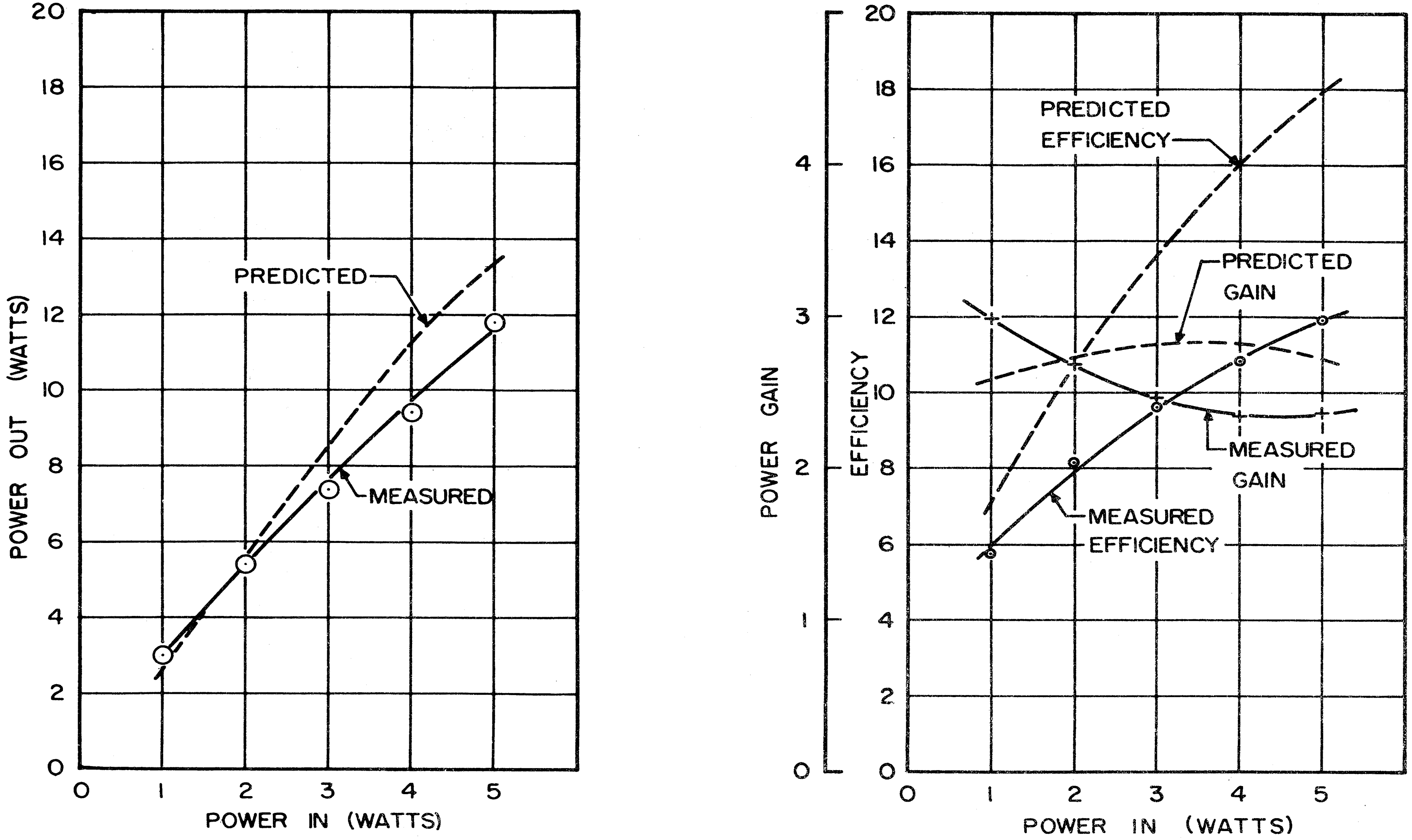

FIG. 9. COMPARISON OF PREDICTED DATA WITH MEASURED DATA FOR SWEPT POWER AMPLIFIER.

These calculations were made for several other values of power into the amplifier. In Figure 9 the results of these calculations are presented along with the measured values for comparison.

3. EXPERIMENTAL RESULTS

3.1 Power Measurements

It was decided to separate the grid from DC ground by an RF bypass capacitor. This was to give flexible control over the grid bias. For the power saturation curves, bias was obtained by cascading 1.5 volt batteries which had low DC impedance. Thus it was simple to keep the grid bias constant even though grid current was flowing. This was true until four batteries were cascaded. With four batteries the internal impedance was sufficiently high so that the bias changed with power input. This was corrected by inserting a potentiometer in the biasing circuit and monitoring the bias with a voltmeter. Figure 10 shows the test setup used to determine the power saturation curves.

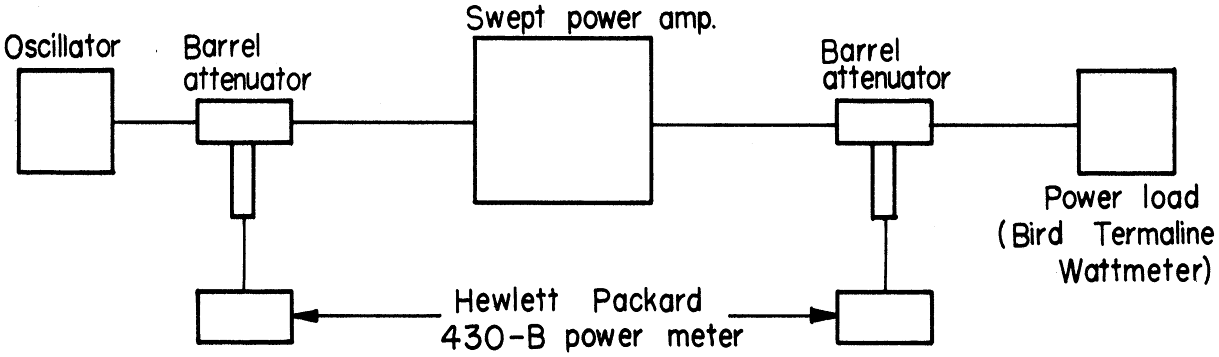

FIG. 10. TEST SETUP USED TO MEASURE POWER GAIN

Figure 11 shows the power saturation curve measured at one frequency in the band (450 mc) using the test setup indicated above. The power gain curve was taken from the saturation curve.

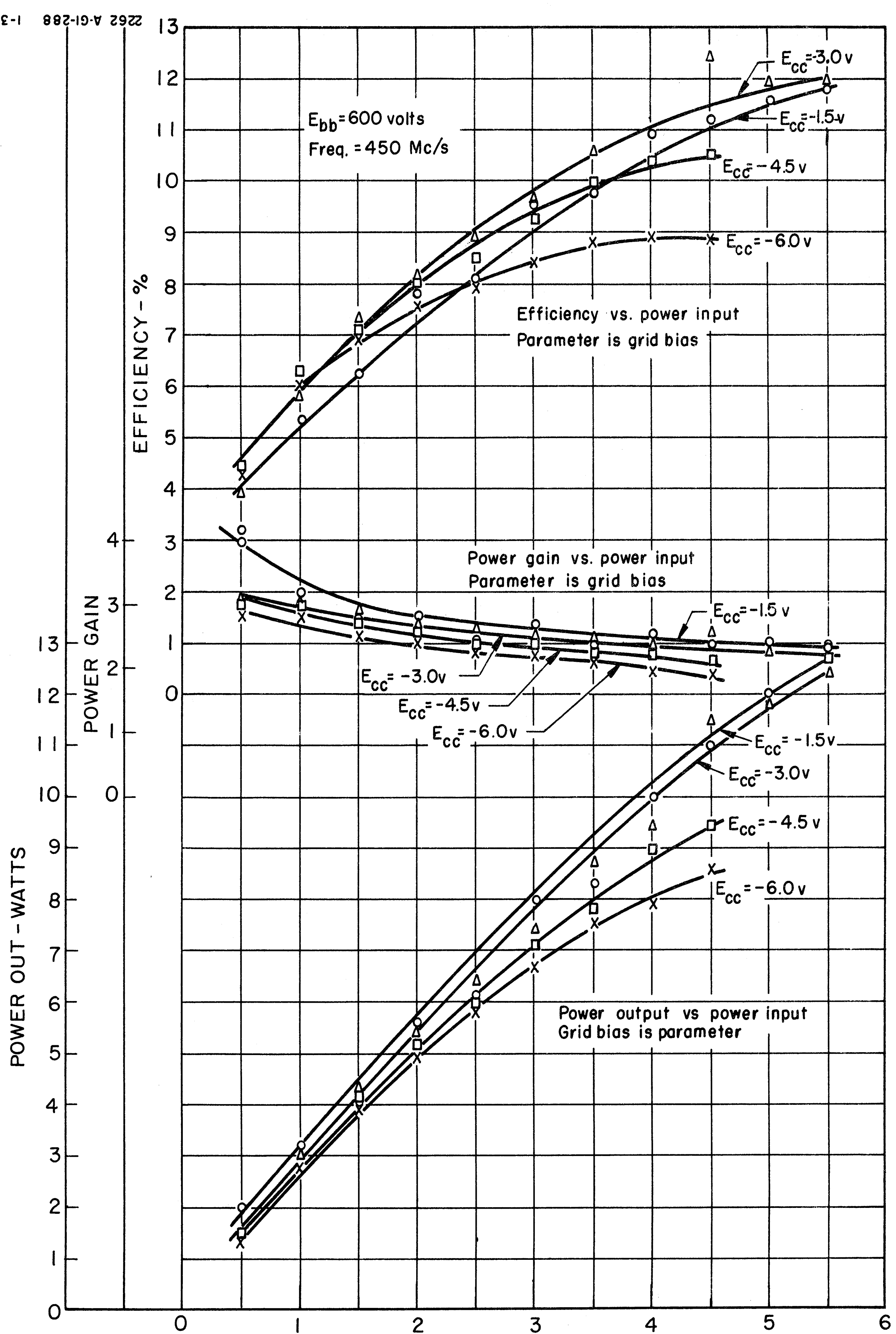

FIG. 11. EXPERIMENTAL CURVES FROM 2C39-A SWEPT POWER AMPLIFIER.

Figure 12 is a photograph of the model built by EDG Task 1.

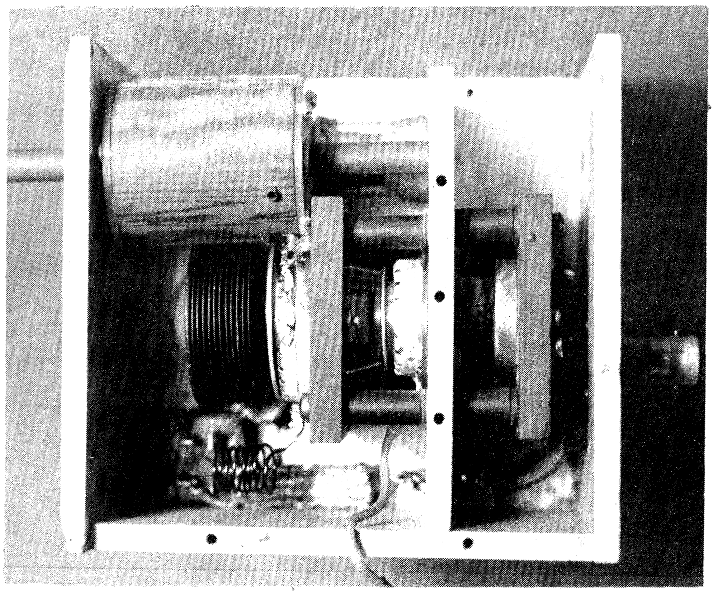

FIG. 12 PHOTOGRAPH OF SWEPT POWER AMPLIFIER

4. CONCLUSIONS

A model of the Swept Power Amplifier has been constructed and demonstrates the following desirable characteristics: (1) useful power output, gain and efficiency; (2) wide tuning range; (3) simplicity; (4) uncomplicated tuning. From this model, one can estimate the performance of similar models using other tube types or under gated conditions. Also, a method for analyzing the amplifier has been described such that one can predict quite accurately the power output, gain and efficiency.

It may be noticed the efficiency of this amplifier was not as good as one would hope for. By examining the characteristic curves of the 2C39-A tube one can see that the efficiency could be improved substantially by going to higher plate voltages. This amplifier was constructed with capacitors having a 600 volt rating which limited the plate voltage to this level. Also, the amplifier was adjusted for optimum power gain rather than optimum efficiency. The efficiency could be improved by increasing the cathode bias at the cost of decreasing gain.

APPENDIX A

Determination of Driving Point Impedance and Transfer Impedance of Plate Circuit

The plate circuit as seen by the tube is shown in Fig. A.1

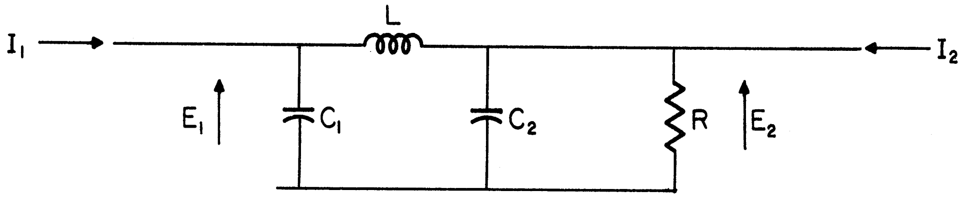

FIG. A.I. PLATE CIRCUIT.

The nodal equations for the circuit are:

$$I_1 = (pC_1 + \frac{1}{pL})\, E_1 - \frac{1}{pL}\, E_2 \qquad A.1$$

$$0 = -\frac{1}{pL}\, E_1 + (pC_2 + \frac{1}{R} + \frac{1}{pL})\, E_2 \qquad A.2$$

Now, eliminating E_2 from the above equations

$$I_1(pC_2 + \frac{1}{R} + \frac{1}{pL}) = (pC_1 + \frac{1}{pL})(pC_2 + \frac{1}{R} + \frac{1}{pL})\, E_1 - (\frac{1}{pL})^2\, E_1 \qquad A.3$$

The driving point impedance is defined by

$$Z_{11} = \frac{E_1}{I_1} \qquad A.4$$

Now, from Equation A.3,

$$Z_{11} = \frac{pC_2 + \frac{1}{R} + \frac{1}{pL}}{(pC_1 + \frac{1}{pL})(pC_2 + \frac{1}{R} + \frac{1}{pL}) - (\frac{1}{pL})^2} \qquad A.5$$

This can be simplified to:

$$|Z_{11}(j\omega)|^2 = \frac{(R-\omega^2 LC_2R)^2+\omega^2L^2}{(1-\omega^2LC_1)^2 + \left[\omega R(C_1+C_2)-\omega^3LRC_1C_2)\right]^2} \qquad \text{A.6}$$

The transfer impedance is defined by

$$Z_{12} = \frac{E_2}{I_1} \qquad \text{A.7}$$

eliminating E_1 from Equations A.1 and A.2

$$I_1\left(\frac{1}{pL}\right) = -\left(\frac{1}{pL}\right)^2 E_2 + \left(pC_1 + \frac{1}{pL}\right)\left(pC_2 + \frac{1}{R} + \frac{1}{pL}\right) E_2 \qquad \text{A.8}$$

so

$$Z_{12} = \frac{\frac{1}{pL}}{-\left(\frac{1}{pL}\right)^2 + \left(pC_1 + \frac{1}{pL}\right)\left(pC_2 + \frac{1}{R} + \frac{1}{pL}\right)}$$

this can be simplified to:

$$|Z_{12}(j\omega)|^2 = \frac{R^2}{(1-\omega^2LC_1)^2 + \left[\omega R(C_1+C_2)-\omega^3LRC_1C_2\right]^2} \qquad \text{A.9}$$

APPENDIX B

Determination of Fundamental and DC Component of Plate Current

Once the plate impedance seen by the tube is known one can draw a load line on a set of tube characteristics. In this case the analysis was simplified by assuming the plate circuit presented a pure resistance of 3130 ohms, to the tube. When the load line is drawn (Fig. B.1) it is a simple matter to plot the plate current for a cycle of cathode voltage of a given amplitude. The amplitude of the sinusoidal cathode voltage is determined by assuming the input power is developed across a pure resistance of 50 ohm.

Assuming a power input of 3 watts the peak cathode voltage can be determined as follows:

$$P_{in} = \frac{E^2}{R}$$

$$E^2 = (3\omega)(50) = 150$$

$$E_{rms} = 12.25 \text{ v.}$$

$$E_{peak} = 17.3 \text{ v.}$$

The plate current with this input is then shown in Fig. B.2 Analyzing this wave using Fourier series techniques[1] gives the result that the DC level is 102 ma and the fundamental component is 109.5 ma rms.

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1. "Reference Data for Radio Engineers," pp.1009-1011, Federal Telephone and Radio Corp., 1956.

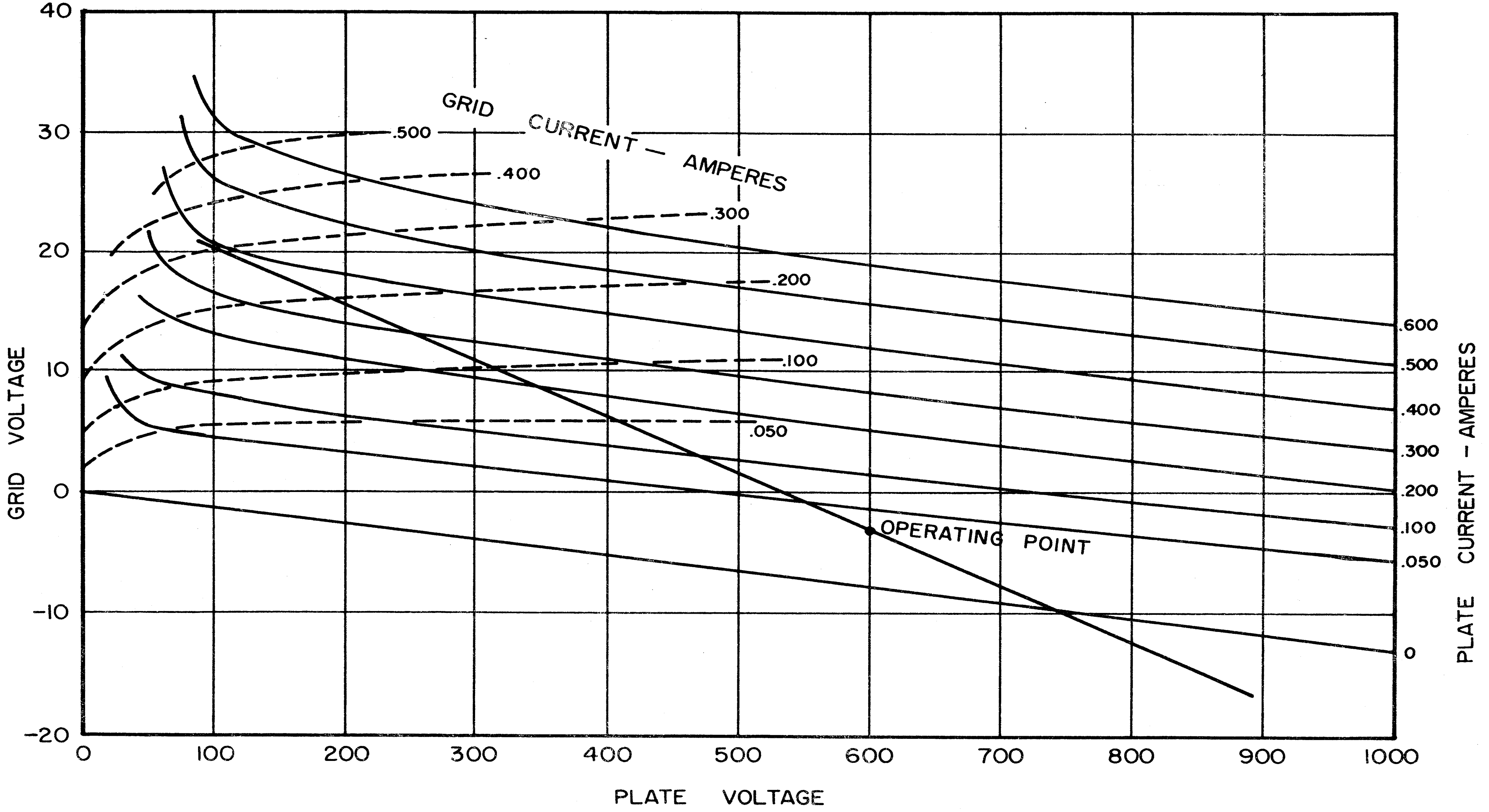

FIG. B.I. LOAD LINE DRAWN ON 2C39-A VACUUM TUBE CHARACTERISTICS.

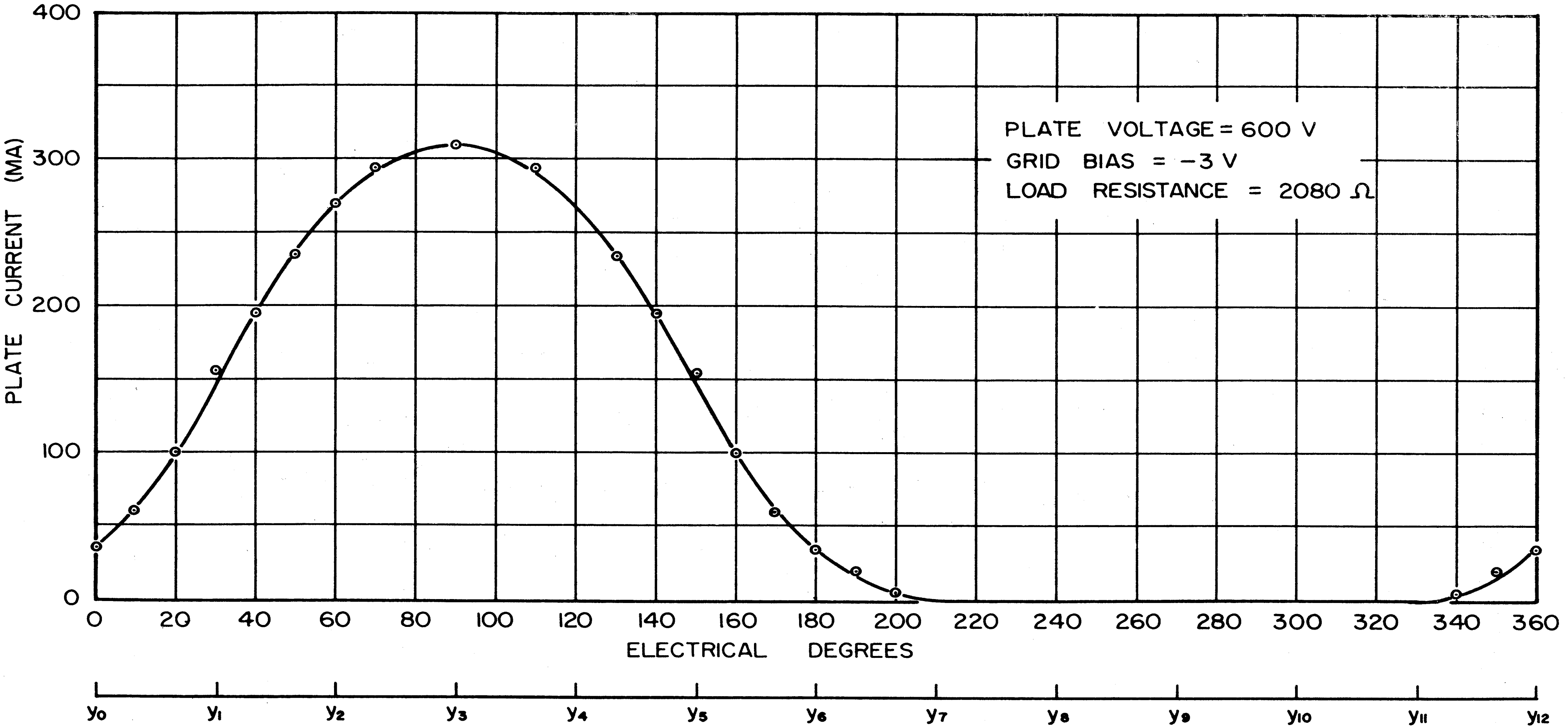

FIG. B.2. PLATE CURRENT FOR 2C39-A VACUUM TUBE IN SWEPT POWER AMPLIFIER WITH SINUSOIDAL INPUT OF 3 VOLTS.

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