THE PLATE LOAD IMPEDANCE CHARACTERISTICS OF A PUSH-PULL AUDIO AMPLIFIER

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1950

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Date thesis is presented June, 1950

Typed by Janet Craine

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ACKNOWLEDGMENTS

I would like to express my appreciation of the interest and suggestions of the faculty of the Department of Electrical Engineering, and to especially commend the counsel and guidance given by Professor Arthur L. Albert in the solution of the problem and in the preparation of the manuscript. I would also like to acknowledge the help and encouragement of my wife, whose assistance proved invaluable.

Lloyd B. Craine

May, 1950

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INTRODUCTION

Of the many factors which affect the design and operation of an amplifier, one of the most important is the load impedance presented to the power amplifier stage. In the design of a power amplifier stage, the usual assumption is that the load is pure resistance. Actually, as will be shown in this paper, the load impedance is complex, consisting of resistance and inductive or capacitive reactance. The magnitude and phase angle of the impedance vary with frequency. Sometimes the variations are quite pronounced when the frequency is changed only a few cycles. These variations may be attributed to various electrical, mechanical, and acoustical resonances which may be present at certain frequencies. A method of measuring the impedance presented directly to the plate circuit of the push-pull amplifier under typical conditions of operation was developed in this investigation. Curves showing the variations in impedance and phase angle with frequency for several typical acoustic transducers are shown.

ANALYSIS OF THE PLATE LOAD IMPEDANCE FOR A PUSH-PULL AMPLIFIER

The usual method of designing an audio frequency power amplifier stage utilizes the static plate characteristics of a vacuum tube and a straight load line properly placed on these static characteristics. The importance of knowing the nature of the plate load impedance can be seen by examining the plate characteristic curves for a push-pull amplifier. Thompson (13, pp 591-600) has shown that a push-pull amplifier can be graphically analyzed if the plate characteristic curves for one of the tubes are inverted and reversed, and placed so that the plate supply voltage point coincided with the same point for the plate characteristic curve of the other tube. Figure 1 shows the average plate characteristics for type 50 tubes connected in push-pull parallel. Note that each half of the graph shows the actual plate voltage - plate current curves for various constant grid voltages for one side of the push-pull amplifier, and that for any given grid voltage, the relationship between plate voltage and plate current is not linear.

In the push-pull circuit, one plate current is increasing in one half of the winding of the primary of the output transformer while the other current is decreasing in the other half of the winding. This results in a change in current in the primary winding of the transformer which may be considered a composite current. This composite current may be obtained from the plate characteristics by adding algebraically the individual plate currents for grid bias voltages at equal voltages each side of the operating grid bias voltage. The composite currents are shown on the graph of Figure 1 by dashed lines, and are seen to be almost linear. Actually, the plate characteristic curves for individual tubes may not be identical, and the composite current may depart from a straight line. However, the concept of a composite current delivered by a fictitious, equivalent, or composite tube having known voltages and currents is helpful in analyzing the performance of the push-pull stage.

If a pure resistive load from plate to plate is assumed, a load line can be plotted on the static characteristics of Figure 1 and the changes in plate current and voltage for given changes in grid voltage can be obtained. From these voltages and currents, the expected power output and distortion for any given variation in grid voltage can be determined. This resistive load line may be plotted on the static characteristics if the operating point of each tube, and the value of the load resistance are known or assumed. Such a load line is shown plotted on the static characteristics (Figure 1) as a straight line. The following conditions were assumed:

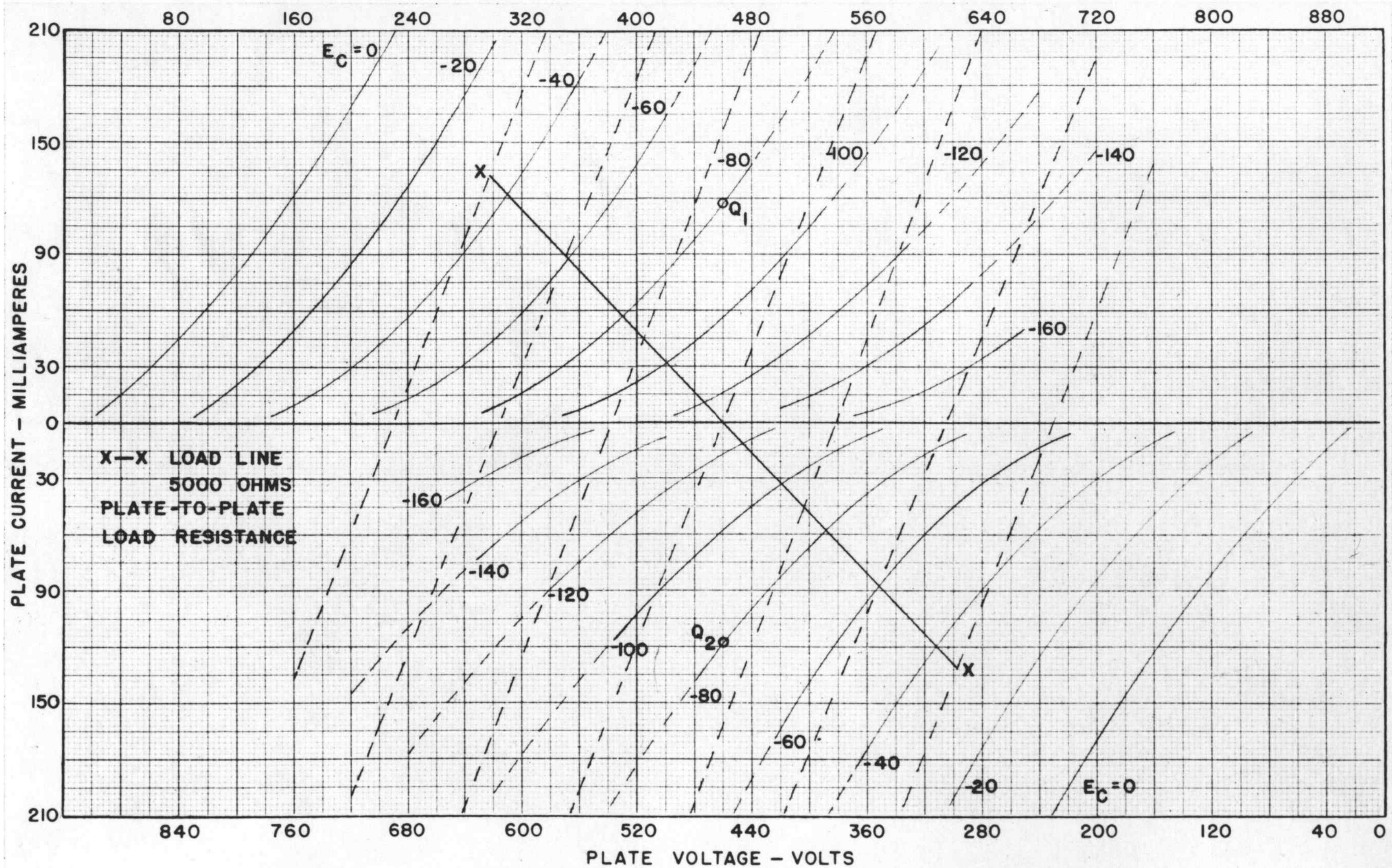


FIG. 1 COMPOSITE PLATE CHARACTERISTICS FOR PUSH-PULL PARALLEL TYPE 50 TUBES

F

Plate-to-plate resistance	=	5000 ohms
Plate voltage	=	460 volts
Grid Bias voltage	=	- 80 volts
Type of operation	-	Class A

The load line for the assumed composite tube will pass through the plate voltage axis at a point corresponding to the no-signal plate voltage. This is the point at which the static characteristics are matched. The other point determining the straight line can be obtained by dividing this plate voltage by the load resistance, giving a point on the current axis. Note that the operating point (Q) of each tube does not lie on this load line, indicating that each tube will draw some no-signal plate current. These currents are equal with balanced tubes, and because the currents flow in opposite directions in the primary windings, they will produce no steady magnetizing force in the output transformer core. The load line for each individual tube has to pass through its operating point, indicating that the individual plate load line does not coincide with the straight composite tube load line, and that the load resistance for each tube changes in magnitude during cyclic operation because of the non-linear plate current of the individual tubes. Thus, although the plate-to-plate resistive load line for the composite tube is straight, and the composite current is linear, the individual tube load line and current is non-linear.

An examination of an equivalent electrical circuit for the push-pull amplifier (Figure 2) shows that the plate load impedance may contain both resistance and inductive or capacitive reactance depending on the frequency. The symbols in Figure 2 may be defined as follows:

E_{g1} = Equivalent voltage rise in first tube due to amplifications of grid signal voltage

E_{g2} = Equivalent voltage rise in second tube due to amplification of grid signal voltage

R_1, R_2 = Internal alternating current plate resistance of each tube

C_{p1}, C_{p2} = Total distributed capacitance between each plate circuit and ground lumped into one capacitance

R_{p1}, R_{p2} = Effective resistance of each half of the primary winding

L_{p1}, L_{p2} = Leakage inductance of each half of the primary winding

R_{c1}, R_{c2} = Resistance to account for the core loss in the magnetic circuit

L_{m1}, L_{m2} = Incremental magnetizing inductance of each half of the primary

C_{ps} = Interwinding capacitance between each half of the primary and secondary

R_s = Effective secondary resistance

L_s = Leakage inductance of the secondary

C_s = Distributed capacitance of secondary windings lumped as one element

C_{sg} = Capacitance of secondary winding to ground

R_{vc} = Effective resistance of the voice coil

L_{vc} = Inductance of the voice coil

L_1 = Electrical equivalent of the mechanical mass of the voice coil and suspension

C_1 = Electrical equivalent of the compliance of the diaphragm suspension

C_2 = Electrical equivalent of the compliance of the voice coil and suspension

L_2 = Electrical equivalent of the mass of the diaphragm

C_3 = Electrical equivalent of the compliance of the air chamber

R - Represents the dissipation of electrical energy to account for the radiation of sound energy

L - Represents the reactance which may occur if the pressure and air velocity in the speaker are not in phase

These equivalent electrical resistances, inductances, and capacitances are not constant as the signal frequency

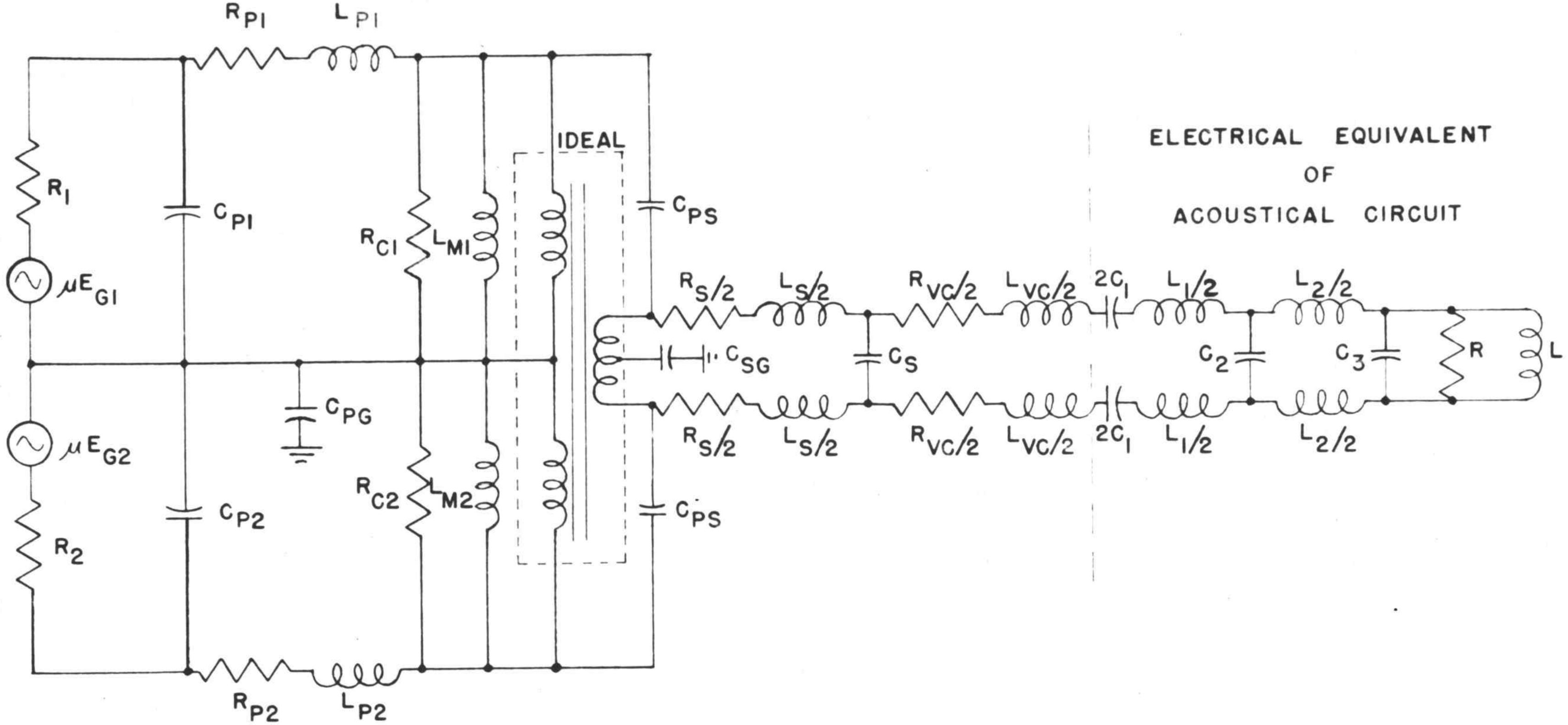


FIG. 2 EQUIVALENT ELECTRICAL CIRCUIT FOR A CLASS A PUSH-PULL AMPLIFIER

is varied. The constants for the truly electrical portion of the circuit can be determined by several methods and, depending on the signal frequency, assumptions as to the effect of certain capacitances and inductances on circuit performance may be made, thus simplifying the equivalent circuit. The indicated "constants" for the acoustical circuit are, in fact, difficult to determine and of different magnitude at different frequencies. Some of the reasons for these variations are:

1. The several different modes of vibration of the diaphragm, the effective mass depending on the mode of vibration.
2. The suspension of the diaphragm may have vibrational modes of its own, further changing the effective mass of the system.
3. The compliance of the suspension may change with amplitude; low frequencies require greater amplitude of movement of the voice coil and diaphragm than do high frequencies.
4. The diaphragm usually reacts on an air chamber located on the opposite side of the diaphragm from the main direction of sound propagation; air leakage from this chamber will change with frequency and amplitude, and affect the compliance of the air chamber.
5. Reflections of the propagated sound energy that

impinges on the diaphragm will change the effective equivalent electrical impedance.

Any or all of these factors may combine to give rapid changes in load impedance with changes in frequency.

It is apparent from these considerations then, that the plate load impedance presented to the push-pull amplifier may contain both resistance and reactance, and the load line plotted on the static plate characteristic curves in general will not be a straight line, as usually assumed, because the plate current will seldom be in phase with the plate voltage.

Presiman (8, pp 124-128) has shown that a reactive load line can be constructed on the static plate characteristics for a single tube by an adaptation of the point-by-point method of solving a differential equation. The equation for the voltages and currents in the circuit is first obtained, and then incremental time intervals of the grid voltage time wave are selected. These are plotted on the graph showing the variations in plate voltage and plate current with changes in grid voltage, and the load line obtained. The graphical process starts from the quiescent point, and thus the initial transient load line must be drawn before the steady-state load line can be obtained.

The relationship between the alternating components of plate voltage and plate current for a push-pull amplifier can be developed from the method suggested by Preisman for single tube amplifiers (8, pp 100-101). This will be done on the succeeding pages. With push-pull operation in class A, the composite current curves are nearly linear as shown in Figure 1. Assuming a sinusoidal grid voltage variation, and no magnetizing component of plate current, the resulting variation in composite tube plate current will be sinusoidal and can be expressed as

$$i_p = I_{pm} \sin \omega t \qquad (1)$$

where

i_p = instantaneous composite tube current

ω = 2π times the signal frequency

I_{pm} = maximum value of composite tube current

t = time

This current flows through the load impedance, which contains resistance and inductive or capacitive reactance at any given frequency.

$$Z_L = R_L + j X_L \qquad (2)$$

A voltage appears across the plate-to-plate load impedance that is not in phase with this current.

$$e_L = i_p Z_L = (I_{pm} \sin \omega t)(R_L + jX_L) \qquad (3)$$

$$e_L = I_{pm} R_L \sin \omega t \quad jI_{pm} X_L \cos \omega t \qquad (4)$$

By a change in variable

$$jI_{pm} X_L \sin \omega t = I_{pm} X_L \cos \omega t \qquad (5)$$

then

$$e_L = I_{pm}R_L \sin \omega t + I_{pm}X_L \cos \omega t \qquad (6)$$

As instantaneous values at certain time intervals are plotted on the graph,

$$I_{pm} \sin \omega t = i_p \qquad (7)$$

$$I_{pm} \cos \omega t = \sqrt{I_{pm}^2 - i_p^2} \qquad (8)$$

Substituting 7 and 8 in 6

$$e_L = i_p R_L + \sqrt{I_{pm}^2 - i_p^2} \quad X_L \qquad (9)$$

Mathematical manipulation to reduce this equation to recognizable form gives

$$e_L - i_p R_L = \sqrt{I_{pm}^2 - i_p^2} \quad X_L \qquad (10)$$

Squaring and combining terms

$$e_L^2 - 2\, e_L i_p R_L + i_p^2 Z_L^2 = I_{pm}^2 X_L^2 \qquad (11)$$

The instantaneous alternating component of plate voltage is the negative of the instantaneous load voltage or,

$$e_p = - e_L \qquad (12)$$

Substituting equation 12 in 11

$$e_p^2 + 2\, e_p i_p R_L + i_p^2 Z_L^2 = I_{pm}^2 X_L^2 \qquad (13)$$

The general equation for a conic section such as an ellipse as given by Sherwood and Taylor (10, p.8) is

$$ax^2 + 2\, bxy + cy^2 + 2\, dx + 2\, cy + f = 0 \qquad (14)$$

Equation 13, then, is the equation of an ellipse, and the instantaneous plate voltage and plate current curves will have an elliptical shape, and an origin at the quiescent point. The major axis will lie on a line determined by the resistance component of the impedance. The step-by-step construction of this elliptical load line on the composite characteristics is tedious, and if the load impedance changes appreciably with the frequency of the applied grid voltage, several such load lines would have to be constructed to graphically analyze the performance of the output stage. If self-bias is used on the amplifier stage, as is usually the case, self-rectification and a consequent shift in the operating point from the quiescent point will occur, thus further complicating the graphical construction.

If the ratio of resistance to reactance is large, the ellipse approaches a straight line whose slope is the negative reciprocal of the resistive component. This greatly simplifies the graphical analysis of the operation of the amplifier stage, as the straight load line can be drawn as indicated on page 3. Such a simplification is only valid where the characteristics of the load impedance are known. As far as could be determined in the literature, although the fact that reactive loads may occur has been recognized for some time (5,pp 490-498)(15, pp 175-6), the characteristics of the actual load impedance presented to the plate circuit of an amplifier stage for typical output transformers and loudspeakers are not available. A major contribution of this paper is the presentation of a set of curves showing the variation in the magnitude and phase angle for typical acoustical load elements.

METHOD FOR DETERMINING THE PLATE LOAD IMPEDANCE

Analysis of Measuring Circuit

The most fundamental method of finding the plate load impedance is by measuring the plate load voltage, the load current, and the phase angle between the voltage and current. The magnitude of the impedance can be obtained from Ohm's Law. The phase angle indicates the relative amount of resistance and reactance in the inpedance, and the nature of this reactance.

The magnitude of the usual plate load impedance, and the power level, indicate that instruments having high internal resistance, low shunt capacitance, and large frequency range of operation should be used to reduce the effect of the instrumentation on the actual load impedance. Certain electronic instruments; such as vacuum tube voltmeters, meet these requirements.

The method of obtaining the plate load impedance under actual operating conditions was developed by first analyzing the plate characteristics for a single tube, and then the plate characteristics for the composite tube of a push-pull amplifier. Figure 1, Page 3, shows that the individual tube currents for large changes in signal voltage will be non-linear, hence, the current flowing in one-half of the output transformer due to the single tube will be sinusoidal for sinusoidal signal voltages. As will be shown later, the measurement of the load impedance for a single tube under actual operating conditions is difficult, and in the usual analysis of a push-pull stage is not important, hence, only the plate-to-plate impedance was determined.

As shown on Page 3, the composite tube current is linear, but flows only in the primary winding. Ryder (9, p. 234) and others, have shown that no fundamental component of signal current flows in the plate voltage supply. The first problem in the measurement of the plate-to-plate load impedance is to measure this composite current. Assuming for the moment a perfect transformer, a sinusoidal alternating current in the total primary winding will give a sinusoidal variation in the magnetic flux, and result in a sinusoidal voltage across the total primary winding. Inasmuch as each half of the primary of a good output transformer has the same number of turns, and occupies a similar position around the core, the voltage across each half of the primary winding should be one-half the full winding voltage, and sinusoidal.

The magnitude of the plate-to-plate load impedance can be obtained from this plate-to-plate voltage, and the total (composite) primary current. The phase angle can be obtained from a Lissajous figure, obtained by applying the plate-to-plate voltage, and a voltage directly proportional to the alternating component of load current, to the deflection plates on an oscilloscope (11, pp 324-5). If a small resistor is inserted in series with the plate supply voltage and the lead to one-half of the primary winding, a voltage proportional to the single-tube plate current will appear across the resistor. Unfortunately, this single-tube current is non-linear. If a second identical resistor is placed in the plate supply lead to the other half of the primary winding, and a voltage measured across the two resistors in series, the non-linearity in tube currents cancels, just as in the construction of the composite current wave, and a sinusoidal grid signal voltage will result in a sinusoidal variation in voltage appearing across the two resistors. This voltage is directly proportional to the total alternating component of current in the total primary (plate-to-plate) winding. Figure 3 shows the ellipse which will result if two voltages of equal magnitude, but differing in phase position by 22.5 electrical degrees are applied to the horizontal and vertical deflection plates of a cathode ray tube. The phase angle in degrees can be obtained from the following equation if the ellipse is centered on a set of coordinate axes.

$$\text{Phase Angle} = \sin^{-1}\frac{B}{A} \tag{15}$$

Where

B = Distance between intersections of the ellipse with the ordinate

A = Total vertical height of the figure

An inspection of the figure will show that in-phase voltages will reduce the figure to a straight line, and out-of-phase voltages will enlarge the ellipse to a circle. The use of sinusoidal voltages is required for good accuracy, and constitutes the major limitation to this method of measuring plate load impedance.

Measuring Circuit Used

The preliminary analysis just given indicates the type of actual measurement circuit which was used. The method of obtaining the primary plate-to-plate current required an output transformer with each half of the primary winding brought out to separate terminals. Most push-pull output transformers have only one lead brought out for the two ends of the windings which connect to the plate voltage supply. One amplifier was found which had all output transformer primary connections brought out to separate terminals. This was a specially designed high-quality amplifier constructed at Oregon State College. The portion of the amplifier used in the tests consisted of a push-pull triode stage driving a triode push-pull parallel Class A power amplifier, completely transformer coupled. Preliminary tests showed that typical phase inverters would not give balanced grid voltages at all frequencies to the power amplifier stage. The

PHASE ANGLE MEASUREMENT BY LISSAJOUS FIGURE

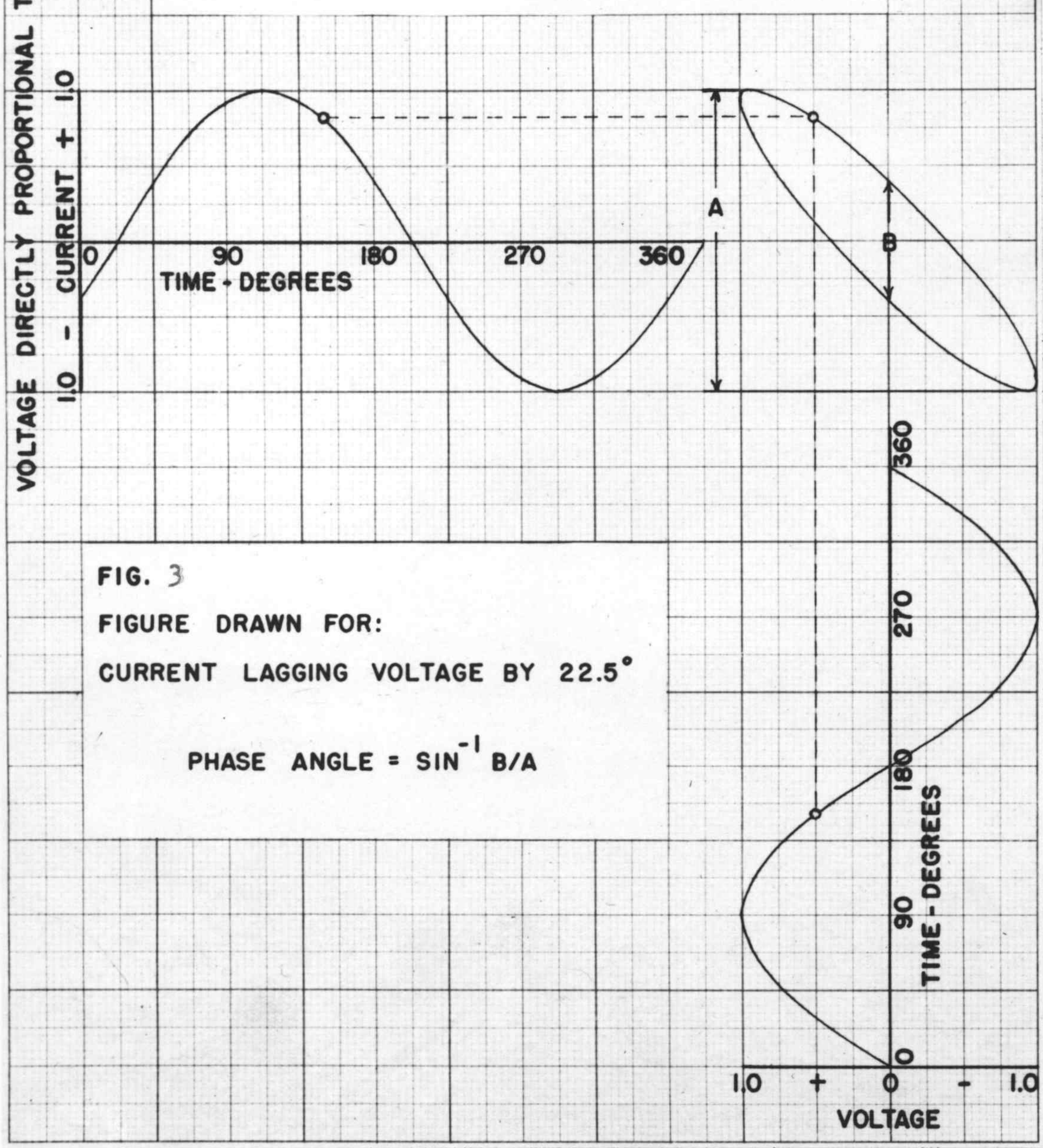


FIG. 3

FIGURE DRAWN FOR:

CURRENT LAGGING VOLTAGE BY 22.5°

PHASE ANGLE = $\sin^{-1} B/A$

characteristics of the amplifier as designed, and as established by preliminary test are listed in the Appendix (Page 64).

Preliminary measurements of the amplifier showed that conditions in practice were not exactly as predicted in the preceding theoretical analysis. Outputs at high power levels resulted in definite visible distortion in the voltage and current wave shape as viewed on an oscilloscope. All preliminary tests were conducted below this point of definite distortion, as the analysis by a General Radio Wave Analyzer of the voltage proportional to the primary (composite) current showed that a measured sinusoidal grid signal giving about half of the rated power output from the amplifier gave almost a true sinusoidal variation in the primary current (Appendix, Page 68). Some harmonic components were evident and were especially noticeable at the low frequencies below 100 cycles per second. This distortion is due primarily to the magnetizing requirements of the output transformer at low frequencies, and establishes the lower limit at which test measurements could be made. The upper frequency limit was established at 15,000 cycles per second, the highest frequency to which the average human ear responds. The total primary voltage and the voltages across one-half of the primary winding were analyzed in the same way (Appendix, Page 65) and found to contain harmonic components. These components were predominately third harmonics at the lower frequencies. This distortion of both voltage and current wave forms by the magnetizing requirements of the output transformer can be deduced from the wave forms obtained for the limiting cases of a perfect sinusoidal voltage generator, which has zero internal resistance, and the perfect sinusoidal current generator, which has infinite internal resistance, and hence has distortion of both voltage and current. Second harmonic components were present in both the voltage and current waves indicating the difficulty in obtaining exactly balanced conditions in a practical push-pull amplifier.

The voltage wave form across one-half of the primary, and the voltage obtained from a voltage divider connected across the full primary were analyzed for signal frequencies of 100 to 5000 cycles per second (Appendix, Page 66). The grid signal voltage of the power amplifier stage had already been analyzed, and the harmonic components were negligible.

The voltage across the full primary had less harmonic content that the voltage across one-half of the primary, however, the loading effect of the unbalanced wave analyzer may have affected the results. These measurements indicated that the harmonic components in the voltage waves were less than three per cent. The second harmonic component increased and the third harmonic component decreased with an increase in frequency.

This distortion in the voltage and current wave shapes indicated that the instrumentation should have some tolerance for harmonics. The Hewlett-Packard Model 400-A vacuum tube voltmeter (Electrical Specifications, Appendix Page 67) responds to the average value of the rectified full wave which minimizes the errors due to harmonics in the applied voltage. The instrument has nine ranges from 0.03 volts to 300 volts and is calibrated to read directly in effective values of the sine wave. Its tolerance for harmonics as specified by the manufacturer is (3, p 1):

% Harmonic	Actual Rms Value	400-A Indication
0	100.	100
10 % 2nd	100.5	100
20 % 2nd	102.	100-102
50 % 2nd	112.	100-110
10 % 3rd	100.5	96-104
20 % 3rd	102.	94-108
50 % 3rd	112	90-116

The instrument is accurate to three per cent for voltages having a frequency from 10 to 100,000 cycles per second. The very high input resistance and low shunt capacitance will not introduce appreciable errors in the measurements. The instrument has an unbalanced input (one terminal at instrument case potential) which means that measurement from plate-to-plate of the push-pull stage is not practical. As has already been shown, the voltage across one-half of the primary winding is essentially equal to one-half the full primary winding voltage, and indentical with it. Measurements confirm this equality, therefore, the one-half primary voltage was measured in the test.

The vacuum tube voltmeter connections are shown in the circuit diagram (Figure 4) for measuring plate-to-plate load impedance. The instrument measures the voltage directly across one-half of the primary winding. A knife switch allowed the same voltmeter to be used to measure the voltage proportional to the full primary current as indicated on the diagram. The case of the instrument is above alternating current ground potential by 3.15 ohms, and hence, shunts an estimated capacitance of 500 micro-microfarads across one resistor that does not appear across the other. The low value of resistance makes negligible the shunting effect of this capacitance at the audio frequencies used. The 3.15 ohm resistance introduced in this current measuring circuit did not appreciably affect the operation of the amplifier, as this resistance was less than ten per cent of the inherent direct current resistance of one-half of the primary winding. The actual value of the primary signal current was determined by dividing the measured voltage across the two resistors by 6.30 ohms.

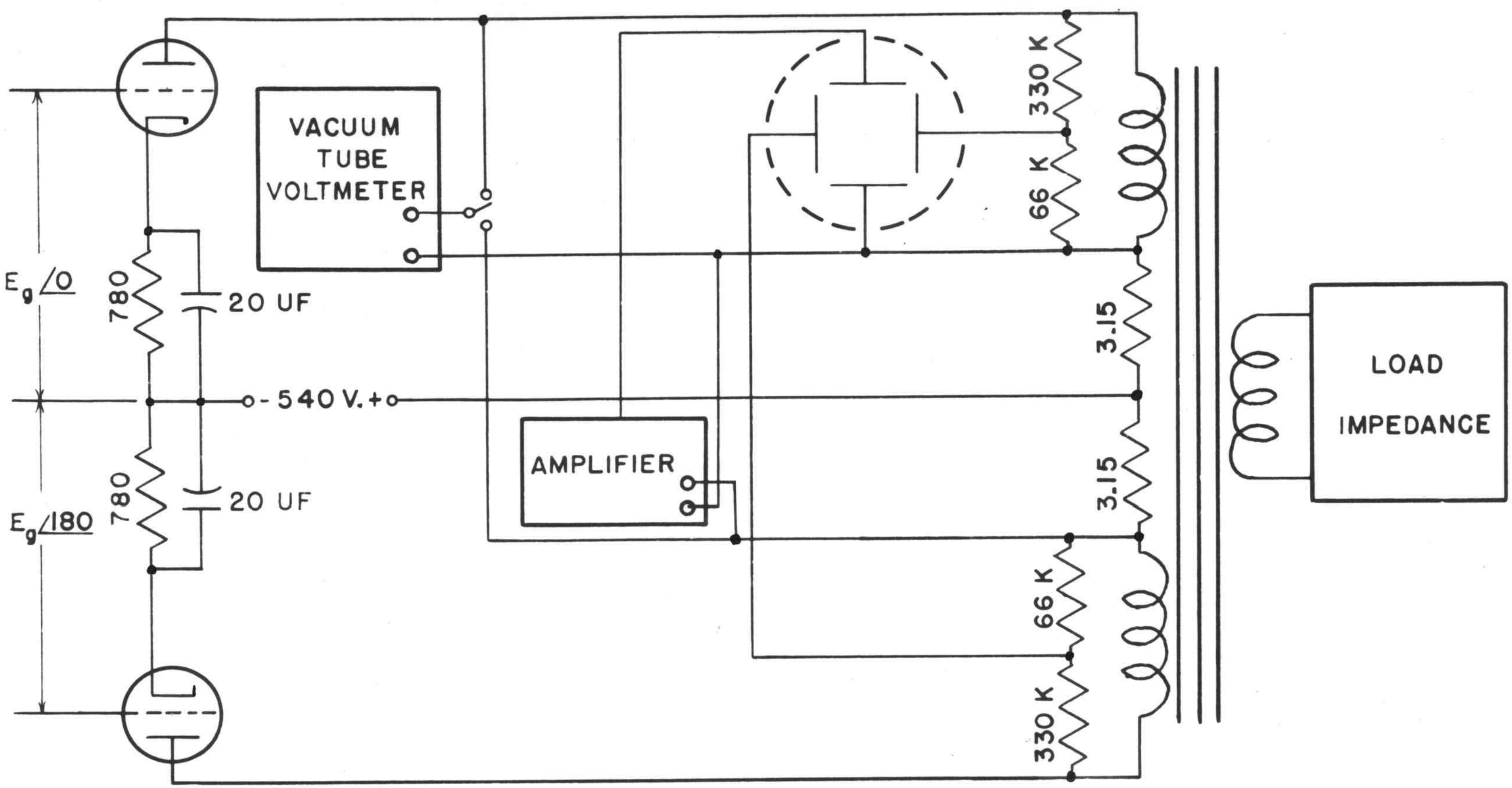


FIG. 4 CIRCUIT FOR MEASURING PLATE TO PLATE LOAD IMPEDANCE

The magnitude of the plate-to-plate load impedance was calculated by:

$$/Z/ = \frac{2 R E_{p2}}{E_I}$$

where

E_{p2} = Effective value of voltage across one-half of the primary winding

E_I = Effective value of voltage proportional to primary current

R = Total series resistance of the current measuring circuit

The oscilloscope used to obtain the phase angle of the impedance from a Lissajous figure was a Tektronix Model 511AD (Electrical Specifications, Appendix, Page 68). The oscilloscope allowed direct connection to the horizontal deflection plates, however, the available plate load voltage greatly exceeded the amount required for a reasonable sized figure, and the beam-centering control was inoperative. Tests showed that the direct current voltage drop across one-half of the primary winding would decenter the beam, therefore a voltage divider was designed and placed across the full primary winding as shown in Figure 4, and a balanced voltage proportional to the full primary voltage applied to the horizontal deflection plates. Due to the balanced design, it was not necessary to frequency compensate these dividers. The total resistance of the dividers is at least eighty times the measured impedance, and thus is negligible.

The voltage proportional to the total primary current was about 0.4 volt, and thus inadequate for direct vertical deflection of the oscilloscope. The two-stage video-type amplifiers incorporated within the scope have sufficient amplification to give adequate deflection on the cathode ray tube with this small amount of voltage. The use of an amplifier between the voltage proportional to current, and the actual deflection voltage will usually introduce a phase angle between these voltages which varies with frequency. Allowance must be made for this amplifier phase shift when calculating the plate load impedance phase angle. A special frequency compensated voltage divider was designed, and the phase shift of the amplifiers measured. Due to the wide band design of these amplifiers, the phase shift over the portion of the audio frequency spectrum used in these tests was found to be zero degrees. In this case, then, the phase angle as calculated from the Lissajous figure is the actual phase angle of the load impedance.

A theoretical analysis of the amount of distortion of the voltage waveshapes that can be tolerated for good accuracy in measurement showed that the magnitude and phase position of the harmonic components of the distorted wave affected the measurement of the phase angle considerably.

The magnitude of each harmonic component can be easily measured by a wave analyzer, as was done in the tests, but the phase position is difficult to determine. In general, the magnitude of the harmonic components should not exceed five per cent of the fundamental for good accuracy in measuring the phase angle. Typical Lissajous figures for frequencies from 10,000 to 75 cycles per second are shown in Figures 5, 6, and 7. These photographs were made directly from the screen of the cathode ray tube and show a broad trace because of the high beam intensity and long exposure time required. The photographs show the ellipses which were obtained between 10,000 and 500 cycles per second. At 100 cycles per second (Figure 7 A) the ellipse is becoming visibly distorted. At 75 cycles per second (Figure 7 B) the figure is not elliptical because of a large, predominately third, harmonic component, and the phase angle cannot be determined directly.

The sign of the angle can not be easily determined directly from the Lissajous figure, however, the shunting of a known kind of reactance across the load will result in an increase or decrease in the size of the ellipse. If the ellipse increases in size, the unknown reactance is of the same kind as the known reactance. Switched capacitors are the most convenient sources of reactance to use.

As it is necessary to use the total primary current

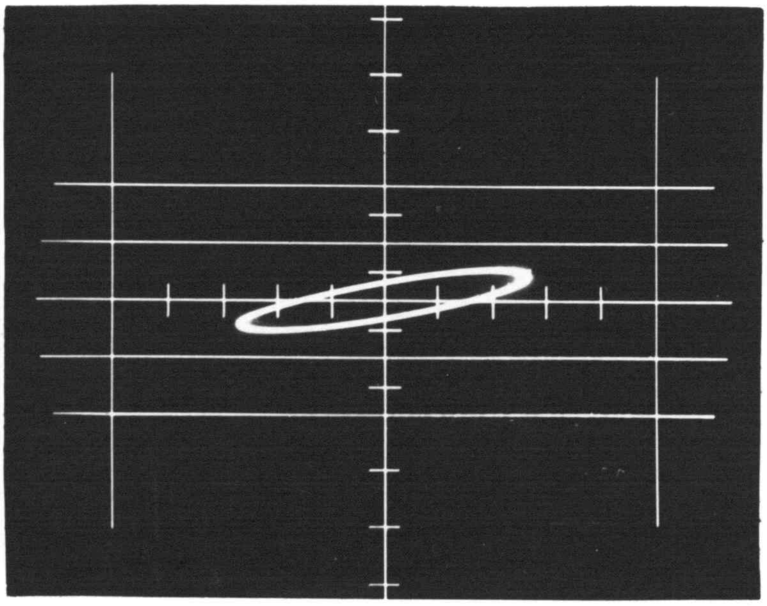


Fig. 5-A 10,000 cycles per second

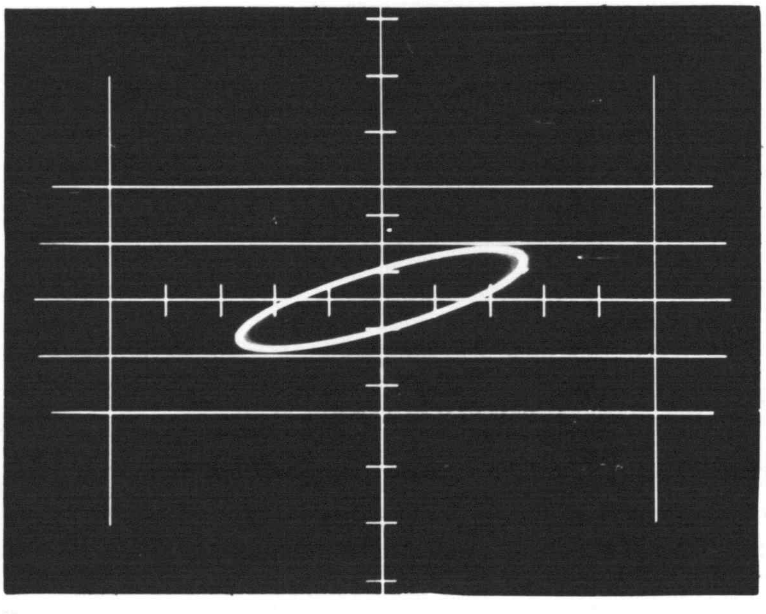


Fig. 5-B 5,000 cycles per second

Fig. 5 Typical Lissajous Figures

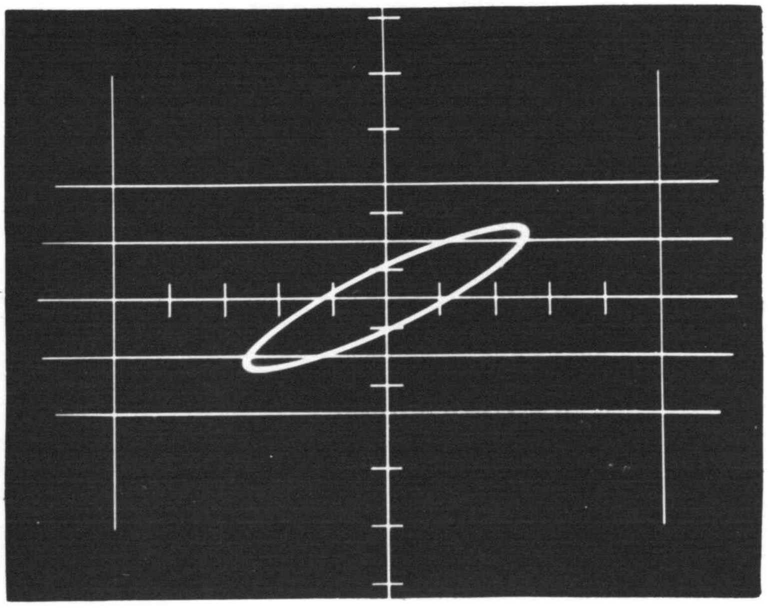


Fig. 6-A 1000 cycles per second

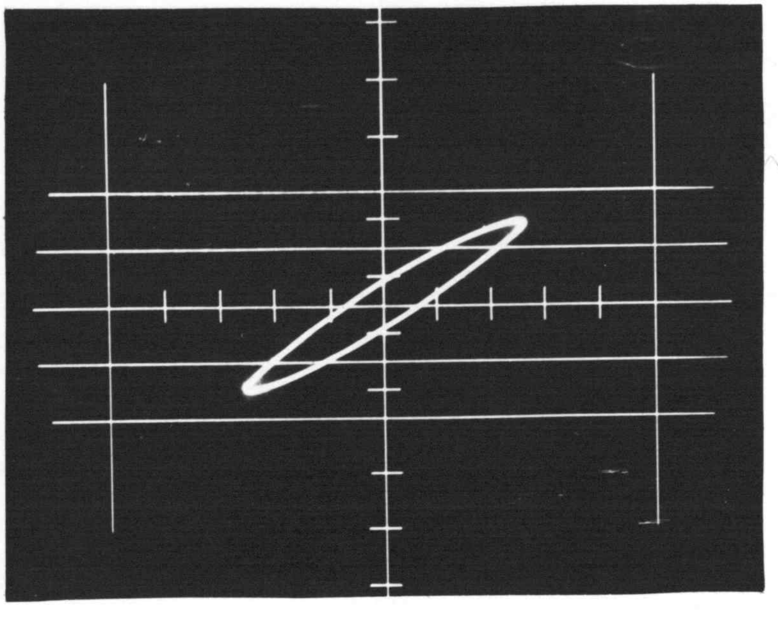


Fig. 6-B 500 cycles per second

Fig. 6 Typical Lissajous Figures

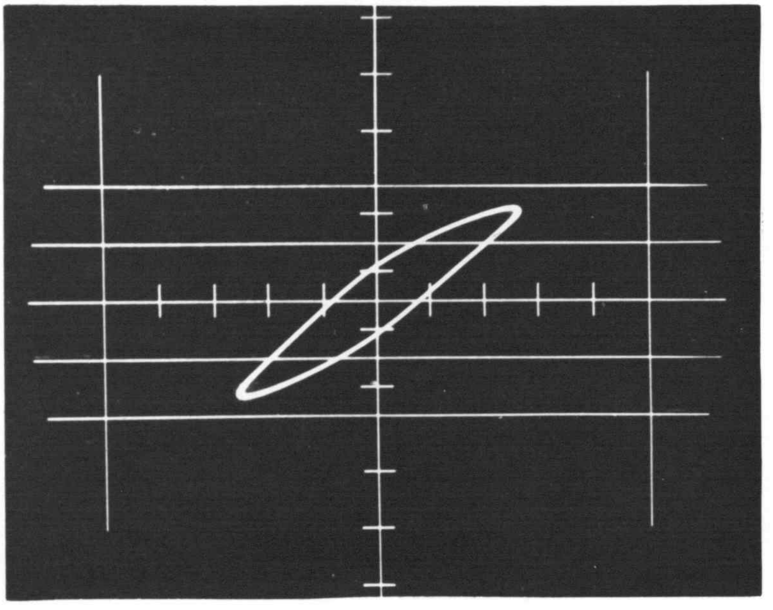


Fig. 7-A 100 cycles per second

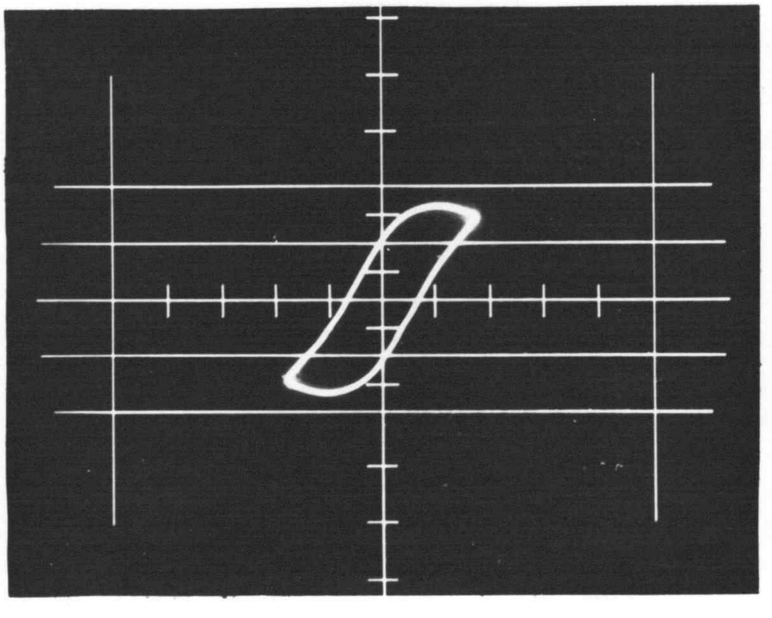


Fig. 7-B 75 cycles per second

Fig. 7 Typical Lissajous Figures

wave shape for the oscilloscope deflection, and the amplifier input is unbalanced to ground, the case-to-ground capacitance of this instrument is also shunted across one of the 3.15-ohm resistors, but can be neglected, because the ratio between this reactance and the 3.15-ohm resistance is very large at the highest frequency used.

Estimated Accuracy of Measurements

The magnitude of the impedance was determined from a voltmeter measuring the voltage across one-half of the primary, and a total primary current obtained by dividing a voltage by a known resistance.

1. Measurement indicated the voltage across one-half of the primary was essentially one-half of the total primary voltage.
2. The manufacturer states the instrument is accurate to three per cent (3, p. 3). Preliminary calibration at 60 cycles per second showed the two scales used (0-300), (0-1.0) were within one per cent of the secondary standard. Although higher frequencies were used, and small harmonic components were present, it is felt the instrument accuracy is within three per cent.
3. The non-inductive resistors in the current measuring circuit were selected and measured with a standard impedance bridge having an accuracy of

one per cent (1, p. 1).

The maximum error in the magnitude of the impedance was calculated from the following expression:

$$\% \text{ error} = \frac{\text{Maximum Impedance - Correct Impedance}}{\text{Correct Impedance}} \times 100 \qquad (17)$$

The maximum impedance was calculated from Equation 16 using the extreme expected deviation in each of the quantities and choosing the direction of the deviation so as to give the maximum impedance. The maximum error in the magnitude of the impedance is 7.2 per cent.

The accuracy of the phase angle measurement is not as easily determined. The height of the Lissajous figure varied from about 0.56 to 1.4 inches. A special graticule was made having a set of coordinatesaxes with dividing lines 0.10 inch apart. The intersection with the ordinate, and the total height of the figure were obtained from these lines, and by estimating to the nearest tenth between lines. The elliptical beam trace on the oscilloscope was not of uniform width at the center and at the ends, and it was necessary to be consistent in measuring to the same side of the trace. The error would be larger for a small figure than a larger one, and as the sine of the angle depends on two lengths, one often as much as five to ten times the other, the accuracy of the phase angle measurement is estimated to be between five and ten per cent.

TEST PROCEDURE

The tests were performed in the roof-top Radiation Laboratory of Dearborn Hall, Oregon State College. Modifications of some of the equipment, construction of voltage dividers and current shunts and assembly of the units into test position was required. Figures 8, 9, and 10 show the test position and physical location of equipment. The loudspeakers, with one exception, were mounted on the roof directly above the test position and connected to the amplifier by twenty-two feet of No. 18 stranded parallel conductor copper cable. Figure 11 shows the typical location of the test speakers.

The loudspeakers were mounted on a stand about three feet above roof level which brought the bell of the horn well above the parapet. The loudspeakers were directed vertically toward free space, thus eliminating any reflections from surfaces in front of the speaker. The horn type projectors are quite directive, and the vertical orientation reduced the annoyance to other groups in the locality. Although loudspeakers are normally operated in horizontal rather than vertical position, the method of suspension of the voice coil, and the relative lightness of the aluminum diaphragm in the horn-type loudspeakers indicates that results will not appreciably be affected by this vertical position. The manufacturers do not

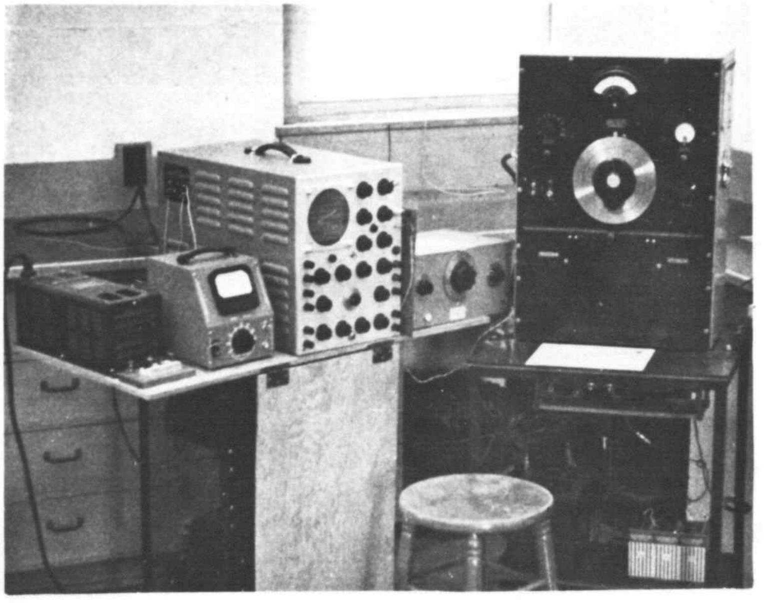


Fig. 8 Instruments in test position. Left to right, Voltage regulating transformer, vacuum tube voltmeter, oscilloscope, and audio oscillator mounted on plywood cover above amplifier. Wave analyzer on separate table.

Fig. 9 Rear view of amplifier and power supply with plywood cover removed. Driver stage on left, power amplifier stage on right of upper chassis, power supply on lower chassis.

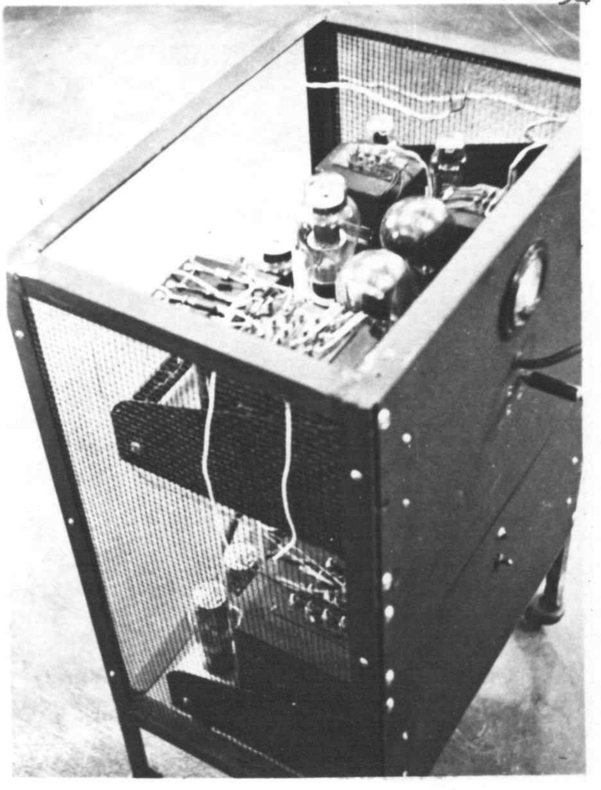


Fig. 10 Top view of amplifier. Voltage dividing network mounted on output transformer (Long leads connect to instruments on removable plywood cover).

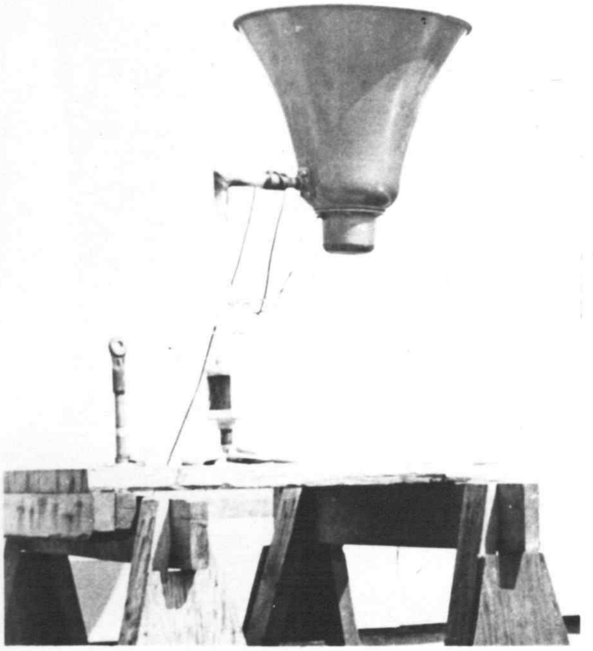


Fig. 11 Test position of re-entrant horn type speaker. Jensen Annular driver and projector.

specify any limitations as to speaker position.

Certain modifications, adaptations, and tests were necessary before the plate-to-plate load impedance could be measured.

The amplifier was modified in the following manner:

1. Variable potentiometer inserted in one cathode bias circuit of the power output stage to allow small bias changes in order to match the no-signal plate current of each set of tubes.
2. Tubes switched around to match plate currents at same grid bias voltage.
3. Bias control on driver tubes installed to allow balancing of driver tube current.
4. 500-ohm resistor installed across primary of input transformer to driver stage to serve as load impedance for audio-oscillator. This was necessary to give sinusoidal output voltages from oscillator.
5. General Electric voltage stabilizing transformer installed to regulate the line supply voltage, as the commercial supply varied intermittently, changing conditions of operations and introducing low frequency transients.
6. Plywood cover and front panel installed to isolate instruments from grounded frame of amplifier and protect personnel.

7. Voltage divider network and resistors for obtaining a voltage proportional to current were assembled on a bakelite terminal board and mounted on the output transformer.

The Hewlett-Packard Model 400A vacuum tube voltmeter to be used in the tests was calibrated at 60 cycles against a General Electric Type P-3 voltmeter (a secondary standard calibrated in 1949). The greatest deviation from the standard was less than one per cent of full scale indication. The manufacturer states the accuracy should be within three per cent. The voltmeter connections are shown in Figure 4, Page 23.

The Tektronix Model 511AD oscilloscope did not require modification, as convenient banana plugs allow connection directly to the deflection plates. As has been mentioned before, the vertical amplifiers were calibrated for phase shift and found to have zero phase shift over the 100 to 20,000 cycles per second audio frequency range. The graticule furnished with the oscilloscope has divisions as indicated in the pictures of typical Lissajous figures on Pages 27-29. This graticule is excellent for photographic purposes but is not satisfactory for the measurements required to obtain the phase angle. A square of Plexiglass was obtained and a new graticule machined, with dividing lines each 0.10 inch, the fifth lines accentuated for easy identification. The co-ordinates B and A, from which the phase angle was calculated, could then be read, the intervals between the lines being estimated by eye. Because of the distance between the engraved screen and the actual fluorescent image on the screen of the cathode ray tube, precautions were taken to eliminate parallax. With proper lighting conditions, it was found that the image of the eye could be seen reflected from the glass face of the tube. Superimposing the point to be read on the image of the eye eliminated the parallax.

The cases of the oscilloscope and the vacuum tube voltmeter were each at a direct current potential of 540 volts above ground as shown in Figure 4. Extreme caution in the handling and adjustment of controls had to be observed while the equipment was in operation. The voltage stabilizing transformer supplying line voltage to the amplifier had a loud hum; as this transformer was energized only when the amplifier was in operation, it served as an audible warning that high voltage existed on certain equipment.

The Hewlett-Packard Model 200-B Audio-oscillator (Electrical Specifications, Appendix, Page 67) furnished the sinusoidal voltages to the input transformer to the Type 56 driver tubes. The oscillator has three ranges, 20-200, 200-2,000, and 2,000-20,000 cycles per second. The dial has a logarithmic scale, with major divisions and sub-divisions indicated. Because of the short length of scale, and width of division markers, the frequencies used in the test are accurate to two figures, the third figure is obtained by interpolation.

The oscillator at ground potential was located within one inch of the oscilloscope, but was isolated from accidental contact by a partition which also served to restrain the operator from changing the voltmeter switch while adjusting frequency.

The General Radio Wave Analyzer Type 636A (Electrical Specifications, Appendix, Page 68) was used to measure the magnitude of the harmonic components of primary voltage and current. It was mounted on a separate table, battery operated, and has the manufacturer's rated accuracy of five per cent. The readings of the fundamental applied voltage were within two per cent of the voltage as measured by the Hewlett-Packard voltmeter.

Many preliminary measurements were made to establish the operating conditions of the amplifier and to obtain voltage and currents to use in the design of the load impedance measuring circuit. For alternating current voltages, the Hewlett-Packard Model 400A voltmeter was used. Direct current voltages and currents were measured with Weston Type 301 Instruments of two per cent accuracy. All precautions were taken to obtain precise measurements.

Each measurement of plate-to-plate load impedance was preceded by a one-half hour or longer warm-up period.

During this warm-up period, the power output was approximately 15 watts at 1000 cycles per second, and 140 volts across one-half of the output transformer.

The primary voltage, the voltage proportional to current, and the coordinates of the Lissajous figure were recorded and the primary voltage checked before changing frequency for each measurement. The frequency was reduced slowly toward the next specified frequency. The Lissajous figure was observed closely during the transition, and if sufficient change in shape of the Lissajous figure occurred indicating a change in impedance or phase angle, the frequency was adjusted to show the maximum deviation, the voltage adjusted to 140 volts, and the frequency, current, and phase angle were measured. This gave many intermediate points, especially where slight changes in frequency resulted in obvious changes in the Lissajous figure. Measurements were continued to 100 cycles per second, except in two cases where visible distortion of the Lissajous figure indicated that measurements of phase angle would be in error below 200 cycles per second.

The magnitude and phase angle were calculated, and the power output of the amplifier to the output transformer was calculated by

$$P = E\,I\cos\theta \qquad (18)$$

where

E = Effective value of plate-to-plate voltage--volts.

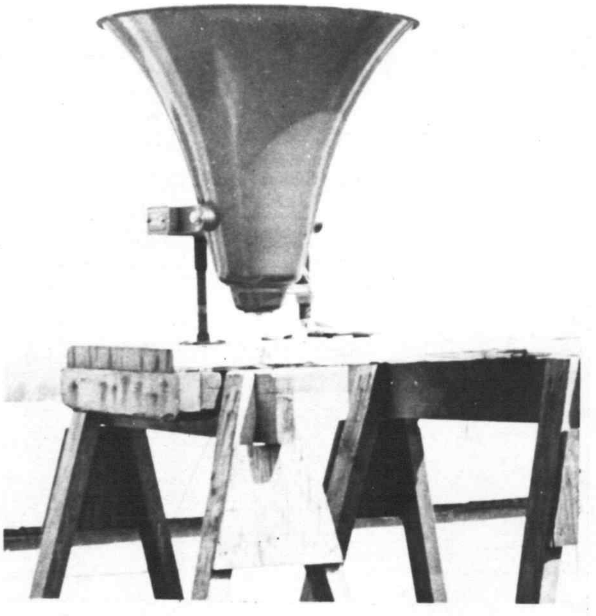
I = Effective value of plate-to-plate current--amperes.

θ = Phase angle between voltage and current.

The plate-to-plate impedance, phase angle, and power output were plotted as a function of the signal frequencies on semi-logarithmic graph paper. Each point plotted was connected to the next by a straight line. Although the variations between points of measurement were smooth, the straight line procedure was used as the measurements were made at small frequency intervals, and the rapid variation of the quantities for a small change in frequency in many cases precluded obtaining any but the maximum and minimum readings. These curves are discussed in a subsequent section.

Measurements were made on six different loudspeakers and one pure resistance. Four of the loudspeakers tested were of the re-entrant horn type, one of cone type with short exponential horn, and one of cone type enclosed in a bass-reflex baffle. These are typical of acoustical loads placed on audio frequency power amplifiers. The horn type speakers are usually used outdoors or in large enclosed spaces, where reflections to the driver element are negligible. This condition was simulated in the test positions as shown in Figures 12 and 13. A cone

Fig. 12 Test position of re-entrant horn type speaker. Jensen Hypex driver and projector.



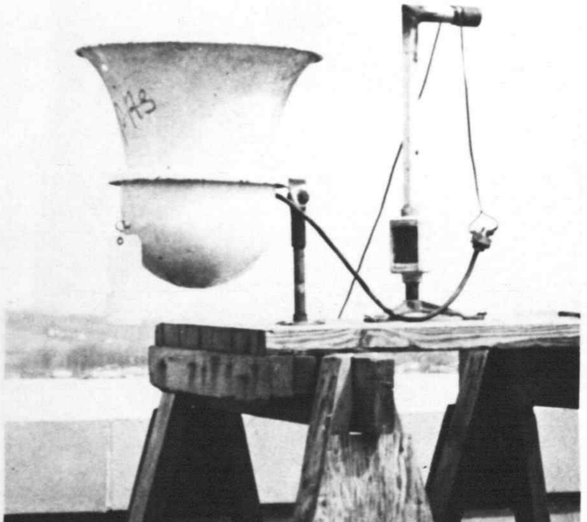


Fig. 13 Test position of cone-type speaker with short exponential horn. Radio Corporation of America - MI 4220

type speaker in a baffle is usually used in a small confined space where reverberations and reflections are present. It is difficult to obtain an "average" operating location, so this speaker was also tested with free space in front of the speaker, as shown in Figure 14. The baffle was laid flat on the roof about twenty feet from the penthouse. This position gave some reflection from the penthouse wall, as definite standing waves could be heard between the wall and the speaker. Due to the wide angle of dispersion of sound energy from the baffle, reflections probably occurred from the roof surface. The test conditions would simulate a baffle mounted on a wall of a room having good but not perfect sound absorbing qualities.

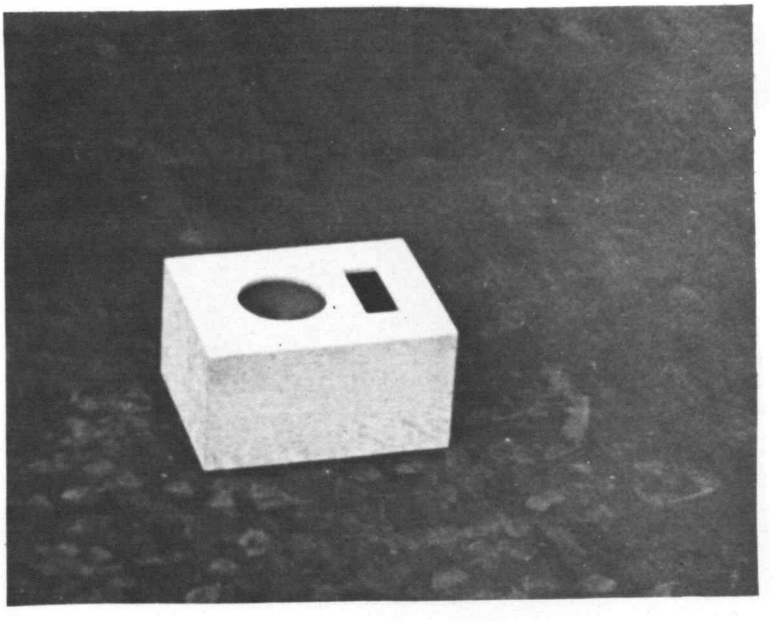


Fig. 14 Test position of cone-type speaker in bass reflex baffle.

DISCUSSION OF RESULTS

In the following pages are shown variations in plate-to-plate impedance and power output for a pure resistive load, and for six different loudspeakers, connected separately to the amplifier.

The impedance transforming and phase angle characteristics of the output transformer were obtained by using a special non-inductive low-capacitance 16.5-ohm resistance (Ward-Leonard Plaque Type) as a load element. Figure 15 shows the small variation in plate load impedance between 100 and 15,000 cycles per second. The deviation from the 1000 cycle value is only 3.5 per cent at each end of the frequency range. The impedance curve shows only a slight variation. The phase angle indicates inductive reactance, and decreases uniformly from 10 degrees at 100 cycles to 3.5 degrees at 1000 cycles and increases smoothly to 14 degrees at 15,000 cycles per second. Lee (6, p. 126) indicates that the maximum phase angle of an output transformer should not exceed 30 degrees, and states that for the best design, it will not exceed 15 degrees. The power output is relatively constant, decreasing at the higher frequencies as would be expected with an increase in impedance and phase angle. Although the transformer is rated for a 5000 to 16-ohm (313 - 1) impedance transformation, the actual impedance transformation is 4550 to 16.5 (282-1).

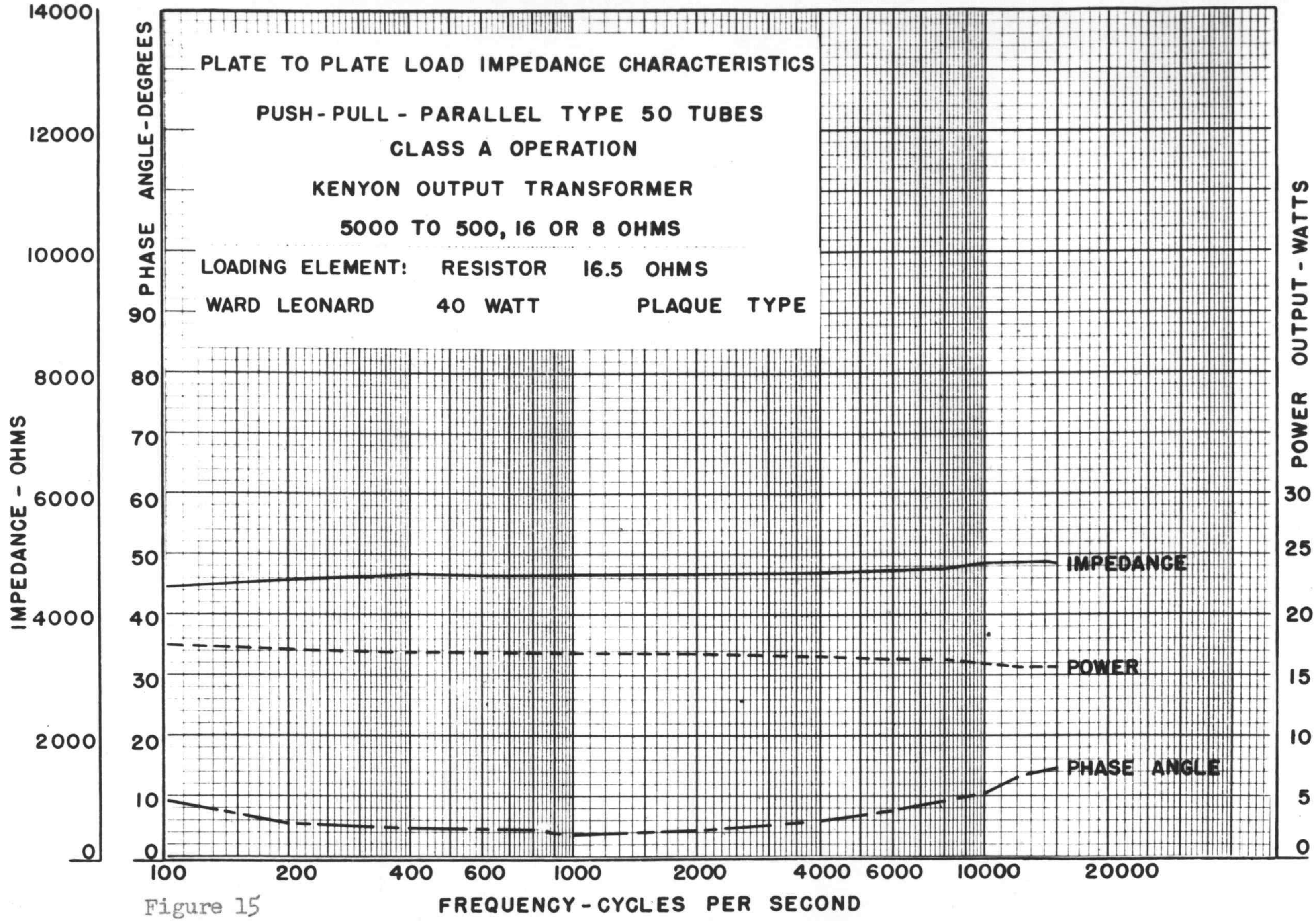


PLATE TO PLATE LOAD IMPEDANCE CHARACTERISTICS
PUSH-PULL - PARALLEL TYPE 50 TUBES
CLASS A OPERATION
KENYON OUTPUT TRANSFORMER
5000 TO 500, 16 OR 8 OHMS
LOADING ELEMENT: RESISTOR 16.5 OHMS
WARD LEONARD 40 WATT PLAQUE TYPE
IMPEDANCE - OHMS
14000
12000
10000
8000
6000
4000
2000
0
PHASE ANGLE-DEGREES
90
80
70
60
50
40
30
20
10
0
POWER OUTPUT - WATTS
30
25
20
15
10
5
0
IMPEDANCE
POWER
PHASE ANGLE
100
200
400
600
1000
2000
4000
6000
10000
20000
FREQUENCY - CYCLES PER SECOND

Figure 15

The significance of these smooth, relatively constant curves characteristic of a pure resistance load on the output transformer, is that a loudspeaker offering a pure load resistance would show the same characteristics. The assumption of a single resistive load line in the design of an amplifier using such a loudspeaker would be justifiable. The plate load impedance, phase angle, and power output expressed as a per cent of the value at 1000 cycles per second for the acoustical loads used in the test are tabulated in Figure 16.

Type of Load Element	Load Impedance 100 cycles	Load Impedance 15000 cycles	Phase Angle 100 cycles	Phase Angle 15000 cycles	Power Output 100 cycles	Power Output 15000 cycles
Resistance	96.	104.	225.	350.	103.	91.
Jensen Hypex	82.	220.	80.	267.	125.	35.
Jensen Annular	79.	238.	70.	200.	132.	35.
University[1] Small Horn	70.	(1) 125.	153. (3)	270.	130.	69.
University[2] Large Horn	81.	(2) 131.	67	142.	138.	73.
Cone Type With Horn	85. (3)	396.	76. (3)	99.	117.	25.
Cone Type With Baffle	93.	374.	18.	89.	120.	28.

Note 1. Maximum impedance at 1590 cycles - 130
Note 2. Maximum impedance at 1590 cycles - 178
Note 3. At 200 cycles

Figure 16. Plate Load Impedance, Phase Angle, and Power Output Expressed as a Per Cent of the Value at 1000 Cycles per Second

Jensen Hypex Horn Loudspeaker

The plate load impedance and power output characteristics with the Jensen Hypex re-entrant horn type loudspeaker connected to the amplifier are shown in Figure 17. Variations are smooth, the magnitude of the impedance and phase angle increase at higher frequencies, and the power output decreases. Over the manufacturer's rated frequency range, from 200 to 5000 cycles per second, this loudspeaker shows the best plate-to-plate load characteristics of any tested.

Jensen Annular Horn Loudspeaker

The characteristic curves of this speaker are shown in Figure 18. The variations in plate load impedance, phase angle and power output show several rapid changes for only a small change in frequency. Above the rated frequency range, the impedance and phase angle increase markedly. Both Jensen speakers show an inductive reactance associated with the plate-to-plate load impedance.

University Driver and Small Horn Loudspeaker

The characteristic curves of the University Driver and small re-entrant horn are shown in Figure 19. The plate load impedance and phase angle do not change over as wide a range as did the Jensen speakers, however, the

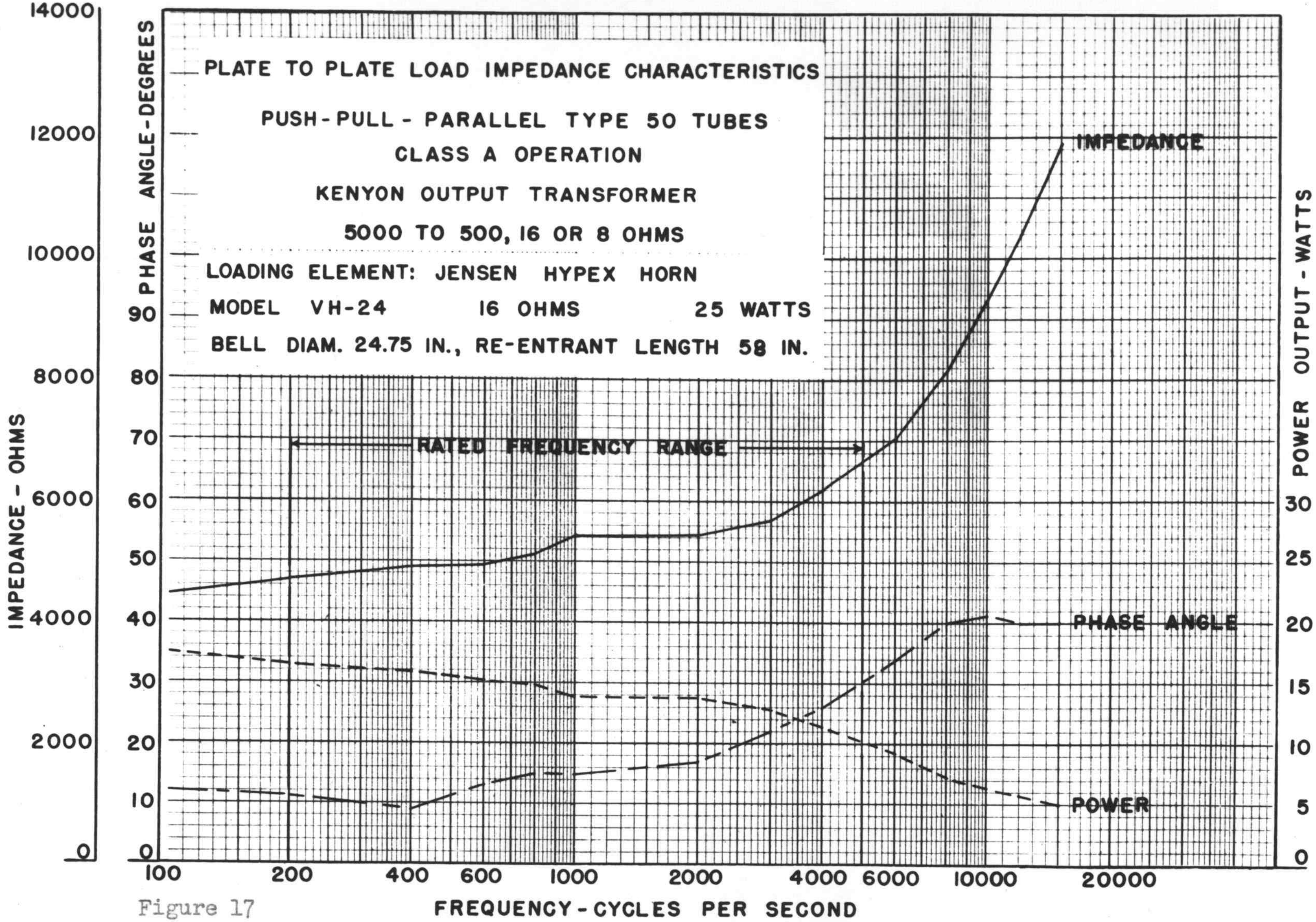


PLATE TO PLATE LOAD IMPEDANCE CHARACTERISTICS
PUSH-PULL - PARALLEL TYPE 50 TUBES
CLASS A OPERATION
KENYON OUTPUT TRANSFORMER
5000 TO 500, 16 OR 8 OHMS
LOADING ELEMENT: JENSEN HYPEX HORN
MODEL VH-24 16 OHMS 25 WATTS
BELL DIAM. 24.75 IN., RE-ENTRANT LENGTH 58 IN.
IMPEDANCE
RATED FREQUENCY RANGE
PHASE ANGLE
POWER
IMPEDANCE - OHMS
14000
12000
10000
8000
6000
4000
2000
0
PHASE ANGLE-DEGREES
90
80
70
60
50
40
30
20
10
0
POWER OUTPUT - WATTS
30
25
20
15
10
5
0
100
200
400
600
1000
2000
4000
6000
10000
20000
FREQUENCY - CYCLES PER SECOND
Figure 17

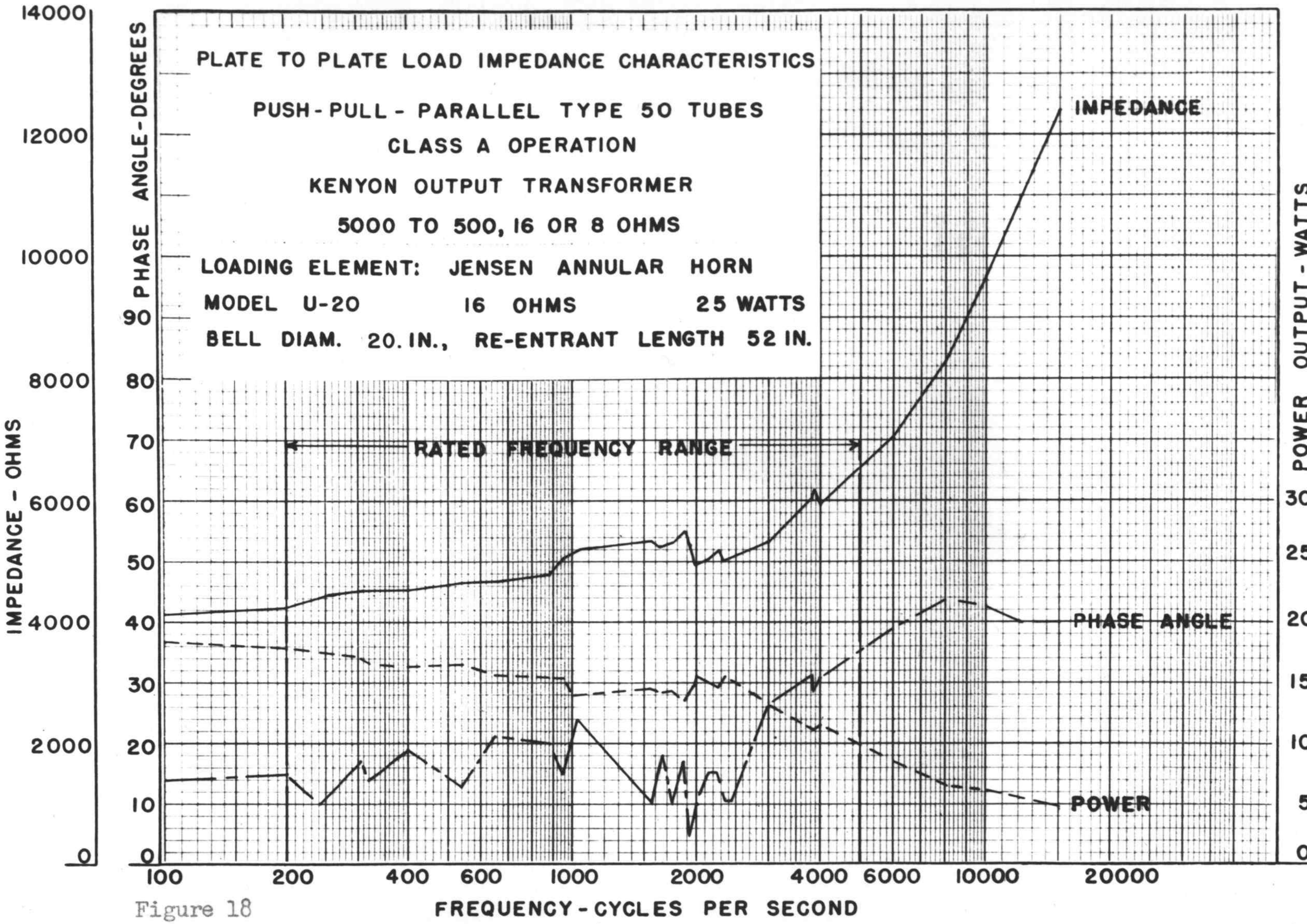


PLATE TO PLATE LOAD IMPEDANCE CHARACTERISTICS
PUSH-PULL-PARALLEL TYPE 50 TUBES
CLASS A OPERATION
KENYON OUTPUT TRANSFORMER
5000 TO 500, 16 OR 8 OHMS
LOADING ELEMENT: JENSEN ANNULAR HORN
MODEL U-20 16 OHMS 25 WATTS
BELL DIAM. 20. IN., RE-ENTRANT LENGTH 52 IN.
RATED FREQUENCY RANGE
IMPEDANCE
PHASE ANGLE
POWER
IMPEDANCE - OHMS
PHASE ANGLE-DEGREES
POWER OUTPUT - WATTS
FREQUENCY-CYCLES PER SECOND
0
2000
4000
6000
8000
10000
12000
14000
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
100
200
400
600
1000
2000
4000
6000
10000
20000

Figure 18

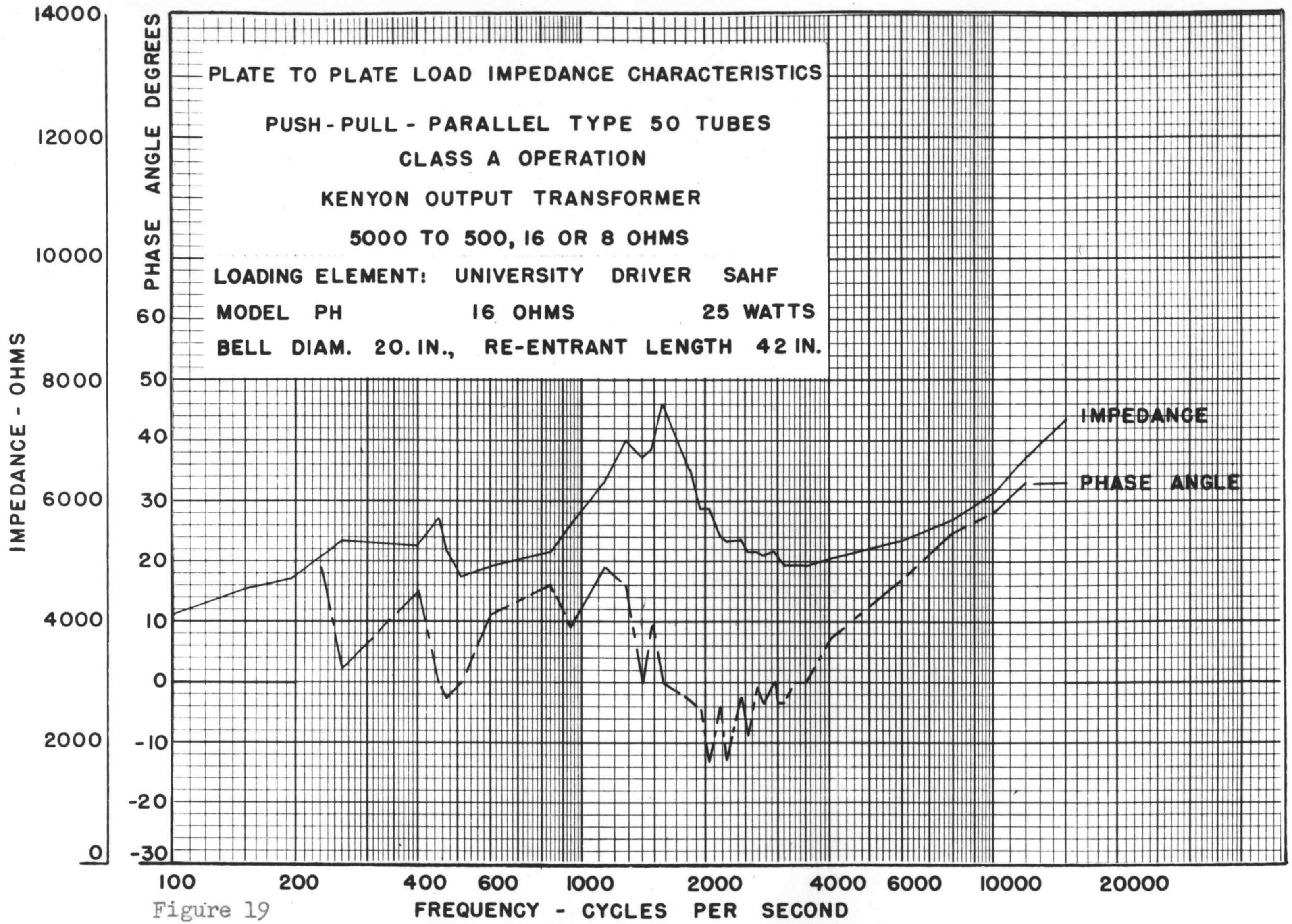


PLATE TO PLATE LOAD IMPEDANCE CHARACTERISTICS
PUSH-PULL - PARALLEL TYPE 50 TUBES
CLASS A OPERATION
KENYON OUTPUT TRANSFORMER
5000 TO 500, 16 OR 8 OHMS
LOADING ELEMENT: UNIVERSITY DRIVER SAHF
MODEL PH 16 OHMS 25 WATTS
BELL DIAM. 20. IN., RE-ENTRANT LENGTH 42 IN.
IMPEDANCE
PHASE ANGLE
IMPEDANCE - OHMS
PHASE ANGLE DEGREES
14000
12000
10000
8000
6000
4000
2000
0
60
50
40
30
20
10
0
-10
-20
-30
100
200
400
600
1000
2000
4000
6000
10000
20000
FREQUENCY - CYCLES PER SECOND

Figure 19

variations are not nearly as smooth. In the center of the audio frequency range, the plate load impedance reaches its highest value, and shows several marked changes for small variations in frequency. The phase angle curve shows many rapid changes. In portions of the audio frequency spectrum, the phase angle indicates a change from inductive to capacitive reactance. These rapid variations indicate resonances in the driver unit or in the re-entrant type horn. A re-examination of the electrical equivalent circuit for the loudspeaker (Figure 2, Page 8) shows that such resonances are definite possibilities. Because of the distortion of the Lissajous figure, phase angle measurements could not be made below 200 cycles per second. The power output curve was not shown, although it is apparent that the power output is considerably reduced in the vicinity of 1590 cycles where the highest impedance occurs. The specified range of this University driver unit is from 90 to 10,000 cycles. As it is difficult to design a single loudspeaker to cover a wide band of frequencies effectively, the extended response may have been achieved at the expense of resonant points in the specified frequency range.

University Driver and Large Horn Loudspeaker

The characteristics of the University driver and large re-entrant horn are shown in Figure 20. The same

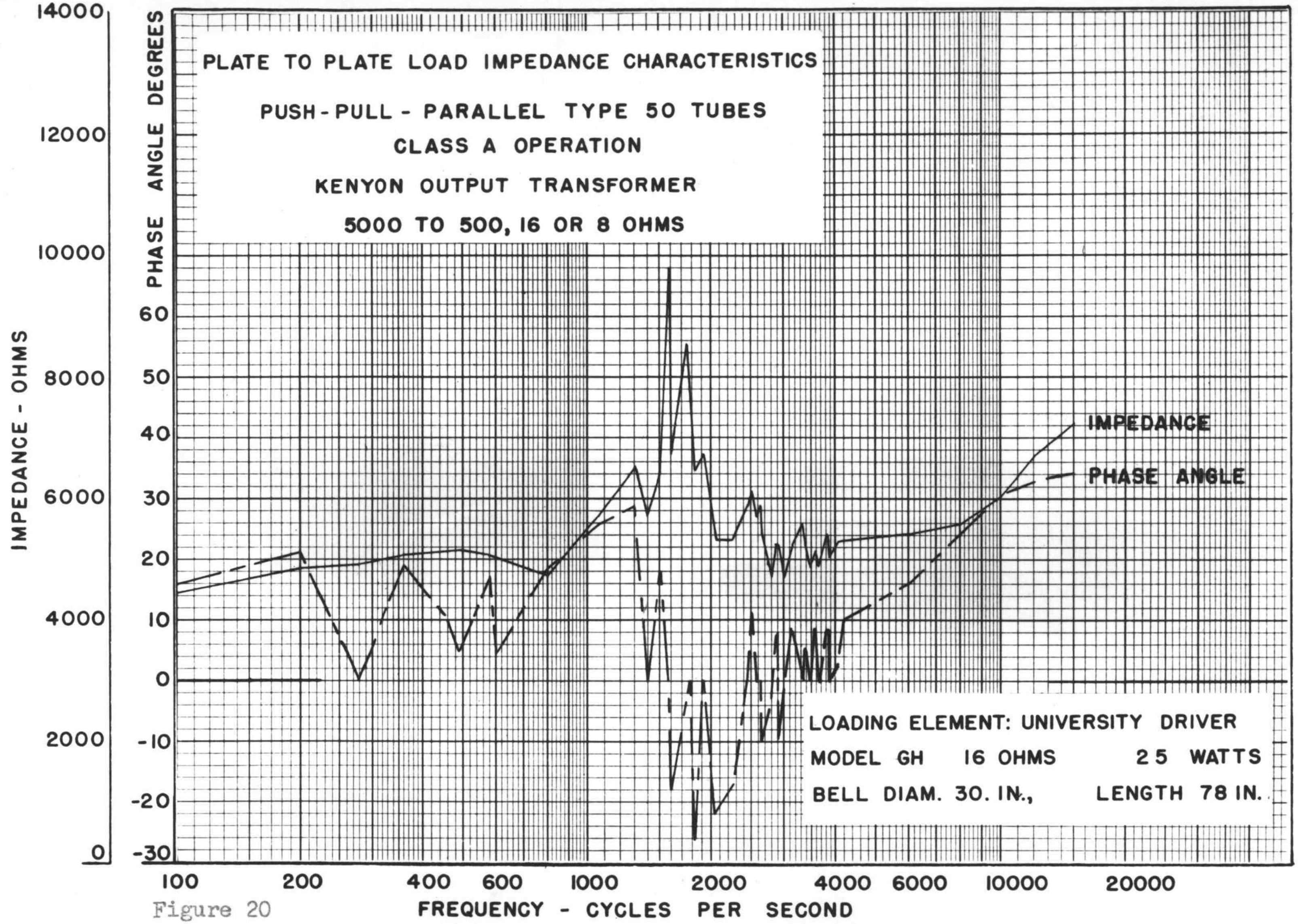


PLATE TO PLATE LOAD IMPEDANCE CHARACTERISTICS
PUSH-PULL - PARALLEL TYPE 50 TUBES
CLASS A OPERATION
KENYON OUTPUT TRANSFORMER
5000 TO 500, 16 OR 8 OHMS
IMPEDANCE - OHMS
PHASE ANGLE DEGREES
14000
12000
10000
8000
6000
4000
2000
0
60
50
40
30
20
10
0
-10
-20
-30
IMPEDANCE
PHASE ANGLE
LOADING ELEMENT: UNIVERSITY DRIVER
MODEL GH 16 OHMS 25 WATTS
BELL DIAM. 30. IN., LENGTH 78 IN.
100
200
400
600
1000
2000
4000
6000
10000
20000
FREQUENCY - CYCLES PER SECOND
Figure 20

driver unit was used with the large horn and the small horn previously considered. The plate load impedance and phase angle do not differ greatly at the extreme ends of the audio frequency range, but show very definite and sharp resonances between 1300 and 4000 cycles. The impedance reaches a peak at 1590 cycles, 78 per cent greater than the 1000 cycle value. This is at the same frequency as the peak with the small horn, and indicates a resonance peculiar to the driver unit itself. The other resonant points have much the same pattern as when the driver unit was used with the small horn, however, these resonances are sharper and more emphasized, indicating that the re-entrant construction of the horn affects the characteristics of the driver considerably, and thus the plate load impedance.

The phase angle curve shows the same rapid variations with small changes in frequency which characterized this driver and the small re-entrant horn. The variations are more extreme, and indicate that over part of the audio frequency range tested, the capacitive reactance of the speaker was great enough to cancel the inherent inductive reactance of the output transformer, and still make the plate load impedance appear capacitive.

These large impedances for certain small frequency bands would have the effect of a filter. The power output to the output transformer would be reduced, thus reducing the sound intensity from the loudspeaker for these frequencies.

Cone Type with Short Exponential Section

The characteristics of a cone-type dynamic speaker with a short exponential horn attached are shown in Figure 21. The curves vary relatively smoothly, and exhibit only one resonant point. The impedance increases rapidly to a value at 15,000 cycles four times the 1000 cycle value. The phase angle is always inductive, and is greater than 25 degrees over much of the frequency range. The phase angle below 250 cycles was not measured because of visible distortion of the Lissajous figure. The specified frequency range for this speaker is not available, however, the decrease in power output at the higher frequencies is apparent.

Cone Type with Bass Reflex Baffle

The characteristic curves for a cone-type dynamic speaker mounted in a solidly constructed bass reflex baffle are shown in Figure 22. The curves show no marked resonant points. The impedance increases rapidly to four times the 1000 cycle value at 15,000 cycles. The phase angle is more than 30 degrees above 1400 cycles and shows inductive reactance. The manufacturer's specifications give the frequency response of the speaker

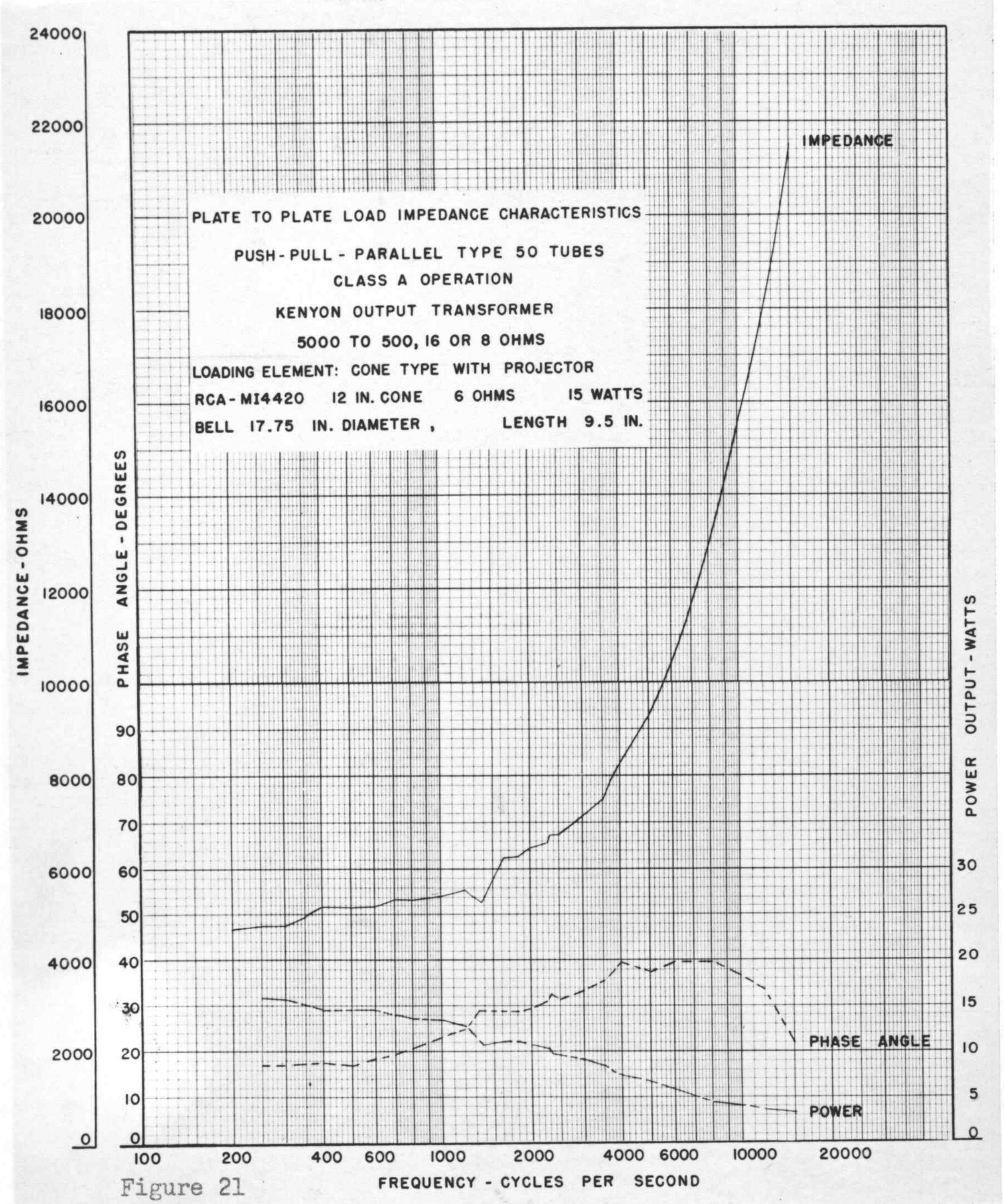


PLATE TO PLATE LOAD IMPEDANCE CHARACTERISTICS
PUSH-PULL - PARALLEL TYPE 50 TUBES
CLASS A OPERATION
KENYON OUTPUT TRANSFORMER
5000 TO 500, 16 OR 8 OHMS
LOADING ELEMENT: CONE TYPE WITH PROJECTOR
RCA-MI4420 12 IN. CONE 6 OHMS 15 WATTS
BELL 17.75 IN. DIAMETER , LENGTH 9.5 IN.
IMPEDANCE
PHASE ANGLE
POWER
IMPEDANCE - OHMS
PHASE ANGLE - DEGREES
POWER OUTPUT - WATTS
FREQUENCY - CYCLES PER SECOND
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
10
20
30
40
50
60
70
80
90
5
15
25
100
200
400
600
1000
2000
4000
6000
10000
20000

Figure 21

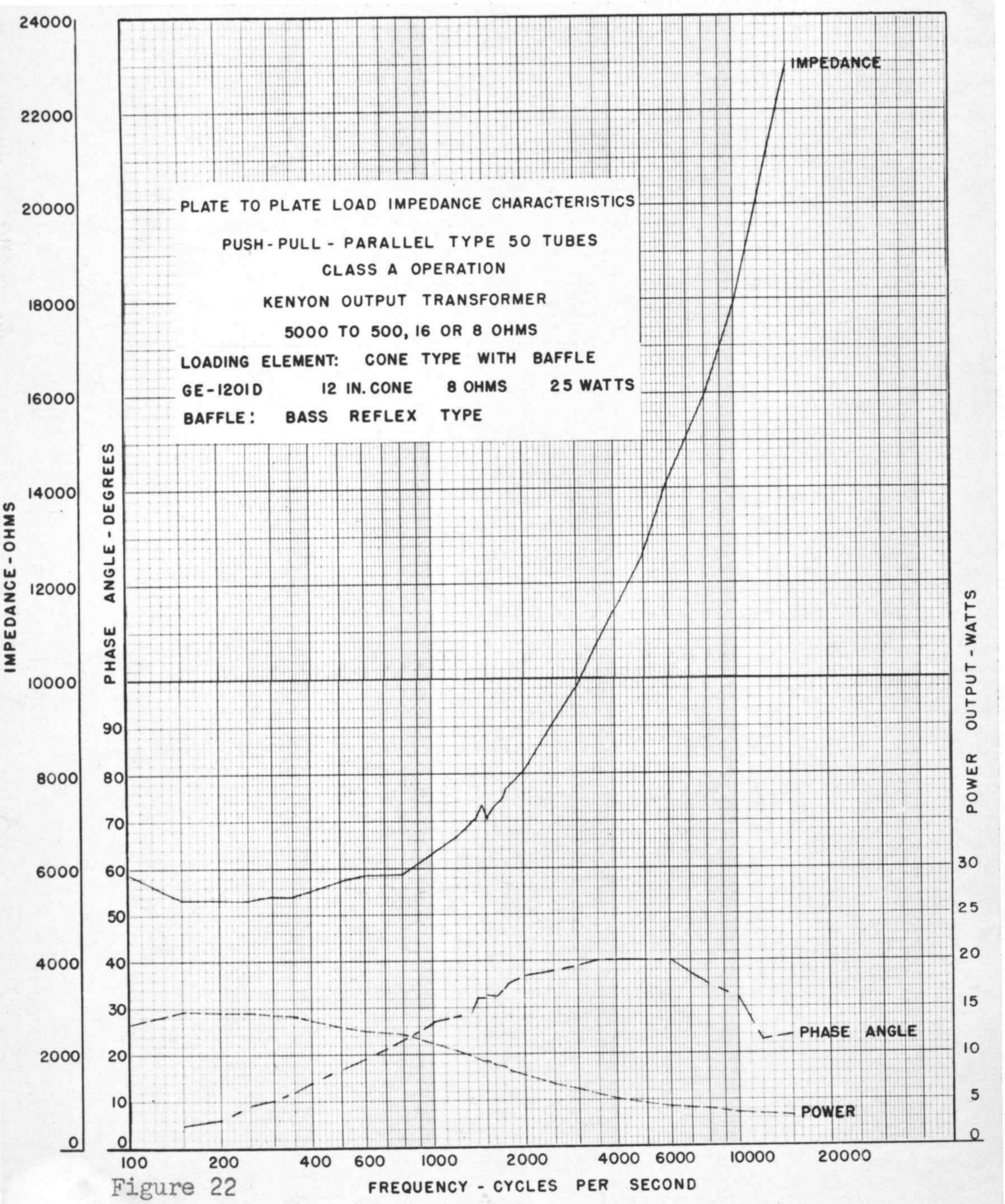


PLATE TO PLATE LOAD IMPEDANCE CHARACTERISTICS
PUSH-PULL - PARALLEL TYPE 50 TUBES
CLASS A OPERATION
KENYON OUTPUT TRANSFORMER
5000 TO 500, 16 OR 8 OHMS
LOADING ELEMENT: CONE TYPE WITH BAFFLE
GE-1201D 12 IN. CONE 8 OHMS 25 WATTS
BAFFLE: BASS REFLEX TYPE
IMPEDANCE
PHASE ANGLE
POWER
IMPEDANCE - OHMS
PHASE ANGLE - DEGREES
POWER OUTPUT - WATTS
FREQUENCY - CYCLES PER SECOND
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
100
200
400
600
1000
2000
4000
6000
10000
20000

Figure 22

as between 80 and 13,000 cycles per second.

Although the load impedance of four of the speakers tested were given by the manufacturers as 16-ohms, the impedance ratio of the transformer, as obtained using a pure 16.5-ohm resistance as a load, indicated that the actual load impedance of these speakers is variable, and is greater than 16 ohms. This confirms the conclusions reached by Thurman (14, p. 48) in his tests on the dynamic impedance characteristics of a moving-coil loud-speaker motor element.

CONCLUSIONS

The following conclusions were reached:

1. The plate-to-plate load impedance presented to a push-pull audio frequency power amplifier stage can be readily obtained by the method discussed in this paper. The only component that is not ordinarily available is the output transformer with both halves of the primary winding brought out to separate terminals. The method cannot be used at frequencies where appreciable distortion of the voltage or current wave occurs.

2. The magnitude of the plate-to-plate impedance for typical loudspeaker loading elements varies considerably with frequency. The impedance at 100 cycles may be eighty per cent, and at 10,000 cycles, 200 per cent of the mid-frequency impedance for horn-type speakers. Horn type speakers may have rapid variations in impedance with slight changes in frequency in the most-used portion of the audio frequency spectrum. These variations may be attributed to mechanical resonances in the driver unit and acoustical resonances in the driver and re-entrant horn. The plate-to-plate load impedance of cone-type speakers at 100 cycles may be 85 per cent, and

at 10,000 cycles, 330 per cent of the mid-frequency impedance. The cone-type speakers did not have marked resonant points over the range of frequencies tested.

3. The phase angle of the plate-to-plate load impedance indicates that inductive reactance due to the output transformer and loudspeaker is usually associated with the resistive component. Certain loudspeakers at certain frequencies may have capacitive characteristics great enough to cancel the inherent inductive nature of the output transformer, giving the plate load impedance a combination of capacitive reactance and resistance. The magnitude of the Phase angle is such that the ratio of resistance to reactance ranges from about 1.7 to 3.7, indicating that the plate load impedance is predominately resistive.

4. The characteristics of the plate-to-plate load impedance depend almost entirely on the impedance characteristics of the loud speaker. The test on the output transformer showed only a small variation in its impedance transforming properties with changes in frequency.

5. The changes in magnitude of the plate-to-plate load impedance with frequency indicate that the

analysis of the operation of the push-pull power amplifier should not be predicted from a single load line on the plate characteristic curve. Because of the involved method of plotting an elliptical load line, and the predominately resistive character of the load impedance, the use of several straight load lines, selected according to the load impedance to be presented to the amplifier at different frequencies should be used in the design of a power amplifier stage.

LITERATURE CITED

1. General Radio Company. Operating instructions for type 650-A impedance bridge. Boston, Spaulding-Moss, No date. 12 p.

2. General Radio Company. Operating instructions for type 636-A wave analyzer. Boston, Spaulding-Moss, No date. 8 p.

3. Hewlett-Packard Company. Instruction manual for model 400 A vacuum tube voltmeter. Palo Alto, California, No date. 11 p.

4. Hewlett-Packard Company. Instruction manual for model 200 B audio oscillator. Palo Alto, California, No date. 11 p.

5. Kellog, E. W. Design of non-distorting power amplifier. Journal, American institute of electrical engineers 44:490-498.

6. Lee, Reuben. Electronic transformers and circuits. New York, Wiley, 1947. 282 p.

7. McLachlan, N. W. Loudspeakers. Oxford, England, Clavendon Press, 1934. 399 p.

8. Preisman, Albert. Graphical construction for vacuum tube circuits. New York, McGraw-Hill, 1943. 237 p.

9. Ryder, John D. Electronic engineering principles. New York, Prentice-Hall, 1947. 389 p.

10. Sherwood, G. E. F., and Angus E. Taylor. Calculus. New York, Prentice-Hall, 1943. 496 p.

11. Terman, Frederick Emmons. Measurements in radio engineering. New York, McGraw-Hill, 1935. 391 p.

12. Tektronix Inc. Instruction manual cathode-ray oscilloscope model 511AD. Portland, Oregon, 1949. 28 p.

13. Thompson, B. J. Graphical determination of performance of push-pull amplifiers. Proceedings of the institute of radio engineers. 21:591-600. 1933.

14. Thurman, Harry L. Dynamic impedence characteristics of a moving-coil loudspeaker motor element. Thesis, Oregon State College, 1949. 67 p.

15. Van der Bijl, Hendrick J. The thermionic vacuum tube and its applications. New York, McGraw-Hill, 1920. 391 p.

APPENDIX

APPENDIX

Specifications of the Push-Pull Parallel Amplifier

Power Amplifier Stage	Push-Pull Parallel Type 50 Tubes
Driver Stage	Push-Pull Type 56 Tubes
Coupling	Transformer couple throughout
Output Transformer	5,000 ohms Plate-to-plate to 500, 16, 8, 4 or 2 ohms
Power Amplifier Power Supply	540 volts at 250 milli-amperes
Power Amplifier Bias Voltage	82 volts by cathode bias resistor
Rated Power Output	30 watts
Residual Hum	57 decibels below a power level of 16.3 watts
Power Amplifier Frequency Response	Essentially flat from 100 to 15,000 cycles

Wave Analysis of the Voltage

Proportional to the Primary (Composite) Current

Frequency cps	Per cent Fundamental Component	Per cent Second Harmonic	Per cent Third Harmonic
100	100	0.3	2.7
500	100	0.5	0.5
1000	100	0.5	0.6
2500	100	0.4	0.8
5000	100	0.4	0.7

Wave Analysis of the Voltage

Across One-Half of the Primary Winding

Frequency cps	Per cent Fundamental Component	Per cent Second Harmonic	Per cent Third Harmonic
100	100	0.5	1.2
500	100	1.0	0.1
1000	100	1.3	0.1
2500	100	1.4	Negligible

Wave Analysis of the Total Primary Voltage

Frequency cps	Per cent Fundamental Component	Per cent Second Harmonic	Per cent Third Harmonic
100	100	0.52	1.2
500	100	0.4	0.1
1000	100	0.3	Negligible
2500	100	0.1	Negligible

Electrical Specifications of Instruments

Hewlett-Packard Model 400 A

Vacuum Tube Voltmeter

Voltmeter Indication	Proportional to the average value of the rectified full wave.
Voltmeter Calibration	Rms value of the sine wave.
Overall Accuracy	Three per cent from 10 to 100,000 cps.
Input Impedance	About 15 micromicrofarads capacitance. Shunt resistance, 1 megohm on ranges below 30 volts, 2.4 megohms on 300 volt range.
Line Voltage Variations	Less than three per cent on all frequencies below 100,000 cps.

Hewlett-Packard Model 200 B Audio Oscillator

Frequency Range	20 to 20,000 cycles per second.
Calibration Accuracy	Within two per cent.
Power Output	One watt into 500 ohms.
Distortion	Less than one per cent from 35 cycles to 15 kilocycles at rated output.
Frequency Stability	Within two per cent under normal temperature conditions.
Hum	60 decibels below rated output.

Tektronix Model 511AD Oscilloscope

Vertical Deflection Sensitivity	Two stages of amplification, 0.27 volts per centimeter maximum, 4 volts per centimeter minimum for 4 centimeter deflection of beam
Vertical Amplifier Bandwidth	Two stages, down 3 decibels from the 1 mc. response at 5 cps. and 10 mc.
Input Impedance	One megohm shunted by 40 micromicrofarads.
Horizontal Deflection Sensitivity	32 volts per centimeter (direct current or peak-to-peak alternating current).

General Radio Wave Analyzer

Type 636 A

Frequency Range	0 to 17,000 cycles per second.
Voltage Range	1 millivolt to 200 volts.
Accuracy	Five per cent.
Power Supply	Battery operated.