AN ABSTACT OF THE THESIS OF

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(Name) (Degree) (Major)

Date Thesis presented 5-3-49

Title Dynamic Impedance Characteristics of a Moving-Coil Loudspeaker Motor Element.

Abstract Approved Redacted for privacy
(Major Professor)

The design of a loudspeaker is approached, in practice, from the standpoint of frequency response and area of sound coverage rather than from the standpoint of the characteristics of the loudspeaker as an impedance load. A study of the advertising material published on many types of loudspeakers has shown the primary selling features to be; first, the frequency response characteristics; second, angle of sound projection, and third, physical appearance, size, and cost. The manufacturers neglect to include details of how the test results were obtained in the description of characteristics of a loudspeaker. Furthermore, sufficient information regarding power handling capacity, operaitional efficiency, and load impedance characteristics are not supplied by most manufacturers.

In a mathematical analysis of a moving-coil motor element it is possible to account for the acoustical and mechanical impedances of the unit. These acoustical and mechanical impedance parameters can be segregated and measured in practice only with great difficulty and in some cases not at all.

The study and measurement of the dynamic impedance characteristics of a moving-coil loudspeaker motor element show the motor element impedance to be a variable load over the operating frequency range for any audio amplifier. The nominal impedance presented by a loudspeaker is, $Z = 20 \quad +18^{\circ}$ or $Z = 19.02 + j6.18$. The variation of the motor element impedance is form ten to forty ohms with a change in impedance angle of from plus thirty degrees ($+30^{\circ}$) to minus thirty degrees (-30°). This makes the loudspeaker impedance both inductive and capacitive in character over the operating frequency range of the unit.

The motor elements are over rated by the manufacturers at twenty-five watts. Investigation shows that the motor elements will absorb only seventeen watts before permanent damage is done to both the voice-coil and diaphragm. The average power input at the point of over drive is thirteen watts.

A change in acoustic impedance occurs at each fold of a re-entrant horn causing wave reflections which affect the load on the diaphragm causing the impedance characteristics of any motor element with which a re-entrant horn is used to be

extremely erratic over the frequency range of the unit. This phenomena of sound wave reflection was reaffirmed by measuring the lengths of the air columne in the horns used during the tests and calculating the resonant frequencies of the various air columns. This information is one of the contributions of this study.

Finally, the constant-current test methods and procedures developed in this paper are an easy and accurate means of determining the operational impedance characteristics of a loudspeaker. The measured motor element impedance indicates also the acoustical quality of the loudspeaker. It is believed that the constant-current method of loudspeaker testing developed in this paper and th information on loudspeaker impedance characteristics presented will lead to the improvement in the design of horn-type loudspeakers.

DYNAMIC IMPEDANCE CHARACTERISTICS
OF A
MOVING - COIL LOUDSPEAKER MOTOR ELEMENT

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 1949

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Redacted for privacy

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PREFACE

The author wishes to express his gratitude to Professors A. L. Albert and F. O. McMillan for the guidance that was given to him during the preparation of this paper and for the priviledge of working in cooperation with them.

The author is also indebted to his wife who offered encouragement when the going was difficult and successful completion of the thesis seemed unattainable. Furthermore, the manual labor unselfishly donated to help assemble this paper in its final form is deeply appreciated.

Thanks is also extended to Dean G. W. Gleeson, Dean of the School of Engineering, who helped pacify those people who were inconvenienced by the nerve shattering noise that resulted during the tests.

H. L. Thurman

June 1949

DYNAMIC IMPEDANCE CHARACTERISTICS
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MOVING - COIL LOUDSPEAKER MOTOR ELEMENT

INTRODUCTION

The impedance characteristics of the horn-type loudspeaker as a load for an amplifier has not been given sufficient study. This statement is based on information obtained from loudspeaker manufacturers.

The design of a loudspeaker is approached, in practice from the standpoint of frequency response and area of sound coverage rather than from the standpoint of the characteristics of the loudsp eaker as an impedance load. A study of the advertising material published on amny types of loudspeakers has shown the primary selling features to be; first, the frequency response characteristics; second, angle of sound projection; and third, physical appearance, size and cost. The manufacturer neglects to include details of how the test results were obtained in the description of the characteristics of a loudspeaker. This renders a comparison of operational characteristics of several loudspeakers useless, since it is not known whether the test data were obtained under similar co nditions. Furthermore, sufficient information regarding the power handling capacity, operational efficiency, and load impedance characteristics are not supplied by most manufactuers.

The purpose of the following study and series of tests is to gain information regarding the operation of the loudspeaker as an impedance load and of its characteristics as an acoustical transducer. The input, or load, impedance is not a simple function due to the inter-relation of electrical, mechanical, and acoustical impedance that go to make up the equivalent electrical input impedance of a loudspeaker.

The experimental techniques developed for the following studies present and accurate means by which it is possible to obtain operational data on loudspeakers. It is believed that the information presented in this paper will assist manufacturers in the improvement in design of horn-type loudspeakers.

ANALYSIS OF MOTOR ELEMENT

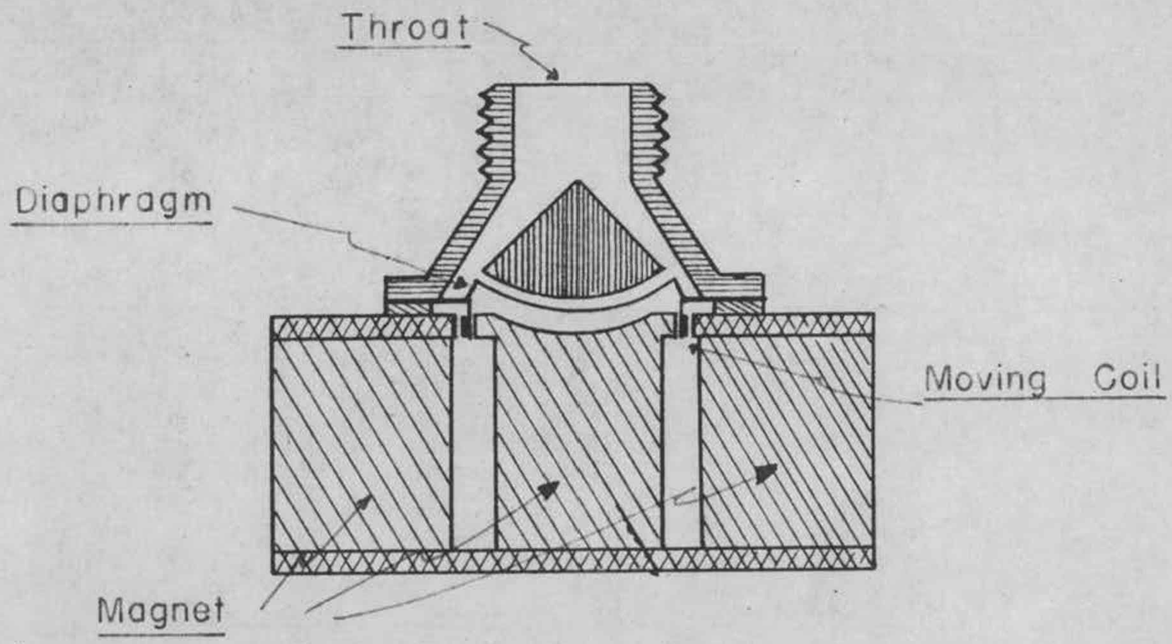
The primary function of any loudspeaker is to transform electrical signals into acoustic energy without a change in wave shape. The horn-type loudspeaker is made up of two primary components:

(A) The motor element, often called a driver, or driving element.

(B) The horn, or acoustical transformer and radiator.

The moving-coil motor element is as shown in Figure 1. It consists of three principal parts, a movable coil of several turns of wire which carry the electrical signal currents, a large permanent magnet that provides a field in which the moving coil operates, and lastly a movable diaphragm, attached to the coil, which imparts motion to the air surrounding it. The current variations in the coil, reacting with the strong magnetic field in which the coil is located, cause the coil and diaphragm to move in accordance with these variations. The motion of the diaphragm creates sound waves which are a replica of the electrical signal applied to the motor element.

The following qualitative analysis of the moving-coil motor element is being presented in this paper to indicate the general theory so that the electrical impedance measurements presented herein can be more clearly understood and



Schematic diagram of moving coil motor element.

FIGURE I

interpreted.

Consider first a motor element with a diaphragm having a single degree of freedom in which the diaphragm is not stretched or damped in any way. Figure 2 shows the electrical equivalent of such a motor element, where:

$F_o \varepsilon^{j\omega t}$ = the alternating force operating on the diaphragm

M_o = effective mass of the diaphragm

S_o = diaphragm stiffness

R_o = mechanical resistance of the diaphragm.

The absolute value of velocity of the diaphragm is expressed by the equation,

$$V = \frac{F}{M\left[4\Delta^2 + \left(\frac{\omega^2 - \omega_o^2}{\omega}\right)^2\right]^{1/2}} \qquad 1$$

and the amplitude of movement of the diaphragm is given by the equation,

$$A = \frac{V}{\omega} \qquad 2$$

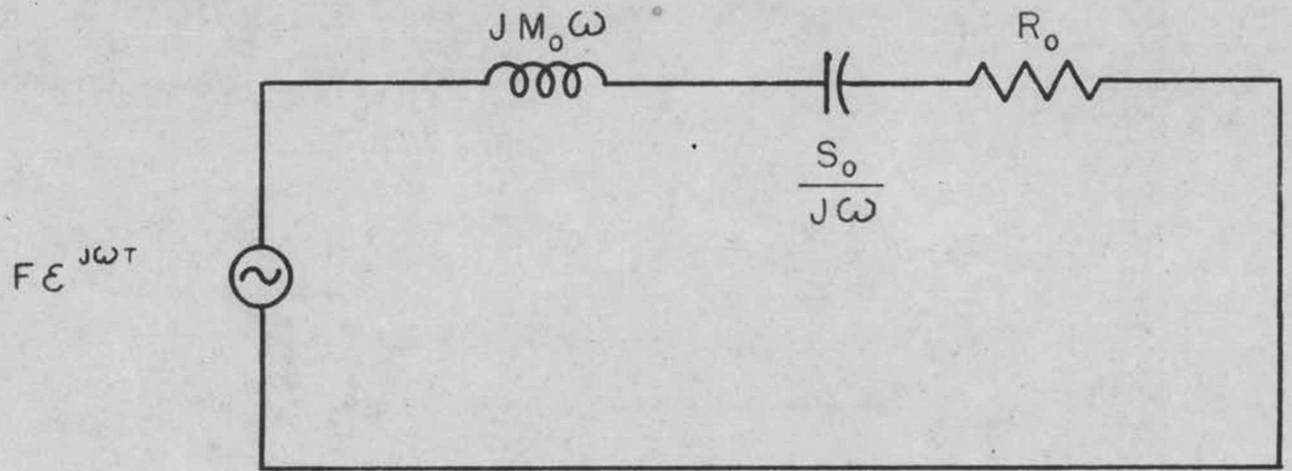
where,

$\Delta = \frac{R_o}{2M_o}$, the damping factor

$\omega_o = \sqrt{S_o/M_o} = 2\pi f_r$

f_r = the resonant frequency of the motor element diaphragm.

By plotting equations 1 and 2 for different values of



Equivalent electrical network of motor element having a diaphragm with a single degree of freedom.

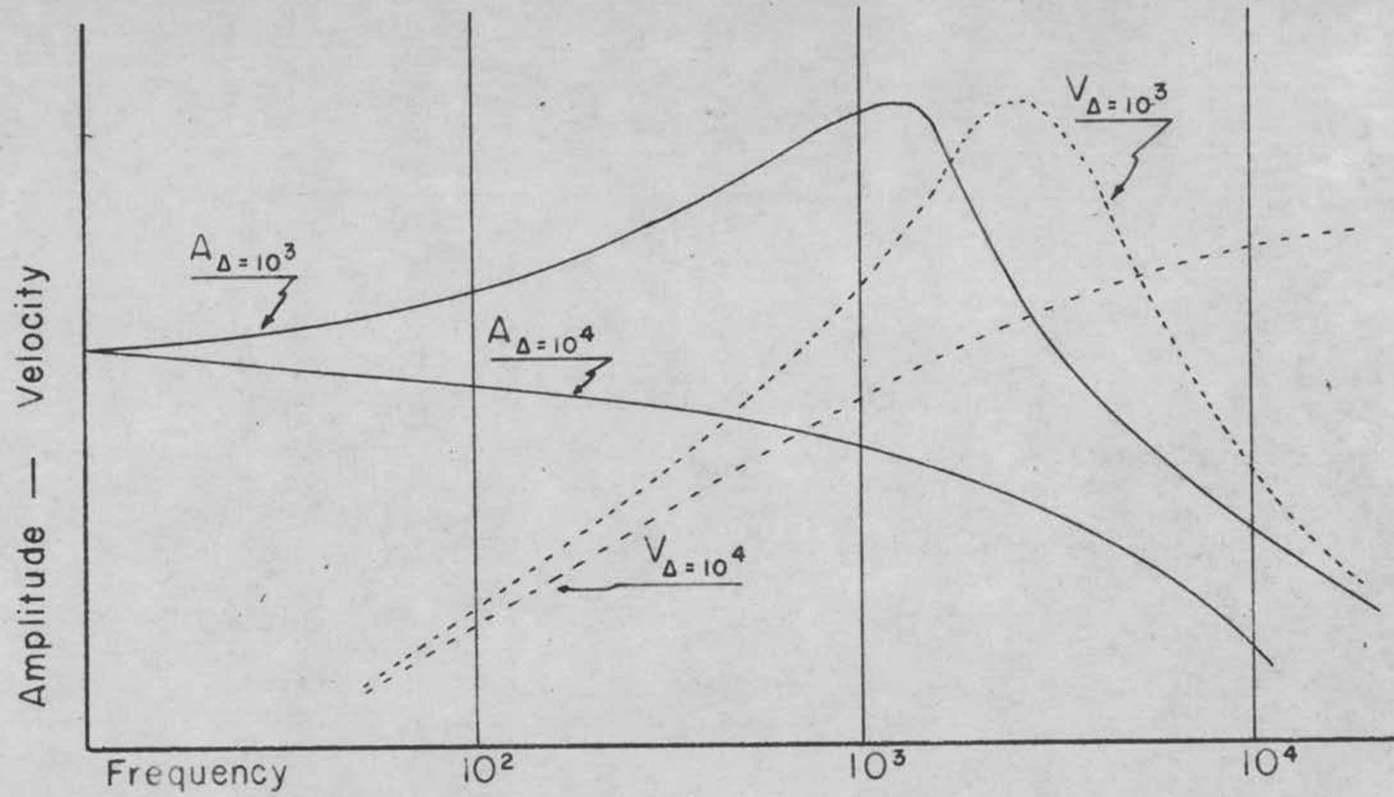
FIGURE 2

damping factor (Δ) curves similar to those shown in Figure 3 will result. It will be noted that there is a great change in both the amplitude and velocity of the moving diaphragm as the damping factor of the motor element is changed. Figure 3 shows further that the resonant frequency of the equivalent electrical circuit and the damping factor must be high to obtain constant amplitude and velocity over a large frequency range.

It can be readily understood that a motor element designed with a high damping factor and high resonant frequency would be insensitive to low signal levels because of the weight and size of the diaphragm. By changing the mechanical construction of the motor element diaphragm so that it is no longer a simple vibrating system it is possible to alter materially the characteristics of the motor element.

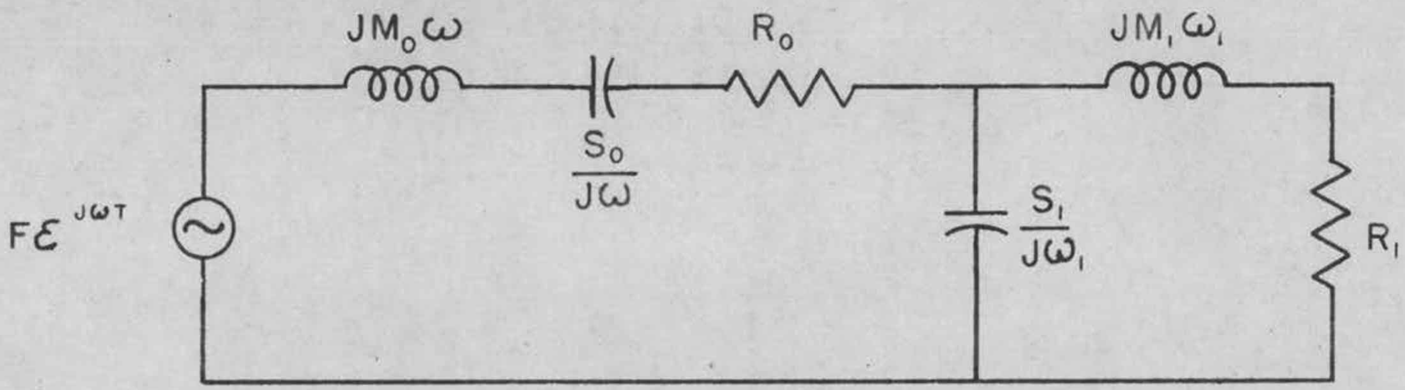
In the design of wide-band electrical networks for transmission systems combinations of resonant electrical circuits are connected together to attain the desired results. This, in effect, is accomplished in loudspeaker motor elements when a mechanical rearrangement of the magnet and diaphragm are made. By making the appropriate mechanical changes in the motor element an equivalent electrical network similar to that shown in Figure 4 may be obtained.

The absolute value of impedance at the input terminals of the network will be:



Amplitude — Velocity
$A_{\Delta=10^3}$
$A_{\Delta=10^4}$
$V_{\Delta=10^3}$
$V_{\Delta=10^4}$
Frequency
10^2
10^3
10^4

FIGURE 3



Equivalent electrical network af a moving coil motor element.

FIGURE 4

$$|Z| = \sqrt{R^2 + X^2}$$

where,

$$R = \frac{S_1^2 R_1}{R_1^2\,\omega^2 + M_1^2\,(\omega_1^2 - \omega^2)^2} + R_o \qquad 3$$

$$X = \frac{S_1\omega\left[M_1^2(\omega_1^2 - \omega^2)\right] - R_1^2}{R_1^2\omega^2 + M_1^2(\omega_1^2 - \omega^2)} + M_o\omega - \frac{S_o}{\omega} \qquad 4$$

$$\omega_1^2 = \frac{S}{M_1} . \qquad 5$$

The parameters of the coupled network shown in Figure 4 are:

S_1 = stiffness of coupled network

M_1 = mass of coupled network

R_1 = resistance of coupled network.

Figure 5 shows the "Annular" type of moving-coil motor element used during a portion of the loudspeaker tests. The conventional type of moving-coil motor element shown in Figure 6 also was used during the series of impedance measurements. Construction details and operational characteristics of these units will be discussed in other sections to follow.

The efficiency of a loudspeaker as defined by the "American Recommended Practice for Loudspeaker Testing," is the ratio of the total acoustical power radiated into the

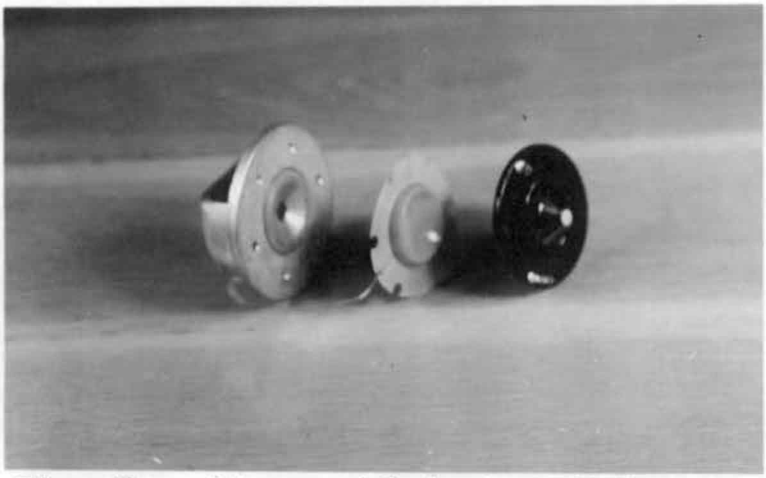


Fig. 5A - Disassembled view of "Annular" type motor element showing from left to right: Permanent magnet, Diaphragm with Voice-Coil attached, and Cover Piece.

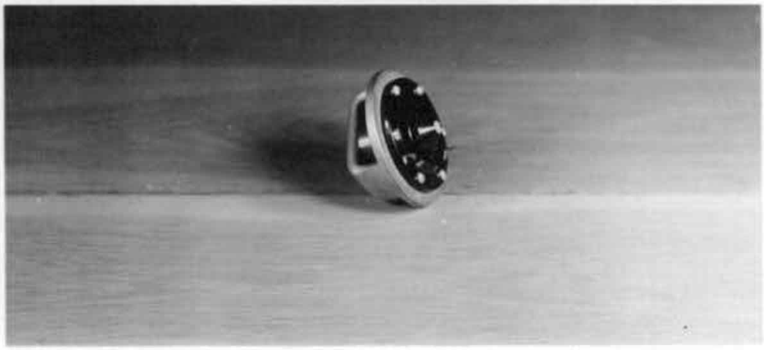


Fig. 5B - Assembled view of "Annular" type motor element.

FIGURE 5

Fig. 6 - Model SAH moving-coil motor element with a short tubular section attached.

FIGURE 6

surrounding medium to the electrical power supplied. A prediction of the efficiency of the loudspeaker unit can be made by measuring the major loss in the motor element, this loss being the so-called blocked diaphragm resistance loss of the voice coil. The efficiency calculated in this manner will not result in the exact efficiency of the loudspeaker since the losses due to air friction and mechanical vibration are not included. Compared to the effective resistance loss in the voice coil of the motor element the mechanical vibration and air friction losses are small and can be neglected. The power supplied to the loudspeaker is expressed by the equation,

$$P_s = I^2 (R_m)$$

and the losses within the motor element are,

$$P_l = I^2 (R_d)$$

where,

R_m = voice coil motional resistance

R_d = blocked diaphragm resistance.

The efficiency of the loudspeaker is determined from the equation,

$$\text{Efficiency} = \frac{P_s - P_l}{P_s}$$

Substituting and simplifying,

$$\text{Efficiency} = \frac{I^2(R_m - R_d)}{I^2R_m} = \frac{R_m - R_d}{R_m} .$$

The procedure followed in obtaining the damped diaphragm resistance of the motor element will be discussed in a later section.

ANALYSIS OF LOUDSPEAKER HORN

The loudspeaker horn is employed to match properly the impedance of the air to that of the moving diaphragm of the motor element and to radiate and direct the sound energy. The ability of the horn to present a proper impedance match between the air and the motor element over a wide range of frequencies is a measure of the fidelity of reproduction of the horn.

The qualitative analysis of the loudspeaker horn is being reviewed here so that a clear understanding of horn characteristics can be gained without the necessity of consulting the references listed at the end of this paper. Furthermore, comparisons of theory and test results as they affect the electrical impedance of the loudspeaker will be made and discussed.

The equations for the general solution of the horn of a loudspeaker are based on the following assumptions:

1. All fundamental acoustical equations are applicable.
2. The diameter of the horn at any point along the horn is small compared to the wave length of the highest frequency of sound transmitted.
3. The wave must be a plane wave and air particle displacement occurs only

longitudinally along the axis of the horn.

4. The pressure and velocity of the sound wave are small so that second order and higher terms may be neglected.

Definition of terms:

ΔX = incremental distance along axis of horn.

S = area of horn at point X.

ρ = density of medium (air).

μ = component velocity of air particle along axis of horn.

c = velocity of sound.

s = ratio of the increment of density change to the original air density.

$\dot{\phi}$ = component of sound wave along axis of horn.

Refering to Figure 7, it can be seen that the difference between the flow into, and flow out of, the elemental volume $(\Delta X)S$ will be equal to the growth of the mass of the element of air as it moves from the throat of the horn to the mouth of the horn. Considering the influx and efflux through each pair of faces the difference between the two becomes,

$$-\Delta X \frac{\partial(S\rho\mu)}{\partial X} . \qquad 6$$

Equating the time rate of growth of the elemental mass of

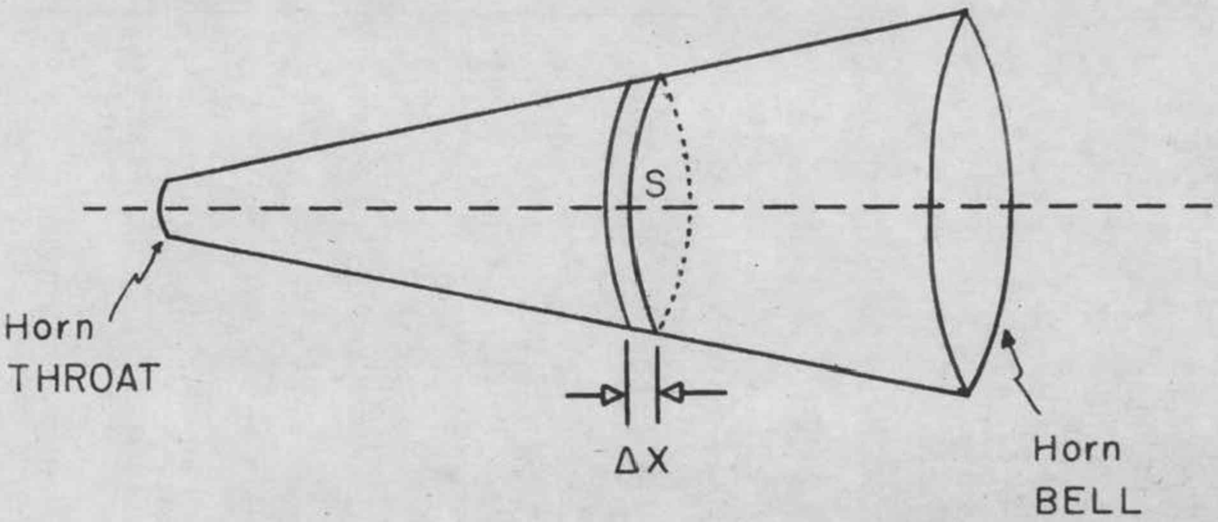


FIGURE 7

air to equation six gives,

$$\frac{\partial \rho}{\partial t} S(\Delta X) = -\Delta X \frac{\partial (S\rho\mu)}{\partial X} \qquad 7$$

$$\frac{\partial \rho}{\partial t} S + \frac{\partial (S\rho\mu)}{\partial X} = 0 \ . \qquad 8$$

Equation eight shows the continuity of the sound wave as it moves through the horn.

The fundamental theory of wave propagation gives the following two expressions,

$$\dot{\phi} = -c^2(s) \qquad 9$$

and

$$\mu = \frac{\partial \dot{\phi}}{\partial X} \ . \qquad 10$$

Substituting equations nine and ten into equation eight a differential equation is developed,

$$c^2 \frac{\partial \dot{\phi}}{\partial X} \frac{\partial (\log S)}{\partial X} - c^2 \frac{\partial^2 \dot{\phi}}{\partial X^2} = 0 \qquad 11$$

which expresses the general wave equation for axial motion of a media along a tube of varying cross section.

Since this study if of the finite exponential horn the general wave equation may be applied to this type of horn. The equation for the exponential horn is,

$$S = S_o \mathcal{E}^{mx} \qquad 12$$

where,

S_o = throat area of horn

S = area of horn at any point X along the axis of the horn

m = flare constant of the horn.

Substitution of the exponential horn equation into the general wave equation (equation eleven) gives,

$$0 = c^2 \frac{\dot{\phi}}{X^2} + c^2 m \frac{\dot{\phi}}{X} - \ddot{\phi} . \qquad 13$$

From the basic principles of differential equations a general solution for equation thirteen can be written in the form,

$$\dot{\phi} = \mathcal{E}^{ax} \left[A \cos bx + B \sin bx \right] \mathcal{E}^{j\omega t} \qquad 14$$

where

$a = - \frac{m}{2}$

$b = \frac{\sqrt{4k^2 - m^2}}{2}$

$k = \frac{2\pi}{\lambda}$

λ = wave length

$\omega = 2\pi f$

f = frequency in cycles.

The pressure, P, at any point along the horn can be expressed by the equations,

$$P = -c^2 s = -\dot{\phi}$$

$$P = -j\omega\rho\varepsilon^{ax}\left[A \cos bx + B \sin bx\right]\varepsilon^{-j\omega t}. \quad 15$$

The volume current at any point along the horn may be expressed by the equation,

$$U = S \frac{\partial \dot{\phi}}{\partial X}$$

$$U = S \left[a^{ax} (A \cos bx + A \sin bx) + \ldots \right.$$
$$\left. \ldots b(B \cos bx - A \sin bx)\right] \varepsilon^{j\omega t} . \quad 16$$

With the expression for the wave pressure and volume current along the horn it is now possible to determine the acoustical impedance at any point along the axis of the horn. The expression for the impedance at any point becomes,

$$Z_a = \frac{P}{U} . \quad 17$$

If equations are written expressing the acoustical impedance at the throat of the horn, and at the bell of the horn, it can be seen that the exponential horn is a step-down transformer. That is, the pressure (P) is decreased while the volume current (V) is increased as a sound wave travels from the throat to the bell of the horn.

When the ratio ω/c is very large compared to the rate of taper of the horn (m) the impedance of the horn reduces to c, the characteristic impedance of air. Near the cut-off frequency of the horn,

$$\frac{\omega}{c} = m \qquad 18$$

or,

$$f = \frac{mc}{2\pi}, \qquad 19$$

the impedance differs considerably from this and large interaction peaks occur, causing the horn to introduce an uneven response over the operating range.

DESCRIPTION OF EQUIPMENT TESTED

Among the factors that determine the electrical and acoustical performance of a loudspeaker are:

1. Frequency response.
2. Directional characteristics.
3. Power handling capability.
4. Operational efficiency.

The primary criterion upon which loudspeaker manufacturers judge all types of loudspeaker units for quality and faithfulness of response is to measure the frequency response and directional characteristics of the combined motor element and horn by driving the motor element with a sine-wave input and measureing the sound output by means of a calibrated microphone and amplifier system or by other suitable means.

It might be well to comment here upon the fact that the other characteristics of a loudspeaker unit are not considered to be of great importance by most manufactuers of acoustical equipment. A study of the advertising material published on amny types and kinds of loudspeakers has shown that a response characteristic, angle of sound radiation, and cost are the primary selling features presented. Usually little information is given on the power handling capacity or operational efficiency of the unit.

Inquiries were addressed to the leading loudspeaker manufacturers to gain more information upon the operational characteristics of loudspeakers. Several of the manufacturers ignored the inquiry and failed to answer the letters addressed to them. Those who did answer phrased their replies in such a hazy and general manner that no information of value was forthcoming. When more direct questions were asked regarding the impedance characteristics and efficiency of loudspeakers the manufacturers said that they did not have such information.

Requests for equipment were answered by two manufacturers, University Loudspeakers Incorporated, and the Jensen Manufacturing Company. With the equipment already available in the laboratory a total of two driving units and three horns were used for study and testing. For the sake of convenience the various driver units and horns will be designated by an identifying letter as follows:

1. Driver "U" - This motor element is the model SAH unit manufactured by University Loudspeakers Incorporated. The manufacturer has published the following information on the unit - Maximum power output = 25 watts; Nominal impedance = 16 ohms; Frequency range = 90 to 6,000 cps.
2. Driver "J" - This motor element is identified as a U-20 motor element, designed and

manufactured by the Jensen Manufacturing Company. The characteristics of the unit as published by the manufactrer are as follows: Maximum power output = 25 watts; Nominal impedance = 16 ohms; Frequency range = 200 to 5,000 cps.

3. Horn "U" - The model GH, reflex horn unit is manufactured by the University Loudspeakers Incorporated. The horn is described as having a bell diameter of thirty inches and an air column of seventy-two inches. The dispersion angle is ninety degrees. The cutoff frequency was not specified by the manufacturer.

4. Horn "R" - This horn is manufactured by the Racon Electric Company. It is described as a storm proof type acoustic trumpet with the code designation of RIDER. The total length of the unit is seventy-two inches having a thirty-four inch cast aluminum throat with the remaining length being constructed of a patented non-vibrating acoustic material. This horn is not of the reentrant variety as can be seen from Figure 9. The diameter of the bell is thirty

inches. No operational data were available on this particular model of horn. The test curves indicate that the low frequency cut-off of the horn is near two hundred cycles.

5. Horn "J" - This is the model H-24 "Hypex" horn made by the Jensen Manufacturing Company. The unit has an acoustical length of five feet and the bell diameter is twenty four and seventy five hundreths inches. The model H-24 is of the conventional re-entrant type of unit used in most outdoor public address installations. The nominal acoustical cutoff for the horn at low frequencies is 140 cps. In the literature published by the manufacturer it has been stated that the "Hypex" horn is not an exponential but is an exclusive development by the company. A picture of the "Hypex" horn is shown in Figure 10.

The possible combinations of motor elements and horns were limited due to the differences in construction of the various units. The motor element and horn combinations that were used during the tests are indicated below:

1. Horn "U" - Driver "U", This combination is shown in Figure 8.

2. Horn "R" - Driver "U", Figure 9 shows this unit ready for test.
3. Horn "J" - Driver "J", It will be noted in Figure 10 that the motor element is an integral part of the horn. This type of design is termed "Annular" loudspeaker construction. The motor element and horn are integrated into a single unit that cannot be separated for use with other units. The test results indicated that the "Annular" type of design gives better operational characteristics.

Fig. 8 - Loudspeaker unit composed of Driver "U" and Horn "U" in position and ready for test.

FIGURE 8

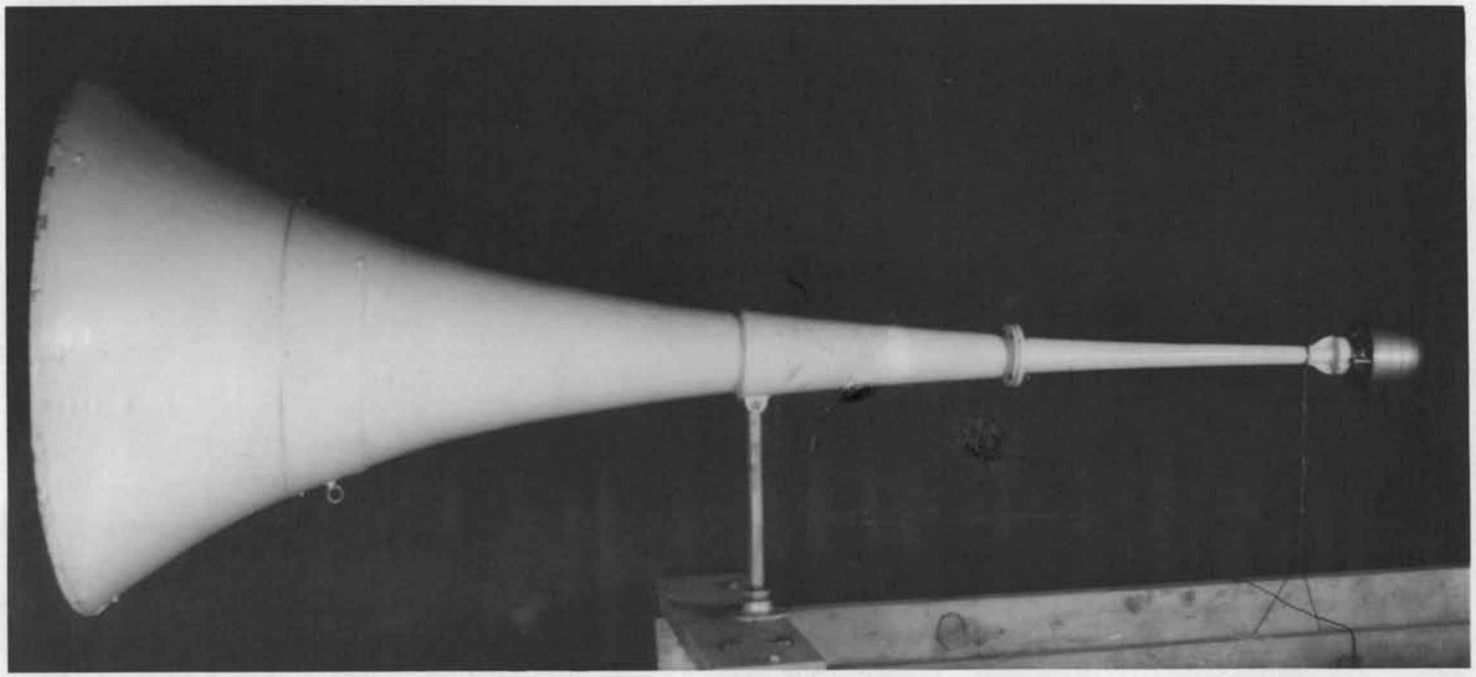


Fig. 9 - Driver "U" and Horn "R" assembled and ready for operation.

FIGURE 9

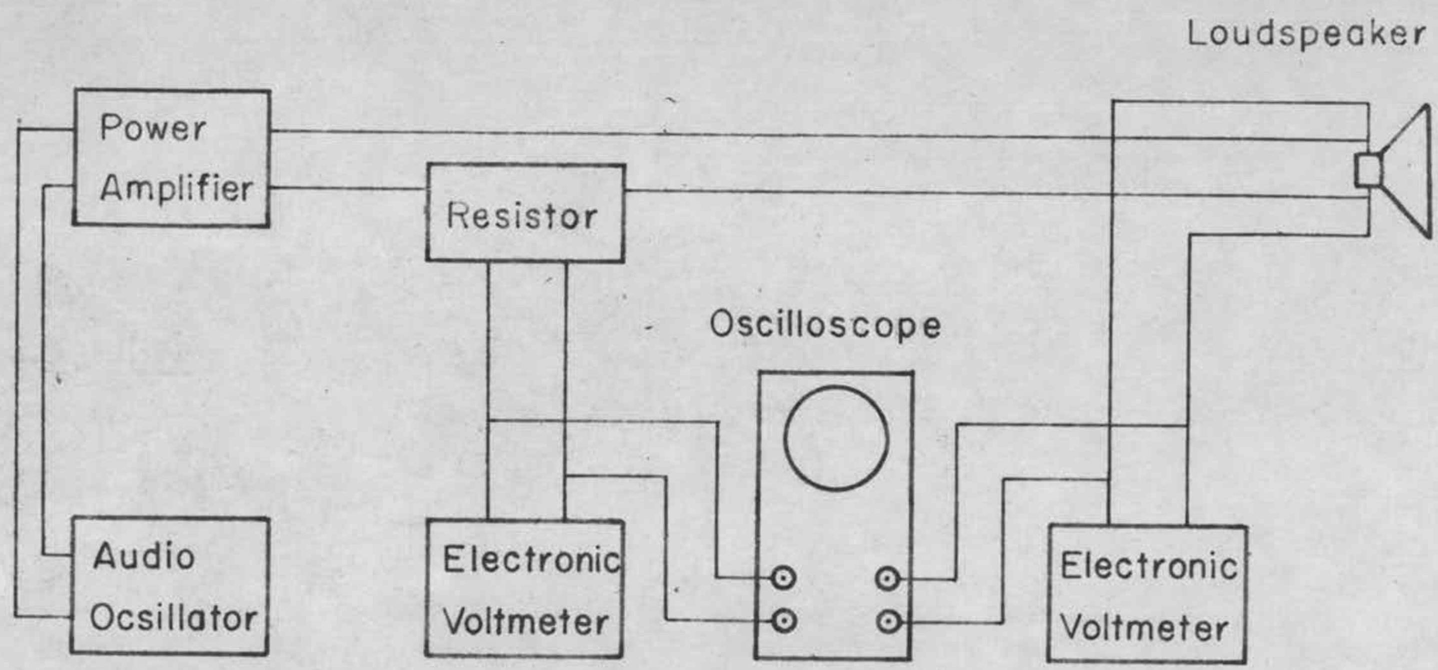
Fig. 10 - Loudspeaker unit Driver "J" and Horn "J" mounted in the test rack and ready for operation.

FIGURE 10

DISCUSSION OF TEST CIRCUIT

The circuit used throughout the entire program of loudspeaker testing is shown in Figure 11. Briefly, the testing circuit makes it possible to determine the voltage applied to the motor element, the current flowing through the circuit, and by measurement of a Lissajous figure on an oscilloscope, the phase angle between voltage and current. Calculations of power, impedance, resistance, reactance, and efficiency can be made from the data taken. These quantities reflect the operational characteristics of the loudspeaker, and furthermore, provide information that has hitherto been unknown.

A Hewlett-Packard, model 200C, audio oscillator was used as a variable frequency source in the testing circuit. The unit has a tunable range of twenty to twenty-thousand cycles. It was found that the output of the oscillator remained sinusoidal only when delivering small amounts of power. A model M14288G, fifty watt, audio power amplifier, manufactured by the Radio Corporation of America was used to drive the loudspeaker units under test. Experimentation indicated that the amplifier was capable of delivering up to thirty watts with negligible distortion. The high input impedance of the power amplifier offered an ideal load for the audio oscillator while several output impedance taps were provided making it possible to match the power



Schematic diagram of loudspeaker test circuit.

FIGURE II

amplifier to the impedance of the loudspeaker units.

A dummy-antenna loading unit was used in the test circuit to obtain a voltage proportional to the current flowing in the circuit. This voltage must have the same phase relationship to the voltage at the terminals of the loudspeaker as is had by the current flowing in the circuit. The dropping resistor, therefore, must be a pure resistance having no reactive component. The ordinary wire-wound resistor can not be used due to a perceptible reactive component of impedance. The dummy-antenna unit used has a resistive component of eight ohms and an inductive component of only three microhenries at one-thousand cycles.

To make certain that the test circuit was not disturbed by low impedance measuring instruments, vacuum-tube voltmeters were used to measure all voltages. A model 726A instrument manufactured by the General Radio Company was used to measure the drop across the series resistor, while a General Radio, model 1800A vacuum-tube voltmeter was used to measure the voltage at the terminals of the loudspeaker.

A Du Mont, type 208, oscilloscope was used to measure the phase angle between the voltage applied to the loudspeaker and the current flowing in the circuit. This oscilloscope was used because of its large screen and operational stability. Another oscilloscope, RCA model 155C, was used to check the wave form of both the current and

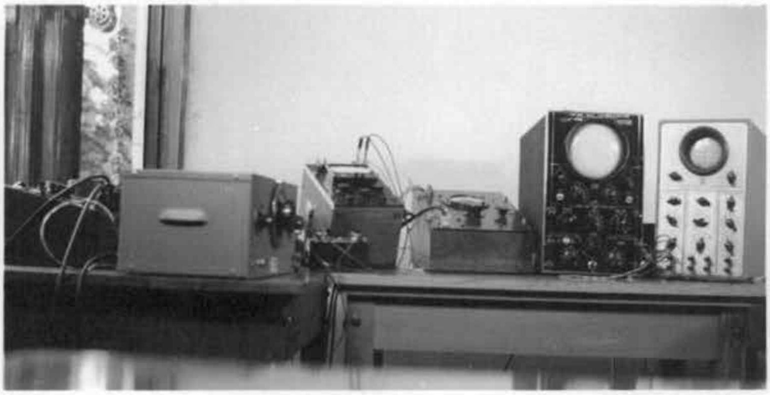


Fig. 12 - Two pictures of testing position showing the arrangement of the testing circuit components.

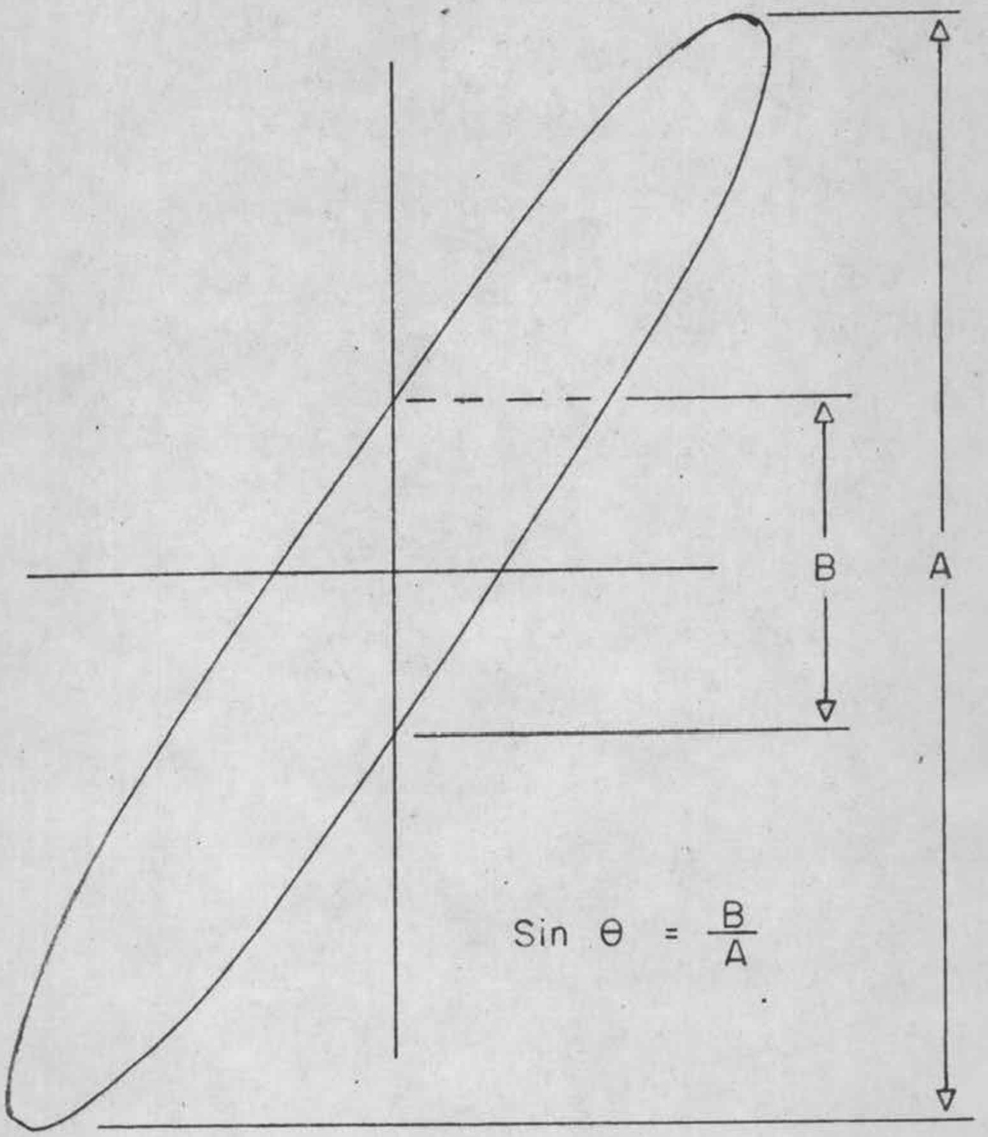
FIGURE 12

voltage waves to make certain that no distortion was present during the tests. Figure 12 shows two pictures of the experimental circuit.

To ascertain the reliability and accuracy of the test circuit, known impedances were inserted into the test circuit in place of the motor element and the voltage, current and phase angle measured. From the measured values the impedance was calculated and compared with the known values. It was found that measurements of any given impedance could be readily repeated to within a two percent error. Experimentation indicated that most of the error was introduced in measuring the phase angle from the Lissajous figure on the oscilloscope. Reading the figure on the screen was difficult because of the width of the trace on the screen. It was necessary to read the pattern measurements on the same side of the trace to maintain good accuracy.

The angular relationship between the voltage and current was determined as shown in Figure 13. The sine of the angle is the ratio of the minor length (B) to the major length (A). An angle of zero degrees is a straight line figure lying at an angle on the oscilloscope screen of forty-five degrees. A ninety degree phase angle will show a circle on the oscilloscope screen.

Two condenser sections connected across the terminals of the loudspeaker were used to determine the character of



Determination of phase angle from a Lissajous figure.

FIGURE 13

the reactive component of the loudspeaker impedance. The change in the Lissajous figure on the oscilloscope was noted as small amounts of capacitance were placed in parallel with the loudspeaker. If the pattern opened, the motor element reactance was capacitive in nature, and conversely, if the pattern closed with the addition of capacitance the motor element impedance was inductive in character.

Figure 14A shows a trace made at a point of small angle between the voltage and current in the test circuit. In Figure 14B is shown a trace indicating a large phase angle between the voltage and current. The traces shown in Figure 14 are the exact replica of the patterns that appear on the oscilloscope screen. The wave shape of both the voltage and current are sinusoidal and no distortion is discernable.

Traces showing distortion due to mechanical and acoustical resonances in the loudspeaker unit may be seen in Figure 15. Distortion evident at high frequencies is shown in Figure 15A. Figure 15B shows a distorted trace that occurs at the lower frequencies. These distorted traces are caused by the change in acoustical impedance as the current is increased in the moving-coil motor element under test. The change in the wave shape of both the voltage and current by the distortion introduced gives rise to the unsymmetrical patterns shown.

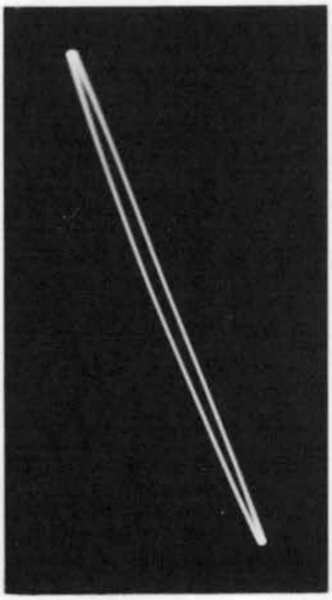


Fig. 14A - A Lissajous figure showing a small phase angle between the voltage and current.

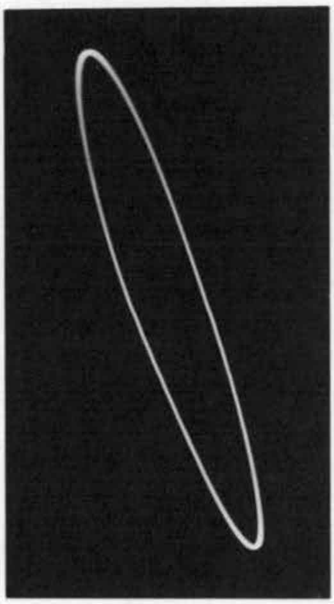


Fig. 14B - A Lissajous figure showing a large phase angle between voltage and current.

FIGURE 14

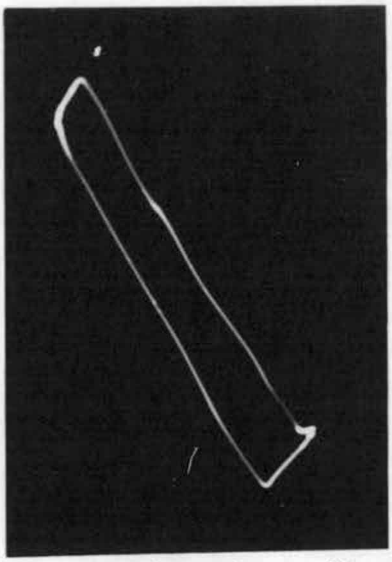


Fig. 15A - A Lissajous figure showing distortion introduced at high audio frequencies.

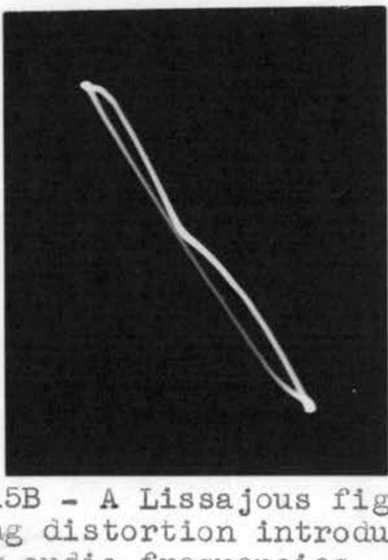


Fig. 15B - A Lissajous figure showing distortion introduced at low audio frequencies.

FIGURE 15

PERFORMANCE OF TESTS

The measurements made on the moving-coil motor element to determine its dynamic impedance characteristics are briefly outlined below:

1. Interference measurements
   - A. Proximity of object
   - B. Shape of object
2. Impedance measurements
   - A. Constant-current operation
   - B. Constant-intensity operation
   - C. Blocked voice-coil measurements.

Several quantitative tests were made to ascertain the effect that the proximity and shape of sound reflecting surfaces have on the input impedance of a loudspeaker motor element. The measurements were made at several frequencies chosen at random. At each frequency sound reflecting surfaces and bodies of heterogeneous shape were placed in the acoustic path of the horn. Any change in the characteristics of the motor element due to these obstructions were reflected in the Lissajous figure on the test oscilloscope.

In the case of flat reflecting surfaces placed in the path of the horn, it was found that no change in characteristics occurred until the surface was within ten to fifteen feet of the bell of the loudspeaker. The distance varied depending upon the frequency being used. The higher frequencies were affected first and distortion gradually appeared at the lower frequencies as the surface was brought nearer the bell of the loudspeaker. These measurements were conducted with a constant audio input of fifteen watts. With the completion of the interference tests a location for the remainder of the impedance measurements was selected. A discussion of the test location will be found near the end of this section.

Three series of impedance measurements were made. The first series of tests were based on a constant current flowing in the voice coil of the motor element. The current was used as a reference because it is proportional to the force acting on the diaphragm of the motor element. In a constant magnetic field the force acting on a conductor is:

$$f = B(l)ni.$$

Since B, the magnetic field strength; l, the conductor length; and n, the number of conductors in the field; are all constants, then the force acting on the diaphragm of the motor element is proportional to the current flowing. Complete data were taken on the motor element and horn combinations listed on page twenty-five using a constant current of five-tenths ampere. The results of this group of tests are shown on curves located in the appendix of this paper.

The second series of measurements were based on a constant intensity at a point six feet from the bell of the horn. The intensity was measured by a General Radio, type 759A, noise meter. The microphone of the noise meter was attached to a boom so that it could be moved along the axis of the horn. Pictures of the experimental arrangement may be seen in Figures 16 and 17. Complete test results using a constant intensity of one-hundred decibels appear in the appendix of this report. The main purpose of this second series of tests is to obtain information that could be compared with the results of the series of tests based on a constant current flowing in the circuit.

The third series of measurements were made to determine the blocked voice-coil resistance of the motor element. The blocked voice-coil resistance is determined by solidly blocking the diaphragm in its proper operating position and obtaining the impedance of the blocked motor element over the frequency range desired. Solidly blocking the voice-coil is a problem since the diaphragm traverses only a short distance and the large current and intense magnetic field in which the voice coil is located cause it to move with considerable force. In order not to disturb the magnetic field only non-metalic plasters and glues can be used. Several attempts to block the motor element diaphragm by a mechanical means ended in failure. It was found, also, that most resin base glues shrink during drying thus leaving space for the diaphragm to move. Plaster of Paris and patching plaster were tried and found to be satisfactory if only a small amount of water was used in mixing. The addition of too much water causes the plaster to shrink during drying leaving space for the voice coil to move. Plaster of Paris was used to block the diaphragm of Driver "J" (page eleven). The entire unit, voice-coil, magnet, and wiring were imbedded in the plaster and allowed to dry very slowly until hard. A motor element identical to Driver "U" (page twelve) was supplied by the manufacturer already solidly blocked. The means of blocking this motor element was not divulged by the manufacturer. The impedance measurements were made on the blocked diaphragm motor elements in the same manner as those made on the complete loudspeaker units. Results of these blocked diaphragm tests can be seen from curves located in the appendices of this paper. As previously mentioned, the purpose of the blocked diaphragm impedance measurements is to determine the blocked diaphragm resistance of the motor element. The blocked diaphragm resistance is used to calculate the efficiency of the loudspeaker unit as indicated on pages ten to fourteen of this paper.

Two miscellaneous tests were performed to determine the resonant point of the motor element diaphragm. First, an attempt was made to measure the displacement of the voice coil but no successful method was found. Any object fastened to the diaphragm changed the mass and acceleration characteristics of the diaphragm thus changing the electro-acoustical properties of the motor element. A light beam could not be used due to the very small throat opening of the driver unit. The angle of reflection was so small that the deflection could not be recorded.

The second series of tests were more successful in determining the resonant point of the motor element diaphragm. Short tubular sections were attached to the throat of the motor element thus changing slightly the enclosed volume above the motor element diaphragm. A change in the enclosed volume will cause resonant points due to the internal space about the voice coil and diaphragm to be changed also. The mechanical resonance of the motor element diaphragm will not be influenced perceptibly so that the resonant point due to mechanical resonance will reoccur at nearly the same frequency. It will be noted from the test curves in the appendices that the addition of the small tubular sections caused some of the resonance points to be displaced while the large resonant point near two-thousand cycles did not change. This would indicate, then, that this point is the major resonant frequency of the motor element. Figure 6 shows a picture of a motor element with a tubular section attached.

Theoretically, a loudspeaker should be tested in free space. However, the interference tests indicate that objects over twenty feet away from the horn of the loudspeaker so not affect the impedance characteristics of the loudspeaker unit. The test location shown in Figures 16 and 17 was selected because it provided an unobstructed area into which the test loudspeaker could be operated as well as giving access to electrical facilities and equipment storage. The background foliage shown in the pictures is more than thirty feet to the side of the loudspeaker. Although not clearly shown, no interfering object lies within the area directly in front of the loudspeaker for a distance of approximately one-half mile.

Fig. 16 - Two pictures of the loudspeaker testing location showing Driver "U" and Horn "U" extended on the apparatus boom and ready for test.

FIGURE 16

Fig. 17 - Two pictures of the loudspeaker testing location showing Driver "U" and Horn "R" in position and ready for operation.

FIGURE 17

DISCUSSION OF TEST RESULTS

The results of the dynamic impedance tests of a moving-coil loudspeaker motor element bring out the following salient points.

In a mathematical analysis of a moving-coil motor element it is possible to account for the acoustical and mechanical impedances of the unit. These acoustical and mechanical impedance parameters can be segregated and measured in practice only with great difficulty and in some cases not at all.

The usual location of a loudspeaker in rooms, auditoriums, or out-of-doors apparently does not affect appreciably the input impedance of the motor element. The interference tests proved that only objects within ten feet of the bell of the loudspeaker cause the input impedance of the unit to be noticeably altered. Comparison of the test curves will show that the construction of the loudspeaker horn affects materially the input impedance of the motor element.

The re-entrant type of horn produces more points of resonance because of sound reflections at every fold of the horn. This change in acoustic impedance of the re-entrant horn at each fold, causes wave reflections which affect the load on the diaphragm causing the impedance characteristics of any motor element with which a re-entrant horn is used to be extremely erratic over the frequency range of the unit. This phenomena of sound wave reflection was reaffirmed by measuring the lengths of the air columns in the horns used during the tests and calculating the resonant frequencies of the various air columns. Comparison of the calculations and the test curves indicate that most of the resonant points on the test curves are due to wave reflections within the loudspeaker horn. This information is one of the contributions of this study.

The nominal impedance of the motor element more closely approaches twenty ohms rather than the sixteen ohms quoted by the manufacturers. The impedance angle of the motor element varies from a plus thirty degrees (+30°) to a minus thirty degrees (-30°) over the operating range of frequencies. The average angle is approximately a plus eighteen degrees (+18°). This makes the average load a lagging, or inductive, load for any vacuum-tube amplifier. It wil be noted further from the test curves in the appendices of this report that the loudspeaker unit appears as a resistive load over only a very small percent of the operating range.

The power handling capacities of the motor elements are overrated by the manufacturers. It was found that the continuous power input to the loudspeaker could not be made to exceed seventeen watts. The manufacturers rated the motor elements at twenty-five watts. If the units were forced to take more load permenant damage was done to the diaphragm and voice coil. The condition of "over drive" becomes apparent long before the maximum power point is reached. In most instances the point of "over drive" occurred near a power input of from twelve to fourteen watts. The point of over drive was taken as the point of change in symmetry of the Lissajous figure on the oscilloscope. As long as the Lissajous figure remains undistorted the input to the loudspeaker will be sinusoidal. It was found that by calculating the power handling capabilities of the unit using maximum instead of effective values of voltage and current a value corresponding to the twenty-five watts as published by the manufacturers could be obtained. Inspection of the test curves indicate that the output of the loudspeaker units is more constant over the operating range of motor elements having the more stable input impedance characteristic. This means that the average operating power output of the unit is greater over the frequency range.

A comparison of the constant-intensity and constant-current tests show that both approaches give similiar results. The constant- intensity curves show fewer resonant points than do the constant-current curves. This may be due to a high noise level masking some of the resonant points. The disadvantages of the constant-intensity tests are the difficulties in establishing a good technique and obtaining consistent results. It is difficult to find an outside location that has a low noise level, a large unobstructed area, and the necessary electrical conveniences. The measurements of sound intensities with high background levels and standing waves make it nearly impossible to reproduce tests at will. The constant-intensity tests cannot be conducted in an enclosed space due to the acoustical characteristics of the enclosure affecting the operation of the noise level meter. An enclosed space can be acoustically treated to closely approach outside conditions but no practical amount of acoustical treatment can entirely eliminate room reverberation and standing waves completely.

The constant-current tests as outlined in this paper and the results shown in the test curves indicate that the testing procedure is rather simple and the experimental results accurate. This testing method gives the complete electrical characteristics as well as indicating the acoustical quality of the loudspeaker unit. The Lissajous figure shows the introduction of distortion in the loudspeaker output due to new harmonics, resonance points, and over drive by a change in symmetry about the axis of the Lissajous figures. The power limits of the loudspeaker can be easily determined by driving the unit with large amounts of power and taking notice of the resulting pattern on the oscilloscope screen.

CONCLUSION

The study and measurement of the dynamic impedance characteristics of a moving-coil loudspeaker motor element show the motor element impedance to be a variable load over the operating frequency range for any audio amplifier. The nominal impedance presented by a loudspeaker is, $Z = 20 \angle +18$ or $Z = 19.02 + j6.18$. The variation of the motor element impedance is from ten to forty ohms with a change in impedance angle of from plus thirty degrees to minus thirty degrees. This makes the loudspeaker impedance both inductive and capacitive in character over the operating frequency range of the unit.

The amount of impedance variation for a given motor element depends upon the type of horn used with the motor element. The re-entrant type horn presented the greatest variation of impedance. This is caused by the resonant air columns and change in acoustical impedance due to the folds in the horn construction.

The motor elements are rated by the manufacturers at twenty-five watts. The motor elements will absorb only seventeen watts before permanent damage is done to both the voice coil and diaphragm. The average power input at the point of over drive is thirteen watts.

The average loudspeaker efficiency of the units tested is thirty-five percent. The efficiency of the loudspeaker varied depending upon the character of the input impedance of the motor element and horn.

Objects in the path of the loudspeaker do not change the motor element impedance unless located within ten feet of the bell of the horn.

Finally, the test methods and procedures developed in this paper are an easy and accurate means of determining the operational impedance characteristics of a loudspeaker. The measured motor element impedance indicates also the acoustical quality of the loudspeaker. A comparison of the constant-intensity and constant-current methods of loudspeaker testing show the constant- intensity method to be cumbersome to perform and to give inconsistent results.

It is believed that the constant-current method of loudspeaker testing developed in this paper and the information on loudspeaker impedance characteristics presented will lead to the improvement in the design of horn-type loudspeakers.

APPENDIX I

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and

REFERENCES

BIBLIOGRAPHY AND REFERENCES

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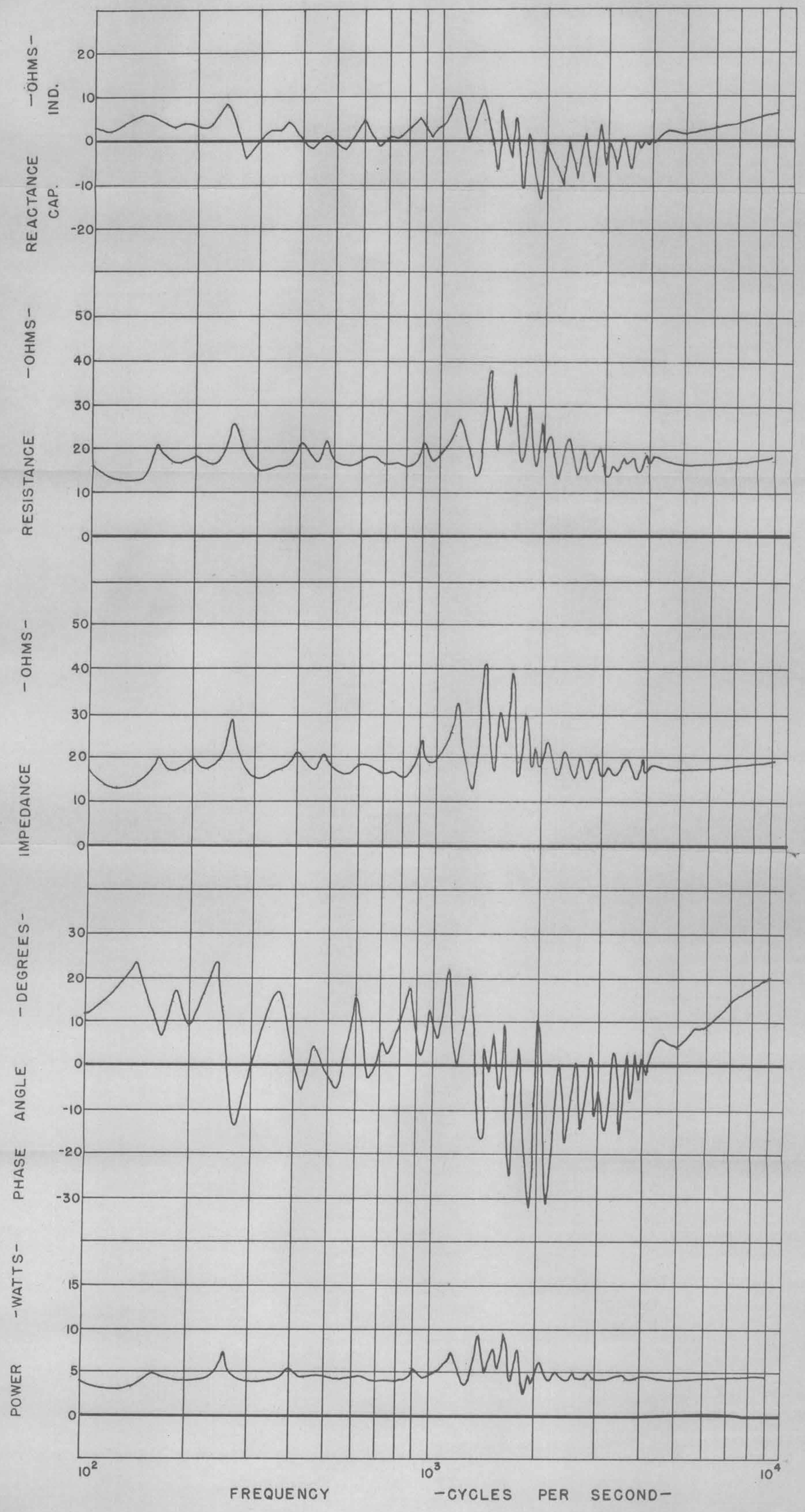
APPENDIX II

TEST CURVES

INDEX TO APPENDIX II

CONSTANT CURRENT—VARIABLE FREQUENCY
CHARACTERISTICS OF
DRIVER (U) AND HORN (U) IN FREE SPACE



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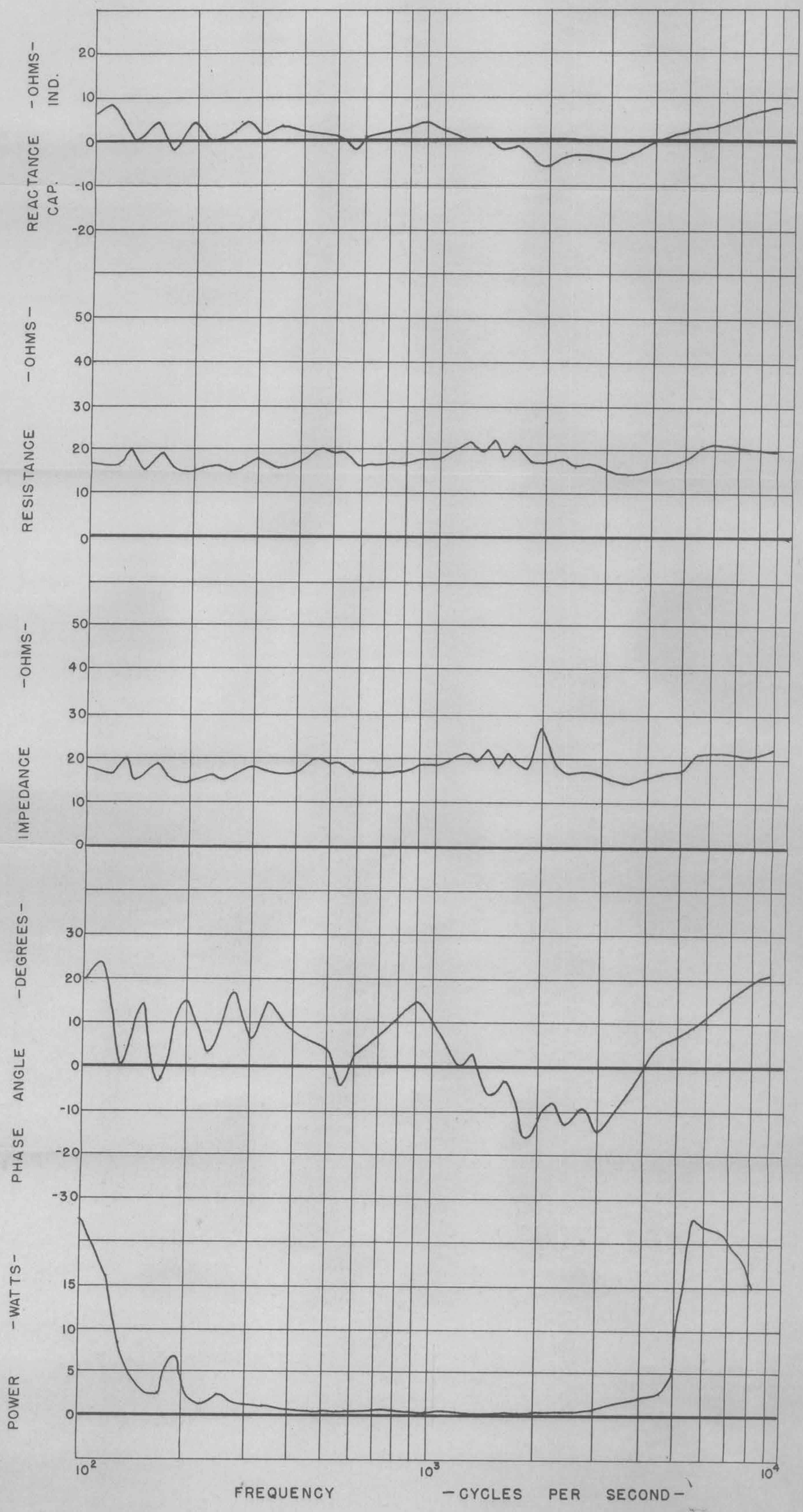

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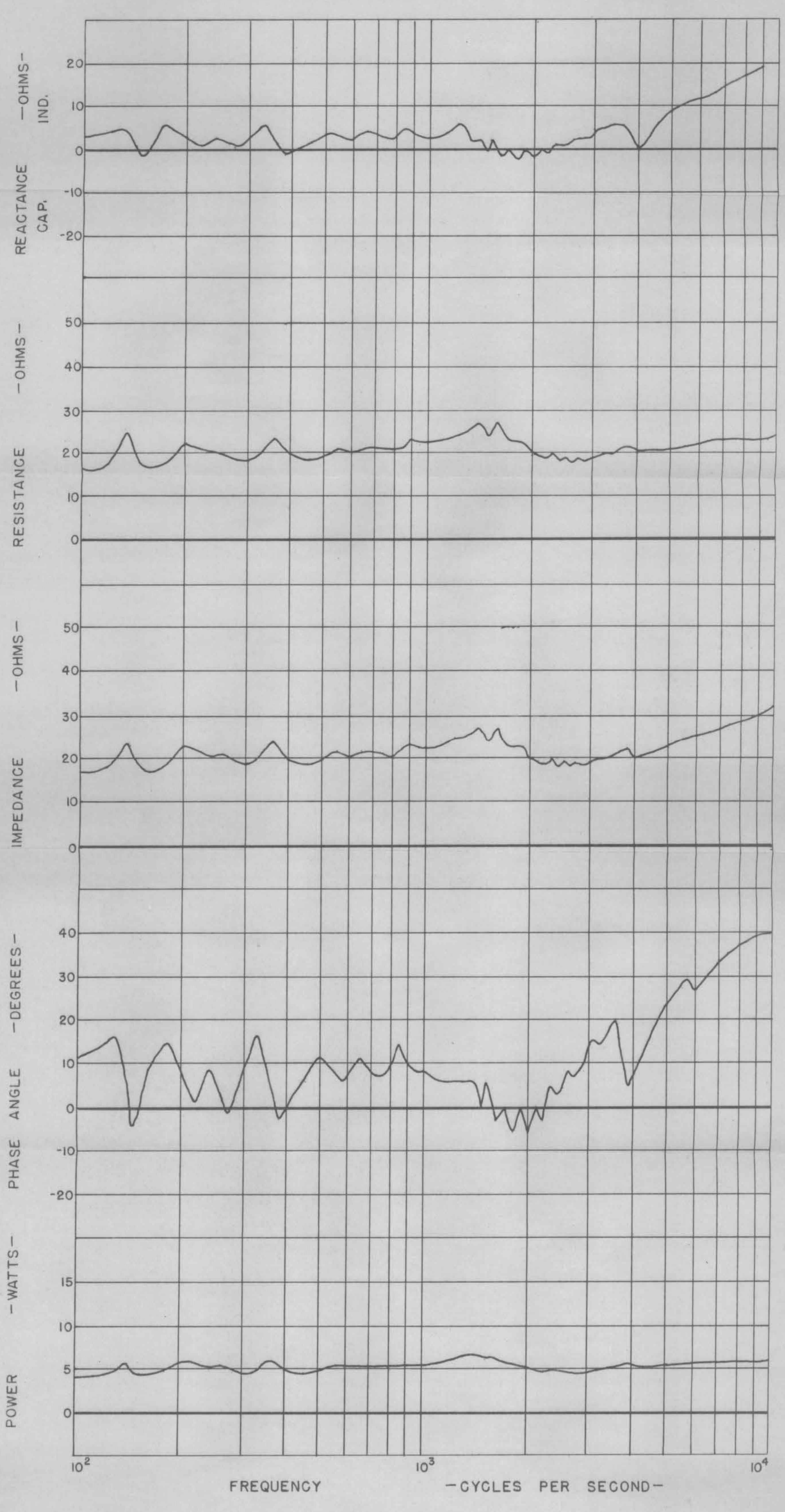

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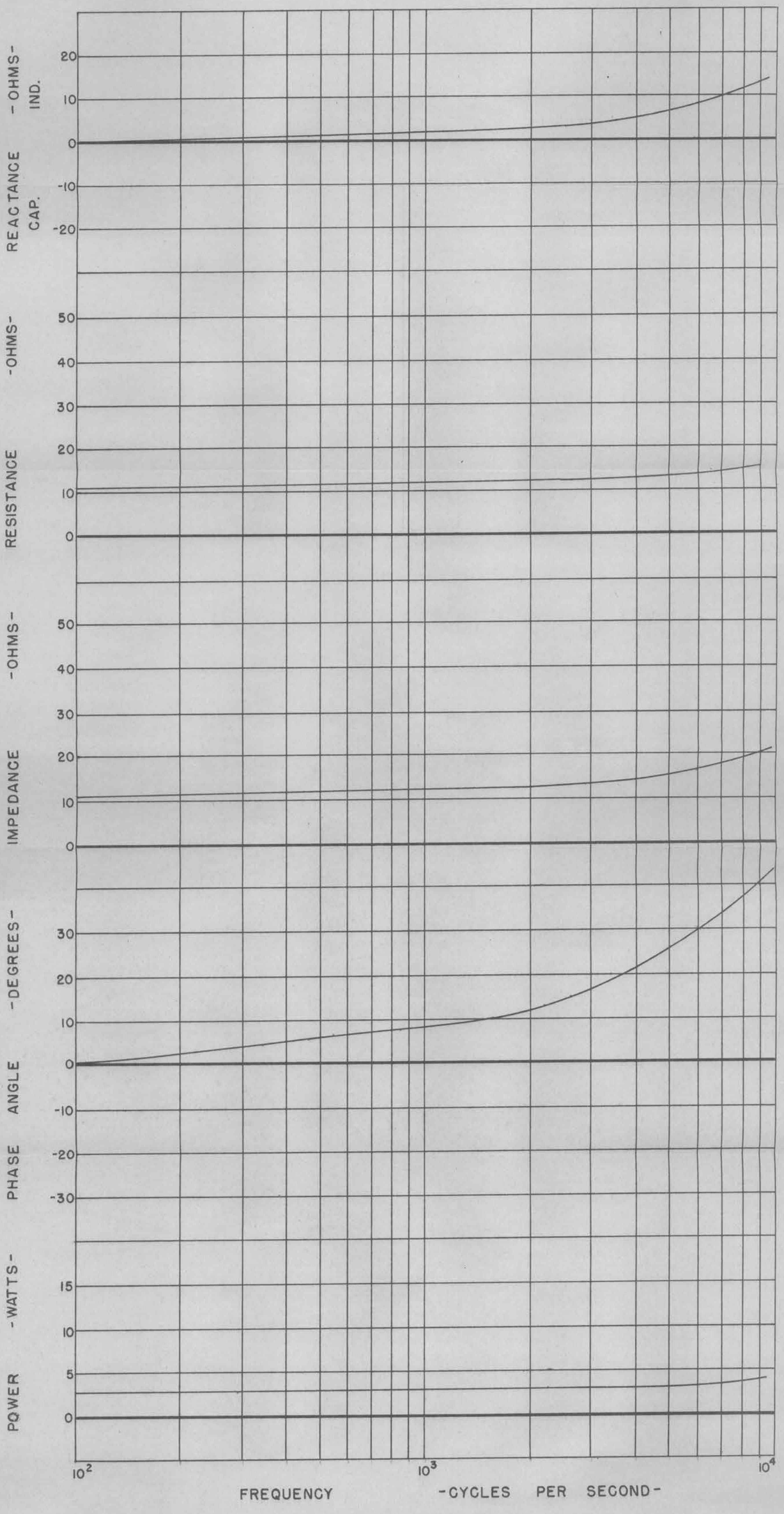

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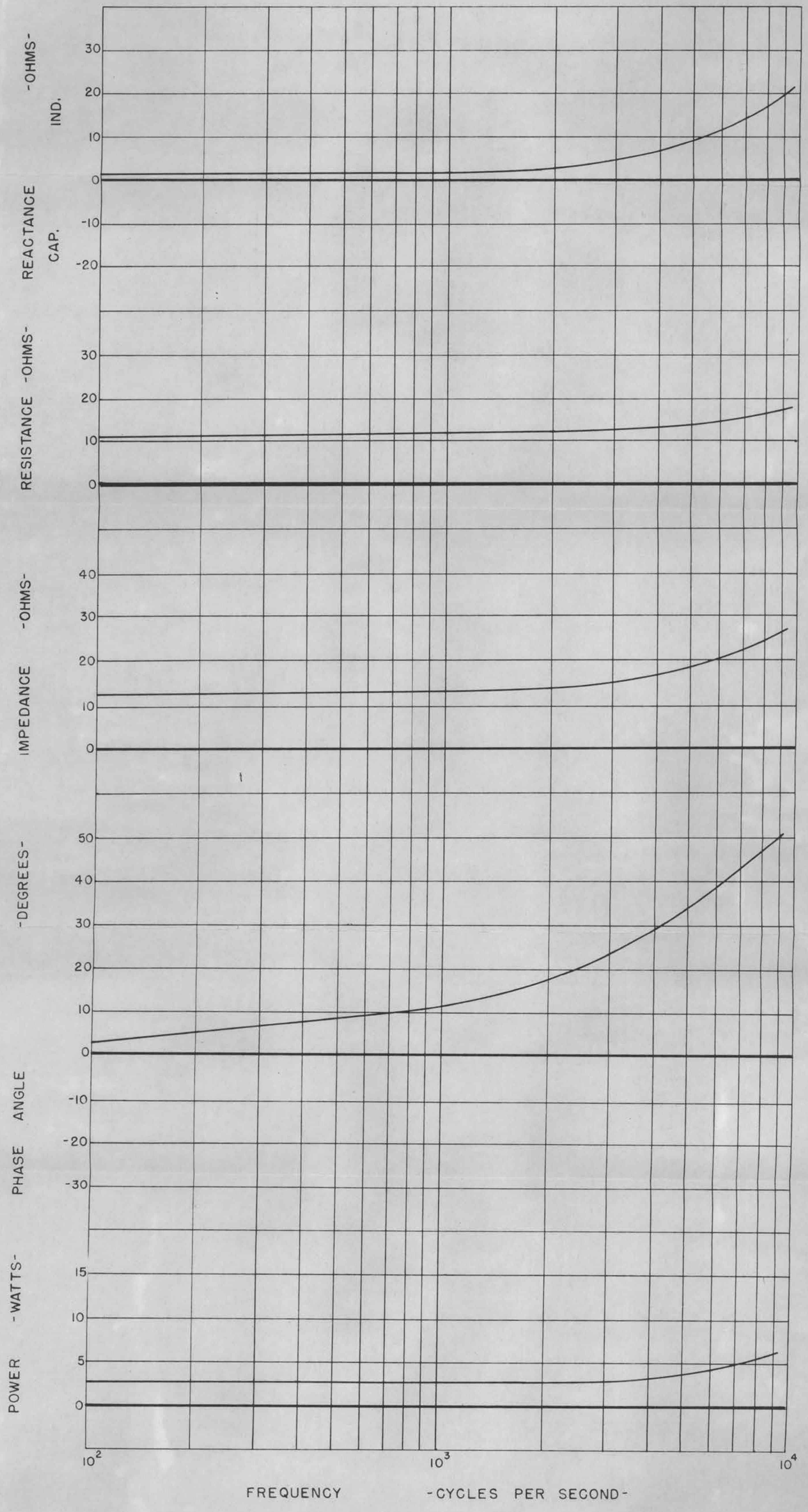

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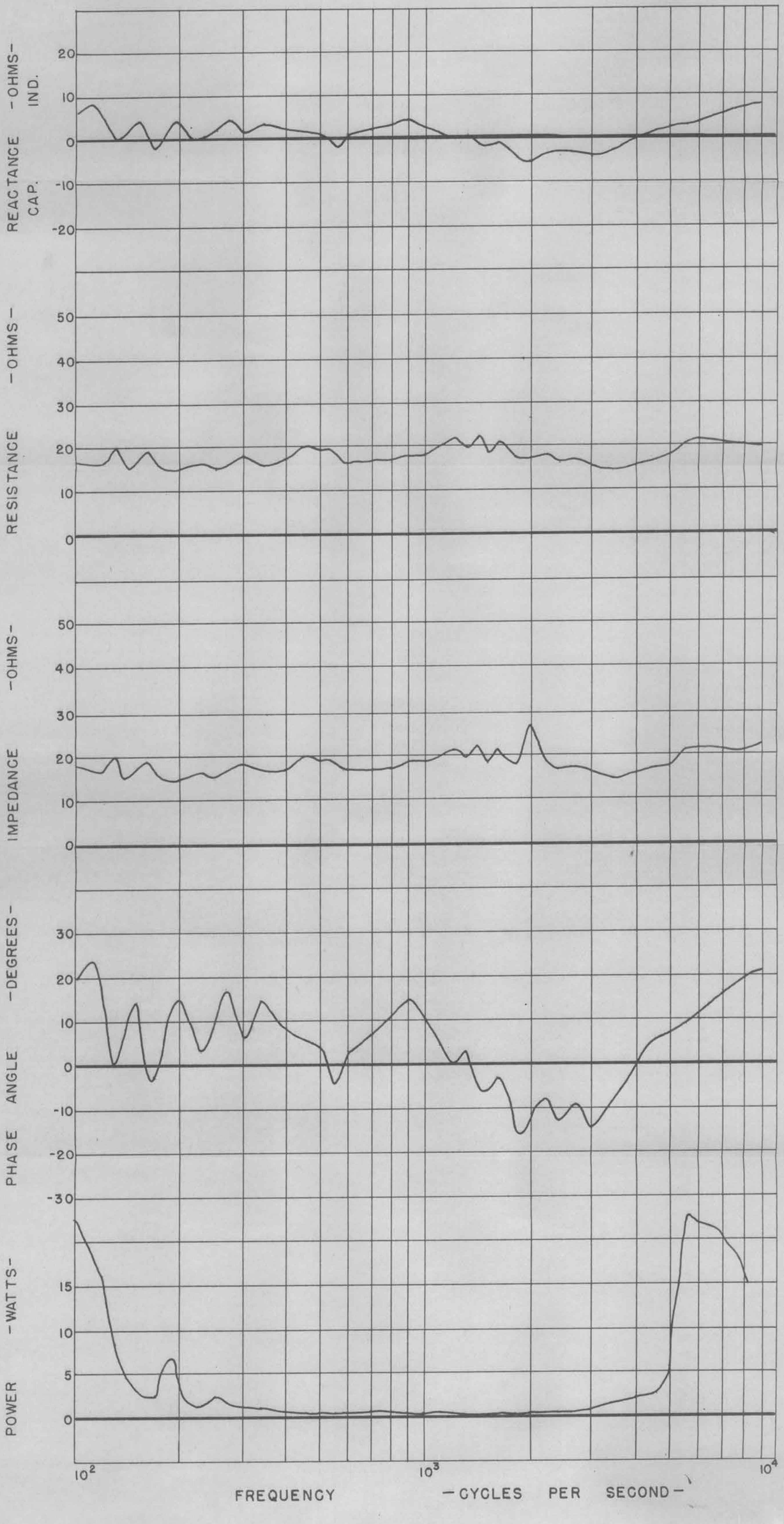

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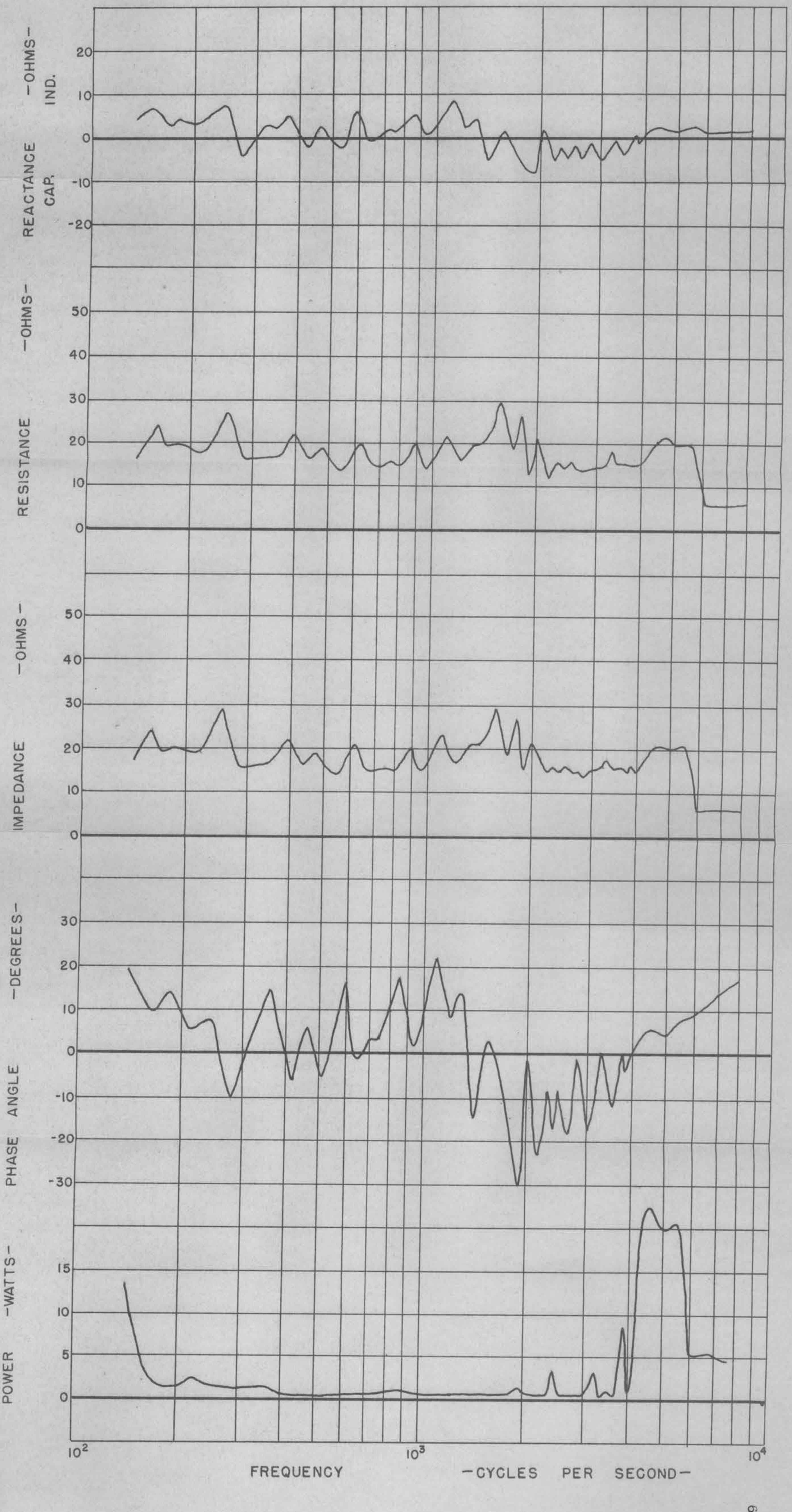

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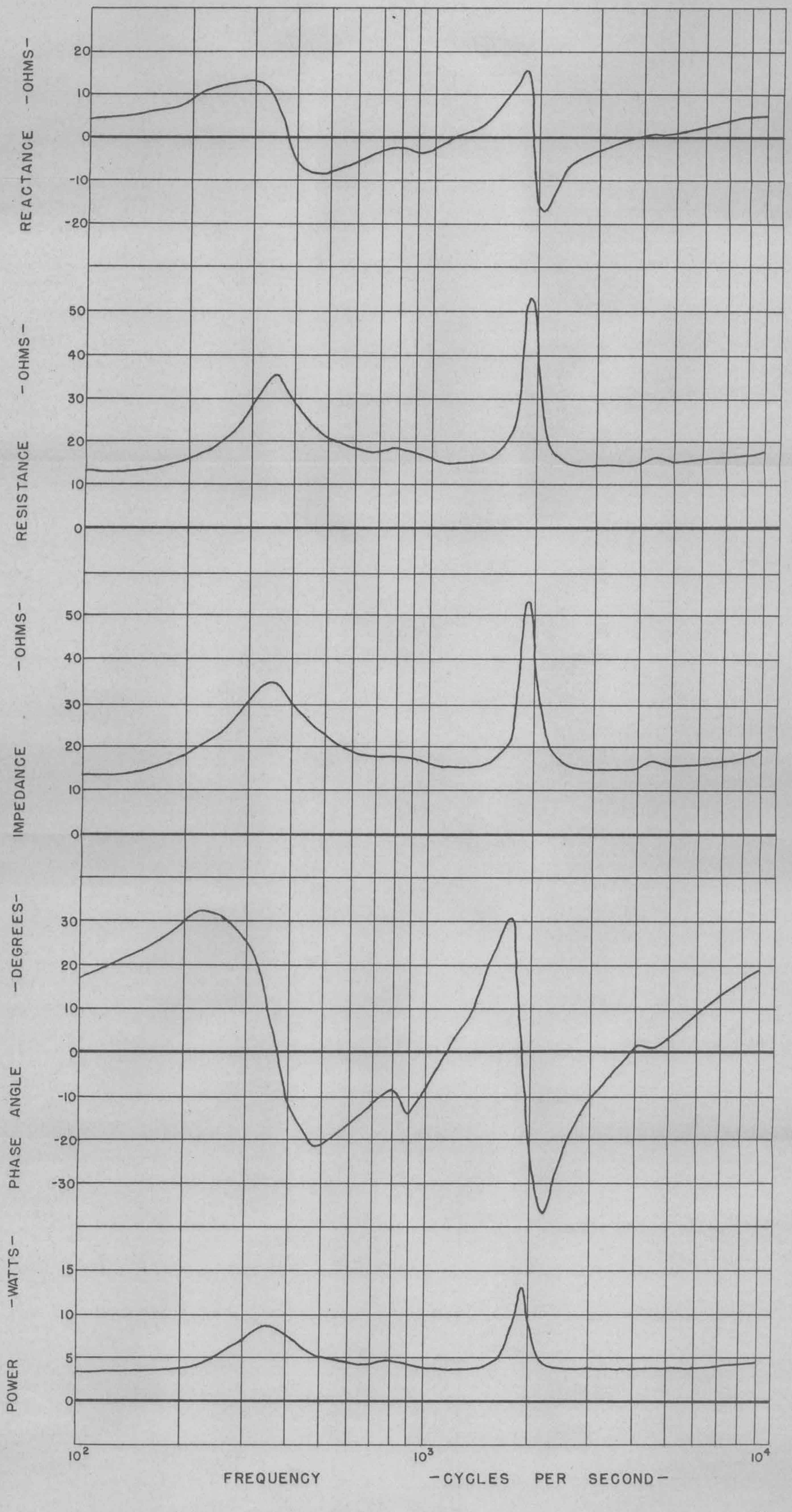

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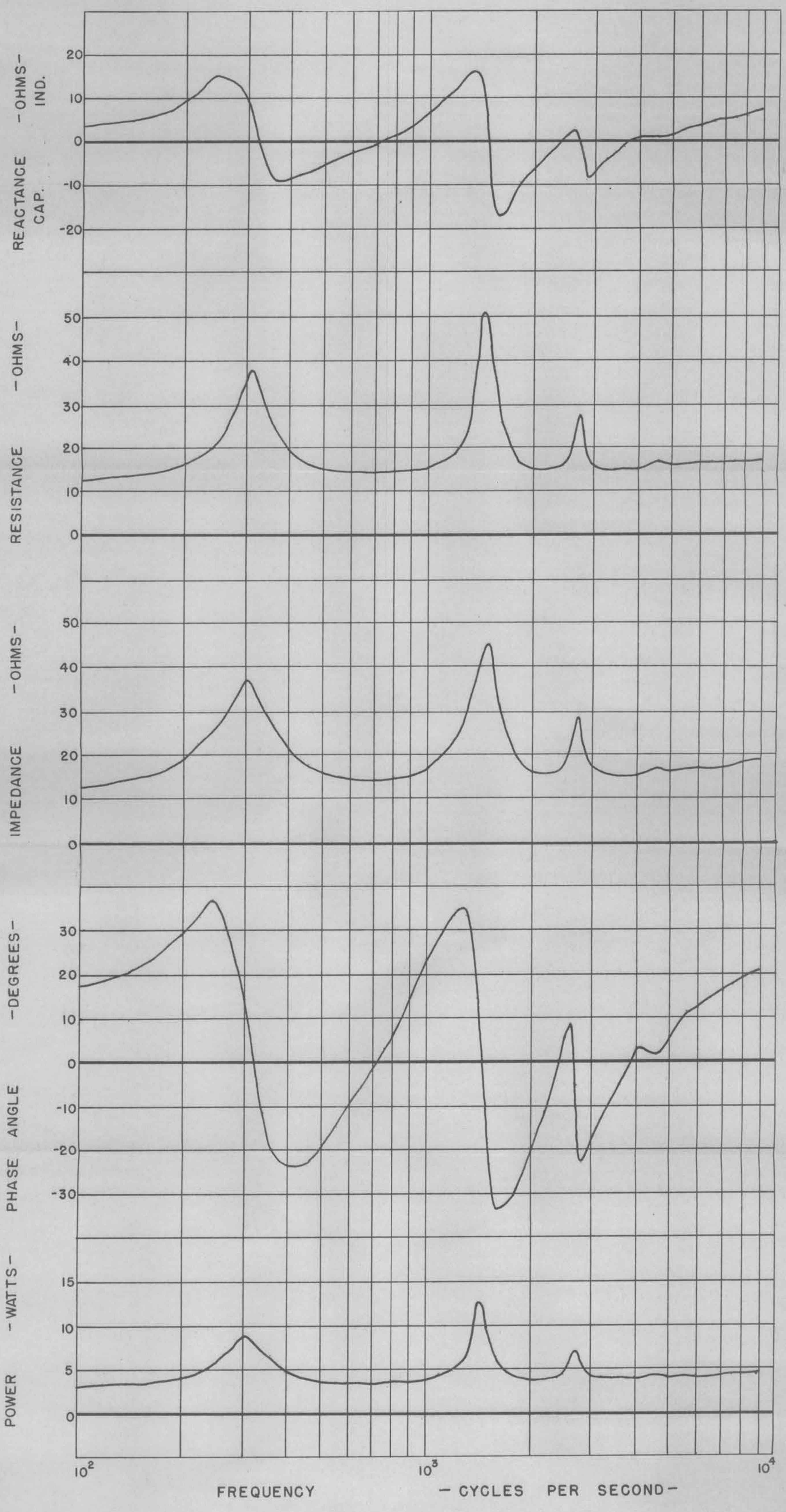

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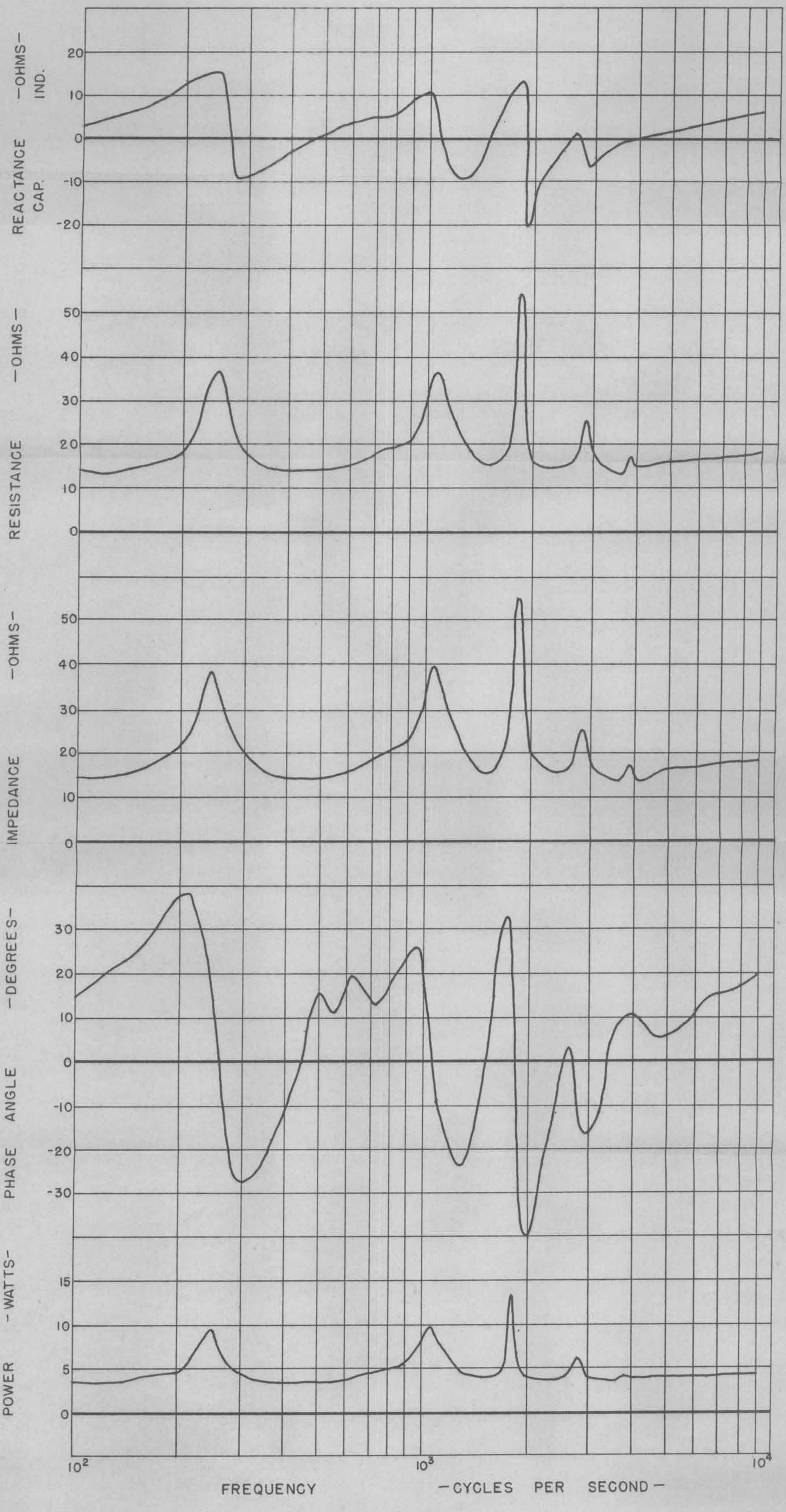

OPERATIONAL EFFICIENCY CHARACTERISTICS OF DRIVER AND HORN COMBINATIONS TESTED