IMPEDANCE MATCHING IN AURAL PROSTHESIS

By

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Bachelor of Science
Oklahoma State University
Stillwater, Oklahoma
1971

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
May, 1973

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PREFACE

The purpose of this work was to determine whether impedance matching concepts could yield significant improvements in aural prosthesis. This did not imply the design of an appropriate device to achieve such a match.

One problem with considerations of impedance of human ears is the absence of reliable methods to measure impedance offered to hearing aids at high frequencies. For this reason, a device had to be developed that could be used to measure impedance at higher frequencies.

This work was supported by a Biomedical Sciences grant from the OSU Research Foundation and by the OSU Center for the Systems Science. This support made possible the purchase of equipment used in the experimental phase of the work. My special thanks go to my thesis adviser, Dr. Larry Zirkle, who provided many helpful suggestions and comments. Also, thanks are in order to the OSU Library and Computer Center for their assistance. My thanks go to Dr. Richard Lowery for his valuable assistance with the instrumentation. Special gratitude is extended to my wife, Karen Whaley, for her assistance with the rough draft copies and for her patience and sacrifice during the long hours spent in the laboratory. A note of thanks is given

to Mrs. Lynn Danvers for her comments on the manuscript and preparation of the final copy.

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NOMENCLATURE

k	spring constant in mathematical model
m	piston mass in mathematical model
b	damping coefficient in mathematical model
P_i	incident pressure wave
P_r	reflected pressure wave
ω	radian frequency of pressure wave
c	speed of sound in air
K	wave number, ω / c
xx	distance from eardrum
U	volume velocity
A_1	area of piston in mathematical model
ℓ	length of tube in mathematical model
Z_o	input acoustical impedance of mathematical model
A	amplitude of incident pressure wave
B	amplitude of reflected pressure wave
Z_e	acoustical impedance at the piston of the mathematical model
$a\ell$	length of acoustical impedance matching device
R_T	radius of acoustical impedance matching device

Rad	radius of hole drilled in wall of impedance matching device
λ	wave length of pressure wave
L	generalized inductance
C	generalized capacitance
V	volume
$\overline{P}$	power
R_e	resistance of mathematical model
X_e	reactance of mathematical model
p_r	reference pressure
p_k	source calibration pressure
$G_s(j\omega)$	transfer function of source probe
ϕ_s	phase angle between p_r and p_k
U_k	volume velocity through coupler cavity
p_m	microphone calibration pressure frequency response
$G_m(j\omega)$	probe microphone transfer function
ϕ_m	phase angle between p_r and p_m
$G_{mm}(j\omega)$	overall measured transfer function for impedance
ϕ_{mm}	overall measured phase shift for impedance
p_e	pressure inside ear canal

CHAPTER I

INTRODUCTION

Hearing Aid Fitting

Conventional hearing aid fitting follows a procedure developed by Davis[1] in 1947. At the end of World War II many servicemen were returning home with hearing impairments, and there was no general technique of hearing aid fitting. The procedure that was developed was one which relied heavily on trial and error using audiogram data as a guide. All patients were fitted with hearing aids possessing the same basic types of frequency response curves, specified by slightly differing slopes.

Present-day hearing aid fitting is hampered by technical difficulties. It has been suggested that aural prosthesis should be accomplished with hearing aids having wider frequency ranges and less harmonic distortion.[2] This would provide better hearing aid performance for the patient whose hearing loss is in higher frequencies and would provide music enjoyment for the hard of hearing.[3] Technical improvements are needed so that these improvements can be made possible.

The performance characteristics of hearing aids are measured by connecting them to acoustical cavities which approximate the imaginary part of human ear impedance. These cavities, known as artificial ears, represent the average of many human ears, and any single person's hearing might not conform to that average. Consequently, the hearing aid may not perform the same in the real ear as it did in the artificial ear, and the audiologist may not really know whether the hearing aid is effective or not. Since artificial ears used in testing hearing aids attempt to represent human ear impedance, conventional hearing aid design indicates some consideration of the loading effect of the ear. This attempt is not successful, however, as artificial ears include only a reactive component of impedance. Basic considerations of impedance matching should be included in aural prosthesis.

Impedance Matching

Any sort of improvement in aural prosthesis must be undertaken from a scientific point of view as the human ear is an extremely complicated mechanism. Hearing is dynamic in nature and has been characterized as nonlinear and unsymmetric, qualities that can best be analyzed by engineering methods.[4] Many peculiarities have been noted about the hearing mechanism, not the least of which is the wide range of sound intensities that can be heard by the healthy ear. The acoustic reflex protects the ear from extremely loud sounds by contraction of the middle ear muscles, and the middle ear ossicles are known to vibrate in two distinct stable modes.[5] The human ear has three degrees of freedom for positive pressures and only one degree of freedom for negative pressures.[6] Such a complicated mechanism can have a large variety of things go wrong, and yet audiologists must attempt to correct this wide variety of defects with hearing aids of the same basic type.

When the output impedance of the hearing aid is matched to the input impedance of the ear, maximum power will be transferred. Experience has shown that this impedance match improves the performance of the entire system. Therefore, in addition to improvements in power requirements, there would be improvements in dynamic qualities. The power requirements of the hearing aid might be made smaller, its dynamic characteristics could be improved, and the audiologist would have more complete information regarding the performance of the hearing aid in the actual ear.

Objectives and Procedures

It is the intention of this thesis to determine if improvements in hearing aid performance are possible by means of impedance matching. This will be done by establishing a mathematical model of the human ear to determine those parameters that are important in input impedance to the human ear. The parameters of this model are determined from existing data on the properties of the middle ear, and then adjusted after computations to make the model more like a real ear.

The input acoustical impedance of a human ear is measured and compared to the input acoustical impedance of the mathematical model. Results show that the model impedance is similar to a real ear.

An acoustical device is proposed which might be used to match the output impedance of the transducer to the input impedance of the ear. This device is similar to the tubes that connect conventional hearing aid receivers to the ear with a few additions, so the resulting impedance match is representative of what probably exists in hearing aids. The impedance match is attempted by a curve fit on the computer to determine the properties of the proposed device that represent optimum behavior. The quality of the impedance match by this device is rather poor.

Chapter III describes the measurement of ear impedance on a human subject, and results are given which are similar to that found in the literature. Certain variables are suggested as an explanation for the wide discrepancies observed in ear impedance, and it becomes obvious that impedance matching must reflect these periodic fluctuations. Therefore, impedance matching becomes the fitting of the device into some acceptable band of impedances that are found by a statistical analysis of human ear impedance.

A nonlinear phenomenon was discovered during testing which has not been reported before. The subject heard beats when the stimulus signal was a pure tone, and it is believed that these beats result from either almost periodicity or the superposition of a subharmonic signal on the primary signal to cause periodic fluctuations which sound like beats.

Chapter IV is a summary of the work done and conclusions that were reached. Recommendations are given for future research on impedance matching in aural prosthesis.

FOOTNOTES

[1] H. Davis, Hearing Aids: An Experimental Study of Design Objectives, (Cambridge, Massachusetts, 1947).

[2] Anne Harrison, "Better Amplifying Prosthesis," Journal of the Audio Engineering Society, Vol. 19, April, 1971, pp. 316-318.

[3] Ibid.

[4] Georg Von Bekesy, "The Mechanical Properties of the Ear," in S. S. Stevens (ed.), Handbook of Experimental Psychology (New York, 1960), pp. 1086-1087.

[5] Ibid.

[6] Ibid.

CHAPTER II

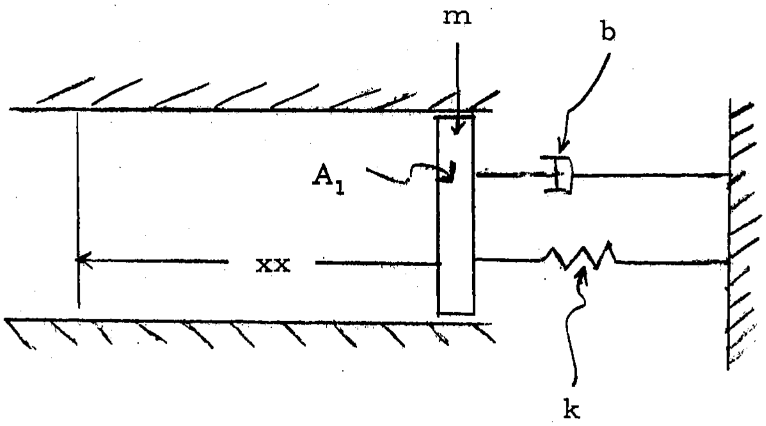
MATHEMATICAL MODEL

Physical Model

The model that will be used here consists of a cylinder terminated at its right end with a piston that is connected to a spring and damper (Figure 1). Certainly the behavior of a membrane should be more like the real ear than that of a piston, but a damped inner boundary condition on a membrane model makes it difficult to solve the resulting eigenvalue problem. This simplification was necessary in order to obtain a solution to the resulting equations, and since the ear-drum behaves like a piston at frequencies below 1000 hz., the simplification is justified.[1] It is felt that this model can be made to behave sufficiently like the real ear (Figure 2) by appropriate adjustment of the physical parameters. Although the ear is known to behave nonlinearly, this nonlinear effect is small for low intensities and may be neglected.

Derivation of Equations

The input acoustical impedance of the mathematical model may be determined in terms of known quantities in Figure 1. The



k = spring constant
b = damping coefficient
m = piston mass
xx = distance to eardrum

Figure 1. Mathematical Model

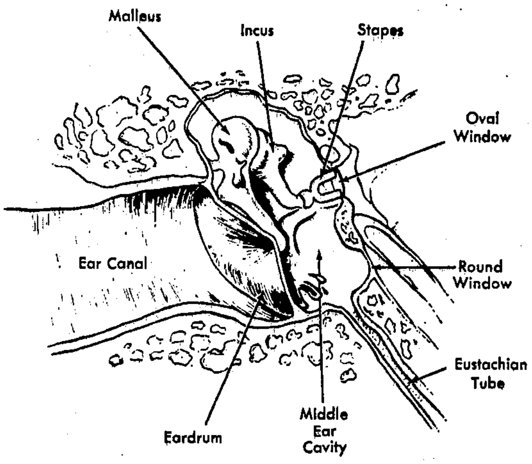


Figure 2. Parts of the Ear[2]

mechanical impedance at the right end is denoted by Z_e. When incident sound waves enter the cylinder, some are reflected from the right end and some are transmitted. Denoting those quantities incident by subscript i and those reflected by subscript r, the acoustical impedance at a distance x becomes

$$Z = \frac{P_i + P_r}{U_i + U_r} \tag{1}$$

where

$P_i = A\,e^{j(\omega t - Kx)}$

$P_r = B\,e^{j(\omega t + Kx)}$

p = pressure

ω = angular velocity

K = wave number, ω/c

xx = distance

The volume velocities may be related to the pressures for plane waves as

$$U_i = \frac{P_i A_1}{\rho c} \quad , \; U_r = \frac{-P_r A_1}{\rho c}$$

where

A_1 = area

ρ = density of air

c = speed of sound in air

The insertion of these relationships into Equation (1) yields

$$Z_o = \frac{A e^{-jKx} + B e^{jKx}}{A e^{-jKx} - B e^{jKx}} \cdot \frac{\rho c}{A_1} \tag{2}$$

In terms of the coordinate system indicated, there are two equations that result from applying boundary conditions:

$$Z\big|_{x=0} = \frac{A + B}{A - B} \cdot \frac{\rho c}{A_1} \tag{3}$$

$$Z\big|_{x=\ell} = Z_e = \frac{A e^{-jK\ell} + B e^{jK\ell}}{A e^{-jK\ell} - B e^{jK\ell}} \cdot \frac{\rho c}{A_1} \tag{4}$$

By combining Equations (3) and (4), the input impedance is determined in terms of known quantities and Z_e.

$$Z_o = \frac{\rho c}{A_1} \cdot \frac{Z_e + j\frac{\rho c}{A_1}\tan K\ell}{\frac{\rho c}{A_1} + jZ_e \tan K\ell} \tag{5}$$

For further information see Kinsler and Frey (1962). Taking a free body diagram of the mass in Figure 1, the equation of motion may be obtained by using Newton's second law. This free body diagram is shown in Figure 3, and the resulting differential equation is:

$$m\ddot{x} + b\dot{x} + kx = PA_1 e^{j\omega t} \tag{6}$$

To determine the steady state response assume $x = X e^{j\omega t}$ and substitute into Equation (5).

$$-\omega^2 mX e^{j\omega t} + b j\omega X e^{j\omega t} + kX e^{j\omega t} = PA_1 e^{j\omega t}$$

Solving for X, x may be determined in terms of the input pressure.

$$x = \frac{PA_1 e^{j\omega t}}{(k - \omega^2 m) + jb\omega} \tag{7}$$

Differentiating Equation (7) and forming the ratio of PA_1 to $\dot{x}$, the mechanical impedance results.

$$Z_m = b + j(\omega m - \frac{k}{\omega})$$

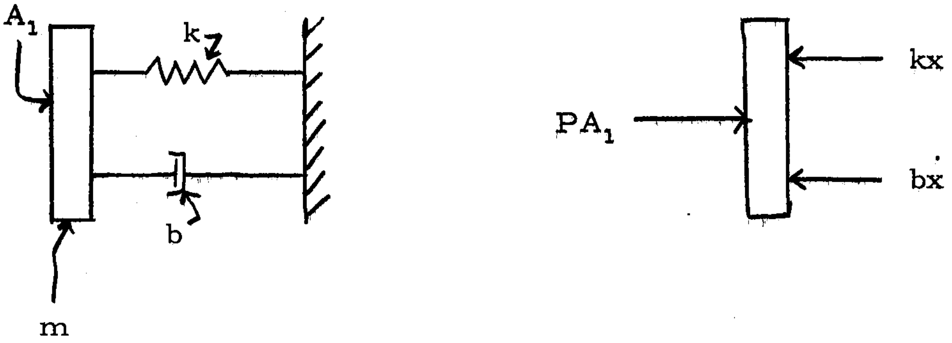


Figure 3. Free Body Diagram of Eardrum Model

The acoustical impedance may be obtained by dividing Z_m by A_1^2.

$$Z_e = \frac{b}{A_1^2} + \frac{j(\omega m - \frac{k}{\omega})}{A_1^2} \tag{8}$$

Equation (5) represents the input acoustical impedance of the mathematical model in terms of known quantities and may be used to compute impedance for various distances from the eardrum.

Model Parameters

The model parameters may be approximated using existing information. Because of physical appearance it is felt that the principal mass effect is due to the malleus. This effect may be any combination of translational mass or rotational moment of inertia as is common knowledge in elementary dynamics. The mass to be used in the mathematical model may be approximated by an effective mass that includes the translational and rotational mass effects of the ossicles. Since the malleus is directly connected to the eardrum, its mass will be taken as a first guess for m. The mass of the malleus as determined by Bekesy[3] is 23 mg.

The cross-sectional area and length of the ear canal are given as .5 cm.^{2} and 2.7 cm., respectively.[4] The spring constant of the eardrum was approximated by Onchi[5] as 5.49×10^6 dynes/cm.^{2} so this value is taken for k. Bekesy[6] measured the frictional forces in the middle ear over moderate frequencies as 100 gm./sec., so this value is taken for b. These parameters were used as an initial guess, and the input impedance was calculated for different distances from the eardrum. Comparisons with impedance data from other researchers indicated that the parameters were in error, so they were adjusted to make the mathematical model fit the real ear impedance more closely.[7] The adjusted parameters were

$$m = 25.\ \text{mg}, \qquad \ell = 2.0\ \text{cm}.$$

$k = 10^6$ dyne/cm. $A_1 = .5$ cm.^{2}

$b = 100$ gm. /sec.

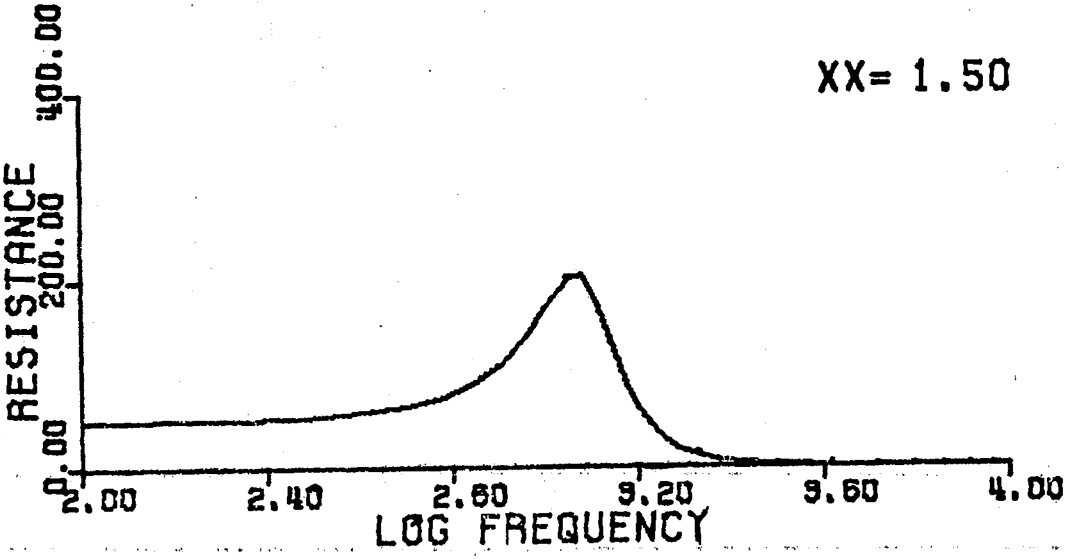
The resulting curves of input acoustical impedance as a function of x are shown in Appendix B. The variation in impedance with distance from the eardrum indicates that this distance is important in impedance matching. For purposes of modeling, a representative distance will be chosen for use in deriving the criteria for impedance matching.

It is felt that since the hearing aid insert is closer to the eardrum than is the ear canal opening, then the distance for impedance matching should be less than ℓ. The values of $xx = 1.5$ is arbitrarily chosen as a representative distance for impedance matching purposes, and the impedance curves for this condition are shown in Figure 4.

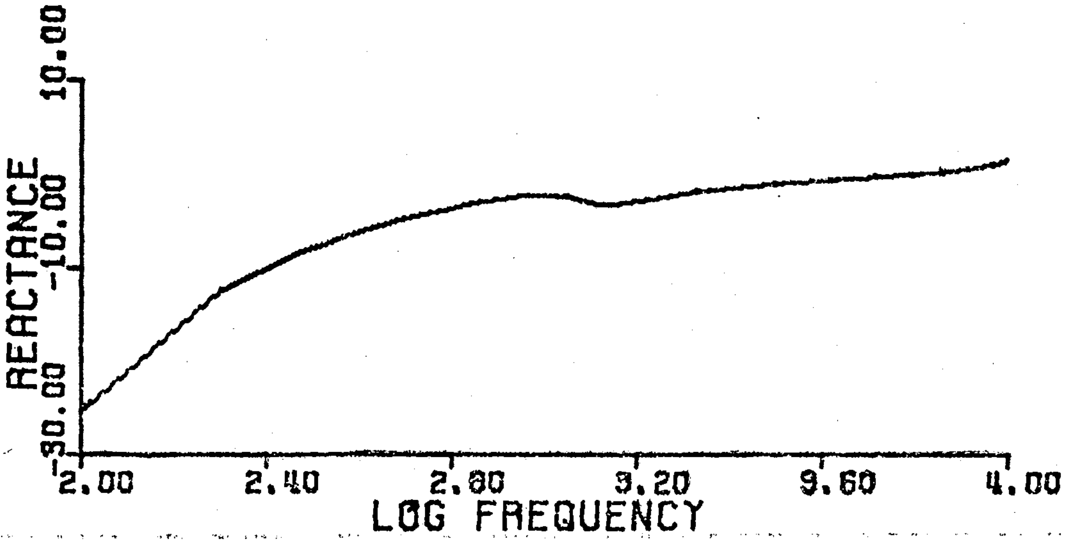
Matching Impedances

The criterion for impedance matching is that a maximum power be transferred from the source to the load. The acoustical device shown in Figure 5a is similar to the receiver of conventional hearing aids. The equivalent electrical circuit is easier to work with and is shown in Figures 5b and 5c.

The equivalent electrical circuit is determined by a system of analogies. The acoustical volume is analogous to capacitance, acoustical resistance is analogous to resistance, and changes of area are analogous to inductance. Volume velocity is analogous to current, and

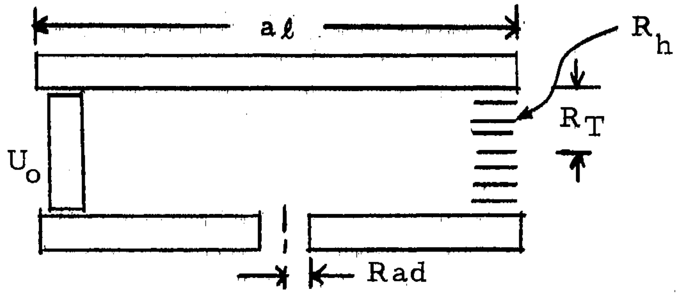


a.) Resistance

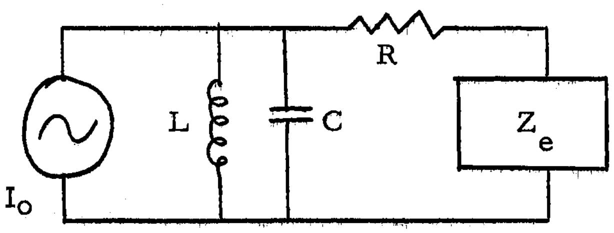


b.) Reactance

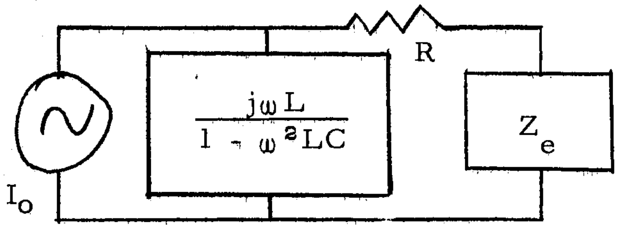
Figure 4. Acoustical Impedance for Mathematical Model in CGS Ohms



a.) Acoustical System



b.) Equivalent Electrical Circuit



c.) Simplified Equivalent Electrical Circuit

Figure 5. Impedance Matching Device

pressure is analogous to voltage. The conditions under which this equivalent electrical circuit is valid are that the physical dimensions of the acoustical transducer be small compared to a wavelength which means that the acoustical model may be considered as a lumped parameter model.[8] The length of a tube must be less than a quarter wavelength, or resonance will occur. The limitations on dimensions that were used here are:

$$a\ell < \frac{\lambda}{4}, \quad Rad < \frac{\lambda}{20}, \quad R_T < \frac{\lambda}{20}$$

where λ = wavelength of the incoming pressure wave. If the device is to be used up to a frequency of 8500 hz., these dimensions become:

$$a\ell < 1.00 \text{ cm.}, \quad Rad < .2 \text{ cm.}, \quad R_T < .2 \text{ cm.}$$

This device may be thought of as one generating a constant volume velocity, and the lumped elements can be determined from the physical dimensions above.[9]

$$L = \frac{\rho L'}{\pi R_T} \quad , \quad C = \frac{V}{\rho c^2}$$

where

ρ = density of air

c = speed of sound in air

V = acoustical volume

C = equivalent capacitance

L = equivalent inductance

Substitution of $L' = 16 \ Rad/3\pi$ and $V = \pi R_T^2 a\ell$ yields

$$L = \frac{16\rho \, Rad}{3\pi^2 R_T}$$

and

$$C = \frac{\pi R_T^2 a \ell}{\rho c^2}$$

For a more complete discussion of this, see Kinsler and Frey (1962).

The equivalent electrical circuit of Figure 5b is simplified to that shown in Figure 5c by summing admittances of parallel combinations. This makes it easier to solve for the conditions of maximum power transfer.

For the circuit shown in Figure 5c, the power delivered to the ear is

$$\overline{P} = I_2^2 R_e \quad ,$$

$$I_2 = \frac{I \, |X_h(\omega)|}{\sqrt{(R + R_e)^2 + (X_h + X_e)^2}} \quad ,$$

and

$$X_h(\omega) = \frac{j\omega L}{1 - \omega^2 LC}$$

Combining these two expressions the power becomes

$$\overline{P} = \frac{I^2 X_h(\omega)^2 R_e}{(R + R_e)^2 + (X_h(\omega) + X_e)^2} \tag{9}$$

Then using the concept of a circuit "Q", $Q = X_e / R_e$, the expression for power becomes

$$\overline{P} = \frac{I^2 X_h^2(\omega) R_e}{(R + R_e)^2 + (X + Q R_e)^2} \tag{10}$$

The conditions for maximum power transfer may be determined by taking the derivative of power with respect to R_e.

$$\frac{d\overline{P}}{dR_e} = \frac{I^2X_h^2(\omega)\left[(R+R_e)^2 + (X_h(\omega) + QR_e)^2\right]}{\left[(R+R_e)^2 + (X_h + QR_e)^2\right]^2}$$

$$- \frac{I^2X_h^2(\omega)R_e\left[2(R+R_e) + 2Q(X_h(\omega) + QR_e)\right]}{\left[(R+R_e)^2 + (X_h + QR_e)^2\right]^2}$$

By solving this for the values of R_e which make this expression zero, the value of R_e is determined as

$$R_e = \frac{|Z|}{\sqrt{1 + Q^2}}$$

where

$$Z = R + jX_h(\omega)$$

Substituting this expression into Equation (10) and simplifying, the result is

$$\overline{P}_{max} = \frac{I^2X_h^2(\omega)}{2|Z|\sqrt{1 + Q^2} + 2(R + QX_h(\omega))} \qquad (11)$$

The maximum value of $\overline{P}_{max}$ may be determined by computing the derivative with respect to Q.

$$\frac{d\overline{P}_{max}}{dQ} = \frac{-I^2X_h(\omega)^2\left[2|Z|\frac{Q}{\sqrt{1 + Q^2}} + 2X_h(\omega)\right]}{\left[2|Z|\sqrt{1 + Q^2} + 2(R + QX_h(\omega))\right]^2}$$

Solving for Q to make this expression zero, $Q = \pm X/R$. To determine which value to take, substitute back into Equation (11),

$$\overline{P}_{\max\max} = \frac{I^2 X_h^2(\omega) R}{2|Z|\sqrt{R^2 + X_h^2(\omega)} + 2(R^2 \pm X_h^2(\omega))}$$

and it is obvious that $Q = -X/R$ will result in more power being transferred. Then the following equations may be used to determine those conditions that are necessary for a maximum power transfer.

$$Q = \frac{-X_h(\omega)}{R}$$

$$R_e = \frac{\sqrt{R^2 + X_h^2(\omega)}}{\sqrt{1 + \frac{X_h^2(\omega)}{R^2}}} = R$$

$$X_e = QR_e = -\frac{X}{R}R_e = -X$$

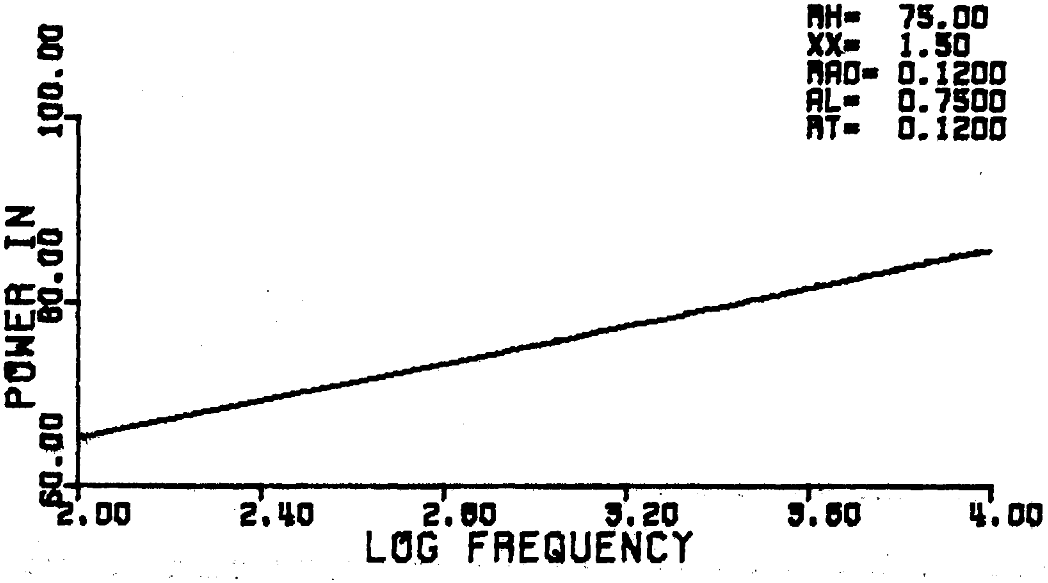
So these conditions are

$$R = R_e \quad , \qquad X_h(\omega) = -X_e$$

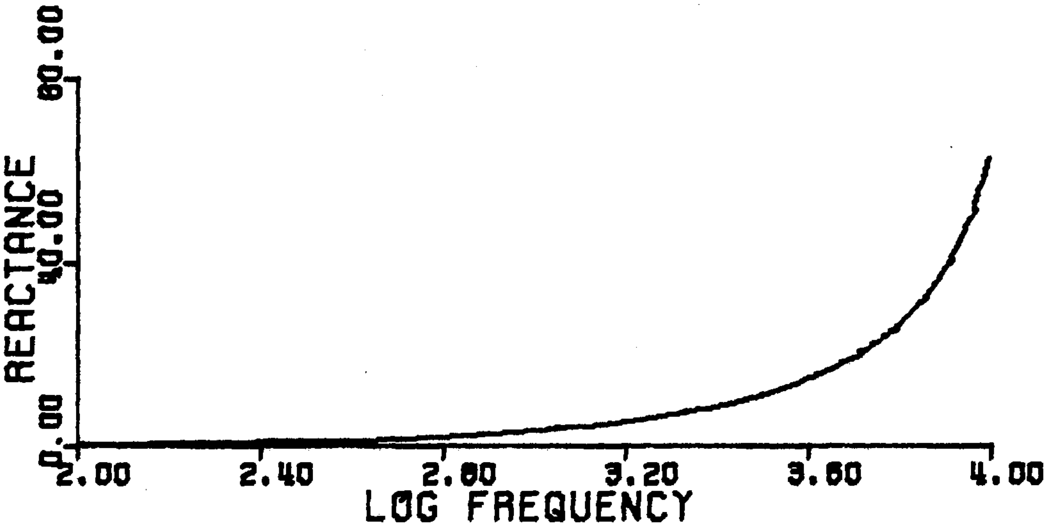
In order to achieve a perfect impedance match at any frequency, this condition must be met at that frequency. Since the resistance of the acoustical device is a constant over the entire frequency range and the resistance of the ear is not, it is obvious that this criterion cannot be met exactly at every frequency. In addition, for resonant circuits a perfect impedance match is possible only at a specific frequency. Therefore, the perfect impedance match is not possible, and the curve fitting process is the next best method to try to make the impedance match optimum.

The indicated curve fit was performed on the computer using subroutine GRID4 with the performance index being the integral of the difference between the impedance curves of the mathematical model and the impedance curve calculated for the circuit shown in Figure 5c. An alternate performance index of maximizing power transfer was tried, but results indicated that this performance index was the best one. The physical parameters that resulted from the curve fit are shown in Figure 6a and the resulting reactance, power in, power, and sound pressure level produced in the ear are shown in Figures 6 and 7.

The success of the impedance match may be determined in Figures 6 and 7. First, considering the two power curves, the output power delivered to the ear is much less than that produced by the device. The optimum power delivered is half that produced by the source. On this basis, the impedance match is not very good (Schure, 1958). In addition, a comparison of the reactance curve of Figure 4 with the reactance curve of Figure 6 indicates a very poor reactance match. Improvements in the reactance match may be achieved by using a device whose reactance starts large and positive for low frequencies and decreases with increased frequency. Such a requirement cannot be met with passive elements whose reactances occur in the form k/ω and ωm. Active elements might be used to fit the reactance requirements.

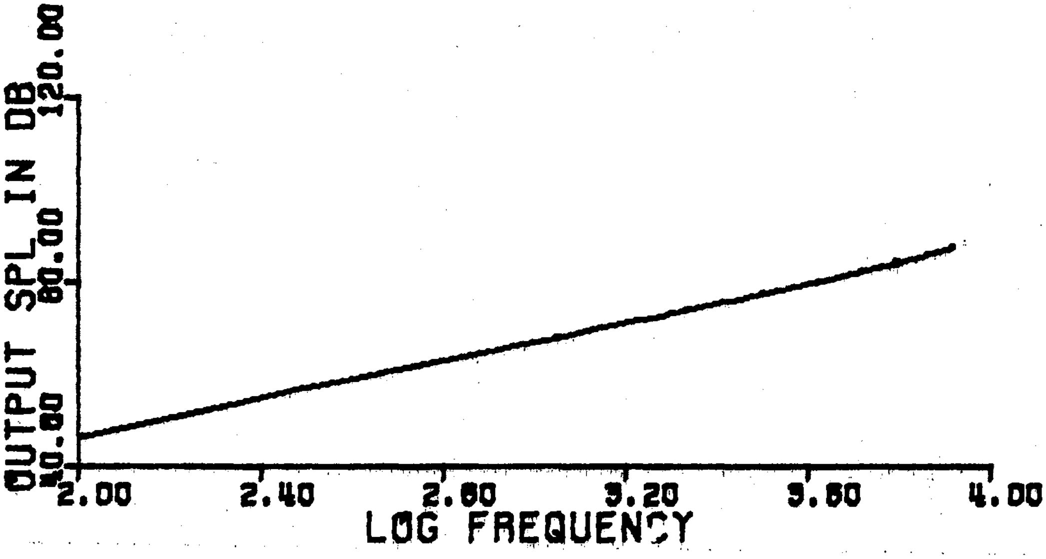


a.) Power Developed by Hearing Aid Source in DB

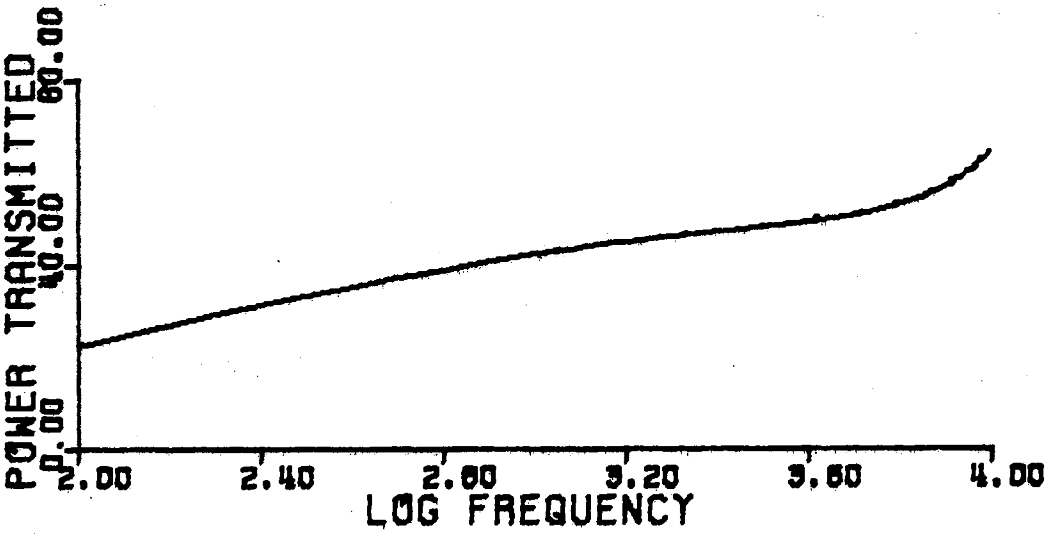


b.) Acoustical Reactance in CGS Ohms

Figure 6. Computer Results



a.) Output Sound Pressure Level Delivered to the Ear Model



b.) Power Transmitted to the Ear Model in DB

Figure 7. Performance of Impedance Matching Device

FOOTNOTES

[1] Georg Von Bekesy, Experiments in Hearing (New York, 1960).

[2] Peter B. Denes and Elliot N. Rinson, The Speech Chain (Bell Telephone Laboratories, 1963), p. 68.

[3] Georg Von Bekesy, "Mechanical Properties of the Ear," Handbook of Experimental Psychology, in S. S. Stevens (ed.) (New York, 1960), p. 1079.

[4] Ibid.

[5] Y. Onchi, "Mechanisms of the Middle Ear," Journal of the Acoustical Society of America, Vol. 33, 1969, p. 802.

[6] Georg Von Bekesy, Experiments in Hearing (New York, 1960), p. 104.

[7] J. Y. Morton and R. A. Jones, "The Acoustical Impedance Presented by Some Human Ears to Hearing Aid Earphones of the Insert Type," Acustica, Vol. 6, 1956, p. 329.

[8] Lawrence E. Kinsler and Austin R. Frey, Fundamentals of Acoustics (New York, 1962), p. 186.

[9] Ibid., p. 191.

CHAPTER III

EXPERIMENTAL PROCEDURE

Introduction

The input acoustical impedance of the mathematical model described in Chapter II was compared to existing ear impedance measurements. However, these existing measurements do not include all frequencies encountered in speech so impedance data should be taken at higher frequencies. Individual testing should also indicate individual variations in ear impedance. For these reasons it is felt that input acoustical impedance to human ears should be measured in an attempt to further validate the mathematical model of Chapter II and determine other variables that may be present in ear impedance.

There are two basic methods that have been used to measure acoustical impedance: comparison and direct. A comparison method is similar to an electrical wheatstone bridge that compares an unknown impedance to a variable known impedance. By nulling the pressure difference between the two impedances the unknown impedance may be determined. A direct method depends on a source with a large enough internal impedance so that an approximately constant volume velocity can be generated. For further information concerning impedance measuring, see Ayers, Aspenall and Morton (1956).

Impedance Measuring Device

The direct method was chosen as the most appropriate for this application, because impedance measurements were required over a large frequency range and because of the lack of a dependable null reference. The problem of size is one that is always present in acoustical impedance measurement. The source must be small enough to fit in the human ear canal alongside a microphone, and still have large internal impedance. The only way this can be accomplished is by use of probe tubes. Since the mathematical model indicates that the impedance is a function of distance from the eardrum, it is desirable to measure ear impedance at different distances from the ear canal. This was not done because medical personnel were not available to assure the safety of measuring this distance on a subject and because of physical limitations on the device used.

A horn driver used on conventional loudspeakers was chosen as a sound source. An acoustic coupler shaped like a reversed exponential horn was used to connect the horn driver to a probe tube. This device had unreliable phase characteristics (see Appendix B), so a B&K one-quarter inch condenser microphone was placed near the inlet to the probe tube, and the phase shift was measured between this microphone and the probe tube output. The measuring microphone used a B&K

one-half inch condenser microphone, and a probe tube. A photograph of this device is shown in Figure 8. Henceforth in this study, the subscript s will signify the source reference microphone, and subscript m will signify the measuring microphone.

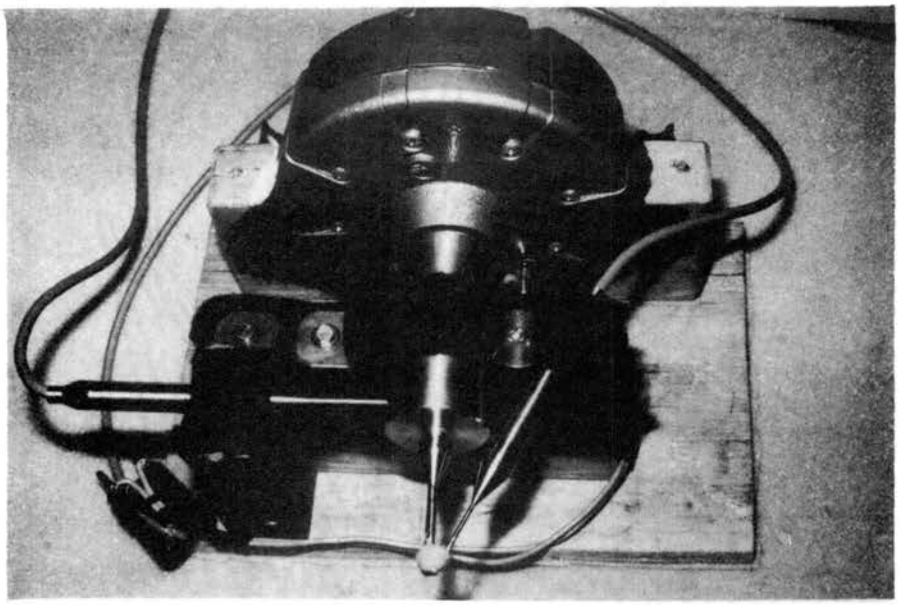


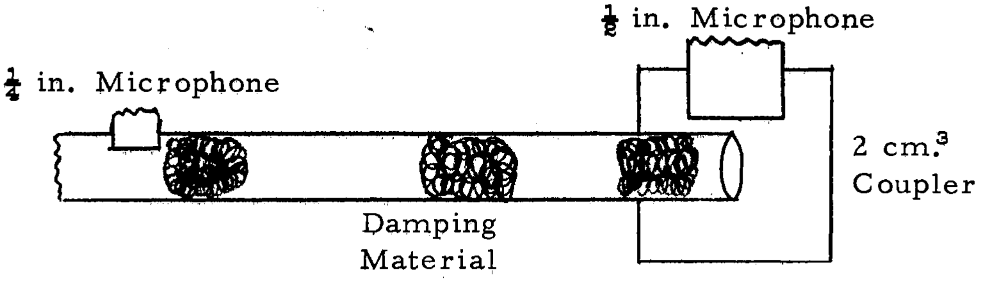
Figure 8. Acoustical Impedance Measuring Device

An adequate seal around the outside of the probe tubes was achieved using a receiver seal furnished by Beltone Hearing Aid Service. The receiver seal was then filled in with silicon rubber sealer, as it had to be sheared in order to insert the microphone probe tube. Both probe tubes were filled partially with steel wool damping material to smooth out the resonant peaks that occur in acoustical transmission tubes. Since the horn driver is so massive and the probe tube so small and highly damped, it is felt that the assumption of high internal source impedance is a good one.

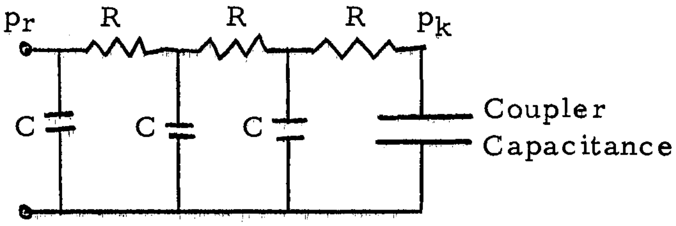
Calibration Procedure

The calibration of the measuring probe tube consisted of finding a transfer function that could be used to relate actual pressures at the probe input to measured pressure at the probe tip. For the high impedance source the calibration consisted of relating measured pressures to volume velocity. The experimental setup and equivalent electrical circuit shown in Figure 9 were used to determine a source transfer function. Again, the equivalent electrical circuit is included to help understand the physical process.

The volume velocity going through the calibration volume will be approximately the same as that delivered to the ear because of the large internal impedance of the source. This volume is the standard artificial ear volume used with hearing aid earphones, so even if the source internal impedance were not large compared to the ear, the calibration impedance is similar to a real ear impedance, and the results can be expected to be reasonable. The assumption of lumped parameter acoustical elements can be used here to determine the volume velocity because the diameter of the coupler cavity is small compared to a wavelength.



a.) Experimental Setup



b.) Equivalent Electrical Circuit

Figure 9. Calibration Procedure

When the calibration output pressure p_k is measured over the desired frequency range for any given reference pressure p_r, the following transfer function may be calculated:

$$\frac{p_k}{p_r} = |G_s(j\omega)|\, e^{j\phi_s} \tag{12}$$

The volume velocity may then be calculated by writing a loop equation for the pressure drop through the coupler cavity shown in Figure 9.

$$p_k = \frac{U_k}{j\omega C} \qquad (13)$$

where

$C = \frac{V}{\rho c^2}$

U_k = volume velocity.

Then the volume velocity may be computed in terms of the measured pressure by combining Equations (12) and (13).

$$U_k = j\omega C p_r \, |G_s(j\omega)| \, e^{j\phi_s} \qquad (14)$$

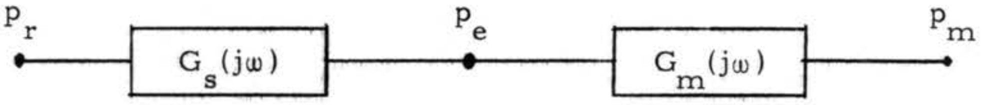
A similar calibration procedure may be used for computing the probe microphone transfer function.

$$\frac{p_m}{p_r} = |G_m(j\omega)| \, e^{j\phi_m} \qquad (15)$$

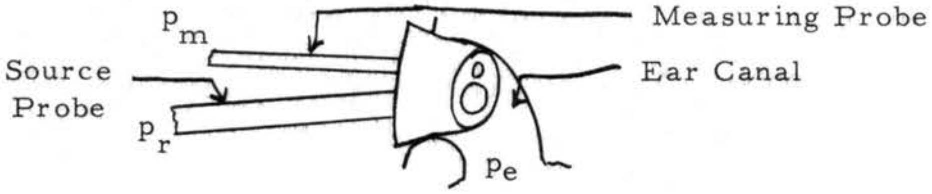
Using Equation (15), the measured pressure may be related to the actual pressure in the ear. These calibration curves are shown in Appendix B.

Measurement Procedure

The ear mold was inserted into the subject's ear, and the pressures in the reference microphone and measuring microphone were measured. The relationship between the measured pressures and phase angles and the desired ear impedance may be obtained by using the transfer functions indicated in Figure 10.



a.) Block Diagram Representation



b.) Arrangement of Probes in Subject's Ear

Figure 10. Measurement Setup

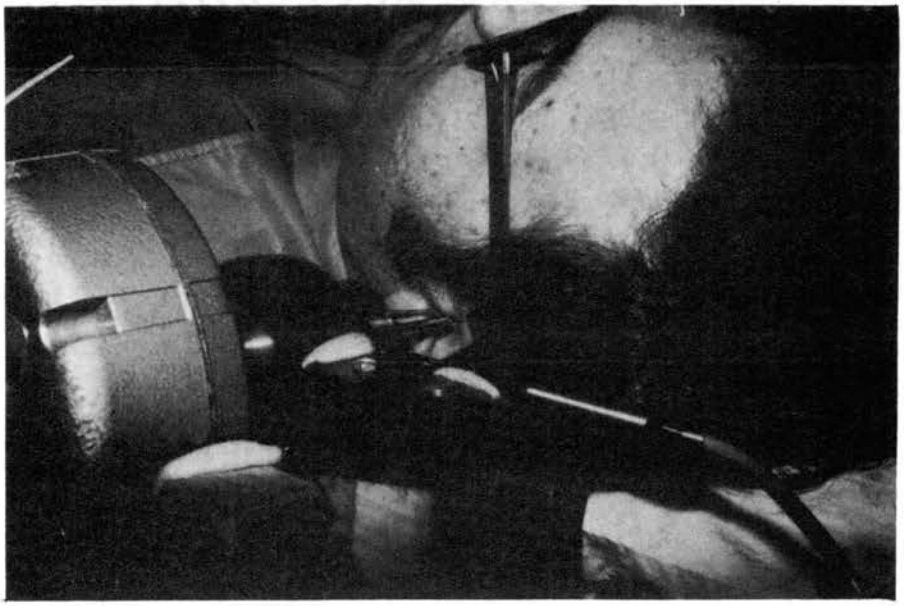


Figure 11. Photograph of Experimental Setup

It was difficult at first to get an adequate seal, and the subject had to learn how to insert the ear mold himself. There was a slight problem with inserting the probes because the ear canal opening is not perpendicular to the head. If the probes are not inserted straight, the microphone probe tube may be closed off. This problem was corrected by having the subject tilt his head slightly. A photograph of the device and subject is shown in Figure 11, and the list of equipment used, along with wiring details, is described in Figure 12.

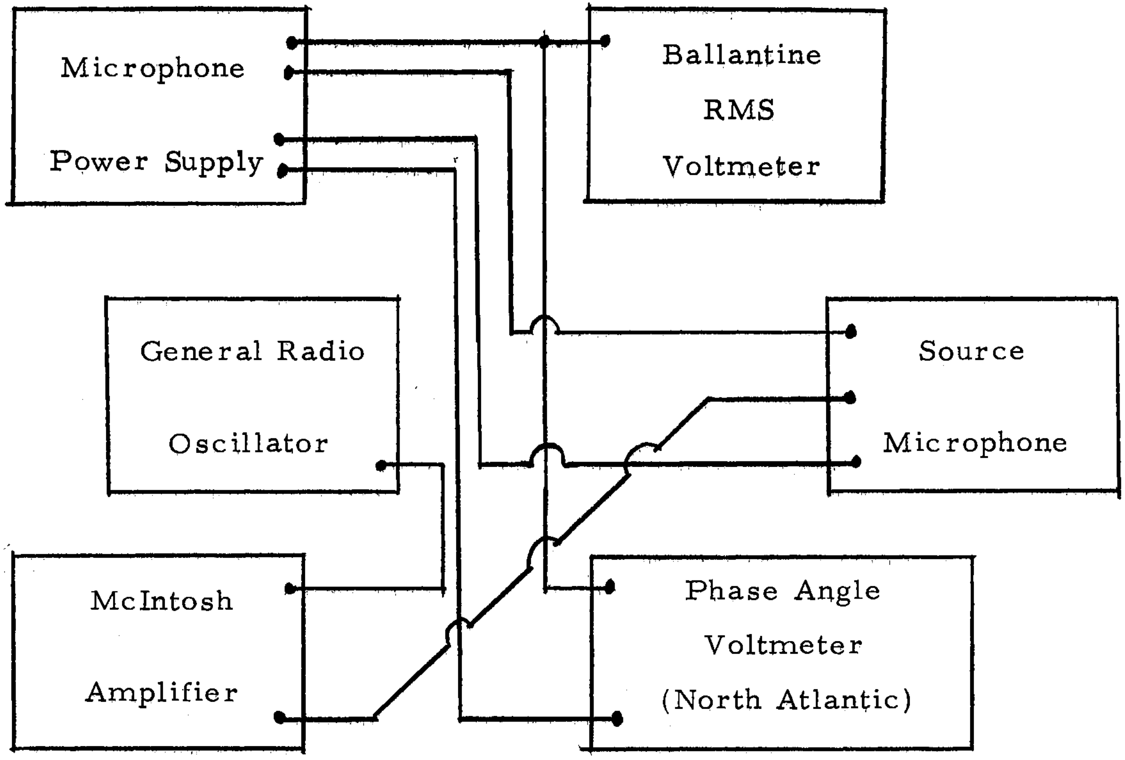


Figure 12. Wiring Diagram for Testing Session

The overall measured transfer function described in Figure 10 can be expressed as

$$\frac{p_m}{p_r} = |G_{mm}(j\omega)|e^{j\emptyset_{mm}} \tag{16}$$

The pressure in the ear may be computed in terms of Equation (16) as

$$\frac{p_m}{p_e} = |G_m(j\omega)|e^{j\emptyset_m} \tag{17}$$

and the relationship between p_e and p_m becomes

$$\frac{p_e}{p_r} = \frac{|G_{mm}(j\omega)|}{|G_m(j\omega)|} e^{j(\emptyset_{mm} - \emptyset_m)} \tag{18}$$

upon combining Equations (16) and (17). Since the volume velocity may be computed using Equation (14), the ear impedance becomes

$$Z_e = \frac{p_e}{U_e} = \frac{|G_{mm}(j\omega)|e^{j(\emptyset_{mm} - \emptyset_m - \emptyset_s)}}{j\omega c|G_m(j\omega)|\;|G_s(j\omega)|} \;. \tag{19}$$

The ear impedance in Equation (19) was computed using the computer program shown in Appendix A for several test sessions. The device is unreliable above about 5000 hz., which is no surprise because of the unreliable phase characteristics at those frequencies. This is because the assumption of lumped parameter modeling became invalid above a certain frequency, and the effect of reflected waves was no longer negligible. Experimental accuracy also proved to be a problem which is easily recognizable whenever the resistance becomes negative. This is due to slight error which pushes the ear impedance phase angle from the first to the fourth quadrant making the sine function change signs. When this happens, the calculated resistance may be assumed to be zero, and the reactance is not affected very much.

Discussion of Results

The test subject reported hearing a beat phenomenon which depended both on stimulus intensity and frequency. The beats were noticed every time the intensity exceeded about 105 DB and the frequency of the beat changed with the frequency of the stimulus. Since ear nonlinearity becomes more pronounced with increased intensity, it is likely that this phenomenon is associated with the ear's nonlinearity (Bekesy, 1960a). Since it is desirable to obtain data for impedance both with and without this phenomenon present, data was collected for two testing sessions at each intensity level. The results are shown in Figures 13 and 14.

There are several human variables associated with ear impedance that can affect the results of this experiment. It is known that ear impedance may change if the testing session lasts too long.[1] This may be due to fatiguing of muscles or adaptation of the ear to a new environment. Consequently, testing sessions were limited to about 15 minutes each.

Notice in Figures 13 and 14 that the ear impedance varies with the different testing sessions. These changes are quite large and are most noticeable for frequencies below about 1000 hz. Since the

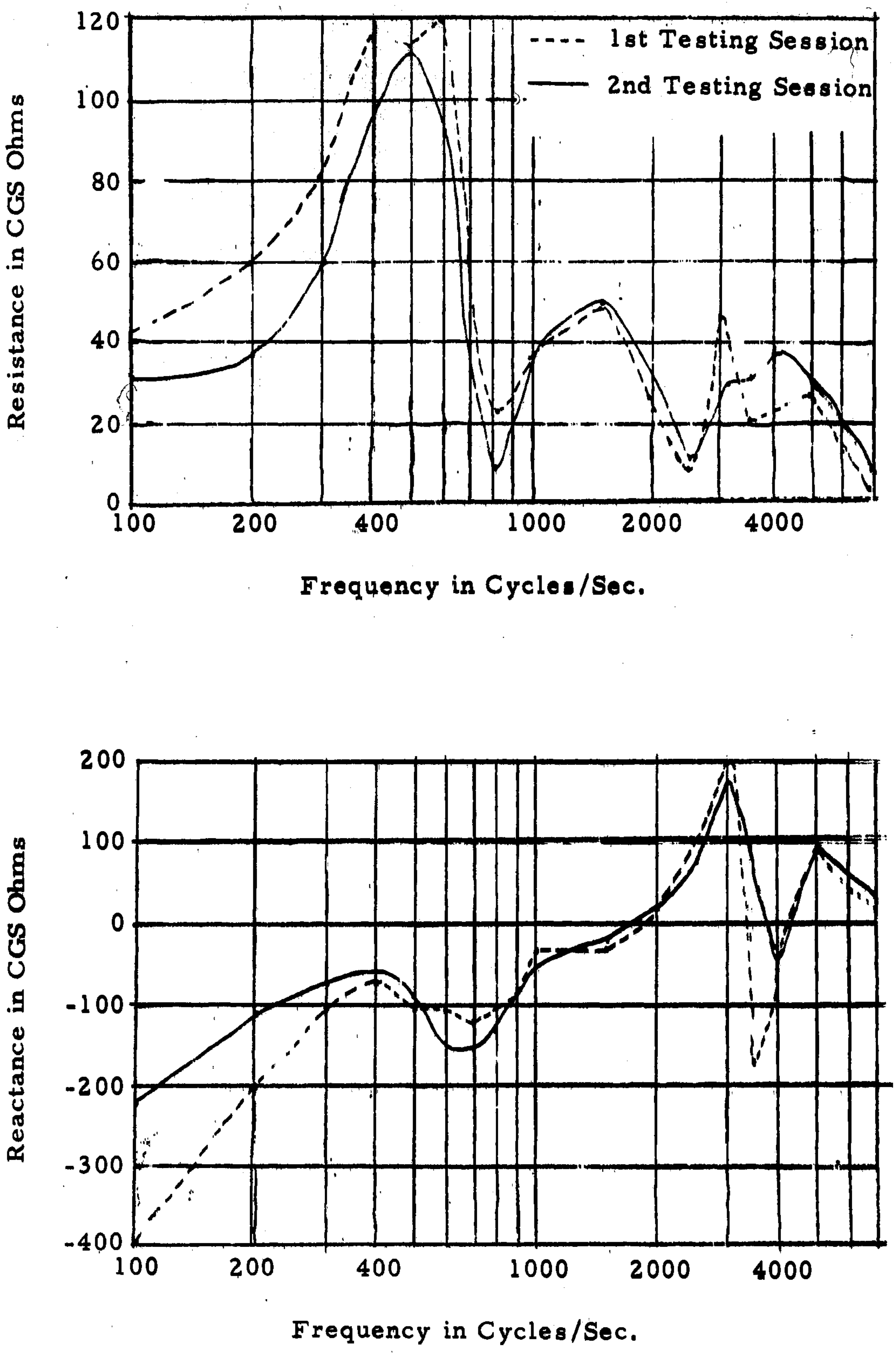
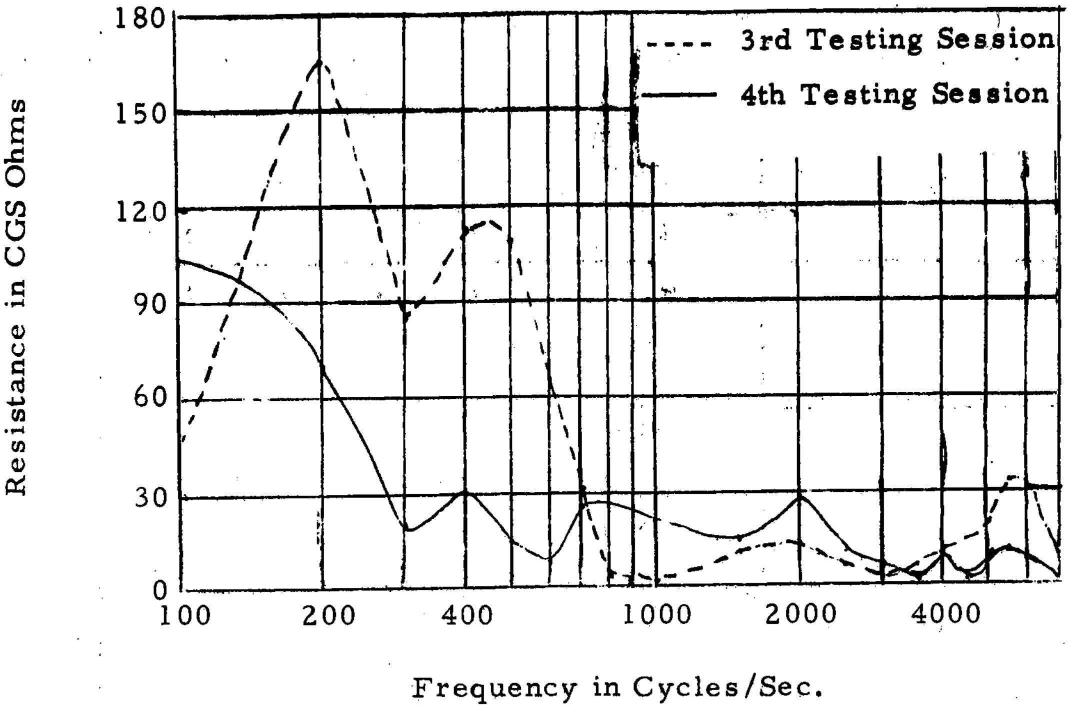


Figure 13. Acoustical Impedance of Human Ear for Two Different Sessions With Beat Phenomenon



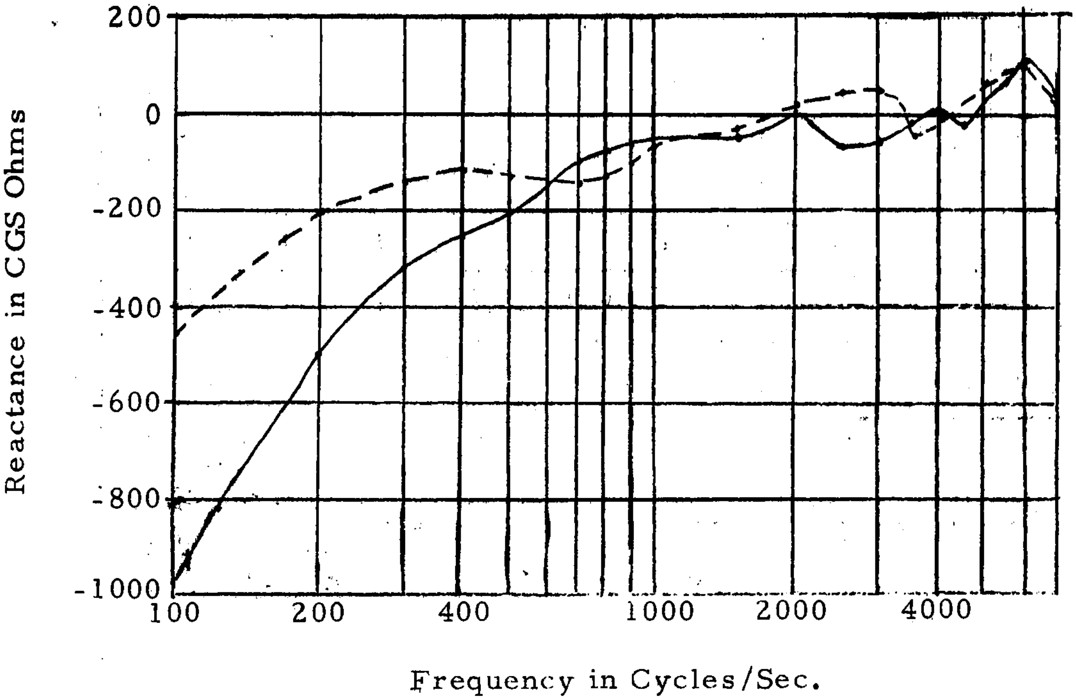


Figure 14. Acoustical Impedance of Human Ear for Two Sessions Without Beat Phenomenon

impedance calculated on the mathematical model indicates a change in impedance with a change in the distance to the eardrum, it seems logical to consider differences in the extension of the ear mold as an explanation for these differences. However, since the ear mold is of constant size, it seems that it was always inserted approximately the same distance as indicated in Figure 15. Therefore, this may not be an explanation for large fluctuations.

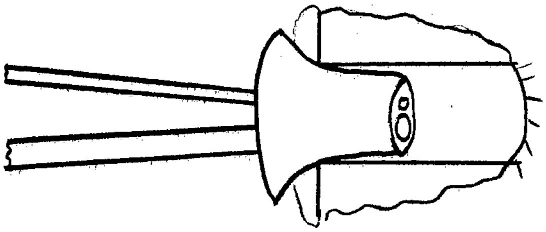


Figure 15. Drawing Representing How Far Into the Ear Canal the Ear Mold Goes

In further attempts to explain the variations, the subject was questioned concerning his state of fatigue, mental activity, and tension. During the first testing session the subject was extremely tired. During the second testing session the subject reported excessive mental activity and tension. During the third and fourth testing sessions, the subject was rested and mental activity was controlled. It seems that all these factors may be involved in ear impedance, but on the basis of the work here, it is not possible to relate specific impedance changes to the factors mentioned above. Further controlled experiments must be undertaken to determine whether fatigue, mental activity, and tension affect ear impedance, and if so, how.

The impedance curves that result from measurement look similar in shape to the impedance curves calculated from the mathematical model. The hump in the resistance curve and the inflection in the reactance curve consistently appear at about 500 hz. Other researchers have not observed these factors when using lower stimulus intensity, so it is likely that they are related to the properties of the ear at higher intensity.[2] The reason for this similarity is that the real eardrum behaves like a piston for lower frequencies.[3]

The wide variation in measured impedance indicates that impedance matching will involve the fitting of device impedance into acceptable bands of ear impedance. Further testing is necessary in order to determine the properties of these bands based on the variation of ear impedance for a particular person and based on variation of ear impedance between persons.

FOOTNOTES

[1] J. Y. Morton and R. A. Jones, "The Acoustical Impedance Presented by Some Human Ears to Hearing Aid Earphones of the Insert Type," Acustica, Vol. 6, 1956, p. 329.

[2] Ibid.

[3] Georg Von Bekesy, Experiments in Hearing (New York, 1960), p. 102.

CHAPTER IV

CONCLUSIONS

Summary

A mathematical model was developed which approximates the input acoustical impedance to the human ear. An acoustical device similar to what is used in conventional hearing aids was proposed as a means of impedance matching, and the impedance match was performed by a curve fit on the computer. Results indicate that this impedance match is not very good.

Passive elements cannot provide very much improvement in impedance matching because of requirements on the reactance. Reactive components must start large and positive for low frequency and decrease with an increase in frequency in order to fit the criteria developed. The conclusion is that improvements in aural prosthesis are possible by consideration of impedance matching, but such improvements require active devices as passive devices fail to satisfy the reactive requirement.

The input acoustical impedance of the human ear was measured, and variations were noted which make an exact impedance match impossible. These variations may be caused by fatigue, tension, and mental activity, factors which are difficult to control. This means that any attempts at impedance matching will never exactly fit the criterion but must settle for fitting into some acceptable band of impedance requirements.

Recommendations

A beat phenomenon was discovered during testing which should be studied further. Since this phenomenon occurred only at higher intensities, it is likely that it is associated with ear nonlinearity. Nonlinear systems have been known to exhibit almost periodic behavior which can cause beats, and subharmonics can superimpose themselves on the primary signal to generate sounds like beats. A nonlinear analysis of hearing should be used to characterize and study this phenomenon.

Although the acoustical device that was used here did not match impedances very well, other devices might represent significant improvements. A comparison of the reactances of the proposed device and the ear indicates that they are the reason for the poor curve fit. This problem is common with resonant circuits, but if a device could be found whose reactance is more similar in shape to ear reactance, then significant improvements might result. If more work is to be done with this idea, more testing will be required in order to characterize the acceptable bands for the impedance of human ears. This will involve improvements in the impedance measuring device in order to make measurements at higher frequencies more reliable.

In the course of carrying out this study it was observed that conventional artificial ears used in earphone calibration procedures attempt to approximate ear impedance with a reactive component alone. An improvement in artificial ears could be achieved by including a resistive component in the form of a damper and piston similar to the mathematical model that was included here. Certainly this would represent a more accurate picture of what the hearing aid sees when it is fitted to a human ear. Using conventional artificial ears for testing, the hearing aid sees a load that does not dissipate power. Certainly the ear does dissipate power, so the inclusion of resistance would come closer to the real ear. This improvement in artificial ears might give audiologists a better idea of the true performance of hearing aids. The improved artificial ear might be built similar to the mathematical model of the ear proposed here which does include damping,

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APPENDIXES

APPENDIX A

COMPUTER PROGRAMS

80/80 LIST

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C
C COMPUTER PROGRAM TO COMPUTE THE INPUT ACOUSTICAL IMPEDANCE TO THE
C HUMAN EAR.
C
C
C
C DEFINITION OF PARAMETERS.
C R=DAMPING COEFFICIENT.
C S = CROSS SECTIONAL AREA OF EAR CANAL.
C RK = SPRING CONSTANT ON EARDRUM MODEL.
C RM = EQUIVALENT MASS OF MALLEUS, INCUS, STAPES.
C CA= WAVE PROPOGATION VELOCITY OF AIR.
C DENS= DENSITY OF AIR.
C RL= LENGTH OF EAR CANAL.
C DELXX= STEP IN LONGITUDINAL DIRECTION IN EAR CANAL.
C DELFRQ= FREQUENCY STEP.
C
      DIMENSION ZI(10,100),ZR(10,100)
      DIMENSION XARRAY(101),YARRAY(101)
      READ(5,100) R,S,RM,RK,CA,DENS,RL ,DELXX  ,DELFRQ
      WRITE(6,150) R,S,RM,RK,CA,DENS
      L=99
      XX=RL
      DO 6 I=1,10
      FRQ=100.
      DO 7 K=1,L
      KK=K-1
C
      FRR=FRQ*(2.*3.141592)
      CHAR=(DENS*CA)/S
      RE=R/(S*S)
      XE=(FRR*RM-RK/FRR)/(S*S)
      VAL1=ABS((FRR*XX/CA)-(.5*3.141592))
      VAL2=ABS((FRR*XX/CA)-(1.5*3.141592))
      IF(VAL1.LT.1.00E-02.OR.VAL2.LT.1.00E-02) GO TO 5
      DUF=(CHAR-XE*TAN(FRR*XX/CA))*(CHAR-XE*TAN(FRR*XX/CA))
     1 + (RE*TAN(FRR*XX/CA))*(RE*TAN(FRR*XX/CA))
      ZR(I,K)=CHAR*CHAR*RE*(1.+(TAN(FRR*XX/CA))*(TAN(FRR*XX/CA)))/DUF
C
      ZI(I,K)=(XE*CHAR-(XE*XE+RE*RE)*TAN(FRR*XX/CA)+
     1 CHAR*(TAN(FRR*XX/CA))*(TAN(FRR*XX/CA)))/DUF
      IF(VAL1.GE.1.00E-02.AND.VAL2.GE.1.00E-02) GO TO 7
    5 ZR(I,K)=ZR(I,KK)
      ZI(I,K)=ZI(I,KK)
    7 FRQ=FRQ+DELFRQ
    6 XX=XX-DELXX
C
C GENERATE XARRAY FOR CALCOMP PLOT.
      FRQ=100.
      DO 4 K=1,L
      XARRAY(K)=ALOG10(FRQ)
    4 FRQ=FRQ+DELFRQ
      XX=RL
      CALL PLOTS
      DO 8 I=1,10
```

80/80 LIST

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      CALL PLOTC(0.0,-11.,-3)
C DO-LOOP TO PLOT REACTANCE AT DISCRETE POINTS ALONG EAR CANAL.
      DO 9 K=1,L
      YARRAY(K)=ZI(I,K)
    9 CONTINUE
      CALL PLOTC(0.0,5.5,2)
      CALL PLOTC(8.5,5.5,3)
      CALL PLOTC(8.5,0.0,2)
      CALL PLOTC(0.0,0.0,2)
      CALL PLOTC(0.0,1.5,-3)
      CALL PLOTC(2.0,0.0,-3)
C  SCALE VALUES AND DRAW AXES
      CALL SCALE(XARRAY,5.0,99,1)
      CALL SCALE(YARRAY,2.0,99,1)
      CALL AXIS(0.0,0.0,'LOG FREQUENCY',-13,5.0,0.0,XARRAY(100),
     1 XARRAY(101))
      CALL AXIS(0.0,0.0,'REACTANCE',9,2.0,90.0,YARRAY(100),YARRAY(101))
      CALL LINE(XARRAY,YARRAY,99,1,10,75)
      CALL PLOTC(-2.0,4.0,-3)
C DO -LOOP TO PLOT RESISTANCE AT DISCRETE POINTS ALONG EAR CANAL.
      DO 10 K=1,L
      YARRAY(K)=ZR(I,K)
   10 CONTINUE
      CALL PLOTC(0.0,5.5,2)
      CALL PLOTC(8.5,5.5,3)
      CALL PLOTC(8.5,0.0,2)
      CALL PLOTC(0.0,0.0,2)
      CALL PLOTC(0.0,1.5,-3)
      CALL PLOTC(2.0,0.0,-3)
C  SCALE VALUES AND DRAW AXES
      CALL SCALE(XARRAY,5.0,99,1)
      CALL SCALE(YARRAY,2.0,99,1)
      CALL AXIS(0.0,0.0,'LOG FREQUENCY',-13,5.0,0.0,XARRAY(100),
     1 XARRAY(101))
      CALL AXIS(0.0,0.0,'RESISTANCE',10,2.0,90.0,YARRAY(100),YARRAY(101)
     1)
C PLOT POINTS.
      CALL LINE(XARRAY,YARRAY,99,1,10,75)
      CALL SYMBOL(4.00,2.00,.14,'XX=',0.0,3)
      CALL NUMBER(4.50,2.00,.14,XX,0.0,2)
      CALL PLOTC(8.0,-6.5,-3)
    8 XX=XX-DELXX
  100 FORMAT(4E15.4/4E15.4/E15.4)
  150 FORMAT(10H DAMPING= E10.4,20H AREA OF EAR CANAL= E10.4//
     1 5H RM= E10.4,5H RK= E10.4,5H CA= E10.4,7H DENS= E10.4//)
      STOP
      END
```

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                                 80/80 LIST

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      DIMENSION XL(9),XR(9),XLOW(9),XHIGH(9),X(9)
      N=4
      READ(5,100) (XL(I),XR(I),I=1,N )
      MPRINT=1
      MPRINT=0
      F=.1
      F=.01
      R=.667
      CALL GRID4(N,MPRINT,XL,XR,F,R,Y,X,XLOW,XHIGH,NN)
      WRITE(6,48) Y,NN,F
   48 FORMAT(//
     154H LARGEST MERIT ORDINATE FOUND DURING SEARCH ..........,E15.8/
     254H NUMBER OF FUNCTION EVALUATIONS USED DURING SEARCH ...,I15/
     354H FRACT. REDUCTION IN INTERVAL OF UNCERTAINTY EXTANT ..,E15.8/)
      DO 101 I=1,N
  101 WRITE(6,102) XLOW(I),X(I),XHIGH(I)
  100 FORMAT(8E10.2)
  102 FORMAT(5HXLOW=E15.8,2X,2HX=E15.8,2X,6HXHIGH=E15.8)
      STOP
      END
      SUBROUTINE MERIT4(U,Y)
      DIMENSION ZI(100),ZR(100),YI(100),YR(100),XI(100),XH(100)
      DIMENSION U(1)
C DEFINITION OF PARAMETERS.
C R=DAMPING COEFFICIENT.
C S = CROSS SECTIONAL AREA OF EAR CANAL.
C RK = SPRING CONSTANT ON EARDRUM MODEL.
C RM = EQUIVALENT MASS OF MALLEUS, INCUS, STAPES.
C CA= WAVE PROPOGATION VELOCITY OF AIR.
C DENS= DENSITY OF AIR.
C RL= LENGTH OF EAR CANAL.
C DELXX= STEP IN LONGITUDINAL DIRECTION IN EAR CANAL.
C DELFRQ= FREQUENCY STEP.
C RH=RESISTANCE OF HEARING AID IMPEDANCE MATCHING DEVICE.
C RAD=RADIUS OF HOLE DRILLED IN TUBE OF IMPEDANCE MATCHING DEVICE.
C AL =LENGTH OF ACOUSTICAL COMPLIANCE.
C RT=RADIUS OF ACOUSTICAL COMPLIANCE.
C     U(1)=RA
C     U(2)=RAD
C     U(3)=AL
C     U(4)=RT
      R=1.00E 02
      S=5.00E-01
      RM=2.50E-02
      RK=1.00E 06
      CA=3.62E 04
      DENS=1.23E-03
      RL=1.5
      DELFRQ=1.00E 02
C
      L=99
      XX=RL
      FRQ=100.
      DO 7 K=1,L
```

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                              80/80 LIST

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      KK=K-1
C
      FRR=FRQ*(2.*3.141592)
      CHAR=(DENS*CA)/S
      RE=R/(S*S)
      XE=(FRR*RM-RK/FRR)/(S*S)
      VAL1=ABS((FRR*XX/CA)-(.5*3.141592))
      VAL2=ABS((FRR*XX/CA)-(1.5*3.141592))
      IF(VAL1.LT.1.00E-02.OR.VAL2.LT.1.00E-02) GO TO 5
      DUF=(CHAR-XE*TAN(FRR*XX/CA))*(CHAR-XE*TAN(FRR*XX/CA))
     1 + (RE*TAN(FRR*XX/CA))*(RE*TAN(FRR*XX/CA))
      ZR(K)  =CHAR*CHAR*RE*(1.+(TAN(FRR*XX/CA))*(TAN(FRR*XX/CA)))/DUF
C
      ZI(K)  =(XE*CHAR-(XE*XE+RE*RE)*TAN(FRR*XX/CA)+
     1 CHAR*(TAN(FRR*XX/CA))*(TAN(FRR*XX/CA)))/DUF
      IF(VAL1.GE.1.00E-02.AND.VAL2.GE.1.00E-02) GO TO 6
    5 ZR(K)=ZR(KK)
      ZI(K)=ZI(KK)
    6 CONTINUE
      RH=U(1)
      XH(K)=FRR*DENS*1.7*U(2)/( 3.141592*U(2)*U(2)
     1-FRR*FRR*1.7*U(2)*((3.141592*U(4)*U(4)*U(3))/(CA*CA)))
    7 FRQ=DELFRQ+FRQ
      Z1=1.+ABS(ZR(20)-RA)
      Z2=1.+ABS(ZI(20)+XH(20))
      PI=Z1+Z2
      Y=1./PI
      RETURN
      END
      SUBROUTINE GRID4(N,MPRINT,XL,XR,F,R,Y,X,XLOW,XHIGH,NN)            GRI 0010
C     SUBROUTINE GRID4(N,MPRINT,XL,XR,F,R,Y,X,XLOW,XHIGH,NN)            GRI CCCC
C     GRID SEARCH                                                       GRI CCCC
C                                                                       GRI CCCC
C     THIS SUBROUTINE EXERCISES A GRID SEARCH IN A MERIT HYPERSURFACE   GRI CCCC
C     OF UPTO EIGHT DIMENSIONS BY CALLING SUBROUTINE MERIT4(X,Y)        GRI CCCC
C                                                                       GRI CCCC
C     CALLING PROGRAM REQUIREMENTS                                      GRI CCCC
C                                                                       GRI CCCC
C     PROVIDE A DIMENSION STATEMENT AS FOLLOWS.                         GRI CCCC
C                                                                       GRI CCCC
C          DIMENSION XL(9),XR(9),XLOW(9),XHIGH(9),X(9)                  GRI CCCC
C                                                                       GRI CCCC
C     NOMENCLATURE                                                      GRI CCCC
C                                                                       GRI CCCC
C     N = NUMBER OF INDEPENDENT VARIABLES                               GRI CCCC
C     MPRINT = 0 CONVERGENCE MONITOR DOES NOT PRINT                     GRI CCCC
C            = 1 CONVERGENCE MONITOR WILL PRINT                         GRI CCCC
C     XL = ORIGINAL LOWER EXTREMITY OF INTERVAL OF UNCERTAINTY          GRI CCCC
C     XR = ORIGINAL UPPER EXTREMITY OF INTERVAL OF UNCERTAINTY          GRI CCCC
C     F = FRACTIONAL REDUCTION IN INTERVAL OF UNCERTAINTY DESIRED       GRI CCCC
C     R = FRACTIONAL GRID REDUCTION UTILIZED                            GRI CCCC
C     Y = EXTREME ORDINATE TO MERIT SURFACE DISCOVERED BY GRID SEARCH   GRI CCCC
C     X = COLUMN VECTOR OF ABSCISSAS CORRESPONDING TO Y                 GRI CCCC
C     XLOW = FINAL LOWER EXTREMITY OF INTERVAL OF UNCERTAINTY           GRI CCCC
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C     XHIGH = FINAL UPPER EXTREMITY OF INTERVAL OF UNCERTAINTY          GRI CCCC
C     NN = NUMBER OF FUNCTION EVALUATIONS EXPENDED IN GRID SEARCH       GRI CCCC
C                                                                       GRI CCCC
      DIMENSION XL(9),XR(9),X(9),XLOW(9),XHIGH(9),CENTER(9),SAVEX(9)    GRI 0020
C                                                                       GRI CCCC
C     ..... PROTECTION .....                                            GRI CCCC
C                                                                       GRI CCCC
      IF(N-8)11,11,12                                                   GRI 0030
   12 WRITE(6,13)N                                                      GRI 0040
   13 FORMAT(41H *****ERROR MESSAGE SUBROUTINE GRID4*****,/,            GRI 0050
     19H       I1=,I3,16H GREATER THAN 8.)                              GRI 0060
      RETURN                                                            GRI 0070
   11 IF(F-1.0)14,14,15                                                 GRI 0080
   15 WRITE(6,16)F                                                      GRI 0090
   16 FORMAT(41H *****ERROR MESSAGE SUBROUTINE GRID4*****,/,            GRI 0100
     110H        A5=,E15.8,16H GREATER THAN 1.)                         GRI 0110
      RETURN                                                            GRI 0120
   14 DO 50 I = 1,N                                                     GRI 0130
      IF(XR(I)-XL(I))51,51,50                                           GRI 0140
   51 XRR = XR(I)                                                       GRI 0150
      XLL = XL(I)                                                       GRI 0160
      WRITE(6,52)I,XLL,I,XRR                                            GRI 0170
   52 FORMAT(41H *****ERROR MESSAGE SUBROUTINE GRID4*****,/,            GRI 0180
     19H       A3(,I1,2H)=,E15.8,16HGREATER THAN A4(,I1,2H)=,E15.8)     GRI 0190
      RETURN                                                            GRI 0200
   50 CONTINUE                                                          GRI 0210
      IF(R-2.0/3.0)53,54,54                                             GRI 0220
   54 IF(R-1.0)58,58,53                                                 GRI 0230
   53 WRITE(6,55)R                                                      GRI 0240
   55 FORMAT(41H *****ERROR MESSAGE SUBROUTINE GRID4*****,/,            GRI 0250
     19H       A6=,E15.8,33H DOES NOT LIE BETWEEN 2/3 AND 1.0)          GRI 0260
      RETURN                                                            GRI 0270
C                                                                       GRI CCCC
C     ..... INITILIZE .....                                             GRI CCCC
C                                                                       GRI CCCC
   58 NN = 0                                                            GRI 0280
      SIDE = 1.0                                                        GRI 0290
      IF(MPRINT)1,3,1                                                   GRI 0300
    1 WRITE(6,2)                                                        GRI 0310
    2 FORMAT(37H1CONVERGENCE MONITOR SUBROUTINE GRID4,//,               GRI 0320
     1114H     NN    SIDE        Y        X(1)       X(2)       X(3)       X(4)GRI 0330
     2   X(5)        X(6)       X(7)       X(8)       BIGGEST Y,/)      GRI 0340
    3 DO 4 I=1,N                                                        GRI 0350
      CENTER(I) = 0.5                                                   GRI 0360
    4 CONTINUE                                                          GRI 0370
      JJ = 0                                                            GRI 0380
C     JJ = 0                                                            GRI CCCC
C     ..... DETERMINE CENTRAL MERIT ORDINATE .....                      GRI CCCC
C                                                                       GRI CCCC
      CALL UNNORM(N,XL,XR,CENTER)                                       GRI 0390
      CALL REGION(N,XL,XR,CENTER)                                       GRI 0400
      CALL MERIT4(CENTER,YMID)                                          GRI 0410
      NN = NN + 1                                                       GRI 0420
      CALL NORMAL(N,XL,XR,CENTER)                                       GRI 0430
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      DO 5 I=1,N                                                        GRI 0440
      XLOW(I) = 0.0                                                     GRI 0450
    5 CONTINUE                                                          GRI 0460
C                                                                       GRI CCCC
      YBIG = YMID                                                       GRI 0470
C                                                                       GRI CCCC
C     ..... DETERMINE MERIT ORDINATES IN GRID, NOTE LARGEST .....       GRI CCCC
   10 STEP = SIDE/3.0                                                   GRI 0480
C                                                                       GRI CCCC
C     ..... AT EVERY GRID REDUCTION OCCASION, ALTERNATE BETWEEN A ..... GRI CCCC
C     ..... SQUARE SURVEY PATTERN AND A STAR SURVEY PATTERN,      ..... GRI CCCC
C                                                                       GRI CCCC
C     ..... DEPENDING ON ODDNESS OR EVENNESS OF JJ.               ..... GRI CCCC
      IF(JJ/2*2-JJ)600,510,600                                          GRI 0490
C                                                                       GRI CCCC
C     ..... SQUARE GRID SURVEY                                    ..... GRI CCCC
C                                                                       GRI CCCC
  510 DO 500 I=1,N                                                      GRI 0500
      X(I) = XLOW(I)                                                    GRI 0510
  500 CONTINUE                                                          GRI 0520
      GO TO (71,72,73,74,75,76,77,78),N                                 GRI 0530
   78 I8 = 0                                                            GRI 0540
   88 I8 = I8 + 1                                                       GRI 0550
      X(8) = X(8) + STEP                                                GRI 0560
   77 I7 = 0                                                            GRI 0570
   87 I7 = I7 + 1                                                       GRI 0580
      X(7) = X(7) + STEP                                                GRI 0590
   76 I6 = 0                                                            GRI 0600
   86 I6 = I6 + 1                                                       GRI 0610
      X(6) = X(6) + STEP                                                GRI 0620
   75 I5 = 0                                                            GRI 0630
   85 I5 = I5 + 1                                                       GRI 0640
      X(5) = X(5) + STEP                                                GRI 0650
   74 I4 = 0                                                            GRI 0660
   84 I4 = I4 + 1                                                       GRI 0670
      X(4) = X(4) + STEP                                                GRI 0680
   73 I3 = 0                                                            GRI 0690
   83 I3 = I3 + 1                                                       GRI 0700
      X(3) = X(3) + STEP                                                GRI 0710
   72 I2 = 0                                                            GRI 0720
   82 I2 = I2 + 1                                                       GRI 0730
      X(2) = X(2) + STEP                                                GRI 0740
   71 I1 = 0                                                            GRI 0750
   81 I1 = I1 + 1                                                       GRI 0760
      X(1) = X(1) + STEP                                                GRI 0770
      CALL UNNORM(N,XL,XR,X)                                            GRI 0780
      CALL REGION(N,XL,XR,X)                                            GRI 0790
      CALL MERIT4(X,Y1)                                                 GRI 0800
      NN = NN + 1                                                       GRI 0810
      CALL NORMAL(N,XL,XR,X)                                            GRI 0820
      IF(Y1-YBIG) 171,171,6                                             GRI 0830
    6 YBIG = Y1                                                         GRI 0840
      DO 30 K=1,N                                                       GRI 0850
      SAVEX(K) = X(K)                                                   GRI 0860
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   30 CONTINUE                                                          GRI 0870
      IF(I1.EQ.2) GO TO 171                                             GRI 0880
      GO TO 81                                                          GRI 0890
  171 X(1) = XLOW(1)                                                    GRI 0900
      IF(N.EQ.1) GO TO 501                                              GRI 0910
      IF(I2.EQ.2) GO TO 172                                             GRI 0920
      GO TO 82                                                          GRI 0930
  172 X(2) = XLOW(2)                                                    GRI 0940
      IF(N.EQ.2) GO TO 501                                              GRI 0950
      IF(I3.EQ.2) GO TO 173                                             GRI 0960
      GO TO 83                                                          GRI 0970
  173 X(3) = XLOW(3)                                                    GRI 0980
      IF(N.EQ.3) GO TO 501                                              GRI 0990
      IF(I4.EQ.2) GO TO 174                                             GRI 1000
      GO TO 84                                                          GRI 1010
  174 X(4) = XLOW(4)                                                    GRI 1020
      IF(N.EQ.4) GO TO 501                                              GRI 1030
      IF(I5.EQ.2) GO TO 175                                             GRI 1040
      GO TO 85                                                          GRI 1050
  175 X(5) = XLOW(5)                                                    GRI 1060
      IF(N.EQ.5) GO TO 501                                              GRI 1070
      IF(I6.EQ.2) GO TO 176                                             GRI 1080
      GO TO 86                                                          GRI 1090
  176 X(6) = XLOW(6)                                                    GRI 1100
      IF(N.EQ.6) GO TO 501                                              GRI 1110
      IF(I7.EQ.2) GO TO 177                                             GRI 1120
      GO TO 87                                                          GRI 1130
  177 X(7) = XLOW(7)                                                    GRI 1140
      IF(N.EQ.7) GO TO 501                                              GRI 1150
      IF(I8.EQ.2) GO TO 178                                             GRI 1160
      GO TO 88                                                          GRI 1170
  178 X(8) = XLOW(8)                                                    GRI 1180
      GO TO 501                                                         GRI 1190
C                                                                       GRI CCCC
C     ..... STAR SURVEY PATTERN .....                                   GRI CCCC
C                                                                       GRI CCCC
  600 DO 601 I=1,N                                                      GRI 1200
      X(I) = CENTER(I)                                                  GRI 1210
  601 CONTINUE                                                          GRI 1220
      DO 620 I=1,N                                                      GRI 1230
      X(I) = CENTER(I)+STEP                                             GRI 1240
      CALL REGION(N,XL,XR,X)                                            GRI 1250
      CALL UNNORM(N,XL,XR,X)                                            GRI 1260
      CALL MERIT4(X,YPLUS)                                              GRI 1270
      NN = NN + 1                                                       GRI 1280
      CALL NORMAL(N,XL,XR,X)                                            GRI 1290
      IF(YPLUS-YBIG)611,611,610                                         GRI 1300
  610 YBIG = YPLUS                                                      GRI 1310
      DO 612 K=1,N                                                      GRI 1320
      SAVEX(K) = X(K)                                                   GRI 1330
  612 CONTINUE                                                          GRI 1340
  611 X(I) = CENTER(I) - STEP                                           GRI 1350
      CALL UNNORM(N,XL,XR,X)                                            GRI 1360
      CALL REGION(N,XL,XR,X)                                            GRI 1370
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      CALL MERIT4(X,YMINUS)                                             GRI 1380
      NN = NN + 1                                                       GRI 1390
      CALL NORMAL(N,XL,XR,X)                                            GRI 1400
      IF(YMINUS-YBIG)614,614,613                                        GRI 1410
  613 YBIG = YMINUS                                                     GRI 1420
      DO 615 K=1,N                                                      GRI 1430
      SAVEX(K) = X(K)                                                   GRI 1440
  615 CONTINUE                                                          GRI 1450
  614 CONTINUE                                                          GRI 1460
      X(I) = CENTER(I)                                                  GRI 1470
  620 CONTINUE                                                          GRI 1480
C                                                                       GRI CCCC
C     ..... CHECK TO SEE IF GRID SIZE IS SMALL ENOUGH .....             GRI CCCC
C                                                                       GRI CCCC
  501 JJ = JJ+1                                                         GRI 1490
      IF(F-SIDE)32,45,45                                                GRI 1500
C                                                                       GRI CCCC
C     ..... GRID SIZE NOT SUFFICIENTLY SMALL, SELECT LARGEST .....      GRI CCCC
C     ..... ORDINATE LOCATION FROM GRID AND CENTER NEXT      .....      GRI CCCC
C     ..... SMALLER GRID ABOUT THIS POINT.                   .....      GRI CCCC
C                                                                       GRI CCCC
   32 IF(YBIG-YMID)44,44,33                                             GRI 1510
   33 YMID = YBIG                                                       GRI 1520
      DO 40 K=1,N                                                       GRI 1530
      CENTER(K) = SAVEX(K)                                              GRI 1540
   40 CONTINUE                                                          GRI 1550
C                                                                       GRI CCCC
C     ..... IF PRINTING OF CONVERGENCE MONITOR IS REQUIRED, DO SO ..... GRI CCCC
C                                                                       GRI CCCC
   44 IF(MPRINT)41,43,41                                                GRI 1560
   41 CALL UNNORM(N,XL,XR,CENTER)                                       GRI 1570
      WRITE(6,42)NN,SIDE,YMID,(CENTER(I),I=1,8),YBIG                    GRI 1580
   42 FORMAT(1X,I5,11E10.3)                                             GRI 1590
      CALL NORMAL(N,XL,XR,CENTER)                                       GRI 1600
C                                                                       GRI CCCC
C     ..... REDUCE SIZE OF GRID AND CONTINUE SEARCH .....               GRI CCCC
C                                                                       GRI CCCC
   43 SIDE = SIDE*R                                                     GRI 1610
      DO 502 I=1,N                                                      GRI 1620
      XLOW(I) = CENTER(I)-SIDE/2.0                                      GRI 1630
      XHIGH(I) = CENTER(I)+SIDE/2.0                                     GRI 1640
  502 CONTINUE                                                          GRI 1650
      CALL UNNORM(N,XL,XR,XLOW)                                         GRI 1660
      CALL UNNORM(N,XL,XR,XHIGH)                                        GRI 1670
      CALL REGION(N,XL,XR,XLOW)                                         GRI 1680
      CALL REGION(N,XL,XR,XHIGH)                                        GRI 1690
      CALL NORMAL(N,XL,XR,XLOW)                                         GRI 1700
      CALL NORMAL(N,XL,XR,XHIGH)                                        GRI 1710
      GO TO 10                                                          GRI 1720
C                                                                       GRI CCCC
C     ..... GRID SIZE SUFFICIENTLY SMALL, EXIT FROM SEARCH .....        GRI CCCC
C                                                                       GRI CCCC
   45 CALL UNNORM(N,XL,XR,SAVEX)                                        GRI 1730
      CALL REGION(N,XL,XR,SAVEX)                                        GRI 1740
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      CALL MERIT4(SAVEX,Y)                                              GRI 1750
      NN = NN + 1                                                       GRI 1760
      CALL NORMAL(N,XL,XR,SAVEX)                                        GRI 1770
      DO 46 K=1,N                                                       GRI 1780
      X(K) = SAVEX(K)                                                   GRI 1790
      IF(CENTER(K)-SAVEX(K))60,61,62                                    GRI 1800
   60 XLOW(K) = CENTER(K)                                               GRI 1810
      XHIGH(K) = CENTER(K)+SIDE/2.0                                     GRI 1820
      GO TO 46                                                          GRI 1830
   61 XLOW(K) = CENTER(K)-SIDE/2.0                                      GRI 1840
      XHIGH(K) = CENTER(K)+SIDE/2.0                                     GRI 1850
      GO TO 46                                                          GRI 1860
   62 XLOW(K) = CENTER(K)-SIDE/2.0                                      GRI 1870
      XHIGH(K) = CENTER(K)                                              GRI 1880
   46 CONTINUE                                                          GRI 1890
      CALL UNNORM(N,XL,XR,XLOW)                                         GRI 1900
      CALL UNNORM(N,XL,XR,XHIGH)                                        GRI 1910
      CALL UNNORM(N,XL,XR,SAVEX)                                        GRI 1920
      CALL UNNORM(N,XL,XR,X)                                            GRI 1930
      IF(MPRINT)47,49,47                                                GRI 1940
   47 FF = SIDE                                                         GRI 1950
      WRITE(6,48)Y,NN,FF                                                GRI 1960
   48 FORMAT(/,                                                         GRI 1970
     154H LARGEST MERIT ORDINATE FOUND DURING SEARCH ..........,E15.8,/,GRI 1980
     254H NUMBER OF FUNCTION EVALUATIONS USED DURING SEARCH ...,I15,/,  GRI 1990
     354H FRACT. REDUCTION IN INTERVAL OF UNCERTAINTY EXTANT ..,E15.8,/)GRI 2000
      DO 100 I=1,N                                                      GRI 2010
      X1 = XLOW(I)                                                      GRI 2020
      X2 = SAVEX(I)                                                     GRI 2030
      X3 = XHIGH(I)                                                     GRI 2040
      WRITE(6,101)I,X1,I,X2,I,X3                                        GRI 2050
  101 FORMAT(1X,5HXLOW(,I1,2H)=,E15.8,2X,                               GRI 2060
     12HX(,I1,2H)=,E15.8,2X,6HXHIGH(,I1,2H)=,E15.8)                     GRI 2070
  100 CONTINUE                                                          GRI 2080
   49 RETURN                                                            GRI 2090
      END                                                               GRI 2100
      SUBROUTINE NORMAL(N,XL,XR,XNORM)                                  NOR 0010
      DIMENSION XL(9),XR(9),XNORM(9)                                    NOR 0020
      DO 1 I=1,N                                                        NOR 0030
      XNORM(I)=(XNORM(I)-XL(I))/(XR(I)-XL(I))                           NOR 0040
    1 CONTINUE                                                          NOR 0050
      RETURN                                                            NOR 0060
      END                                                               NOR 0070
      SUBROUTINE UNNORM(N,XL,XR,EX)                                     UNO 0010
      DIMENSION XL(9),XR(9),EX(9)                                       UNO 0020
      DO 1 I=1,N                                                        UNO 0030
      EX(I)=XL(I)+EX(I)*(XR(I)-XL(I))                                   UNO 0040
    1 CONTINUE                                                          UNO 0050
      RETURN                                                            UNO 0060
      END                                                               UNO 0070
      SUBROUTINE REGION(N,XL,XR,X)                                      REG 0010
      DIMENSION XL(9),XR(9),X(9)                                        REG 0020
      DO 4 I=1,N                                                        REG 0030
      IF(XL(I)-X(I))2,2,1                                               REG 0040
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 1    X(I)=XL(I)                                                        REG 0050
      GO TO 4                                                           REG 0060
 2    IF(XR(I)-X(I))3,4,4                                               REG 0070
 3    X(I)=XR(I)                                                        REG 0080
  4   CONTINUE                                                          REG 0090
      RETURN                                                            REG 0100
      END                                                               REG 0110
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      DIMENSION ZR(100),ZI(100),POWERO(100),PRESS(100),POWERI(100)
      DIMENSION XH(100)
      DIMENSION XARRAY(101),YARRAY(101)
      READ(5,100) RA,DENS,RAD,AL,RT,CA
      READ(5,200)  UO,R,S,RM,RK,RL
C    COMPUTE OUTPUT ACOUSTICAL IMPEDANCE OF IMPEDANCE MATCHING DEVICE.
      L=99
      FRQ=100.
      DO 16 K=1,L
      XX=RL
      FRR=FRQ*(2.*3.141592)
      RH=RA
      KK=K-1
C
      CHAR=(DENS*CA)/S
      RE=R/(S*S)
      XE=(FRR*RM-RK/FRR)/(S*S)
      VAL1=ABS((FRR*XX/CA)-(.5*3.141592))
      VAL2=ABS((FRR*XX/CA)-(1.5*3.141592))
      IF(VAL1.LT.1.00E-02.OR.VAL2.LT.1.00E-02) GO TO 5
      DUF=(CHAR-XE*TAN(FRR*XX/CA))*(CHAR-XE*TAN(FRR*XX/CA))
     1 + (RE*TAN(FRR*XX/CA))*(RE*TAN(FRR*XX/CA))
      ZR(K)  =CHAR*CHAR*RE*(1.+(TAN(FRR*XX/CA))*(TAN(FRR*XX/CA)))/DUF
C
      ZI(K)  =(XE*CHAR-(XE*XE+RE*RE)*TAN(FRR*XX/CA)+
     1 CHAR*(TAN(FRR*XX/CA))*(TAN(FRR*XX/CA)))/DUF
      IF(VAL1.GE.1.00E-02.AND.VAL2.GE.1.00E-02) GO TO 6
    5 ZR(K)=ZR(KK)
      ZI(K)=ZI(KK)
    6 CONTINUE
      XH(K)=FRR*DENS*1.7*RAD/( 3.141592*RAD*RAD - FRR*FRR*1.7*RAD*
     1((3.141592*RT*RT*AL)/(CA*CA)))
C
      XARRAY(K)=ALOG10(FRQ)
C
      POWERO(K)=(UO*UO*XH(K)*XH(K)*ZR(K)/((RA+ZR(K))*(RA+ZR(K))+
     1 (XH(K)+ZI(K))*(XH(K)+ZI(K))))*1.00E-07
C
      POWERI(K)=(UO*UO*((RA+ZR(K))*(RA+ZR(K))+ZI(K)*ZI(K))*XH(K)/
     1((RA+ZR(K))*(RA+ZR(K))+(XH(K)+ZI(K))*(XH(K)+ZI(K))))*1.00E-07
      PRS=UO*XH(K)/SQRT((RA+ZR(K))*(RA+ZR(K))+(XH(K)+ZI(K))*(XH(K)+ZI(K)
     1))
      PRESS(K)=20.*ALOG10(PRS/.0002)
C
      WRITE(6,116) FRQ,POWERI(K),POWERO(K),XH(K),PRESS(K)
   16 FRQ=FRQ+100.
C
C
      CALL PLOTS
      CALL PLOTC(0.0,-11.,-3)
      DO 9 K=1,L
      YARRAY(K)=XH(K)
    9 CONTINUE
C
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      CALL PLOTC(0.0,5.5,2)
      CALL PLOTC(8.5,5.5,3)
      CALL PLOTC(8.5,0.0,2)
      CALL PLOTC(0.0,0.0,2)
      CALL PLOTC(0.0,1.5,-3)
      CALL PLOTC(2.0,0.0,-3)
C  SCALE VALUES AND DRAW AXES
      CALL SCALE(XARRAY,5.0,99,1)
      CALL SCALE(YARRAY,2.0,99,1)
      CALL AXIS(0.0,0.0,'LCG FREQUENCY',-13,5.0,0.0,XARRAY(100),
     1 XARRAY(101))
      CALL AXIS(0.0,0.0,'REACTANCE',9,2.0,90.0,YARRAY(100),YARRAY(101))
C PLOT POINTS.
C PLOT POINTS.
      CALL LINE(XARRAY,YARRAY,99,1,10,75)
      CALL PLOTC(-2.0,4.0,-3)
      DO 10 K=1,L
      YARRAY(K)=10.*ALOG10(POWERI(K)/(1.00E-12))
   10 CONTINUE
C
      CALL PLOTC(0.0,5.5,2)
      CALL PLOTC(8.5,5.5,3)
      CALL PLOTC(8.5,0.0,2)
      CALL PLOTC(0.0,0.0,2)
      CALL PLOTC(0.0,1.5,-3)
      CALL PLOTC(2.0,0.0,-3)
C  SCALE VALUES AND DRAW AXES
      CALL SCALE(XARRAY,5.0,99,1)
      CALL SCALE(YARRAY,2.0,99,1)
      CALL AXIS(0.0,0.0,'LCG FREQUENCY',-13,5.0,0.0,XARRAY(100),
     1 XARRAY(101))
      CALL AXIS(0.0,0.0,'POWER IN',8,2.0,90.0,YARRAY(100),YARRAY(101))
C PLOT POINTS.
      CALL LINE(XARRAY,YARRAY,99,1,10,75)
      CALL SYMBOL(4.00,2.50,.10,'RH=',0.0,3)
      CALL NUMBER(4.5,2.50,.10,RA,0.0,2)
      CALL SYMBOL(4.0,2.35,.10,'XX=',0.0,3)
      CALL NUMBER(4.50,2.35,.10,RL,0.0,2)
      CALL SYMBOL(4.00,2.20,.10,'RAD=',0.0,4)
      CALL NUMBER(4.50,2.20,.10,RAD,0.0,4)
      CALL SYMBOL(4.00,2.05,.10,'AL=',0.0,3)
      CALL NUMBER(4.50,2.05,.10,AL,0.0,4)
      CALL SYMBOL(4.00,1.90,.10,'RT=',0.0,3)
      CALL NUMBER(4.50,1.90,.10,RT,0.0,4)
      CALL PLOTC(8.0,-6.5,-3)
C
      DO 11 K=1,L
   11 YARRAY(K)=10.*ALOG10(POWERO(K)/(1.00E-12))
C
C
      CALL PLOTC(0.0,5.5,2)
      CALL PLOTC(8.5,5.5,3)
      CALL PLOTC(8.5,0.0,2)
      CALL PLOTC(0.0,0.0,2)
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      CALL PLOTC(2.0,0.0,-3)
      CALL PLOTC(0.0,1.5,-3)
C    SCALE AND LABEL AXES
      CALL SCALE(XARRAY,5.0,99,1)
      CALL SCALE(YARRAY,2.0,99,1)
      CALL AXIS(0.0,0.0,'LOG FREQUENCY',-13,5.0,0.0,XARRAY(100),
     1 XARRAY(101))
      CALL AXIS(0.0,0.0,'POWER TRANSMITTED',17,2.0,90.0,YARRAY(100
     1),YARRAY(101))
C     PLOT POINTS.
      CALL LINE(XARRAY,YARRAY,99,1,10,75)
      CALL PLOTC(-2.0,4.0,-3)
C
      DO 12 K=1,L
   12 YARRAY(K)=PRESS(K)
C
      CALL PLOTC(0.0,5.5,2)
      CALL PLOTC(8.5,5.5,3)
      CALL PLOTC(8.5,0.0,2)
      CALL PLOTC(0.0,0.0,2)
      CALL PLOTC(2.0,0.0,-3)
      CALL PLOTC(0.0,1.5,-3)
C  SCALE AND LABEL AXES.
      CALL SCALE(XARRAY,5.0,99,1)
      CALL SCALE(YARRAY,2.0,99,1)
      CALL AXIS(0.0,0.0,'LOG FREQUENCY',-13,5.0,0.0,XARRAY(100),
     1 XARRAY(101))
      CALL AXIS(0.0,0.0,'OUTPUT SPL IN DB',16,2.0,90.0,YARRAY(100),
     1 YARRAY(101))
C     PLOT POINTS.
      CALL LINE(XARRAY,YARRAY,99,1,10,75)
  100 FORMAT(3E20.8/3E20.8)
  116 FORMAT(2X,5H FRQ=E10.4,9HPOWER IN=E20.8,10HPOWER OUT=E20.8,
     1 4H XH=E20.8,9H PRESS = E20.8)
  200 FORMAT(3E15.4/3E15.4)
      STOP
      END
```

```
                                  80/80 LIST

00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890

C   VRM= REFERENCE VOLTAGE FOR MICROPHONE CALIBRATION, IN VOLTS.
C   VRS= REFERENCE VOLTAGE FOR SOURCE CALIBRATION, IN VOLTS.
C   VM   = MICROPHONE FREQUENCY RESPONCE, IN DECIBELS RE 1 VOLT.
C   VK   = SOURCE VOLTAGE FREQUENCY RESPONCE +KNOWN IMPEDANCE IN DBV.
C   SM   = PROBE MICROPHONE OPEN CIRCUIT SENSITIVITY.
C   SS   = SOURCE MICROPHONE OPEN CIRCUIT SENSITIVITY.
C   FSK = SOURCE PHASE RESPONCE + KNOWN IMPEDANCE IN DBV.
C   FM   = MICROPHONE PROBE TUBE PHASE RESPONCE, IN DEGREES.
C   PM   = PROBE MICROPHONE PRESSURE IN DYNES/SQUARE CM.
C   PS   = SOURCE PRESSURE IN DYNES/SQUARE CM.
C   FMM = PHASE DIFFERENCE BETWEEN SOURCE AND MICROPHONE, MEASURED.
C   GS   = MAGNITUDE OF SOURCE TRANSFER FUNCTION.
C   GSR   = MAGNITUDE OF SOURCE OPEN CIRCUIT TRANSFER FUNCTION.
C   GM   = MAGNITUDE OF MICROPHONE TRANSFER FUNCTION.
C   GMM =  OPEN CIRCUIT TRANSFER FUNCTION, MEASURED FOR SOURCE.
C   FSR   = OPEN CIRCUIT PHASE RESPONCE.
C   FSM   = OPEN CIRCUIT PHASE RESPONCE, MEASURED.
C   EO   = OPEN CIRCUIT VOLTAGE RESPONCE, IN VOLTS.
C   VO   = OPEN CIRCUIT VOLTAGE RESPONCE, IN DBV.
C   VMM = VOLTAGE OF PROBE MICROPHONE, MEASURED IN DECIBELS.
C   VSM = VOLTAGE OF SOURCE MICROPHONE, MEASURED IN DECIBELS.
C   VREF= MEASURING REFERENCE VOLTAGE.
C   RE   = RESISTANCE OF EAR.
C   XE   = REACTANCE OF EAR.
C   PR   = REFERENCE PRESSURE.
      DIMENSION VM(22),VK(22),FSK(22),RE(22),XE(22),VMM(22),FMM(22),
     1FM(22)
      READ(5,100) (VM(I),I=1,22),(VK(I),I=1,22),(FSK(I),I=1,22),
     1(FM(I),I=1,22)
      READ(5,105) (VMM(I),I=1,22),(FMM(I),I=1,22)
      READ(5,110) VRM,VRS,SM,SS,V,CA,DENS,VREF
      DELFRQ=100.
      FRQ=100.
      DO 10 I=1,22
      FSK(I)=(3.141592/180.)*FSK(I)
      FM(I)=(3.141592/180.)*FM(I)
      FMM(I)= (3.141592/180.)*FMM(I)
      FRR=2.*3.141592*FRQ
      IF(FRQ.GE.1000.) DELFRQ=500.
      EM=10.**(VM(I)/20.)
      ES=10.**(VK(I)/20.)
      EMM=10.**(VMM(I)/20.)
      GM = EM*SS/(VRM*SM)
      GS=ES*SS/(VRS*SM)
      GMS = EMM*SS/(VREF*SM)
      C=V/(DENS*CA*CA)
      F1=FMM(I)-FM(I)-FSK(I)
      P1=GMS/(GM*GS*FRR*C)
      RE(I)=P1*SIN(F1)
      XE(I)=-P1*COS(F1)
      PE=20.*ALOG10(EMM/(SM*GM*.0002))
      F2=F1*180./3.141592
      WRITE(6,200) FRQ, RE(I), XE(I) ,PE,P1,F2
   10 FRQ=FRQ+DELFRQ
```

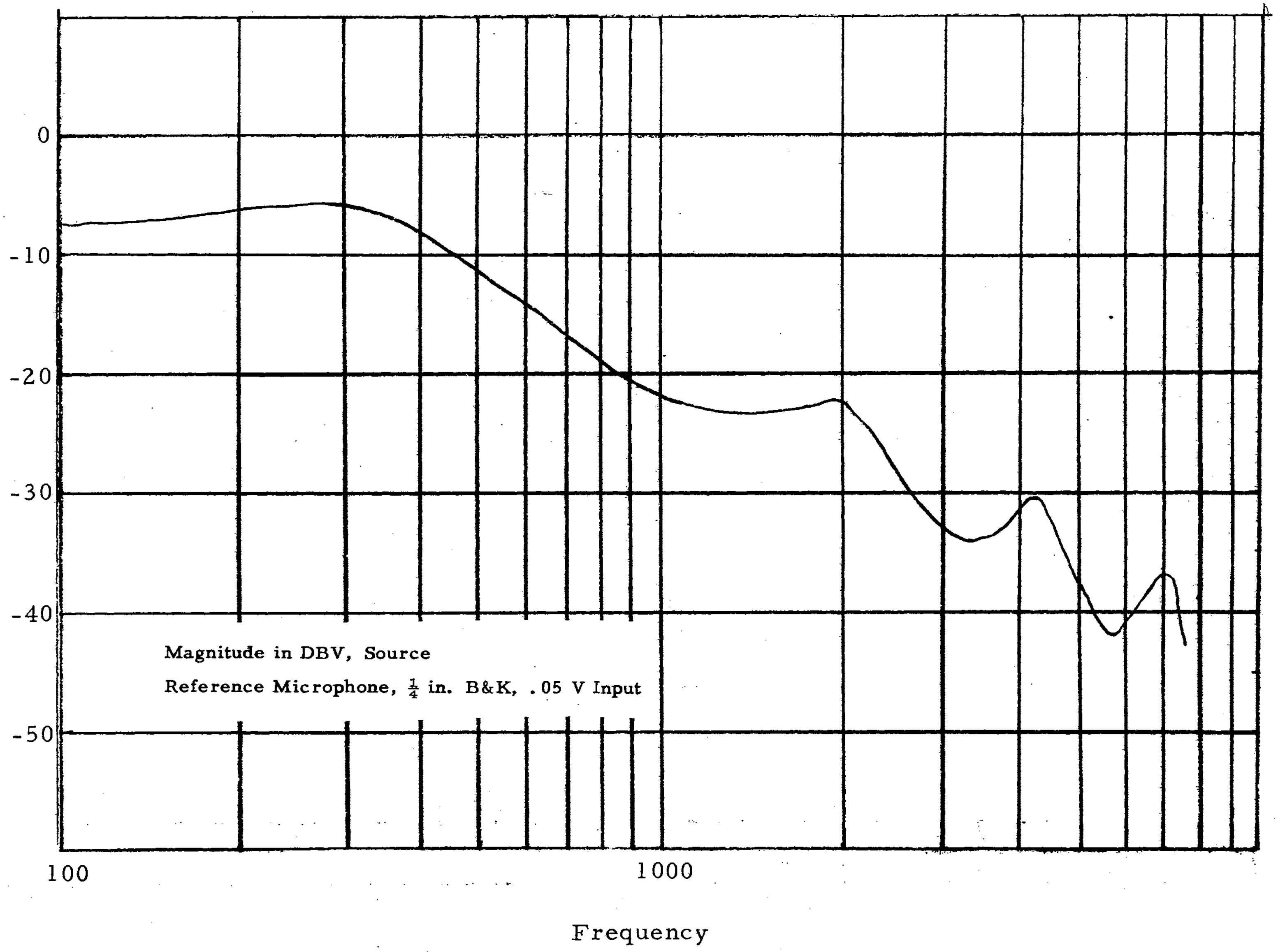
```
                                80/80 LIST

00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890

  100 FORMAT(5E15.4/5E15.4/2E15.4/5E15.4/5E15.4/
     1       5E15.4/5E15.4/2E15.4/5E15.4/5E15.4/
     2       5E15.4/5E15.4/2E15.4/5E15.4/5E15.4/
     3       5E15.4/5E15.4/2E15.4/5E15.4/5E15.4/)
  105 FORMAT(5E15.4/5E15.4/2E15.4/5E15.4/5E15.4/
     1       5E15.4/5E15.4/2E15.4/5E15.4/5E15.4/)
  110 FORMAT(5E15.4/3E15.4)
  200 FORMAT(5H FRQ=E10.4,2X,2HR=E10.4,2X,2HX=E10.4,2X,2HP=E10.4,2X,
     14HMAG=E10.4,2X,5HPHAS=E10.4/)
      STOP
      END
```

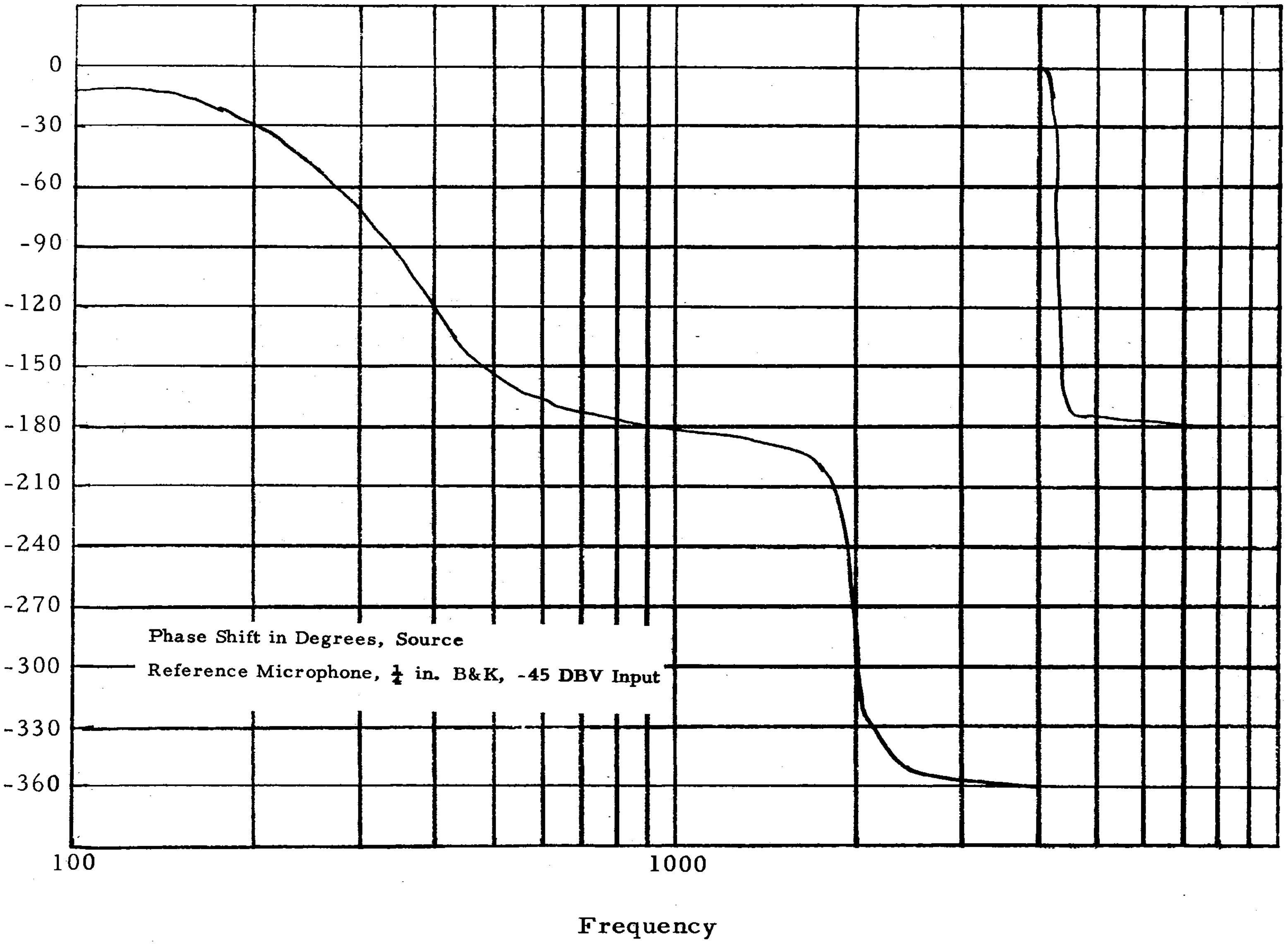
APPENDIX B

CALIBRATION CURVES AND MODEL IMPEDANCE CURVES AS A FUNCTION OF DISTANCE

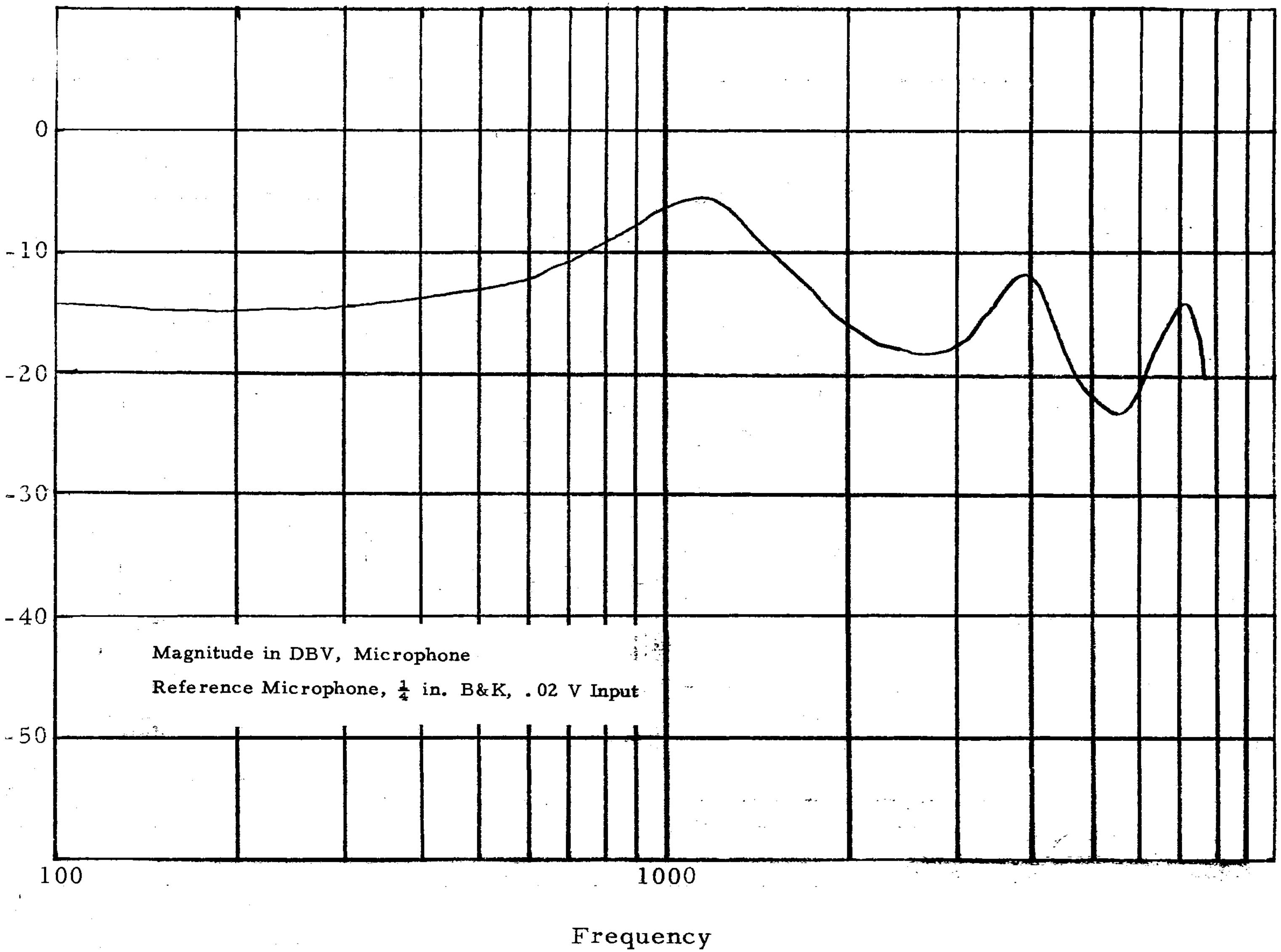


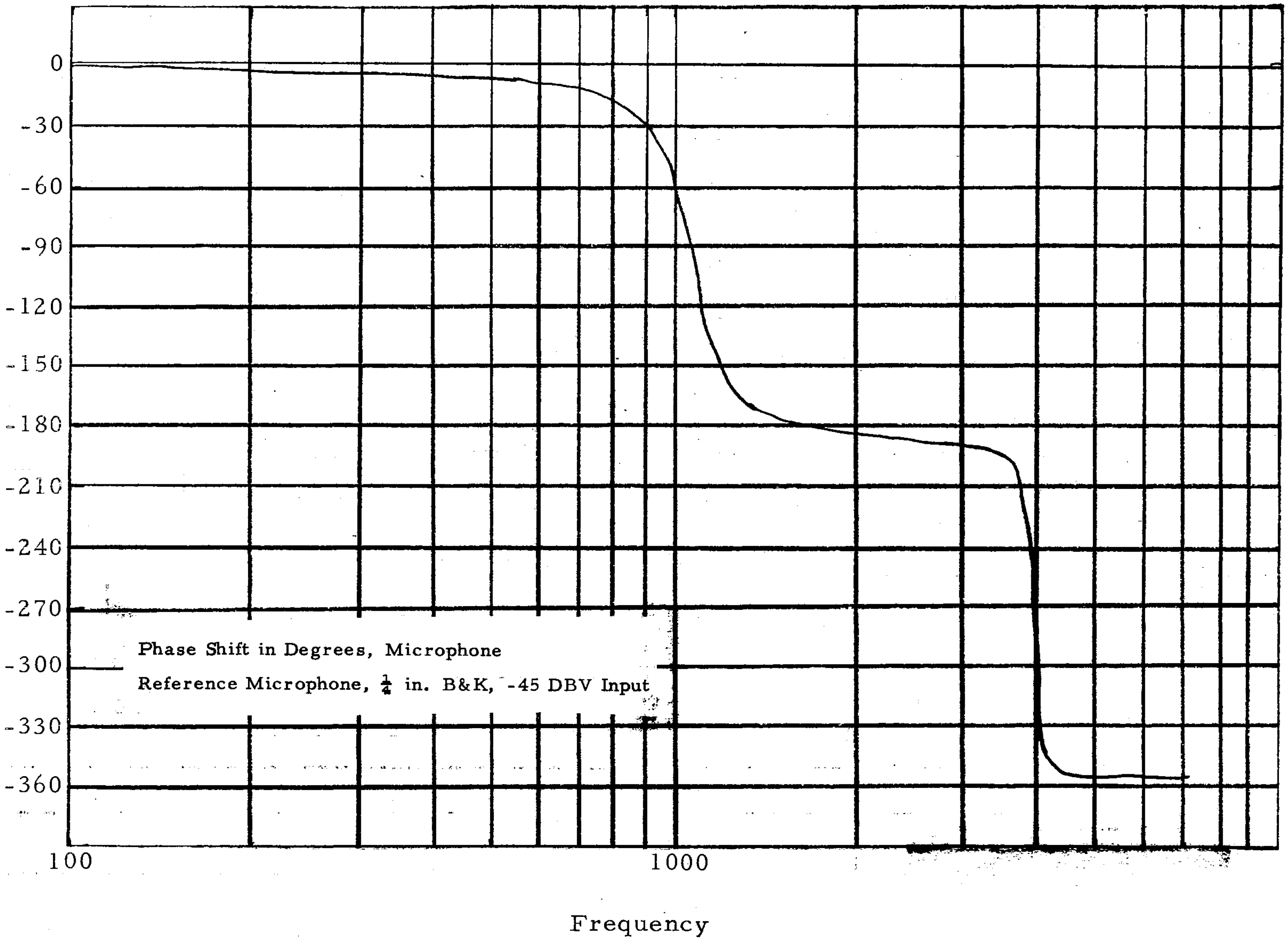
Magnitude in DBV, Source

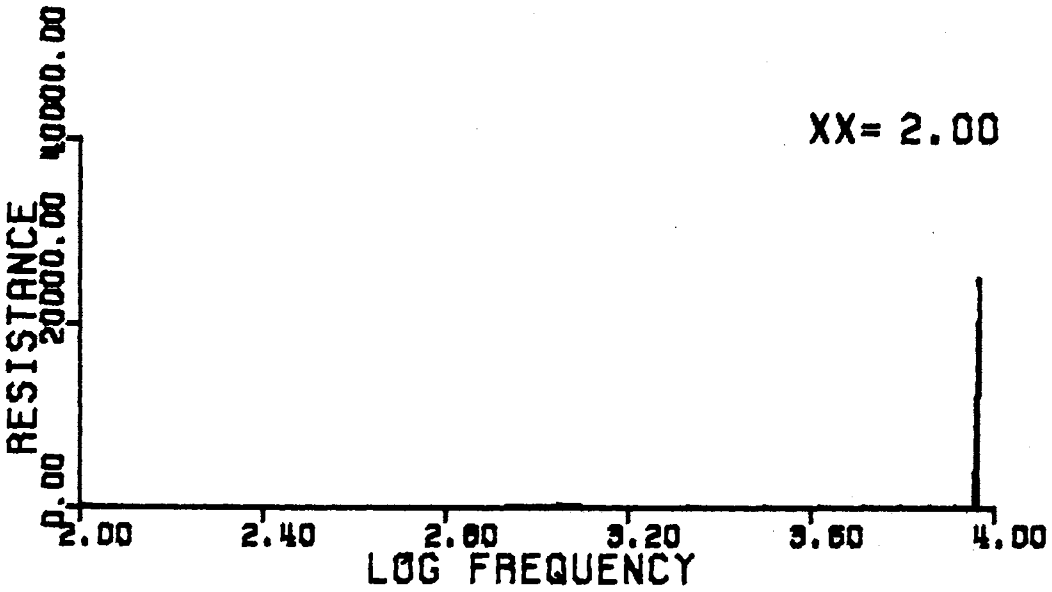
Reference Microphone, $\frac{1}{4}$ in. B&K, .05 V Input

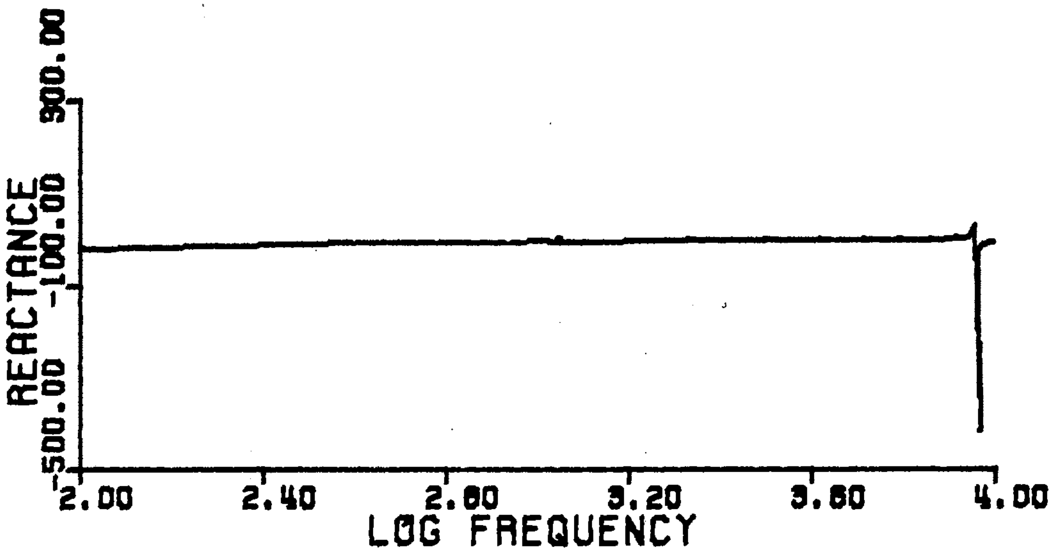


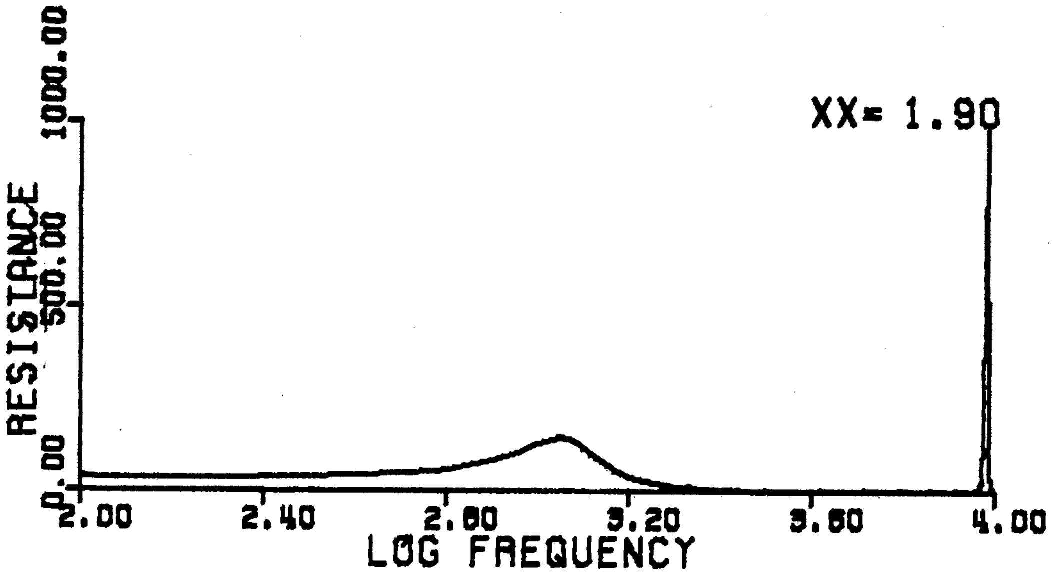
Phase Shift in Degrees, Source Reference Microphone, ¼ in. B&K, -45 DBV Input

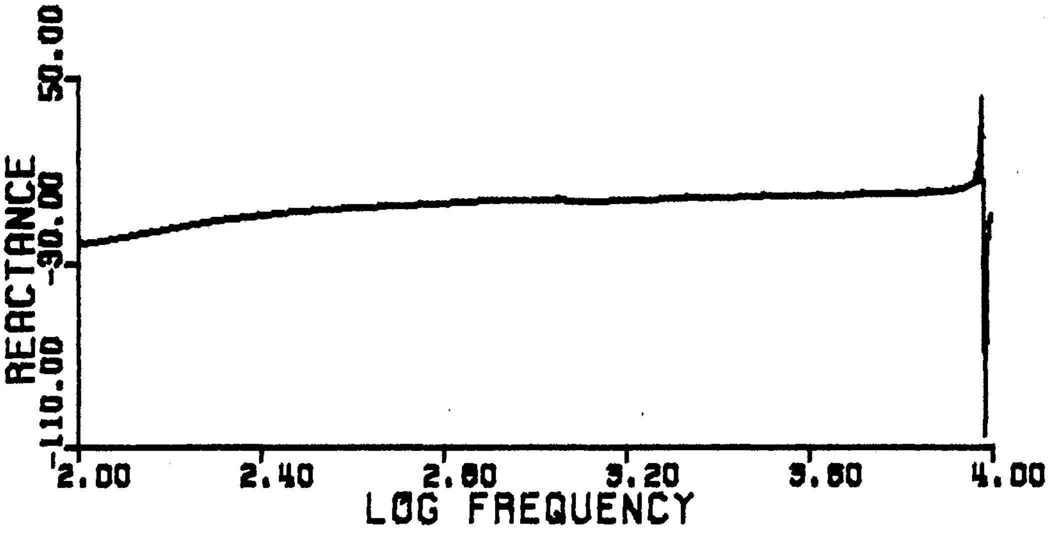

0
-10
-20
-30
-40
-50
100
1000
Frequency
Magnitude in DBV, Microphone
Reference Microphone, $\frac{1}{4}$ in. B&K, .02 V Input

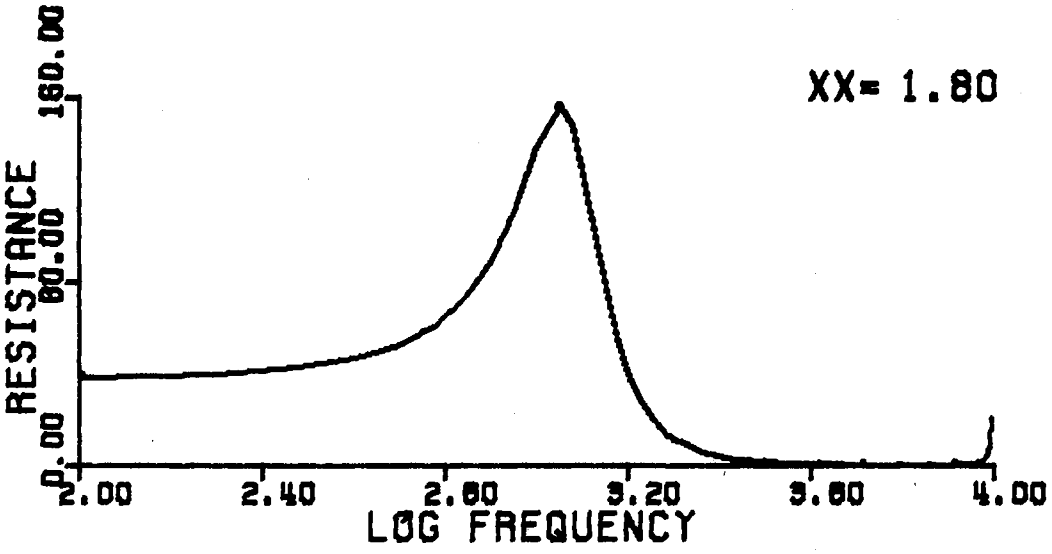

0
-30
-60
-90
-120
-150
-180
-210
-240
-270
-300
-330
-360
Phase Shift in Degrees, Microphone
Reference Microphone, ¼ in. B&K, -45 DBV Input
100
1000
Frequency

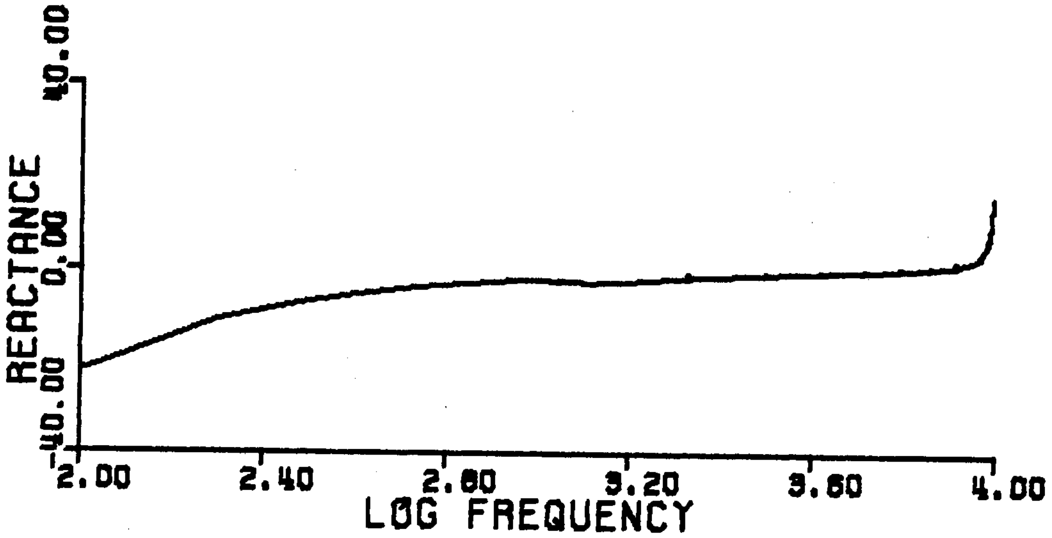

XX= 2.00
RESISTANCE
0.00
20000.00
40000.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

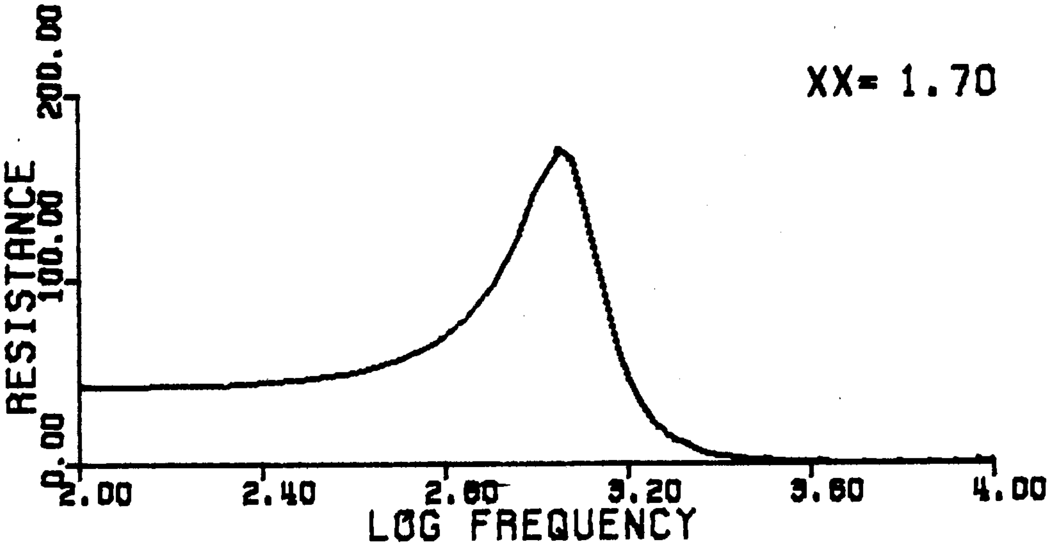

REACTANCE
-500.00
-100.00
300.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

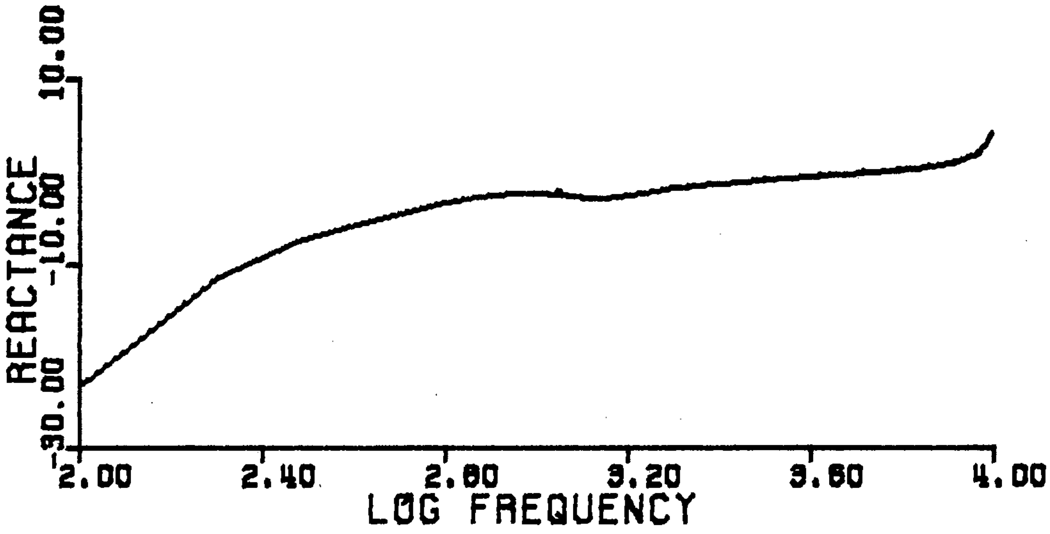

XX= 1.90
RESISTANCE
1000.00
500.00
0.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

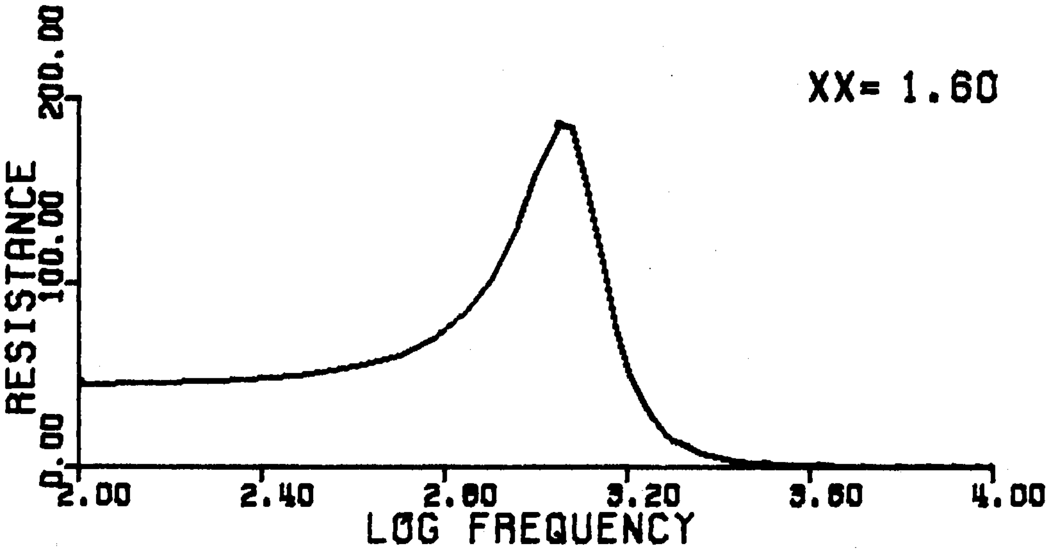

REACTANCE
50.00
-30.00
-110.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

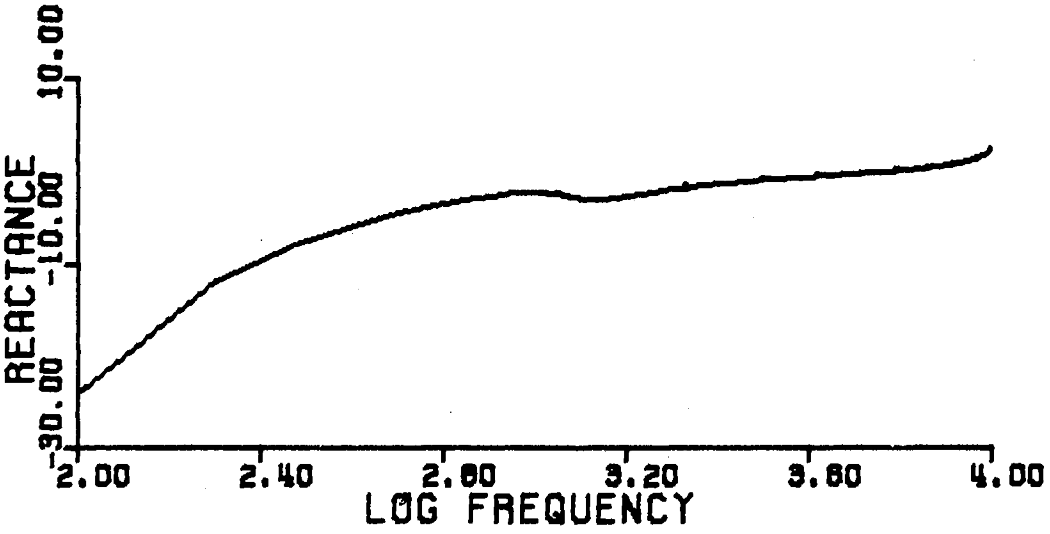

XX= 1.80
RESISTANCE
0.00
80.00
160.00
2.00
2.40
2.80
3.20
3.60
4.00
LØG FREQUENCY

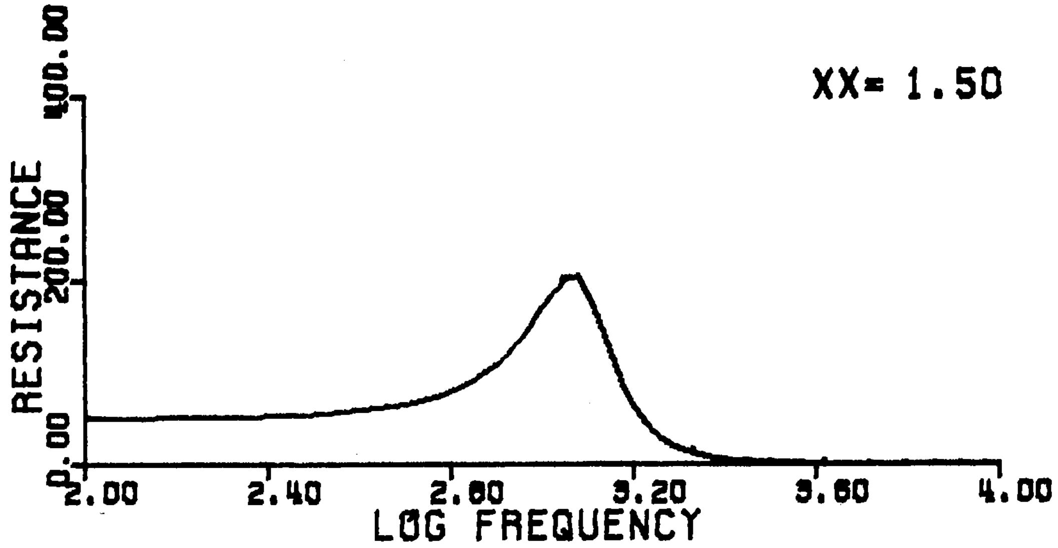

REACTANCE
-40.00
0.00
40.00
2.00
2.40
2.80
3.20
3.60
4.00
LØG FREQUENCY

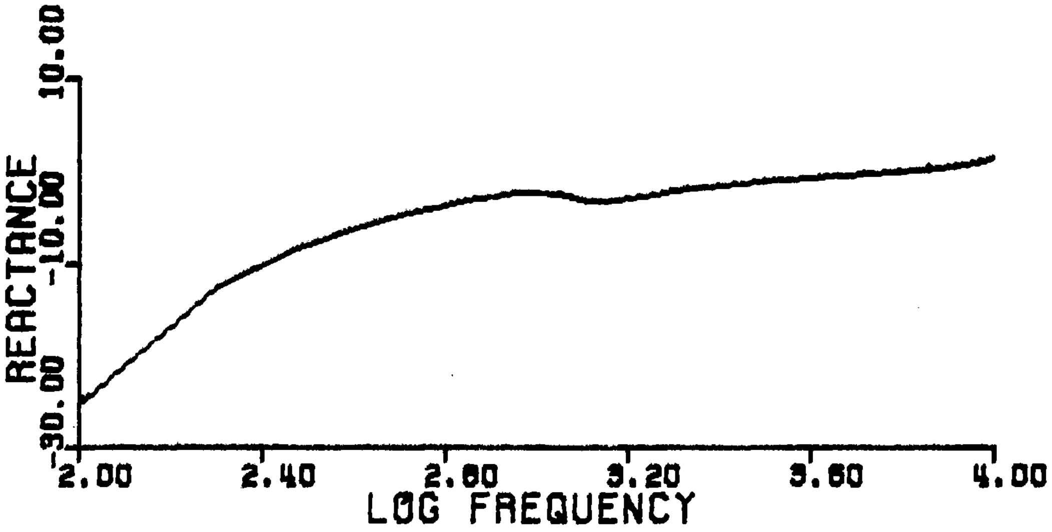

XX= 1.70
RESISTANCE
0.00
100.00
200.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

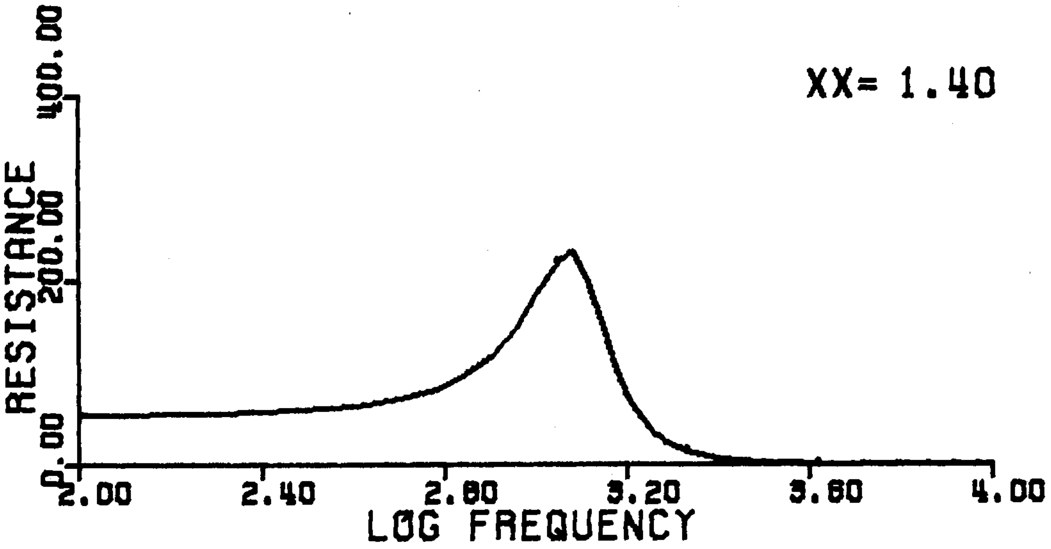

REACTANCE
-30.00
-10.00
10.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

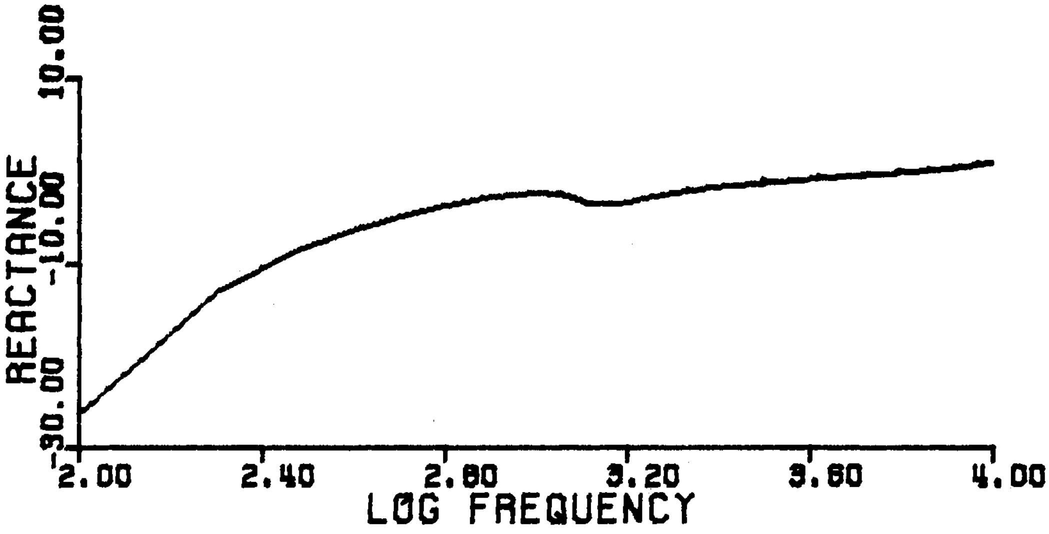

XX= 1.60
RESISTANCE
0.00
100.00
200.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

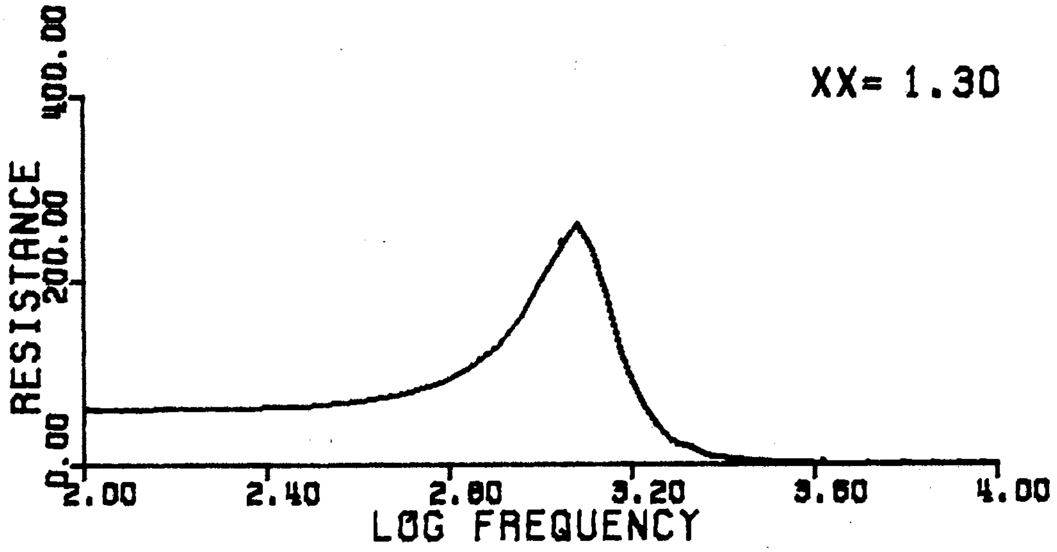

REACTANCE
-30.00
-10.00
10.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

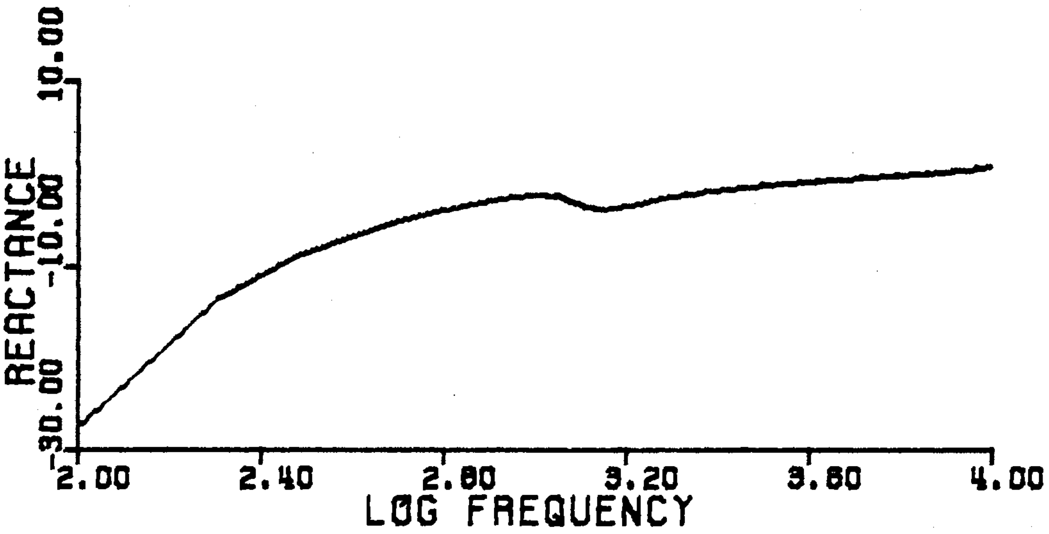

XX= 1.50
RESISTANCE
0.00
200.00
400.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

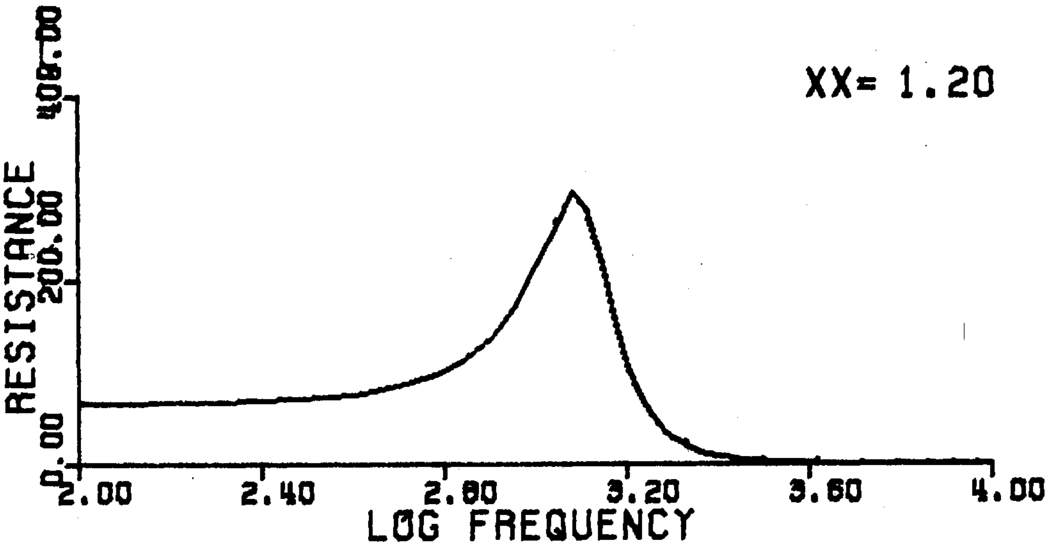

REACTANCE
-30.00
-10.00
10.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

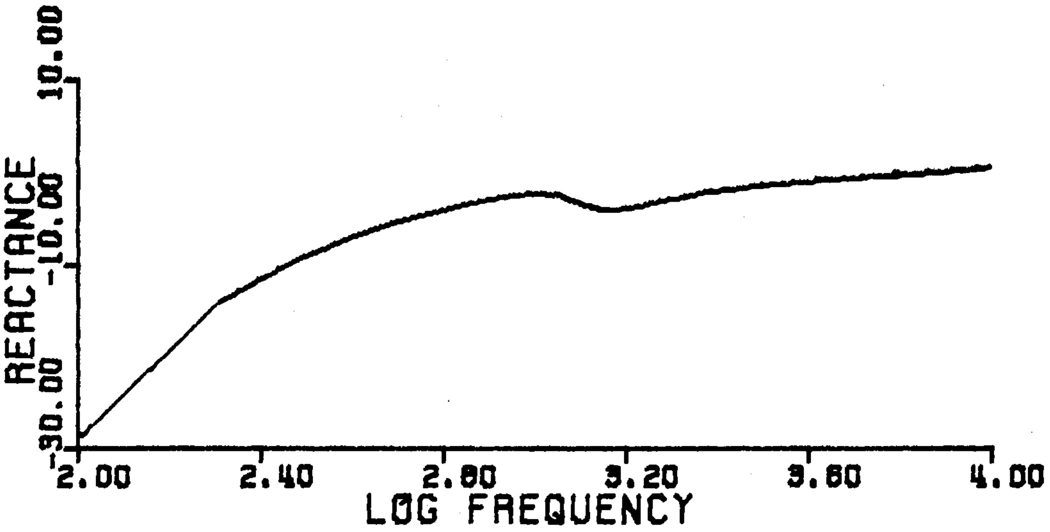

XX= 1.40
RESISTANCE
0.00
200.00
400.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

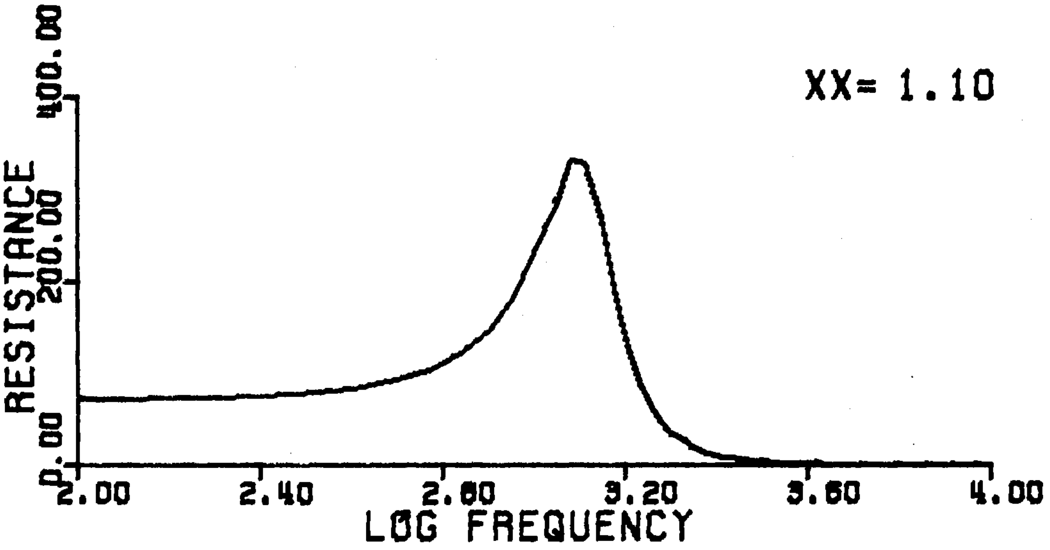

REACTANCE
-30.00
-10.00
10.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

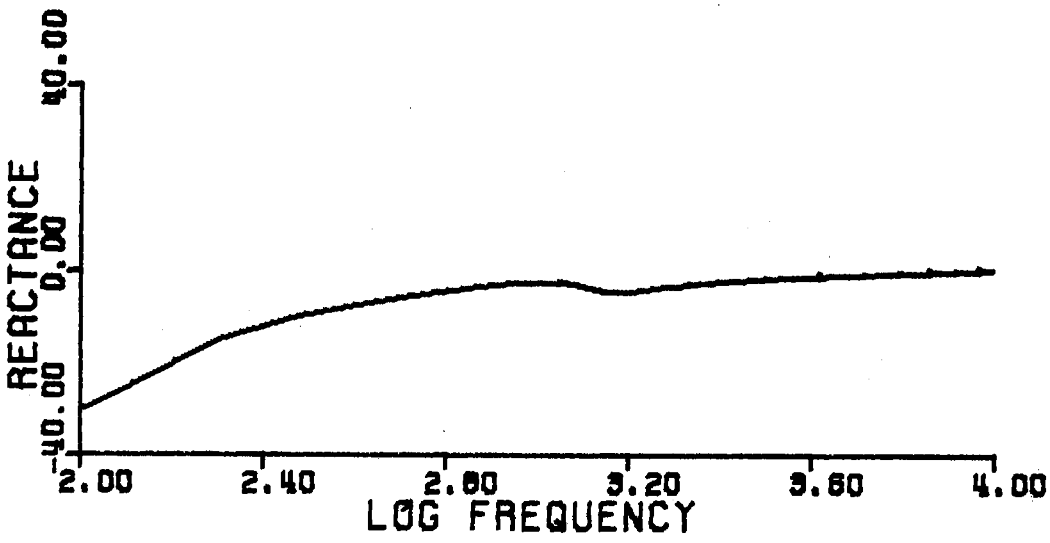

XX= 1.30
RESISTANCE
0.00
200.00
400.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY


REACTANCE
-30.00
-10.00
10.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY


XX= 1.20
RESISTANCE
0.00
200.00
400.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY


REACTANCE
-30.00
-10.00
10.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY


XX= 1.10
RESISTANCE
400.00
200.00
0.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY


REACTANCE
40.00
0.00
-40.00
2.00
2.40
2.80
3.20
3.60
4.00
LOG FREQUENCY

VITA

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Master of Science

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