NASA CONTRACTOR REPORT

NASA CR-1075

NASA CR-1075

INVESTIGATION OF THE CALIBRATION OF MICROPHONES FOR SONIC BOOM MEASUREMENT

by J. J. Van Houten and R. Brown

Prepared by
LTV RESEARCH CENTER
Dallas, Texas
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1968

NASA CR-1075

INVESTIGATION OF THE CALIBRATION OF MICROPHONES FOR SONIC BOOM MEASUREMENT

By J. J. Van Houten and R. Brown

Issued by Originator as Technical Report No. 0-71200/7TR-112

Prepared under Contract No. NAS 1-5652 by
LTV RESEARCH CENTER
Dallas, Texas

for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Continued)

INVESTIGATION OF THE
CALIBRATION OF MICROPHONES FOR
SONIC BOOM MEASUREMENT

By John J. Van Houten and Ron Brown
LTV Research Center, Western Division
Ling-Temco-Vought, Inc.

SUMMARY

The primary objective of this investigation was to provide NASA with the tools necessary for the precise calibration of microphones to be used for sonic boom measurement. Examination of the various procedures available for microphone calibration indicated that application of the electrostatic actuator technique and the use of an infrasonic pistonphone would satisfy NASA's microphone calibration requirements. These instruments provide the equipment necessary for a comprehensive evaluation of microphones currently being used by NASA as well as those which may be used in the future. An N-wave simulation of a sonic boom by use of the electrostatic actuator technique at levels consistent with those pressures currently being measured in the various sonic boom assessment programs was a paramount goal of the study. An actuator system which provided a peak N-wave pressure at the microphone of 128 dB (re: 0.0002 dyne/cm^2) or one pound per square foot and a variable time duration of the N-wave between 0.1 and 0.4 seconds was desired. This report describes the approach taken to meet this goal and reviews the problems associated with developing electrostatic pressures in this range. Furthermore, due to a low frequency deficiency in the electrostatic method of condenser microphone calibration, an infrasonic pistonphone has been provided as a laboratory tool to permit microphone calibration over the complete range of frequencies of interest.

The system delivered to NASA is capable of sinusoidal evaluation of the frequency response and sensitivity of a microphone over the range of 0.01 Hz to above 20 kHz. Sinusoidal Sound Pressure Levels of 94 dB and 114 dB are achieved with the infrasonic pistonphone and sound pressures in excess of 128 dB are obtained by use of the electrostatic actuator system developed for NASA.

As a parallel effort the use of weak shock waves generated by conventional shock tube techniques in combination with an acoustic horn was used to evaluate the microphone response to a progressive shock wave. This technique provided a basis for comparison of the above mentioned calibration procedures with the more realistic situation involved in a shock wave progressing over the diaphragm of a microphone. The investigation indicated the compatibility between the microphone response to a shock wave progressing over the diaphragm and the steady state response. The technique utilized weak shock waves with peak pressures in the range of approximately 140 dB or 3 pounds per square foot.

Finally, by application of the tools developed under this study, a calibration procedure evolved and has been described for use by NASA. This procedure demonstrates the compatibility of steady state and transient response characteristics of the microphone and provides illustrations of idealized N-waveform measurement capability of currently available microphones and complementing instrumentation.

INTRODUCTION

This report was prepared by LTV Research Center under NASA Contract No. NAS1-5652. A number of individuals at LTV Research Center assisted in the work specified under the contract. Mr. B. R. Beavers acted as overall project consultant and reviewed each phase of the study. Messrs D. A. Robinson and T. E. Siddon assisted in developing and evaluating the analytical procedures. Dr. H. E. Dahlke and Mr. G. T. Kantarges were instrumental in the development of the infrasonic pistonphone and provided assistance in preparing the equipment for use by NASA.

The investigation of the transient response of microphones currently being used by NASA to measure the pressures associated with sonic boom phenomena consisted of a two-phase program of study. Phase 1 involved the simulation of dynamic pressures on a microphone diaphragm by the application of an electrostatic force and the use of an infrasonic pistonphone. The second phase was devoted to a study of the generation of transient pressures utilizing bursting diaphragm techniques and weakened shock waves from acoustic horns. Microphones were subjected to these transient pressures and compatibility of response between the electrostatic technique and this direct application of dynamic pressure has been shown. Both phases of the investigation demonstrated the compatibility of steady state frequency response and transient response of the transducers being studied. Furthermore, detailed specifications of the transducer characteristics as well as required calibration procedures were developed for microphones being used for the assessment of sonic boom pressures.

Methods of Calibration

Examination of the variety of microphone calibration techniques which have been developed during the last 40 years reveals a broad cross section of devices and techniques. Each plays an important role in defining the performance of a pressure transducer. Table I summarizes the techniques which are most clearly understood and indicates the range of sound pressures and frequencies which are generally accepted as encompassing the utility of the procedure indicated. The summary indicates the most useful reference material relating to the procedure described and attempts to identify whether the procedure is considered a primary standard or is based on comparison with a calibrated microphone or secondary standard. A liberal interpretation of the information obtained has been indicated. However, in actual practice the potential utility of the various techniques is not realized. For example, in the case of the electrostatic actuator and comparison calibration techniques, linearity of response is generally not measured over a very broad range of sound pressures.

The accuracy of each procedure has been indicated and must be qualified since it is an indication of the state-of-the-art and not necessarily the capability of an individual laboratory which may perform the procedure. The quality of each procedure is highly dependent on the readout equipment and the ability of the experimenter to obtain the desired precision available within the accuracy indicated.

TABLE I MICROPHONE CALIBRATION PROCEDURES

Sound Pressure Level, dB (re: 0.0002 dynes/cm^2)

MAXIMUM SPL	APPARATUS	FREQUENCY RANGE, HZ	METHOD OF STANDARD-IZATION	WAVEFORM GENERATED	INFORMATION OBTAINED	ESTIMATED ACCURACY AT MAXIMUM SPL, dB	PRINCIPLE REFERENCES
190	Shock Tube	100 - 500,000	Primary	Step Function	Frequency Response, Sensitivity, Linearity	± 2	37
	Standing Wave Tube	100 - 1000	Secondary	Sinusoidal	Linearity	± 1 1/2	1
180	Pistonphone	0.1 - 200	Primary	Sinusoidal	Sensitivity, Linearity	± 1	22
170							
	Comparison Calibrator (Coupler)	10 - 1000	Secondary	Sine or Random	Frequency Response, Sensitivity, Linearity	± 3/4	13
160							
150							
	Progressive Wave Tube	30 - 5000	Secondary	Sine or Random	Frequency Response, Sensitivity,	± 1/2	—
140							
130	Electrostatic Actuator	0.1 - 500,000	Primary	Sine, Random, Transient	Frequency Response, Sensitivity, Linearity	± 1/4	22
120	Comparison Calibration (Free Field)	50 - 10,000	Secondary	Sine or Random	Frequency Response, Sensitivity, Linearity	± 1/4	19, 20
	Infrasonic Pistonphone	0.01 - 10	Primary	Sinusoidal	Frequency Response, Sensitivity, Linearity	± 1/4	22
110							
100	Reciprocity Calibration (Coupler)	10 - 20,000	Primary	Sinusoidal	Frequency Response, Sensitivity	± 1/4	11
	Audio Pistonphone	10 - 300	Primary	Sinusoidal	Frequency Response, Sensitivity	± 1/4	22
90	Reciprocity Calibration (Free Field)	50 - 100,000	Primary	Sinusoidal	Frequency Response, Sensitivity	± 1/4	16

Evaluation of a Microphone for Transient Pressure Measurement

As indicated in Table I, a single measurement is insufficient to completely identify the characteristics of a microphone over a broad range of pressures and frequencies. Interpretations of measurements require a knowledge of the sensitivity of the transducer, linearity over the range of pressures of interest and frequency response over a broad range from infrasonic pressures extending through the audio frequency range. The rise time and overshoot characteristics of the microphone are of interest in examining the capability of the transducer for a given transient measurement situation. For example, in the case of sonic boom assessment, the rise time, overshoot and flat top response to an idealized N-wave provides a direct illustration of the capability of the transducer in actual operation. The response of the microphone to progressive waves and at normal incidence also provides further information regarding microphone capability. Various calibration procedures and devices are needed to provide the above mentioned information. These devices include the electrostatic actuator, pistonphone, and the application of shock tube technology. A summary of the characteristics and the devices used in their evaluation is given in Table II. In order to provide a flexible calibration capability for use in a laboratory situation, the electrostatic actuator

TABLE II - EVALUATION OF A MICROPHONE FOR TRANSIENT PRESSURE MEASUREMENT

CHARACTERISTIC	METHOD OF EVALUATION
REFERENCE SENSITIVITY	PISTONPHONE
LINEARITY	PISTONPHONE
FREQUENCY RESPONSE	
MID & HIGH FREQUENCY	ELECTROSTATIC ACTUATOR
LOWER CUTOFF FREQUENCY	INFRASONIC PISTONPHONE
RISE-TIME, OVERSHOOT	
PROGRESSIVE WAVE	SHOCK/EXPANSION TUBE
NORMAL INCIDENCE	ELECTROSTATIC ACTUATOR
FLAT TOP RESPONSE	SHOCK TUBE

and pistonphone methods of microphone evaluation were selected. These units provide a basis for supplying a measurement of sensitivity with a primary standard, the pistonphone. Linearity of response is again measured by use of the pistonphone. The electrostatic actuator provides a basis for measurement of steady state response at low audio frequencies to well above 20 kHz. It also provides a method of subjecting the microphone to both idealized N-wave and step function pressures for evaluation of rise time, overshoot and flat top response characteristics.

GENERATION OF ELECTROSTATIC PRESSURE

Experimentation and analysis to establish the maximum electrostatic pressure which can be produced on a microphone indicates that a level slightly in excess of 130 dB may be achieved. The primary limitation involves arcing at high potentials (voltage breakdown) across the air dielectric between the electrostatic actuator and microphone diaphragm. This phenomenon places an upper limit on the pressures produced electrostatically.

The effective sound pressure on the diaphragm of a microphone as produced by an electrostatically driven plate is established by the application of Gauss' law. It is assumed that the electric field between the parallel plates, consisting of the microphone diaphragm and the actuator, is uniform and perpendicular to the plates. With these assumptions, it may be shown that the pressure on the diaphragm of the microphone is*

$$P = 1.433 \times 10^{-10} \frac{kV^2}{d^2} \tag{1}$$

where P is the sound pressure (lbs/ft^2), V is the potential between plates in volts, d is the spacing between plates in inches, and k is a dimensionless factor dependent on the geometry of the actuator. If the potential, V, consists of a large dc voltage, V_0, and a smaller time dependent component, $V_1(t)$, such that

$$V = V_0 + V_1(t)$$

the pressure produced will be

$$P = 2.87 \times 10^{-10} \frac{kV_0 V_1(t)}{d^2} \left[1 + \frac{V_1(t)}{2V_0}\right] \tag{2}$$

The term involving a steady state pressure on the diaphragm, $V_0{}^2$, has been dropped since it does not affect the apparent sound pressure of interest. If

$$\frac{V_1(t)}{V_0} << 1$$

this term may be neglected and the pressure observed at the diaphragm will be linear in the time dependent portion of the potential across the plates.

For a sinusoidal time dependent potential, the expression above for electrostatic pressure may be written in terms of a root-mean-square pressure and applied voltage in the form

---

* The basic theory has been discussed by S. Ballantine. (Ref. 1).

$$P = 2.87 \times 10^{-10} (\beta^2 + 1/8)^{\frac{1}{2}} \frac{kV_{rms}^2}{d^2} \qquad (3)$$

where β is the ratio of dc potential to the rms value of the time dependent voltage. The parameter, β, reflects the inherent non-linear distortion associated with the electrostatic actuator technique being used. Constant distortion is achieved for constant β as indicated by Equation (3). The percentage of total harmonic distortion is given by

$$D = \frac{1}{1 + 2\sqrt{2}\beta} \times 100\% \qquad (4)$$

Breakdown Voltage

If it is assumed that a uniform electric field exists between the plates of the capacitor formed by the actuator and microphone diaphragm, it is possible to estimate the potential at which arcing (voltage breakdown) will occur. (Ref.2,3). It is extremely important to avoid this arcing since it is very likely that damage to the microphone diaphragm will result. This damage is observed by discoloration of the diaphragm at the point at which breakdown occurs. Small holes have been produced in the diaphragm as evidenced by experimentation. Surface roughness, dust particles, and other protrusions increase the likelihood of breakdown and decrease the voltage potential at which breakdown will occur.

Experimental Verification of Actuator Response

The pressures predicted by Equation (3) have been verified by use of the apparatus shown in Figure 1 and the system components of Figure 2. Measurements were made using center-supported actuators

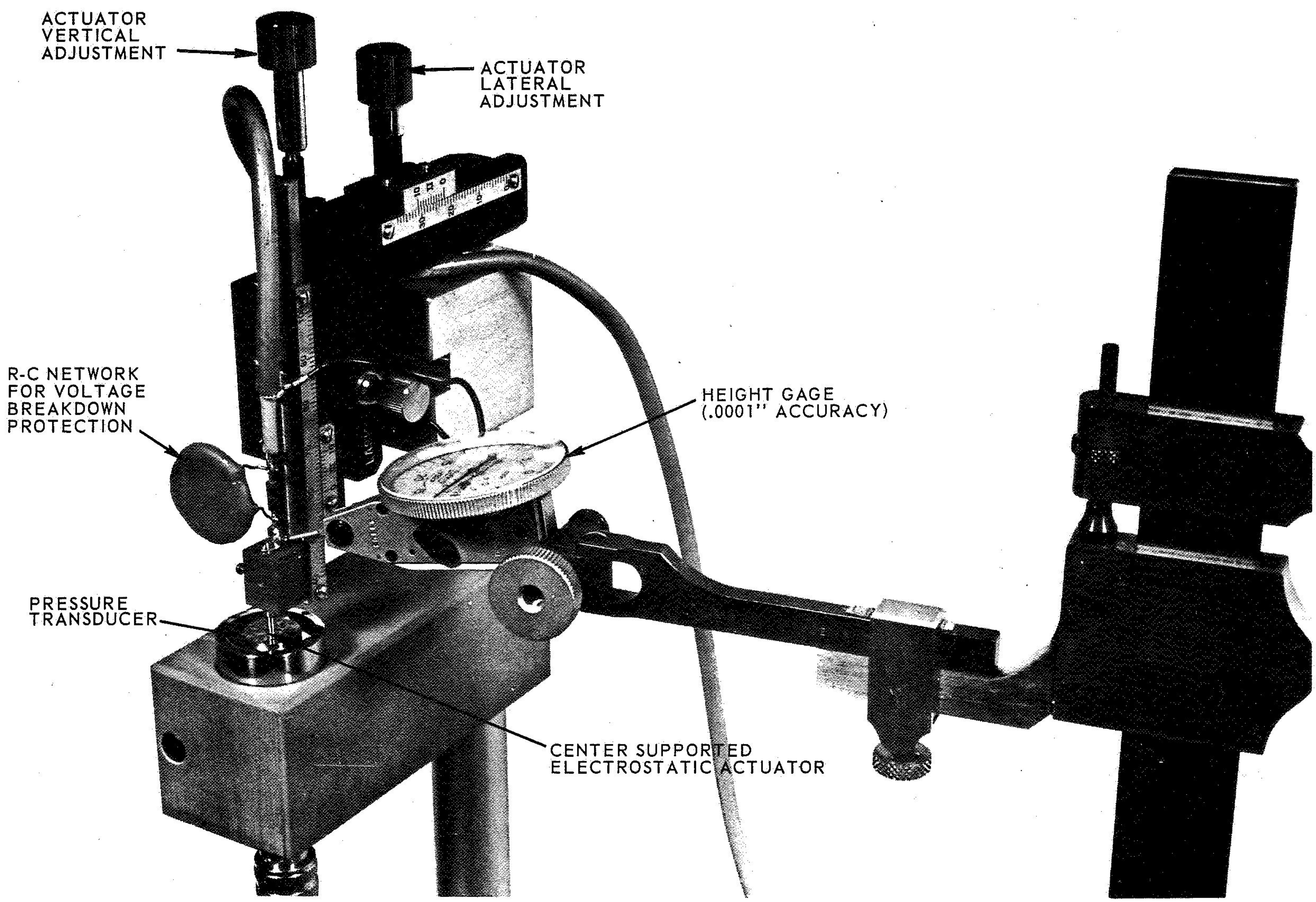


Figure 1 Apparatus Used to Examine the Pressure by Various Electrostatic Actuator Configurations

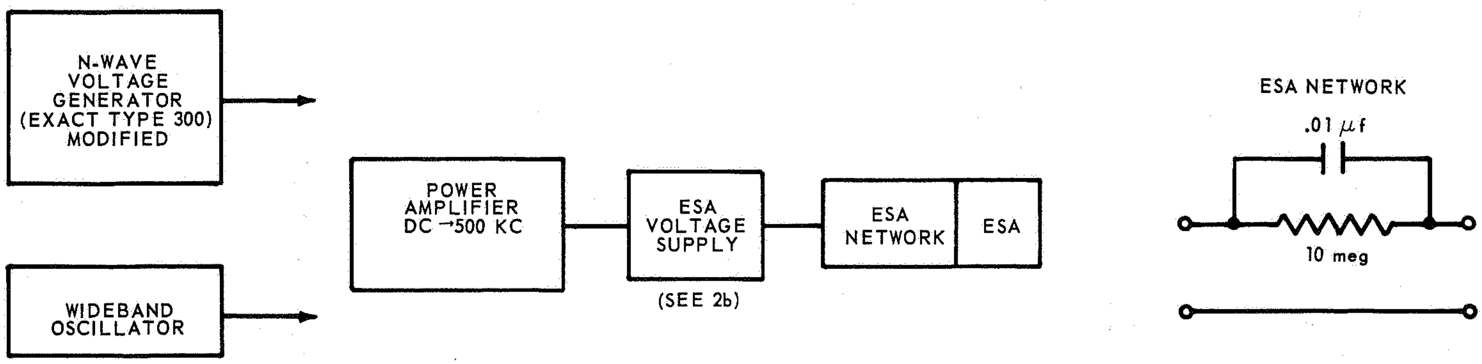


Figure 2(a) Electrostatic Actuator (ESA) System

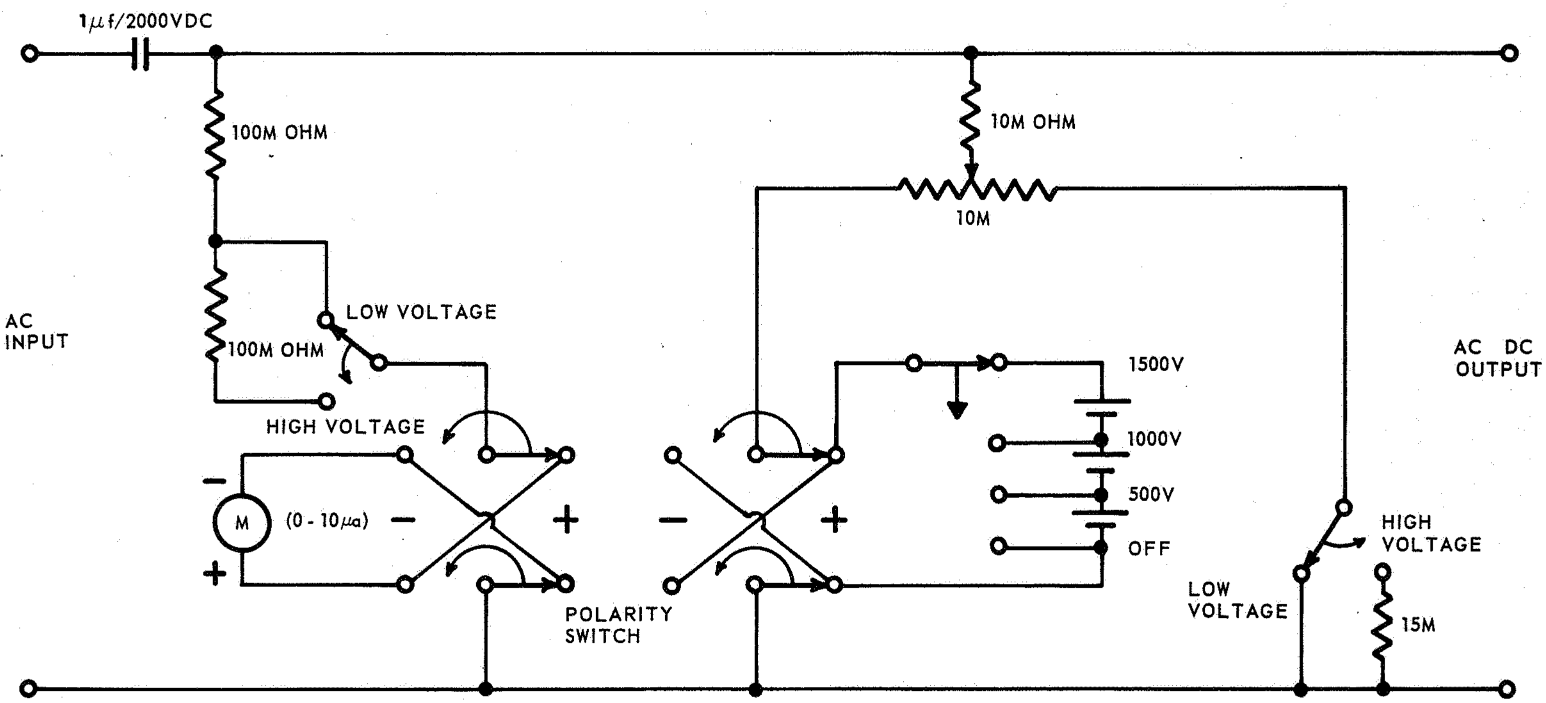


Figure 2(b). Electrostatic Actuator Voltage Supply

having diameters of 1/4, 1/2, and 3/4 inch. The measured variation in pressure with actuator diameter indicates that the optimum diameter coincides with the active diameter of the microphone. No advantage in increased actuator diameter over that of the microphone is obtained. Positioning of the actuator relative to the microphone diaphragm was accomplished with a precision of $\pm$ 0.0001 inch with continuous adjustment of the spacing. Figure 3 illustrates the correspondence between measured and calculated electrostatic pressure. The measured data points corrected by application of the procedure discussed in Appendix I are also indicated.

Figure 4 illustrates similar calculated pressures and shows the limitations imposed by (a) breakdown voltage, (b) ambient noise, and (c) the power amplifier maximum voltage output.

In order to experimentally examine voltage breakdown, the R-C network indicated in Figure 1 is placed between the actuator and voltage supply. This network limits the power that may be dissipated in the conductor formed by the actuator and microphone diaphragm and therefore protects the microphone diaphragm from the previously mentioned arcing. The network consists of a large resistor to dissipate the energy and a bypass capacitor to provide frequency compensation. Measurements indicated close agreement with the breakdown voltages predicted and indicated as a limitation in electrostatic pressure as shown in Figure 4. Figure 5 illustrates the close correspondence between measured and calculated distortion as predicted by Equation (4).

N-Wave Response Studies

The basic waveform associated with sonic boom pressures is identified as an N-wave transient. Application of this transient

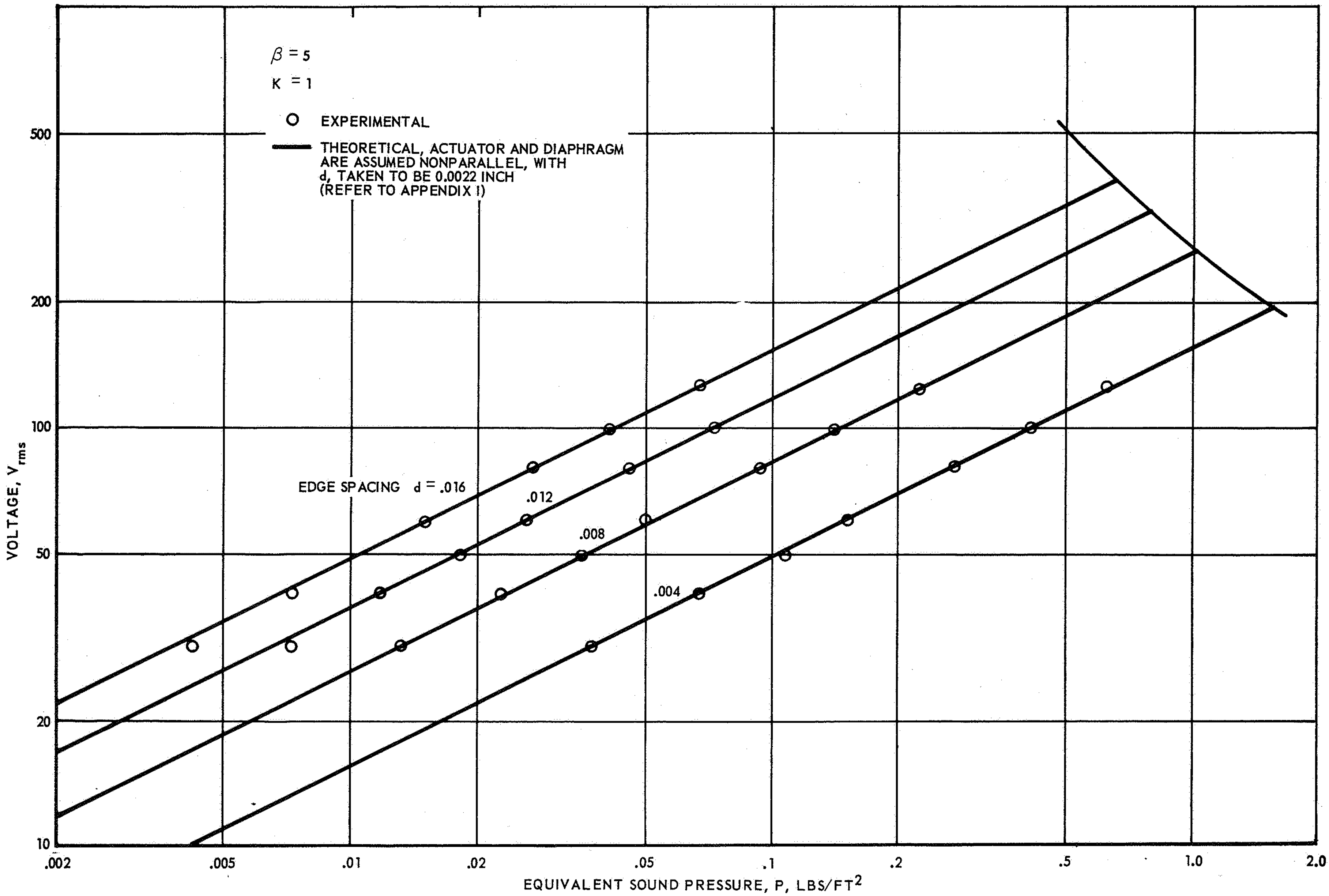


Figure 3. Electrostatic Pressure - Sinusoidal Comparison of Theory with Experimental Data

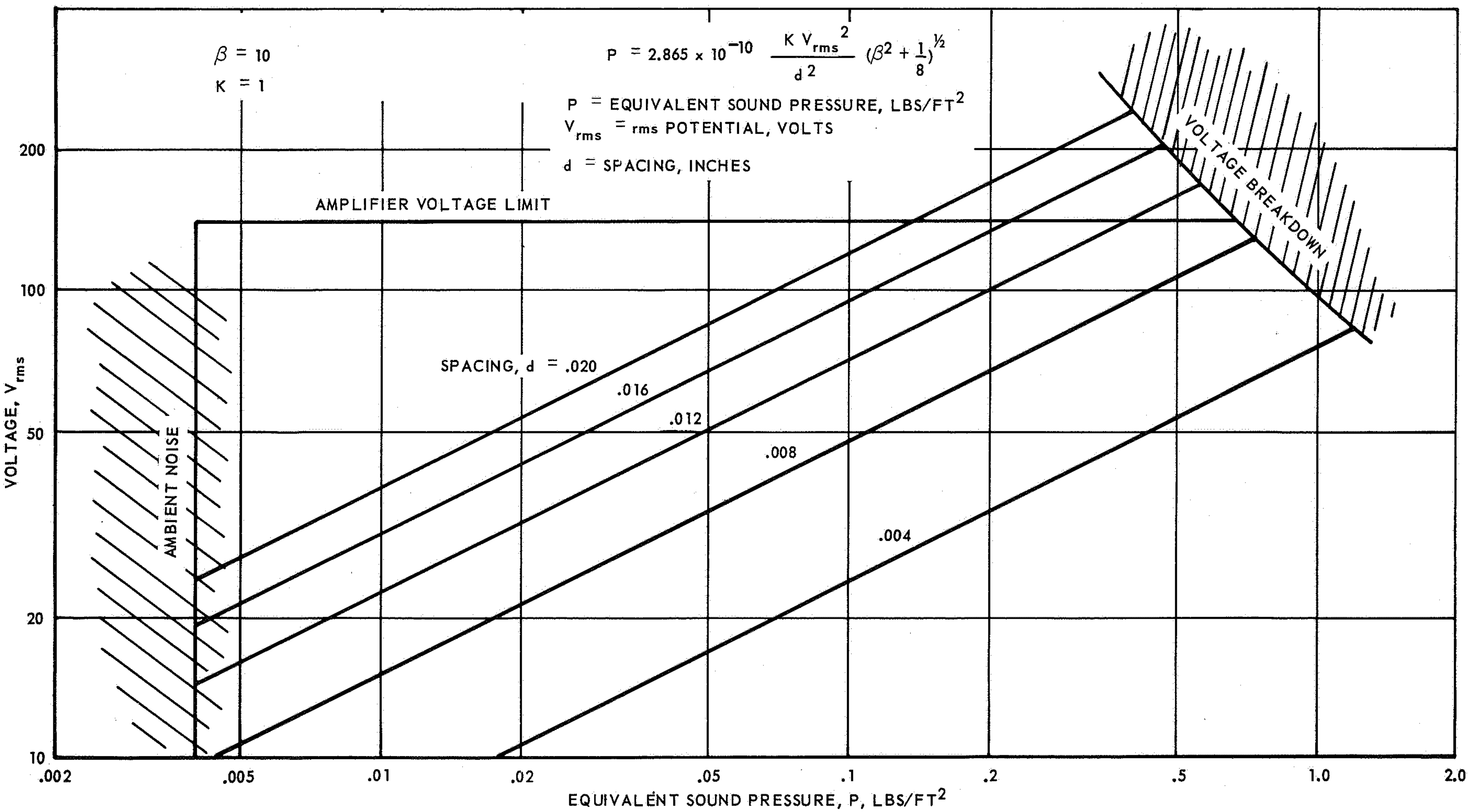


Figure 4. Electrostatic Pressure - Sinusoidal

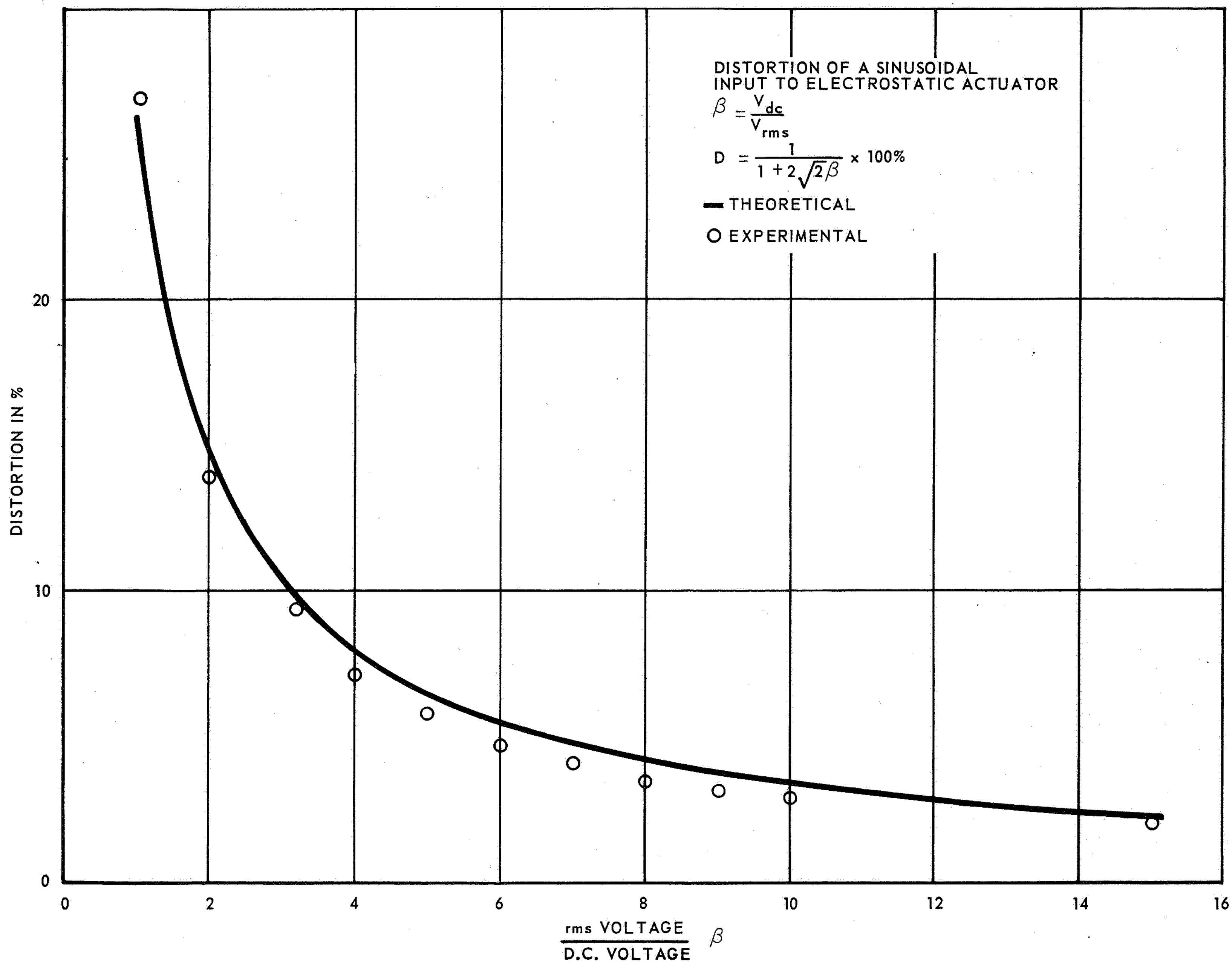


Figure 5. Distortion of a Sinusoidal Input to Electrostatic Actuator

to the electrostatic actuator system of Figure 2 yields a pressure at the microphone diaphragm described by

$$P = 2.87 \times 10^{-10} \frac{kV_0V_1}{d^2} \left[\mu(\xi) - \mu(\xi-1)\right] \left[(1-2\xi) + \frac{V_1}{2V_0} (1-2\xi)^2\right] \quad (5)$$

where V_1 is the amplitude of applied N-wave voltage, $\xi = t/\tau$ which is the ratio of real time to period of N-wave, and $\mu(\xi)$ is the unit step function and the remaining parameters have previously been defined. Figure 6 illustrates the deviation from the "ideal" N-waveform and that expected as a result of the nonlinearity introduced by the electrostatic drive and expressed by Equation (5). It is apparent that values of β, the ratio of dc to time dependent voltage amplitude, should be at least 10. Examination of the limitations imposed by available amplifier voltage indicates the desirability of increasing β to a value as high as 20. Hence, peak amplitudes on the order of 75 volts are used with dc potentials approaching 1500 volts. It has been possible to achieve equivalent peak N-wave pressures of one pound per square foot with the system of Figures 1 and 2. This was accomplished with a peak N-wave amplitude of 60 volts and a dc potential of 800 volts. The actuator to diaphragm spacing was 0.004 inch.

Figure 7 provides a comparison of the microphone response to a step function pressure simulated by use of the actuator and that of a simple mathematical model of a condenser microphone.* The relative response obtained indicates the rise time characteristic of the transducer to a normal incident wave front. Diffraction

---

* For an example of a detail treatment of the dynamics of a condenser microphone, refer to P. M. Morse, Vibration and Sound, McGraw-Hill Book Company, (1948) p. 195.

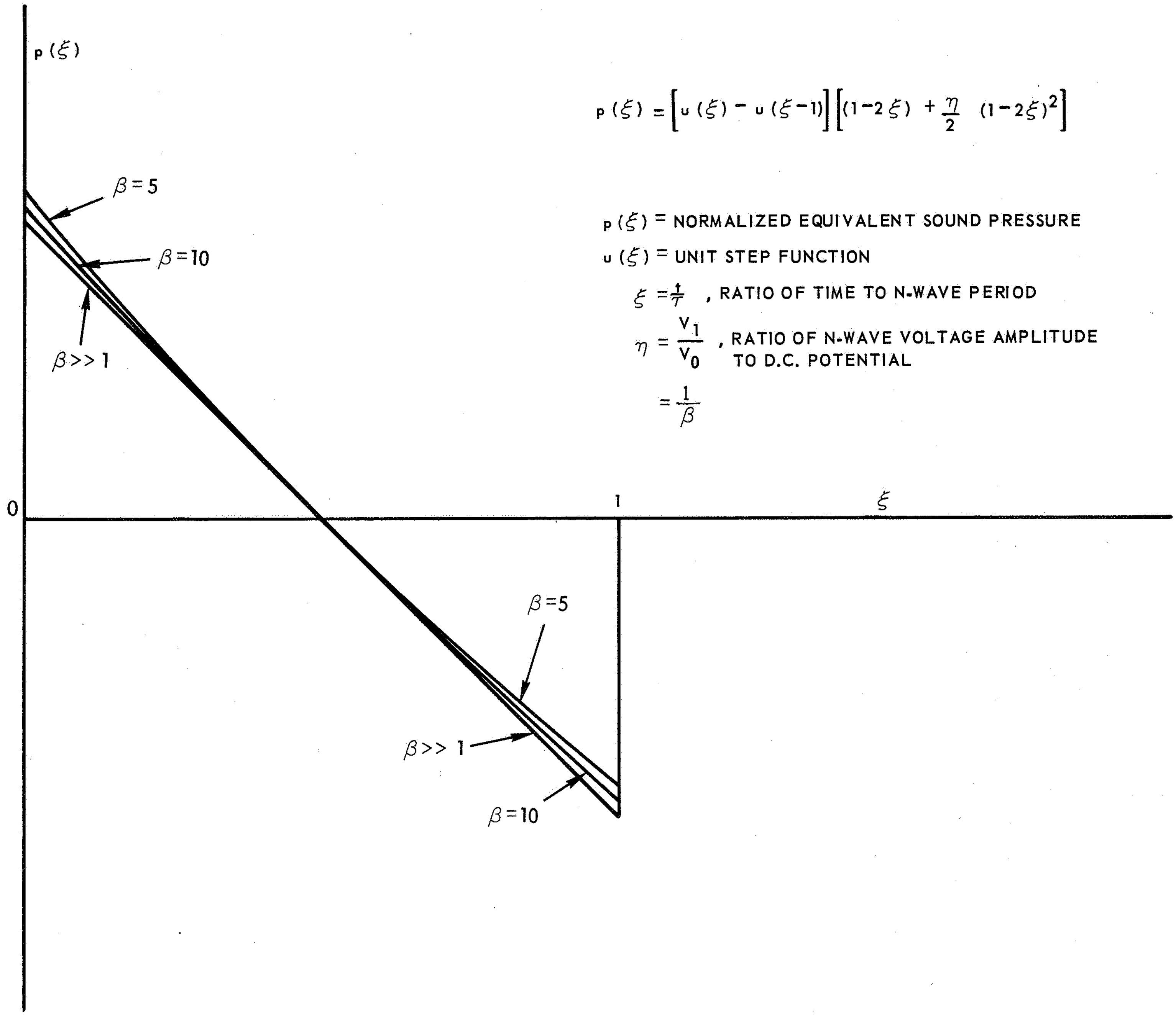


Figure 6 Distortion of an N-wave Transient Pressure Produced by an Electrostatic Actuator

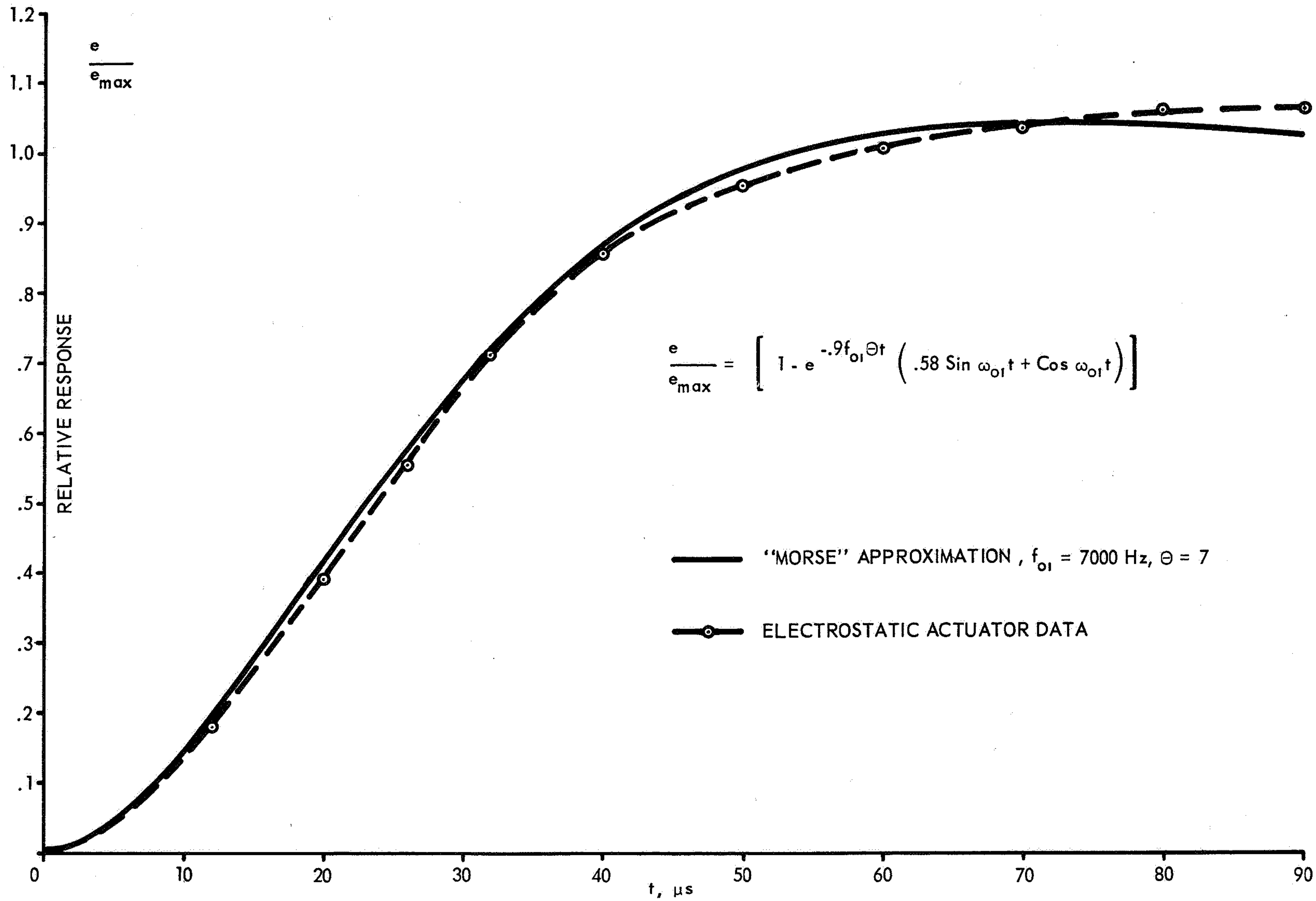


Figure 7. Microphone Step Function Response Produced by Application of the Electrostatic Actuator

around the transducer is not simulated by application of the electrostatic pressure. Therefore, the pressure response or response experienced by a transducer flush mounted is measured. Since this is the configuration being used by NASA, the measurement provides a realistic evaluation of the operational situation.

Passive Analog of a Condenser Microphone

Operational techniques have been applied to an analog representation of a condenser microphone. The analog consists of two linear resonances with variable damping and center frequencies as well as the low frequency rolloff characteristic of capacitive-type transducers. Laplace transforms of a linear system description of this analog provide the frequency response or transfer characteristic of the simulated condenser microphone. This transfer function is operated on by both step function and N-wave transforms to establish the spectral content required to provide acceptable waveform simulation. To simplify the calculations, a passive analog was constructed using high quality resistors, capacitors, and inductors to represent the various elements associated with the desired response characteristics. A schematic of this analog is shown in Figure 8. The sinusoidal frequency response of this system was measured directly as well as its time response to both step function and N-wave inputs. The results of this experiment are shown in Figure 9. Excellent agreement between the previously mentioned analysis and time response characteristic measured using the passive analog was obtained. Direct correspondence between time and frequency response of systems specifically being used by NASA have been obtained with the actual microphones of interest as well as their analog simulation.

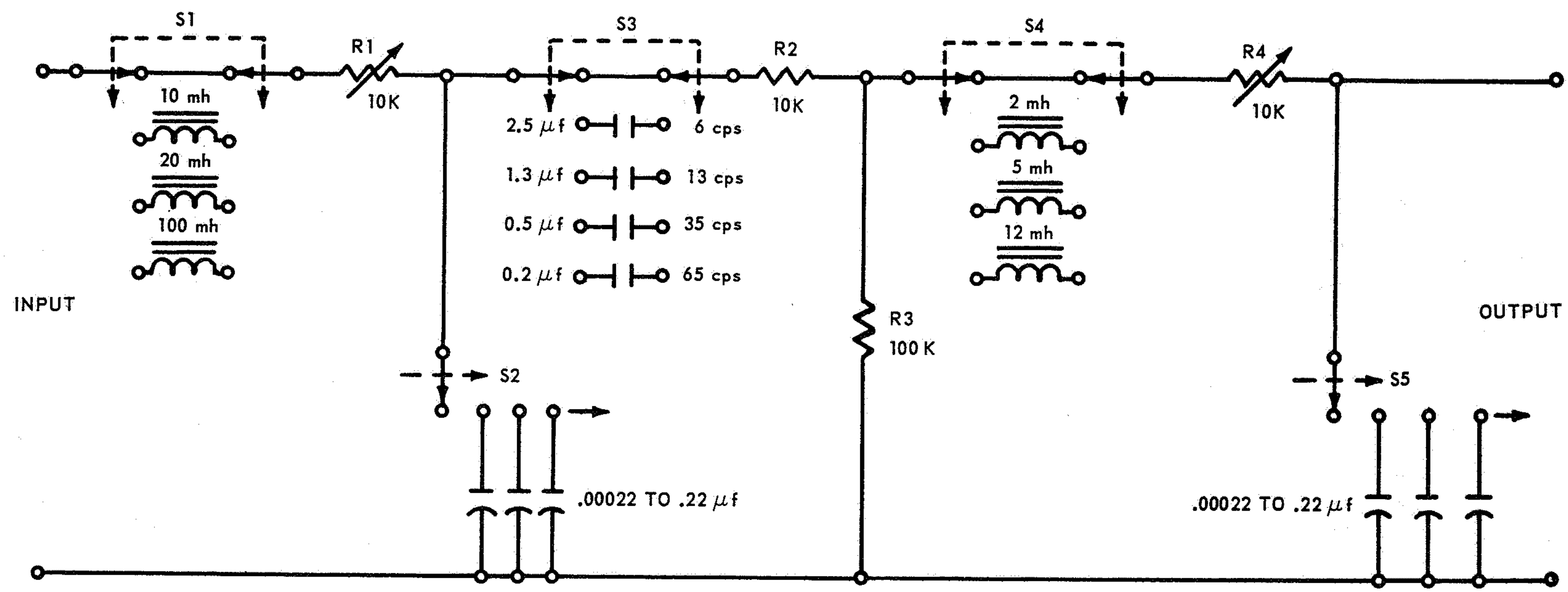


Figure 8. Passive Analog of a Condenser Microphone

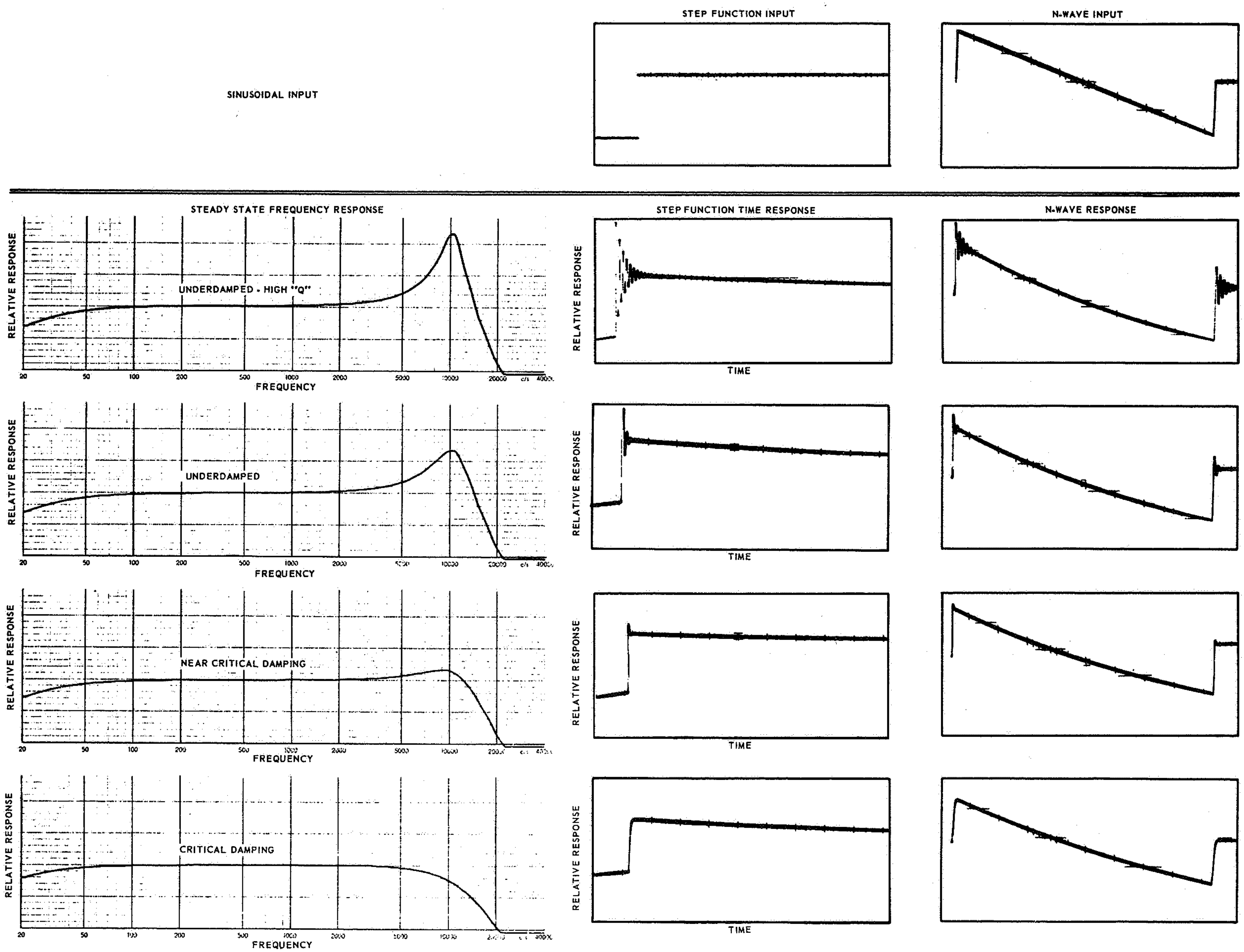


Figure 9. Passive Analog of Condenser Microphone - Frequency and Time Response to Step and N - Wave Functions

Actuators for Laboratory and Field Calibration

Figure 10 illustrates the technique of packaging an electrostatic actuator for laboratory and field use by NASA and indicates the complementing equipment which provides the required voltage potentials. This device provides continuously variable actuator-to-diaphragm spacing and will be used for laboratory applications. In anticipation of the need for field calibration, the protecting grids of a Photocon Pressure Transducer and a B&K Condenser Microphone were modified to permit their use as an electrostatic actuator as shown in Figure 11. Without altering the grid geometry, its center portion was isolated electrically from an outer ring which secures it to the microphone. The center portion acts as an electrostatic grid and may be attached to the previously mentioned electrostatic drive system. This method of actuating a microphone for field use has a distinct advantage in that the protective grid need not be removed and the potential hazards of damaging an exposed diaphragm are eliminated.

INFRASONIC PISTONPHONE CALIBRATION

The pistonphone provides an absolute calibration of microphones. (Ref. 1). It generates an altering pressure above the ambient in a closed chamber by the sinusoidal motion of a piston. The pressure level can be calculated very accurately from the dimensions of the chamber and the displacement and diameter of the piston. Because the enclosure dimensions must be small compared to the wavelength in the chamber, the pistonphone is a low frequency device with an upper frequency limit established by the size of the enclosure and the rotational frequency of the piston drive

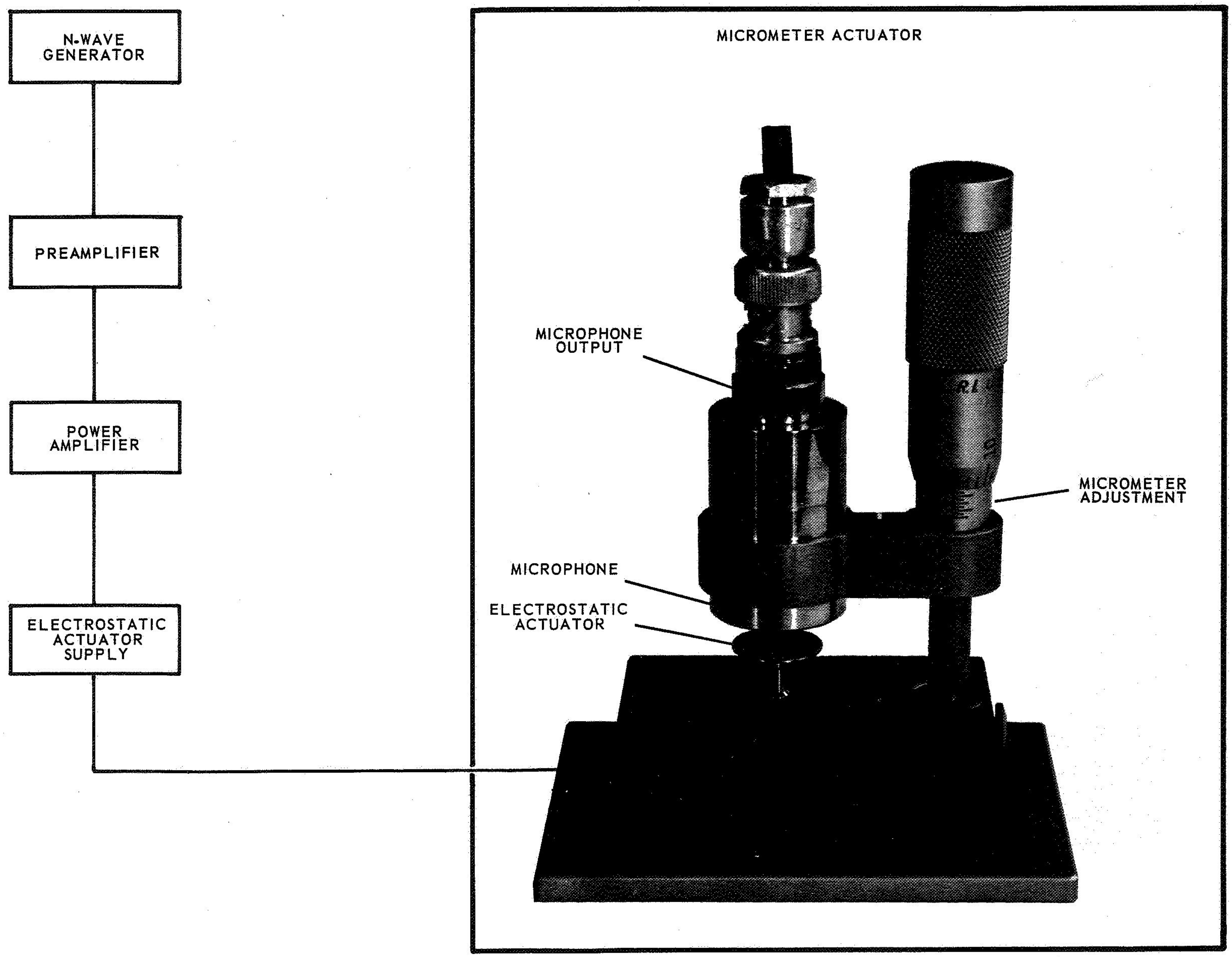
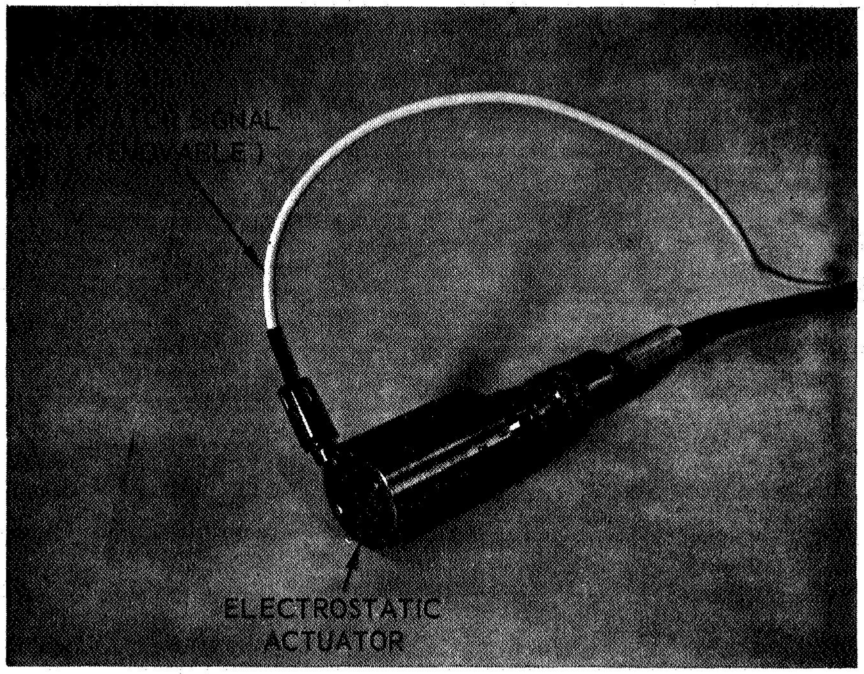


Figure 10. Electrostatic Actuator System

PRESSURE TRANSDUCER



MICROPHONE WITH COIL ADAPTER

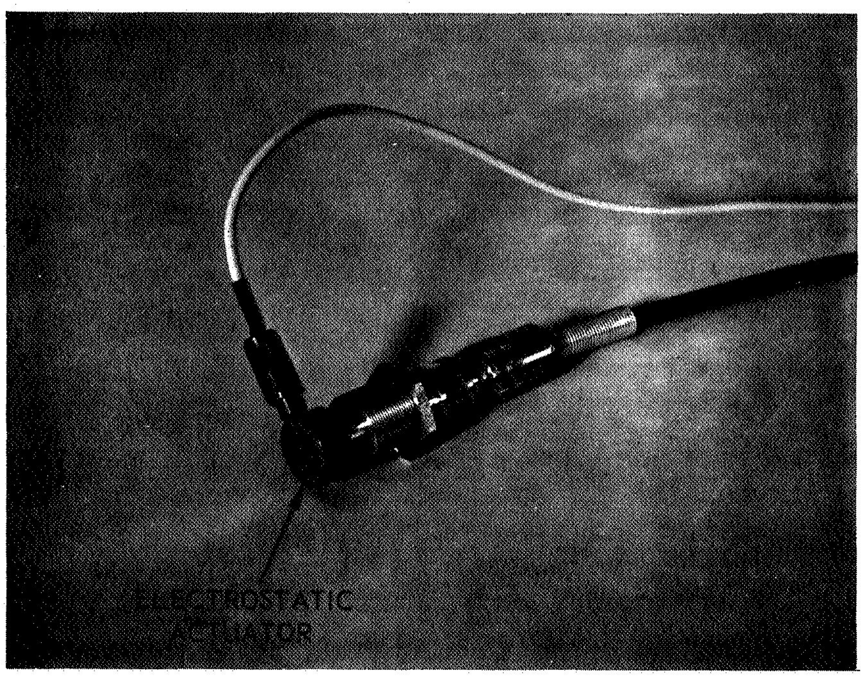


Figure 11. Electrostatic Actuator/Protective Grid Assemblies

mechanism. The system recommended for NASA's microphone calibration requirements, Figure 12, provides either a sound pressure of 94 dB or 114 dB at frequencies to 10 Hz.

The calculated Sound Pressure Level in the pistonphone chamber as a function of change in volume, ΔV, to the volume, V_0, of the chamber is illustrated in Figure 13. This pressure is given by

$$\Delta P = \frac{\gamma}{\sqrt{2}} P_0 \frac{\Delta V}{V_0} \tag{6}$$

The amplitude of the sinusoidal volume change, ΔV, is determined by the piston displacement and the piston diameter. The atmospheric pressure is denoted by P_0 and γ is the ratio of the specific heats of the gas in the chamber. The graph of Figure 13 also contains the pressure associated with the second harmonic distortion. It indicates that the nonlinearity is significant only at extremely high Sound Pressure Levels and is not of concern for the unit provided for use by NASA.

Equation (6) is correct only if the compression and expansion of the gas in the chamber are adiabatic. This is the case at high frequencies. At infrasonic frequencies with their long time period between compression and expansion, the process gradually converts to the isothermal case. A transfer of heat occurs in the chamber. This lowers the impedance of the chamber and as a result, the sound pressure generated is lower.

The pressure decrease in the isothermal case is equal to the ratio of the specific heats of the gas in the chamber. This ratio is equal to 1.40 for air. At extremely low frequencies, an isothermal expansion occurs and the acoustic pressure in the

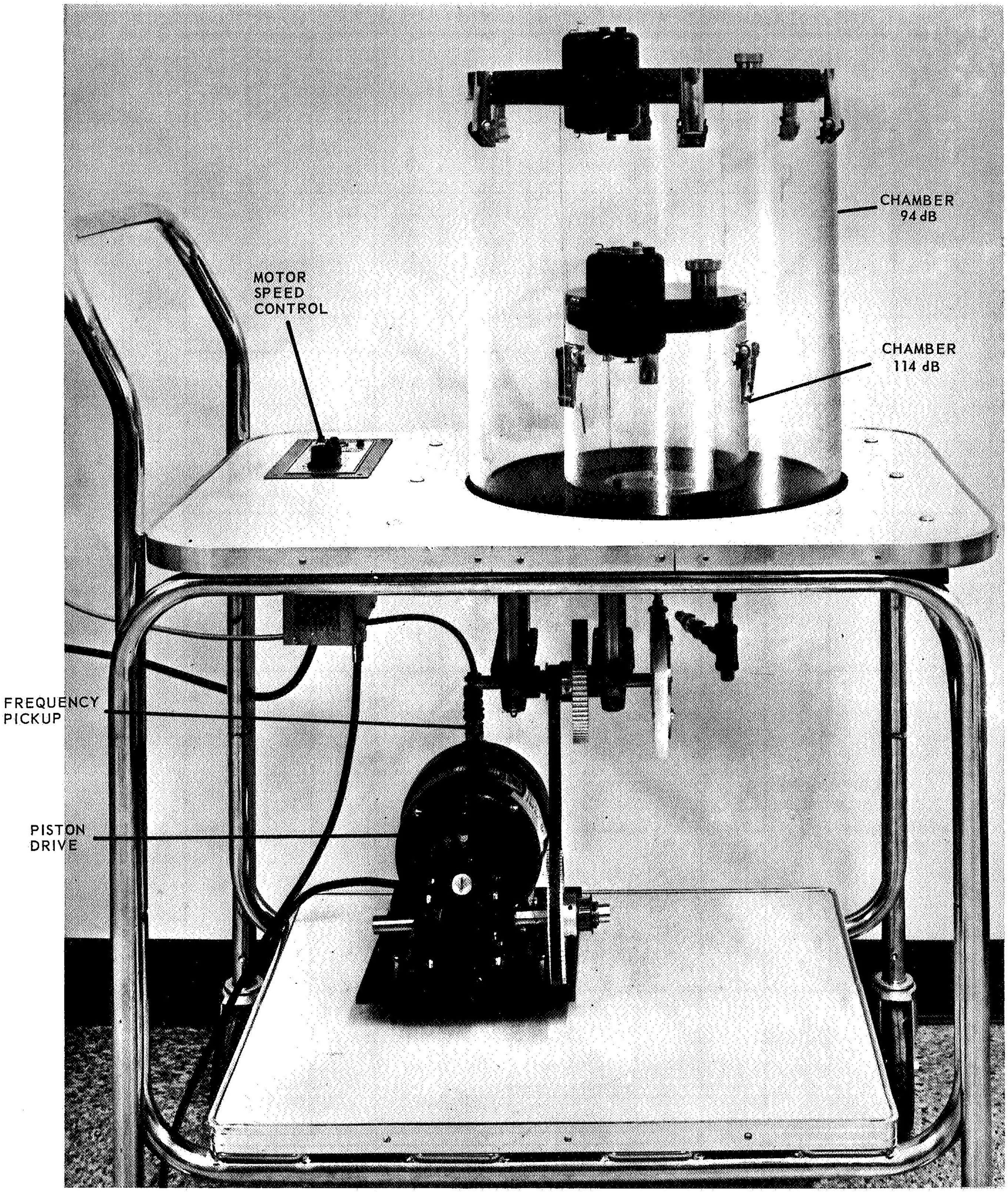


Figure 12. Infrasonic Pistonphone for Generation of Sound Pressure from .01 Hz to 10 Hz

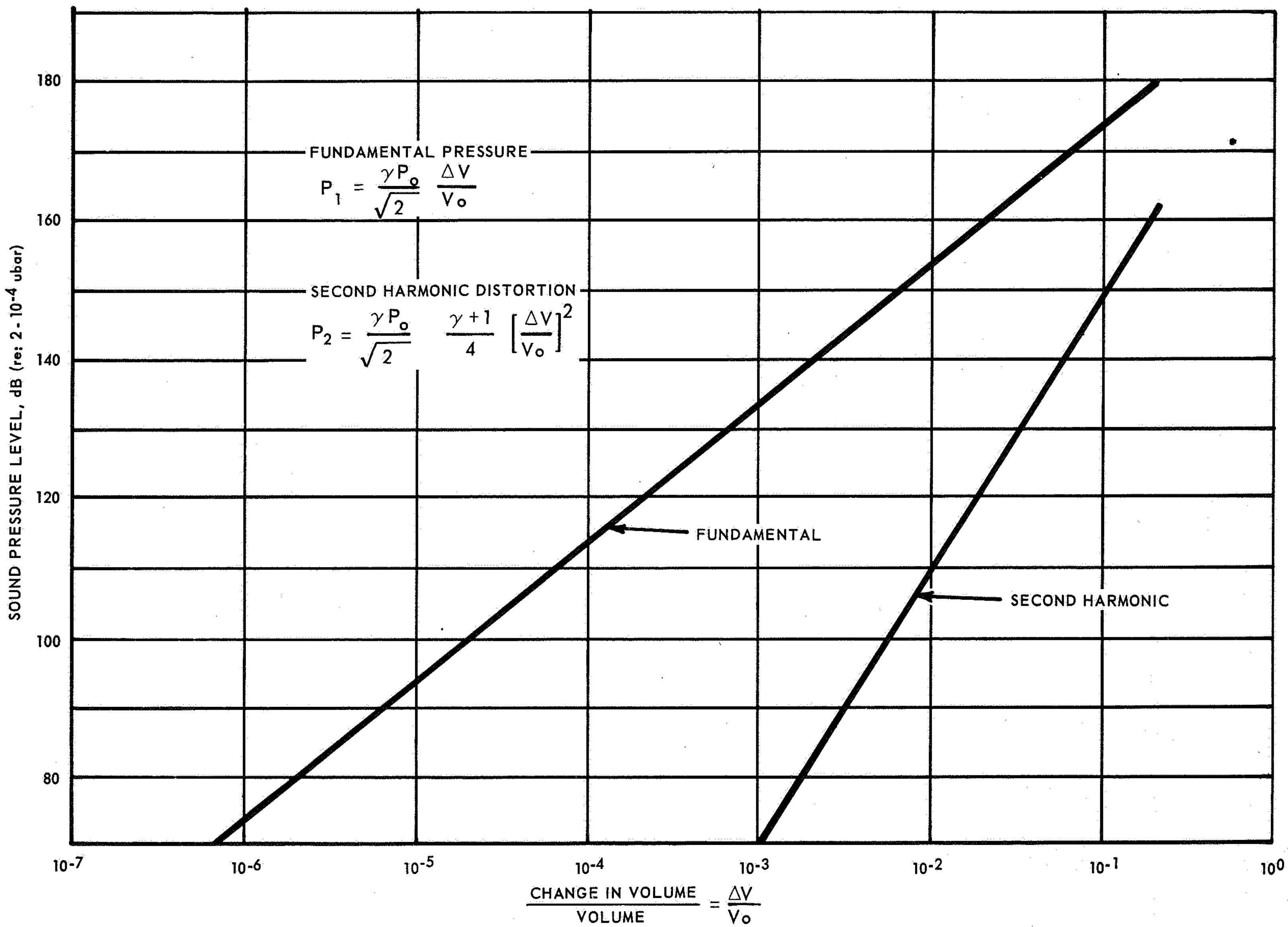


Figure 13. Pistonphone Pressure

chamber is 2.9 dB lower than at higher adiabatic frequencies. The question arises when working in the infrasonic frequency range concerning the sound pressure between the adiabatic and the isothermal case.

This problem has been studied by several investigators; the results of these studies are summarized in Figure 14 for the pistonphone provided to NASA for calibration of microphones at infrasonic frequencies. Ballantine considered the cooling effect of the walls in his publication of 1932 (Ref. 1). His results agree with Daniels' investigation in 1947 (Ref. 4) and those of Biagi and Cook in 1954 (Ref. 5). Daniels investigated the infinitely long cylinder, Biagi and Cook consider cylinders with finite length. Gerber recently provided an analysis for the infrasonic acoustic impedance of gas-filled chambers (Ref. 6). His investigation includes the effect of the driver impedance on the chamber.

The pistonphone provided to NASA has a low frequency limitation of 0.01 Hz. A correction of 0.7 dB is required at this lower limit as shown by Figure 13. Since the majority of calibrations utilizing the infrasonic pistonphone will be at frequencies from 0.1 Hz to 10 Hz, a heat conduction correction will not be required.

MICROPHONE RESPONSE TO PROGRESSIVE SHOCK WAVE

The response of microphones to a shock wave progressing across the diaphragm has been examined in order to establish the limitations of the transducer imposed by both finite diaphragm size and sensing element dynamics. This examination included

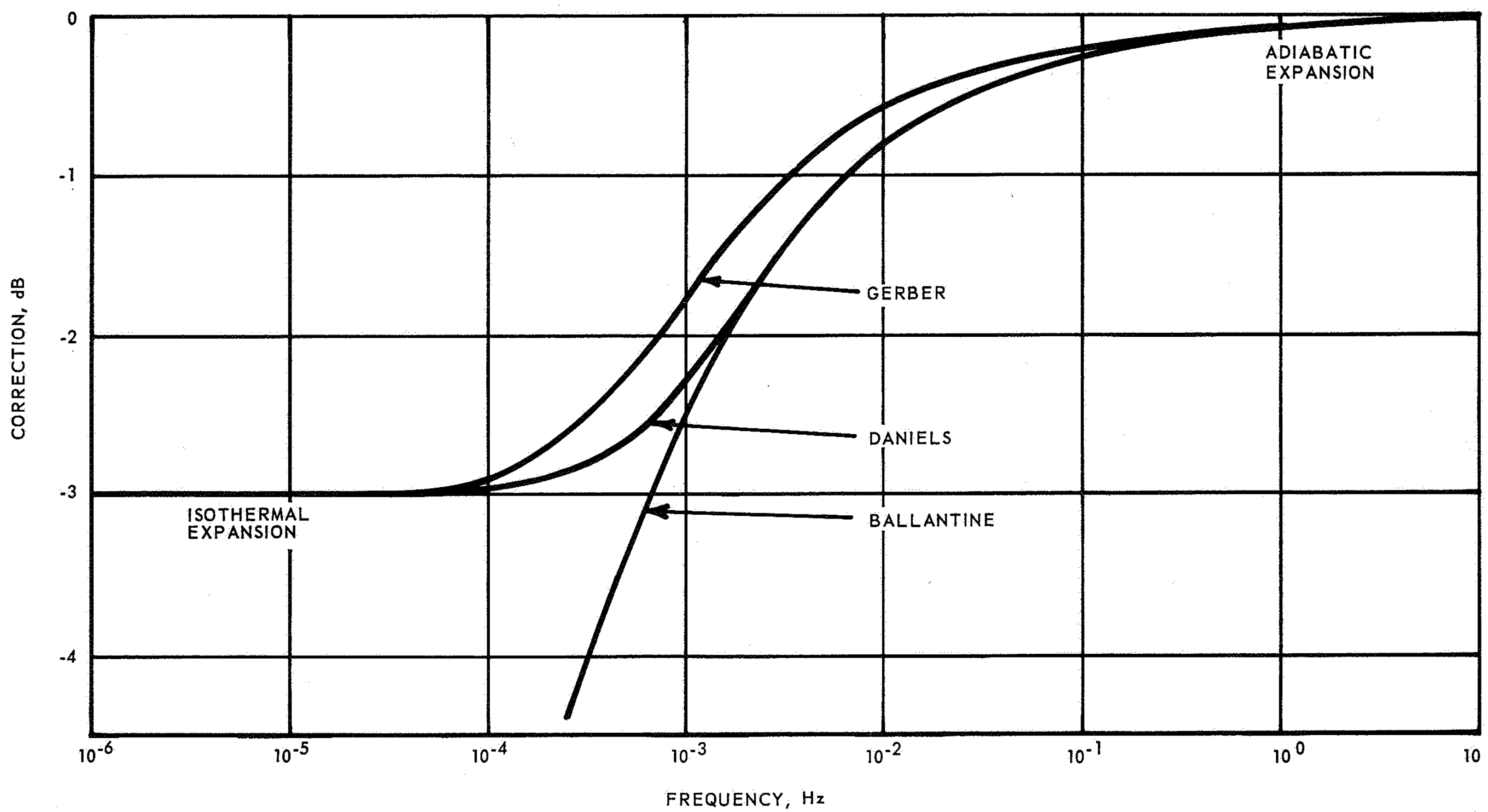


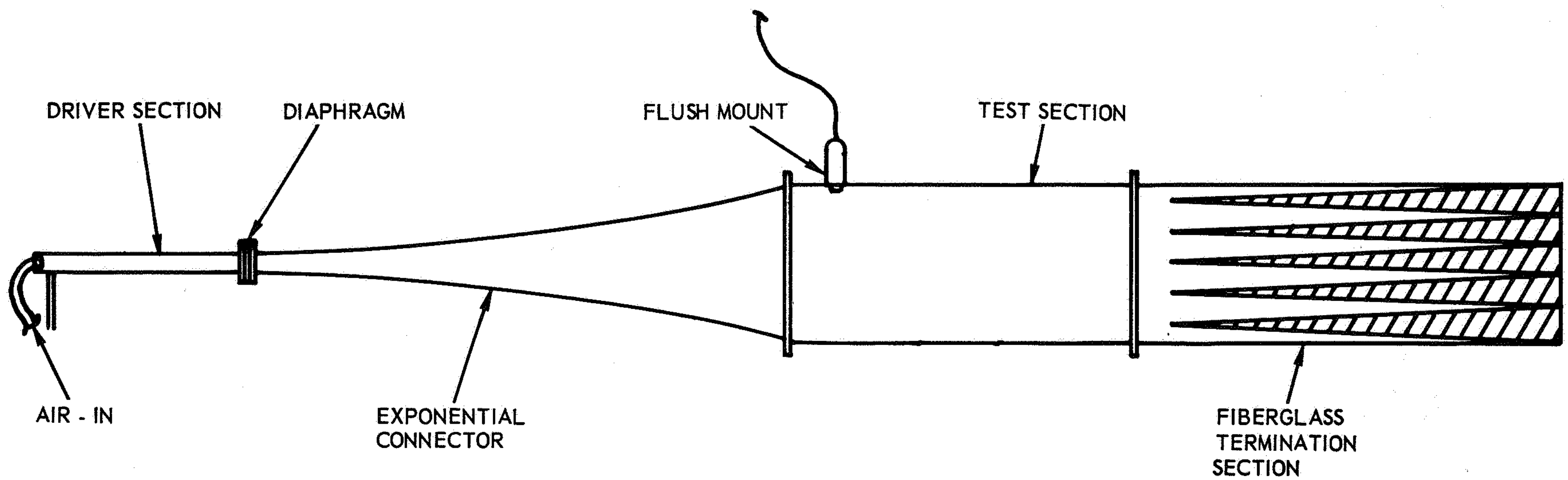
Figure 14. Infrasonic Pistonphone Heat Conduction Correction

experimentation and analysis with application of the expansion tube to generate weak progressive shock waves. The experimentation utilizing the expansion tube provides a direct illustration of the finite size effect and basic limitations in transducer rise time response contributed by the sensing element.

Shock Wave Expansion Tube

NASA's requirements involve the response of microphones to sonic boom phenomena with pressure amplitudes in the order of 140 dB or 3 pounds per square foot. It is not possible to obtain "jump pressures" or shock waves at these weak pressures with conventional shock tube techniques. However, the expansion tube, a combination of the shock tube and an acoustic horn, as shown in Figure 15, will permit the development of weak shock waves using compressed air and a bursting diaphragm as is done in the shock tube. The mechanics of this process are summarized in the characteristics diagram of Figure 16. This diagram illustrates the various waves and wave interactions which occur in the shock tube/horn combination. The location of a wave at a given time after diaphragm burst is depicted by the various characteristics in the x-t plane. The projection of wave motion on this plane is readily accomplished since predictable wave velocities are graphically represented by the slope of a line shown in the x-t diagram. Mathematical expressions for each characteristic of interest have been established by I. I. Glass (Ref.7) and G. B. Whitham (Ref.8). These expressions have been included in Figure 17. The notation used will be found in the List of Symbols, Appendix II.

The previously mentioned wave characteristics have been computed by Glass for the shock tube application over a broad range of shock strengths, P_{21}. Computations have been made covering



EXPANSION IN AREA FROM DRIVER TO TEST SECTION IS 1.4 SQUARE INCH TO 144 SQUARE INCH

Figure 15. Shock Wave Generation in a Variable Area Tube

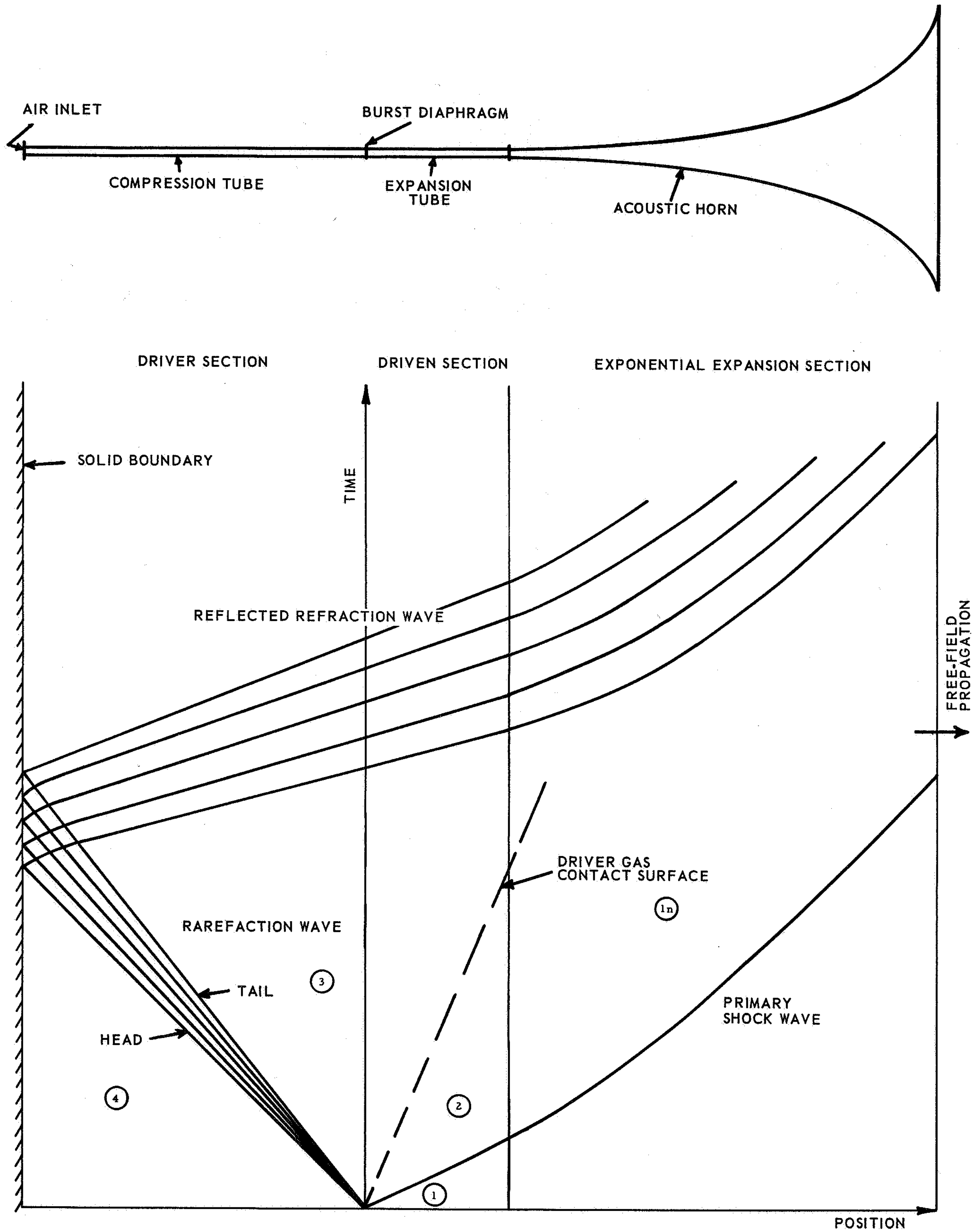


Figure 16. Characteristics in the Shock Wave Expansion Tube

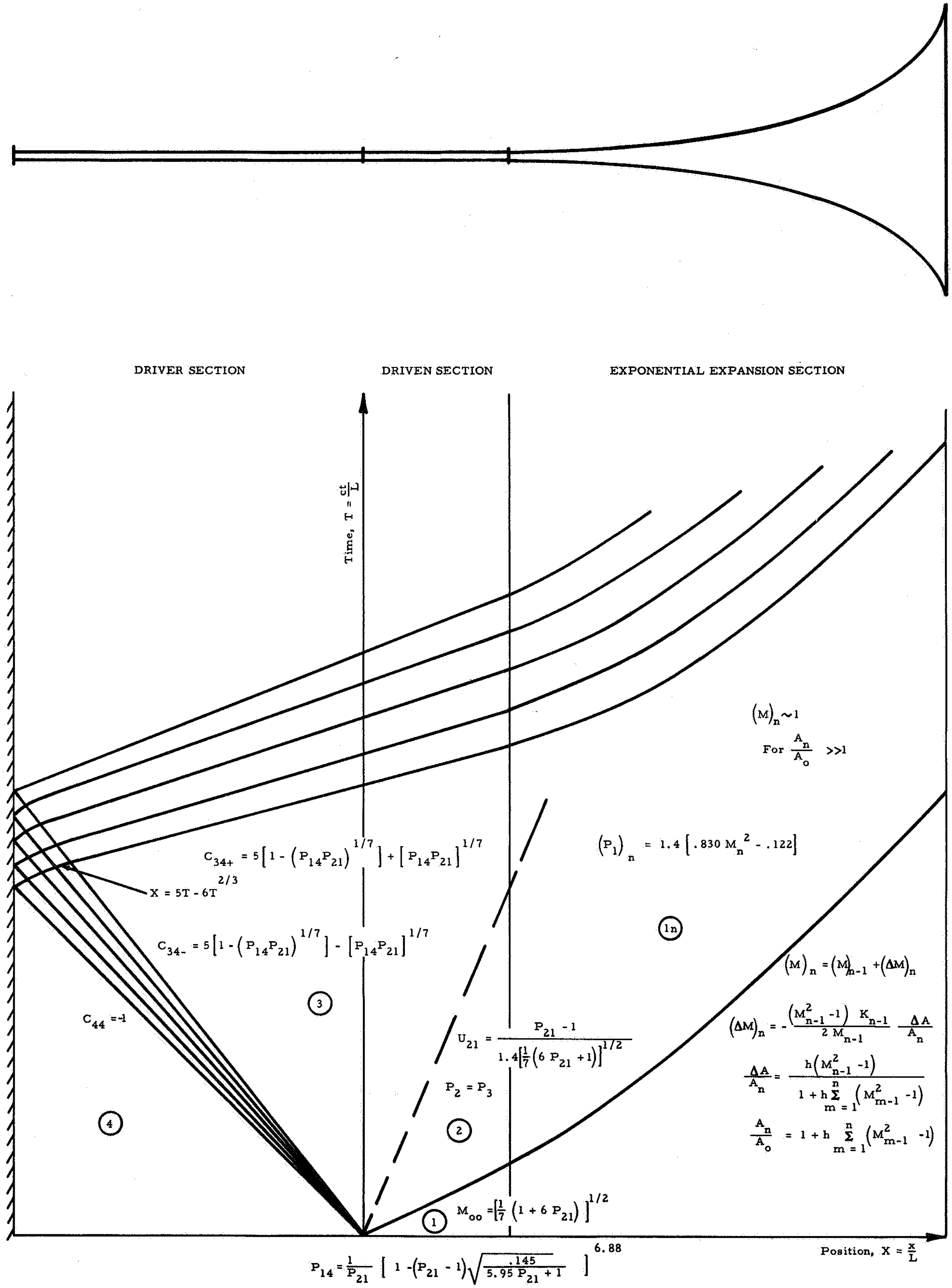


Figure 17. Characteristics in the Shock Wave Expansion Tube

the shock strength ratios, P_{12}, from 1 to 3 at considerably finer increments than were reported by Glass. These computations have been reported to NASA in an LTV Research Center, Western Division, Technical Report (Ref. 9).

The method of characteristics discussed by Whitham is required in the expansion region through the acoustic horn in order to predict the slope of these characteristics. Again, the pertinent analytical expressions are shown in Figure 16. Computations have been made for wave motion in this exapnsion region at incremental changes of acoustic horn area (Ref.9). The strength or pressure of the primary wave is predicted from the wave speed by

$$(P_1)_n = \gamma \left\{ \frac{2}{\gamma + 1} M_n^2 - \frac{\gamma - 1}{\gamma(\gamma + 1)} \right\}$$

Calculations were made of primary wave strength for incremental changes in expansion tube area and initial shock strength, P_{21}. These provide a basis for predetermining the jump pressure and the area expansion required to achieve a given weak shock pressure.

To investigate the response of microphones to progressive shock waves, a system consisting of a conventional shock tube and an exponential acoustic horn has been fabricated. The system, Figure 14, utilizes a horn having a 17-inch by 17-inch cross section at the microphone location and a length of 15 feet. The horn is designed with a lower cut-off frequency of 25 Hz. This horn is being driven by a shock tube having a 3-foot length of driver section with a diameter of 1.4 inches. Cellophane diaphragms isolate the driver section from the driven tube. These diaphragms are punctured by use of a mechanically driven plunger. Experiments have been performed to establish the validity of the previously mentioned analysis and to investigate the pressure-time history of the shock waves generated.

Figure 18 illustrates the weak shock wave signatures obtained at the microphone location. The illustration of Figure 18 shows the waveform for the basic configuration corresponding to the characteristic diagram of Figure 16. The amplitude of the primary wave, 3 pounds per square foot, is in reasonable agreement with that predicted from the preliminary wave velocity at the throat of the horn for the expansion ratio experienced.

Effective Rise Time of a Microphone to a Progressive Shock Wave

The electrostatic force applied to the microphone simulates a pressure transient impinging normal to the diaphragm. In actual use, the angle of incidence may vary from normal to that of a parallel wave excitation. This latter case, the parallel incidence of a progressive wave, was analyzed and compared to the response obtained in the shock/expansion tube to establish the microphone response to this wave directional extreme. Comparison of the rise time between this extreme and normal incidence, Figure 7, will provide a basis for establishing the microphone response in the variety of situations encountered in the field.

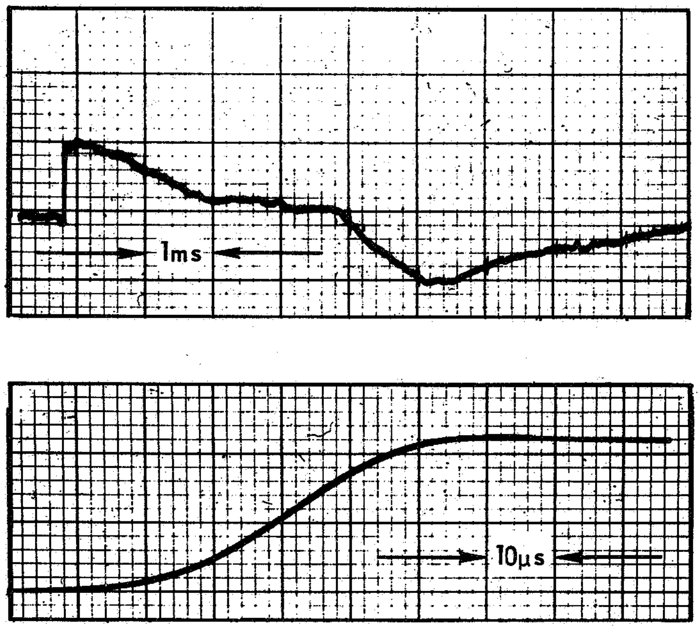
The wave equation for the membrane with the forcing function, F, describing the progressive shock wave such that

$$F = \left[\text{Pressure of "step wave"}\right]\left[\text{Area per unit time}\right]$$

which may be written

$$F = \begin{cases} 0 & t < 0 \\ P_o A_t & 0 \leq t \leq \dfrac{C}{2R} \\ 0 & t > \dfrac{C}{2R} \end{cases}$$

MICROPHONE RESPONSE TO A PROGRESSIVE SHOCK WAVE



RESPONSE OF 1" DIA.
MICROPHONE IN SHOCK/
EXPANSION TUBE

RISE - TIME RESPONSE

$$\sim \left[1 - e^{-\omega_o t} \right]$$

Figure 18. Microphone Response to a Progressive Shock Wave in the Shock/Expansion Tube

essentially defines the problem of interest. The area/time relation is best described in a rectangular coordinate system and by integrating the area covered by a line as it progresses across a circle of area A_o. This integration yields

$$\frac{A_t}{A_o} = \frac{1}{\pi} (\beta - 1) \sqrt{\beta(2 - \beta)} + \sin^{-1}(\beta - 1) + \frac{\pi}{2}$$

as is indicated in Figure 3 as the 0^{th} order approximation. In this expression $\beta = \frac{ct}{R}$ where c is the speed of sound, R is the diaphragm radius, and t is time.

Direct application of this function, as shown in Figure 3, yields the response of the microphone assuming it to respond as a very flexible membrane. This is not exactly its actual response. A more realistic evaluation of this situation evolves from the solution of the wave equation with the previously mentioned forcing function. The first order approximation is established by numerical integration of

$$\int_0^{A(t)} \frac{J_0 \left[k(r)\right] dA(t)}{A_o}$$

for the same forcing function as described for the 0^{th} order approximation. These approximations, shown in Figure 19, are compared to the experimental result for a microphone currently being used by NASA for sonic boom measurement. This result clearly shows the linear response anticipated—the rise time being dictated by a fundamental diaphragm resonance described by $J_0 k(r)$.*

* P. M. Morse, Vibration and Sound, McGraw-Hill Book Company, (1948) p. 195.

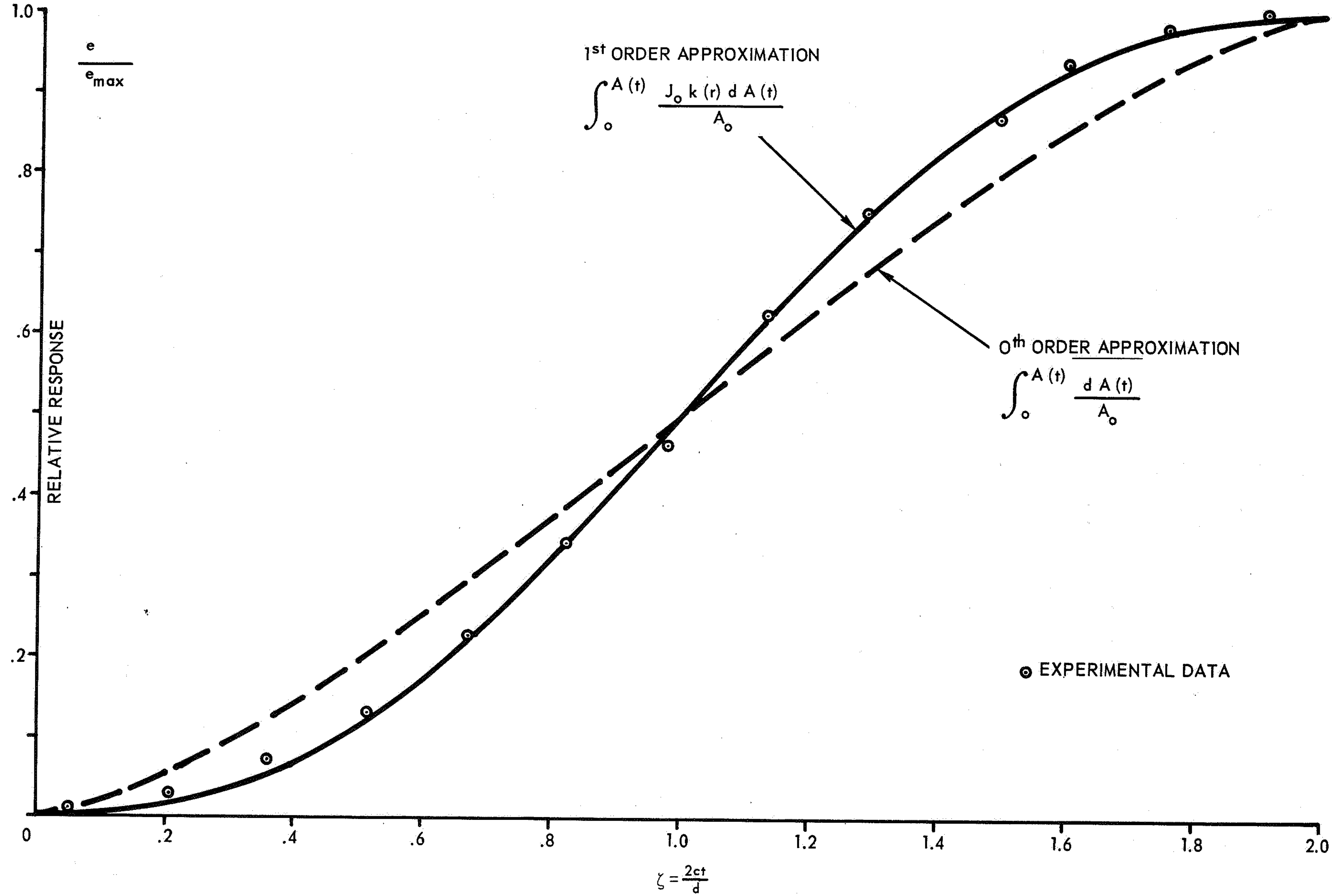


Figure 19. Microphone Response to Progressive Shock Wave

Further examination of the response of microphones to progressive waves was accomplished using a variety of commercially available transducers having active diameters from 1/4 inch to two inches. The results of the response of these transducers to progressive waves is shown in nondimensional form in the illustration of Figure 20. Again the 1-inch diameter microphone used by NASA appears to provide the response most nearly approaching a simple resonant system. However, it is apparent by comparing the rise time to 98 percent of maximum response that the smaller, but less sensitive transducers, provide a closer representation of the progressive wave pressure. It is interesting to note that when subjected to a progressive wave, none of the transducers examined exhibited a marked overshoot characteristic. This is undoubtedly due to the high internal damping inherent in these transducers near their resonant frequency.

RECOMMENDED CALIBRATION PROCEDURE

Table III indicates the steps suggested for a complete calibration of a microphone system for steady state and transient pressure measurement. The four steps essentially indicate the various calibrations which may be made with the tools available to NASA. These steps are summarized as follows:

Step 1 Initial calibration of the microphone system consists of checking the microphone sensitivity in the pistonphone (large volume for 94 dB SPL or small volume for 114 dB SPL). If only the microphone sensitivity is required, a measurement at two frequencies within the flat portion of the passband is adequate. However,

TABLE III CALIBRATION PROCEDURE

STEP	PROCEDURE DESCRIPTION	INFORMATION DERIVED
1A	Infrasonic Pistonphone Calibration (2 Frequencies in Passband)	Microphone Sensitivity at 94 or 114 dB SPL
1B	Infrasonic Pistonphone Frequency Response (0.01 Hz to 10 Hz)	Microphone Low Frequency Responce at 94 or 114 dB SPL
2A	ESA Frequency Response (0.1 to 20,000 Hz)	a) Electronics Low Frequency Response b) Microphone Pressure Response
2B	ESA Sensitivity Calibration (2 Frequencies in Passband)	Microphone Sensitivity at Levels to 128 dB SPL for Comparison with Step 1A
3	ESA Complex Waveform Response	N-Wave Response, Rise Time Characteristics, etc.
4	ESA Environmental Measurements a. High and Low Pressure b. High and Low Temperature c. High and Low Humidity (fixed or variable frequency)	Microphone Environmental Characteristics

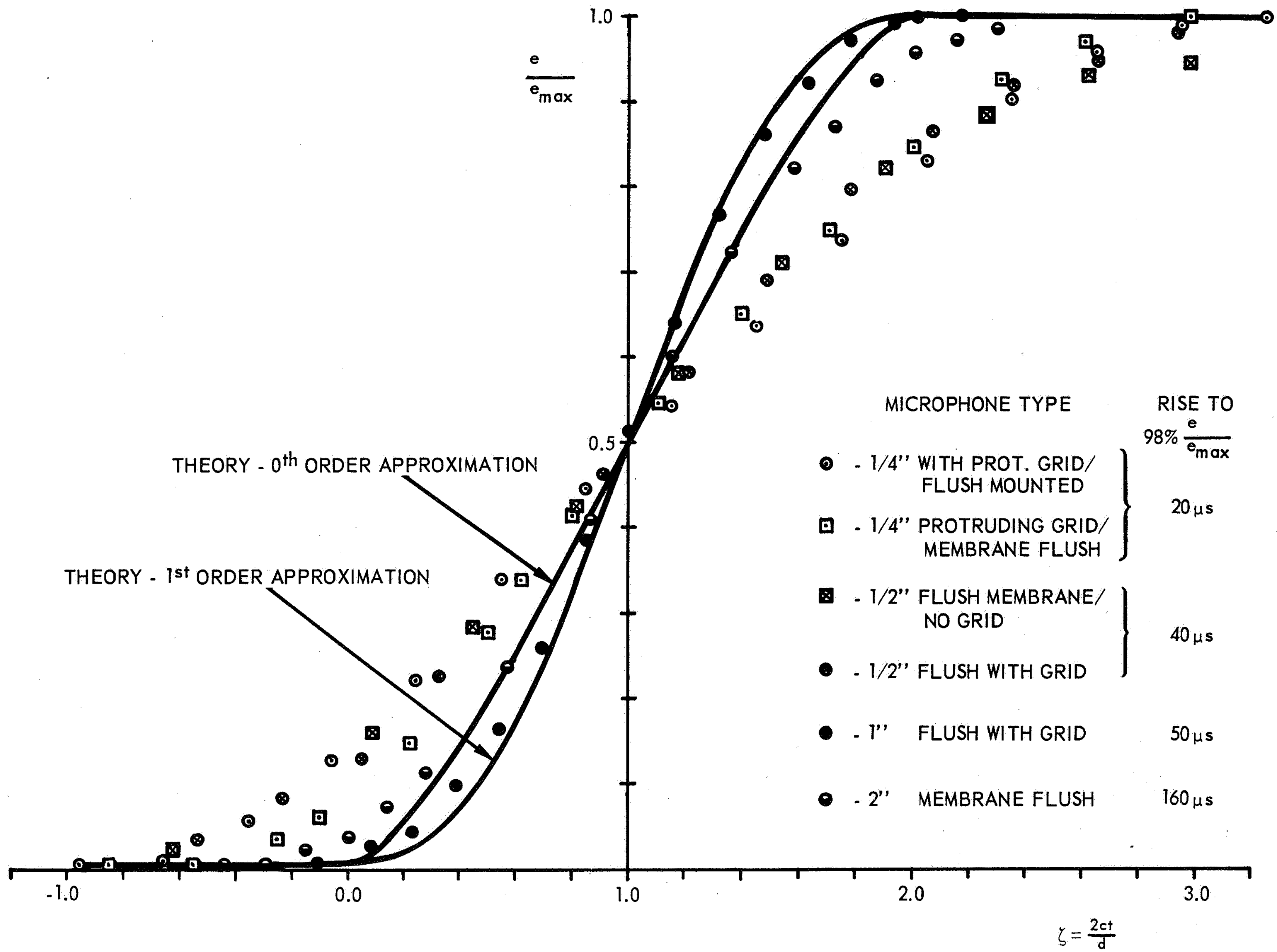


Figure 20. Microphone Response to Progressive Shock Wave

the complete low frequency response from 0.01 to 10 Hz is easily confirmed by use of the infrasonic pistonphone. The most useful instrument for measuring the output of the microphone system is an oscilloscope with response to dc.

Step 2 The microphone high frequency pressure response is easily obtained by use of the electrostatic actuator. The microphone may be mounted in the Micrometer Electrostatic Actuator provided, the spacing adjusted, and the ac/dc drive connected. A spacing of less than 5 mils (0.005 inch) should not be used except when low drive voltages are applied. With the system assembled, the frequency response from 0.1 (limited by the drive system electronics and the microphone system electronics) to 20,000 Hz may be determined. To measure the frequency response, an external signal generator is required. It is also possible to obtain a rather accurate measurement of the microphone sensitivity if a known spacing is utilized by referring to Figures 3 and 4.

Step 3 With the microphone installed in the electrostatic actuator device the response of the microphone to complex waveforms may easily be determined. An N-wave generator is built into the calibration equipment but other waveforms may be used from external generators.

Step 4 Environmental measurements on the microphones may easily be performed using the electrostatic actuators, both adjustable and fixed. The fixed actuators would normally be preferred if environmental extremes are encountered which may harm the mechanism of the micrometer.

CONCLUSIONS

Excellent agreement between the theoretically established electrostatic pressure and that obtained experimentally has been obtained. Electrostatically induced pressures have been generated with both sinusoidal and N-wave characteristics approaching an amplitude of one pound per square foot. Voltage breakdown caused by arcing at high potentials establishes an upper limit on achievable pressure amplitude. It appears from theoretical and experimental examination of voltage breakdown that it will not be possible to obtain pressure amplitudes much greater than one pound per square foot. The application of the electrostatic actuator system developed for NASA will provide both steady state and transient calibration of microphones currently being used.

The recommended calibration procedure is outlined in Table I as discussed previously. In terms of relative importance, the following sequence of calibration should be performed:

1. Microphone sensitivity and low frequency response characteristics as established by use of the infrasonic pistonphone in the frequency range from 0.01 to 10 Hz.

2. High frequency response characteristic which is established by use of the electrostatic actuator. The steady state frequency response of the microphone may be determined at frequencies to 20 kHz and sound pressures approaching 1 pound per square foot. An

N-wave transient may also be produced to establish the capability of the microphone system for the measurement of a sonic boom pressure-time history.

3. Linearity of microphone response at low frequencies may be established by use of the infrasonic pistonphone at sound levels of either 94 dB or 114 dB. Also, the electrostatic actuator system is capable of simulating steady state or transient pressures on the diaphragm of the microphone over a broad range of up to 1 pound per square foot.

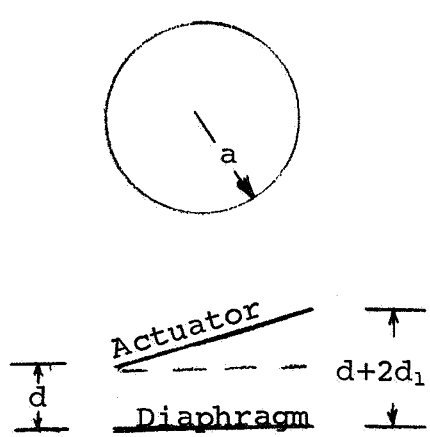
4. Detailed evaluation of the rise time, overshoot, and flat top response may be examined by use of the electrostatic actuator with both an N-wave or "step-function" transient.

APPENDIX I

Electrostatic Pressure for Actuator Nonparallel with Diaphragm

To obtain sound pressures in the order of 1 lb/ft^2, it is necessary to maintain actuator-to-diaphragm spacings of about 0.005 inches. At this close spacing with normal design tolerances, it is quite likely that the actuator will not be exactly parallel with the diaphragm. The examine the effect of nonparallelism on the electrostatic pressure, it has been assumed that the microphone sensitivity is uniform over the diaphragm. Also, edge effects have been neglected.

It is assumed that the following configuration exists between actuator and diaphragm.



Appendix I

For this geometric arrangement,

$$\bar{P} = \frac{C}{\pi a^2} \int_{-a}^{a} \frac{2\sqrt{a^2 - x^2}}{\left(d + \frac{d_1}{a} x\right)^2} dx$$

$$= \frac{2C}{d_1^2} \left\{ \left[1 - \frac{d_1^{\,2}}{(d+d_1)^2} \right]^{-\frac{1}{2}} - 1 \right\}$$

where $\bar{P}$ = average electrostatic pressure on diaphragm, lbs/ft^2

$C = 1.433 \times 10^{-10}\ KV^2$

and V = potential, volts

Hence, the expression for the electrostatic pressure is modified, since $1/d^2$ must be replaced by

$$\frac{2}{d_1^2} \quad 1 - \frac{d_1^{\,2}}{(d+d_1)^2} \quad ^{-\frac{1}{2}} \quad -1$$

It may be noted that for $d_1^{\,2} \ll (d + d_1)^2$

$$\bar{P} \asymp \frac{C}{(d+d_1)^2}$$

APPENDIX II
LIST OF SYMBOLS

A_n = area in the expansion region at station n

A_0 = cross sectional area of the shock tube and acoustic horn throat

c = speed of sound

c_{34+} = reflected rarefaction wave leading edge velocity

c_{34-} = rarefaction wave trailing edge velocity

c_{44} = rarefaction wave leading edge velocity

h = incremental change in expansion ratio selected for numerical integration

$$K_{n-1} = 2\left[\left(1 + \frac{2}{\gamma + 1}\ \frac{1 - \mu^2}{\mu}\right)\ (2\mu + 1 + M^{-2})\right]$$

where $\mu^2 = \dfrac{(\gamma - 1)M^2 + 2}{2\gamma M^2 - (\gamma - 1)}$

L = driver section length

M_n = Mach number in the expansion region at station n

M_{00} = driven section Mach number of primary shock wave

P_{14} = ratio of driven section pressure to driver section pressure prior to diaphragm burst

P_{21} = ratio of upstream to downstream pressure across the primary shock wave

$(P_1)_n$ = ratio of upstream to downstream pressure across the primary shock in the expansion region at station n

T = nondimensionalized time

t = time

U_{21} = ratio of driver gas velocity to ambient sound speed in region 1

X = nondimensionalized position

x = axial position in the shock tube/horn combination as measured from the diaphragm location

γ = ratio of specific heats

REFERENCES

1 Ballantine, Stuart: Technique of Microphone Calibration. J. Acoust. Soc. Am., vol. 3, no. 3, p. 319.

2 Dakin, T. W.; and Berg, T.: Theory of Gas Breakdown. Progress in Dielectrics, vol. 4, (London) 1962, pp. 151-98.

3 American Institute of Physics Handbook, Second Edition. McGraw-Hill Publishing Company, 1963, 5-151 and 5-152.

4 Daniels, Fred B.: Acoustical Impedance of Enclosures. J. Acoust. Soc. Am., vol. 4, 1947, p. 569.

5 Biagi, F.; and Cook, R. K.: Impedance of Enclosures. J. Acoust. Soc. Am., vol. 4, 1954, p. 506.

6 Gerber, H.: Acoustic Properties of Fluid-Filled Chambers at Infrasonic Frequencies in Absence of Convection. J. Acoust. Soc. Am., vol. 36, no. 8, Aug. 1964, p. 1427.

7 Glass, I. I.; and Hall, J. Gordon: Handbook of Supersonic Aerodynamics. Navord Report, 6:1488, Department of Defense.

8 Whitham, G. B.: On the Propagation of Shock Waves Through Regions of Non-Uniform Area or Flow. J. Fluid Mech., vol. 4, 1958, p. 337.

9 Siddon, T. E.; and Van Houten, J. J.: Characteristics of the Shock/Expansion Tube. Technical Report No. 0-71200/6TR-102, LTV Research Center, Western Division, 1966.

BIBLIOGRAPHY AND REFERENCES

General

[1]Beranek, L. L.: Acoustic Measurements. John Wiley & Sons, Inc. 1949.

[2]Fischer, F. A.: Fundamentals of Electroacoustics. Interscience Publishers, 1955.

[3]Hilliard, J. K.; and Fiala, W. T.: Condenser Microphones for Measurement of High Sound Pressures. J. Acoust. Soc. Am., vol. 29, no. 2, Feb. 1957, p. 254.

[4]Hunt, F. V.: Electroacoustics. John Wiley & Sons, Inc., 1954.

[5]Veneklasen, Paul S.: Instrumentation for the Measurement of Sound Pressure Level with the Western Electric 640AA Condenser Microphone. J. Acoust. Soc. Am., vol. 20, no.6, p. 807.

Diffraction Corrections

[6]Ballantine, Stuart: Effect of Diffraction Around the Microphone in Sound Measurements. Physical Review, vol. 32, 1928, p. 988.

[7]Baumzweiger, Benjamin: Graphical Determination of the Random Efficiency of Microphones. J. Acoust. Soc. Am., vol. 11 April 1940, p. 477.

[8]Riuin, A. N.; and Cherpak, V. A.: Method for Measuring and Calculating the Diffraction Coefficient of Microphones. Soviet Physics Acoustics, vol. 5, no. 3, p. 352.

Reciprocity Calibration

[9]Ballantine, Stuart: Technique of Microphone Calibration. J. Acoust. Soc. Am., vol. 3, no. 3, p. 319.

[10]Cook, Richard K.: Absolute Pressure Calibration of Microphones. J. Acoust. Soc. Am., vol. 12, no. 3, p. 415.

Bibliography and References

[11]Embleton, T. F. W.: Reciprocity Couplers Without Effects of Wave Motion to 10 kc/sec. J. Acoust. Soc. Am., vol. 35, no. 10, p. 1548.

[12]Embleton, T. F. W.; and Dagg, I. R.: Statistical Detection of Errors in Microphone Calibrations. J. Acoust. Soc. Am., vol. 35, no. 1, p. 108.

[13]Embleton, T. F. W.; and Dagg, I. R.: Accurate Coupler Pressure Calibration of Condenser Microphones at Middle Frequencies. J. Acoust. Soc. Am., vol. 32, p. 320.

[14]Koidan, Walter: Hydrogen Retention System for Pressure Calibration of Microphones in Small Couplers. J. Acoust. Soc. Am., vol. 35, no. 4, p. 614.

[15]Koidan, Walter: Method of Measurement of $\left|\frac{E'}{I'}\right|$ in the Reciprocity Calibration of Condenser Microphones. J. Acoust. Soc. Am., vol. 32, no. 5, p. 611.

[16]Rudnick and Stein: Reciprocity Free Field Calibration of Microphones to 100 kc in Air. J. Acoust. Soc. Am., vol. 20, no. 6, Nov. 1948, p. 818.

[17]Wiener, Francis M.: Phase Characteristics of Condenser Microphones. J. Acoust. Soc. Am., vol. 20, no. 5, p. 707.

[18]Wiener, Francis M.: Phase Distortion in Electroacoustic Systems. J. Acoust. Soc. Am., vol. 13, Oct. 1941, p. 115.

Secondary Calibration

[19]Beranek, L. L.; and Sleeper, H. P., Jr.: The Design and Construction of Anechoic Sound Chambers. J. Acous. Soc. Am., vol. 18, no. 1, p. 140.

[20]Hawley, M. S.: The Substitution Method of Measuring the Open Circuit Voltage Generated by a Microphone. J. Acoust. Soc. Am., vol. 21, no. 3, p. 183.

[21]Madella, G. B.: Substitution Method for Calibrating a Microphone. J. Acoust. Soc. Am., vol. 20, no. 4, p. 550.

Bibliography and References

Pistonphone

[22] Ballantine, Stuart: Technique of Microphone Calibration. J. Acoust. Soc. Am., vol. 3, no. 3, 1932, p. 319.

[23] Biagi, F.; and Cook, R. K.: Impedance of Cylindrical Enclosure. J. Acoust. Soc. Am., vol. 4, 1954, p. 506.

[24] Daniels, Fred B.: Acoustical Impedance of Enclosures. J. Acoust. Soc. Am., vol. 4, 1947, P. 560.

[25] Gerber, H.: Acoustic Properties of Fluid-Filled Chambers at Infrasonic Frequencies in Absence of Convection. J. Acoust. Soc. Am., vol. 36, no. 8, Aug. 1964, p. 1427.

[26] Merhaut, Josef; and Vlcek, Miroslav: Pistonphone and Differential Piston. J. Acoust. Soc. Am., vol. 30, no. 4, p. 263.

[27] Riety, P.: Le Thermophone Pistonphone Aerodynamique. Acoustica, vol. 6, no. 2, 1956, pp. 251-258.

Probe Tube Microphone Calibration

[28] Benson, R. W.: The Calibration and Use of Probe Tube Microphones. J. Acoust. Soc. Am., vol. 25, no. 1, Jan 1953, p. 128.

[29] Goff, K. W.; and Mercer, D.: Probe Microphone Analysis and Testing at High Temperatures and High Intensities. J. Acoust. Soc. Am., vol. 27, Nov. 1955, p. 1133.

System Noise - Electrical

[30] Becking, A. G.: Noise in Condenser Microphones. Acoustica, vol. 4, no. 1, 1954, p. 96.

[31] Perls, T. A.: Electrical Noise from Instrument Cables Subjected to Shock and Vibration. J. Appl. Phys., vol. 23, no. 6, June 1952, p. 674

Bibliography and References

Flush Mounted Microphone - Boundary Layers

[32] Corcos, G. M.: Resolution of Pressure in Turbulence. J. Acoust. Soc. Am., Feb. 1963.

[33] Fiala, W. T.; and Van Houten, J. J.: The Condenser Microphone for Boundary Layer Noise Measurement. Director of Defense Research and Engineering, Shock and Vibration Bulletin, no. 33, Part III Mar. 1964.

Reduced Pressure

[34] Chalupnik, J. D.; Rule, Eric; and Suellentrop, Fred J.: Pressure Response of Condenser Microphones at Low Ambient Pressures. J. Acoust. Soc. Am., vol. 33, no. 2, Feb. 1961, p. 177.

[35] Massa, Frank: Comments on Pressure Response of Condenser Microphones at Low Ambient Pressures. J. Acoust. Soc. Am., vol. 33, no. 6, p. 810.

Shock Tube Calibration

[36] Glass, I. I.; and Hall, J. Gordon: Handbook of Supersonic Aerodynamics. Navord Report, 6:1488, Department of Defense.

[37] Schweppe, J. L., et al: Methods for the Dynamic Calibration of Pressure Transducers. National Bureau of Standards Report No. 67, 1963.

[38] Ziemer, R. E.; and Lambert, R. F.: Shock Wave Transducer Calibration. J. Acoust. Soc. Am., vol. 34, 1962, p. 987.

[39] Whitham, G. B.: On the Propagation of Shock Waves Through Regions of Non-Uniform Area or Flow. J. Fluid Mech., vol. 4, 1958, p. 337.

[40] Siddon, T. E.; and Van Houten, J. J.: Characteristics of the Shock/Expansion Tube. Technical Report No. 0-71200/6TR-102, LTV Research Center, Western Division, 1966.

Bibliography and References

Vibration

[41] Rule, E.; Suellentrop, F. J.; and Perls, T. A.: Vibration Sensitivity of Condenser Microphones. J. Acoust. Soc. Am., vol. 32, no. 7, 1960, p. 821.

Nuclear Radiation

[42] Manhart, J. K.: Evaluation of Microphone Performance in a Field of Intense Nuclear Radiation. Engineering Paper No. 1356, Douglas Aircraft Company, 1962.

Voltage Breakdown

[43] Dakin, T. W.; and Berg, T.: Theory of Gas Breakdown. Progress in Dielectrics, vol. 4, (London) 1962, pp. 151-98.

[44] American Institute of Physics Handbook, Second Edition, McGraw-Hill Publishing Company, 1963, 5-151 and 5-152.

NASA-Langley, 1968 — 14 CR-1075

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546