NASA TM-83227

NASA Technical Memorandum 83227 82N-17476

NASA-TM-83227 19820009602

ACOUSTIC GROUND IMPEDANCE METER

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DECEMBER 1981

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Space Administration

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SUMMARY

A compact, portable instrument has been developed to measure the acoustic impedance of the ground, or other surfaces, by direct pressure-volume velocity measurement. A Helmholz resonator, constructed of heavy-walled stainless steel but open at the bottom, is positioned over the surface having the unknown impedance. The resonator chamber measures 0.229 m in diameter by 0.152 m high. The sound source, a cam-driven piston of known stroke and thus known volume velocity, is located in the neck of the resonator. The cam speed is variable up to a maximum 3600 rpm. The sound pressure at the test surface is measured by means of a microphone flush-mounted in the wall of the chamber. An optical monitor of the piston displacement permits measurement of the phase angle between the volume velocity and the sound pressure, from which the real and imaginary parts of the impedance can be evaluated. Measurements using a 5-lobed cam can be made up to 300 Hz; these can be extended by means of a 15-lobed cam, presently under fabrication, to nearly 1000 Hz. Detailed design criteria and results on a soil sample are presented.

INTRODUCTION

The earth's ground surface has become the subject of increasing acoustical investigation because of its importance in aircraft noise prediction and measurement. The past several years have witnessed a proliferation of methods to measure the acoustic impedance of the ground as a result of various unsatisfactory features of the preceding methods. These methods are organized into the three basic categories listed in table I.

TABLE I. METHODS OF MEASUREMENT

1. Impedance tube (and waveguide methods in general)
2. Free field
3. Direct sound pressure-volume velocity measurement

The impedance tube (ref. 1) has long been the workhorse of acoustic impedance measurement, but in field applications it suffers a major disadvantage: It requires an accurate measurement of the distance from the first interference minimum to an ill-defined test surface. Furthermore, because each frequency of operation requires several sound pressure measurements, the method is time-consuming and often introduces modifications of the test surface during the course of the measurement.

Free field methods include a multitude of variations based on the type of excitation (refs. 1, 2, 3), angle of incidence (refs. 4, 5, 6, 7, 8, 9, 10), number of microphones (refs. 11, 12), and parameter-evaluation technique (refs. 13, 14). All enjoy the advantage that the measurement is performed on the ground in its natural condition, unencumbered by an enclosure, but this is a mixed blessing, for free field acoustical propagation is subject to environmental disturbances, such as wind, turbulence, thermal gradients, and background noise. Several of these methods utilize wave interference and suffer the same disadvantages as the impedance tube; many are mathematically intricate, relying on the validity of questionable assumptions, e.g., the planarity or sphericity of the wave front.

The major difficulty with a direct pressure-volume velocity method lies in the measurement of volume velocity. The instrument described here defines the volume velocity by the known stroke of a cam-driven piston and avoids the pitfalls of direct measurement (refs. 15, 16).

PRINCIPLE OF MEASUREMENT

The principle of the measurement is illustrated in figure 1. A Helmholz resonator, constructed of heavy-walled stainless steel, but open at the bottom, is positioned over the surface having the unknown impedance. The vibrating piston is located in the neck of the resonator. A variable speed motor controls the cam speed and thus the sonic frequency. The sound pressure at the test surface is measured by means of a microphone flush-mounted in the wall of the chamber. Since the amplitude of the volume velocity U is known from the given piston stroke, the real and imaginary parts of the unknown impedance Z_s can be obtained from measurements of both the amplitude of the pressure p_o and the phase of p_o relative to U. The volume velocity source is mounted on a tripod and connected to the chamber through a flexible hose to suppress transmission through the walls.

The size of the chamber is chosen to be 0.229 m (9 in.) in diameter by 0.153 m (6 in.) in height--a size which fulfills two conflicting requirements: (1) The chamber is large enough to fit comfortably over coarse surfaces and moderately tall grass, but (2) all linear dimensions are much smaller than the acoustical half-wavelength at the maximum operating frequency and thus permit operation in the Helmholz resonator mode. A 0.0508 m (2 in.)-deep knife-edge seals the chamber.

An equivalent circuit of the resonator is shown in figure 2. The piston is represented by a stiff volume velocity source U. In the upper circuit the test surface is replaced by a 0.0191 m (3/4 in.)-thick stainless steel calibration plate, assumed to have infinite impedance. The microphone measures the pressure across the chamber alone. When the calibration plate is replaced by the test surface, as shown in the lower circuit, the microphone measures the pressure across the chamber and test surface admittances in parallel. The difference between the two measured admittances is the admittance of the test surface alone.

THE VOLUME VELOCITY SOURCE

Figure 3 shows details of the volume velocity source. This particular design contains three favorable features: (1) Push-pull action to prevent chatter at high frequencies, (2) cam-follower bearings to avoid sliding parts, and (3) symmetrical piston arrangement to prevent unbalanced loading of the cam. The cam rotates on the camshaft driven by a synchronous motor at selected speeds up to 3600 rpm. The cam follower bearings press against the cam with a slight preload, rotate with the cam, and force the pistons into reciprocating motion. Such push-pull action is possible only if the cam has an odd number of lobes, as can be seen from figure 3. The initial design utilized a 5-lobed cam, operating at frequencies up to 300 Hz, but a later design will incorporate a 15-lobed cam to attain operating frequencies up to 900 Hz. The lower piston serves as the sound generator; the upper piston interrupts an LED beam and permits measurement of the phase angle between the piston stroke (volume velocity) and the sound pressure at the microphone.

TABLE II. DESIGN CRITERIA

(1) Cam		
Number of lobes N	5	15
Maximum operating frequency f_{max}	300 Hz	900 Hz
Radius R	0.0254 m	0.0254 m
(2) Piston		
Stroke S	2.03×10^{-3} m	5.08×10^{-4} m
	0.08 in.	0.02 in.
Predicted sound pressure level P_c	107.3 dB	95.3 dB
(3) Cam follower bearing		
Radius r	9.53×10^{-3} m	9.53×10^{-3} m
	0.375 in.	0.375 in.
Maximum speed ω_B	9600 rpm	9600 rpm
Mean radial load @ max. speed F_R	77.8 N	174.8 N
	17.5 lb	39.3 lb
Expected life L	210 000 hr	8300 hr
(4) Motor		
Maximum torque τ	1.55×10^{-2} N·m	3.49×10^{-2} N·m
	2.2 in.-oz	4.9 in.-oz
Rated torque	4.94×10^{-2} N·m	4.94×10^{-2} N·m
	7 in.-oz	7 in.-oz
(5) Resonator geometry		
Neck area A_N	2.85×10^{-2} m^2	2.85×10^{-4} m^2
	0.442 in.^{2}	0.442 in.^{2}
Chamber volume V_c	6.255×10^{-3} m^3	6.255×10^{-3} m^3
	381.7 in.^{3}	381.7 in.^{3}

Table II is a summary of design criteria for the volume velocity source. For a given chamber size and neck bore, the piston stroke determines the sound pressure in the chamber, but too large a stroke will overload the cam follower bearings. The values listed here represent a design compromise. The sinusoidal contour about the cam periphery determines the maximum allowable cam follower radius, its maximum operating speed, its radial load due to the inertia of the piston assembly, and its expected life. The motor is chosen to accommodate the expected torque on the 15-lobed cam. These design values are based on the formulas summarized in the appendix.

RESULTS

The measured microphone response with the resonator attached to the calibration plate appears in figure 4. The gradual rise in sound pressure amplitude with frequency is consistent with the response predicted from the upper equivalent circuit of figure 2. The small broad peak appearing at low frequencies is attributable to a resonance of the piston assembly. The solid line is the best fit to the data taking this effect into account.

Figure 5 shows the real and imaginary parts of the impedance of a small sample of sod, 0.3556 x 0.3556 x 0.1524 m (14 x 14 x 6 in.), taken from a field at Langley Research Center and measured in the laboratory. The data appear to fit the empirical power law relations of Delaney and Bazley (ref. 17), corresponding to a specific flow resistance $\sigma = 75$ cgs units, except at the lowest frequencies, where the deviation may be real or attributable to the small size of the sample. The total time for the measurement at these 47 frequencies, including the setup time of the instrument, was less than an hour.

CONCLUSIONS

An acoustic ground impedance meter has been developed and tested on a sod sample. The instrument offers the following advantages:

1. Compactness and portability. It can be set up at any desired test site, irrespective of landscape features, weather, or other environmental conditions.

2. Speed of operation. This makes it well suited for use in conjunction with other acoustic measurements, e.g., aircraft noise measurements.

3. Simplicity. At each frequency the acoustic admittance is evaluated from measurement of one sound pressure and one phase angle for the test surface, and similar data for the calibration plate.

APPENDIX

FORMULAS FOR DETERMINING DESIGN PARAMETERS OF THE RESONATOR

Quantitative relationships for the design results listed in table II are presented here.

1. The maximum operating frequency is given by

$$f_{max} = N\ \omega_M/60,$$

where N is the number of lobes on the cam and ω_M the rated motor speed in rpm. Since $\omega_M = 3600$ rpm, $f_{max} = 300$ Hz for $N = 5$ and 900 Hz for $N = 15$.

2. The sound pressure P_c in the chamber is related to the piston stroke S as follows:

$$P_c = \frac{S\ A_N\ \rho_o\ c_o^2}{2\sqrt{2}\ V_c},$$

where V_c is the volume of the chamber, A_N the area of the neck, ρ_o the air density, and c_o the speed of sound in air. For the 5-lobed cam

$$P_c = \frac{2.03 \times 10^{-3} \times 2.85 \times 10^{-4} \times 1.205 \times 343^2}{2\sqrt{2} \times 6.255 \times 10^{-3}} = 4.64 \text{ Pa (107.3 dB)},*$$

and for the 15-lobed cam

$$P_c = \frac{5.08 \times 10^{-4} \times 2.85 \times 10^{-4} \times 1.205 \times 343^2}{2\sqrt{2} \times 6.255 \times 10^{-3}} = 1.16 \text{ Pa (95.3 dB)}.$$

It is necessary to reduce the stroke on the 15-lobed cam in order to fulfill the remaining design criteria.

3. The minimum radius of curvature about the cam periphery must exceed the radius of the cam follower. Mathematically this condition is expressed as follows:

$$2R^2/SN^2 > r,$$

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*Re: 2×10^{-5} Pa.

where R is the cam radius and r the cam follower radius. Since $r = 0.009525$ m (0.375 in.) a cam radius of 0.0254 m (1 in.) fulfills this requirement for both cams.

The mean radial load on each bearing is

$$F_R = \frac{MS\ (2\pi\ f_{max})^2}{2\pi},$$

where M is the mass of the piston-cam follower assembly. For the 5-lobed cam

$$F_R = \frac{67.60 \times 10^{-3} \times 2.03 \times 10^{-3}\ (2\pi \times 300)^2}{2\pi} = 77.6\ \text{N}\ (17.5\ \text{lb})$$

and for the 15-lobed cam

$$F_R = \frac{67.60 \times 10^{-3} \times 5.08 \times 10^{-4}\ (2\pi \times 900)^2}{2\pi} = 174.8\ \text{N}\ (39.3\ \text{lb}).$$

While operating at a maximum bearing speed

$$\omega_B = (R/r)\ \omega_M = (0.0254/0.009525) \times 3600 = 9600\ \text{rpm},$$

the life L of a cam follower bearing under the above loads is expected to be (ref. 18)

$$L = 7.4 \times 10^{16}/F_R^{\ 4}\ \omega_B$$

$$= 7.4 \times 10^{16}/(77.6^4 \times 9600) = 210\ 000\ \text{hr for the 5-lobed cam}$$

$$= 7.4 \times 10^{16}/(174.8^4 \times 9600) = 8300\ \text{hr for the 15-lobed cam.}$$

4. The maximum torque on the camshaft, due to inertial loading must not exceed the rated load of the motor:

$$\tau = \tfrac{1}{2} R\mu MS (2\pi\ f_{max})^2,$$

where μ is the coefficient of friction of the cam follower bearing (estimated at 0.0025, ref. 18). For the 5-lobed cam

$$\tau = \tfrac{1}{2} \times 0.0254 \times 0.0025 \times 67.6 \times 10^{-3} \times 2.03 \times 10^{-3} \times (2\pi \times 300)^2$$

$$= 1.55 \times 10^{-2}\ \mathrm{N \cdot m}$$

for the 15-lobed cam

$$\tau = \tfrac{1}{2} \times 0.0254 \times 0.0025 \times 67.6 \times 10^{-3} \times 5.08 \times 10^{-4} \times (2\pi \times 900)^2$$

$$= 3.49 \times 10^{-2}\ \mathrm{N \cdot m}.$$

REFERENCES

1. Dickinson, P. D. and Doak, P. F.: "Measurement of the Normal Acoustic Impedance of Ground Surfaces," J. Sound Vib., Vol. 13, pp. 309-322 (1970).

2. Noise Control Laboratory, The Pennsylvania State University: unpublished results, cited in reference 11.

3. Kintsl, Zdenek: "Investigation of the Sound Absorption of Wall Sections by a Pulse Technique," Sov. Phys. Acoust., Vol. 21, No. 1, pp. 30, 32 (1975).

4. Piercy, J. E., Embleton, T. F. W., and Olson, N.: "Impedance of Soft Ground and Its Effects on Practical Measurements," J. Acoust. Soc. Am., Vol. 54, p. 341(A) (1973).

5. Davies, J. D. and Mulholland, K. A.: "An Impulse Method of Measuring Normal Impedance at Oblique Incidence," J. Sound Vib., Vol. 67, No. 1, pp. 135-149 (1979).

6. Lantern, Sean K.: "A Method for Determining Acoustic Impedance of Ground Surfaces," Master's Thesis, Department of Mechanical and Industrial Engineering, University of Utah, June 1971.

7. Ingard, V. and Bolt, R. H.: "A Free Field Method of Measuring the Absorption Coefficient of Acoustic Materials," J. Acoust. Soc. Am., Vol. 23, pp. 509-516 (1951).

8. Ando, Y.: "The Interference Pattern Method of Measuring the Complex Reflection Coefficient of Acoustic Materials at Oblique Incidence," Paper E 33, 6th International Congress on Acoustics (1968).

9. Sides, D. J. and Mulholland, K. A.: "The Variation of Normal Layer Impedance with Angle of Incidence," J. Sound Vib., Vol. 14, pp. 139-142 (1971).

10. Myles, Mark: "A Technique for the Measurement of the Complex Acoustic Impedance of Flat Ground Surfaces," Bolt, Beranek, and Newman Report No. 3989, May 1979.

11. Glaretas, C.: "A New Method for Measuring the Acoustic Impedance of the Ground." Ph.D. Thesis, The Noise Control Laboratory, The Pennsylvania State University, May 1981.

12. Yamada Ichiro: "Cross Spectral Method for the Estimation of Ground Reflection Characteristics and Free-Field Spectrum of Noise," J. Acoust. Soc. Jpn (e), Vol. 1, No. 4, pp. 249-259 (1980).

13. Thomasson, S. I.: "Sound Propagation Above a Layer with a Large Refraction Index," J. Acoust. Soc. Am., Vol. 61, No. 3, pp. 659-674 (March 1977).

14. Bass, H. E. and Bolen, L. N.: "Propagation of Sound Through the Atmosphere," Technical Report U.S.A.R.O. DAAG-29-76-G-0258. 19 June 1978,

15. Pratt, R. L., Elliot, S. J., and Bowsher, J. M.: "The Measurement of the Acoustic Impedance of Brass Instruments," Acustica 38, 236-246, 1977.

16. Salava, T.: "An Electroacoustic Transducer for Measuring Acoustic Impedance," J. Audio Eng. Soc. 18, 384-390, 1970.

17. Delaney, M. E. and Bazley, E. N.: "Acoustical Properties of Fibrous Absorbent Materials," Applied Acoustics 3, 105-116, 1970.

18. Delco New Departure - Hyatt Catalog 2C-110, Revision B, 1967.

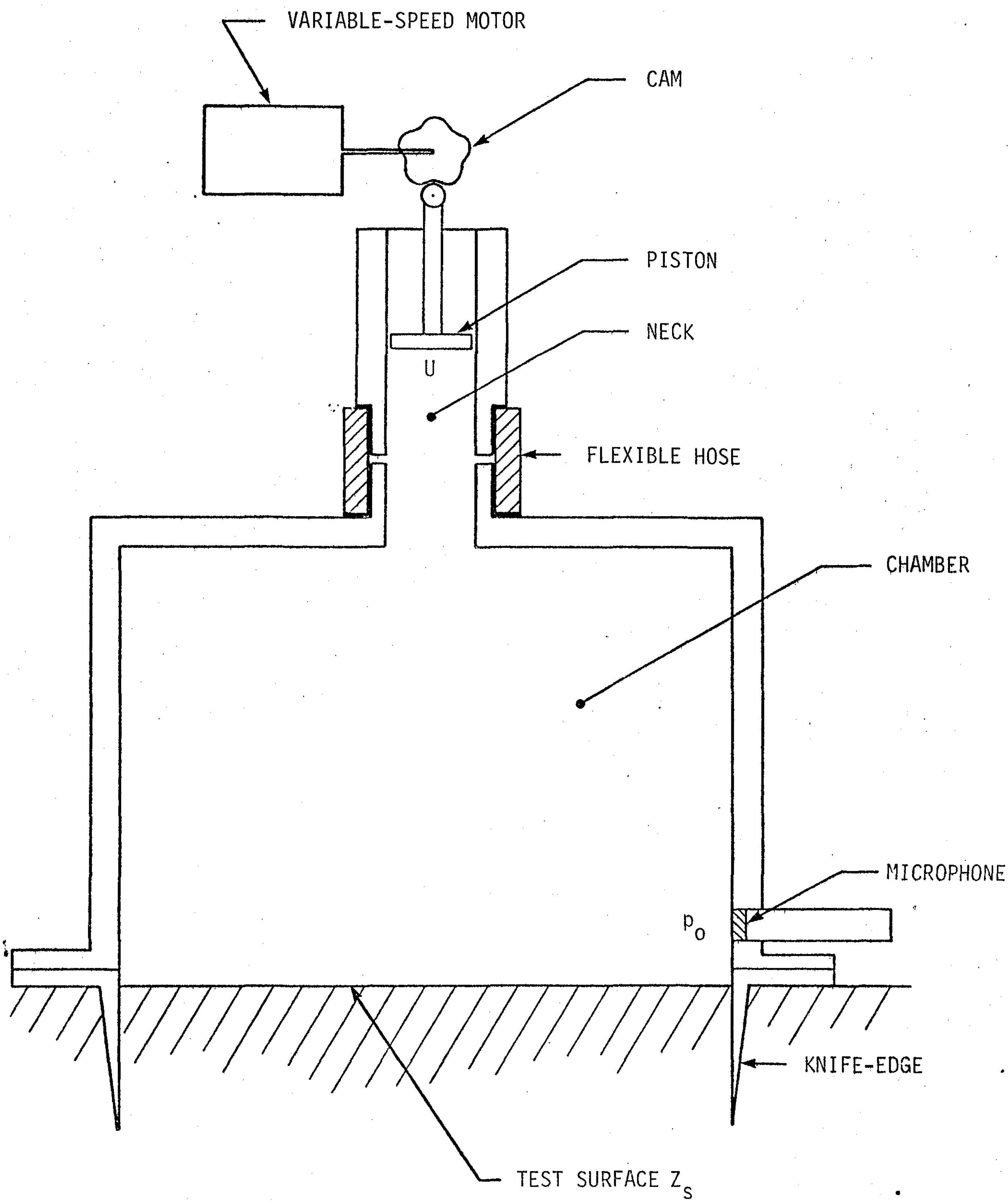

Figure 1.- Principle of measurement.

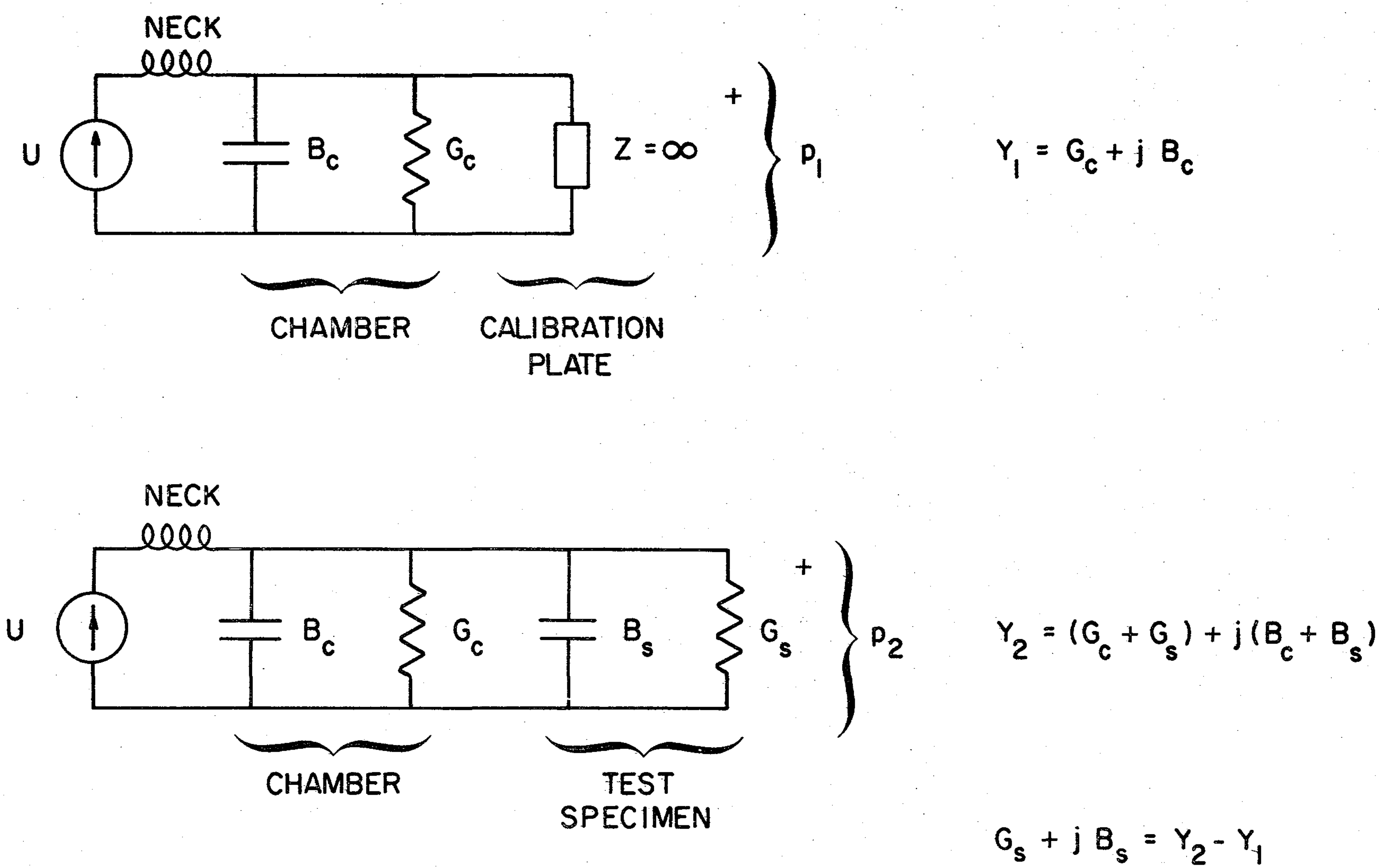

Figure 2.- Equivalent circuit of resonator attached to the calibration plate (upper) and test surface (lower).

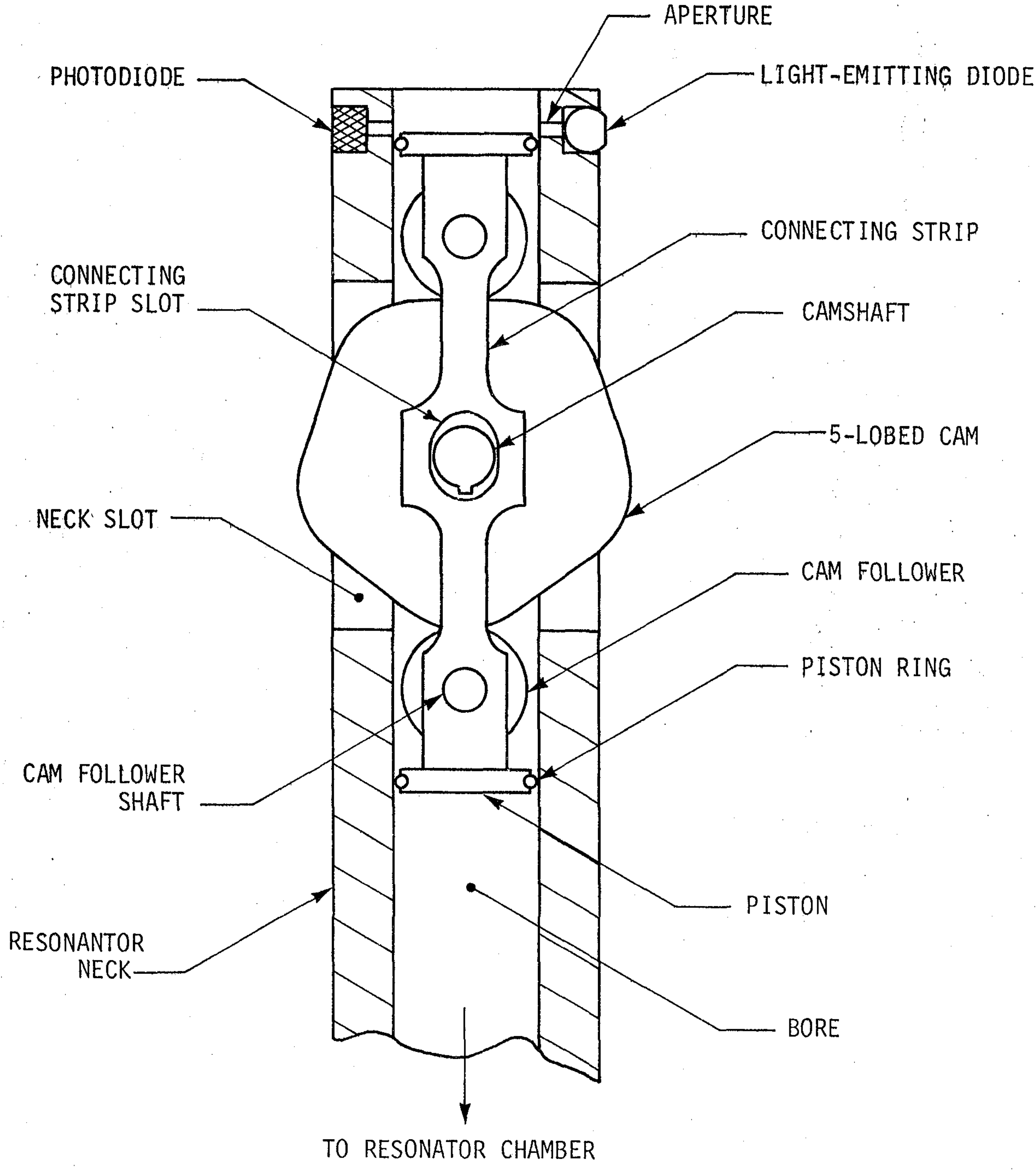

Figure 3. The volume velocity source.

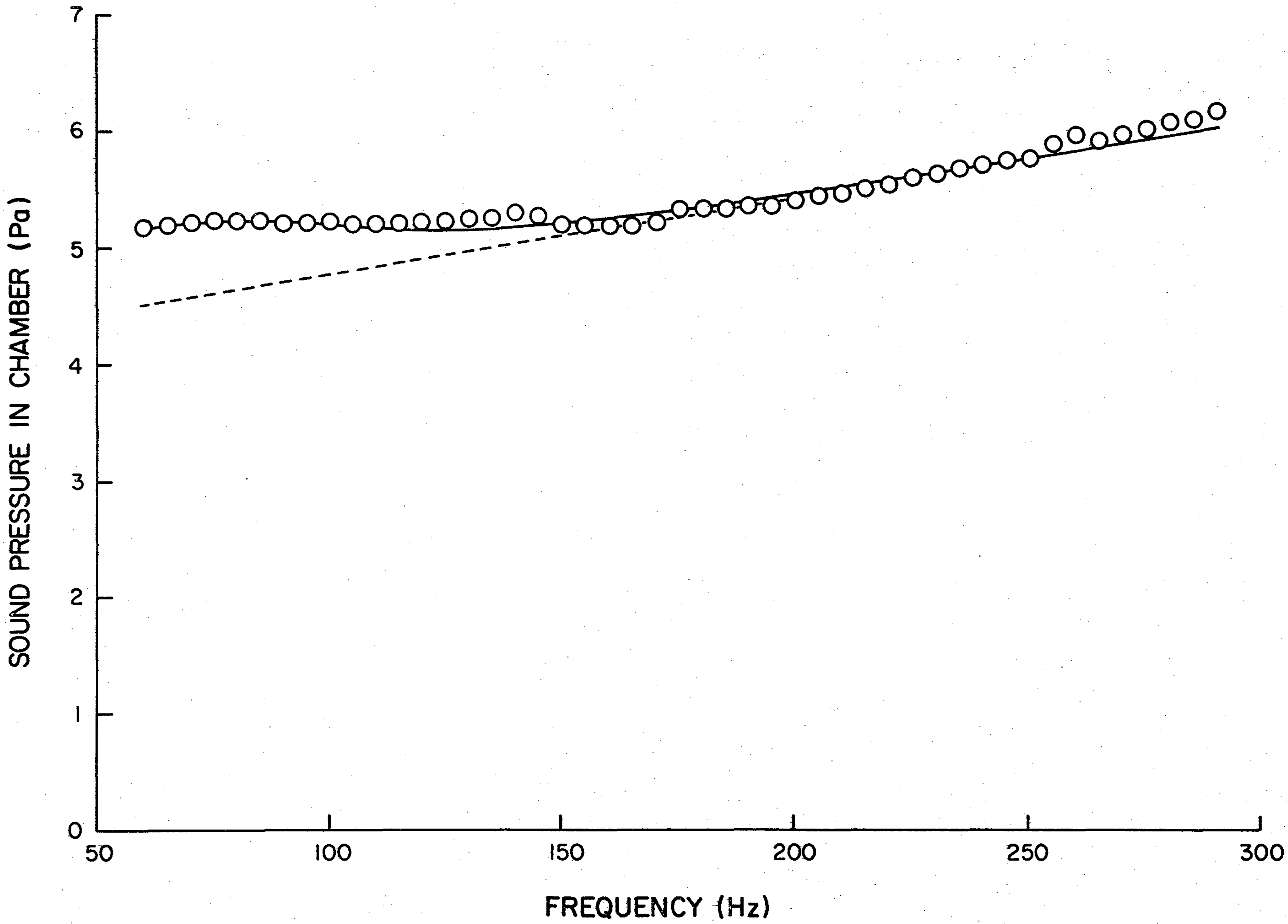

Figure 4.- Microphone response with the resonator attached to the calibration plate: Circles: Experimental. Lines: Best-fit including piston resonance (solid) and excluding piston resonance (dashed).

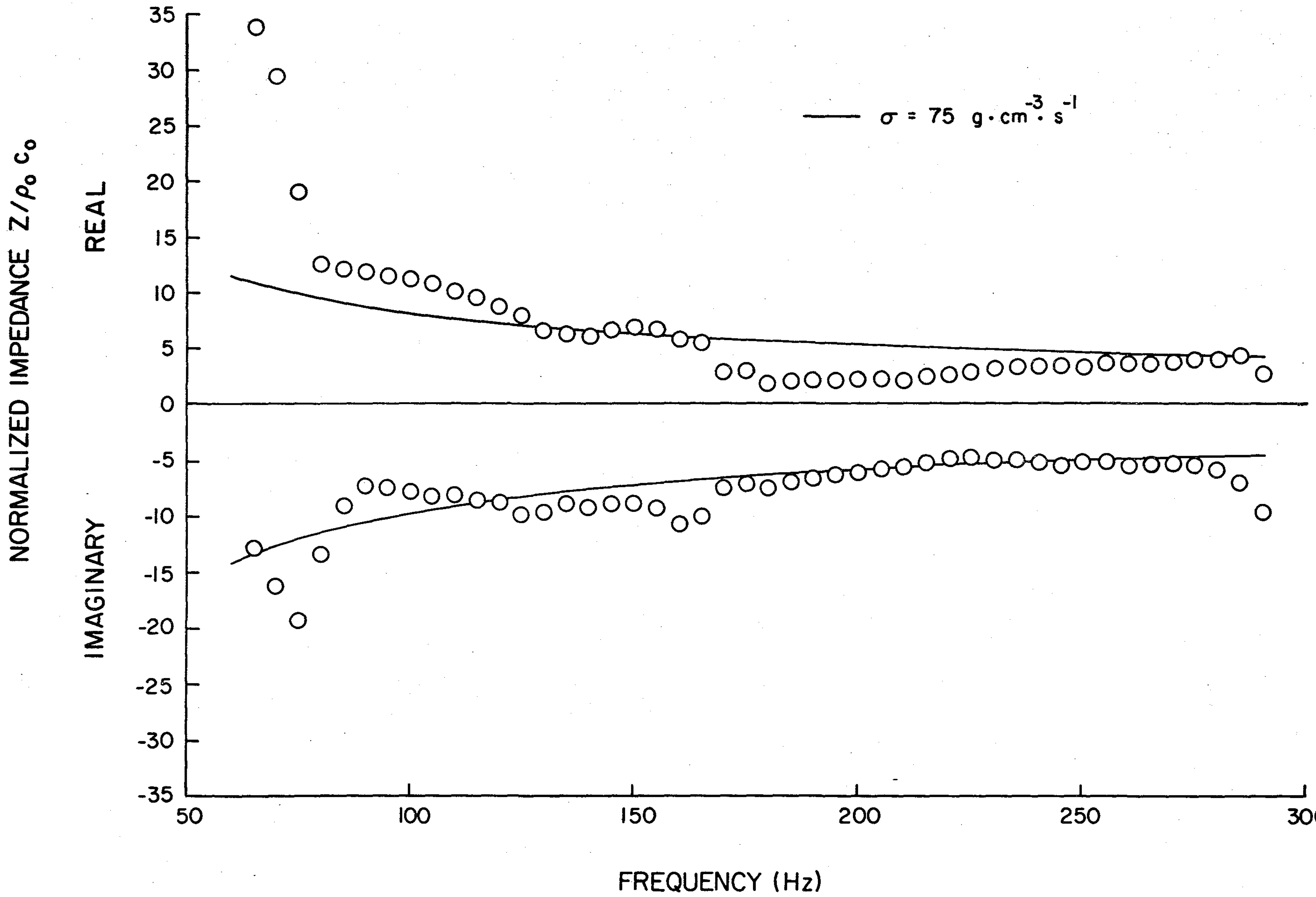

Figure 5.- Acoustic impedance of a small sample of sod. Circles: Experimental. Lines: Best-fit using σ = 75 cgs units.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83227		

4. Title and Subtitle	5. Report Date
Acoustic Ground Impedance Meter	December 1981
	6. Performing Organization Code 505-32-03-02
7. Author(s) Allan J. Zuckerwar	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address Langley Research Center Hampton, VA 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Army Project No.

15. Supplementary Notes

Presented in part at the 102nd Meeting of the Acoustical Society of America, December 3, 1981.

16. Abstract

A compact, portable instrument has been developed to measure the acoustic impedance of the ground, or other surfaces, by direct pressure-volume velocity measurement. A Helmholz resonator, constructed of heavy-walled stainless steel but open at the bottom, is positioned over the surface having the unknown impedance. The resonator chamber measures 0.229 m in diameter by 0.152 m high. The sound source, a cam-driven piston of known stroke and thus known volume velocity, is located in the neck of the resonator. The cam speed is a variable up to a maximum 3600 rpm. The sound pressure at the test surface is measured by means of a microphone flush-mounted in the wall of the chamber. An optical monitor of the piston displacement permits measurement of the phase angle between the volume velocity and the sound pressure, from which the real and imaginary parts of the impedance can be evaluated. Measurements using a 5-lobed cam can be made up to 300 Hz; these can be extended by means of a 15-lobed cam, presently under fabrication, to nearly 1000 Hz. Detailed design criteria and results on a soil sample are presented.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Ground Impedance, Acoustic Impedance, Helmholz Resonator	Unclassified - Unlimited Subject Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	15	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161