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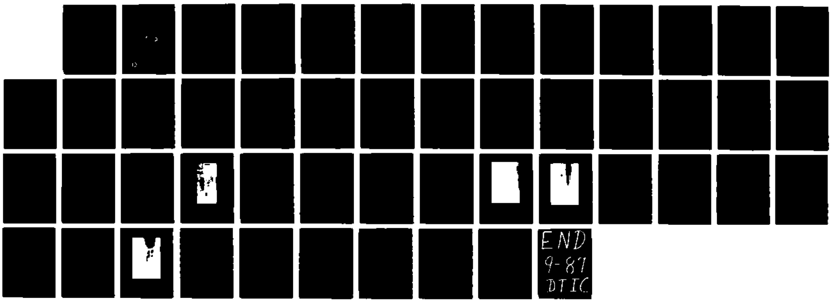

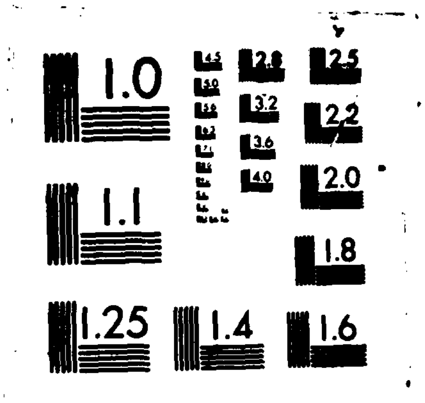

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DTNSRDC PAS-86-50 Investigation of Structure/Fluid Interaction in Piping Systems Using an Intensity Measurement Approach

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Propulsion and Auxiliary Systems Department

Research and Development Report

Investigation of Structure/Fluid Interaction in Piping Systems Using an Intensity Measurement Approach

by
G. P. Carroll

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Methods for measuring both acoustic and vibrational power flow in piping systems are presented. A non-invasive dynamic pressure sensor for this application is hypothesized and a prototype based on polyvinylidene flouride (PVDF) piezoelectric film strip is developed. Acoustic intensity measurements made in a straight pipe section indicate measurable interaction with the pipe wall along its length corresponding to acoustic column resonance mode shape. Difficulties are encountered in implementing structural intensity measurements for verifying energy flow paths for this particular experimental configuration. PVDF strip prototype indicates excellent capabilities for noninvasive measurement of dynamic pressure inside pipe at low frequencies. Future investigations on a similar system with a 90 degree elbow are discussed.

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FIGURES

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NOTATION

c	Speed of sound in fluid
d_r	Radial displacement
f	Frequency
G_{31}	Piezoelectric stress constant
$G_{21}(f)$	Cross spectrum between sensors 2 and 1
I	Moment of inertia
$Im(\ )$	Imaginary part of complex number
k	Bending wave number
L	Length of beam
m	Order of axial vibration form
n	Order of circumferential vibration form
p	Dynamic pressure
$\|PN\|$, $\|PAN\|$	RMS pressure at node and antinode
R	Complex reflection coefficient
t	Pipe wall thickness
Δx	Sensor spacing
E	Young's modulus
$I_x(f)$	Intensity spectrum (x direction)
ρ	Density of fluid medium
ε_b	Normalized bias error
$\Delta\Phi$	Measurement phase error
Φ_{21}	Phase of cross spectrum between sensors 2 and 1
η	Loss factor
ν	Poisson's ratio
ε_c	Circumferential strain
$\Pi(f)$	Structural Power spectrum

NOTATION (Continued)

r	Radius of pipe
$I_x(f)$	Intensity in x direction
mw,	10^{-3} watts

ABSTRACT

Methods for measuring both acoustic and vibrational power flow in piping systems are presented. A non-invasive dynamic pressure sensor for this application is hypothesized and a prototype based on polyvinylidene flouride (PVDF) piezoelectric film strip is developed. Acoustic intensity measurements made in a straight pipe section indicate measurable interaction with the pipe wall along its length corresponding to acoustic column resonance mode shape. Difficulties are encountered in implementing structural intensity measurements for verifying energy flow paths for this particular experimental configuration. PVDF strip prototype indicates excellent capabilities for non-invasive measurement of dynamic pressure inside pipe at low frequencies. Future investigations on a similar system with a 90 degree elbow are discussed.

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INTRODUCTION

The measurement of power flow associated with both fluid acoustic and structural wave propagation has become possible in the last decade due to the development of two point intensity measurements. The direct measurement of fluid acoustic intensity was first attempted by Olson[1]. Although numerous other investigators have made contributions to this field in the ensuing period[2,3,4], no significant improvements in the measurement approach were realized until the mid 70's when Fahy[5] and Chung[6] determined that acoustic intensity was proportional to the imaginary component of the cross spectrum obtained from two closely spaced microphones. This insight coincided with the development of inexpensive portable dual channel fast Fourier transform (FFT) spectrum analyzers which made these measurements simple to perform. Furthermore, the use of this fully digital analysis equipment hastened the development of intensity measurements since an order of magnitude better precision could be achieved. Since Fahy and Chung's work there has been much activity in the area of acoustic intensity measurements although the area still remains one of active research.

The use of intensity measurements in structures, i.e., to measure the analogous power flow associated with vibrational motions in structures has received much less attention. An intensity measurement approach for measuring vibrational power flow in structures was first attempted by Noiseux[7]. Prior to this work, the measurement of vibrational power flow had been considered by experiments in the area of statistical energy analysis (SEA)[8,9] using other measurement approaches. Although intensity measurements in structures are inherently subject to greater errors, good experimental results have been reported by a few authors[10,11,12]. It is these successes in the use of intensity measurements, at least in laboratory settings that led to the idea of using this measurement approach for studying structure/fluid interaction in piping systems. Since the transfer of energy from one medium to the other is implicit in any interaction phenomena, intensity measurements which have the potential of measuring this energy exchange directly provide an excellent tool for investigating these phenomena.

THEORY

Intensity Measurements

The formula to be used for measuring acoustic power using 2 point intensity measurements is given below and derived in reference [12].

$$I_x(f) = \frac{1}{\rho \Delta x 2\pi f} \, \mathrm{Im}\left[G_{21}(f)\right] \tag{1}$$

Where $G_{21}(f)$ is the cross spectrum between two closely spaced pressure transducers (hydrophones, microphones, etc.). This expression is derived from the basic definition of power, i.e., the average force exerted thru a distance, which for the acoustic case is the time average product of the pressure and the particle velocity. The velocity which is proportional to the pressure gradient is estimated using a finite difference approximation from the output of two closely spaced pressure transducers. The spacing between the sensors should be less than 1/4 wavelength. If plane wave propagation in a pipe is assumed, the x direction corresponds to the longitudinal axis of the pipe. Since the sensors are very close together, the accuracy of the measurement depends largely on the phase accuracy of the sensors and the measurement system. This is especially true if large reverberation levels are present as will be discussed later. This fact represents a potential liability for using the intensity technique for examining sometimes small local interaction between media in the presence of large local reverberation since the possibility exists that the errors in the intensity measurement due to phase errors may be greater than the interaction phenomena being studied.

The analogous expression for the power flow associated with one dimensional flexural vibrations in simple structures is given in equation (2).

$$\Pi(f) = \frac{k^2 EI}{\Delta x (2\pi f)^3} \ \mathrm{Im}\left[G_{21}(f)\right] \qquad (2)$$

This expression is also derived in detail in reference [12] and results from a number of simplifying assumptions. Most importantly, the expression is not valid near discontinuities since it is assumed in the derivation that the evanescent nearfield terms corresponsing to flexural motion are negligible. This does not represent a major difficulty, however, since for modes above the first few it is usually possible to be suffiently far (1/4 wavelength) from the ends. There are a number of other related methods based on measurements from combinations of strain gages, longitudinally mounted accelerometers and transversely mounted accelerometers which can also be used to measure the one dimensional flexural power flow[13] although the one given has been best documented experimentally. Although equation (2) has been derived for a beam, it is easily extended to the beam like vibrations of pipes (n=1) simply by using the appropriate value for moment of inertia.

The largest source of error associated with both structural and acoustic intensity measurements is due to phase inaccuracies of the measurement system[14]. Equations which predict the error in the intensity measurement resulting from a measurement phase error $\Delta\phi$ are derived in detail in reference (12) and are given for the acoustic and the structural case respectively by equations (3) and (4).

$$\varepsilon_b = \sin \Delta\varphi \ \cot k\Delta x \left(\frac{1 + |R|^2}{1 - |R|^2}\right) \qquad (3)$$

$$\varepsilon_b = \frac{\sin \Delta\phi \cot k\Delta x}{Lk\eta} \quad (4)$$

Perhaps the most important parameter in these equations are η and R which relate to the reverberation levels present. For very large levels of reverberation, extremely precise phase accuracies, i.e., on the order of .1 degrees are required to make accurate intensity measurements.

STANDING WAVE RATIO MEASUREMENTS

Estimates of power flow in a one dimensional field can be obtained from measurements of the standing wave nature of the field. In a way analogous to the measurement of absorption coefficient using the standing wave ratio (SWR) of the nodal to the antinodal response, the measurement of power flow can be obtained from the product of the RMS pressures at the node and antinode. This was first demonstrated for the acoustic case by Bies and Hansen[15] and was extended to the structural case in reference [12]. For the acoustic case, the formula relating acoustic power flow to the standing wave product is given by equation (5).

$$|I_x(f)| = \frac{|P_N| \cdot |P_{AN}|}{\rho C} \quad (5)$$

It should be pointed out that this approach is also valid if there is distributed loss. For this case, the amount of distributed damping is characterized by the values at the node which become smaller as energy is dissipated along the length. The values at the antinode remain relatively unchanged from one antinode to the next. This idea is discussed in greater detail in reference [16].

ACOUSTIC INTENSITY MEASUREMENTS BASED ON PIPE WALL VIBRATIONS ACCELEROMETER APPROACH

The initial plan for making fluidborne and structureborne intensity measurements in this study was to use the accelerometer data to estimate the power flow in both media. Such a non-invasive acoustic intensity measurement scheme has potential advantages in that it does not require drilling pipe walls for wall mounted pressure transducers. The advantages are that 1. measurements can be easily made at any location along the pipe without a prior knowledge of the pressure field; 2. pipe wall characteristics, therefore, vibration characteristics are not altered and; 3. turbulent boundary layers are not be altered in the case of fluid flow. The concept is roughly based on the work of Davidson and Smith (unreported) who successfully demonstrated that the summed output from four accelerometers mounted around the circumference of a pipe could be used to measure the dynamic pressure inside the pipe. They showed that summing the outputs of the individual accelerometers it is possible to discriminate against motions attributable to the modal characteristics of the pipe at frequencies below the first axisymmetric breathing mode. In this way it is possible to relate the dynamic pressure in the pipe to the radial displacement d_r obtained from summing the accelerometer outputs by the expression:

$$p = \frac{d_r \; 2Et}{r^2(2-\nu)} \qquad (6)$$

Experimental results obtained by Davidson and Smith showing good comparison between pressure measured with a hydrophone and pressure obtained from the four accelerometer approach are shown in figure (1).

The initial concept to be used in this study was based on the fact that although accelerations of pipe are largely due to its structural vibration modes, there is a measurable component due to the elastic "breathing" of the pipe wall in response to the internal dynamic pressure. If the frequency corresponding to this dynamic pressure could be identified, it should be possible to use the information from two accelerometers to measure the acoustic intensity inside the pipe. Again, the assumption here is that the breathing response does not vary significantly around the circumference so that two accelerometer measurements made at arbitrary circumferential locations will yield the same result. Using this assumption, an expression for acoustic intensity based on the response of two accelerometers mounted transversely on the pipe wall with longitudinal spacing Δx is obtained by combining equations (1) and (6) to get

$$I_x(f) = \frac{4E^2 t^2}{r^4 \rho \Delta x (2-\nu)^2 (2\pi f)^5} \, \mathrm{Im}\left[G_{21}(f)\right] \qquad (7)$$

PIEZOELECTRIC STRIP APPROACH

Initial experiments indicated that it was not possible to obtain meaningful acoustic intensity using the two accelerometer approach given in equation (7). This conclusion was reached since accelerometer measurements made at various locations on the pipe wall with the pipe being excited acoustically at frequencies coinciding with acoustical column resonances bore little resemblance to the internal pressure field but rather seemed to coincide with off-resonance excitation structural modes. It was therefore impossible to establish a simple linear relationship between internal pressure and structural response. This led to the need for the development of other, non-invasive techniques for measuring acoustic-pressure and acoustic intensity. The scheme of Davidson and Smith was considered cumbersome since to perform two point intensity measurements would require a total of eight accelerometers. Such a large number of accelerometers creates the possibility of large cumulative errors resulting from even moderate phase errors of the individual accelerometers. Any approach should, however, maintain basic feature of the Davidson/Smith approach, i.e. to be able to discriminate against the pipes modal response characteristics and measure only internal dynamic pressure The basic idea behind the Davidson/Smith approach is shown in figure (2) which shows the various circumferential and axial modes characteristic of thin walled cylinders[17]. These modes correspond to the circumferential and axial standing wave pattern. The output from 4 accelerometer mounted at the locations shown will sum to zero for all modes except $n = 0$. The so called $n = 0$ mode corresponds to the breathing resonance of the pipe wall and usually occurs at very high frequencies . Therefore, in theory cancellation is accomplished up to this mode of vibration. On the other hand, the response of the pipe wall to an internal pressure field will not sum to zero if the accelerometer outputs are summed. If this pressure field is characterized by plane wave propagation, the pipe wall will undergo an elastic $n = 0$ response as described by the simple hoop stress model given by equation (6). In theory, this concept should hold for all frequencies below the breathing resonance frequency. Near this frequency, the resonant behavior of the pipe wall will upset the linear relationship between the summed output and the internal pressure given by equation (6).

The concept discussed above using 4 discrete accelerometers sensors mounted around the circumference of the pipe can be extended to a single continuous sensor. Imagine for example if it were possible to construct an accelerometer which goes all the way around the circumference of the pipe wall. This idea is shown in figure (3). Figure (4) shows the charge generated on the piezoelectric element for a few typical n, m modes. In a way similar to that shown in figure (1), all these modes will cause distributions of charge on the element which will sum to zero. There will, however, be a net charge resulting from axisymmetric motion, i.e., the $n = 0$ mode of vibration corresponding to the axisymmetric internal pressure field.

Initially,, the idea of constructing such an accelerometer was considered. Recently available piezoelectric materials based on polyvinylidene flouride (PVDF)[18,19] are much more flexible than conventional ceramic materials based on titanates or lead zirconite, so that they can be wrapped around a pipe and used on large surface areas without the possibility of breaking. The expected difficulty with the approach was that, to get an adequate signal from the piezoelectric element requires that the piezoelectric element be quite thick and that the seizmic mass be quite heavy. Both these requirements imply that such a device be unacceptably large.

Another approach which was considered was to use a conventional strain gage wrapped around the pipe to measure the circumferential strain and cancel the strains associated with other motions in a way similar to the continuous accelerometer. Initial calculations indicated that strains on the order of 10^{-3} micro-strain would result from the internal dynamic pressure for the experimental setup. These strain levels are much smaller than that conventionally achieved using standard strain gages. These calculations revealed, however, that a continuous piezoelectric film wrapped around the pipe wall will give adequate response to breathing strain. In a way entirely analogous to the continuous accelerometer approach strains associated with circumferential and axial vibration modes will form a charge-pattern on the piezoelectric element similar to that shown in figure (4). In this case however, the charge will be generated by localized strains in the pipe wall as compared to the compression resulting from the force exerted by a seizmic mass for the accelerometer case. The motion of the pipe wall will create a net charge only for the n = 0 mode. The relationship between the internal pressure field and the net dynamic circumferential strain ε_c given by equation (8).

$$p = \frac{2\varepsilon_c Et}{r(2-\nu)} \tag{8}$$

EXPERIMENT

EXPERIMENTAL FACILITY

An experimental facility was established to investigate if intensity measurements could be made with sufficient accuracy to measure fluid/structure interaction phenomena. This facility shown in figures (5) and (6) consists of a 10 ft. long, 4 inch diameter aluminum pipe with 1/4 inch wall thickness. The pipe is acoustically excited by means of a J-9 pressure transducer mounted at the bottom. Structural vibration energy of the transducer was isolated from the pipe wall using the rubber sleeve of the J-9. Initially, only accelerometer measurements were anticipated. The difficulty associated with using these accelerometer measurements to determine internal acoustic pressure led to the necessity of using hydrophones lowered from the open end of the pipe to measure acoustic pressure. Acoustic intensity measurements were made at various locations using two evenly spaced hydrophones which were lowered and raised inside the pipe. Structural intensity measurements were also made on the pipe wall. The pipe also provided the capability of evaluating the effectiveness of the piezoelectric strip for measuring the internal acoustic pressure field. The output from the sensors were all conditioned using Kistler 5004 charge amplifiers. The spectral analysis was performed using a Nicolet 660 dual channel spectrum analyzer.

RMS PRESSURE AND ACOUSTIC INTENSITY MEASUREMENTS

Dynamic pressure measurements were made inside the pipe using two Celesco LC10 hydrophones which are approximately 2-1/8 inches long and 1/3 inch in diameter. By raising and lowering the hydrophones using the pulley arrangement shown it is possible to determine the modal pattern and to measure acoustic intensity at all locations in the pipe. Figure (7) shows typical hydrophone data corresponding to white noise excitation of the fluid column. The fluid column resonances are evident in the figure. The relative size of these resonant peaks varies with measurement location corresponding to the modal pattern for the particular mode. This modal pattern is important to establish since the accuracy of the intensity measurements depends greatly on the proximity of the measurement location to a node or antinode. Furthermore, the standing wave ratio (SWR) obtained from this modal pattern can be used to obtain estimates of acoustic power flow which can be used to verify the accuracy of the intensity approach. The mode shape for the 84 Hz mode and the 250 Hz mode are shown in figures (8) and (9). It is interesting to note that for the 250 Hz mode, the pressure at the node appears to decrease with distance from the source. This indicates some degree of dissipation along the length of the pipe as discussed earlier. Measurements of overall system loss were obtained by exciting the column at a resonant frequency and suddenly shutting off the source. Time decay measurements of loss factor are then possible from the resulting decay pattern similar to that shown in figure (10). This composite loss factor corresponds to loss mechanisms at the fluid terminations, inherent loss of the fluid itself and the loss of energy to the pipe wall.

Before making intensity measurements, it was necessary to calibrate the measurement system to determine the relative phase error between channels. Having determined this phase error it is possible to correct for it. The calibration was accomplished at the frequencies of interest by measuring the response of both channels when the hydrophones were mounted next to one another as shown in figure (11), i.e., at the same location in the pipe. Any difference in phase, either due to the hydrophones themselves, the signal conditioning or the analyzer phase response could then be corrected for. The corrected phase accuracy of the measurement system was about .1 degrees. Using this value in equation (3) along with measured values for the phase ϕ_{21} it is possible to establish error bounds for the intensity measurement accuracy.

Intensity measurements were made using the hydrophone pair shown in figure (12) at evenly spaced increments along the pipe with sinusoidal excitation (84 Hz and 215 Hz) corresponding to these modal resonance frequencies. Figures (13) and (14) show the measured power flow as a function of distance along the pipe. The power flow estimates were obtained using the intensity measurement formulation given by equation (1) and standing wave ratio formulation given by equation (5). Also shown in the figure are estimates of the error bounds on the intensity measurement.

For both the 84 Hz and the 250 Hz modes, there is clearly an overall decrease in the acoustic intensity as distance from the source increases. For the 250 Hz mode, there is about 40 mW lost along the length and about 20 mW lost at the open end. The former corresponds to a distributed loss mechanism whereas the latter corresponds to a local loss characterized by a reflection coefficient, R. The data corresponding to the 84 Hz mode is somewhat difficult to interpret due to the large error bounds indicated in the figure. The 250 Hz node on the other hand indicates that the power levels measured using the intensity method demonstrated a characteristic which corresponds to the mode shape. Comparison with figure (9) indicates that the power levels appear to have local maxima which coincide with the pressure nodes. Furthermore, the power flow appears to at some locations, increase with increasing distance from the source. This type of behavior would indicate that energy is being lost to the pipe wall at some locations, pressure nodes, and is being received from the pipe wall at others, pressure antinodes. The estimated error in the intensity (due to phase errors) does not appear large enough to explain this behavior. Furthermore, an analysis of the possible loss due to dissipation in the medium predicts that there should be no measurable loss resulting from this mechanism[20]. Since this energy loss is not attributable to the air damping, it must in fact be due to fluid/structure interaction, i.e., energy is being transferred from the fluid column to the pipe wall. It should be pointed out at this point that in theory, due to the symmetry of the setup there is no mechanism for the axisymmetric fluid column motion to excite any of the circumferential or axial pipe modes. In practice, however, there are asymmetries in the pipe wall and the foundation system which allow for a substantial excitation of these pipe modes[11].

Very good agreement between the intensity measurement approach and the SWR approach is indicated in the figure. The power flow levels obtained using both approaches confirm that there is an overall loss in energy along the pipe as distance from the source is increased. The discrepancies between the two measurement approaches are probably due to the finite difference bias error associated with 2 point intensity measurements. This error[21] which is given by $\frac{\sin k\Delta}{k\Delta}$ accounts for an 8 percent underestimation by the intensity measurements which is approximately the size of the error observed.

ACCELEROMETER MEASUREMENTS

Structural intensity measurements were made on the pipe wall in an attempt to account for the measured energy transfer from the fluid column. It is possible that the energy is 1) dissipated in the pipe wall, 2) dissipated or transmitted through the foundation system, or 3) being recirculated with the acoustic energy along the length. Ideally, intensity measurements should be able to identify to what degree and by what mechanism the energy exchange occurs. There was a great deal of difficulty, however, in actually measuring power flow in the pipe wall. The primary shortcoming of the structural intensity measurements is that the intensity expression given in equation (1) accounts only for power associated with bending motion (n=1). Figure (15) shows a typical accelerometer spectrum which results when the fluid column is excited. Clearly many modes are excited. These modes correspond in some cases to circumferential as well as axial modes. Even at frequencies below the first circumferential mode, there is difficulty in interpreting the results since there is no unique plane, (x, z plane of figure (2)) for which the axial vibrations are occurring. Therefore, for this setup, power flow corresponding to the bending modes will be associated with x,z planes which are somewhat random since they are determined by random imperfections in the pipe and the pipe suspension system. It was decided that investigation of the energy exchange between the pipe wall and the fluid column could best be achieved in a system where the vibration in the x, z plane is uniquely defined. For example, if there were an elbow in the piping system there would be substantial interaction occurring at the elbow which would result in axial waves in the plane defined by elbow. Such an experiment has been anticipated as the next phase of this research. For such an experimental setup the geometry is complicated by the elbow so that the use of hydrophones raised and lowered in the pipe is not possible. This requirement has led to the development of alternative pressure sensing devices which has in turn led to the development of a piezoelectric strip dynamic pressure transducer. Experiments conducted using this sensor are now discussed.

PIEZOELECTRIC STRIP (PVDF) CHARACTERIZATION

Piezoelectirc film strips in a configuration suitable for use as a measure axisymmetric motions of a pipe wall were procurred from Pennwalt Corporation, King of Prussia, PA. This configuration consists of a .2" x 18" PVFD piezoelectric film which is manufactured by Pennwalt under the brand name KYNAR for another application. The piezoelectric element is metalized on both sides and coated with mylar which acts as an insulator. The overall charge generated along the strip is measured by attaching leads to the top and bottom metalized sections which are not coated with mylar at one end. Since these electrical connections are made at one end, it is possible to cut the piezoelectric strip to any convenient length. Figure (16) shows a section of the piezoelectric element. The piezoelectric stress constant which is most important for this application is the G_{31} constant, i.e., the charge generated in the 3 direction to a strain in the 1 direction. The piezoelectric strips were provided without any information regarding these constants so that it was necessary to devise an experiment for measuring them. A schematic of an experimental setup used for accomplishing this is shown in figure (17). The piezoelectric film element was suspended from a rigid support and was excited by a shaker which was in turn suspended from the piezoelectric element. The element was excited by driving the shaker with white noise. The output of the element was compared to the output of a piezoelectric accelerometer mounted in the shaker impedance head. The output from both these sensors were conditioned using Kistler 5004 charge amplifiers. The analysis was performed using a Nicolet 660 dual channel spectrum analyzer which was capable of integrating the accelerometer spectrum twice to obtain the displacement spectrum of the excitation. Figure (18) shows the ratio of the excitation to piezoelectric strip response. This ratio has constant amplitude and zero phase for all frequencies up to about 500 Hz. Knowing the excitation level it is possible to determine the G_{31} constant for the 12" section of PVFD which was to be used for subsequent tests on a 4" diameter pipe. The lack of linearity at higher frequencies was felt to be an artifact of this experiment and not a characteristic of the material. At these frequencies the resonance of the spring mass system characterized by the piezoelectric strip compliance and the shaker mass are effecting the result.

MEASUREMENTS OF DYNAMIC PRESSURE USING PVDF STRIP

The piezoelectric strip characterized in the preceeding experiment was attached to the outside of the pipe wall as shown in figure (19). Due to the low strain levels anticipated it was necessary to glue the strip to the wall using cyanoacrylate. Figure (20) shows a comparison of the spectrum obtained using the piezoelectric strip to that obtained using a hydrophone at the same location with the fluid column being excited with white noise. Figure (21) shows a comparison of the piezoelectric strip output to the response of an accelerometer mounted near the strip. Figure (20) indicates that there is a measurable response of the strip at frequencies corresponding to the acoustic column resonances up to about 300 Hz. There are, however, other modes present in the PVDF strip output which correspond to the structural pipe modes as indicated by figure (21). This indicates that in its present configuration the device cannot completely cancel out the effects of these structural modes. There is also a considerably large component due to 60 cycle noise and its harmonics evident in the PVDF strip output. This is due to the fact that it was necessary to use very light gage, unshielded wires with the film since the forces exerted by heavier, less flexible wires tended to tear the metal foil off the piezoelectric strip. Piezoelectric film is also known to be sensitive to electromagnetic signals. Figure (22) shows a comparison of the hydrophone output to the PVDF film in the 0 to 100 Hz range indicating that at these frequencies the film is capable of reproducing some of the finer details of the resonant pressure response corresponding to the column resonances. The PVDF strip pressure also exhibited good amplitude linearity when compared to the hydrophone data.

CONCLUSIONS AND RECOMMENDATIONS

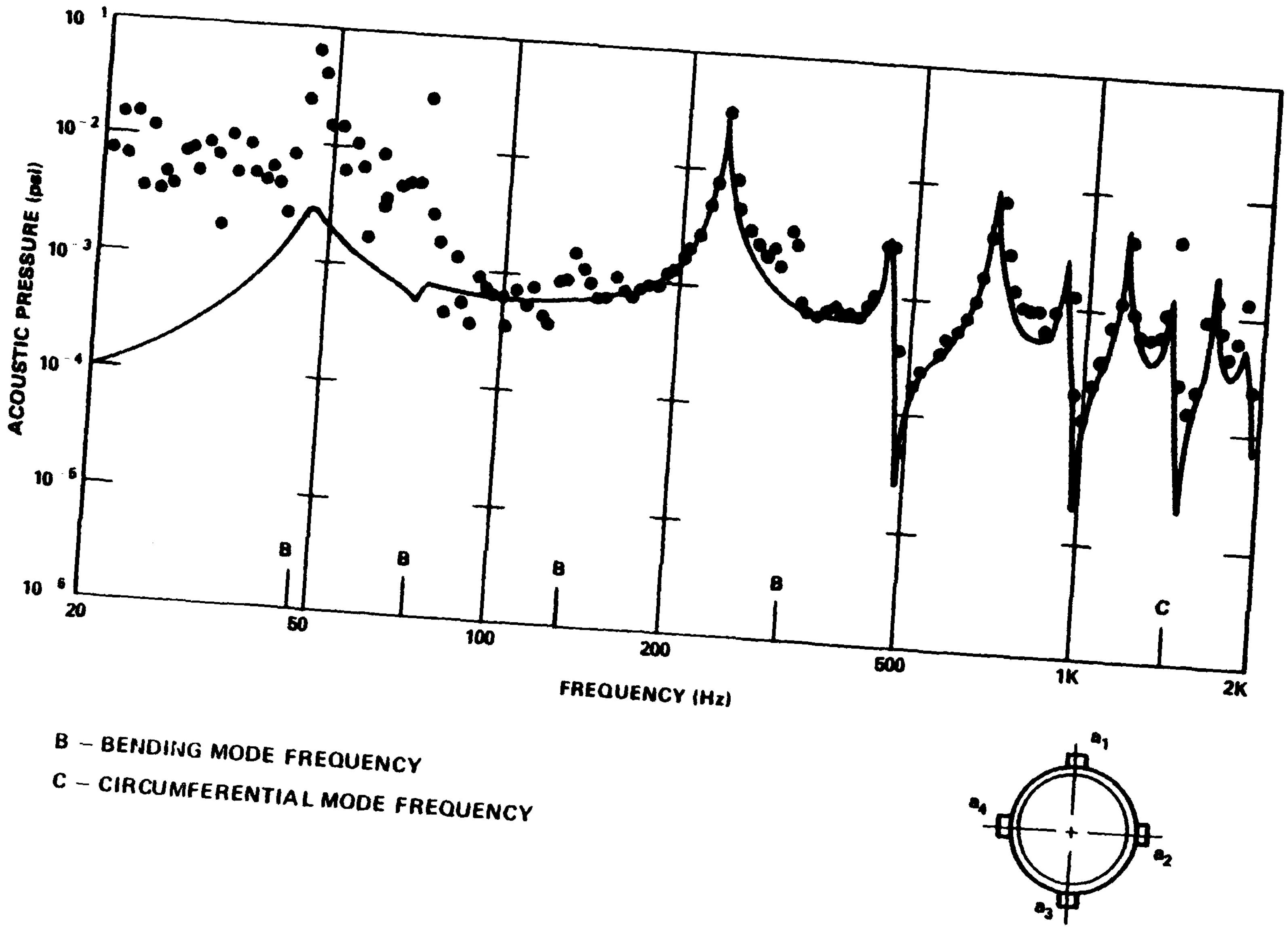
Experiments conducted in the course of this phase of the research lead to the following conclusions:

1. Measurements of acoustic intensity inside the pipe using accelerometer measurements mounted on the pipe wall are not feasible. This is due to the fact that pipe wall breathing is not the principal response to an internal dynamic pressure. Instead, the pipe response demonstrates modal characteristics which offer no information regarding the internal dynamic pressure excitation.

2. Measurements of acoustic intensity made using hydrophones inside the pipe yield very accurate estimates of acoustic power distribution inside the pipe. These estimates point to substantial structure fluid interaction with the possibility of energy being circulated between media along the pipe. These results, however, require further investigation.

3. Structural intensity measurements of bending waves on the pipe wall could not account for the transfer of energy from the fluid to the wall in the present experimental facility since there was no plane of bending which could be clearly identified. A similar experiment is planned on an elbow for which there will be considerable fluid structure interaction at the elbow and for which the plane of bending will be uniquely defined.

4. The capability of using piezoelectric film (PVDF) strip wrapped around a pipe wall to measure internal dynamic pressure has been demonstrated. This development is in its earliest stage. Configurations of this material which have increased sensitivity to pipe wall breathing, while at the same time, discriminating against other circumferential and axial pipe wall vibrations will be sought.



$$P = d_R \frac{2Et}{R^2 (2 - \nu)} \qquad d_R = \frac{a_1 + a_2 + a_3 + a_4}{\omega^2}$$

Fig. 1. Measured pressure and pressure computed from measured radial displacement using four circumferentially mounted accelerometers.

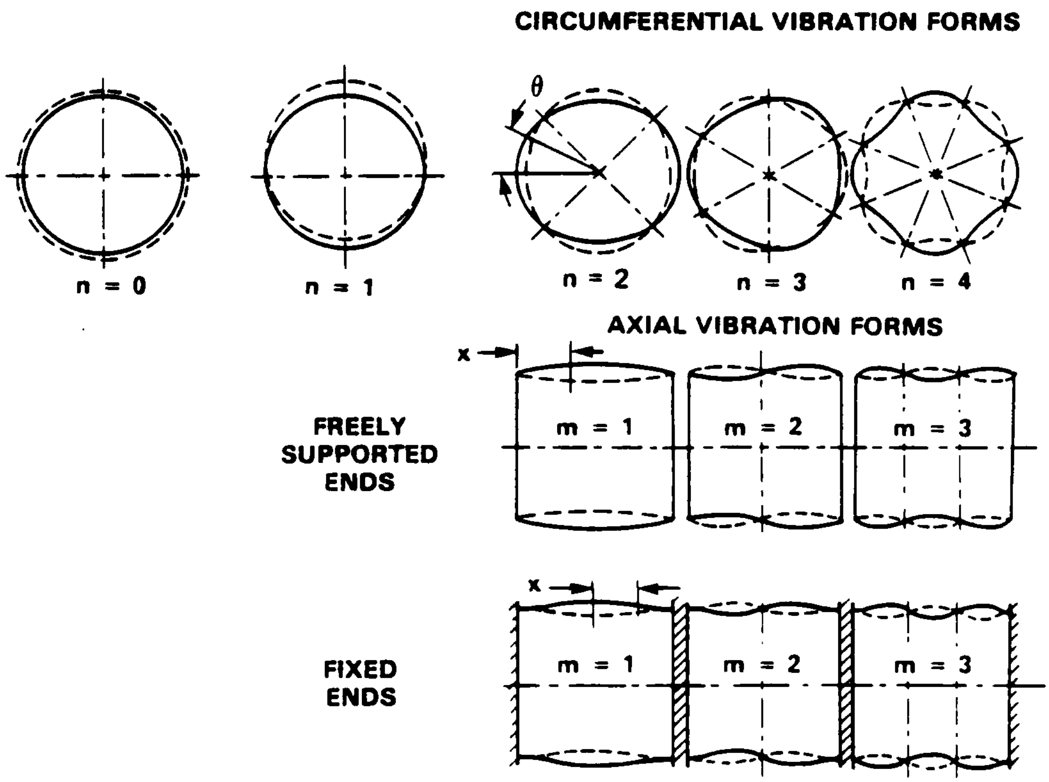


Fig. 2. Circumferential and axial vibrations of thin walled cylinders.

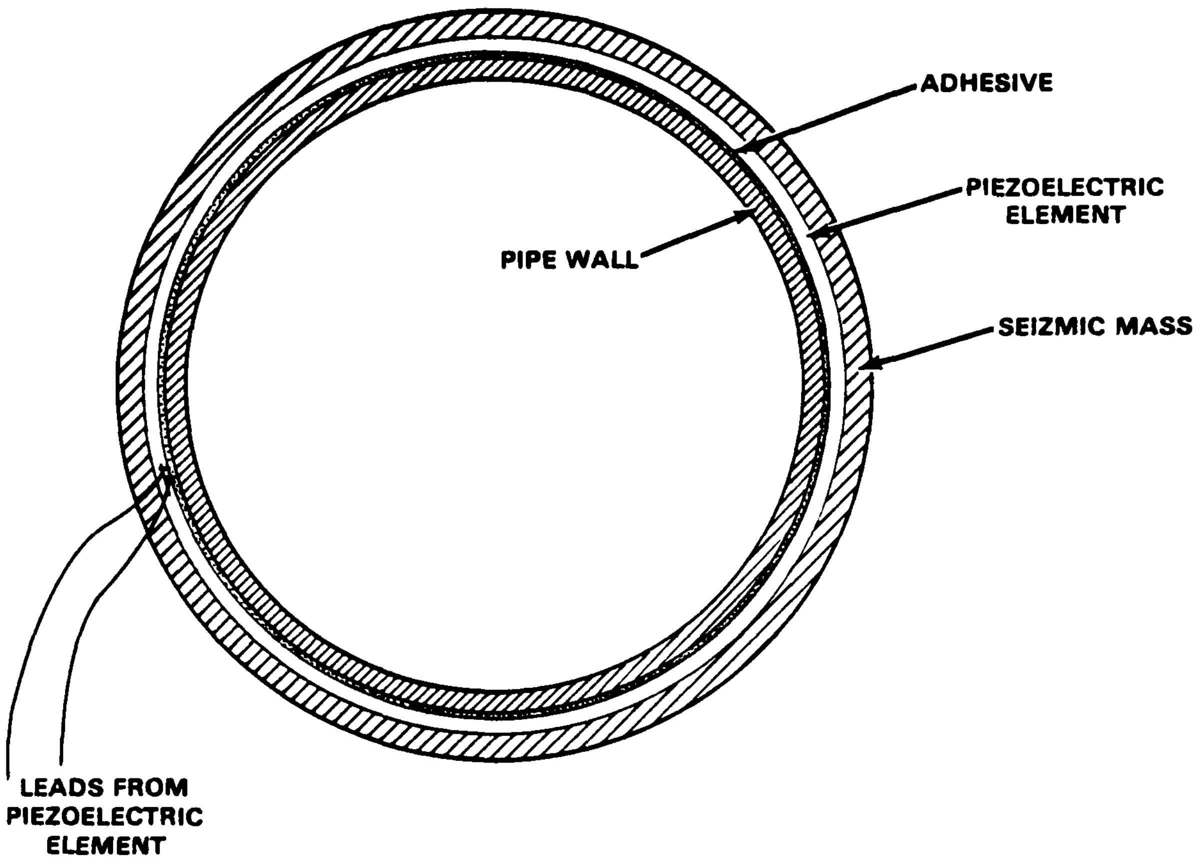


Fig. 3. Circumferential piezoelectric accelerometer.

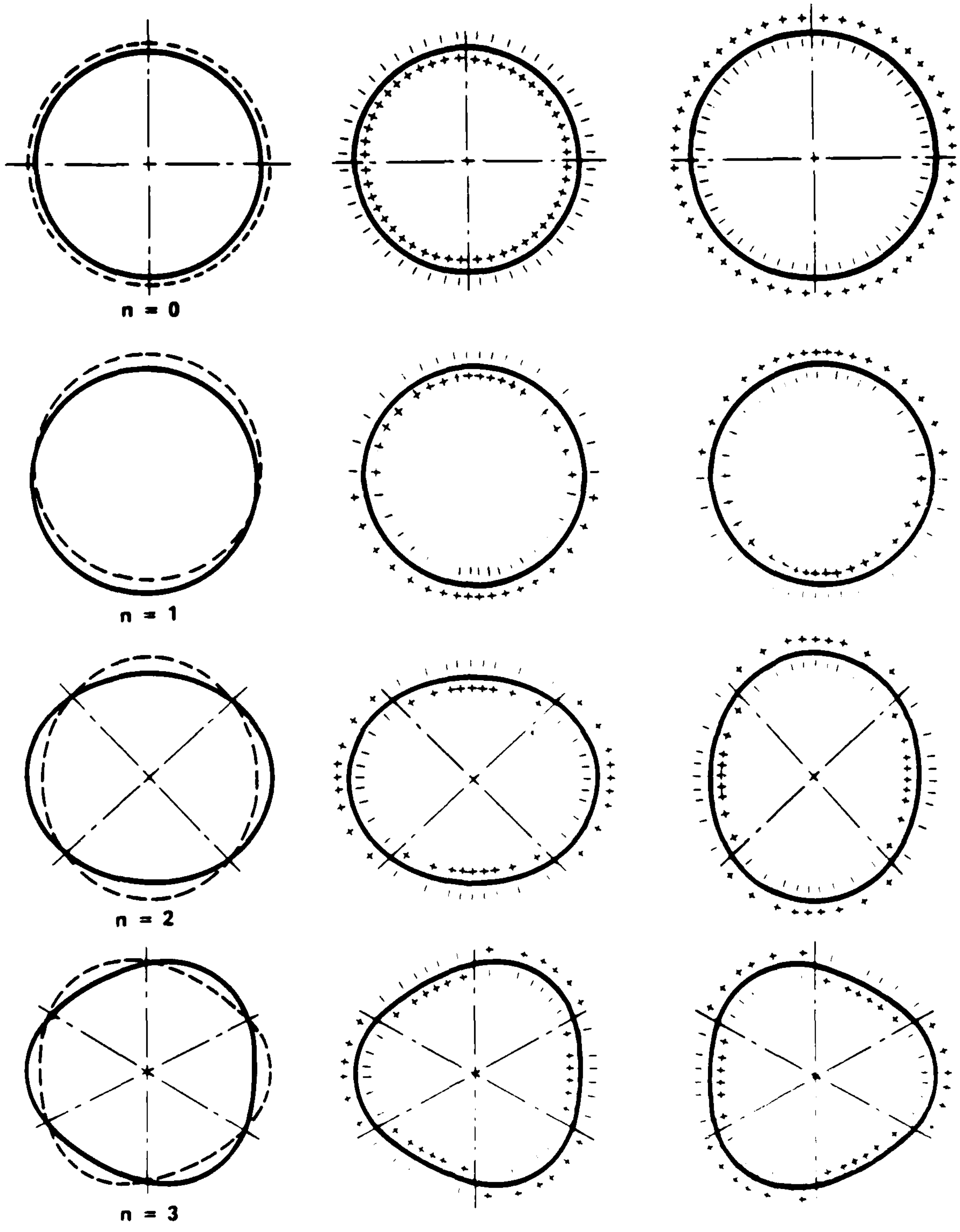


Fig. 4. Charge distribution on piezoelectric element resulting from circumferential vibrations.

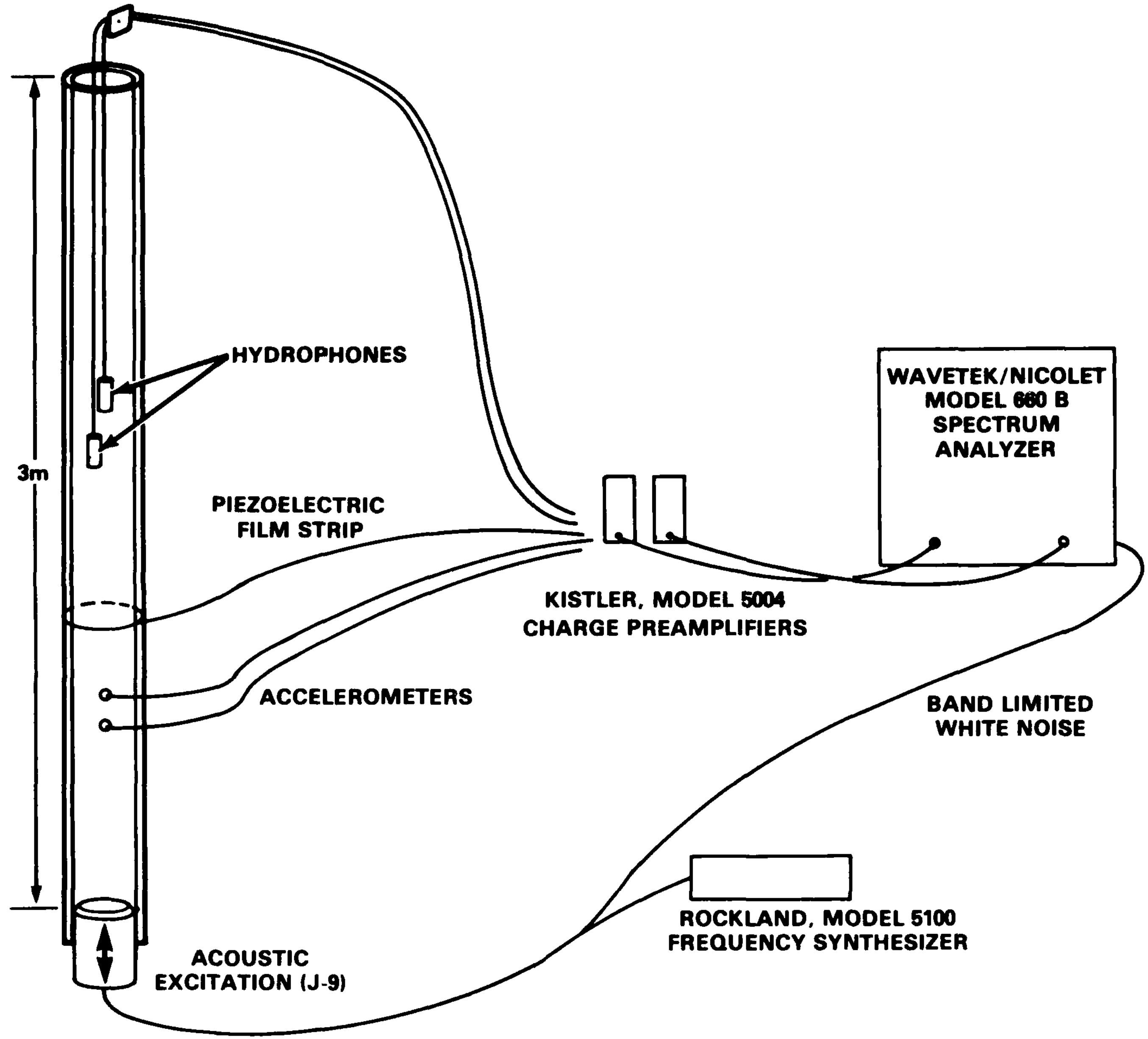


Fig. 5. Experimental setup.

Fig. 6. Experimental facility.

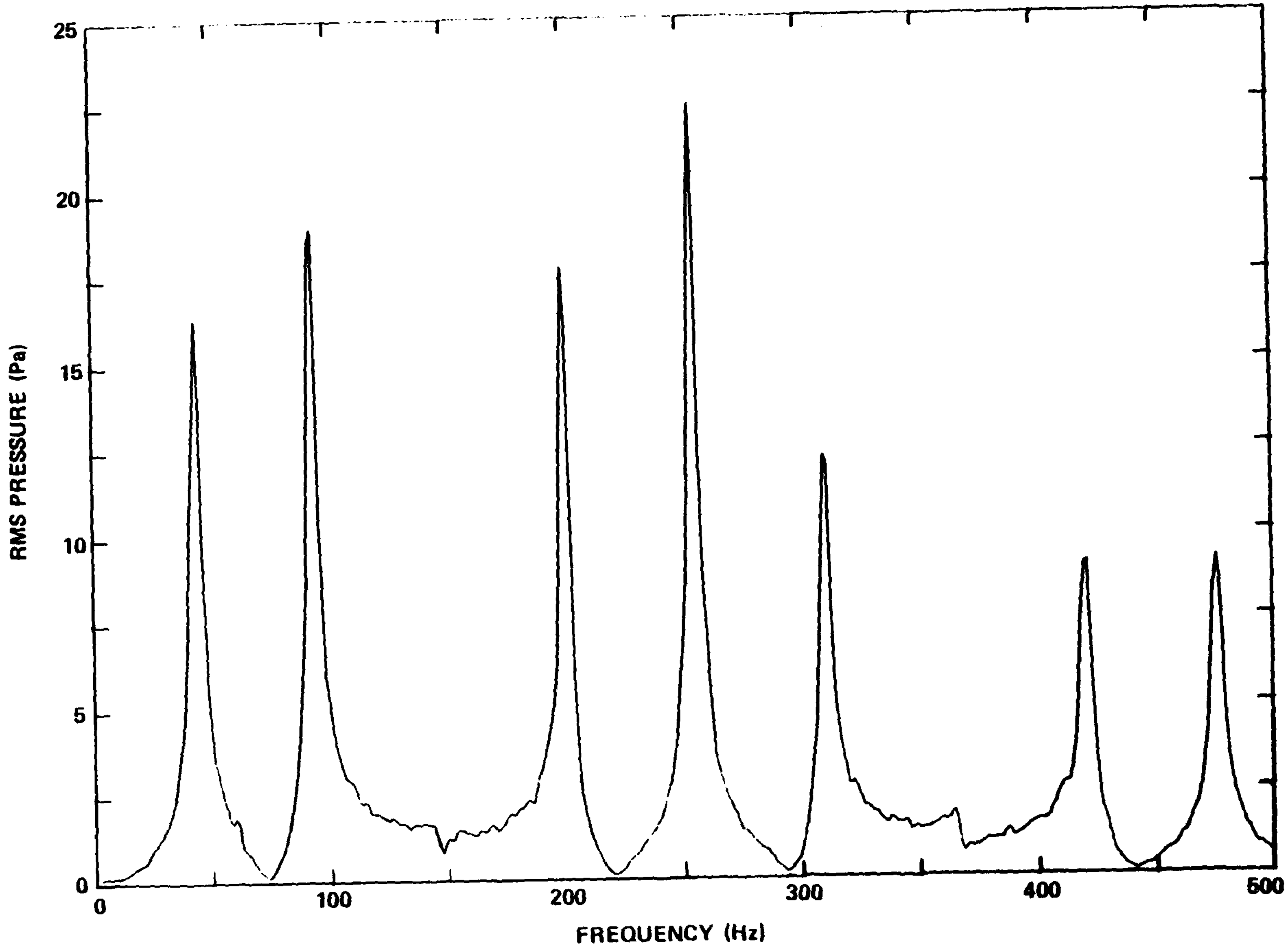


Fig. 7. Hydrophone spectrum, white noise acoustic excitation.

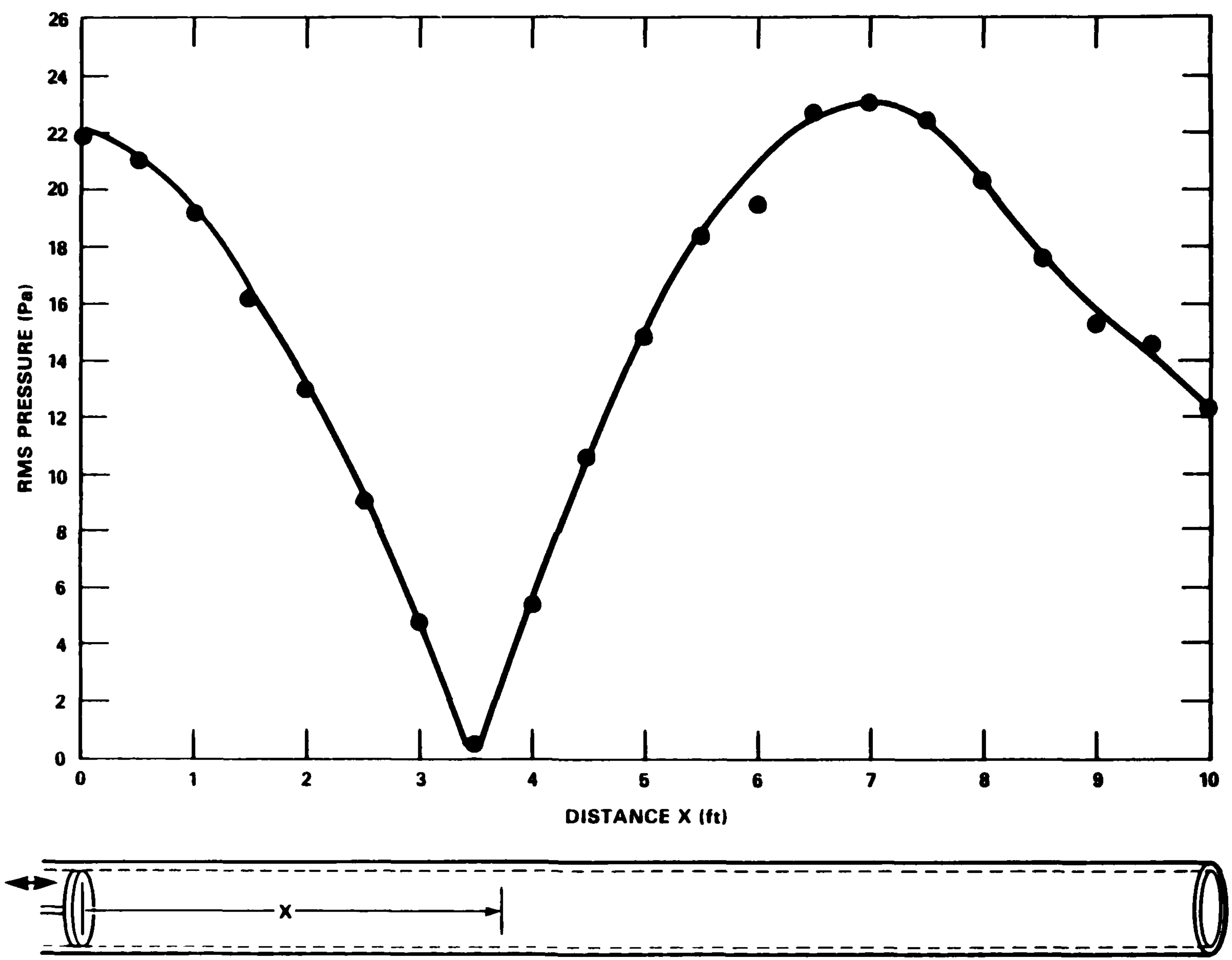


Fig. 8. Mode shape for 84 Hz acoustic column resonance.

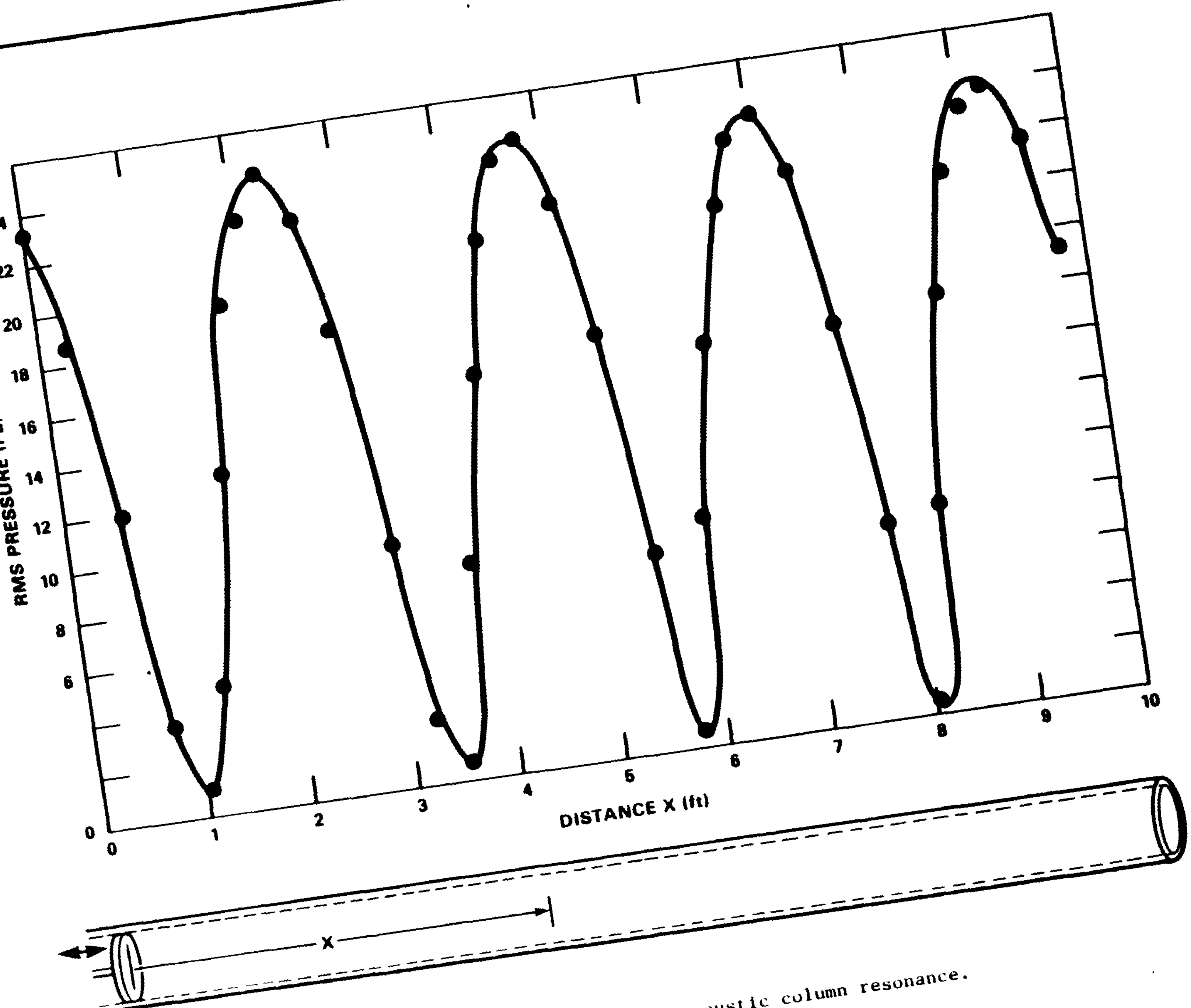


Fig. 9. Mode shape for 250 Hz acoustic column resonance.

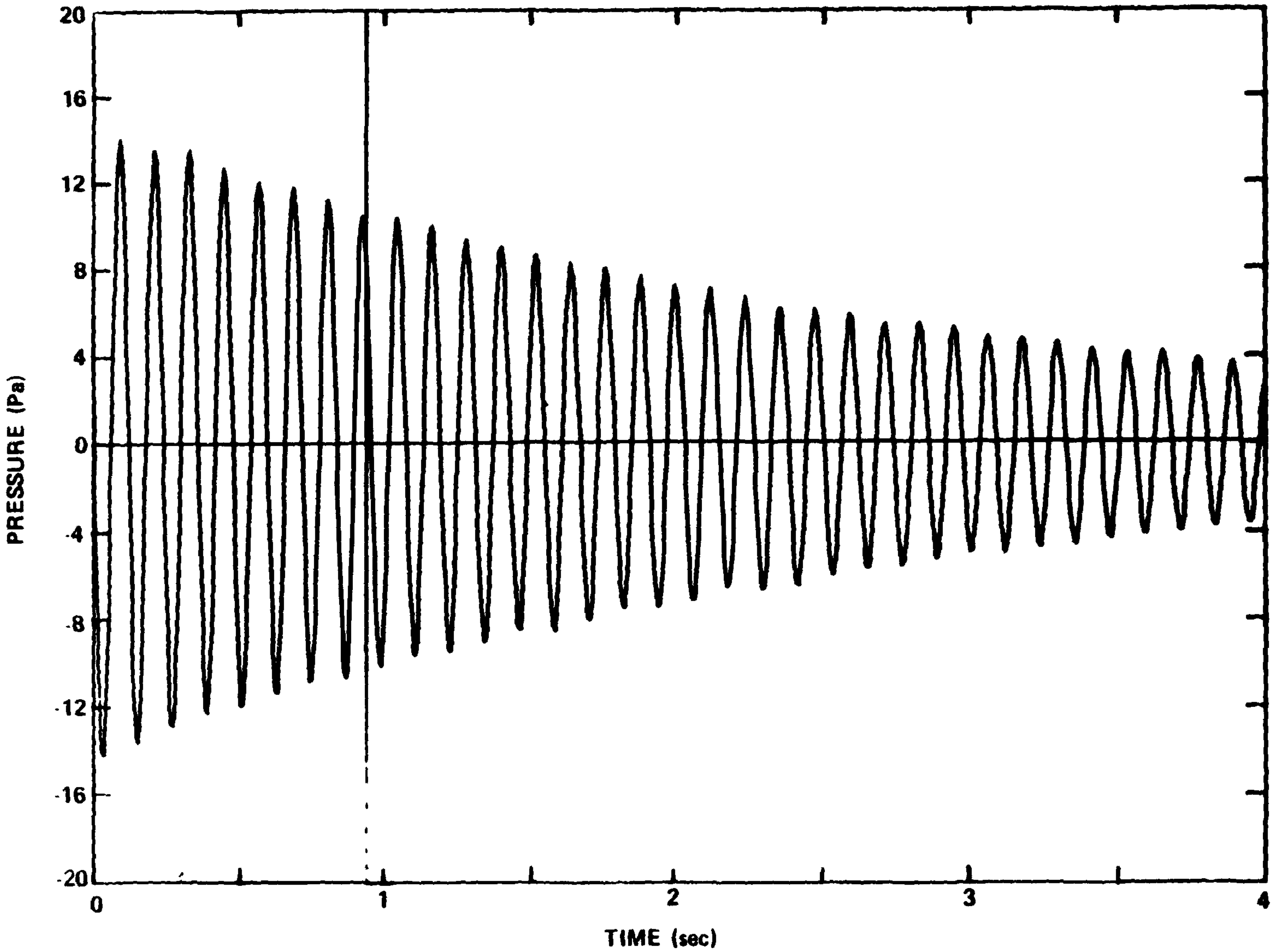


Fig. 10. Time decay measurements of system loss.

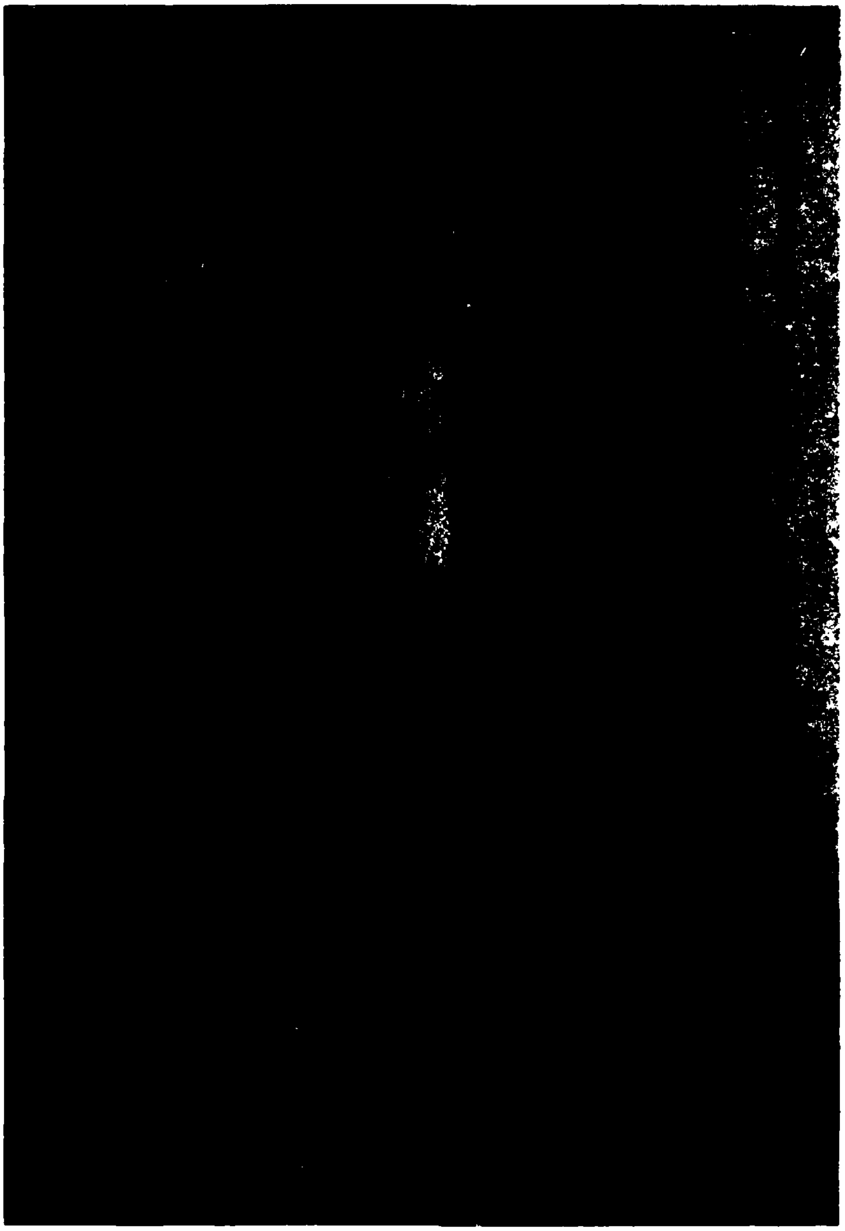


Fig. 11. Hydrophone configuration used for measurement system calibration.

Fig. 12. Hydrophone configuration used for intensity measurements.

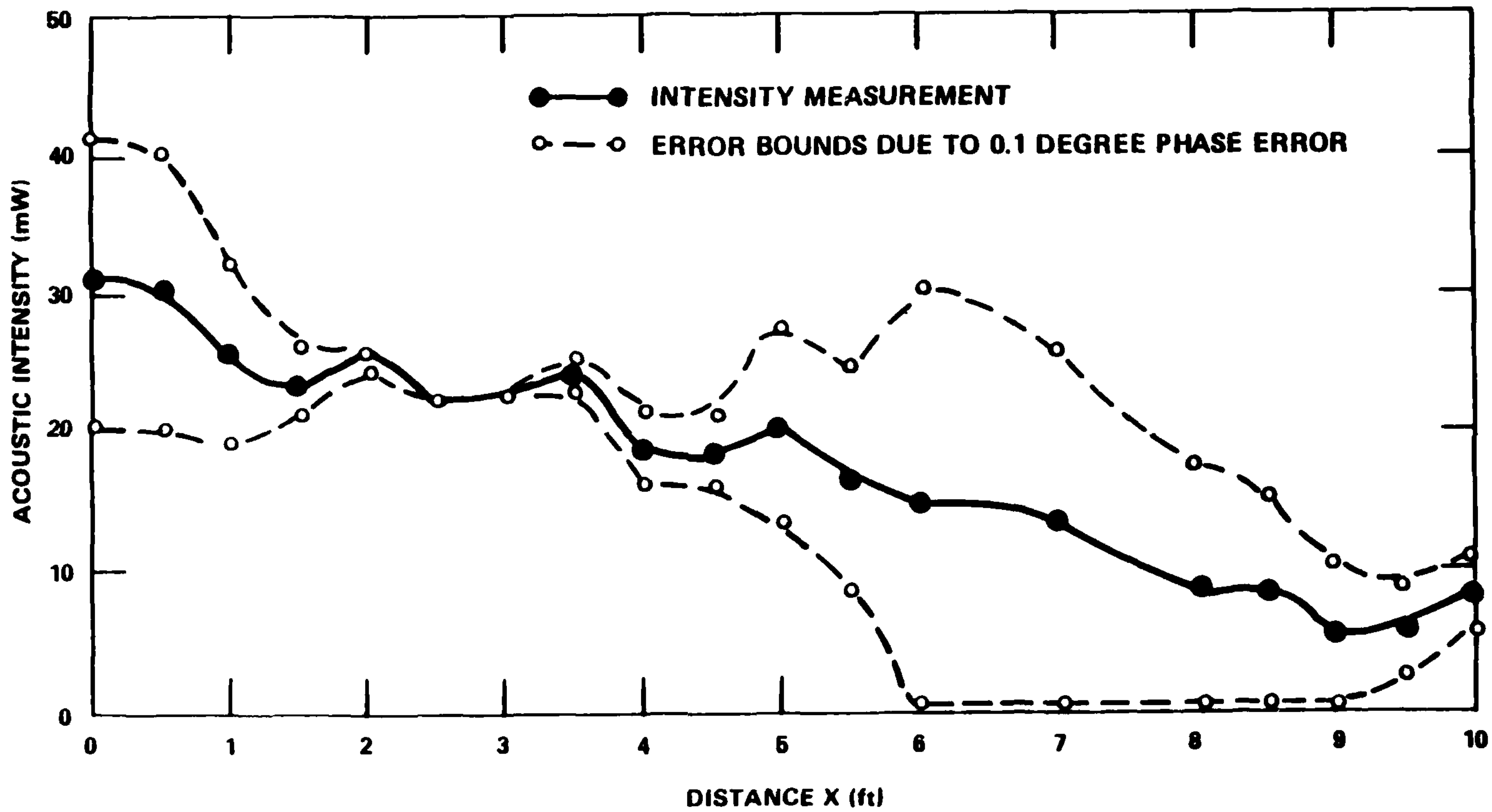


Fig. 13. Intensity distribution along pipe, 84 Hz mode.

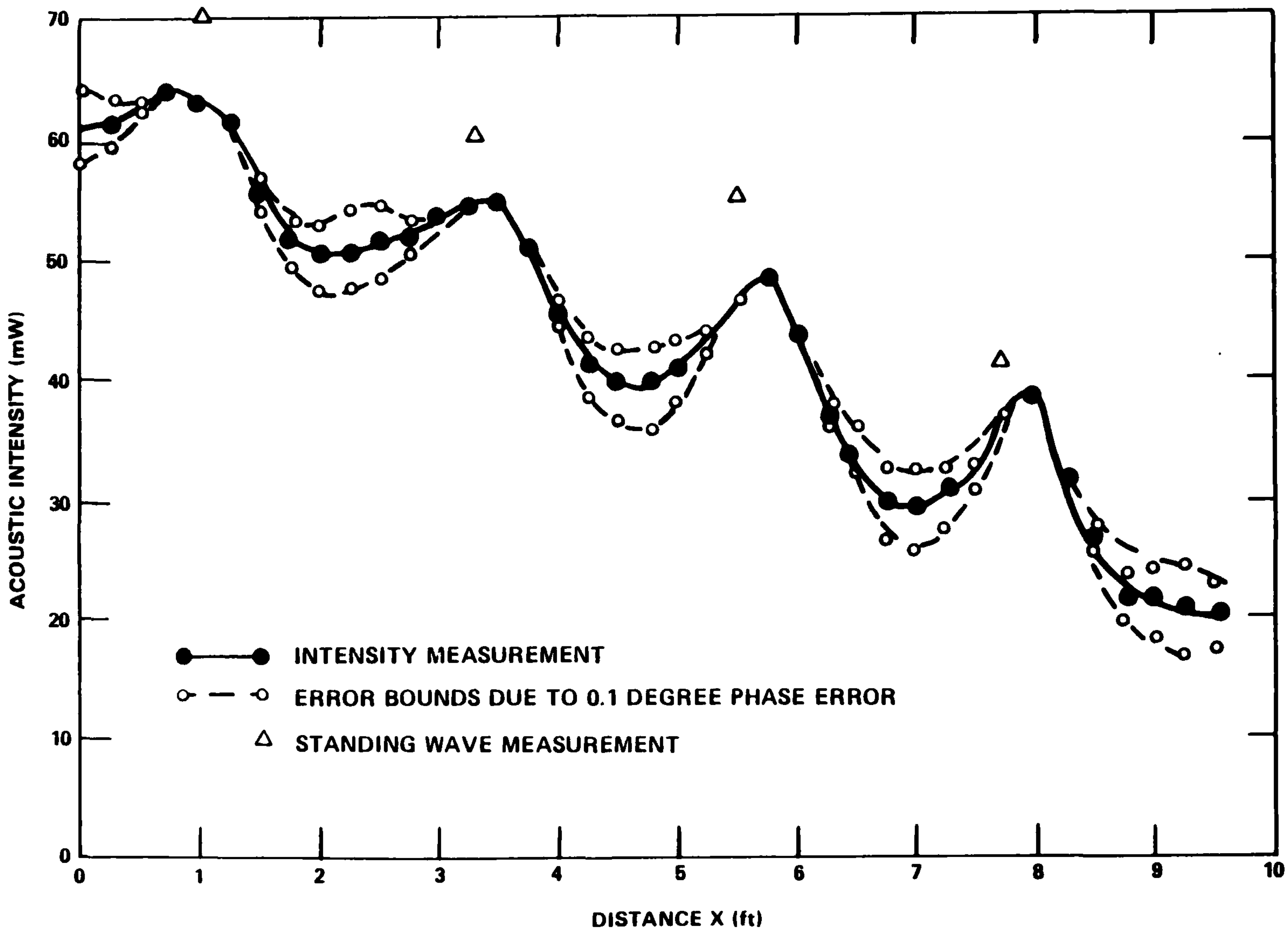


Fig. 14. Intensity distribution along pipe, 250 Hz mode.

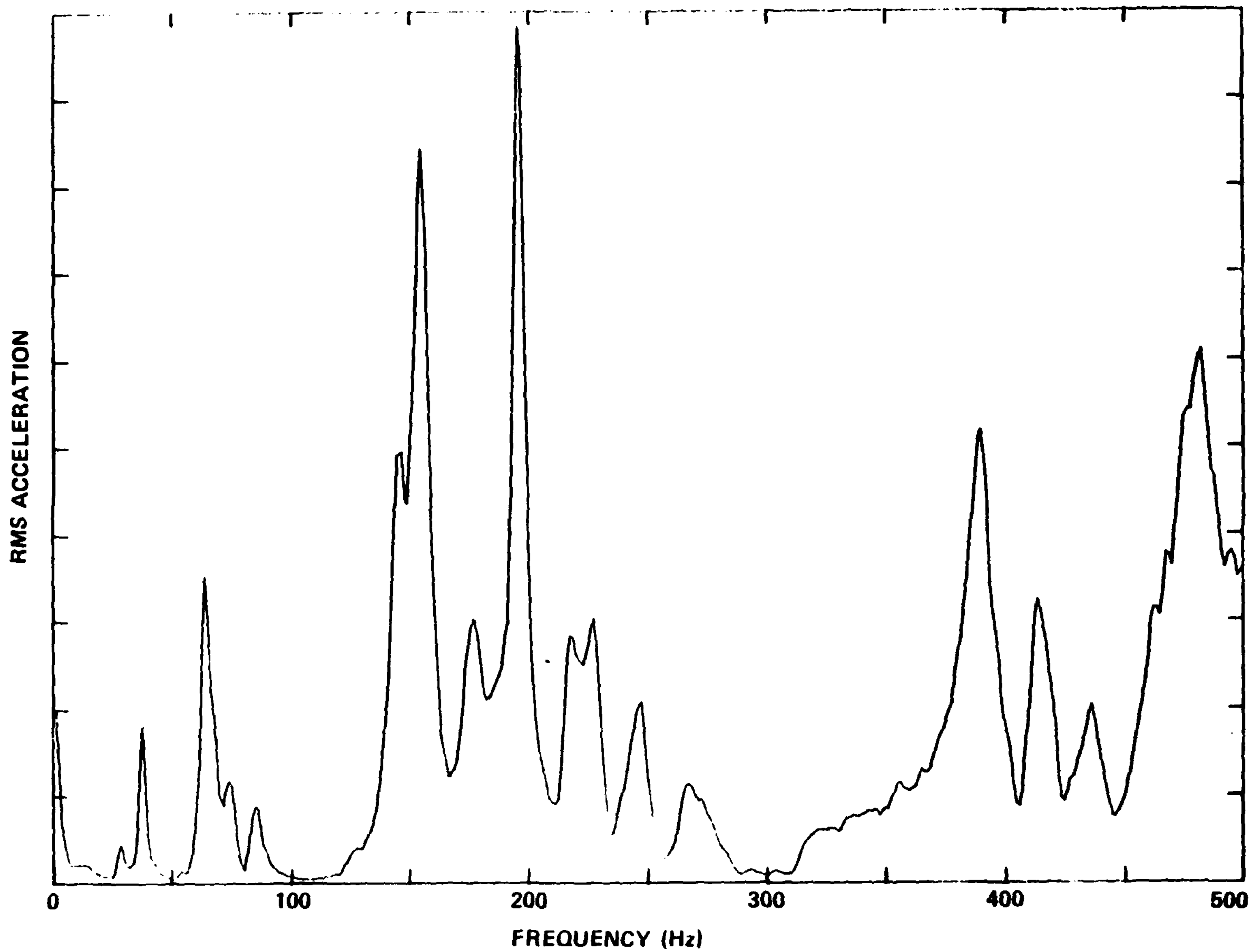


Fig. 15. Accelerometer spectrum, white noise acoustic excitation.

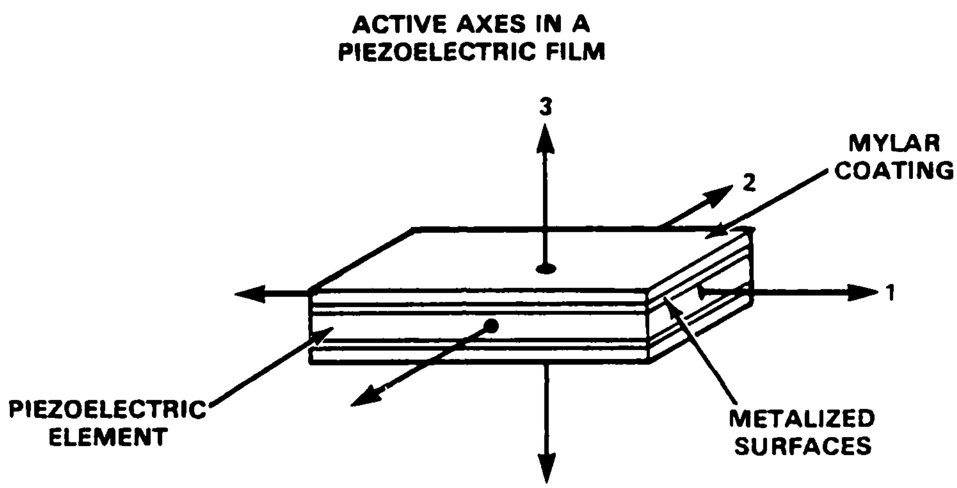


Fig. 16. Section of piezoelectric film strip.

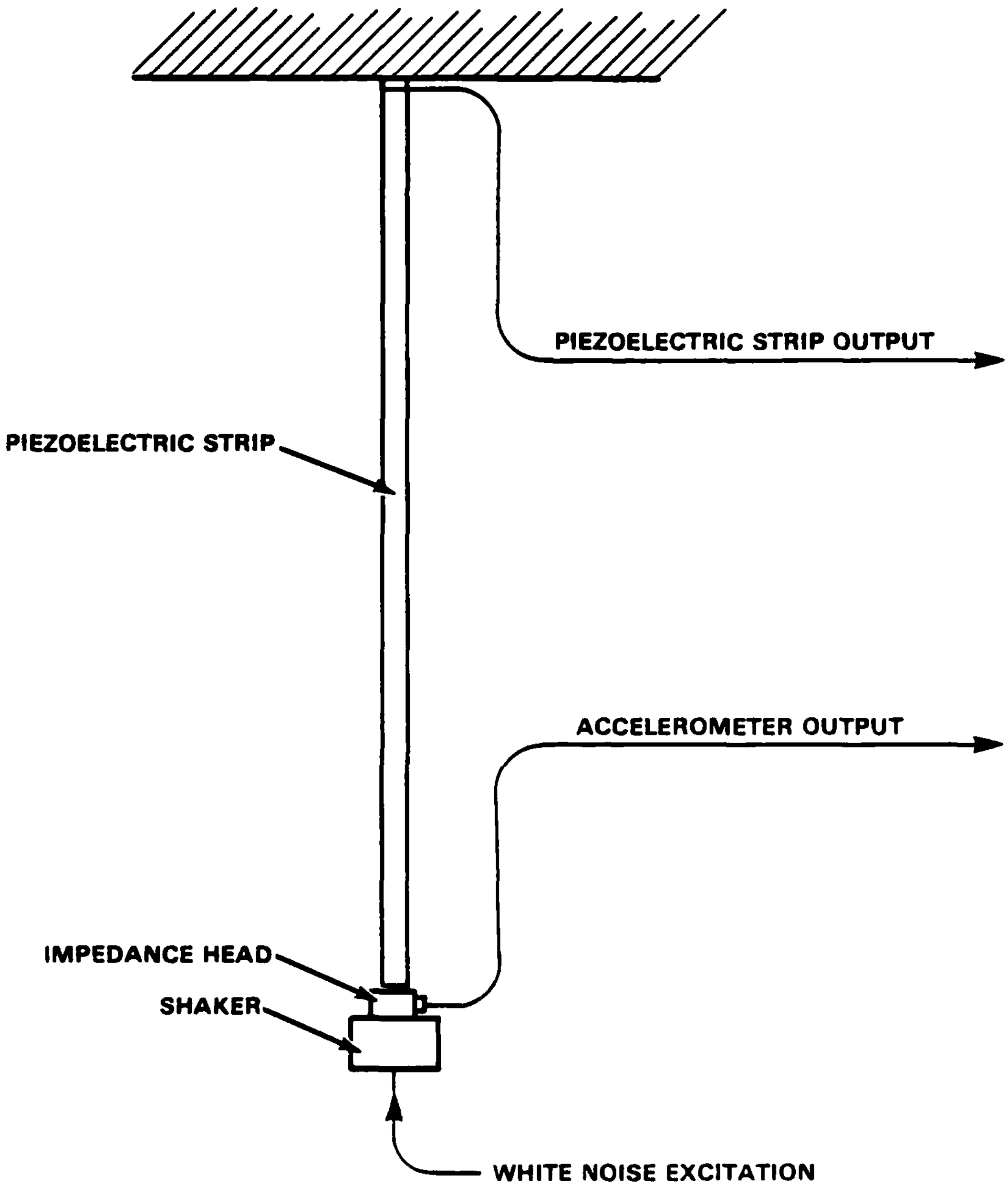


Fig. 17. Experimental setup for characterizing piezoelectric strip.

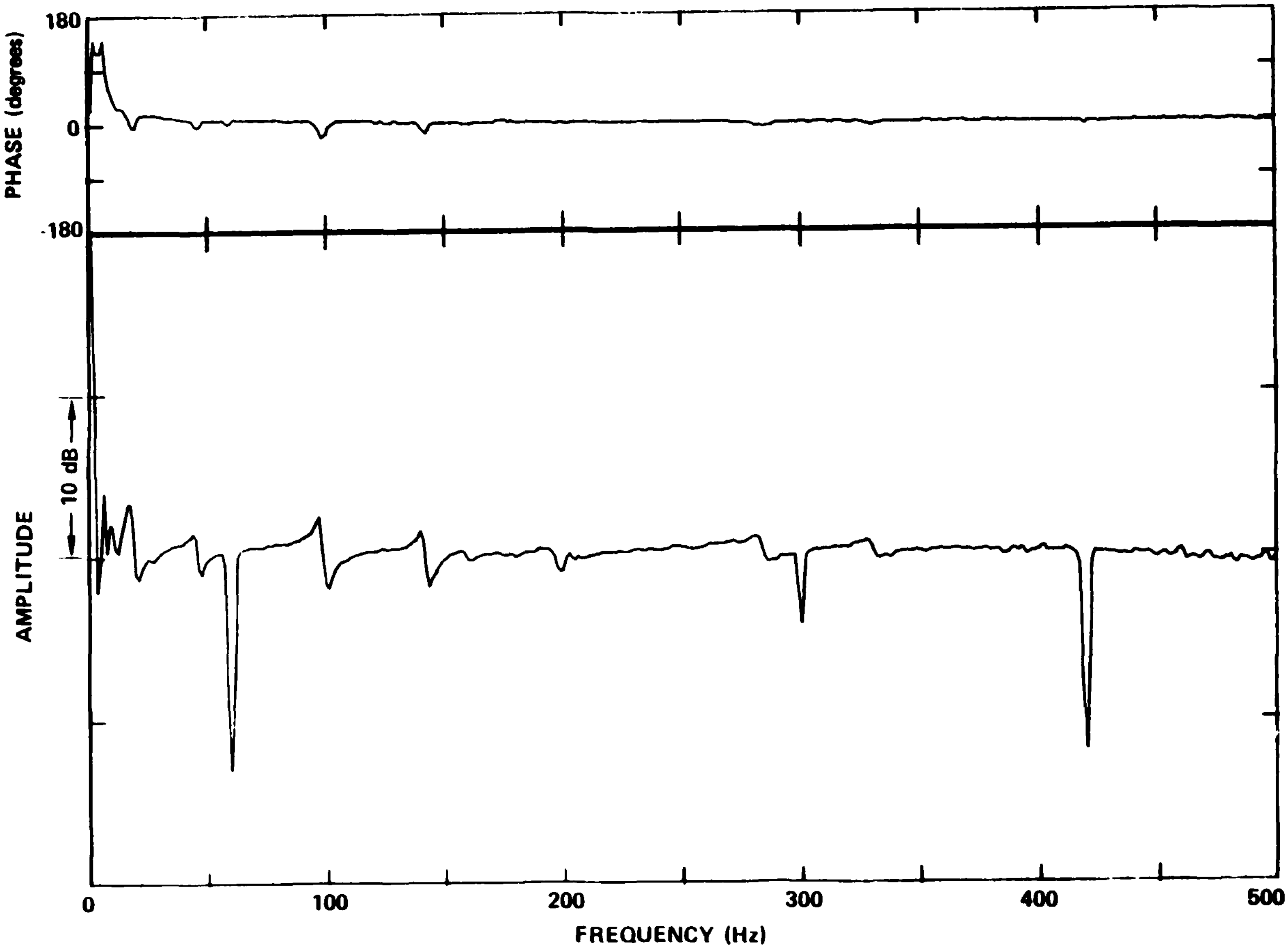


Fig. 18. Ratio of piezoelectric strip output to excitation displacement.

Fig. 19. Piezoelectric strip attached to pipe wall.

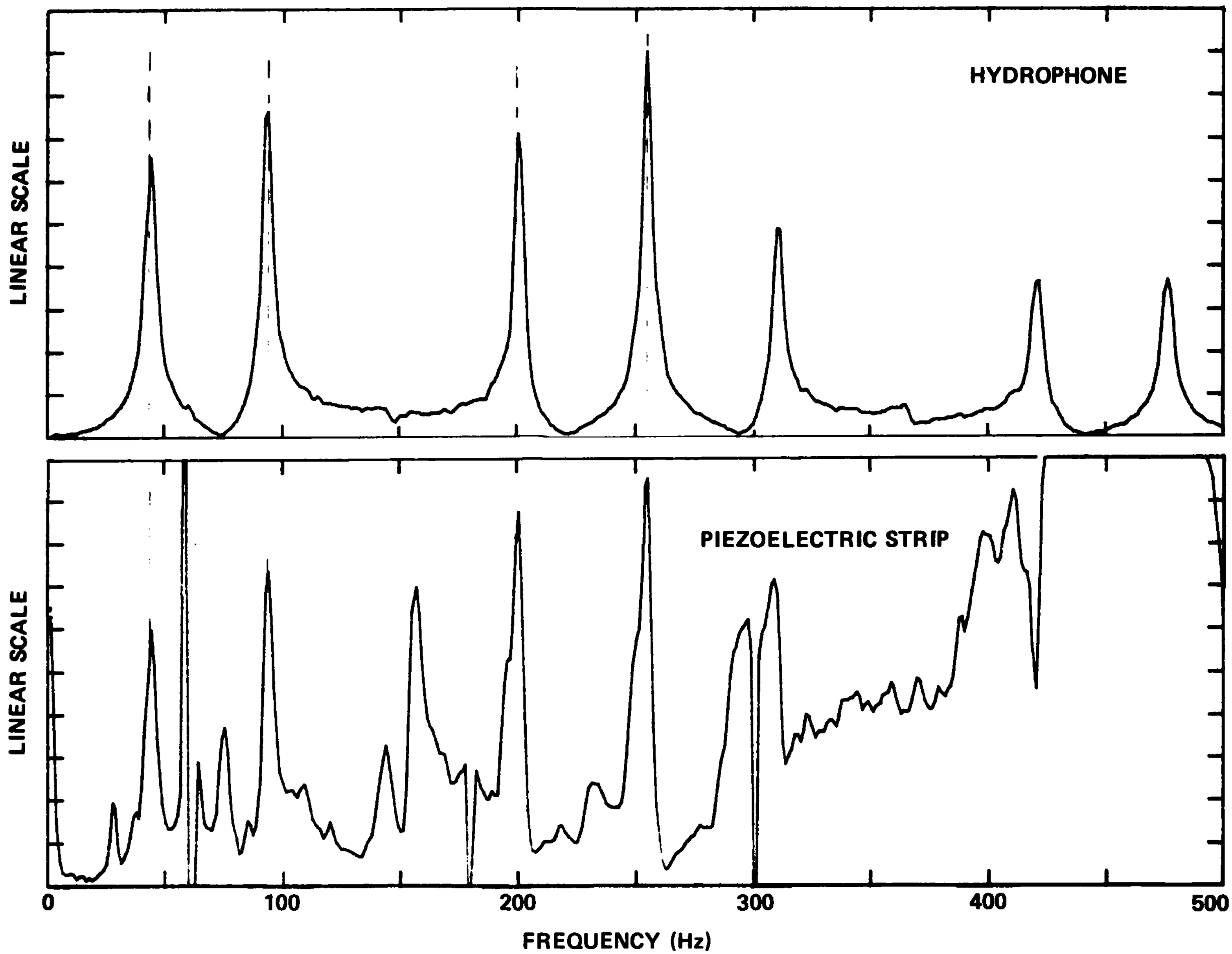


Fig. 20. Comparison of piezoelectric strip output with hydrophone output.

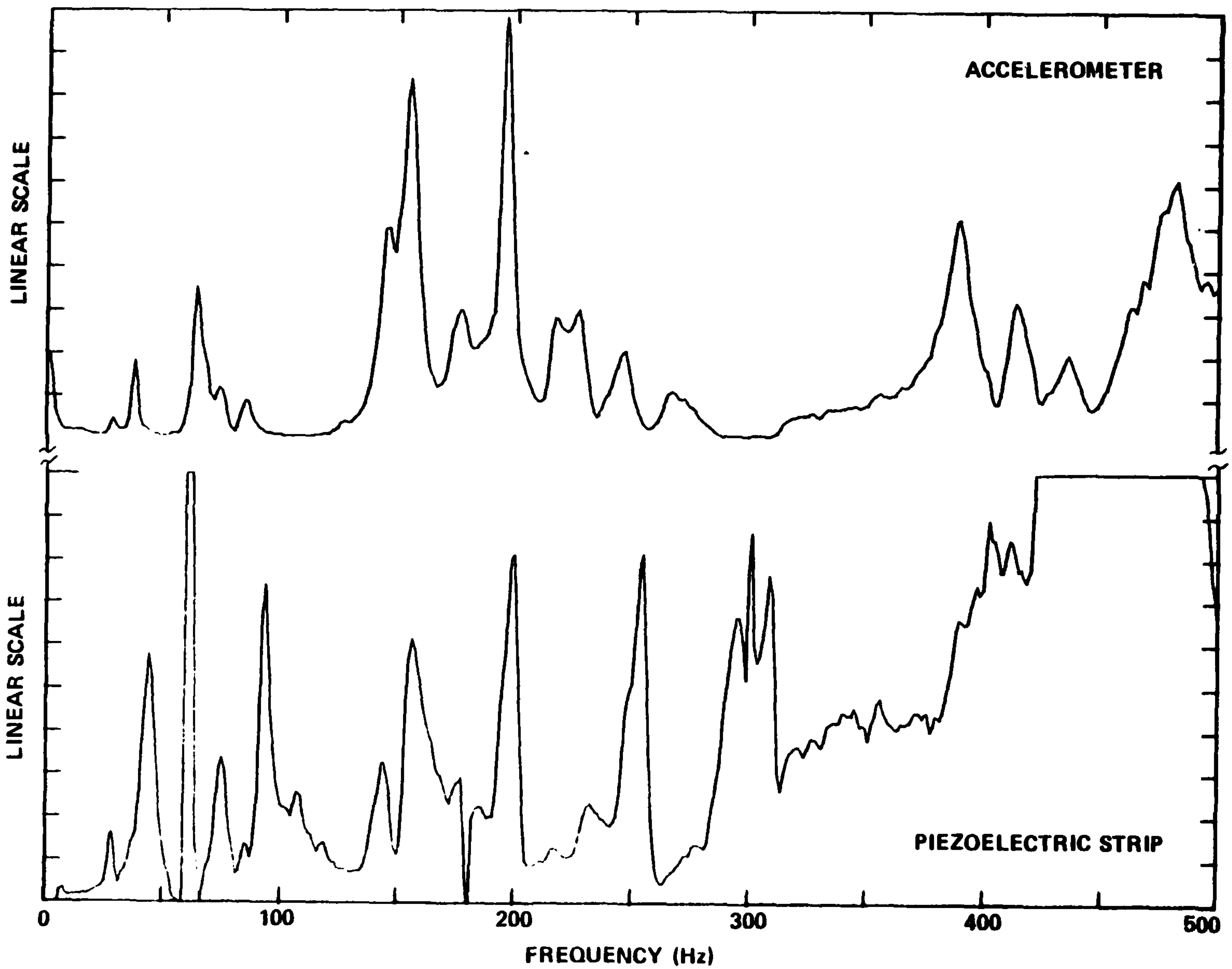


Fig. 21. Comparison of piezoelectric strip output with accelerometer output.

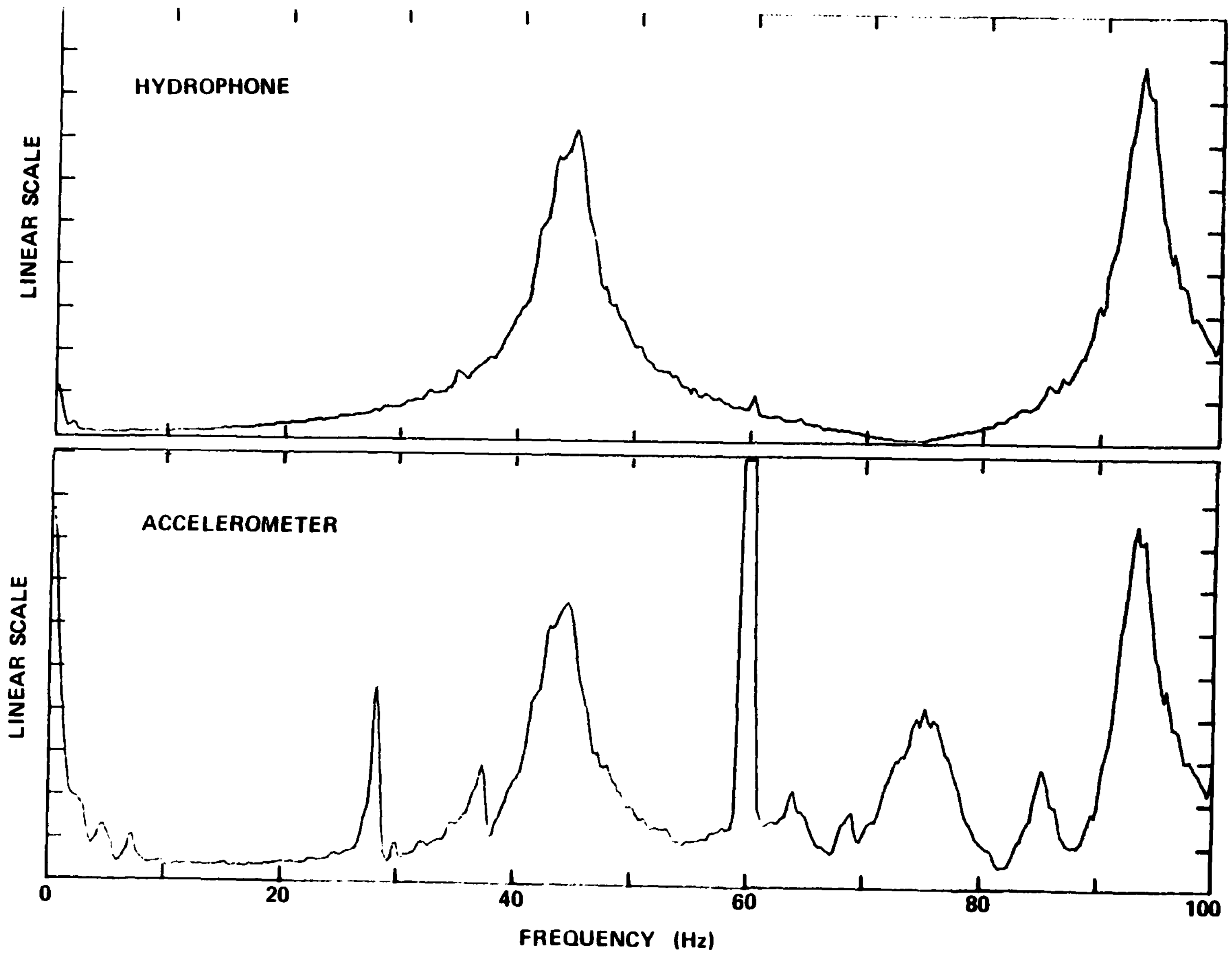


Fig. 22. Comparison of piezoelectric strip output with hydrophone output 0-100 Hz excitation.

REFERENCES

1. Olson, H. F., "System Response to the Energy of Sound Waves," U. S. Patent No. 1,892,644 (1932).
2. Clapp, C. W. and F. A. Firestone, "Acoustic Wattmeter," J. Acoust. Soc. Am, Vol. 13, pp. 124-136 (1941).
3. Schultz, T. J., "Acoustic Wattmeter," J. Acoust. Soc. Am., Vol 28, No. 4 pp. 693-699 (1956).
4. van Zyk, B. G. and F. Anderson, "Evaluation of the Intensity Method of Sound Power Determination," J. Acoust. Soc. Am, Vol. 57, No. 3 pp. 682-686 (1975).
5. Fahy, F. J., "Measurements of Acoustic Intensity Meter using the Cross-Spectral Density of Two Microphone Sensors," J. Acoust. Soc. Am., Vol. 62, No. 4, pp. 1057-1059 (1977).
6. Chung, J. Y., "Cross-Spectral Method of Measuring Acoustic Intensity Without Error Caused by Instrument Phase Mismatch," J. Acoust. Soc. Am. Vol. 64, No. 6, pp. 1613-1617 (1978).
7. Noiseux, D. U., "Measurement of Power Flow in Uniform Beams and Plates," J. Acoust. Soc. Am., Vol. 47, No. 1, pp. 238-247 (1970).
8. Lotz, R. and Stephen Crandall, "Prediction and Measurement of the Proportionality Constants in Statistical Energy Analysis of Structure," J. Acoust. Soc. Am. Vol. 52, No. 2, pp. 516-524 (1973)
9. Fahy, F. and R. Pierri, "Application of Cross Spectral Density to a Measurement of Vibration Power Flow Between Coupled Plates," J. Acoust. Soc. Am., Vol. 62, No. 5 pp. 1927-1928 (1977).
10. Verheij, J. W. and C. van Ruiten, "On the Measurement of Structureborne Energy Flow Along Pipes, Part 3: Analysis of Systematic and Random Errors," Report 308.785, Institute of Applied Physics TNO-14th, Delft (1983).

11. Rasmussen, G., "Measurement of Vibration Intensity," J. Acoust. Soc. Am., Suppl 1, Vol. 72, Q5(A) (1982)

12. Carroll, G. P., "Structural Intensity Measurements in Beams," DTNSRDC Report 86/017 (April 1986).

13. Pavic, G., "Determination of Sound Power Flow in Structures," Proceedings of International Congress on Recent Developments in Acoustic Intensity Measurements, (CETIM) Senlis, France (1981)

14. Pascal, J. C. and Carles, C., "Systematic Measurement Errors with Two Microphone Sound Intensity Meters," J. Sound Vib., Vol. 83, No. 1, pp. 53-65 (1982).

15. Bies, D. A. and C. J. Hansen, "Impedance Tube Calibration of a Reverberant Room for the Measurement of Sound Power in Tones," J. Acoust. Soc. of America, Vol. 59, No. 6 (1976)

16. Cremer, L., M. Heckl, and E. E. Ungar, "Structureborne Sound," Springer-Verlag, New York, p. 95 (1973).

17. Arnold, R. N. and G. B. Warburton, "The Flexural Vibrations of Thin Cylinders," Institute of Mechanical Engineers Proceedings, Section A; Vol. 169, pp. 62-80 (1953).

18. Carlisle, B., "Piezoelectric Plastics Promise New Sensors." Machine Design, Vol. 58, No. 25 (Oct 1986).

19. Chatigny, J. and L. Robb, "Piezo Film Sensors," Sensors, Vol. 3, No. 5. (May 1986).

20. Kinsler, L. and A. Frey, Fundamentals of Acoustics, Wiley and Sons, inc. New York (1962).

21. Seybert, A. F. "Statistical Errors in Acoustic Intensity Measurements," J. Sound Vib., Vol. 75, No. 4, pp. 519-526 (1981).

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