Sound propagation in a pipe containing a liquid of comparable acoustic impedance

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A detailed experimental study of sound propagation in liquids contained by pipes constructed of polymeric materials is discussed. Experiments were conducted with vertically aligned cylinders containing water ensonified at one end by a piston-driven sound source. Significant sound attenuation (as much as 60 dB) was observed in pipes made of flexible polymeric materials, the effect increasing with frequency and loss tangent. Sound propagation in more rigid polymeric pipes exhibited similar characteristics to that in metallic pipe in that negligible attenuation was observed. In this latter case, a comparison was made with recent analytical work for which excellent agreement was obtained.

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INTRODUCTION

A significant body of theoretical and experimental work has been done in the past on propagating wave phenomena within elastic tubes containing fluids. Most generally, concentration has centered about the influence of wall elasticity on the propagation of sound waves through compressible media such as air and nearly incompressible liquids such as water.¹⁻⁵ These studies can be segregated into low-frequency propagation, where the pressure is essentially planar across a wave front and high-frequency propagation, where the axisymmetric wave front becomes nonplanar. Also of practical interest is that general classification of studies concerning both types of wave propagation in flexible tubes with viscoelastic properties.^{6,7} For this case relatively little data has been presented in the literature.

The present paper attempts to remedy this lack of data by reporting a detailed experimental study of sound propagation within liquids contained by polymeric materials with a range of viscoleastic properties. In our circumstances, densities and bulk wave propagation velocities associated with the solid and liquid media are comparable in magnitude. (Previously reported experiments have been conducted almost entirely with pipe wall materials of substantially larger values of these parameters than for the contained fluid.) Sound pressure level (SPL) is reported as a function of axial position in the liquid column, frequency, and pipe wall material. The results indicate the degree of attenuation of propagating sound that can be realized by an appropriate choice of duct wall composition. The SPL is also examined in one pipe wall construction (acrylic) to establish the parameteric ranges over which the propagating wave in the pipe is not only axisymmetric but also nearly planar. The extent to which energy input may affect the characteristics of the moving piston used to ensonify the liquid column is commented upon and a comparison to a recent analytical study⁸ is presented.

I. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental setup used in the present study is shown in Fig. 1. It consisted of a piston-driven sound source, rigid test stand, and a 1.829-m-long pipe section with rigid flanges at both ends. The fluid column (water) was excited by the sound source and an omnidirectional hydrophone (on the pipe centerline) was used to measure the pressure spectra. Particular care was taken to mechanically isolate the sound source from the pipe segment, thereby preventing direct excitation of the pipe walls. Detailed measurements of sound pressure level were made as a function of frequency, location in the liquid column, and pipe wall material over a total bandwidth of 1 kHz. In addition to the hydrophone shown in Fig. 1, one pipe section (acrylic) was instrumented with flush-mounted pressure sensors on the interior wall (located 1.372 m above the sound source) which, together with the omnidirectional hydrophone at various radial locations, were helpful in determining the frequency range over which the propagating wave in the pipe was nearly planar. Accelerometers were mounted both on the pipe wall and the test stand to determine structural vibration modes and their interaction with the fluid column.

As indicated in Fig. 1, two methods of obtaining the data were available. The sound source could be driven



FIG. 1. Schematic of test apparatus.

- 1. FFT analyzer-Nicolet Scientific Corporation Model 0-400, range: 0 to 100 kHz
- 2. Random noise generator-General Radio Co. Type 1390-A, range: 0 to 5 MHz
- 3. XY-plotter-Hewlett Packard No. 136A
- 4. Amplifier-Ithaca Model 252-AM, range: -20 to +60 dB, 1-dB steps
- 5. Power amplifier-Ling Electronics TD-450
- 6. Tracking filter-Spectral Dynamics Corporation Model SD 131L

7.	Sweep oscillator-Spec	tral Dynamics Corporation Model SD	104A-5, range: 5 Hz to 5 KH	[z
8.	Sound sources	Size	Range	
	J9—USRD	5.7 cm	40 Hz-20 KHz	
	J11—USRD	10.0 cm	20 Hz-12 KHz	
9.	Hydrophones	Sensitivity (Ref. 1 V/µPa)	Diameter	
9.	Omnidirectional	-210.0 dB	2.54 cm	
	Flush-mount	-202.0 dB	0.23 cm	

with a white noise generator and the fast-Fouriertransform analyzer used to obtain pressure spectra. Virtually identical results were obtained with the alternative technique of using the sweep oscillator and tracking filter. However, the latter method was utilized in the experiments reported herein because it provided more precise results and was easier to calibrate. Table I lists the pertinent characteristics of the instrumentation and hydrophones used in the investigation.

Pipes constructed of five materials were employed in the study and their physical properties are 'given in Table II. The steel, acrylic, and polyvinylchloride pipes consisted of single 1.829-m-long sections of the diameters indicated. The rubber and hypalon sections (General Rubber Company "Sound Zorbers") were fiber-reinforced pipes obtained in 60.96 cm long, 20.32cm diameter sections. Each section was lined with a 0.635-cm-thick, silicone rubber lining to give them the same diameter as the acrylic and PVC sections. Three sections of each of these two materials were joined to give a single pipe of equivalent length to those made of the other three materials.

In order to assess the possible influence on the experimental results by the size of the moving piston used to ensonify the liquid column, characterization of the SPL in two pipe materials was conducted both with the large and small sound sources (piston diameters of 10.00 and 5.70 cm, respectively). The pressure spectrum was tabulated at 5.08 cm above the sound source and every 30.48 cm thereafter along the pipe centerline. Both sound sources were driven at the same input power level in experiments with the second and fourth pipe materials listed in Table II. In addition, the large sound source was driven at full and half-power for the acrylic pipe to establish that the input power level was proportional to the measured acoustic levels over the frequency range studied.

Finally, the SPL on the centerline of all five pipe materials was compared at a fixed axial position relative to the large sound source as a measure of the sound attenuation in the liquid column which may be realized by an appropriate choice of duct wall material.

II. RESULTS AND DISCUSSION

A. Initial conditions and energy input

The effects of the size of the piston face on the resultant pressure spectrum are shown in Figs. 2 and 3 for acrylic and rubber pipe segments, respectively, where the ratios of the SPL at 91. 44 cm to that at 5.08 cm (along the pipe centerline) are plotted. In these, and subsequent figures, P_i^* is the normalized pressure ratio P_c/P_0 where P_c is the centerline pressure at a specific axial location and P_0 is the centerline pressure at 5.08 cm. The results for the large and small sound sources in each pipe are qualitatively similar. Resonant peaks occur at identical frequencies with both sound sources. The amplitudes of these peaks are greater for the large sound source than for the smaller

TABLE II.	Pipe	material	characteristics
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Туре	Length (cm)	Wall thickness (cm)	Inside diameter (cm)	Density (g/cc)	Elastic modulus (GPa)	
Steel	182.90	0.953	20,32	7.8	200.0	0.001
Acrylic	182.90	0.635	19,05	1.18	2.4	~0.08
Polyvinylchloride (PVC)	182.90	1.365	19,05	1.38	2.8	~0.08
Silicone-lined rubber	182.90	2.54	19.05	0,93	0.20-0.35	0.12-0.15
Silicone-lined hypalon	182.90	2.54	19.05	1,12-1.28	0.08-0.31	0.16-0.95



FIG. 2. Ratio of acoustic pressure recorded at axial positions of 91.4 and 5.1 cm for acrylic pipe.

one (as much as 10 dB for the rubber pipe). This amplitude difference is readily explained. The acoustic energy propagating away from the source will be nearly constant over that portion of the pipe cross-sectional area adjacent to the piston face and zero over the remainder. The hydrophone measurement made at 5.08 cm from the source is influenced only by that portion of the distribution over the sound source. As the wave propagates along the pipe, the energy becomes more uniformly distributed over the pipe cross section. Thus the ratios of the SPL shown in Figs. 2 and 3 have lower peak amplitudes for the smaller sound source due to the normalizing pressure being larger relative to the average value over the whole pipe cross section where the piston is located. In quantitative terms, the average pressure, P_{av} can be expressed as

$$P_{av} = \frac{1}{A_{p}} \int P \, dA \,, \tag{1}$$



FIG. 3. Ratio of acoustic pressure recorded at axial positions of 91.4 and 5.1 cm for rubber pipe.



FIG. 4. Radial variation of acoustic pressure at 1.372 m from the sound source in acrylic pipe.

where A_{p} is the pipe cross-sectional area, A is the piston area, and P is the effective pressure (as a function of radius) generated at the piston face. If the sound pressure level is assumed a constant amplitude P_{0} over the moving piston and zero elsewhere in the pipe cross section, then for circular areas Eq. (1) reduces to

$$P_{av} = P_0 (r_0 / r_p)^2 , \qquad (2)$$

where the subscripts are defined as indicated above. For a pipe segment diameter of 19.05 cm, the peak log ratios shown in Figs. 2 and 3 would increase by approximately 10 dB more for the smaller sound source than the larger one. As indicated, the differences in peak values with the two sound sources are in satisfactory agreement with this simplified analysis.

On a similar note, results obtained with the large sound source established the linear relationship between input acoustic power and recorded acoustic levels at various locations in the liquid column. When comparing pressure ratios, no variation was found to exist between results obtained when driving the large sound source at full and half-power in any of the five pipe materials used.

B. Radial pressure distribution

At 1.372 m above the large sound source, the pressure spectrum was measured at various radial positions. These results, along with that of a flush-mounted sensor located on the interior wall of the acrylic pipe, are compared in Fig. 4. Two points of interest are noted. First, the zeroth-order axisymmetric mode is seen to be nearly planar up to approximately 300 Hz by observing the omnidirectional hydrophone output $(r/r_{\phi} = 0.5, 0.75)$. Thereafter, the wavelength of the propagating wave approaches the pipe diameter, and the radial distribution begins to be frequency dependent.

The experimentally observed radial pressure distribution compares favorably with that which is anticipated from the analytical work by Junger.³ For the case where the ratio

$$(c_a/c)^2 \ll 1$$
, (3)

which is characteristic of the present experimental

work,

$$(P/P_c) = I_0(\omega r/c_a). \tag{4}$$

Here c_a is the propagation velocity of an axisymmetric pressure wave in the pipe fluid and c the propagation velocity of a plane acoustic wave in an infinite domain of the liquid. P and P_c denote the pressures at radius r and on the pipe centerline, respectively, and ω denotes frequency in rad/s. The relationship of c_a to c_{a0} (c_{a0} being the quantity corresponding to c_a in the lowfrequency limit) takes the following form in these circumstances:

$$\left(\frac{c_a}{c_{a0}}\right) = \frac{1 - \nu^2 + (x^4/12)(h/a)^2}{(1 - \nu^2)(x^2/2)[\rho/\rho_i(h/a) + I_0(x)/xI_1(x)]}.$$
 (5)

Here ν , h, and a denote Poisson's ratio, tube wall thickness, and radius, respectively, while ρ and ρ_i are the densities of the tube wall and the interior liquid. $I_0(x)$ and $I_1(x)$ represent modified Bessel functions of the first kind (of order 0 and 1, respectively) and x equals $\omega a/c_a$. The solid lines in Fig. 4 are representative of Eqs. (4) and (5).

The flush-mounted sensor output (at $r/r_p = 1.0$) deviates somewhat from that predicted by the theoretical analysis. In particular, the increase in the ratio P/P_e is quite substantial in the 0- to 300-Hz range. Above 300 Hz, the experimentally measured pressure ratio increases with frequency at about the same rate as the theoretically predicted result. In this higher frequency range, the difference in the absolute value of the experimentally measured and theoretically predicted results differs by slightly more than 3 dB, about the same as the difference at 30 Hz. The explanation for the observed difference is not known with certainty at the present time. One possibility is that the wall-mounted transducer is sufficiently vibration sensitive that its output is influenced by the radial motion of the pipe wall as well as by the pressure imposed by the liquid column. This suggestion is consistent with the accelerometer data obtained during the experiments.

The second point of interest is reflected by the appropriate 2-7-dB increase in pressure at higher frequencies as demonstrated by the results (at 1000 Hz) indicated in Fig. 4. Acrylic pipe, although less rigid than steel, has a considerably higher elastic modulus than rubber and hypalon (see Table II). It is therefore expected that even greater pressure variations would be observed in these pipes, with the propagating axisymmetric wave being planar over a correspondingly lower frequency range.

C. Attenuation characteristics

Figures 5 and 6 show the more practically important results of this investigation. The SPL was measured (along the pipe centerline) at an axial distance of 91.44 cm from the sound source in pipes constructed of all five pipe materials. Table II has indicated the similar properties of the acrylic and PVC pipe segments and this is reflected by the similar magnitudes and peak frequencies in Fig. 5. However, due to the larger PVC wall thickness and its slightly larger density, the reso-



FIG. 5. Comparison of attenuation characteristics between steel and the polymeric pipe materials at 91,44 cm.

nant peaks for PVC have uniformly shifted to slightly higher frequencies. In both cases, the resonant peaks occur at approximately

$$f = 100 \text{ Hz} (2n+1), n = 0, 1, 2...$$
 (6)

As depicted in Fig. 5, the PVC and acrylic pipes have a somewhat lower SPL at the first resonant frequency of 300 Hz for the steel pipe. This is due to the negligible loss tangent of the latter material. [It should be noted that the second apparent peak at about 700 Hz for steel is due to structural resonance only, for by adding mass to the base, this peak could be reduced without changing any of the pressure spectra (see Fig. 9).]

Using the acrylic results from Fig. 5 for comparison a considerable amount of attenuation is observed in Fig. 6 for the rubber and hypalon pipe materials. This attenuation becomes evident at the first resonant peak, reducing it in amplitude by slightly more than 10 dB. It becomes larger with increasing frequency, approaching 15 and more than 60 dB at 1000 Hz in the



FIG. 6. Comparison of attenuation characteristics between viscoelastic materials and the more rigid acrylic pipe at 91.44 cm.



FIG. 7. Acrylic and rubber attenuation properties at larger axial normalizing position (30.48 cm).

rubber and hypalon sections, respectively. The shear storage modulus G', and loss modulus G'', were measured for the rubber and hypalon materials using a Weissenberg Rheogoniometer, model R18. The loss tangent δ was somewhat frequency dependent over the bandwidth investigated with a much larger value for hypalon at 1000 Hz (see Table II), which is explicitly represented in the results of Fig. 6. These combined results indicate the distinct advantage to which visco-elastic materials (with high loss tangent) may be used to eliminate extraneous sound within experimental and industrial facilities.

Referring back to Sec. II A one might well ask if the pressure variation introduced by the finite diameter of the second source (at 5.08 cm) is contributing to these large attenuation characteristics. Therefore a similar log ratio for acrylic and rubber is presented in Fig. 7, in which case a measurement at 30.48 cm from the sound source was used to normalize the pressure spectra. As shown in Fig. 7, the attenuation characteristics of Fig. 6 are substantiated with the



FIG. 8. Comparison of acrylic SPL to theory.



FIG. 9. Comparison of steel SPL to theory.

slightly smaller differences indicative of the closer spacing of the two measuring positions.

Finally, Figs. 8 and 9 show a comparison of the acrylic and steel results to recent analytical work of Skop.⁸ As illustrated, excellent agreement is obtained. The slightly higher amplitudes of the theoretical peaks are due to the magnitude of the value chosen for the complex moduli of elasticity for the two materials.

III. CONCLUSIONS

An experimental study of sound propagation in liquidfilled ducts has established the utility of viscoelastic wall materials for sound attenuation within piping systems. The effectiveness of such materials for attenuation purposes increases with frequency over the range of parameters considered. As would be expected intuitively, the effective materials have low shear moduli and high loss tangents. Pipes made of polymeric materials such as acrylic and polyvinylchloride (PVC), which do not have these characteristics at room temperatures and over the frequency range considered, exhibit relatively small degree of sound attenuation. Viscoelastic materials appear to offer the potential of much needed sound attenuation in experimental and industrial piping configurations where sound filters, such as large cavities or sound baffles, are flow restrictive and therefore prohibited. The chief disadvantage appears to be their lesser effectiveness at very low freguencies.

The experimental results obtained in the more rigid pipes have been compared in detail with previous analytical treatments. Excellent agreement has been found except for the radial pressure distribution at the pipe wall. This one discrepancy may be due to the vibration sensitivity of the flush-mounted probe employed.

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