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Rapid Communication

Measurement of dilatational wave speed using an echo reduction test

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Abstract

Echo reduction is a measure of a materials ability to reduce the reflection of acoustic energy and is a typical measurement performed in acoustic tanks. In this paper, an inverse method is developed to estimate the complex dilatational wave speed of a material using echo reduction data. The theory of echo reduction is briefly discussed, the inverse method is developed and then an experiment is conducted to illustrate the technique. The real parts of the resultant wave speed measurements are then compared to measurements using identification of discrete wavelengths. It is shown that the two measurement techniques produce extremely similar estimates.
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1. Introduction

Echo reduction is calculated by projecting acoustic energy at a piece of material, typically a rectangular shaped slab, and then measuring the reflected pressure on the projector side (Fig. 1). Typically, a finite length duration sinusoidal pulse is projected and the waveform is measured twice, once when it passes by the hydrophone as it travels to the material, and a second time when it reflects off the material and returns back past the hydrophone. These two time domain measurements are time shifted so that they are in alignment, amplitude adjusted to account for spherical spreading loss, and then Fourier transformed, resulting in measurement of the echo reduction of the material in the frequency domain. For underwater applications, the test specimen is submerged in water and an underwater speaker or projector transmits energy at the material.

Measurement of material properties has been an ongoing research area for many years. Resonant techniques [1,2] consist of identifying closed-form natural frequencies of the structures and finding the corresponding resonance in a test, usually on a slender object. Once this is accomplished, material properties can be estimated. Resonant techniques have been extended to determine material properties of plates [3].

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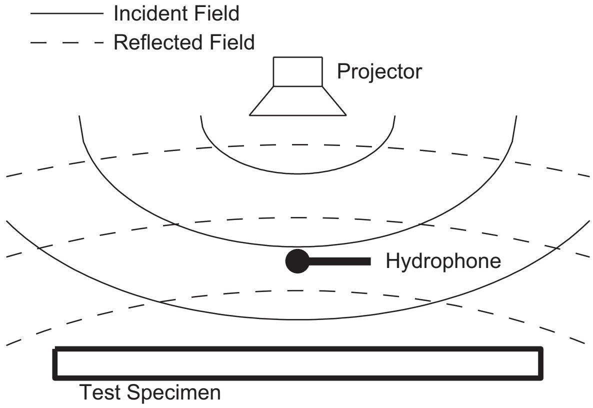

Fig. 1. Echo reduction laboratory configuration.

These methods typically produce estimates for Young's modulus and shear modulus. Non-resonant methods have also been developed for slender materials that typically consist of inverting a transfer function that is equal to data to yield closed form estimates of material properties [4–6]. Sensitivity issues regarding non-resonant methods have been investigated [7]. The frequency dependences of moduli and Poisson's ratio have been discussed [8]. In two separate papers, the measurement of dilatational wave speed was accomplished using an insertion loss measurement [9,10] by exploiting phase angle data. This method was further extended to measure the shear wave speed during an insertion loss measurement [11]. Material properties can also be estimated using impedance tubes [12]. This is accomplished by using the complex impedance measurement of a sample to calculate the material properties.

This paper develops a method to measure the complex dilatational wave speed of a panel subjected to a submerged echo reduction test. An echo reduction test is a common test of a material that determines how effectively it is reducing the strength of reflected acoustic energy after it has been insonified. Because this is a common test, it is desirable to have a technique to measure not just the amount of echo reduction but also to estimate the material properties of the panel. For an echo reduction test with a broadside projector, dilatational waves are excited in the panel, and the method proposed here derives a numerical method to determine the complex wave speed of the dilatational wave in the material. The dilatational wave is commonly also called the acoustic wave or the speed of sound in the material. It is noted that for a finite sized test specimen, wavenumber conversion may occur at the boundary, and some low level shear wave energy may be present, especially near the edges.

2. System model and inverse method

Echo reduction is defined as the ratio of the incident (incoming) acoustic energy to the reflected (outgoing) energy and is typically expressed in a decibel scale. The equation for echo reduction on a submerged panel with the incident wave arriving at broadside can be written in closed form as [13]

$$E(\omega) = \frac{P_I(\omega)}{P_R(\omega)} = \left[\frac{\mathrm{i}2\rho_f c_f \rho c_d \cot\left(\dfrac{\omega}{c_d} h\right) + \rho^2 c_d^2 + \rho_f^2 c_f^2}{\rho^2 c_d^2 - \rho_f^2 c_f^2} \right] \exp\left(-\mathrm{i}2\frac{\omega}{c_f} z_h\right) \exp(\mathrm{i}\omega\delta), \tag{1}$$

where $P_I(\omega)$ is the incident field (N m^{-2}), $P_R(\omega)$ is the reflected field (N m^{-2}), ρ_f is the density of the fluid (kg m^{-3}), c_f is the compressional wave speed of the fluid (m s^{-1}), ρ is the density of the panel (kg m^{-3}), c_d is the unknown complex dilatational wave speed of the panel (m s^{-1}), h is the thickness of the panel (m), z_h is the distance of the hydrophone to the panel (m), ω is frequency of excitation (rad s^{-1}), δ is the amount of time shifting of the Fourier transform (s), and i is the square root of -1. The time shifting of the Fourier transform is necessary because the acoustic water tank where the experiment takes place is finite and continuous transmission of energy will cause unwanted reflections off the tank walls. Because of this, the experiment consists of three continuous cycles of sine waves that are propagated onto the panel. Using time shifting, the incident and reflected pressure waves can be separated and then used to compute the measured echo reduction.

A Newton–Raphson iterative method is now derived to estimate the complex dilatational wave speed in the panel. It is noted that the expression given in Eq. (1) is almost unbounded at specific frequencies, and the corresponding derivatives are numerically unstable at these locations. To avoid this problem entirely, the reciprocal of the echo reduction term is used in the iterative estimation process. This expression is given by

$$M(\omega) = \frac{P_R(\omega)}{P_I(\omega)} = \left[\frac{\rho^2 c_d^2 - \rho_f^2 c_f^2}{\mathrm{i}2\rho_f c_f \rho c_d \cot\left(\frac{\omega}{c_d}h\right) + \rho^2 c_d^2 + \rho_f^2 c_f^2}\right] \exp\left(\mathrm{i}2\frac{\omega}{c_f}z_h\right)\exp(-\mathrm{i}\omega\delta). \tag{2}$$

Using Eq. (2), the Newton–Raphson iterative method is derived to estimate the complex dilatational wave speed in the panel. To increase the numerical stability of this process, the problem is broken down into its real and imaginary components. This equation is written at every frequency as

$$\begin{bmatrix}\mathrm{Re}(c_d)\\ \mathrm{Im}(c_d)\end{bmatrix}_{j+1} = \begin{bmatrix}\mathrm{Re}(c_d)\\ \mathrm{Im}(c_d)\end{bmatrix}_{j} - \left\{\begin{matrix}\mathrm{Re}\left[\frac{\partial M}{\partial\,\mathrm{Re}(c_d)}\right] & \mathrm{Re}\left[\frac{\partial M}{\partial\,\mathrm{Im}(c_d)}\right]\\ \mathrm{Im}\left[\frac{\partial M}{\partial\,\mathrm{Re}(c_d)}\right] & \mathrm{Im}\left[\frac{\partial M}{\partial\,\mathrm{Im}(c_d)}\right]\end{matrix}\right\}_j^{-1} \begin{bmatrix}\mathrm{Re}(M) - \mathrm{Re}(D)\\ \mathrm{Im}(M) - \mathrm{Im}(D)\end{bmatrix}_j, \tag{3}$$

where D represents data from the experiment at each measurement frequency and j is the iteration number at a fixed frequency. When Eq. (3) is applied to the measurements, the complex dilatational wave speed at every measurement frequency can be estimated.

3. Experiment

Echo reduction data versus frequency were measured for a panel of urethane manufactured by H.B. Fuller Company that has the trade name Uralite FH3140. These are shown as the solid line in Fig. 2. The top plot is the magnitude in the decibel scale and the bottom plot is the phase angle expressed in degrees. The abscissa of both plots is the frequency in kilohertz. Directly measurable (known) parameters of the urethane are thickness $h = 0.0254\,\mathrm{m}$ and density $\rho = 1186\,\mathrm{kg\,m^{-3}}$. The water in the acoustic tank had a compressional wave speed $c_f = 1468\,\mathrm{m\,s^{-1}}$ and a density $\rho_f = 1000\,\mathrm{kg\,m^{-3}}$. The time delay of the measurement was $\delta = 0.0010\,\mathrm{s}$ and the distance from the hydrophone to the plate was $z_b = 0.7468\,\mathrm{m}$. The panel size was $0.762\,\mathrm{m} \times 0.840\,\mathrm{m}$ and this allowed dispersion free measurements above 15 kHz. The test was conducted up to 100 kHz and a data point was recorded every 250 Hz. The tank used was the Acoustic Test Facility at the Naval Undersea Warfare Center in Newport, Rhode Island. This tank measures approximately $18.3\,\mathrm{m} \times 12.2\,\mathrm{m} \times 10.2\,\mathrm{m}$ deep and holds 2.46 million litres of fresh water.

Eqs. (2) and (3) were then applied to the data set at each measurement frequency. Because urethanes have dilatational wave speeds similar to the compressional wave speed of water, an initial guess of the dilatational wave speed at the first measurement frequency was $1468\,\mathrm{m\,s^{-1}}$. At subsequent frequencies, the estimated dilatational wave speed of the previous frequency was used as an initial guess. Convergence of the algorithm was determined by comparing the magnitude of the data to the magnitude of the model calculated with the estimated dilatational wave speed. When this difference was less than 0.0001, the algorithm was considered to have converged. This always occurred in four or less iterations. Fig. 3 is a plot of the dilatational wave speed, which is the parameter that was to be estimated. The solid line is the real part and the dashed line is the loss tangent, i.e., the imaginary part divided by the real part. The real part of the wave speed can also be estimated using the frequency values of the relative maxima in the echo reduction data. This equation is

$$\mathrm{Re}(c_d)_n = \frac{hf_n}{n}, \tag{4}$$

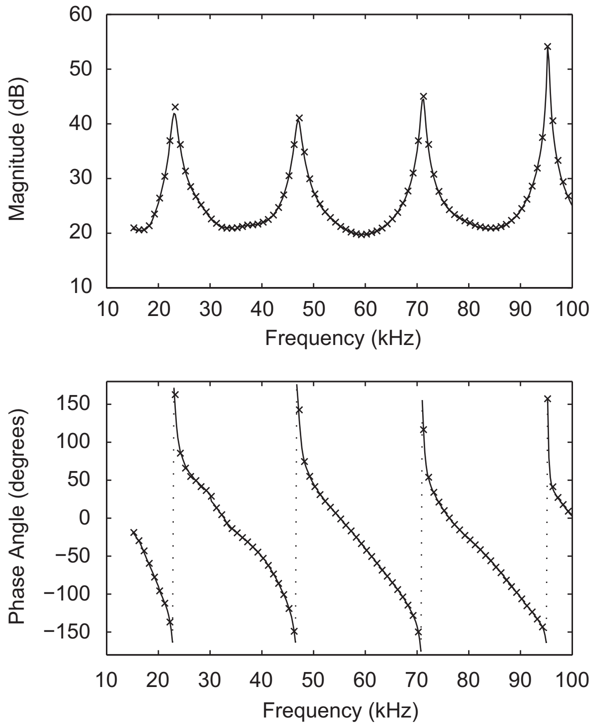

Fig. 2. Echo reduction of the panel. Measurement (____) and model (×) calculated using the estimated dilatational wave speed.

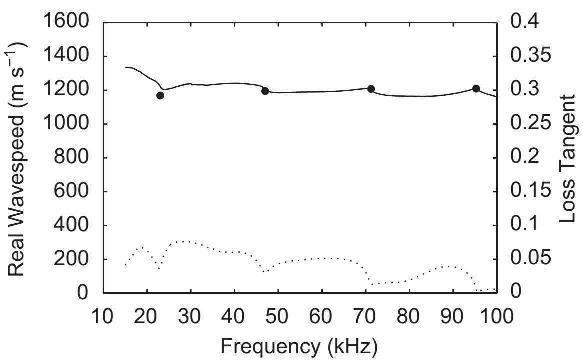

Fig. 3. Estimated dilatational wave speed. Real part (____) and loss tangent (. . . . .) estimated using the Newton–Raphson method. Real part (●) estimated using the relative maxima method.

where f_n is the frequency of the nth relative maxima (Hz or cycles s^{-1}) and n is the number of wavelengths in the material that creates the relative maxima (cycles). For the four relative maxima shown in Fig. 2, the values of n are $\frac{1}{2}$, 1, $\frac{3}{2}$ and 2 cycles, respectively. Using these values, in conjunction with Eq. (4), estimates of the real wave dilatational wave speeds were made and are plotted as round solid markers in Fig. 3 and compared numerically in Table 1. Note that this relative maxima method does not provide for an estimate of the imaginary part of the dilatational wave speed (i.e. the loss tangent). Finally, the model was recalculated using the estimated values of the dilatational wave speed and compared to the data set. This is overlaid in Fig. 2, where the × markers represent the model at various frequency locations calculated using the estimated dilatational wave speeds. (Only one out of five × markers are shown to increase the plot clarity.) The agreement between the data and the model suggests that the inverse method is finding the correct parameters.

Table 1
Real dilatational wavespeed estimates at relative maxima.

n (cycles)	f_n (Hz)	$\mathrm{Re}(c_d)_n$ (m s^{-1})	$\mathrm{Re}(c_d)$ (m s^{-1})	Percent difference
1/2	23000	1168	1223	4.5
1	47000	1194	1207	1.1
3/2	71250	1207	1199	0.7
2	95250	1210	1208	0.2

4. Conclusions

The complex dilatational wave speed of a panel can be accurately estimated using a Newton–Raphson numerical method applied to echo reduction test data. This process produces an estimated value of the wave speed at every frequency where there is a measurement. Comparison of the real part of the estimated dilatational wave speed to that of a relative maxima method yields very good agreement at the specific frequencies where the maxima occur. The complex dilatational wave speed of a panel provides an estimate of the loss tangent that measures the damping of the panel. Comparing the model data calculated using the estimated wave speeds shows almost exact agreement at every measurement frequency.

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References

[1] W.M. Madigosky, G.F. Lee, Improved resonance technique for materials characterization, *Journal of the Acoustical Society of America* 73 (4) (1983) 1374–1377.
[2] S.L. Garrett, Resonant acoustic determination of elastic moduli, *Journal of the Acoustical Society of America* 88 (1) (1990) 210–220.
[3] F. Moussu, M. Nivoit, Determination of elastic constants of orthotropic plates by a modal analysis/method of superposition, *Journal of Sound and Vibration* 165 (1) (1993) 149–163.
[4] S.O. Oyaniji, G.R. Tomlinson, Determination of the complex moduli of viscoelastic structural elements by resonance and non-resonance methods, *Journal of Sound and Vibration* 101 (3) (1985) 277–298.
[5] J.L. Buchanan, Numerical solution for the dynamic moduli of a viscoelastic bar, *Journal of the Acoustical Society of America* 81 (6) (1987) 1775–1786.
[6] A.J. Hull, An inverse method to measure the axial modulus of composite materials under tension, *Journal of Sound and Vibration* 195 (4) (1996) 545–551.
[7] T.-K. Ahn, K.-J. Kim, Sensitivity analysis for estimation of complex modulus of viscoelastic materials by non-resonance method, *Journal of Sound and Vibration* 176 (4) (1994) 543–561.
[8] T. Pritz, Frequency dependences of complex moduli and complex Poisson's ratio of real solid materials, *Journal of Sound and Vibration* 214 (1) (1998) 83–104.
[9] P.H. Mott, C.M. Roland, R.D. Corsaro, Acoustic and dynamic mechanical properties of a polyurethane rubber, *Journal of the Acoustical Society of America* 111 (4) (2002) 1782–1790.
[10] J.C. Piquette, A.E. Paolero, Phase change measurement, and speed of sound and attenuation determination, from underwater acoustic panel tests, *Journal of the Acoustical Society of America* 113 (2) (2003) 1518–1525.
[11] J.C. Piquette, Shear property determination from underwater acoustic panel tests, *Journal of the Acoustical Society of America* 115 (5) (2004) 2110–2121.
[12] R.J. Bobber, *Underwater Electroacoustic Measurements*, Peninsula Publishing, Los Altos, CA, 1970.
[13] A.J. Hull, Analysis of a fluid-loaded thick plate, *Journal of Sound and Vibration* 279 (1–2) (2005) 497–507.