Approximate Material Properties in Isotropic Materials

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***Abstract*—A very important part of the design of ultrasonic transducers and ultrasonic measurement systems is the selection of materials. Typically, materials must be screened on the basis of their acoustic velocity, impedance, and attenuation. The final selection of a material is based upon many other factors, such as how well it adheres to epoxy, its linearity, or how much water it absorbs. This paper is intended to aid in the initial screening process. Some simple techniques for approximating these material properties are presented, and then an extensive table of the materials that have been measured or whose properties have been obtained from the references is given.**

Measurement Techniques

THE FIRST STEP in the measurement of acoustic properties is to prepare a sample of the material of interest. Typically, the sample should have a thickness of approximately ten wavelengths at the measurement frequency and lateral dimensions at least ten times the thickness. The major surfaces should be flat and parallel to within about one percent or less of the thickness. If the material is cast, then special care must be taken to lap or sand the sample sufficiently to remove any variation in thickness due to shrinkage during cure.

Once the sample has been prepared, it is mounted in a measurement system such as the one shown in Fig. 1. The system consists of a water tank, an ultrasonic transducer, and a gimbal jig. The water tank shown has a glass-plate bottom to facilitate alignments in these and other experiments. The ultrasonic transducer used in this case was a Panametrics Videoscan Immersion Transducer (reference number V310), with a center frequency of 5 MHz and an element diameter of 0.25 in. Obviously one should choose a transducer with a center frequency close to the frequency of interest. The element in the transducer should be flat and have lateral dimensions at least ten times the acoustic wavelength in the water. This is important to avoid having to make corrections for diffraction. The gimbal jig in the measurement system is used to mount the sample and to align the major surfaces perpendicular to the ultrasound beam. It is desirable to design this jig such that the axes of rotation intersect near the front surface of the sample, and thereby keep the distance between the sample and the transducer nearly constant during alignment. Alignment is done after the sample is mounted by iteratively rotating the sample on the axes shown in Fig. 1 until the echo amplitudes are maximized.

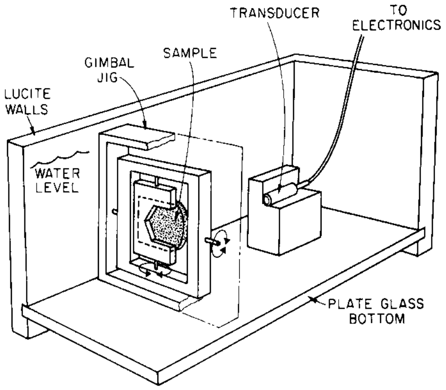

Fig. 1. Measurement tank.

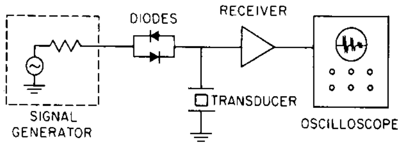

Fig. 2. Measurement system.

The electronic system used to make the acoustic material measurements is shown in Fig. 2. This consists of a signal generator, a pair of diodes, the transducer, a receiver amplifier, and an oscilloscope. The signal generator must be capable of generating a gated sine wave with adjustable frequency and fairly small duty cycle, typically one percent or less. The small duty cycle is important so that the tonebursts can be short, typically five cycles, with a repetition rate low enough for all the reverberations in the measurement system to be well damped before the next excitation pulse is generated. It is helpful to place a pair of silicon diodes, back-to-back as shown in Fig. 2, in series with the signal generator. These have the effect of significantly improving the signal-to-noise ratio at the output of the system by removing the loading effect of the characteristic impedance of the signal generator from the transducer on receive, as well as isolating any low-level noise from the signal generator into the receiver amplifier. The

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diodes are relatively unimportant on transmission when the signal levels are significantly higher than the threshold voltage of the diodes. One must be sure however that all of the received echos have amplitudes less than 1.0 V peak-to-peak to avoid any nonlinearities in the receiver amplifier. Linearity can be verified by adjusting the signal generator amplitude and observing that all received echos vary in proportion to one another. The receiver is typically a 20- to 40-dB high input impedance amplifier with a diode-protected input stage. A Panametrics 5052PR or 5052UA will work very well in this application. The oscilloscope must be capable of measuring time intervals and relative voltages with an accuracy of one percent or better.

Once the material specimen is prepared and the measurement system is assembled, the measurements are carried out as follows. The specimen is put into the gimbal jig and the ultrasonic transducer is mounted nearly normal to a major surface of the sample. The distance between the transducer and the specimen is chosen so that the transit time of an acoustic signal passing between the specimen and the transducer is about four to five times the transit time of an acoustic signal passing through the specimen. Next the signal generator is set to the frequency of interest and then gated to produce tonebursts approximately five cycles long. A train of echos due to reverberations of ultrasound in the specimen and water path between the specimen and the transducer should be observed on the oscilliscope. The amplitude of the echo train should then be maximized by manually adjusting the alignment of the specimen with respect to the ultrasonic beam using the gimbal jig.

If the material specimen is a typical epoxy with an impedance about twice that of water, and the measurement is set up and carried out as described earlier, then an echo train similar to that shown in Fig. 3 should be observed. The first four tonebursts in the received signal, denoted A_1, A_2, A_3, and A_4, are due to the wave that has traveled once through the water between the transducer and the specimen. A_1 is due to the reflection off the front face of the specimen, A_2 is due to the reflection off the back face of the specimen, and A_3 and A_4 are due to reverberations within the specimen. The next group of four tonebursts in the echo train are mainly due to triple transit echos, which traveled to the specimen, reflected back to the transducer, reflected back off the transducer, and traveled once again to the specimen, where reflections and reverberations occurred as before.

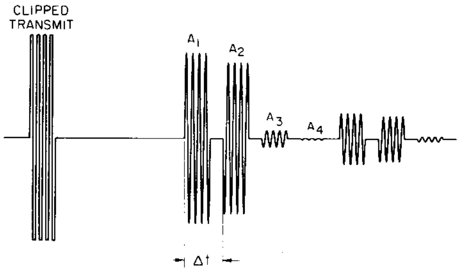


Fig. 3. Measurement signal.

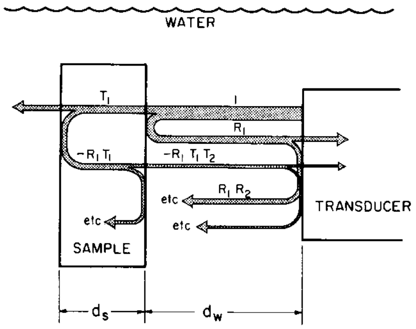


Fig. 4. Reverberation paths.

This rather complicated situation is analyzed using the schematic drawing in Fig. 4. We launch a signal from the acoustic transducer with a stress amplitude of one in the water. This signal propagates through the water path until it hits the impedance discontinuity at the sample–water interface. The reflection coefficient at this interface (R_1), is real and is given by (1). This equation and (2) can be derived from an example given by Auld [1, p. 130]. It is also given by Ristic [2, p. 11]. The portion of the signal that is reflected gives rise to the toneburst in the pulse train with the amplitude A_1. Z_s is the acoustic impedance of the sample, and Z_w is the acoustic impedance of water:

$$R_1 = \frac{Z_s - Z_w}{Z_s + Z_w}. \tag{1}$$

Some of the ultrasound continues on into the material sample. The stress amplitude of the transmitted wave is given by the transmission coefficient (T_1) given by

$$T_1 = \frac{2Z_s}{Z_s + Z_w} = 1 + R_1. \tag{2}$$

A portion of the ultrasound which continues into the sample is lost through the back face of the sample, and the rest is reflected by the back surface towards the front again. The reflection coefficient found at the back face is simply $-R_1$. When this portion of the ultrasound reaches the front face of the sample again, part of it is reflected back into the sample, but some of it is transmitted back into the water toward the transducer. The transmission coefficient here (T_2), is given by

$$T_2 = \frac{2Z_w}{Z_s + Z_w} = 1 - R_1. \tag{3}$$

This portion of the ultrasound, which has been to the back face of the sample and is now traveling back to the transducer, gives rise to the toneburst in the pulse train with amplitude A_2.

Unless the acoustic transducer is perfectly matched to the water, some of the ultrasound that returns to the transducer will be reflected back to the sample. This is the explanation for the subsequent groups of tonebursts observed in the pulse train shown in Fig. 3. The reflection coefficient off the transducer (R_2) is a complex function of frequency. This is why it is desireable to totally immerse the sample in water rather than the transducer in direct contact with it. If one is going to get accurate measurements of acoustic attenuation in a material, it is necessary to know the reflection coefficients on both sides of it.

While the sample is in the water tank and aligned, both the amplitudes A_1 and A_2 are recorded as well as the time delay between them, Δt. The time delay Δt corresponds to the propagation time of the acoustic signal in the sample. When measuring this time delay it should be noted that A_2 is inverted with respect to A_1. This means that if one uses a positive-going first break as the time reference for A_1, one should see a negative-going first break for A_2. Very often lossy materials will distort A_2 and make time determinations difficult. Some oscilloscopes, such as the HP1743, allow you to overlap two separately delayed traces and thereby obtain time-delay measurements with a high degree of accuracy, provided you include the effect of the phase inversion.

The next step in the sequence of measurements is to remove the specimen from the water tank and measure its thickness d with a micrometer. With the propagation delay of the acoustic pulse trough the specimen together with its thickness it is now possible to calculate the longitudinal plane wave velocity V in the specimen as

$$V = \frac{2d}{\Delta t}. \tag{5}$$

The density of the sample is determined next. This can be done either by weighing a known volume of the sample or, if the volume cannot be readily determined by Archemides' method. Archemides' method requires the weight of an object in water W_w and its weight in air W_a. If the material has a density less than 1.0 g/ml, the sample will need to be tethered to a known weight so that its own negative weight in water can be calculated. After these two weights have been determined we calculate the density p as

$$p = \frac{W_a}{W_a - W_w}. \tag{6}$$

The acoustic impedance of the same (Z_s) can not be calculated to be

$$Z_s = pV. \tag{7}$$

Convenient units for expressing typical acoustic velocities are mm/μs. The velocity of water is very close to 1.5 mm/μs. Density is conveniently expressed in g/ml. The product of these two unit choices gives impedances in MRayls (kg/(s $\times$ m^2)) $\times$ 10^6. The impedance of water in these units is very conveniently 1.5. Given Z_s and Z_w it is now possible to calculate R, T_1, and T_2, as given in (1)–(3). Given these values it is possible to calculate what the ratio between A_2 and A_1 should be, given that there is no loss in the sample:

$$\text{calculated} \frac{A_2}{A_1} = T_1 * T_2 = 1 - R ** 2. \tag{8}$$

To actually obtain the loss (in dB/cm) in the sample material we compare the measured ratio of A_2 to A_1 to the above calculated ratio as in

$$\text{Loss in dB/cm} = 20 * \log \left(\frac{\text{Calculated} \frac{A_2}{A_1}}{\text{Measured} \frac{A_2}{A_1}} \right) \Bigg/ (2 * d). \tag{9}$$

If the previously mentioned rules specifying the size of the transducer and sample are followed, then the correction required to (9) due to diffraction is only on the order of 1 dB. Typically, this can be ignored when calculating approximate material properties. However it is highly recommended that after setting up the describd measurement system, and before trusting the attenuation results obtained with it, a sample of plate glass or fused silica must be measured in which the loss is known to be very low relative to what can be measured with this technique. Obviously, if the measured value of the loss is more than about 1 or 2 dB/cm, the assumptions previously made concerning diffraction are suspect. This in turn means that the beam pattern of the transducer is suspect. Stanke [3] has actually measured materials which appeared to have acoustic gain rather than acoustic loss! The distorted beam pattern of the commercial transducer he was using was in fact responsible for this observation, rather than some more interesting miracle. To get over this problem special transducers were constructed using PVF2 on brass backings. The reflection amplitude of these devices was measured as a function of the distance between the transducer and a flat plate reflector, and this function was shown to be in good agreement with diffraction theory. More reasonable results were obtained using these transducers.

A program called PROPRT has been written which prompts the user to enter all of the necessary measured values and then calculates the material properties. It then prints the input and calculated values into a small area which can be cut out and taped onto the box enclosing the measured material. This program is listed in Fig. 5.

Tables of Material Properties

The following tables of material properties are included to aid the reader in the initial screening of materials. Abbreviations are used a great deal to obtain the compact format which is presented. Most abbreviations are explained in a table which follows the table of plastics; however, it is appropriate to at least define the appreviations used for column headings here:

Loss	Attenuation
ρ	density in g/cm^3
σ	Poisson's ratio or $(1 - 2X)/(2 *(1 - X))$ where $X = (V_S/V_L)^2$
$\Delta V/\Delta T$	change of velocity per change in temperature given in m/s/°C referenced to 25°C.
V_L	acoustic longitudinal wave velocity in mm/μs
V_S	acoustic shear wave velocity in mm/μs
Z_L	acoustic impedance $= \rho * V_L$, in kg/(s * m^2) * 10^{-6}.

LOSS, or attenuation, is given in several different formats in these tables. The most specific way is with the @ symbol. The number before the @ is the loss in dB/cm, the number after the @ symbol is the frequency at which the attenuation was measured in MHz. The use of A= means the number given is alpha (nepers per cm) given in s^2/cm times 10^{-17}. To get loss in dB/cm multiply alpha by $8.686 * f^2$, where f is the frequency of interest in Hz. This representation obviously assumes that loss increases in proportion to frequency squared, and is most commonly used for low loss materials such as glass.

Transducer modeling programs will commonly assume loss increases just in proportion to the frequency to the first power. If this is the case then it is appropriate to use the material quality factor, or acoustic Q. To convert between dB/cm and Q the following equations can be useful:

$$Q = \frac{2 * \pi * (\text{Stored energy})}{\text{Energy dissipated per cycle}} \tag{10}$$

$$Q = W_0 \frac{\text{Stored energy}}{\text{Average power loss}} \tag{11}$$

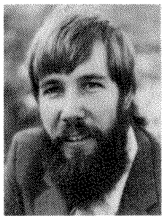
$$Q = \frac{86.9 * \pi * f}{((\text{dB/cm}) * \text{velocity})}. \tag{12}$$

REFERENCES

[1] B. A. Auld, *Acoustic Fields and Waves in Solids*, vol. I and II. New York: John Wiley, 1973.

[2] V. M. Ristic, *Principles of Acoustic Devices*. New York: John Wiley, N.Y., 1983.

[3] Fred Stanke, Schlumberger, Inc., Ridgefield, CT, private communication.



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