MCEN 3027
Updated 02/26/2001

Measurement of Elastic Constants Using Ultrasound

Introduction

Ultrasound uses very high frequency sound, higher than 20 kHz (the limit of human hearing), to determine material characteristics of interest such as the presence of cracks, voids, inclusions, delaminations, porosity, part thickness, weld penetration, and braze and joint integrity. In this experiment, you will measure the speed of sound in several solids including steel, aluminum, brass, and fused quartz. From these measurements you will calculate the Young's modulus and Poisson's ratio for these materials. The pulse-echo technique used to send and receive ultrasound is a simple, quick, and accurate method of measuring the speed of sound in solids.

A sound wave is subject to attenuation, which is dissipation of its energy content as it travels though the medium. The rate of dissipation increases with the frequency of the sound wave, and decreases with the density of the medium. (Why?) This means that high frequency sound (ultrasound) has reasonable attenuation in dense solids like metals. A variety of ultrasound transducers is available for use with various materials in different applications. The ultrasound frequency, and hence the type of transducer used, depends on the attenuation experienced in a material. For measurement purposes, the trade-off is between attenuation and resolution, both of which are a function of sound frequency. Higher frequency yields proportionately higher resolution, but means higher attenuation. Therefore, for instance, one may want to use lower frequency sound when dealing with thicker, highly attenuating materials, thus compromising resolution. On the other hand, thinner, non-attenuating materials permit the use of higher frequencies and lend themselves to better resolution. Clearly, ultrasound therefore is tool that permits us to "see through" opaque materials.

Stress Waves in Solids

Consider a body, which experiences a disturbance on the surface. The propagation of the disturbance through the body follows the wave equation,

$$\frac{\partial^2 \vec{u}}{\partial t^2} = c^2 \nabla^2 \vec{u} \tag{1}$$

where $\vec{u}$ (x,y,z,t) is the displacement vector which describes the change in position of any point in the body at position (x,y,z) at time t, and where c is the speed of sound. In fluids such as air, sound travels as a pressure wave. In solids, which support both normal stress and shear stress, two types of waves, longitudinal and shear, may propagate, as shown schematically in Figure 1. For longitudinal waves, the motion of the particles is parallel to the direction of propagation; for shear waves, the motion of particles is perpendicular to the direction of wave propagation. The wavelength, λ=c/f, is indicated in the figure.

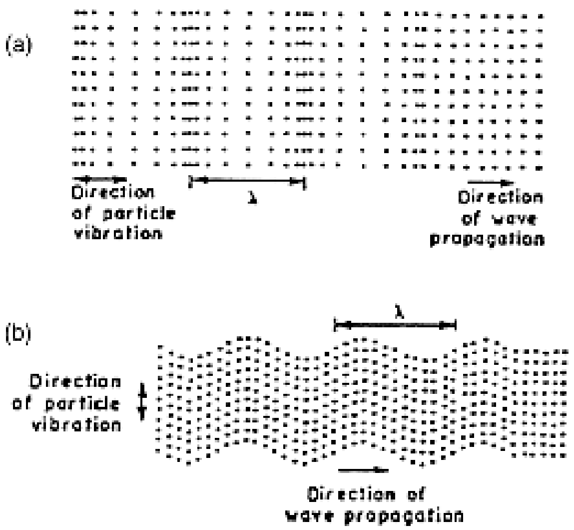

Figure 1. Types of waves in bulk solid: (a) longitudinal waves, (b) shear waves.

It may be shown that the speed of sound of longitudinal and shear waves is given by:

$$C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{2}$$

$$C_S = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}} \tag{3}$$

where E is Young’s modulus (or the modulus of elasticity), ν is Poisson’s ratio, and G is the shear modulus. Solving these equations for E and ν gives:

$$\nu = \frac{1-2\left(\frac{C_S}{C_L}\right)^2}{2-2\left(\frac{C_S}{C_L}\right)^2} \tag{4}$$

$$E = 2\rho C_S^2(1+\nu) \tag{5}$$

Thus, given measurements of ρ, C_L, and C_S, it is possible to determine E and ν.

A table of the nominal density of the specimen materials is given below:

	Steel	**Aluminum**	**Brass**	**Fused Quartz**
Density - ρ (g/cm^3)	7.85 ± 0.05	2.80 ± 0.05	8.50 ± 0.05	2.2 ± 0.05

Table 1. Nominal density of four specimen materials.

Pulse-Echo Method

In the pulse-echo ultrasonic testing technique, an ultrasound transducer generates an ultrasonic pulse and receives its 'echo'. The ultrasonic transducer functions as both transmitter and receiver in one unit. Most ultrasonic transducer units use an electronic pulse to generate a corresponding sound pulse, using the piezoelectric effect. A short, high voltage electric pulse (less than 20 Ns in duration, 100-200 V in amplitude) excites a piezoelectric crystal, to generate an ultrasound pulse. The transducer broadcasts the ultrasonic pulse at the surface of the specimen. The ultrasonic pulse travels through the specimen and reflects off the opposite face. The transducer then 'listens' to the reflected echoes. The ultrasound pulse keeps bouncing off the opposite faces of the specimen, attenuating with time.

Figure 2 shows a train of echoes from multiple round-trips through the specimen. The time between any two echoes is the length of time required for the pulse to travel through the specimen and back to the transducer. The attenuation (amplitude decay) is exponentially with time.

The speed of sound in the solid can be derived from the observed round trip transit time, Δt, and the measured thickness of the specimen, d:

$$c = \frac{2d}{\Delta t} \tag{6}$$

Values for the speed of sound in a variety of solids range from 1 to 8 km/s. ***How does this compare to the speed of sound in air?***

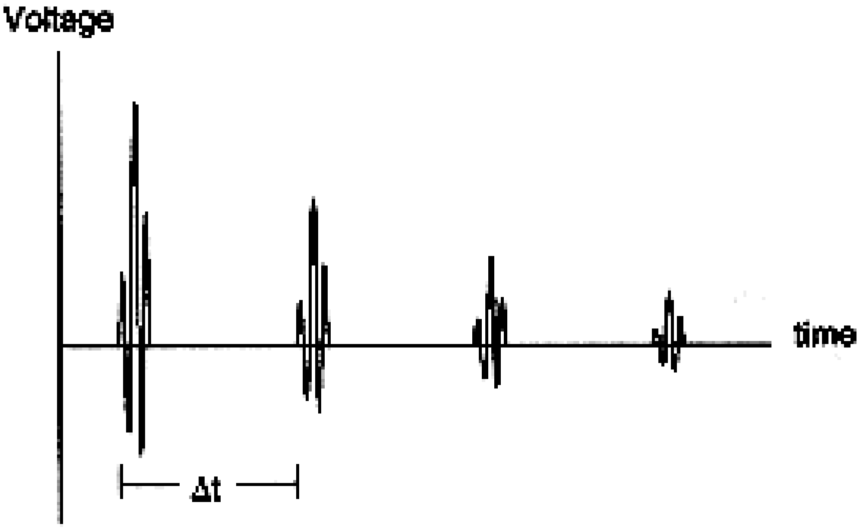

Figure 2. Schematic of echoes received from repeated round trips through a specimen.

Ultrasonic Transducers

This experiment uses direct contact transducers. Such transducers are generally applicable for minimum thickness of 0.5 mm (0.020") for metals and 0.125 mm (0.005") for plastics. These transducers are used where accuracy requirement is not greater than ±0.025 mm (±0.001").

Figure 3 shows a schematic diagram of an ultrasonic contact transducer. The primary component is the piezoelectric quartz crystal that converts a mechanical pulse into an electrical signal, or conversely, an electrical signal to a mechanical pulse. In the pulse-echo method, the crystal functions in both modes. According to the manner in which the piezoelectric crystal is cut, it vibrates in the thickness direction, producing longitudinal waves, or in the tangential direction producing shear waves. The piezoelectric element is mounted adhesively to a wear plate on one side. On the other side is a lossy backing material, which damps the natural vibration of the piezoelectric crystal to facilitate the production of a pulse of short duration. (Why do we need a pulse of short duration at all?) The pulse has a characteristic bell shaped frequency spectrum with maximum near the natural frequency of the piezoelectric element, which depends on its thickness.

Between the contact transducer and the specimen, a coupling is used. (Why?) The most common coupling material used for longitudinal waves is glycerin, which is non-toxic and washes off with water. It is more difficult to transmit shear waves across the transducer/specimen interface, so a high viscosity coupling material is more effective.

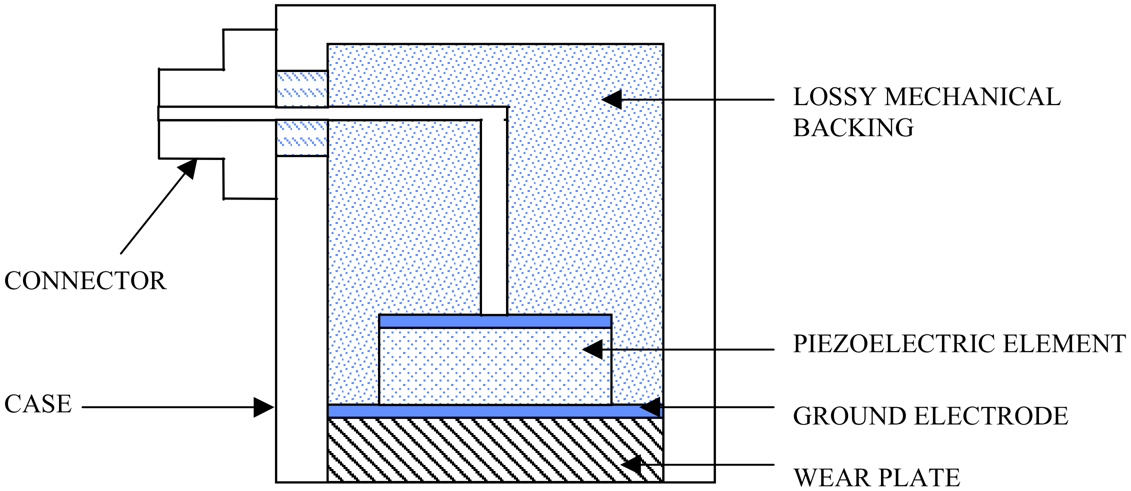

Figure 3. Construction of an ultrasonic transducer.

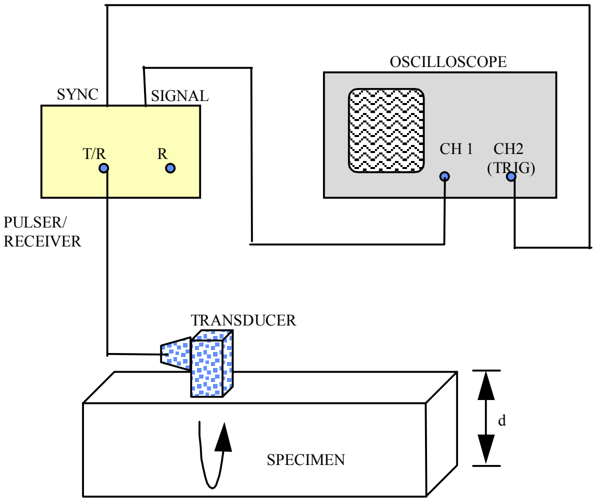

Figure 4. Schematic diagram of ultrasonic testing apparatus.

Equipment

- Ultrasonic Transmitter/Receiver (Panametrics Model 500 PR)
- Transducer cable
- 5 MHz longitudinal wave transducer (Panametrics Model V110)
- 5 MHz shear wave transducer (Panametrics Model V156)
- Oscilloscope (HP Model 54601B)
- Micrometer Caliper
- Specimen Blocks: 303 Steel, 6061-T6 aluminum, brass, quartz disk, red blocks
- Glycerin coupling
- Shear Wave Coupling (jar marked SWC - by Panametrics)
- 2 BNC-BNC cables

Procedure

1. Measure the dimensions of the specimen blocks in the directions through which you will send the ultrasound (the shortest dimension).

2. With the power to the Pulser/Receiver (P/R) turned off, connect the longitudinal wave transducer (marked V110) and the oscilloscope to the P/R as shown in Figure 4. Turn on the oscilloscope and the P/R.

3. Set the P/R to: Pulse Height “Hi”, Damping ~7, Mode Switch “UP” (for a single transducer), Gain Switch -20dB, and Gain Knob ~6. Note that it may be necessary to adjust these values for different specimens and transducers.

4. Set the oscilloscope to: 500 mV/Div, 500 Ns/Div, and Auto-level Triggering. Note that it may be necessary to adjust these values for different specimens and transducers.

5. Hold the transducer against the quartz specimen using a small amount of the glycerin couplant. Adjust the oscilloscope settings until you see a train of echoes, similar to that shown in Figure 2.

6. Make a coarse measurement of the time between the first echo and the second echo using the cursors. Now you will make a more accurate measurement using the horizontal magnification feature on the oscilloscope. Adjust the time/Div, V/Div, and horizontal delay until only the first and second echoes are displayed (not the first pulse, the first echo). Set the horizontal mode to delayed. Magnify the first echo in the lower part of the display. Set the t1 cursor to the start of the first echo. Adjust the horizontal delay until the second echo is displayed in the magnified lower display. Set the t2 cursor to the start of the second echo. Note the round trip transit time.

7. Repeat the longitudinal wave transit time measurement for the other specimen materials: steel, aluminum, and brass. Take more than one measurement on each specimen along different dimensions of the piece (i.e. width, length, and height).

8. Turn off the P/R. Replace the longitudinal wave transducer with the shear wave transducer (marked V156). Turn the Gain switch up. Turn on the P/R.

9. Hold the shear wave transducer against the quartz specimen using the shear wave couplant (SWC). Because it is difficult to transmit shear forces across an interface, it is necessary to use firm pressure between the transducer and the specimen. But do not exceed the pressure that you can apply by hand - DO NOT clamp the transducer as this will result in damage to the device.

10. Again measure the time between the first echo and the second echo as accurately as possible using the horizontal magnification feature.

11. Repeat the shear wave transit time for the other specimen materials and make multiple measurements on each specimen.

12. Measure the longitudinal and shear wave transit time for the red block specimens. A coin is embedded in each specimen, so take measurements across all dimensions that you feel are useful in determining the size of the hidden coin.

13. When finished, clean off the transducers and specimen blocks using a damp paper towel.

Assignment Questions

1. Prove that if density, ρ, has units of [g/cm^3] and velocity, c, has units of [km/s], then Young's modulus, E, has units of [GPa] in Eq. (5).

2. What are the wavelengths of 5 MHz shear and longitudinal waves in aluminum?

3. Calculate the longitudinal wave speed for each of the materials. Estimate the uncertainty in the measurement and identify the major source of error. *Present all of your results in a table.*

4. Calculate the shear wave speed for each of the materials. Estimate the uncertainty and identify the major source of error.

5. Calculate Poisson's ratio and Young's modulus of each of the specimen materials. Using propagation of errors, estimate the uncertainties. How do your measurements of E and ν compare with published, nominal values?

6. Using the measurements taken across the red block specimens, determine the denomination (penny, nickel, dime, etc..) of the coin embedded in each block. What measurement type, longitudinal or shear wave, works best to determine the above? Compare your experimental measurements with the actual size of the coins.

References

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APPENDIX 1

Excerpt from: http://www.panametrics.com/ndt/theory/

FACTORS AFFECTING PERFORMANCE AND ACCURACY

a) **Calibration**: The accuracy of any ultrasonic measurement is only as good as the accuracy and care with which the gage has been calibrated. All quality ultrasonic gages provide a method for calibrating for the sound velocity and zero offset appropriate for the application at hand. It is essential that this calibration be performed and periodically checked in accordance with the manufacturer's instructions. Sound velocity must always be set with respect to the material being measured. Zero offset is usually related to the type of transducer, transducer cable length and mode of measurement being used.

b) **Surface Roughness of the Test Piece**: The best measurement accuracy is obtained when both the front and back surfaces of the test piece are smooth and parallel. If the contact surface is rough, the minimum thickness that can be measured will be increased because of sound reverberating in the increased thickness of the coupling layer. There will also be potential inaccuracy caused by variations in the thickness of the coupling layer beneath the transducer. Additionally, if either surface of the test piece is rough, the returning echo may be distorted due to the multiplicity of slightly different sound paths seen by the transducer, and measurement inaccuracies will result.

c) **Coupling Technique**: In Mode 1 (direct contact transducer) measurements, the coupling layer thickness is part of the measurement and is compensated by a portion of the zero offset. If maximum accuracy is to be achieved, the coupling technique must be consistent. This is accomplished by using a coupling of reasonably low viscosity, employing only enough coupling to achieve a reasonable reading, and applying the transducer with uniform pressure. A little practice will show the degree of moderate to firm pressure that produces repeatable readings. In general, smaller diameter transducers require less coupling force to squeeze out the excess coupling than larger diameter transducers.

In all modes, tilting the transducer will distort echoes and cause inaccurate readings, as noted below.

d) **Curvature of the Test Piece**: A related issue involves the alignment of the transducer with respect to the test piece. When measuring on curved surfaces, it is important that the transducer be placed approximately on the centerline of the part and held as nearly normal to the surface as possible. In some cases a spring-loaded V-block holder may be helpful for maintaining this alignment. In general, as the radius of curvature decreases, the size of the transducer should be reduced, and the more critical transducer alignment will become. For very small radiuses, an immersion approach will be necessary. In some cases it may be useful to observe the waveform display via an oscilloscope or other waveform display as an aid in maintaining optimum alignment.

Often practice with the aid of a waveform display will give the operator a proper "feel" for the best way to hold the transducer. On curved surfaces it is important to use only enough coupling to obtain a reading. Excess coupling will form a fillet between the transducer and the test surface where sound will reverberate and possibly create spurious signals that may trigger false readings.

e) **Taper or eccentricity**: If the contact surface and back surface of the test piece are tapered or eccentric with respect to each other, the return echo will be distorted due to the variation in sound path across the width of the beam. Accuracy of measurement will be reduced. In severe cases no measurement will be possible.

f) **Acoustic Properties of the Test Material**: There are several conditions found in certain engineering materials that can potentially limit the accuracy and range of ultrasonic thickness measurements:

1. **Sound Scattering** -- In materials such as cast stainless steel, cast iron, fiberglass, and composites, sound energy will be scattered from individual crystallites in the casting or boundaries of dissimilar materials within the fiberglass or composite. Porosity in any material can have the same effect. Gage sensitivity must be adjusted to prevent detection of these spurious scatter echoes. This compensation can in turn limit the ability to discriminate a valid return echo from the backside of the material, thereby restricting measurement range.

2. **Sound Attenuation or Absorption** -- In many organic materials such as low density plastics and rubber, sound energy is attenuated very rapidly at the frequencies used for ultrasonic gauging. This attenuation typically increases with temperature. The maximum thickness that can be measured in these materials will often be limited by attenuation.

3. **Velocity Variations** -- An ultrasonic thickness measurement will be accurate only to the degree that material sound velocity is consistent with gage calibration. Some materials exhibit significant variations in sound velocity from point to point. This happens in certain cast metals due to the changes in grain structure that result from varied cooling rates, and the anisotropy of sound velocity with respect to grain structure. Fiberglass can show localized velocity variations due to changes in resin/fiber ratio. Many plastics and rubbers show a rapid change in sound velocity with temperature, requiring that velocity calibration be performed at the temperature where measurements are to be made.

g) Phase Reversal or Phase Distortion: The phase or polarity of a returning echo is determined by the relative acoustic impedance (density x velocity) of the boundary materials. Most commercial gages assume the customary situation where the test piece is backed by air or a liquid, both of which have lower acoustic impedance than metals, ceramics, or plastics. However, in some specialized cases (such as measurement of glass or plastic liners over metal, or copper cladding over steel) this impedance relationship is reversed, and the echo appears phase reversed. To maintain accuracy in these cases it is necessary to change the appropriate Echo Detection polarity, or on instruments where that is not possible, adjust the zero offset to compensate for a timing error equal to one-half cycle of the waveform.

A more complex situation can occur in anisotropic or inhomogeneous materials such as coarse-grain metal castings or certain composites, where material conditions result in the existence of multiple sound paths within the beam area. In these cases phase distortion can create an echo that is neither cleanly positive nor negative. Careful experimentation with reference standards is necessary in these cases to determine effects on measurement accuracy. If the effect is consistent it will usually be possible to compensate by means of a zero offset adjustment, but if echo shape is, highly accurate thickness measurements may not be possible.

APPENDIX 2

Excerpt from: http://www.panametrics.com/ndt/theory/

COUPLING MATERIALS

A wide variety of coupling materials may be used in ultrasonic gauging. We have found that propylene glycol is suitable for most applications. In difficult applications where maximum transfer of sound energy is required, glycerin is recommended. However, on some metals glycerin can promote corrosion by means of water absorption and thus may be undesirable. Other suitable couplings for measurements at normal temperatures may include water, various oils and greases, gels, and silicone fluids.

In some applications involving smooth surfaces, it is possible to substitute in place of liquid coupling a thin compliant membrane (such as a thin piece of polyurethane) between the face of the transducer or delay line and the test piece. This approach will often require changes to gage setup parameters and usually requires that the transducer be pressed firmly to the surface of the test piece.