EMA 611 Advanced Mechanical Testing, University of Wisconsin
Experiment 2. Ultrasonics and Transducers

§1 Preliminaries.

§1.0 Pre-lab assignment Read the web notes on wave velocity and attenuation; on viscoelasticity; on Poisson's ratio in 3D. Review the web notes on graphs.

§1.1 Transducers

§1.1.1 Ultrasonic transducers The ultrasonic transducers used in this laboratory contain piezoelectric ceramic discs; they exhibit strong coupling between the electrical and acoustic signal. Each transducer can generate and also receive an ultrasonic signal. Each transducer has a natural frequency which is marked on it. They are heavily damped to achieve broadband response off the natural frequency. They are available for longitudinal or shear waves. They are intended for non-destructive testing (NDT). The thickness of the piezoelectric element governs its natural frequency. Piezoelectric transducers are available for frequencies between about 0.5 MHz and 20 MHz, the frequency range most commonly used for non-destructive evaluation of machine parts and for diagnostic ultrasonic diagnosis of disorders in the human body. They can be used to find the depth of a flaw but do not provide images.

§1.1.2 Load cell A load cell is a transducer which converts force into an electrical signal. Load cells are used to measure force in screw driven test frames and servohydraulic test frames. Force and torque transducers, known as load cells and torque cells, respectively, involve measuring the displacement or strain of a deformable substrate, typically steel. Torque cells are based on solid or hollow shafts, or cruciform arrangements fitted with strain gages. Load cells typically contain a bar or plate of metal, usually steel, upon which strain gages are cemented. The detected strain signal on the bar is proportional to the force upon it, provided the metal and the strain gages are loaded below their proportional limit, one factor which limits the linear range or 'capacity'. Overload capability is limited by yield in the metal parts of the transducer. Steel itself is not perfectly elastic but exhibits a small viscoelastic response; this is normally not a problem in the kind of tests done with load cells.

Load cells based on piezoelectric crystals are also available; they offer superior stiffness for dynamic studies. However, there is no response at zero frequency, and there are phase errors at low frequency. The low frequency response of any piezoelectric transducer is limited by the electrical resistance of the scope or pre-amplifier to which it is attached. Piezoelectric devices intended as load cells are used with a high-impedance charge amplifier; the frequency range can extend below 0.001 Hz. An ultrasonic transducer can also measure force at relatively low frequency if its signal is amplified by a high impedance amplifier.

§1.2 Waves

Stress waves from 20 Hz to 20 kHz are perceived as sound. Waves above 20 kHz are referred to as ultrasonic; ultrasonic frequencies between 0.5 MHz and 20 MHz are commonly used in the nondestructive evaluation of engineering materials, for materials characterization, and for diagnostic ultrasound in medicine. High frequency impulse waves are also used in lithotripsy to shatter kidney stones without surgery.

§1.3 Anisotropy

Composites such as graphite epoxy as well as natural composites such as bone, wood, and muscle are anisotropic, that is, their properties depend on direction. Hooke's law in one dimension may be written $\sigma = E\varepsilon$, with E as Young's modulus. In three dimensions, allowing anisotropy, Hooke's law appears as follows. You will not need to manipulate these for the lab!

$$\sigma_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3} C_{ijkl}\varepsilon_{kl} \text{ (modulus formulation)} \quad ; \qquad \varepsilon_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3} S_{ijkl}\sigma_{kl} \text{ (compliance formulation)}$$

There are 81 components of the elastic modulus tensor C_{ijkl}, but taking into account the symmetry of the stress and strain tensors, only 36 of them are independent. If the elastic solid is describable by a strain energy function, the number of independent elastic constants is reduced to 21. An elastic modulus tensor with 21 independent constants describes an anisotropic material with the most general type of anisotropy, triclinic symmetry. Materials with orthotropic symmetry are invariant to reflections in two orthogonal planes and are describable by nine elastic constants. For an orthotropic material, the nine elastic constants can be considered as three values of E, three values of G, one for each coordinate direction. Materials with axisymmetry, also called transverse isotropy or hexagonal symmetry, are invariant to 60° rotations about an axis and are describable by five independent elastic constants. For an axisymmetric material, the transverse direction differs from the longitudinal direction, but the Young's moduli for two transverse directions are identical. Materials with cubic symmetry are describable by three elastic constants. Isotropic materials, with properties independent of direction are describable by two independent elastic constants. They may be taken as Young's modulus E and Poisson's ratio ν. For an isotropic material, E and ν are the same regardless of direction.

Ultrasonic methods are useful in that they can reveal all the anisotropic elastic constants of a material.

§2 Ultrasonic waves and material properties.

§2.1 Velocity and modulus

Ultrasonic wave speed v depends on the stiffness and on the density ρ of the material under study. For *longitudinal* waves, $v = \sqrt{E/\rho}$ with E as Young's modulus. This is valid for a long rod of length much longer than the wavelength, and width much less than the wavelength. It is not valid for the present experiment, since the wavelength is so short. If the width is much larger than the wavelength, wave speed is governed by the tensorial modulus. In the 1 or x direction, it is C_{1111}: $v = \sqrt{C_{1111}/\rho}$. In the 3 or z direction it is C_{3333}.

For *isotropic* materials, $C_{1111} = C_{2222} = C_{3333}$ and $C_{1111} = E \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)}$, with ν as Poisson's ratio.

For *anisotropic* materials, the relationship between C_{ijkl} and E is more complex; it involves several tensor elements. The above relationship does *not* apply.

For *shear* waves, $v = \sqrt{G/\rho}$ with G as the shear modulus. For stress and strain both as 2- 3 components, then the corresponding shear modulus is C_{2323}.

§2.2 Measurement of velocity

Velocity can be measured by determining the time delay for the wave to pass through a sample of material. The velocity is the distance (thickness) divided by the time delay. In this method, one transducer sends the waves and another one receives them.

One can also use two samples of the same material and measure the delay difference. The velocity v is determined from the difference Δt in transit times of a particular zero-crossing in the signal, and the known lengths l_1 and l_2 of the specimens,

$v = (l_1 - l_2)/\Delta t$.

It is also possible to determine velocity with one ultrasonic transducer rather than two. In this approach, waves reflect off the free end and back to the transducer, creating a series of echoes. Measure the time delay between adjacent echoes. For calculation, use as a length the total distance traveled by the wave, twice the specimen thickness. A switch on the blue pulser / receiver controls this.

§3 Ultrasonic Testing.

§3.1 Set-up

Connect the pulser to the ultrasonic transducer or transducers and to the oscilloscope. Examine the signal. Measure the dimensions and mass of your specimens. Calculate the density. A stronger signal for compressional waves is obtained if a thin layer of water is used as a couplant between transducer and specimen. Water coupling does not work well for shear waves. Why?

Ultrasonic velocity testing depends critically on obtaining the correct zero reference for the scope time scale. Press the transducers together to obtain the zero time reference. Verify the scope triggers OK.

Echoes from the flat end surfaces occur at time delays corresponding to twice the travel time of a wave through the specimen. There may be other echoes from oblique wave motion; be careful in interpretation.

§3.2 Isotropic material test

Determine the ultrasonic longitudinal wave speed for materials such as brass, aluminum, or a glassy polymer, polymethyl methacrylate (PMMA). Test in different directions. How stiff is the material? Assume a Poisson's ratio of 0.3 to calculate E from C_{1111}. Does the velocity depend on direction? How does the stiffness at ultrasonic frequency compare with the known stiffness at low frequency? For aluminum, these are E = 70 GPa, for brass it depends on composition; 95 to 110 GPa is reasonable; for PMMA, E = 3 GPa to 3.6 GPa. If you have a cube or prism specimen, *determine* whether it is really isotropic; *do not assume it.*

§3.3 Anisotropic material test

Repeat the above test with a cube or prism of fibrous composite, wood, or bone, known to be anisotropic. What modulus do you infer? Does the velocity depend on direction? Is the material isotropic, axisymmetric (transversely isotropic) or orthotropic?

§3.4 Further experiments

Use shear waves, using shear transducers, to obtain the shear modulus G. Shear waves are polarized. Can you see any difference if you rotate one transducer by 90 degrees? If time permits, try also longitudinal waves at a different frequency (10 MHz). Do you expect properties to depend on frequency? Explain.

§3.5 Interfaces

If time permits, look for reflections from interfaces of material specimens which are pressed together. Observation of such reflections is the basis for non-destructive evaluation in which ultrasonic methods are used to detect flaws in structural elements.

§3.6 Attenuation

If time permits, determine the attenuation of one material such as PMMA. See the appendix below for methods. What is the corresponding damping tan δ? Compare with known values given in the web notes. Measure the *width* of the pulse. If a 1 MHz pulse is incident, is the period still 1μsec in received pulse?

§4 Appendix: Measurement of attenuation

The attenuation α, in units of nepers per unit length is determined from the magnitudes of the signals through specimens of different length. The amplitude A_1 of the signal is as follows, with z as distance traveled through the material.

$$A_1 = A_0 \exp\{-\alpha z\}. \qquad \text{(A1)}$$

The best approach is to reproduce as well as possible the contact force holding the transducers and specimen. This can be done by placing a weight on the top transducer. Measure amplitude of pulses through different length specimens. Plot amplitude vs distance z. There will be scatter as a result of differences in surface quality. Perform a curve fit to obtain the attenuation α. Keep in mind that if the wave decays with distance the attenuation is positive. The attenuation has units of inverse length.

The viscoelastic damping tan δ is given in terms of the attenuation by

$$\alpha \approx (\omega/2v)\tan\delta \qquad \text{(A2)}$$

for small δ; the exact version is $\alpha = \frac{\omega}{v} \tan\frac{\delta}{2}$, with $\omega = 2\pi\nu$ and ν as frequency. The physical meaning of δ is the phase angle between stress and strain under sinusoidal load.

One cannot simply obtain attenuation from a ratio of transmitted signal with and without a sample for the following reasons. If the area of the transducer is greater than that of the specimen, the reduction in area will cause a reduction in signal unrelated to the nature of the specimen material. Also, some of the ultrasonic energy is absorbed by the transducer itself. Therefore the transducer extracts considerable energy from the sound wave at each echo. This energy loss is unrelated to the attenuation in the material itself. Therefore a different approach must be used, unless one can deal with the effort of building one's own low-loss transducers.

The method to use is as follows. Attenuation can be measured by comparing the transmitted signal through several specimens of different length. This approach is complicated by the need to control contact force, which influences the strength of the transmitted signal. Nevertheless it is conceptually simple, so use this approach in the lab. Plot log amplitude versus length of at least three samples; use Eq. (A1) to interpret. One can also do a semi-log plot so the logarithmic decay of signal with distance shows up as a straight line.

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