BME 315 Biomechanics

Experiment 6. ***Ultrasonic properties of bone tissue***

§1 Preliminaries.

§1.1 Waves and Transducers

Stress waves from 20 Hz to 20 kHz are perceived as sound. Waves above 20 kHz are referred to as ultrasonic; ultrasonic frequencies between 1 MHz and 10 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. The ultrasonic transducers used in this laboratory are intended for non-destructive testing (NDT). They contain piezoelectric ceramic discs; they exhibit strong coupling between the electrical and acoustic signal. Each transducer has a natural frequency which is marked on it. They are heavily damped to achieve broadband response off the natural frequency. The basic transducers emit and receive longitudinal waves. They can be used to find the depth of a flaw but do not provide images.

§1.2 Anisotropy

Biological materials 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!

$\sigma_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3} C_{ijkl}\varepsilon_{kl}$ (modulus formulation); $\varepsilon_{ij} = \sum_{k=1}^{3}\sum_{l=1}^{3} S_{ijkl}\sigma_{kl}$ (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. 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. 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. For an orthotropic material, there are three values of E, three values of G, one for each coordinate direction. For an axisymmetric material, the transverse direction differs from the longitudinal direction, but the Young's moduli for two transverse directions are identical.

§2 Ultrasonic waves and material properties.

§2.1 Velocity

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. In gneral C_{1111} differs from, usually greater than, E. For *shear* waves, $v = \sqrt{G/\rho}$ with G as the shear modulus.

§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 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.

§3 Testing.

§3.2 Set-up

Connect the pulser to the ultrasonic transducer or transducers and to the oscilloscope. Examine the signal. Measure the dimensions of your specimens.

§3.2 Polymer test: preliminary

Determine the ultrasonic longitudinal wave speed for a glassy polymer, polymethyl methacrylate (PMMA). A stronger signal is obtained if a thin layer of water is used as a couplant between transducer and specimen. How stiff is the polymer? 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 $E \approx 2.6$ GPa at low frequency?

§3.3 Bone test

Repeat the above test with a cube or prism of bone. What modulus do you infer for the bone? Does the velocity depend on direction? Is the bone sample isotropic, axisymmetric (transversely isotropic) or orthotropic?

§3.4 Further experiments (if time permits)

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? Water coupling does not work well for shear waves. Why?

Use longitudinal waves at a different frequency (10 MHz). Do you expect properties to depend on frequency? Explain.

§4 Questions.

1. If the frequency of the ultrasonic waves is 1 MHz, what is the wavelength of the waves? What is the wavelength if the frequency is 10 MHz? For bone the density is about 2 g/cm^3, for PMMA, about 1.1 g/cm^3. Recall $\lambda\nu = v$, with λ as the wavelength of waves, ν as frequency, and v as velocity.
2. The ultrasonic wave speed in soft tissue is about 1540 m/s. A clinical ultrasound system sends pulses from the skin to a lesion 7 cm deep in the liver. How long does it take for the pulses to return? Based on your lab experience, comment on what range of frequency is appropriate.

§5 Appendix: Measurement of attenuation

We will not make such measurements here but this is how it is done. The attenuation α, in units of nepers per unit length is determined from the magnitudes of the signals: A_1 through a specimen of length $\boldsymbol{l}_1$, A_2 through a specimen of length $\boldsymbol{l}_2$.

$\alpha = \frac{\ln(A_1/A_2)}{(\boldsymbol{l}_1 - \boldsymbol{l}_2)}$. The viscoelastic damping tan δ is given in terms of the attenuation by $\alpha \approx (\omega/2v)\tan\delta$ for small δ; the exact version is $\alpha = \frac{\omega}{v}\tan\frac{\delta}{2}$, with $\omega = 2\pi\nu$. 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. One could compensate for this loss by comparing the transmitted signal through specimens of different length, however such an approach is complicated by the need to control contact force, which influences the strength of the transmitted signal.

Attenuation can be measured in a single transducer method. Place a buffer rod between the transducer and the specimen. The rationale for this approach is to eliminate parasitic energy loss from sound waves entering the transducer. A broadband NDT type transducer can be used in the buffer rod approach. Attenuation is inferred from the magnitude of echoes called A, B, and C in order of their time delay following the driving pulse. Echo A is a reflection from the buffer-specimen interface. Echo B is from the specimen-air interface. Echo C has reflected once from the buffer-specimen interface and twice from the specimen-air interface. The reflection coefficient R for the rod-specimen interface must be known. It may be calculated from the echoes as follows. Normalize the echo amplitudes, retaining their sign. $\underline{A} = \frac{A}{B}$, $\underline{C} = \frac{C}{B}$. The reflection coefficient is $R = \sqrt{\frac{\underline{AC}}{\underline{AC} - 1}}$. The attenuation is $\alpha = \frac{1}{2}\frac{1}{\boldsymbol{l}}\ln\{-\frac{R}{\underline{C}}\}$, with $\boldsymbol{l}$ as specimen length. Here the waves reverberate between a reflective free surface and a specimen-buffer surface for which the acoustic reflectivity can be calculated from the echoes.

§6 References.

1. Lang, S.B., Ultrasonic method for measuring elastic coefficients of bone and results on fresh and dried bovine bones, IEEE Trans. Biomed. Eng., BME-17, 101-105, 1970.
2. Lakes, R.S., Yoon, H.S., Katz, J.L., Ultrasonic wave propagation and attenuation in wet bone, J. Biom. Eng., 8 143-148 (1986).
3. Sonstegard, D. and Matthews, L., Sonic diagnosis of bone fracture healing- a preliminary study, J. Biomech., 9, 689-694, 1976.
4. Lippmann, R. K., The use of auscultatory percussion for the examination of fractures, J. Bone Joint Surgery, 14, 118-126, 1932.
5. Brown, S. A. and Mayor, M. B., Ultrasonic assessment of early callus formation, Biomed. Eng. 11, 124-136, 1976.
6. André, M., Craven, J. et.al., Measurement of the velocity of ultrasound in the human femur in vivo, Med. Phys., 7, 324330, 1980.
7. Lees, S., Cleary, P. F., Heeley, J. D., and Gariepy, Distribution of sonic plesio-velocity in a compact bone sample, J. Acoust. Soc. Am., 66, 641-646, 1979.
8. Lees, S., Heeley, J. D., and Cleary, P. F., A study of some properties of a sample of bovine cortical bone using ultrasound, Calcif. Tiss. Intern, 29, 107-117, 1979.
9. Lakes, R.S., Yoon, H.S. and Katz, J.L., Slow compressional wave propagation in wet human and bovine cortical bone, *Science*, 220 513-515, (1983).
10. V. K. Kinra, Dispersive wave propagation in random particulate composites, Special Technical Testing Publication 864, American Society for Testing and Materials, (1985) 309-325.
11 Papadakis, E. Ultrasonic phase velocity by the pulse echo overlap method incorporating diffraction phase corrections. J. *Acoust. Soc. Am.*, 1967,42, 1045
12. Papadakis, E. Ultrasonic velocity and attenuation: measurement methods with scientific and industrial applications. In: *Physical Acoustics* (Eds. W. P. Mason and ILN. Thurston) Academic Press, New York, 1976, vol. XII, 277-374
13. Norris, D. M. Propagation of a stress pulse in a viscoelastic solid. *Experim. Mech.*, 1967, 7, 297
14. Pearson, J. M. *A Theory of Waves,* Allyn and Bacon, Boston, 1966, 88-93