ULTRASONIC THROUGH-TRANSMISSION MEASUREMENT OF ELASTIC CONSTANTS OF FIBER REINFORCED COMPOSITES USING A LARGE APERTURE RECEIVER

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Abstract. *This paper describes the use of a large aperture receiver in angle beam through-transmission method of ultrasonic velocity measurement in fiber reinforced composites. This technique avoids the beam diffraction effect . The beam diffraction has the effect of rising the velocity slightly. It depends on the sample thickness and the frequency bandwidth of the ultrasonic wave. Measurements of carbon-fiber/epoxy composite samples in the frequency range of 1 to 10 MHz has been carried out with a 0.01° resolution goniometer allowing immersion through transmission time delay measurement in a temperature-controlled water tank. A short pulse ultrasonic wave is generated by a piezoelectric transducer and received by a 80-mm-diameter wide-band 52-mm-thick PVDF membrane receiver. The PVDF membrane is bonded to an acoustically matched backing material, stiff enough to prevent low frequency bending vibration. The received signals are amplified, digitized and collected by a computer for further signal processing. The time delays are calculated by the Hilbert transform of the cross-correlation between the through-water and through-sample signals. The experimental velocity measurents using a pair of the same transducer (transmitter and receiver) and the large aperture receiver transducer shows that the result for a pair of the same transducer is around 1% higher than to the large aperture receiver. The elastic constants for samples of composite materials are obtained by inverting the Christoffel equation using a set of velocity data in different propagation directions. The experimental results are compared with the literature.*

Keywords*: ultrasonic characterization, carbon fiber reinforced plastic, PVDF ultrasonic receiver*

1. INTRODUCTION

The determination of elastic constants of anisotropic materials by measurement of the density and ultrasonic velocities has been studied by several researchers in the last four decades (Zimmer and Cost, 1970 and Hosten, 2001).

An anisotropic material is described by 21 independent elastic constants. The number of elastic constants is reduced to nine when the material has orthotropic symmetry. This number may be further reduced when there is more symmetry in the material. A unidirectional carbon-fiber/epoxy laminate can be considered as transversely isotropic and the number of independent elastic constants is reduced to five (Hosten, 2001).

The determination of elastic constants from a set of bulk ultrasonic wave phase velocities in an arbitrary direction of a measured sample of composite material is based on the Christoffel's equation (Auld, 1990).

The accuracy of elastic constants is highly dependent on the precision of the velocity measurement. The immersion through-transmission method is based on the measurement of a time-delay between the time spent by the wave traveling in the absence of the sample material and the time with the sample material. This time-delay is used to calculate the phase velocity and the refraction angle in the sample (Rokhlin and Wang, 1992).

There are many factors which introduce errors when measuring velocities, such as: parallelism of the sample surfaces, temperature gradients in the experiment, velocity dispersion, acoustic diffraction, mechanical precision of the measurement device, etc. (Kushibiki and Arakawa, 2000).

Avoiding temperature gradients is very important when measuring thin sample material because a 0.1°C variation can result in a 20 ns error in a measurement device with 100 mm path which produces a 2% error in a 1 µs time-delay (Chu and Rokhlin, 1994). Due to the high attenuation behavior of composite materials the velocity dispersion introduces error that increases with the frequency and the sample thickness. On the other hand, the acoustic diffraction effect decreases with the frequency for the same transducer's effective area.

It can be shown from the radiation theory that an infinite-plane receiver with uniform sensitivity is a plane-wave filter for the direction normal to the plane (Leeman *et al.*, 1985). In the spatial integration of the field performed by an infinite-plane receiver the contributions made by the edge waves sum to zero, yielding a plane wave-only measurement. In practice, an infinite-plane receiver is modeled by using a piezoelectric PVDF (Polyvinylidene Fluoride) thin-film receiver, sufficiently large to intercept the entire propagating pulse and electroded throughout its entire extent (Adamowski *et al.*, 1995).

In this work a large aperture PVDF receiver is used together with a piezoelectric ceramic emitter in through-transmission method of ultrasonic velocity measurement in solid material plates immersed in water. It is analyzed the diffraction effect in longitudinal velocity measurement when using conventional non-destructive testing (NDT) ultrasonic transducers in the range of 1 to 10 MHz and the velocity dispersion in a plastic material. The elastic constants of a unidirectional carbon-fiber/epoxy plate are determined using phase velocities measured with an angle beam through-transmission assembly using the diffraction-free PVDF receiver.

2. DIFFRACTION EFFECTS ON VELOCITY MEASUREMENTS

Usually, the velocity measurement is done by assuming that a plane wave propagates from the emitter to the receiver ultrasonic transducer. When the dimensions of the ultrasonic transducers are finite, diffraction effects take place. This effect causes errors in the velocity measurement. In order to verify the accuracy of the velocity measurement, it is analyzed how the diffraction affects the velocity measurement. The velocity can be determined by measuring the time that the wave takes to go from the emitter to the receiver transducer. These transducers are show in Fig. 1. The radius of the emitter transducer is *a* and the radius of the receiver is *b*. The distance between the transducers is represented by *d*.

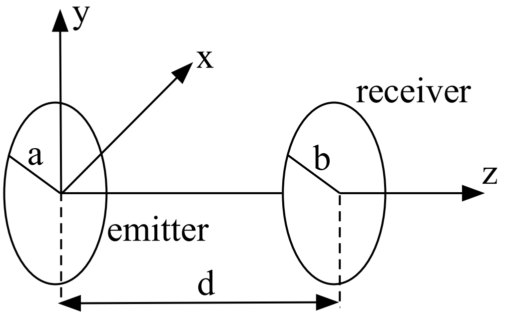

Figure 1. Transducers used in the velocity measurement.

Considering that the emitter transducer is oscillating sinusoidally with angular frequency ω and amplitude V_0, the spatial part of the velocity potential that arrives at the receiver transducer is given by (Rogers and Buren, 1974):

$$\phi = V_0 \int_0^b \int_0^a \int_0^{2\pi} \frac{\exp\left[-ik\left(r^2 + r_0^2 - 2rr_0\cos\theta_0 + z^2\right)^{1/2}\right]}{\left(r^2 + r_0^2 - 2rr_0\cos\theta_0 + z^2\right)^{1/2}} rr_0\, d\theta_0\, dr_0\, dr \tag{1}$$

where *k* is the wavenumber. If the radius of the emitter and the receiver is infinite, then a plane wave is emitted. The velocity potential of a plane wave is given by:

$$\phi_0 = \frac{V_0}{ik}\exp(-ikz) \tag{2}$$

If a pure plane wave propagates from the emitter to the receiver transducer, there are no errors in the velocity measurement. When the transducers are finite, diffraction phenomenon changes the phase of the wave, causing errors in the velocity measurement. A diffraction correction *D* can be defined as the ratio of the velocity potential given by Eq. (1) and the velocity potential given by Eq. (2) (Rogers and Buren, 1974 and Goldstein *et al.*, 1998):

$$D = \left(\frac{ik}{\pi a^2}\right)\exp(ikz) \int_0^b \int_0^a \int_0^{2\pi} \frac{\exp\left[-ik\left(r^2 + r_0^2 - 2rr_0\cos\theta_0 + z^2\right)^{1/2}\right]}{\left(r^2 + r_0^2 - 2rr_0\cos\theta_0 + z^2\right)^{1/2}} rr_0\, d\theta_0\, dr_0\, dr \tag{3}$$

In Eq. (3), the plane wave was normalized in relation to the area of the emitter transducer. Equation (3) was used to simulate the water velocity measurement using the transducers of Fig. 1. It is considered that velocity of water is 1500 m/s and the distance between the transducers is 100 mm. Considering that the radius of the emitter is 9.5 mm, Fig. 2 shows the simulated velocity measurement as a function of the frequency and the radius of the receptor. As it can be seen in this figure, the error in velocity measurement decreases with the increase of the receptor radius. Therefore, a large aperture receiver is desirable.

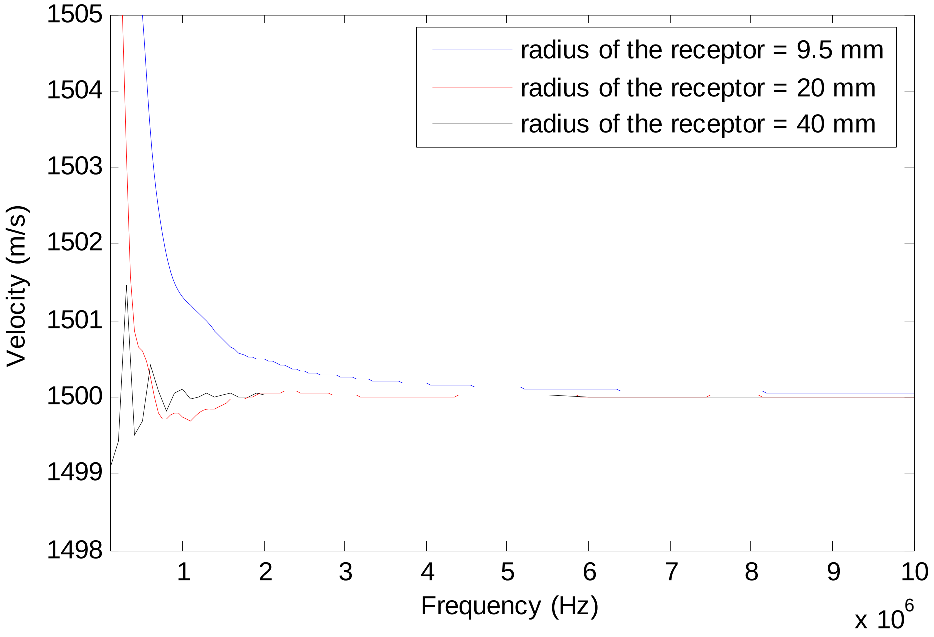

Figure 2. Simulated water velocity measurement as a function of the frequency and the radius of the receiver transducer.

3. EXPERIMENTS

3.1. Diffraction and dispersion effects on velocity measurement

The experiments have been made in a goniometer device immersed in distilled water. The water inside the goniometer was kept at 24.4 ± 0.02°C with the aid of a thermostatic bath. The goniometer device allows changing the emitter and the receiver transducers. To analyze the diffraction effect, measurements of longitudinal velocity in a low attenuation material (9.5 mm thickness aluminum plate) were conducted with 4 pairs (emitter and receiver) of 19 mm diameter NDT, Panametrics model Videoscan, transducers of 1.0, 2.25, 5.0 and 10.0 MHz and a pair of 5 MHz, focused, 10 mm diameter, Karl Deutsch transducers, as shown in Fig. 3.

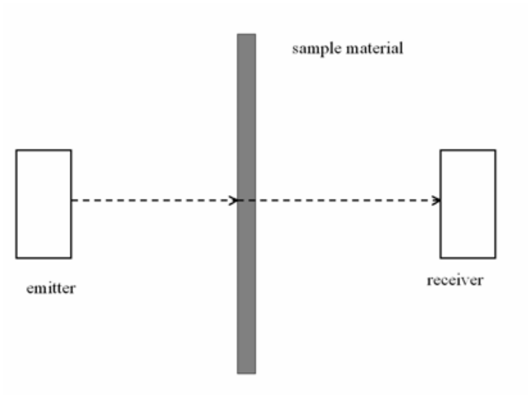

Figure 3. Measurement with a pair of NDT transducers.

The measurements of longitudinal velocity in the aluminum plate were repeated using the same set of emitter transducers but using a 80 mm diameter PVDF receiver as shown in the diagram of Fig. 4.

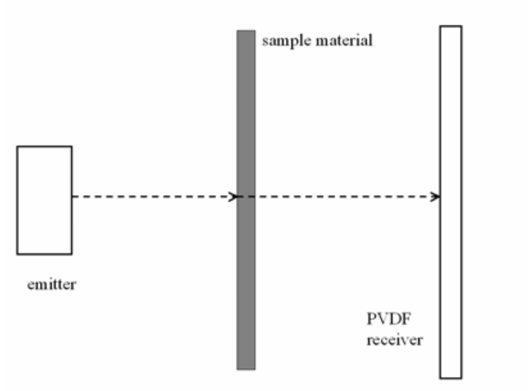

Figure 4. Measurement with the PVDF receiver.

The emitter is excited with a broadband pulse, and the electrical signals of the received waves are amplified (Panametrics 5072PR) and digitized by an oscilloscope (HP Infinium 500 MHz, 2 Gs/s) connected to a computer via ethernet . The echoes are then stored and processed in the computer using MATLAB.

3.1.1. Large-aperture PVDF receiver

The large-aperture receiver is a 52 μm-thick PVDF membrane with gold electrodes. The PVDF membrane is bonded to a matched backing material, stiff enough to prevent low frequency bending vibration. The backing material has almost the same acoustic impedance of water around 25°C and high attenuation (Andrade *et al.*, 2005). The PVDF membrane is slightly stretched by using two concentric brass rings. Each electrode is electrically connected to the corresponding terminal by contact rings. The external ring is grounded and the internal ring is connected to the signal.

The effective diameter of the receiver was chosen in order to intercept the entire ultrasonic field produced by the transmitter. The PVDF receiver used in this work, shown in Fig. 5, has 80 mm active diameter.

Figure 5. Measurement with the PVDF receiver.

3.1.2. Measurement of time delay

The time-delay between two echoes is measured using the Hilbert transform of the cross-correlation between them. It can be shown that the resolution in the time-delay measurement can be increased by a factor of ten when compared to the cross-correlation method (Higuti and Adamowski, 2002).

3.1.3. Diffraction effect

Figure 6 shows the measured longitudinal velocities in the aluminum plate. The results show that the diffraction effect may produce more than 1% error when using pair of transducers with 19 mm diameter and frequency under 2 MHz, or when using small diameter at higher frequency, such as, the 5 MHz, 10 mm, focused transducer. This effect is eliminated with the large-aperture PVDF receiver as shown by the results of the dotted line and the result shown by the triangular mark.

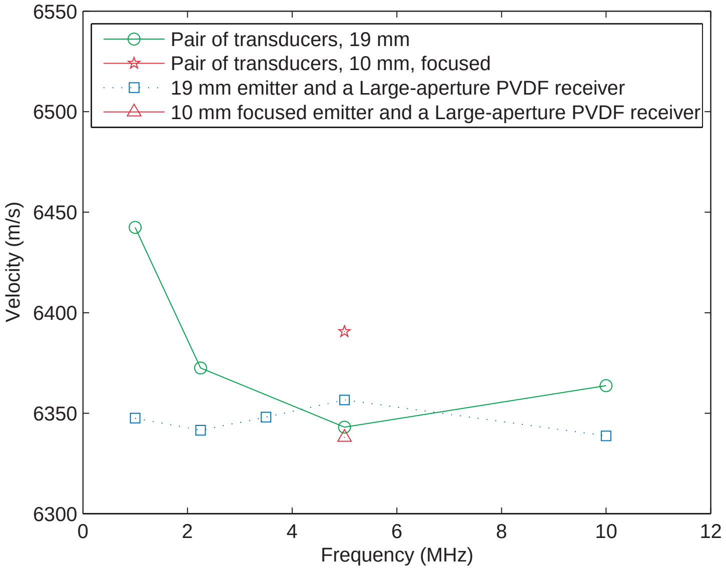

Figure 6. Measurement of longitudinal velocity in a 9.5 mm thick aluminium plate.

3.1.4. Dispersion effect

Figure 7 shows the results of the longitudinal velocity measurement in a acrylic 4.5 mm thickness plate using a set of five NDT transducers of 1.0, 2.25, 3.5, 5.0, and 10.0 MHz, 19 mm diameter, as emitters and the diffraction-free PVDF receiver.

The results show that the longitudinal velocity increases with the frequency, producing an error of about 1% when the frequency increases from 1 to 10 MHz.

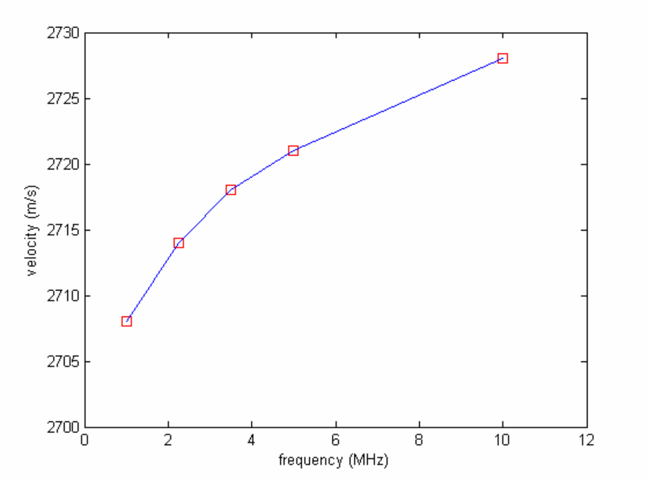

Figure 7. Measurement of longitudinal velocity in a 4.5 mm thick acrylic plate.

4. DETERMINATION OF ELASTIC CONSTANTS

Figure 8 show the coordinate system attached to a unidirectional laminate. The fibers are placed parallel to axis x_3. The plane x_1-x_2 can be considered isotropic (Hosten, 2001).

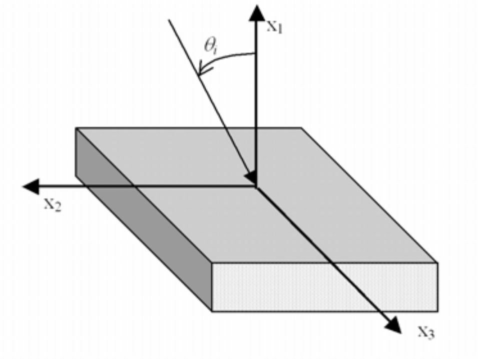

Figure 8. Coordinate system of a unidirectional laminate.

The stiffness tensor of a unidirectional composite laminate material has five independent elastic constants and is represented by Eq. (4).

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & (C_{11}-C_{12})/2 \end{bmatrix} \tag{4}$$

The Christoffel equation allows the calculation of the phase velocity at a given direction from the set of the elastic constants in Eq. (4). The inverse problem consists in the determination of the elastic constants from the phase velocity measurement in several specific directions.

The phase velocity at a refraction angle θ_r is obtained by measuring the time-delay Δt of the ultrasonic wave traveling with and without the composite plate at a known temperature. The acoustic velocity in water v_w is tabulated and can be obtained from the temperature. The phase velocity for a composite plate with thickness h is (Rokhlin and Wang, 1992):

$$v(\theta_r) = \left(\frac{1}{{v_w}^2} - \frac{2\Delta t \cos\theta_i}{h v_w} + \left(\frac{\Delta t}{h} \right)^2 \right)^{-1/2} \tag{5}$$

where:

$$\theta_r = sin^{-1}\left(\frac{v(\theta_r) sin\theta_i}{v_w} \right) \tag{6}$$

and θ_i is the incidence angle. The unknown elastic constants are found by minimizing an objective function F which is the sum of the squares of the deviations between the experimental and calculated phase velocities given by:

$$F = \sum_{i=1}^{N} (v_i^{\exp} - v_i^{calc})^2 \tag{7}$$

where v_i experimental is obtained by Eq. (5), and N is the number of measured velocities. The minimization of F is implemented using the function *fminsearch* of MATLAB.

4.1. Experimental results

The experimental results of the phase velocities were obtained from a 2.107 mm thick unidirectional carbon-fiber/epoxy square plate (80 x 80 mm) with density ρ = 1576 kg/m^3 using a goniometer shown in Fig. 9. The emitter transducer is a 5 MHz, 10 mm, focused, Karl Deutsch, and the receiver is the diffraction-free PVDF transducer. The velocities are measured in the plane 12 and 13. The measurements are made from 0 to 45°, spaced by 1°. The results are shown in Fig. 10.

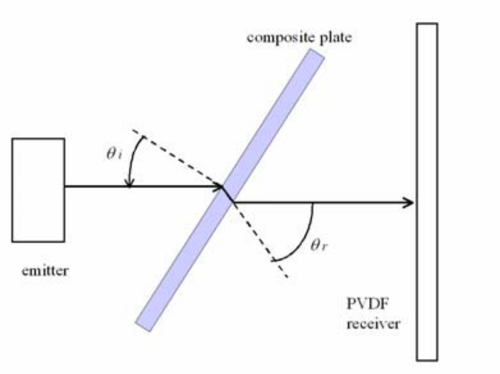

Figure 9. Schematic of the goniometer.

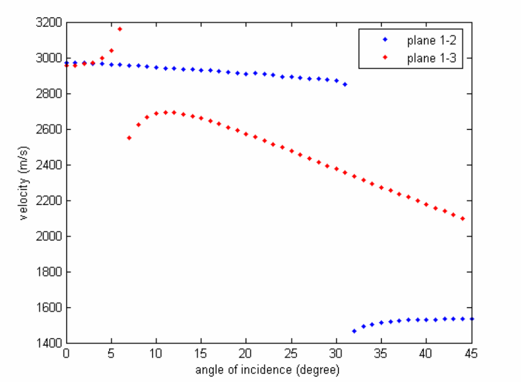

Figure 10. Phase velocities in the planes 12 and 13.

Figure 11 shows the experimental and the calculated velocities after solving the optimization problem to obtain the elastic constants.

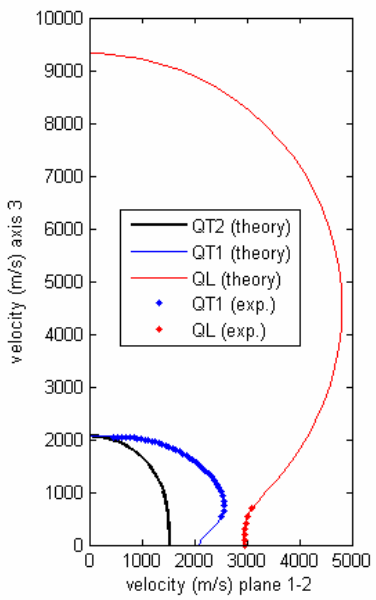

Figure 11. Experimental and calculated phase velocities: QT – quasi-transversal and QL – quasi-longitudinal.

Table 1 shows the initial guess and the calculated results of the elastic constants obtained by minimizing function *F* of Eq. (7).

Table 1. Elastic constants.

Elastic constant	Initial guess (GPa)	Calculated (GPa)
C_{11}	11.0	13.53
C_{12}	5.0	6.26
C_{13}	5.0	5.02
C_{33}	175.0	136.93
C_{44}	5.3	6.77

5. CONCLUSION

The experimental results of the diffraction effect on velocity measurement, in a low attenuation material, show that this error can be more than 1% when using a pair of transducers under 2 MHz with 19 mm diameter. The measurements with the large-aperture PVDF receiver show a clear elimination of the diffraction effect, even when using a 5MHz, 10 mm diameter focused transducer. The dispersion effect is shown for the measurement of longitudinal velocity in an acrylic plate (medium attenuation) with the diffraction-free receiver. The fiber/plastic reinforced composites generally have high dispersive effect. The results of the elastic constant measurement with the large-aperture PVDF receiver show good agreement with the literature (Hosten, 1992).

6. ACKNOWLEDGEMENTS

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