MEASURING IN-PLANE ELASTIC MODULI OF COMPOSITES WITH ARRAYS OF PHASE-INSENSITIVE ULTRASOUND RECEIVERS*

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INTRODUCTION

Ultrasonic measurements of elastic moduli of composite materials have traditionally been made on either small specimens cut from a larger component or by using a scanning technique with the specimen immersed in a water bath. A phase-insensitive array has been developed for rapid nondestructive measurement of in-plane elastic moduli. The array characteristics allow for determination of energy flux deviation angle in the composite, as well as measurement of group and phase velocity. Techniques for computing the phase velocity from array measurements are described.

Energy flux deviation in unidirectional graphite-epoxy specimens has been determined with the array. Comparisons are made herein of results with analytical (bulk wave) predictions.

DETERMINING ELASTIC MODULI IN COMPOSITE MATERIALS

For the following discussion, assume the specimen is a fiber-reinforced composite plate with the fibers aligned along the 1-axis (Figure 1). Orthotropic elastic symmetry is assumed for generality, to permit dealing with specimens having a nonuniform layup.

Bulk wave theory [1] gives expressions for the phase velocity 'V' of a stress wave propagating in an anisotropic elastic solid in terms of the elastic moduli 'C_{ij}' and the direction '$\underline{k}$' of the wave normal. Phase velocity is a function of these quantities.

$$\rho V^2(\underline{k}) = f(C_{ij}, \underline{k}) \qquad (1)$$

where, ρ is the mass density of the anisotropic solid.

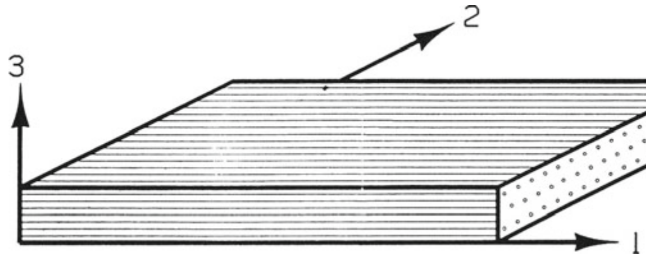

Figure 1. Coordinate Axes Assigned to the Composite Panel

One method for determining the elastic moduli is to propagate ultrasonic waves in various directions '$\underline{k}$' and measure the phase velocity $V(\underline{k})$. Then, one solves for the Cij from a number of simultaneous equations, each of the form of equation (1).

For a composite plate, the measurement technique involves propagating ultrasonic waves off-axis in the 1-3 and 2-3 planes (Figure 1). In the 1-3 plane, the quasilongitudinal and quasitransverse wavespeeds are related to the moduli C_{11}, C_{13}, C_{33} and C_{55}. In the 2-3 plane, the quasilongitudinal and quasitransverse wavespeeds are related to the moduli C_{22}, C_{23}, C_{33} and C_{44}. These measurements yield 7 of the 9 elastic moduli. The remaining constants, C_{12} and C_{66} could be measured by using horizontally-polarized transverse (SH) waves.

USING AN ARRAY TO DETERMINE PHASE VELOCITY VERSUS PROPAGATION DIRECTION

A receiving array may be used as shown in Figure 2 to gather data for calculating phase velocity. The variable-angle wedge transducer generates stress waves in the composite which may be adjusted through a range of refracted directions. The critical angle for the energy flux in the composite determines the upper limit on angle for which measurements are possible. Phase velocity measurements can be made by determining the transit time and direction of the energy flux and measuring the angle-of-arrival of the wavefront at the array.

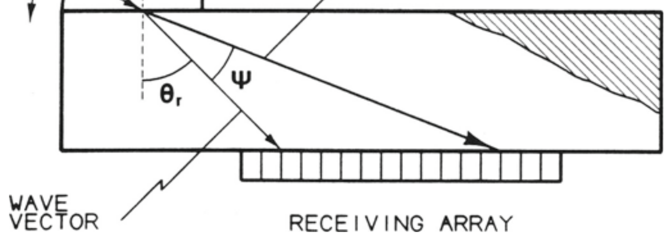

Figure 2. Use of an Array for Transmission Mode Determination of Phase Velocity versus Angle

PHASE VELOCITY MEASUREMENT FROM ARRAY DATA

The procedure for measuring the phase velocity begins by placing the transmitter and receiving array on an isotropic plate (Figure 3) and measuring the transit time 't_1'.

$$t_1 = [(D_1^2 + y_1^2)^{1/2}] / C_1 + \text{constant}, \qquad (2)$$

where the term in the square brackets is the distance travelled through the isotropic slab. The distance y_1 is measured to the position where the center of the transmitted ultrasound beam encounters the array. The constant term is the transit time of the ultrasonic pulse through the variable angle wedge and the coupling layers. This transit time delay can be found since both C_1 and D_1 are known for a well-characterized isotropic sample

Next, the transmitter and array are coupled to the composite plate (Figure 4) and the transit time 't2' is measured. The group velocity is then calculated from

$$C_g = [(y_2^2 + D_2^2)^{1/2}] / t_3, \qquad (3)$$

where, $t_3 = t_2$ - constant.

Using Snell's law at the wedge, anisotropic solid interface

$$[C / \sin(\theta_i)] = [V / \sin(\theta_r)] \qquad (4)$$

and the relationship between phase velocity 'V' and group velocity 'C_g'

$$V = C_g \cos(\psi) \qquad (5)$$

an equation can be written for θr,

$$\theta_r = \tan^{-1} \{ \cos(\theta_g) / [(C/C_g) / \sin(\theta_i)] - \sin(\theta_g) \} \qquad (6)$$

Since C_g and θ_g have been measured (eq (3) and Fig. 4), equation (6) may be used to calculate θ_r.

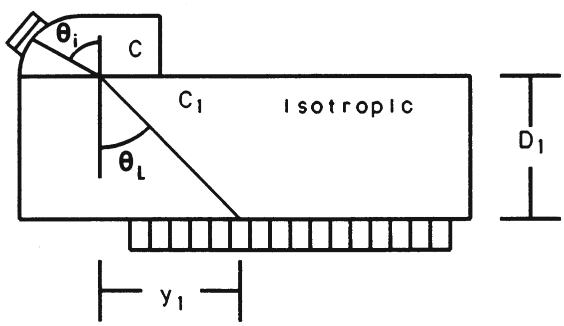

Figure 3. Transmitter and Receiving Array Placement on an Isotropic Plate for Determination of Transit Time Delays.

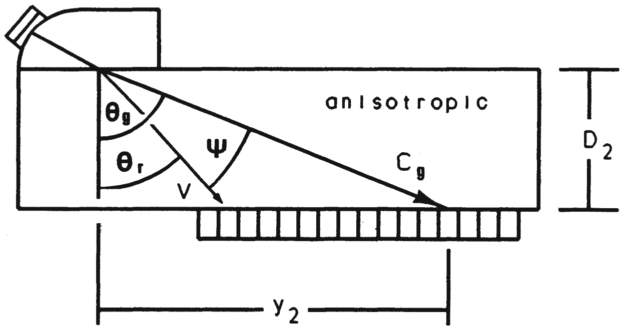

Figure 4. Receiving Array and Variable-Angle Transmitter Coupled to an Anisotropic Plate for Wavespeed Measurements.

Finally, since

$$\psi = \theta_g - \theta_r,$$

the phase velocity may be found from equation (5). Thus, the phase velocity is given in terms of known or measurable quantities.

An alternative method (instead of eq. (6)) for calculating θr may be developed from a consideration of waves in the anisotropic plate arriving at the array. Wavefronts impinging on the receiving array are shown schematically in Figure 5, along with the signals generated. The angulation of the wavefronts is in the direction of the wave normal (angle θ_r), but the energy is carried in the direction of the energy flux vector and travels at the group velocity. ΔT is the delay in arrival time at adjacent elements in the array. This time is related to the distance travelled and the wavespeed,

$$\Delta T = f / C_g = [\ e \sin(\theta_r)\ ] / [\ C_g \cos(\psi)\ ] \ . \qquad (7)$$

Using eq (5) in eq (7) and rearranging gives

$$V / \sin(\theta_r) = e / \Delta T \qquad (8)$$

Replacing $C/\sin(\theta_i)$ in equation (6) by its equivalent $e/\Delta T$ (refer to equations (4) and (8)) gives a relationship for θ_r which does not rely on measurements of the wavespeed in the transmitting wedge or the incident angle.

$$\theta_r = \tan^{-1} \{\ \cos(\theta_g) / [\ e / (\ \Delta T\ C_g\ )\ ] - \sin(\theta_g)\ \} \qquad (9)$$

ARRAY AND ELECTRONICS

Several linear receiving arrays were fabricated for making phase velocity measurements on composite panels. Each array was composed of a number of 0.5 mm diameter elements spaced on 2.5 mm centers. Both 16-element and 32-element arrays were constructed from the

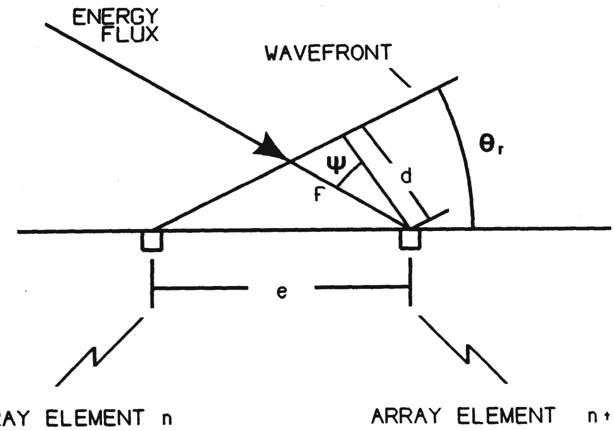

Figure 5. Detail of the Wavefronts in an Anisotropic Material Arriving at an Ultrasonic Receiving Array.

piezoelectric polymer PVDF. The small size and the broad bandwidth of the array elements make these arrays ideal for mapping the ultrasonic field. Small size also renders the receiving elements relatively phase insensitive - an advantage when monitoring ultrasound propagating through inhomogeneous material.

An electronic system was designed and built for multiplexing of the array element signals and for preamplification. Particular attention was given to reducing crosstalk and to maintaining a broad bandwidth. Crosstalk levels were approximately -55 dB (at 5 MHz) for most of the channels. The bandpass range (-3 dB) for the electronics was from 200 kHz to 35 MHz.

EXPERIMENTS

Samples of a graphite-epoxy, unidirectional composite were obtained for study with the arrays. The composite plate and samples sectioned from the plate were available. Elastic moduli for this composite had been measured some time ago [2]. Moduli were remeasured before commencing the array experiments on a set of samples (size: 10 x 25 x 3 mm) excised from the composite panel. Ultrasonic measurements of modulus were made on these samples in pure-mode propagation directions.

Measurements of phase velocity on intact composite plates have been made, using the algorithm detailed herein by equation (1-9). Results to-date have shown +-10% agreement between calculated phase velocity and that measured on composite specimens excised from the plate.

A second series of measurements were performed using the array to map the flux deviated ultrasound field in the composite. The measurements were made on a set of samples machined from the composite plate as shown in Figure 6. With this geometry, ultrasound could be

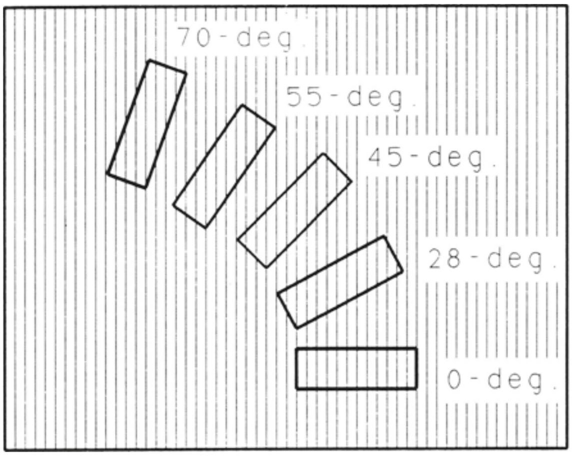

Figure 6. Samples Machined from a Undirectional Composite Plate.

transmitted into the sample at various angles with respect to the fiber axis. A 6.35mm diameter piezoceramic transmitter was coupled to one side of the sample and kept in afixed position. The receiving array was affixed to the opposite side of the specimen. The transmitted ultrasound beam propagated through the composite as quasilongitudinal and quasitransverse waves.

A data set collected with the array is shown in Figure 7. This is a plot of receiver voltage versus time for each of 16 elements in the array. Both the temporal and spatial character of the ultrasonic field are measured. Quasilongitudinal (QL) and quasitransverse (QT) waves are identifiable. The small waveform occurring after the large QL waveform is a QL reverberation (along the energy flux direction) in the sample.

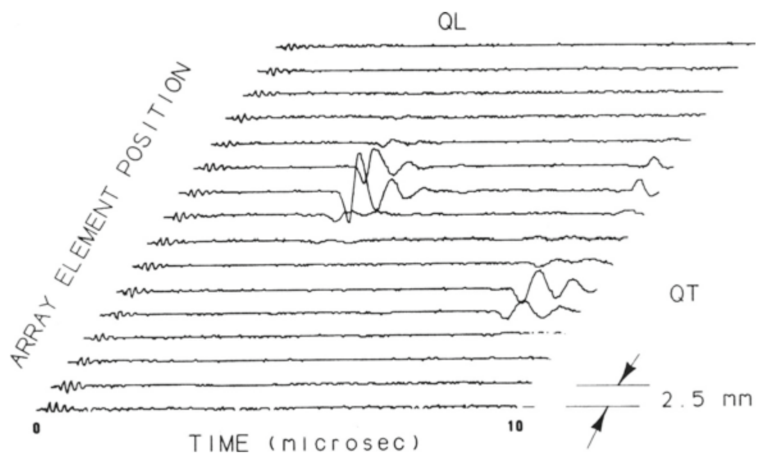

Figure 7. Waveforms at Each of 16 Elements in a Receiving Array Recorded During a Transmission Experiment on a Composite Sample (45-degree Fiber Orientation).

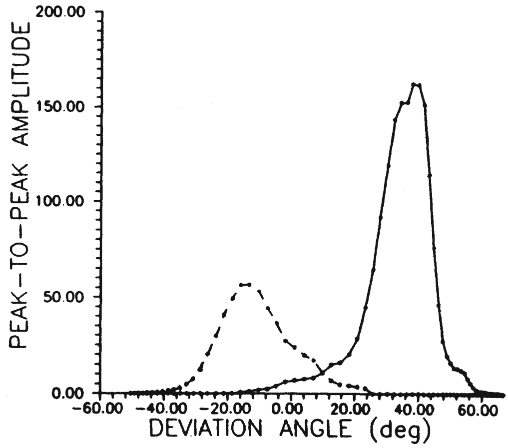

Figure 8. Peak-to-Peak Amplitude of the Array-Measured Quasi-longitudinal (solid line) and Quasitransverse (dashed line) Fields at the Surface of a Composite Specimen During a Transmission Experiment.

An array was used (as described above) to map the transmitted QL and QT fields at the surface of each of the composite specimens shown in Figure 6. Peak-to-peak receiving element voltage was plotted versus deviation angle from the transmitted beam direction for each specimen. An example is given in Figure 8. The deviation angle associated with the peak and centroid of these field distributions is tabulated in Tables 1 and 2 along with deviation angles predicted by a bulk wave model (Christoffel relations). Two specimens with fiber orientations of 28 and 45 degrees were examined.

Table 1
Comparison of Energy Flux Directions
(Quasilongitudinal Wave)

Fiber Angle	Bulk-Wave Predicted	Array, Peak of Measured Amplitude	Array, Centroid of Measured Amplitude
28	26.2	28.0	25.6
28	26.2	32.9	26.0
45	41.6	42.3	40.4
45	41.6	44.8	44.2
55	50.0	50.3	49.6
70	59.0	55.8	55.5

Note: All entries are in degrees.

Table 2
Comparison of Energy Flux Directions
(Quasitransverse Wave)

Fiber Angle	Bulk-Wave Predicted	Array, Peak of Measured Amplitude	Array, Centroid of Measured Amplitude
28	-16.6	-13.3	-13.7
28	-16.6	-13.4	-13.6
45	-16.3	-9.5	-12.2
45	-16.3	-13.2	-11.1
55	-13.3	-9.5	-8.7
70	+0.5	+7.0	+8.6

Note: All entries are in degrees.

CONCLUSIONS

A technique for determining the elastic moduli of composite plates has been developed which utilizes data rapidly-gathered with an ultrasonic receiving array. The array may also be used to measure the fields of the quasilongitudinal and quasitransverse waves generated during ultrasonic transmission experiments.

The energy flux directions of the QL wave as measured by the array are quite similar to the bulk wave predictions. The disparity in the directions of the QT energy flux as measured with the array and that predicted are attributed to alteration of the shape of the broadband ultrasonic beam as it propagates through the anisotropic material and possibly the sensitivity of the array elements to the transverse components of the stress wave field as well as the normal component. Further study is underway to clarify these issues.

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ACKNOWLEDGMENTS

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