Measurement of elastic constants in composite materials using air-coupled ultrasonic bulk waves

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(Received 6 January 1995; accepted for publication 23 December 1995)

This paper presents numerical simulations and experimental measurements of longitudinal and shear bulk waves in composite materials, generated and detected with an air-coupled ultrasonic system. The transfer function of an anisotropic absorbing layered plate immersed in air is computed with the transfer matrix method, and the waveforms produced by transmission through a plate are simulated from the convolution of a reference waveform and the impulse response of the plate. The calculated waveforms compare well to those recorded experimentally, confirming that the waveforms recorded experimentally have the correct characteristics. It is demonstrated that it is possible to identify longitudinal and shear modes. Results are presented showing how this data may be used to recover the stiffness matrix of composite materials, using the angular variation of velocity of both modes. © *1996 Acoustical Society of America.*

PACS numbers: 43.35.Cg, 43.35.Mr

INTRODUCTION

The ultrasonic immersion technique, using a water coupling medium, is now a standard method of the nondestructive inspection of anisotropic composite materials. Using a goniometer to investigate a composite material in any direction of propagation, their anisotropic elastic[1,2] or viscoelastic[3,4] properties can be determined. This method is especially useful for following the evolution of these properties, caused for instance by anisotropic damage,[5,6] when the material is submitted to a tensile stress. A comparative analysis of the through-transmission ultrasonic bulk wave methods was recently published by Chu and Rokhlin.[7]

In a conventional system, the ultrasonic piezoelectric transducers are coupled to the material using a liquid which has an acoustic impedance of the same order of magnitude as the sample. The ratio between solid and fluid impedances is rarely greater than ten, whereas the ratio is approximately 10 000 between solid and air. However, there are many cases for which it is important to eliminate the liquid coupling medium, for instance in presence of high temperatures, porous materials etc. Noncontact techniques such as laser generation and detection of ultrasound were developed for just such reasons.[8,9] This point source/point receiver method is very powerful, but the generated ultrasonic fields, and the theory describing their generation, are rather complicated, as is the inverse problem.[10–13] In addition, the method is sensitive to the optical properties of the solid surface, and can cause damage to the material. The use of air-coupled transducers would be both a simpler and cheaper alternative.

There has been a lot of recent interest in the use of air-coupled transducers, the aim being to generate and detect the ultrasonic waves in the same way as in a conventional immersion system, but replacing the liquid coupling medium with air. There are two popular designs of transducer for this purpose, using either a piezoelectric device with a matching layer for air,[14] or an electrostatic (capacitance) device.[15–18] Work has been presented to illustrate the use of both types of device for performing measurements on composites.[14,19,20] The present work is based on a recent design of capacitance transducer incorporating a micromachined silicon backplate,[17] which have an extended bandwidth over other capacitance devices and piezoelectric designs, a property that is required in the present set of measurements. As will be shown, the combination of sensitivity and bandwidth facilitates the generation and detection of bulk plane waves, which can be used to perform a comparison to theoretically simulated waveforms. It will also be demonstrated that such signals can be used with the relevant simple Christoffel's equations and associated procedures to recover the elastic properties of a fiber-reinforced composite sample.

In an orthotropic material, stresses σ_i and strains ϵ_i are linked by six linear relations $\sigma_i = C_{ij}\epsilon_i$ which define the stiffness matrix C_{ij}, using nine independent constants. Orthotropic materials have three planes of symmetry.[21] Composite materials made of superimposed plies[22] are shaped like a plate, which defines the principal plane (see Fig. 1, which also indicates the nine constants of interest). Using an immersion technique, it is possible to measure seven of these constants routinely, in the two planes P_{12} and P_{23} of Fig. 1. The other two (C_{23} and C_{44}) can be measured in certain materials, if the composite is sufficiently anisotropic, but it is a more difficult measurement.[23] In fact, in a quadratic material, three pairs of constants are equivalent ($C_{22} = C_{33}$, $C_{12} = C_{13}$, and $C_{55} = C_{66}$), thus reducing the re-

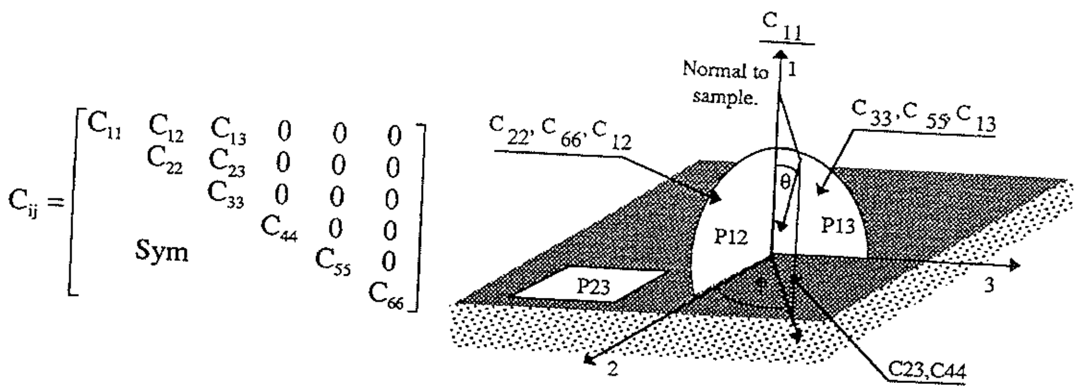

FIG. 1. Axis and planes of symmetry in long fibers composite materials.

quired number of independent measurements of these constants. In this paper, we will measure C_{11}, C_{13}, C_{33}, and C_{55}. Conventionally, the elastic properties of composites are measured using a system where the angle of incidence onto the plate can be changed using an accurate goniometer. The transmitted waveforms through the plate-shaped sample are acquired and compared to a reference waveform recorded without the sample. The sample is immersed in the coupling medium between two ultrasonic transducers, this usually being water. A cross correlation is then used between the reference waveform and that through the composite, for both longitudinal and shear modes, to measure velocities as a function of incidence angle.

It is interesting initially to compare the problems associated with using air coupling instead of water. The wave velocity in air is about five times less than in water, and as a result the changes in time of flight caused by introducing the sample are much greater, when compared to the fluid-only path. Moreover, the use of air-coupled transducers reduces the angular range over which signals can be recorded. According to the Snell–Descartes' laws, the limit angles will be about five times smaller with air than with water, and the transducers can be placed much closer. Therefore, the accuracy of the time-of-flight measurement can be greatly enhanced, an additional advantage of the technique. The main disadvantage of using air-coupled transducers when compared to water immersion is that the amplitude of transmitted waveforms is reduced by at least three orders of magnitude. In addition, the bandwidth of the measurement is somewhat restricted ($\geqslant 1$ MHz in the present measurements).

Despite the above limitations, recent publications[16,17,20] have shown that the signal-to-noise ratio is now large enough for air-coupled transducers to be used in nondestructive evaluation of composite materials, and one purpose of this paper is to demonstrate that the limited frequency bandwidth is not an obstacle to observing separate longitudinal and shear transients in composite materials. This then leads to the possibility of comparing experimental results to the forward modeling problem, where transmitted waveforms are predicted for a sample with known acoustic properties and thickness. It may also be possible to study the inverse problem, where waveforms are recorded as a function of incident angle, and the data used to predict the stiffness matrix of the composite. Both possibilities are studied in the present work.

I. APPARATUS AND EXPERIMENT

The experiments used the usual arrangement for elastic constant determination, modified for use in air as shown in Fig. 2. The sample was mounted on a high precision goniometer stage, with an angular resolution of 0.1°, and the air-coupled transducers mounted to perform through-transmission experiments as shown. The transducers, capacitance devices with micromachined silicon backplates, and metallized polymer membranes, have been described elsewhere.[17] The source was excited by a Panametrics 5052 UA pulser/receiver, and transmitted signals detected using a similar device with a thinner (3 μm) membrane. This was provided with a dc bias via a Cooknell CA6/C charge amplifier, whose output was fed back into the receiver section of the 5052 UA unit to boost signal levels. The amplified signal was then digitized using a LeCroy 9410 oscilloscope. The whole data collection and processing operation was controlled by an Apple Macintosh II computer. Note that refraction effects, leading to sideways displacement of the trans-

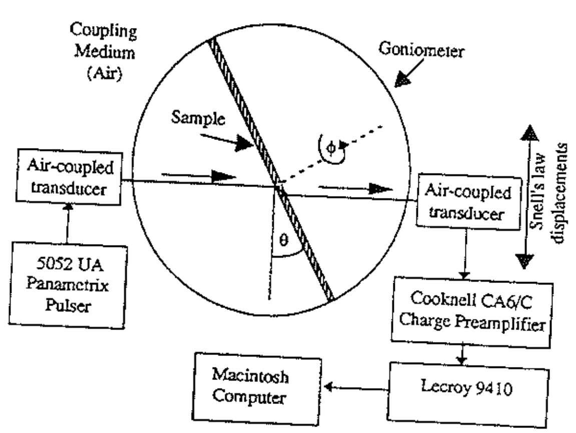

FIG. 2. Setup to investigate a material in through transmission.

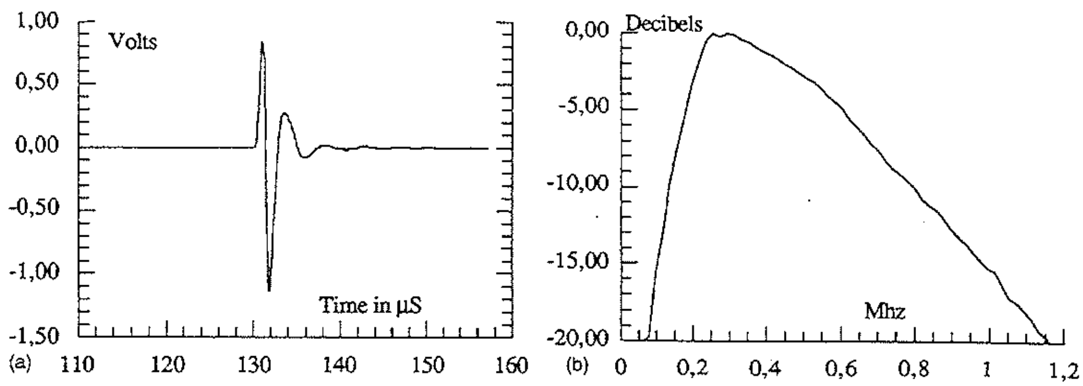

FIG. 3. (a) Experimental waveform in air. (b) Corresponding spectrum.

mitted beam, were also taken into account automatically by scanning the receiving transducer laterally by an appropriate amount, as shown.

A typical waveform transmitted from the source to transmitter in air, without the sample present, is shown in Fig. 3(a). Note the absence of ringing associated with piezoelectric devices, and that the signal level was several volts in amplitude. The corresponding frequency spectrum is shown in Fig. 3(b), and it is clear that usable energy extends to frequencies beyond 1 MHz. With the sample to be tested inserted between source and receiver, the signal level dropped significantly, with a signal-to-noise level that necessitated some signal averaging (typically 1000 sweeps) to obtain a reasonable signal. In the present work, several types of sample were tested. The first was a carbon fiber epoxy sample, in the form of a cross-ply sample with 16 layers to give a final thickness of 2 mm. Also tested was a 5.7-mm-thick $[0,90]_{8s}$ glass fiber cross-ply composite sample, with an epoxy matrix and 32 fiber layers aligned in the 0° and 90° directions. Both types of sample were tested over a range of incident angles in air, typically up to 12°.

II. RESULTS

A. Theory and experiment for waveforms in anisotropic composite plates

The first area of interest is the forward problem, i.e., to measure the properties and characteristics of through-transmitted ultrasonic waveforms when using an air-coupled system, and to compare the results to a theoretical prediction. This is interesting, as a sample in air is likely to lead to different transmission properties than when it is immersed in water. A comparison of theoretical simulations to experimental waveforms over the detection bandwidth would also allow us to be confident that the experimental arrangement is producing reasonable results, and would also allow the identification of various features, such as mode conversion to shear waves in the plate.

Consider first the 16-ply carbon fiber sample. The transmitted waveform recorded at normal incidence (0°) is shown in Fig. 4. It will be seen that the signal is characterized by a decaying longitudinal wave resonance in the thickness direction of the composite. This arises because of the low transmission coefficient across the air/composite boundary, which traps energy within the composite. The rate of decay of this signal will depend on the material properties, including both the impedance and the attenuation. To study this phenomenon further, it is interesting to compare the waveform of Fig. 4 to theoretical simulations. This computes the transfer function of a stratified plate in the frequency domain, for any incident and azimuthal angle, using the transmission coefficient of the plate computed from the anisotropic viscoelastic properties of each layer. This transfer matrix method was recently adapted to take into account the propagation of the heterogeneous modes generated through interfaces, in oblique incidence[24] and the numerical stability was achieved by using the delta operator technique.[25] The Fourier transform of this transfer function is the impulse response $h(t,\theta,\phi)$. The transmitted waveform $s(t,\theta,\phi)$ is computed from the convolution product:

$$s(t,\theta,\phi)=r(t)\otimes h(t,\theta,\phi),$$

where $r(t)$ is the reference waveform, transmitted through the coupling medium between source and receiver (i.e., without the sample). The convolution product is computed in the usual way using

$$R(\nu)=\mathscr{F}((t)),$$

$$H(t,\theta,\phi)=\mathscr{F}(h(t,\theta,\phi)),$$

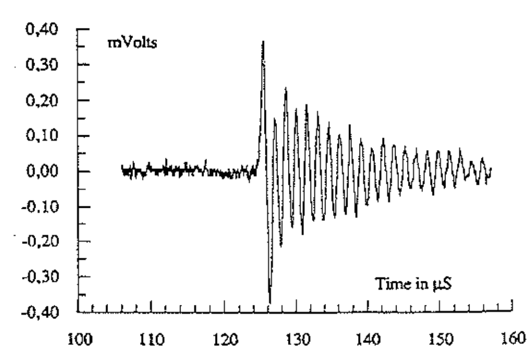

FIG. 4. Experimental waveform at normal incidence in air for the 16-ply carbon fiber sample.

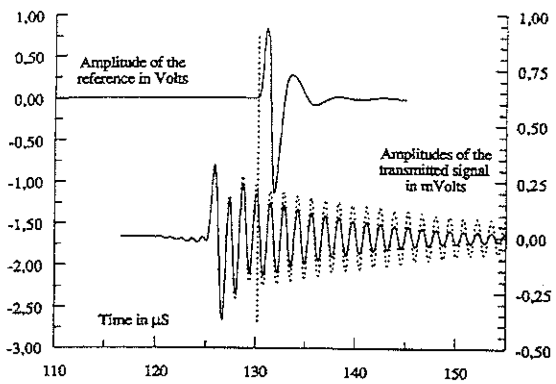

FIG. 5. Theoretical simulation of transmission in normal incidence through a 16-ply carbon/epoxy sample immersed in air. Solid lines: $C_{11}=13+I\ 0.5$ GPa. Dashed lines: $C_{11}=13+I\ 0.25$ GPa.

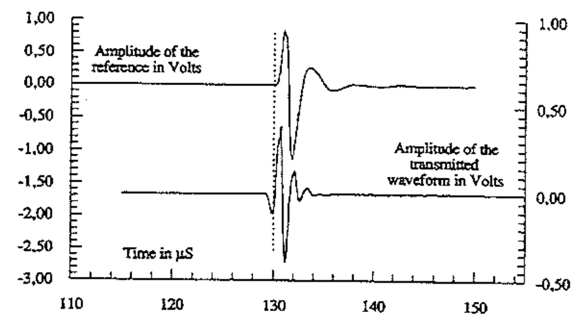

FIG. 6. Transmission in normal incidence through 16 layers of carbon/epoxy immersed in water.

and

$$s(t,\theta,\phi)=\mathscr{F}^{-1}(R(\nu)H(\nu,\theta,\phi)),$$

where $\mathscr{F}$ denotes the Fourier transform in the frequency domain $[\nu_1\cdots\nu_2]$.

In this paper, simulated theoretical waveforms in air were computed with the reference waveform of Fig. 3, as recorded from the micromachined capacitance devices. The mass density and wave velocity in air were, respectively, taken to be 0.0012 and 0.34 mm/μs. The results shown in Fig. 5 are the waveforms computed for through transmission in air by the 16-ply carbon/epoxy composite sample. It is evident that the damped thickness resonance observed experimentally is predicted theoretically, at a similar frequency. The sample mass density and thickness were taken to be 1.5 and 2 mm, respectively, for the calculation, and the viscoelastic properties in normal incidence were taken to be the generally accepted values for this material: $C_{11}=13+I\ 0.5$ GPa. A computation was also performed with a smaller attenuation of $C_{11}=13+I\ 0.25$ GPa. Figure 5 also shows the importance of introducing attenuation into the theoretical simulation, as it is a significant factor in determining the decay of the resonant oscillation. The fact that the waveform predicted in Fig. 5 has similar features (amplitude, shape and duration) to that recorded experimentally in Fig. 4 demonstrates that the computation seems to work well for experiments performed in air.

As mentioned previously, the reflection coefficient of an air/solid or solid/air interface is almost equal to 1, and this leads to a resonant signal at normal incidence. However, because of attenuation within the sample, the resonance is caused to decay. In water this aspect is less evident because a large portion of the energy is transmitted through the interfaces. To illustrate this point, a simulation of transmission of the same incident reference waveform [Fig. 3(a)] through the same material immersed in water results in the waveform presented in Fig. 6. Note several factors of interest. First, the change in propagation delay caused by inserting the sample between the source and receiver in air (Fig. 5) is approximately ten times that expected in a water-coupled experiment (Fig. 6). As it is this change that gives information on velocity within the sample, the accuracy of the measurement should be greater for the air-coupled case. In addition, in the case of water coupling, the simulations indicate that attenuation in the sample has little effect on the waveform for this sample in this frequency domain, whereas it is a big effect for air coupling. This may have implications for recovering the elastic constants in some materials.

Similar measurements were performed in air for the glass fiber/epoxy sample, and the results are shown in Fig. 7 for (a) theoretical simulation and (b) experiment. Note again that there is excellent correlation between the two. Note now that the signal contains discrete longitudinal multiple reflections, and that these can easily be separated. This is due to the greater thickness in this material than within the carbon fiber reinforced sample.

It is now interesting to observe the changes in the wave-

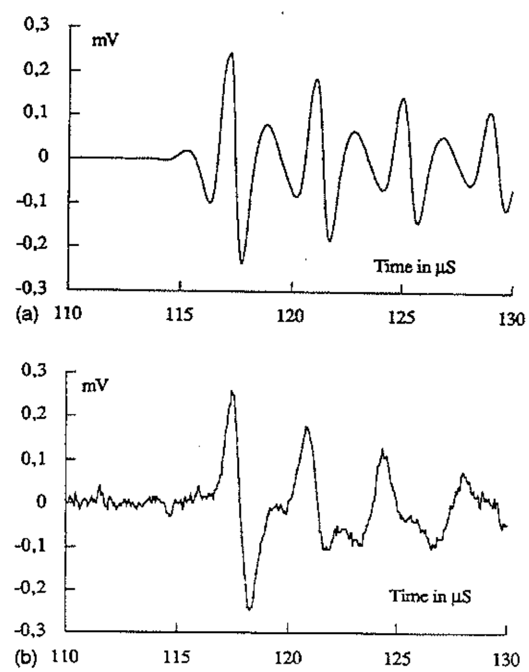

FIG. 7. (a) Normal incidence computed waveform in the glass fiber reinforced sample. (b) Normal incidence experimental waveform in the glass fiber reinforced sample.

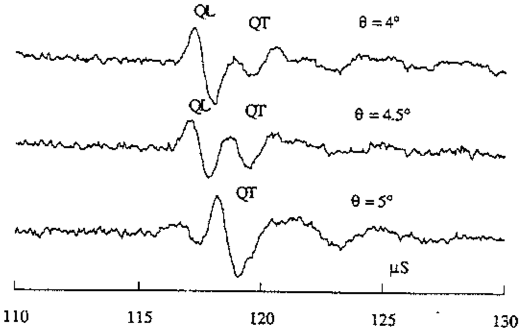

FIG. 8. Experimental waveforms in the $[0,90]_{8S}$ glass fiber sample for incident angles of 4.0°, 4.5° and 5.0°.

form that occurred when the glass fiber sample was rotated, so that oblique incidence could be studied. Selected waveforms are presented in Fig. 8 for plane P_{13} (as defined in Fig. 1), for incident angles of 4°, 4.5°, and 5°. These are more complicated than at normal incidence, but simulations can be used to identify the main features of the problem. This is especially important for the determination of the C_{ij} elastic constants which is described below. As before, it is instructive to compare what is expected to happen in air with the water-coupled case, using the simulation approach. As in the normal incidence case, it is expected that the main difference between water and air immersion is the influence of the interface transmission coefficients. This is well illustrated in the computations of the amplitude (shown in Fig. 9) of the first bulk arrivals transmitted through the composite versus the angle of incidence.[3] Here, the modes of interest are the quasilongitudinal (QL) and quasitransverse (QT) modes. Note as before that when this material is immersed in air, the amplitude is about 3500 times less than the amplitude expected in water. In addition, the first critical angle is at less than 5° in air, and energy is not expected to propagate through the sample at angles beyond 14° (assuming plane wave incidence). For water coupling these angles are much greater.

More information concerning this behavior can be observed in the simulated time waveforms, shown in Fig. 10. These can be compared directly to the experimental waveforms, where similar behavior is observed. At 4°, the quasi-

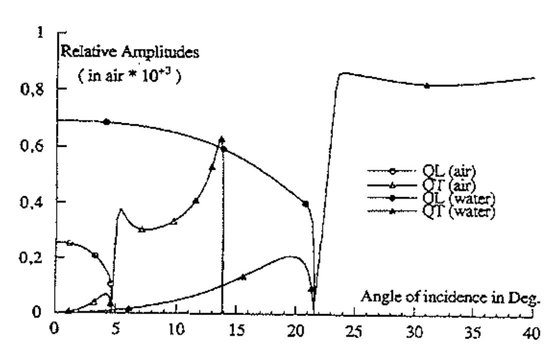

FIG. 9. Relative amplitude of the first transmitted bulk mode through $[0,90]_{8S}$ composite material.

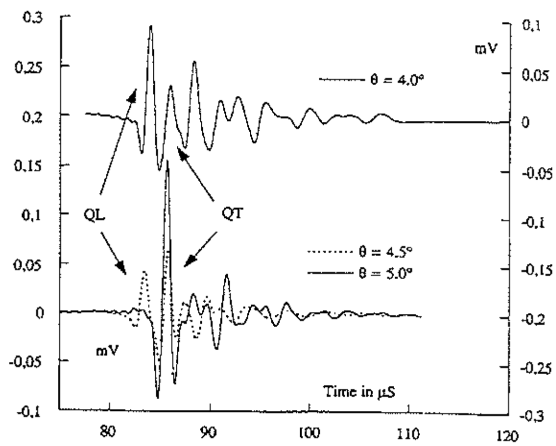

FIG. 10. Transmission before and after the extinction angle of quasilongitudinal mode. $[0,90]_{8S}$ composite material. Plane P_{13}. Angles of incidence: 4.0°, 4.5°, 5.0°.

longitudinal (QL) signal is present as the first arrival, with a smaller quasishear (QT) component following some time later (as expected from Fig. 9). At 4.5° the modes are of equivalent amplitude, and by 5° the QT signal predominates. It is evident that from such simulations, the modes can be identified, and that the air-coupled capacitance devices have a sufficient bandwidth to allow the modes to be separated experimentally. This is important for the inverse problem that will now be described. Note that the phase shift between theory and experiment is unimportant, and is due to the path length between source and receiver through the sample (which is difficult to determine accurately in the experiment). Here, we are interested in changes in the waveform time of arrival. In addition, losses due to attenuation in air were ignored in the simulations, and would not be expected to be a big effect on received through-transmitted waveforms (which tended to be of narrow bandwidth in any case). Note, however, that such an effect could easily be incorporated in the theory if necessary.

B. Simulations of elastic constant C_{ij} determination

Initially, a computer simulation of the process involved in elastic constant C_{ij} determination was performed. This took a $[0,90]_{8S}$ plate, modeled the waveform in the forward direction as above, and then used this data to simulate the process of trying to obtain the elastic constants from the simulated data. The idea was to compare the water and air coupling cases in a simulation, to see whether the process would be viable. Figure 11 shows the main steps of this process. The complex viscoelastic tensor of the ply is known or measured from a unidirectional sample. The properties of such a stratified medium are described by a series of variables, including the viscoelastic tensor, the thickness, the density, the relative orientation of each ply, the number of plies and the repetition number of elementary superlayers.[24] From this information, the transfer function in the frequency domain is then computed and applied to the reference waveform. As long as the first bulk transmitted mode can be iso-

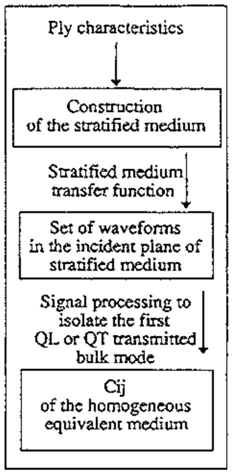

FIG. 11. Method to predict equivalent moduli of a stratified medium.

lated in these waveforms, the equivalent medium can be considered to be of infinite extent. This condition depends on the viscoelastic and geometric properties of the medium and the frequency content of the reference, and not on the coupling medium. Angular variations of the times of flight of the first transmitted bulk modes (i.e., before multiple reflections take place) give the phase velocities versus the direction of propagation. The elastic constants required in the present experiments (C_{11}, C_{13}, C_{33}, and C_{55}) can then be computed from these velocities using Christoffel's equations and Newton–Raphton's algorithms.

The above method for determining the elastic constants (C_{ij}'s) has been investigated by comparing the results likely to be obtained in water with those determined in air, using the computer-based simulation described by Fig. 11. This was done for the same $[0,90]_{8S}$ 5.7-mm-thick glass fiber/epoxy sample as before, containing 32 plies and with a mass density of 1.8. To allow such a simulation, the viscoelastic properties of a real unidirectional composite were measured with the water immersion method.[3] The five complex constants are given in column 2 of Table I. They are here rounded for the clarity of the paper.

The elastic constants of a perfect composite can be deduced using the invariant linear combinations.[23] C_{11}, $C_{22}+C_{33}+2C_{44}$, $C_{66}+C_{55}$, $C_{12}+C_{13}$, and $C_{44}-C_{23}$ are invariant whatever the stacking sequence. For any kind of stacking sequences such as $[0_N,90_M]_{rS}$, whatever the N, M, r numbers, the C_{44} in-plane Coulomb's modulus is also invariant. If $N=M$, direction 2 is equivalent to direction 3 for a $[0_N,90_N]_{rS}$ sequence, and in these structures, $C_{22}=C_{33}$, $C_{66}=C_{55}$, and $C_{12}=C_{13}$. Using these relations, it is easy to compute the elastic moduli, given in column 3 of Table I.

TABLE I. Elastic constants of simulated glass/epoxy composite in GPa.

	$[0]_{32}$ Initial values	$[0,90]_{8S}$ Deduced from UD	$[0]_{32}$ In water	$[0,90]_{8S}$ In water	$[0]_{32}$ In air	$[0,90]_{8S}$ In air
c11	15(+i0,6)	15,0	15,0	15,0	15,0	14.9
c22	15(+i0,6)	30,0	15,0	29,5	15.3	30,3
c33	45(+i3,0)	30,0	44,8	29,3	46,2	29,4
c66	3,5(+i3,5)	3.75	3,5	3,5	3,2	3,2
c55	4,0(+i0,2)	3,75	3,9	3,6	3,6	3,4
c12	8,0(+i0,1)	8,25	8,0	8,5	8,3	8,6
c13	8,5(+i0,8)	8,25	8,5	8,5	8,9	8.5
c22+c33	60,0	60,0	59,8	58,8	61,5	59,7
c66+c55	7,5	7,5	7,4	7,1	6,8	6,6
c12+c13	16,5	16.5	16,5	17,1	17,1	17,1

With the T-matrix method,[24,25] the waveforms produced by the transmission through the unidirectional $[0]_{32}$ and $[0,90]_{8S}$ cross-ply composites were computed for a water coupled system, and the recovered C_{ij} are given in columns 4 and 5 of Table I. The recovered constants are slightly different. This is due to the fact that the simulation method attempts to reproduce the exact conditions of the acquisition process (e.g., signals are digitized with only 8-bit resolution, the number of waveforms is limited, modes may overlap, etc.). The values of columns 4 and 5 give a good estimation of the errors and the precision of the water immersion method at these frequencies. Simulations of the values of C_{ij} likely to be obtained from an air-coupled system are given in columns 6 and 7 of Table I. The C_{ij} values and precision reached in air immersion are seen to be comparable to the water immersion method, in the frequency range covered by the present capacitive air-coupled transducers. Note that this simulation did not include the lower signal-to-noise levels likely to be seen in practice, but gave an indication that the air-coupled technique had some promise for elastic constant determination.

C. Experimental air-coupled determination of elastic constants (C_{ij})

It was mentioned earlier that it is possible to use an ultrasonic method for predicting the elastic moduli of a layered composite material.[26] This can be done without prior knowledge of the layup configuration of the sample; all that is required is that the overall sample density and thickness are known. However, individual plies must be sufficiently thin that, at the shortest wavelength used, the material can be assumed to be homogeneous (i.e., so that multiple reflections within each layer are not observed). These conditions are satisfied in the present air-coupled experiments. The simulations above indicated that the use of air-coupled ultrasonic transducers could lead to a reasonable estimation of elastic constants. Hence, an experiment was performed to determine the elastic constants (C_{ij}'s) of a $[0,90]_{8S}$ plate. This used the goniometer stage of Fig. 2, to record series of 17 waveforms, which were collected over an incident angular range of 0°–12°, and used as input to the software for velocity reconstruction. This experiment was repeated several times, and the repeatability was seen to be excellent. Note that in all such experiments, careful alignment of the transducers was performed prior to the start of a scan. The reproducible nature of the results indicated that alignment of the transducers was not a problem. Some example waveforms from this experiment were shown earlier in Figs. 7 and 8. For each waveform, a time window was used to define the first arrival of the QL or QT mode, and a cross-correlation performed with the reference waveform of Fig. 3(a) to give the time of flight.

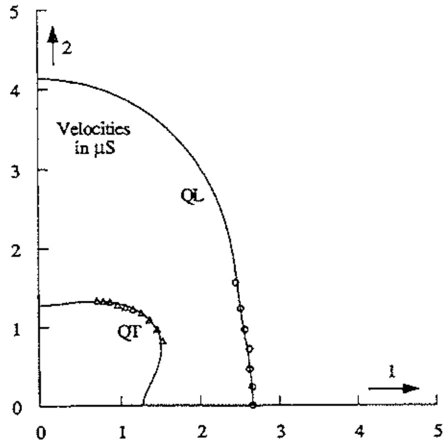

FIG. 12. Velocities of the QL and QT modes in the $[0,90]_{8S}$ sample. Horizontal axis: direction 1; vertical axis direction 2 or 3.

From this information, the velocity of either mode could be determined for selected directions of propagation through the composite, and the results from this experiment are shown in Fig. 12.

It is evident from Fig. 12 that the QL and QT velocity data (shown as the data points) are well behaved, and that each mode was well separated in velocity. Also shown is the result of the optimization procedure, which has determined the values for the relevant C_{ij} coefficients to give the best fit lines plotted on the figure. The values obtained to produce the best fit lines to the experimental data in Fig. 12 are presented in Table II. These can be compared to the values expected from both a water coupled experiment, and from simulation of the air-coupled experiment, shown earlier in Table I. The values of the four C_{ij} constants completely characterize this material, and the values are seen to be very close to those in Table I. From this comparison it may be concluded that the air-coupled experiment has produced excellent estimates of elastic constants for this anisotropic composite material. One interesting point is the differences in the C_{11} value. This arises because the value of this constant tends to be frequently dependent. The value of 15 GPa used for simulation was obtained as an average of several values, taken from prior water immersion studies at different frequencies; the air-coupled experimental result is one from the measurement bandwidth of about 1 MHz, and would thus be expected to be slightly different, as observed in Table II.

Note that the purpose of this paper is to demonstrate the feasibility of measuring C_{ij} values with air-coupled transducers, and a more detailed analysis of the precision of the measurements will be presented in a future paper. However, it is clear from Fig. 12 that the velocity measurements fit the velocity curves reconstructed from C_{ij} values very well

TABLE II. C_{ij} values (in GPa) for the $[0,90]_{8S}$ sample obtained from an air-coupled experiment.

C_{11}	C_{22}	C_{66}	C_{12}
13	31	3	8

(with a standard deviation of 0.6%). Signal averaging had to be used to reduce signal-to-noise levels, but this was acceptable after 1000 averages, and could possibly be improved if more efficient transducers were used. Moreover, the majority of the noise in Fig. 7(b) is outside the useful bandwidth of the air coupled devices (<1 MHz), and could be easily filtered out if necessary. This paper has thus shown that C_{ij} values can be determined using air-coupled ultrasound, and it is hoped to continue this work to increase the sensitivity and precision of the technique.

III. CONCLUSIONS

In this paper, it has been demonstrated that it is possible to measure the elastic properties of anisotropic materials such as composites with air-coupled transducers. Waveforms have been obtained in two types of sample, and it has been demonstrated that it is possible to record waveforms over a wide range of incident angles. Simulations have been presented of the waveforms, and the behavior interpreted in terms of the two expected wave modes. Finally, a preliminary experiment has shown that it is possible to obtain good estimates of the C_{ij} elastic constants for a glass fiber reinforced sample. These measurements seem to be the first of their kind using bulk waves in air. The noncontact aspect is very useful if elastic constants need to be followed *in situ* during a long-term experiment, such as the effect of stress on a material, at elevated temperatures etc. It may also be the case that air coupling leads to an increased accuracy of C_{ij} estimation.

Further work by the authors is presently underway to investigate transmitted waveforms in a wider range of materials, using both air-coupled experiments and numerical simulations, and to improve the accuracy of the C_{ij} determination in anisotropic materials using the capacitance transducers. These results will be presented in future publications.

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