Ultrasonic point-source/point-receiver measurements in thin specimens[a)]

003834

Martin Veidt[b)] and Wolfgang Sachse
Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, New York 14853

(Received 19 April 1994; accepted for publication 17 May 1994)

This paper reports on the application of the ultrasonic point-source/point-receiver technique (PS/PR) to thin, anisotropic specimens. By using a scanned source and viewing a large number of signals measured at adjacent source/receiver configurations, one obtains a so-called *scan image* which represents the detailed spatial and temporal characteristics of the elastic wave field in a specimen. The measurement system uses either a focused, pulsed laser beam operating as a dipole source or a small aperture, piezoceramic shear transducer serving as a monopolar source. Detection of the signals is with a sensitive piezoceramic sensor that responds to the lateral or shear motions of the specimen surface. Scan images were obtained in a Silicon wafer whose thickness was 625 μm and in one- or two-ply, unidirectional, graphite/epoxy laminates whose thicknesses were approximately 145 and 275 μm, respectively. The experimental data are analyzed using a simple plane-wave, plane-stress model that describes the propagation of quasilongitudinal and quasitransverse membrane waves in the plane of the plate. Good agreement is obtained between the experimental and theoretical group velocity curves of the membrane waves in the laminates. It is shown that the measured group velocity data of different wave modes can be inverted to recover the elastic constants of a material with excellent reliability and accuracy. The measurement system was also used to map out the group velocities in branches comprising the cuspidal region of the quasi-transverse group velocity curve.

PACS numbers: 43.35.Sx, 43.35.Yb

INTRODUCTION

Over the past several years, we have reported the development of an ultrasonic *point-source/point-receiver* (PS/PR) measurement system and its application to a number of materials inspection and characterization applications.[1–3] As its name implies, the essential elements of such a system are a small-aperture source and a receiver of ultrasound whose requirements and operational characteristics have been reviewed in Ref. 4. With such a system, measurements are possible in a wide variety of specimen geometries with minimal surface preparation. But, in addition to these practical advantages, a PS/PR system is intrinsically a powerful ultrasonic measurement tool. In most cases, a point source generates both longitudinal and shear waves in a bulk specimen, therefore information about each of these wave modes can usually be extracted from each detected waveform. Further, since PS/PR signals are simultaneously propagated in a wide range of directions in a specimen, one can use an array of sensors or scan either the source or the receiver over the specimen surface to determine the directional dependence of the speeds of propagation and amplitudes of various wave modes in a material. Obviously, an understanding of the propagation of transient elastic waves in a bounded specimen is required in order to properly process the detected PS/PR signals so that the characteristics of the material can be recovered. Calculation of the propagation of elastic waves in anisotropic materials remains an area of active research.

Although PS/PR waveform data is generally more complex than that obtained using conventional, plane-wave ultrasonic measurements, many of the measurement problems and limitations of the latter are minimized or avoided. For example, when generating signals in thick and absorptive materials,[5] such as fiber-reinforced thermoset composites, a broadband excitation that is rich in low frequencies is often desired and for this application, a step-type source function may be used. To obtain such an excitation, the point source may be a normal force which can be generated by the fracture of a capillary or a focused, pulsed laser that is operating in its ablative regime. A horizontal, dipolar source can be realized by using a pulsed laser operating in its thermoelastic regime. The application of pulsed lasers as a source of ultrasound in metals, in single crystal specimens and in thick composite materials has been reported in a number of publications, cf. Refs. 6–9.

The signals can be detected by a small-aperture piezoelectric or capacitive sensor or with an optical interferometer system. Each of these sensing systems is principally sensitive to wave motions that are normal to the surface of a specimen.

A pulsed laser is an example of a convenient noncontacting source that can form the basis of a repetitive and scanable ultrasonic measurement system. By viewing a large number of signals measured at adjacent source/receiver configurations, one obtains, a so-called *scan image* which represents the detailed spatial and temporal characteristics of the elastic wave field in a material. Features in such an image

---

[a)]This paper is dedicated to Prof. F. G. Kollmann on the occasion of this 60th birthday.

[b)]Present address: EMPA, Abt. 121, Überlandstrasse 129, CH-8600 Duebendorf, Switzerland.

can be directly related to the material's anisotropy and macrostructure.[10]

To date, the PS/PR technique is most often applied to bulk specimens in which the smallest dimension was in every case greater than the dominant wavelength of the probing signals. The application of laser point-source generated and detected ultrasonic waves in thin platelike specimens has been described by Hutchins *et al.*,[11] Dewhurst *et al.*,[12] Nakano and Nagai[13] and by Bobbin *et al.*[14] In these studies, the focus was on measurements of the lowest-order symmetric and antisymmetric Rayleigh–Lamb wave modes in specimens which were elastically isotropic. The detection of these wave modes was made by measuring the normal displacements of a specimen surface. Dean[15] used piezoelectric line source transducers that were sensitive to the normal motions of the specimen surface. The wave speeds of the lowest-order symmetric and antisymmetric Rayleigh–Lamb modes were measured in unidirectional graphite/epoxy and carbon-reinforced PEEK specimens that were 2–3 mm thick. In contrast to the foregoing, the present study deals with the use of PS/PR measurements in anisotropic platelike specimens whose thickness is of the order of 200 μm. The focus is on the lowest-order symmetric and shear horizontal Lamb modes of the thin plate. In every case, the thickness dimension is so small that the dominant signals of interest are those associated with the in-plane motions of the specimen. The detection of these wave modes requires the use of small-aperture shear sensors.

In the following section, we consider the essential features of a PS/PR system that is designed for measurements on specimens of such dimensions. We demonstrate the usefulness of the technique to determine the elastic wave field in a thin wafer of silicon and to characterize the wave propagation characteristics in a thin laminate of graphite/epoxy.

I. MEASUREMENTS

A. Ultrasonic system for thin specimens

Because of their utility, PS/PR measurements in bulk specimens often rely on sources such as a capillary fracture or a pulsed laser operating in the ablative regime. However, such normal force sources launch principally flexural waves into a thin specimen because of the small bending stiffness characteristic of such specimens. In contrast, the characteristics of a pulsed thermal source, when it is operating thermoelastically, can be modelled as an array of double forces of arbitrary orientation but all parallel to the surface of the specimen. Such a source can be used to generate in-plane waves in a thin specimen.

To detect waves whose principal motions are in the plane of a specimen, it is necessary to use small-aperture detectors which are sensitive to these in-plane motions. The thickness dimension of the specimens of interest here is so small that the normal components that are induced by the in-plane waves through the Poisson effect are of insufficient amplitude to be easily detectable by capacitive or piezoelectric transducers which are principally sensitive to out-of-plane motions of the surface of a specimen. Rather, transducers that directly respond to the lateral or shear motions of the specimen surface need to be used. Noncontact, optical interferometric sensing systems are now available which are capable of detecting such motions.[16] While they possess a broad frequency response, the sensitivity of such systems is at least an order of magnitude or two less than is available from piezoelectric sensors. Furthermore, such an expensive instrument was not available to us. For this reason, piezoceramic shear transducers were used in this study to detect and in some instances, to generate the ultrasonic signals. They were fabricated by cutting square or rectangular-shaped pieces with lateral dimensions of the order of 1.5 mm from a larger piezoceramic shear element (Philips, PXE4). These transducer elements were glued directly to the surface of the specimen using either Salol (Eastman Kodak Company, Phenyl Salicylate) or a fast-curing epoxy (Permabond, 5-Minute Epoxy). No systematic differences were found in the sensitivity of transducers that had been attached to the specimens with either of these coupling materials.

In cases where the propagational characteristics of waves in an anisotropic material is to be investigated in detail, a measurement system capable of selective excitation of various wave modes is desirable. For this purpose, a system consisting of one or two small aperture shear transducers was fabricated. Such a transducer operating as a source can be modelled as a monopole acting parallel to the surface of the specimen that excites the in-plane motions in the plate. Its operation as a detector is similar to that described in the previous paragraph. With such a system, the amplitudes of the signals are much larger than those excited by a laser impact even when a highly viscous shear couplant is used in attaching the transducer(s) to the surface of the specimen. The small aperture shear transducers were designed using coaxial shear elements whose center frequency was 2 or 10 MHz and whose sensitive area was about 0.8 mm in diameter (Valpey Fisher, PZT-4, PZT-5A).

The sensor signals were amplified by 40 or 60 dB using a low-noise preamplifier, whose bandwidth extended from 2 kHz to 2 MHz. The signals were digitized to 10-bit resolution at a sampling rate of 60 MHz. Each of the signals in the scan images consisted of 1-K sampled points. In recording the scan images, each of the signals has been delayed so that the noise associated with the pulsing of the laser was avoided and that the data collection was optimized as to signal temporal resolution and duration. The specimens were moved through the laser beam using a scanning stage running under PC control. Each scan image typically consisted of 201 waveforms acquired along one scan line across a specimen. The acquisition of these data required between five and 20 min, depending on the signal averaging count.

B. Specimens

To demonstrate the operation of the measurement technique, measurements were made on a {111} p-type, semiconductor quality, Silicon wafer, that was 12.5 cm in diameter and 625 μm thick. This material was chosen because its mechanical properties are well known. These include its density, 2332 kg/m^3 and elastic stiffnesses: $C_{11}=165.7$, $C_{12}=63.9$, and $C_{44}=79.56$ GPa.[17]

TABLE I. Characteristics of the composite materials tested.

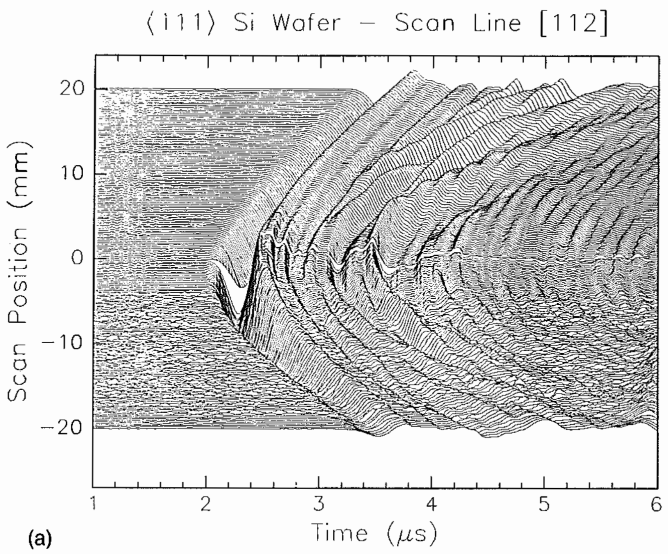
Ply-layup	Curing process	Thickness[a] (μm)	Density[b] (g/cm^3)	Fiber fraction[c] (%)
$[0]_T$	Autoclave	152	1.52	55
$[0]_T$	Hot press	140	1.53	58
$[00]_T$	Autoclave	280	1.53	58
$[00]_T$	Autoclave	287	1.53	56
$[00]_T$	Hot press	260	1.56	64
$[00]_T$	Hot press	273	1.55	62

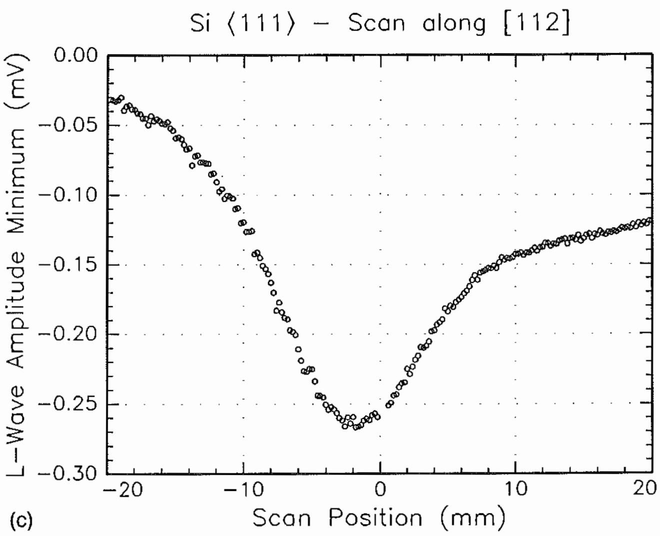
[a]Measured mechanically and optically by analyzing polished cross sections of strips 10 mm wide imbedded in an epoxy matrix.
[b]Measured using the gravimetric (Archimedes) principle.
[c]Calculated from the measured density and an image analysis of the polished specimen cross sections.

The inhomogeneous, anisotropic specimens used in this study were unidirectional, carbon fiber-reinforced epoxy laminates consisting of one or two laminae in the shape of square plates whose lateral dimensions ranged between 150 and 190 mm. Typical specimen characteristics are listed in Table I. The laminates were fabricated using a hot press or an autoclave following the curing cycle recommended by the manufacturer of the prepreg material (Hercules Inc., carbon prepreg tape IM6/3501-6).

C. Measurements

Multiple PS/PR measurements were carried out on each of the specimens. The scan images were generated with a scanned, pulsed laser operating as a source and a fixed shear-wave transducer as a detector. An example is the scan image that is shown in Fig. 1(a) that was obtained for the Silicon wafer. In this measurement, the laser was scanned along a line 20 mm from the detector in the $\langle 11\bar{2}\rangle$ direction normal to the $\langle 110\rangle$ direction. The arrivals of the different wave modes can be identified. To the authors' knowledge, a *Monte Carlo* simulation procedure, analogous to that available for synthesizing scan images in bulk specimens,[18] is not yet available for thin anisotropic plates. It is clear, however, that, as in bulk specimens, the signals detected in thin specimens exhibit considerable ringing. This artifact results from the piezoelectric sensor used to detect the signals. While this may complicate the detection of small-amplitude features in the image, the dominant features, such as the signal arrival time





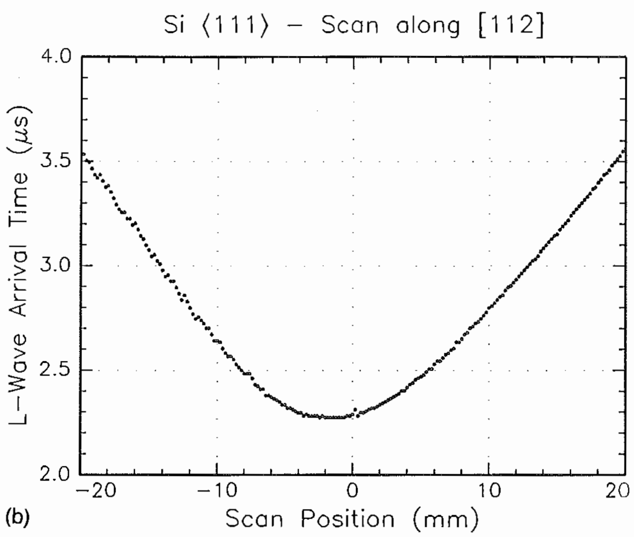


FIG. 1. (a) Scan image of a 625-μm-thick Si wafer of $\langle 111\rangle$ orientation. The scan was along $\langle 11\bar{2}\rangle$. Normal distance from the scan line to the receiver was 20 mm along $\langle 1\bar{1}0\rangle$. The anomalous time record near the center of the image is the result of a mistrigger. (b) Arrival time of the peak (minimum) amplitude of the quasilongitudinal wave as a function of scan position. (c) Amplitude (minimum) of the quasilongitudinal wave as a function of scan position. The scan lines Nos. 100–102 were omitted from the processing.

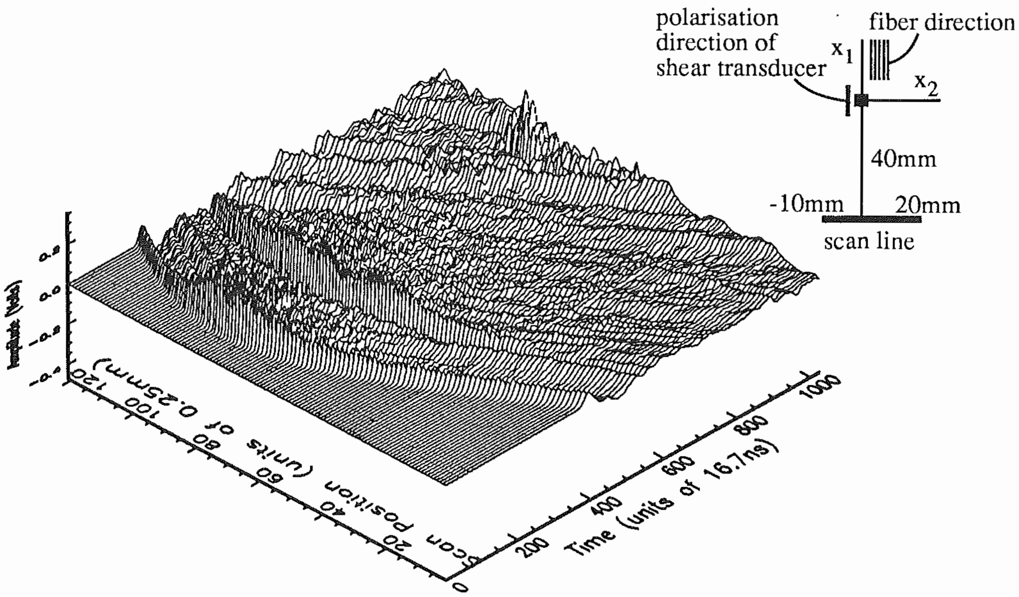


FIG. 2. Scan image of a two-ply, 280-μm-thick, unidirectional graphite/epoxy laminate. Scan line perpendicular to the fibers. Normal distance from the scan line to the receiver was 40 mm.

and relative amplitude of particular wave modes, are not obscured and detection and analysis is possible using image processing techniques.

A simple but particularly useful scan image processing procedure is a tracking algorithm in which the location of a particular peak or valley is identified in one of the waveforms comprising the scan image. The algorithm subsequently tracks the arrival and amplitude of this selected feature throughout the image. The examples shown in Fig. 1(b) and (c) are the arrival times and amplitude minima of the first signal arrival extracted from the scan image shown in Fig. 1(a). These data characterize the quasilongitudinal wave mode propagating along 201 directions between $\pm 45°$ to the $\langle 1\bar{1}0 \rangle$ direction of the Silicon wafer of (111) orientation. The group velocity of this wave mode along each direction is found by dividing the source/receiver separation by the corresponding arrival time. It should be noted that while the arrival-time data shown in this figure are those associated with the amplitude minimum, algorithms have recently been demonstrated that can be used to detect the signal onset.[19]

A second example, shown in Fig. 2, is the result obtained when the two-ply, unidirectional plate of graphite/epoxy, 280 μm in thickness was tested. In this measurement, the successive impacts of the pulsed laser source were along a line perpendicular to the fibers and at a distance of 40 mm from the detecting transducer. That is, the laser was scanned along a line perpendicular to the fibers. The arrivals of different wave modes are easily identified in this image.

Because the sensitivity of a shear transducer is polarization dependent, the output of such a detector is dependent on its orientation relative to the fiber axes. This property can be used to delineate between different wave modes in a specimen. Figure 3 shows two scan images that were collected in a unidirectional, two-ply specimen of graphite/epoxy with scans of the laser along the lengths of the fibers. The perpendicular distance between the detector and the scan line in each case was 40 mm. For the image shown in Fig. 3(a), the detecting transducer polarization was aligned within approximately $\pm 20°$ of the direction of energy propagation between the source and receiver points. In the testing configuration used to collect the data shown in Fig. 3(b), the detecting transducer polarization was approximately $\pm 20°$ to the normal to the energy propagation direction. The fiber direction is, in both, cases is identical and parallel to the scan line of the laser source. Because the transducer polarization is nearly aligned with the direction of energy propagation, the first arrival signal has essentially the same shape for all waveforms comprising the scan image shown in Fig. 3(a). In contrast, when the shear detector is turned 90°, the first arrival signals in the detected waveforms reverse their polarity according to the position of the source along the scan line, as shown in Fig. 3(b). It is evident from these scan images that the particle motions for the first-arrival signal are principally perpendicular to the fibers.

This result illustrates how the orientation-dependent sensitivity of a shear transducer can be used to selectively control the detected signal amplitudes corresponding to different wave modes, thus enabling a delineation between them. On the other hand, this characteristic of the detector may also complicate the measurements. This is particularly true when quantitative amplitude data is to be determined. Examples include investigations of wave focusing effects in anisotropic specimens or determination of the damping characteristics of a material.[18,20]

II. DATA ANALYSIS AND RESULTS

A. Membrane waves in thin specimens

It was observed that the measured signals, while broadband in frequency content, have their principal amplitudes in the low MHz range. The wavelength/thickness ratio, λ/d, of these signals is greater than 7.5. Consequently, it is appropri-

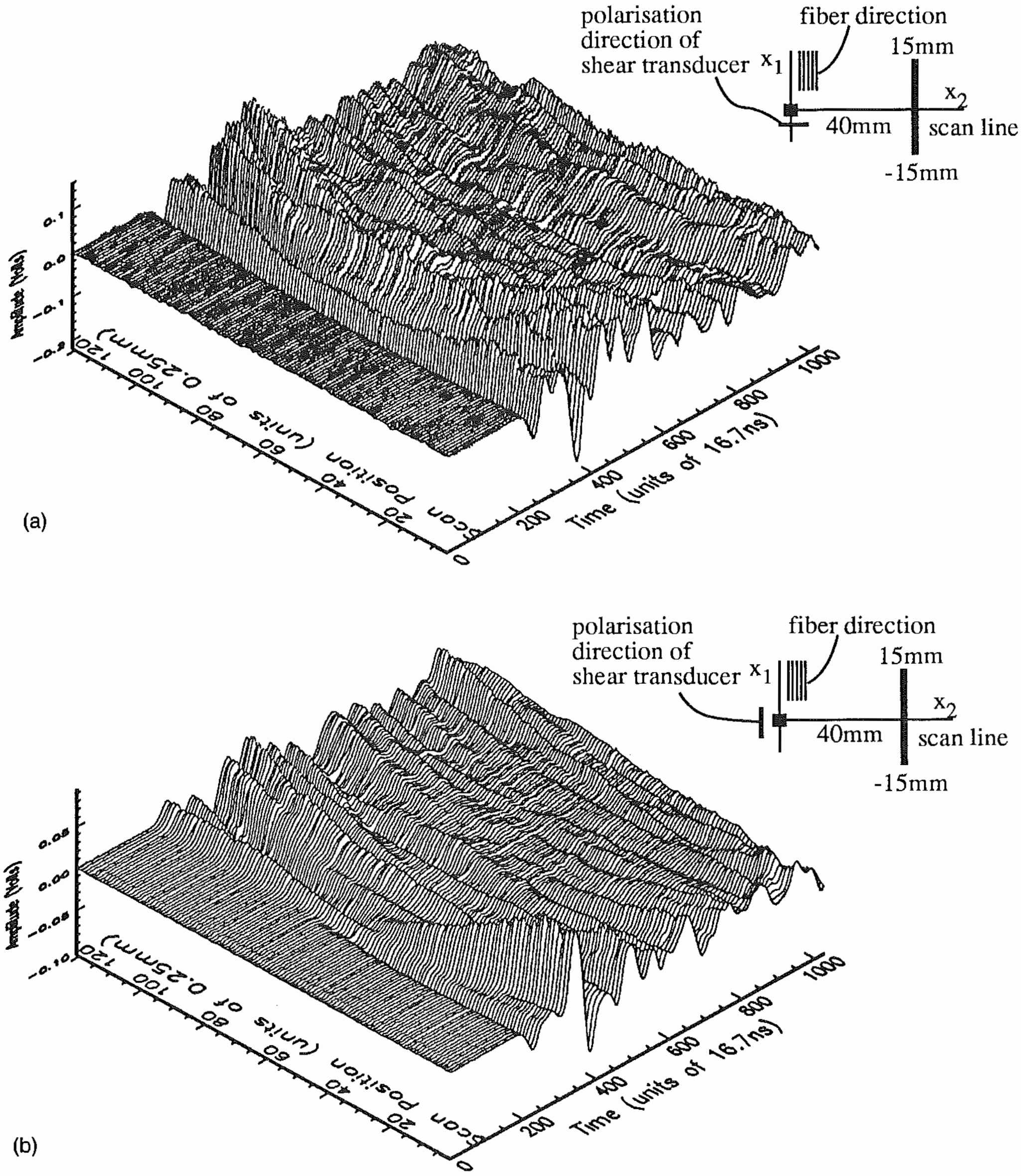


FIG. 3. (a) Scan line parallel to the fibers. Normal distance from the scan line to the receiver was 40 mm. Polarization of the receiver was perpendicular to the fibers. (b) Scan line parallel to the fibers. Normal distance from the scan line to the receiver was 40 mm. Polarization of the receiver was parallel to the fibers.

ate to describe the wave propagation in terms of the in-plane longitudinal and shear modes of the plate. These correspond to the lowest-order Lamb modes of the plate, the symmetric S_0 mode and the shear-horizontal mode, SH_0. We call these waves the *membrane waves* of the plate. Higher modes can be omitted from consideration since the corresponding cutoff frequencies are estimated to be between 5 and 10 times greater than the central frequency of response of our measurement system.

The centrally induced waves are approximated as plane waves propagating in a homogeneous, anisotropic plate under plane stress. The elastic stiffnesses of such a specimen are written as $\hat{C}_{\alpha\beta}$, where the hat (i.e., $\hat{}$) denotes the coefficients appropriate to the plane stress case, cf. Ref. 21. A material that is elastically cubic, such as the silicon wafer, is specified by the three elastic stiffnesses, $\hat{C}_{11}$, $\hat{C}_{12}$, and C_{44}. A transversely isotropic material, such as a unidirectional laminate, has its elastic properties completely specified by the four stiffnesses $\hat{C}_{11}$, $\hat{C}_{22}$, $\hat{C}_{12}$, and C_{66}.

The analysis of the propagation of elastic waves in an anisotropic plate under plane stress is analogous to that for a plane wave in a bulk anisotropic material.[22] If the mass density of the medium is specified by ρ, then the governing wave equation for the displacements $\mathbf{u}$, in a thin plate of material that is elastically transversely isotropic, are given by

$$\begin{aligned} \hat{C}_{11}u_{1,11}+C_{66}u_{1,22}+(\hat{C}_{12}+C_{66})u_{2,12}&=\rho\ddot{u}_1. \\ C_{66}u_{2,11}+\hat{C}_{22}u_{2,22}+(\hat{C}_{12}+C_{66})u_{1,12}&=\rho\ddot{u}_2. \end{aligned} \tag{1}$$

In the plane-wave approximation, the in-plane displacement vector $\mathbf{u}$ can be expressed in the form

$$\mathbf{u}=\begin{Bmatrix} u_1^0 \\ u_2^0 \end{Bmatrix}\exp[ik(n_1x_1+n_2x_2-ct)], \tag{2}$$

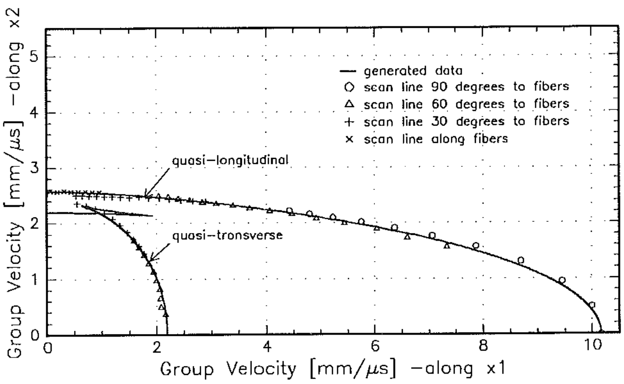


FIG. 4. Measured group velocity data and generated group velocity curves for a unidirectional, two-ply graphite/epoxy laminate.

where the real vector $\mathbf{u}^0=[u_1^0,u_2^0]^T$ describes the amplitude and polarization of the plane waves, k is the wave number, c is the phase velocity and the vector $\mathbf{n}=[n_1,n_2]^T$ describes the propagation direction. Using Eqs. (1) and (2), the Christoffel equation which governs the wave propagation in elastically, anisotropic solids becomes

$$\begin{bmatrix} (\hat{C}_{11}n_1^2+C_{66}n_2^2)-\rho c^2 & (\hat{C}_{12}+C_{66})n_1n_2 \\ (\hat{C}_{12}+C_{66})n_1n_2 & (C_{66}n_1^2+\hat{C}_{22}n_2^2)-\rho c^2 \end{bmatrix} \begin{Bmatrix} u_1^0 \\ u_2^0 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}. \quad (3)$$

The directional dependence of the phase velocities of the quasilongitudinal and quasitransverse waves is determined from the solution of the characteristic equation:

$$\begin{vmatrix} (\hat{C}_{11}n_1^2+C_{66}n_2^2)-\rho c^2 & (\hat{C}_{12}+C_{66})n_1n_2 \\ (\hat{C}_{12}+C_{66})n_1n_2 & (C_{66}n_1^2+\hat{C}_{22}n_2^2)-\rho c^2 \end{vmatrix} \equiv \Omega(\mathbf{n},\hat{C}_{\alpha\beta},C_{66})=0. \quad (4)$$

The energy or group velocity vector $\mathbf{V}$ is, in general, different from the phase velocity in anisotropic materials. It can be determined from[22]

$$\mathbf{V}=-\frac{\partial\Omega/\partial\mathbf{n}}{\partial\Omega/\partial c}. \quad (5)$$

B. Laser-generated acoustic imaging

It was already shown how the arrival times of the quasilongitudinal and quasitransverse wave modes can be determined from the time signals comprising the scan images. From such arrival-time data, where each set typically consists of more than a hundred data points, the elastic constants of the specimen material can be recovered using an inversion procedure that has been described in earlier publications.[23,24] Alternatively, it is possible to detect large scale inhomogenities or flaws in the specimen.[25]

Figure 4 shows a comparison between the group velocity data measured on a unidirectional two-ply specimen and the quasilongitudinal and quasitransverse group velocity curves that have been regenerated using the recovered elastic constants. These data pertain to the specimen that was fabricated using an autoclave and whose elastic constants are listed in Table II. For clarity, not all of the experimental data points are shown in Fig. 4. For the quasilongitudinal data, only every 8th point was drawn while for the quasitransverse mode, it was only every 12th point.

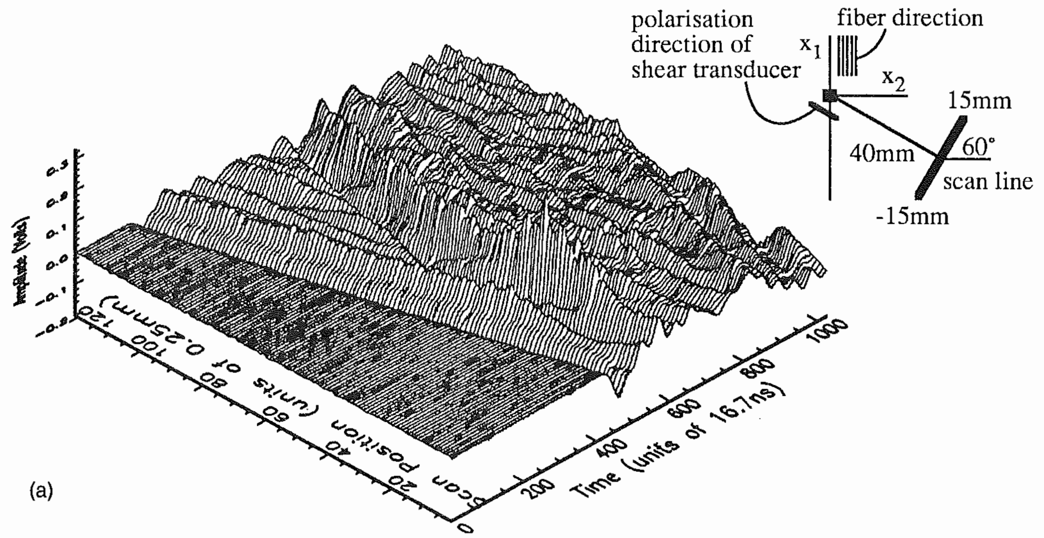
TABLE II. Recovered elastic constants.

Specimen material	Elastic constants (GPa) $\hat{C}_{11}$	$\hat{C}_{22}$	$\hat{C}_{12}$	C_{66}
two-ply graphite/epoxy (Autoclave)	157	10	3	7.5
two-ply graphite/epoxy (Hot pressed)	155	10	5.5	5

The agreement between the measured and regenerated data is excellent for the quasilongitudinal wave. The experimental data of the quasitransverse wave that was measured for directions near the principal axes, x_1 and x_2, and on some of the branches in the cuspidal region does not fall on the computed group velocity curve. In these cases, the peak and valley tracking algorithm that is employed to extract the arrival times of the quasitransverse wave mode from the scan image failed. There are two possible explanations for this. Because of the convexity of the slowness surface of the quasitransverse wave along the principal directions in a transversely isotropic material, the rays associated with this wave mode diverge and correspondingly, the amplitudes of these signals are very small in these directions. Additionally, when the source/receiver separation is small, the arrival of the quasitransverse wave signals occurs shortly after the arrival of the quasilongitudinal signal. Because the amplitudes of these signals are small, they are easily obscured by the ringing of the transducer.

An obvious remedy would be to increase the source/receiver separation so that the ringing associated with the quasilongitudinal signal will have subsided when the quasitransverse wave modes arrive. However, the signal amplitudes generated by a laser when it is operating as an in-plane, dipole source are relatively small when compared to other ultrasonic sources. Because of the absorption of the sound in fiber-reinforced, thermoset composite materials, the maximum separation between the location of the laser source and the detector is typically limited to about 50 mm. In the detected signals, the individual peaks associated with the quasitransverse wave arrivals are not sufficiently separated in time to permit their identification and measurement.

Figure 5(a) shows the image of a scan made at 30° to the fibers in a two-ply unidirectional specimen. The perpendicular distance between the detector and the scan line was 40 mm. The group velocity data correspond to the region indicated in Fig. 5(b). It is seen that at the midpoint of the scan, the arrivals of the quasilongitudinal signals are followed in rapid succession by the arrivals of the quasitransverse wave signals, denoted as "qt1," "qt2" and "qt3" in Fig. 5(b). For a source/receiver separation of 40 mm, these arrive at 1.8, 2.19, and 2.87 μs after the arrival of the quasilongitudinal signal and they are difficult to identify in the detected signals.



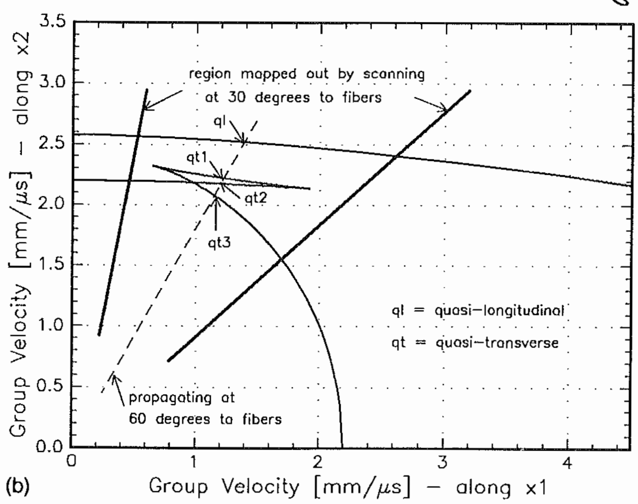


FIG. 5. (a) Scan image of scanning at 30° to the fibers. Normal distance from scan line to the receiver was 40 mm. (b) Region of the wave curve covered by scanning at 30° to the fibers.

C. Piezoelectrically generated acoustic waves

The larger signal amplitudes that can be realized when using a monopolar in-plane source permits measurements at larger source/receiver separations. When using such a source, the location of the detector becomes limited only by the specimen size even for highly absorptive materials, although interfering reflections from the boundaries may lead to complications in the scan image which are sometimes difficult to identify. Figure 6 shows a typical waveform that was detected in a unidirectional, two-ply specimen. In this example, the source and receiver shear transducers were separated by 80 mm along a line under 30° to the fibers. The arrivals of the three quasitransverse wave modes are well separated. By changing the angle between the sensor line and the fibers, the directional dependence of the wave speed of each of the wave modes can be determined. Data as this has been used to map out the details of the cuspidal region of the quasitransverse wave. Figure 7 provides a comparison between measured group velocity data points and the regenerated group velocity curves. The latter have been calculated using the elastic constants of the specimen fabricated in a hot press that is listed in Table II.

III. CONCLUSIONS

We have demonstrated in this paper that the scan image technique utilizing a point source and a point receiver is a powerful tool for determining the temporal and spatial characteristics of membrane waves in thin specimens. Such measurements permit mapping out the spatial dependence of the amplitudes and arrivals of quasilongitudinal and quasitransverse wave modes propagating in thin samples.

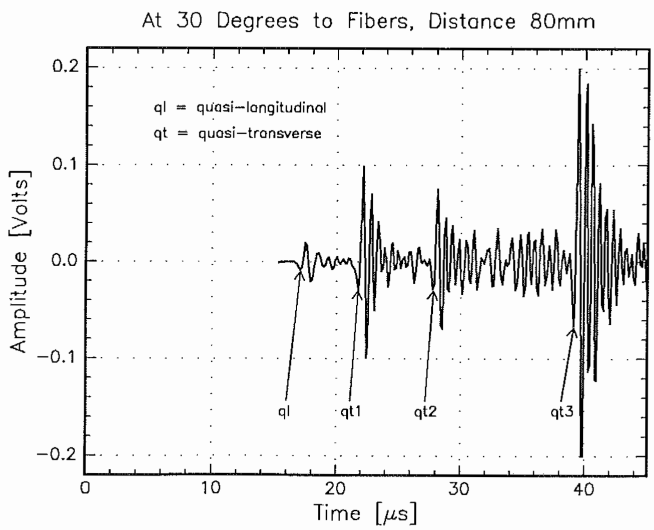


FIG. 6. Typical time signal of piezoelectric pulse excitation experiments; sensor line at 30° to the fibers, at a source/receiver separation of 80 mm.

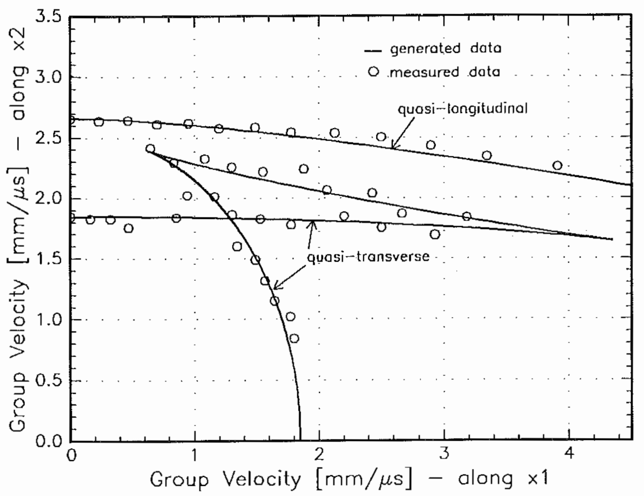


FIG. 7. Measured and generated group velocity data of piezoelectric pulse excitation experiments measured in the cuspical region of the quasitransverse group velocity curve.

The measurement system described here utilizes either a focused, pulsed laser beam operating as a dipole source or a small aperture, piezoceramic shear transducer serving as a monopolar source. With the laser source, scan images are easily obtained for source/receiver separations which are less than about 150 specimen thicknesses. In applications in which the wave arrivals, corresponding to particular wave modes, are to be clearly identified, a large source/receiver separation is often useful. In these cases, a stronger excitation is essential. We have shown that a piezoceramic shear transducer operating as a source can be used to generate large amplitude membrane waves which are detectable at receiver locations that are several hundred thickness dimensions away, even in highly absorptive materials. Detection of the signals in either case was with a highly sensitive piezoceramic sensor that responded to the lateral or shear motions of the specimen surface. Such transducers are capable of selective detection of different wave modes which is an important advantage in some applications.

The technique has been successfully applied to single-ply, graphite fiber-reinforced epoxy laminates whose thicknesses were less than 150 μm. The experimental data was analyzed using a simple plane-wave, plane-stress model. Excellent agreement was obtained between the experimental and theoretical quasilongitudinal and quasitransverse group velocity curves of the membrane waves propagating in the plane of the laminates. It was shown that the measured group velocity data of different wave modes could be processed to recover the elastic constants of a material with excellent reliability and accuracy.

By using a measurement configuration that permitted a clear delineation of the arrivals of various wave modes, we have mapped out the group velocities of the longitudinal as well as the three shear waves in branches comprising the cuspidal region of the quasitransverse group velocity curve.

Although the results we have presented in this paper include only a small number of examples, the measurement approach described here should be applicable to a broad range of other materials and specimens for which a plane stress approximation is adequate to describe the wave propagation.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research (Solid Mechanics Program) under Contract No. N00014-90-J-1273. Portions were also supported by the National Science Foundation through the Materials Science Center at Cornell University. The visit of M. V. to Cornell was sponsored by the Swiss National Science Foundation. This support is greatly appreciated. Special acknowledgments are due to two of our friends and colleagues. We have benefitted from many useful discussions with Dr. K. Y. Kim and thank him also for his design and help in fabricating the small-aperture shear-wave transducer. We thank Professor M. O. Thompson for the generous use of his superb laser facilities.

[1] W. Sachse and K. Y. Kim, "Point-source/point-receiver materials testing," in *Review of Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (Plenum, New York, 1986), Vol. 6A, pp. 311–320; or in *Ultrasonic Materials Characterization II*, edited by J. Boussiere, J. P. Monchalin, C. O. Ruud, and R. E. Green (Plenum, New York, 1987), pp. 707–715.

[2] W. Sachse and K. Y. Kim, "Quantitative acoustic emission and failure mechanics of composite materials," Ultrasonics **25**, 195–203 (1987).

[3] W. Sachse, B. Castagnede, I. Grabec, K. Y. Kim, and R. L. Weaver, "Recent developments in quantitative nltrasonic NDE of composites," Ultrasonics **28**, 97–104 (1990).

[4] W. Sachse, "Transducer considerations for point-source/point-receiver materials measurements," in *Ultrasonics International '87—Conference Proceedings* (Butterworths, Guildford, UK, 1987), pp. 495–501.

[5] W. Sachse, "Towards a quantitative ultrasonic NDE of thick composites," in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (Plenum, New York, 1991), Vol. 10B, pp. 1575–1582.

[6] C. B. Scruby, R. J. Dewhurst, D. A. Hutchins, and S. B. Palmer, "Laser generation of sound in metals," in *Research Techniques in Nondestructive Testing*, edited by R. S. Sharpe (Academic, London, 1982), Vol. 5, pp. 281–327.

[7] D. A. Hutchins, "Ultrasonic generation by pulsed lasers," in *Physical Acoustics*, edited by R. N. Thurston and A. D. Pierce (Academic, New York, 1988) Vol. 18, pp. 21–99.

[8] W. Sachse, A. G. Every, and M. O. Thompson, "Impact of laser pulses on composite materials," in *Impact Responses and Elastodynamics of Composites*, edited by A. K. Mal and Y. D. S. Rajapakse (Am. Soc. Mech. Engrs., New York, 1990), AMD Vol. 116, pp. 51–62.

[9] W. Sachse, A. G. Every, and I. Grabec, "Quantitative ultrasonic measurements in compsite matcrials," in *NDE-Vol. 10, Enhancing Analysis Techniques for Composite Materials*, edited by L. Schwer, J. N. Reddy and A. Mal (Am. Soc. Mech. Engrs., New York, 1991), Book No. H00669, pp. 77–88.

[10] A. G. Every, W. Sachse, and M. O. Thompson, "Materials characterization from elastic wave anisotropy images," in *Non-Destructive Characterization of Materials, IV*, edited by C. O. Ruud and R. E. Green, Jr. (Plenum, New York, 1991), pp. 493–500.

[11] D. A. Hutchins, K. Lundgren, and S. B. Palmer, "A laser study of transient Lamb waves in thin materials," J. Acoust. Soc. Am. **85**, 1441–1448 (1989).

[12] R. J. Dewhurst, C. Edwards, A. D. W. McKie, and S. B. Palmer, "Estimation of the thickness of thin metal sheet using laser generated ultrasound," Appl. Phys. Lett. **51**, 1066–1068 (1987).

[13] H. Nakano and S. Nagai, "Laser generation of antisymmetric Lamb waves in thin plates," Ultrasonics **29**, 230–234 (1991).

[14] S. E. Bobbin, J. W. Wagner, and R. C. Cammarata, "Interpretation of laser-generated low-order Lamb waves for elastic modulus measurements in thin films," Ultrasonics **30**, 87–90 (1992).

[15] G. D. Dean, "Use of plate bending waves for elastic property determination of polymers," Composites **20**, 575–583 (1989).
[16] A. McKie and J. Wagner, "Optical sensing of in-plane ultrasonic transients," Appl. Pbys. Lett. **53**, 1043–1044 (1988).
[17] J. J. Hall, "Electronic effects in the elastic constants of *n*-type Silicon," Phys. Rev. **161**, 756–761 (1967).
[18] A. G. Every and W. Sachse, "Imaging of laser-generated ultrasonic waves in silicon," Phys. Rev. B, **44**, 6689–6699 (1991).
[19] W. Sachse, A. N. Netravali, and A. R. Baker, "An enhanced, acoustic emission-based single-fiber-composite test," J. Nondestruct. Eval. **11**, 251–261 (1992).
[20] W. Sachse, A. G. Every, and R. L. Weaver, "Interpretation of ultrasonic PS/PR amplitude data," in *Review of Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (Plenum, New York, 1991), Vol. 10A, pp. 129–136.
[21] R. M. Christensen, *Mechanics of Composite Materials* (Wiley, New York, 1979).
[22] B. A. Auld, *Acoustic Waves in Solids* (Krieger, Malabar, FL, 1990), 2nd ed., Chap. 7.
[23] A. G. Every, W. Sachse, K. Y. Kim, and L. Niu, "Determination of elastic constants of anisotropic solids from group velocity data," in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (Plenum, New York, 1991), Vol. 10B, pp. 1663–1668.
[24] A. G. Every and W. Sachse, "Determination of the elastic constants of anisotropic solids from acoustic-wave group-velocity measurements," Phys. Rev. B, **42** 8196–8205 (1990).
[25] M. Veidt and W. Sachse, "Ultrasonic evaluation of thin, fiber-reinforced composites," J. Comp. Mater. **28**, 329–342 (1994).