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Ultrasonic Wave Considerations for the Development of an NDE Feature Matrix for Anisotropic Media

J. L. Rose

A. Pilarski

K. Balasubramaniam

A. Tverdokhlebov

J. Ditri

Department of Mechanical Engineering and Mechanics,
Drexel University,
Philadelphia, Pa. 19104

The problem of ultrasonic surface and bulk wave propagation in an anisotropic media and/or a composite material is addressed so that applications in Nondestructive Evaluation can be considered, emphasis in this paper being placed on bulk wave propagation. Global material property determination is considered in an inverse wave velocity computation of stiffness coefficients based on principles of anisotropic elasticity. A one-sided inspection technique based on practical considerations of a field environment is developed. The concept of a feature matrix, based on the stiffness coefficients, is then introduced as a means of both material characterization and defect analysis in composite materials. A brief discussion on a test protocol and an interpretation of the elements in the feature matrix from an NDE point of view is also presented. The conclusions of a previous theoretical investigation of wave propagation in anisotropic media are considered from an experimental point of view by way of the bulk wave technique. A result of fundamental value is that the actual propagation of quasilongitudinal waves, generated by a standard broad band pulsed transducer, is indeed well matched with the theoretical approximation obtained earlier. This approximation was based on the generalized retarded potential principle with variable energy velocity of the quasilongitudinal mode in an anisotropic medium as the substitute for the constant longitudinal velocity used in the retarded potential scheme for an isotropic medium.

Background

In carrying forward a number of work efforts on the subject of the Nondestructive Evaluation of composite materials, several concerns, including practicality of the research, implementation potential, and in general, the use of advanced wave mechanics, have surfaced. It was clear that, for complete material and defect characterization purposes, the traditional normal beam longitudinal wave inspection technique, in either a contact or immersion mode, would not be sufficient. The use, therefore, of obliquely incident bulk waves, longitudinal or shear, and/or guided waves, including surface, subsurface, or plate waves, was considered because of their different sensitivities to different material states, geometries, and defect situations. With the increasing number of wave modes and signal features for decision analysis, it became obvious, however, that a carefully planned set of inspection and decision rules would have to be established for a particular material system in order to produce optimal sensitivity to defect detection, location, classification, and sizing. In an attempt to address these issues, three principal problems were considered.

1. Global material properties should be known, including the potential severity of the inhomogeneities and anisotropy. This would lead to a reliable inspection protocol and transducer selection process for proper beam penetration to, and reflection from, any particular area of interest inside the composite material. Theoretical analysis would be required in both the material property determination phase and also in the establishment of an optimal inspection protocol.
2. A one sided inspection procedure would be necessary since access to both sides of a test specimen, or careful cutting of a specimen to achieve direct measurements in a particular plane, would not be possible in a field environment. Theoretical and experimental considerations of surface waves and bulk waves were considered for a one-sided inspection procedure. Initial attempts at solving this problem with surface waves is presented in [1]. This current paper emphasizes the use of bulk waves, even though the overall philosophy on NDE applications by way of a feature matrix is the same as that presented in [1].
3. A discriminant function, which would be based on a set of signal features from a combination of test modes, would be necessary in signal classification analysis. Therefore, a set of physically based features would be required. A description of Feature based methodologies and F-maps for composite material inspection can be found in references [2-3].

All three concerns were addressed by introducing the concept of a feature matrix that would be based on principles from anisotropic elasticity.

An inverse surface and/or bulk wave velocity technique will

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be introduced to calculate the stiffness coefficients for the composite material. The stiffness coefficients could then be considered as actual feature values, with the entire set, forming a so-called feature matrix. In essence, the inverse computation can be thought of as a transformation function or even a discriminant function itself, from a pattern recognition point of view, and the feature values can then be used to carry out nondestructive evaluation analysis of the anisotropic material. This analysis could include determining material properties, anisotropic state, inhomogeneity characteristics, defect presence, and possible stress state.

Introduction

A two step approach to reliable ultrasonic inspection is necessary for anisotropic materials. Before examining waveform characteristics and arrival time for defect detection, location, classification and/or sizing, it becomes necessary to know material characteristics for suitable transducer selection and proper signal analysis. As a result of developing a one-sided material characterization routine, which is based on practical considerations, the concept of feature matrix determination and analysis can be introduced which is based on elastic constant determination using concepts from anisotropic elasticity. A careful study of the elements of the feature matrix could then be used to determine material integrity and potential global deterioration from a particular reference state.

An important first step in the reliable ultrasonic inspection of anisotropic materials is therefore to acquire accurate material properties, particularly the matrix of elastic constants, which fully describe the homogeneous medium of a perfectly manufactured material, or at least the virgin state of the material at some reference point. The elastic properties of unidirectionally reinforced composite (anisotropic) materials, which are the subject of the given investigation, are completely determined by five elastic constants (the case of hexagonal symmetry) and by the unit vector d (director), which shows the direction of the principal symmetry axis. In a practical sense, the director d points in the direction of the fibers in graphite-epoxy composites or, for example, in the direction of polycrystalline columns in centrifugally cast stainless steel (CCSS). Such a material is also called transversely isotropic, because its properties do not depend on direction in any cross-section plane, transverse to the director d.

The use of ultrasonics for the determination of dynamic elastic constants is well known [4]. In the literature, many examples of bulk wave velocity measurements for the evaluation of elastic constants can be found [5-8]. For specially prepared test specimens that are cut along off-symmetry planes, the elastic constants can be determined with measurements of longitudinal and transverse wave velocities for an assumed type of elastic anisotropy and mass density. If access to the opposite side of a composite structure exists, the utilization of obliquely incident longitudinal waves, in either an immersion or contact mode, and their subsequent refraction into quasilongitudinal and quasitransverse waves can be used for elastic constant evaluation. See for example [9]. In such a case, the group velocity (velocity of energy flux) is measured. All solutions to problems in wave propagation are tied however, to phase velocities, therefore, the utilization of group velocity and consideration of skew angle calls for extra mathematical and experimental considerations. Elastic constant computations based on phase velocity measurements alone might be beneficial due to the simplicity of interpretation. Both the special preparation of the test specimens and the mandatory two-sided access are the very inconveniences that necessitate the development of a one-sided evaluation measurement procedure which could be used on the material as it is. In the first case, the technique requires specimen cutting and is hence destructive in nature. Homogeneity is also assumed. The second technique, with oblique incidence, requires access to both sides of a composite layer. This approach eliminates the necessity of specially prepared specimens, but is still practically difficult to carry out.

To some degree, an attempt to avoid the inconveniences of destructive assay and two sided inspection was recently carried out [10]. A method is proposed that is based on the application of two angle beam probes placed on the same surface in front of each other, one as a sender and the other as a receiver. By changing the incidence and receiving angles, one can generate and receive the quasilongitudinal waves, which are propagating in an oblique manner in the composite layer. By measurements of group velocity and the different angles of propagation, the characteristics of that particular material can be obtained. Comparing such characteristics with those obtained from numerical calculations for different material properties, one can indirectly obtain the condition of the composite. This comparative method can be treated as a next step towards the more practical solutions for composite characterization in field conditions. Even for unidirectionally reinforced composites being inspected in the plane of symmetry (along the fibers), however, there is mathematical complexity.

For the above mentioned reasons, and the lack of a one-sided technique for a full determination of the elastic constant matrix for orthotropic composites, a search for another practical solution has led to guided wave considerations. The possibility of using guided waves in composite material characterization, for thin composite layers, has led to a number of papers dealing with plate waves [11-12]. First results were encouraging. By critical angle or resonance frequency measurements, phase velocity determination, and hence indirect material characterization, seems possible.

We have also considered the possibility of using surface waves for thick composites [1]. This one sided technique requires a thorough understanding of the wave propagation of such waves. The oretical solution of the characteristic equation for surface waves in an orthotropic semispace loaded by a liquid is also presented in that paper. Theoretical solutions for the so-called dry cases, (i.e., for solids with a free surface), are also well known [13].

Quantitative Nondestructive Evaluation, and especially ultrasonic inspection, are currently experiencing tremendous complications, caused by the anisotropy of the materials. The very basic aspects of wave propagation are changed, yielding such phenomenon as changes in energy velocity, beam skewing, beam splitting, unsymmetrical field profiles, unusual side lobe formations, and unusual focusing and divergence, all causing errors in reflector detection, location, classification, sizing, and in overall imaging. The problems of ultrasonic wave propagation in anisotropic materials are currently under wide and intensive investigation [14-29].

This presentation is devoted to both bulk quasilongitudinal and surface wave techniques with emphasis on the bulk quasilongitudinal technique since the surface wave procedure was presented in [1]. The main contributions of this study are the demonstration of the feasibility of the two techniques and the further development of the feature matrix concept, which would implement the results of these techniques in a suitable decision algorithm to locate, classify and size defects within composite materials.

An additional contribution of fundamental value is the direct experimental proof that the actual propagation of the quasilongitudinal mode of ultrasonic waves, generated by a standard broad band pulse transducer, is indeed well matched with the theoretical approximation, obtained in [30]. This approximation was based on the generalized retarded potential principle with variable energy velocity of the quasilongitudinal mode in an anisotropic medium, as a substitute for the con-

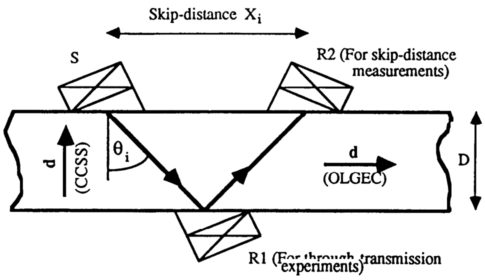

Fig. 1 Schematic of the bulk wave technique:

S (Sender) An ultrasonic transducer with variable incident angle.
R1, R2 (Receivers) Ultrasonic transducers positioned on either the same or opposite side.
d (Director) Anisotropy vector pointing along the axis of symmetry (i.e., along **polycrystalline** columns in CCSS, or in the fiber direction for **graphite-epoxy).**

stant longitudinal velocity used in the retarded potential scheme for an isotropic medium.

Experimental Techniques

A Centrifugally Cast Stainless Steel (CCSS) specimen, marked B504, was comprised of two, equally sized pieces of different pipe sections welded together. One side of the pipe had a columnar grain anisotropic structure, while the other isotropic side, used as a control, had equiaxed grains. Results of this study are reported in [20]. A specially made unidirectional, one-lamina piece of graphite-epoxy composite (referred to as OLGEC bar or specimen A) was also studied with the bulk wave technique. Two additional graphite-epoxy specimens, marked as specimens B and C (the latter is of the orthotropic symmetry) were used in the surface wave technique.

The Bulk Wave Technique. The use of bulk waves is depicted in Fig. 1. Sender S generates plane wave vibrations of a given mode (quasilongitudinal) in the vicinity of the attached area with the preferential energy directivity as shown. The induced vibrations propagate through the bulk of the anisotropic material, with thickness D, in the form of an energy packet., The magnitude of the energy velocity is a function of the angle between the wave propagation direction and the director **d**. By virtue of the material properties and the manufacturing design characteristics, in both specimens, the director **d** is either perpendicular or parallel to the free boundaries (external and internal surfaces). That is, **d** is either vertical along the grain columns of the CCSS or horizontal along the fibers of the unidirectional graphite-epoxy composite. This is a very fortunate circumstance that keeps the reflection angles equal to the incident angles and allows the simple geometric interpretation of the energy packet reflections depicted in Fig. 1. Note that data analysis could still take place even if the director **d** were inclined at some angle other than 90 or 0 deg, but the analysis would be more complicated and the feasibility of the technique could be affected.

After the wave reaches the opposite surface of the specimen, it is detected by the receiver R1 (in through-transmission experiments) or allowed to come back as a reflected wave to the top surface, where detection takes place with the receiver R2 (in skip-distance experiments).

The arrival time of the peak (and/or the leading edge) of the signal amplitude was measured as a function of the flight distance, which was determined from the geometry of the experiment (in either through-transmission or skip-distance). If the transducer diameter is essentially less than the total length of the path, including the distance inside the sender shoe, it is reasonable to consider it as a point source and, therefore, to calculate the energy velocity simply from the geometry of the travelling path. Alternative setups, of course, are possible, whereby simultaneous solutions of a large number of equations should be used to evaluate the anisotropic material properties.

It is obvious that the skip-distance, as opposed to the through transmission design, is more practical from an NDE point of view, since one sided inspection is possible. Therefore, all data for the columnar CCSS and its equiaxed control specimen were gathered in the skip-distance arrangement. Unfortunately, the large overall diffraction caused by the graphite-epoxy interfaces may effectively mask the reflected signal, therefore, most data on the graphite-epoxy composite was first gathered by the through-transmission arrangement, where both leading edge and peak value signals were recorded. This information was then used to identify the correct peak in the skip-distance experiments.

B504 Measurements. Two similar transducers (1 MHz, 0.5 in.), together with five different pairs of plastic wedges were used as a sender and a receiver in the skip-distance arrangement (Fig. 1) to gather five sets of data. The time and distance reference points were determined by the position of the maximum response in the direct transmission measurements from one wedge to another for each pair of wedges.

The arrival time t was measured by the maximum signal amplitude for each position of the transducers, which were separated by a distance X. The data, in pairs (X_i, t_i), were then used to generate the values of energy velocity W_i versus angle θ_i according to the simple formulas:

$$\tan(\theta_i) = X_i/2D, \quad W_i = 2D/(t_i \cos\theta_i)$$

Additionally, the pulse-echo method was used to measure the velocities in the perpendicular direction ($\theta = 0$ deg). The results [20] show that the differentiation of columnar from equiaxial (and hence the anisotropic versus the isotropic case) can be obtained by observing the profiles of energy velocity versus skip distance or angle θ values. The feature matrix constants were also obtained for this specimen, and from them, the two sides can be clearly distinguished.

OLGEC Measurements. The one-lamina, graphite-epoxy composite specimen (OLGEC bar), was a specially made, unidirectional, calibration block, with a length of 229 mm, thickness of 12.7 mm, and width of 25.5 mm. The graphite fibers were oriented in the longitudinal direction, so the (width) x (thickness) cross-section was in the plane of transverse isotropy.

Preliminary data on the ultrasonic velocities, along and perpendicular to the fibers, were obtained by the standard pulse-echo method. The results are as follows: for longitudinal waves V_l (0 deg) = 9.467 mm/us; V_l (90 deg) = 3.058 mm/us; for vertical shear waves V_{vs}(90 deg) = 1.855 mm/μs; for horizontal shear waves V_{hs}(90 deg) = 1.439 mm/us. Note that there is no difference between phase and energy velocities for either the 0 deg or 90 deg directions, which again, is in reference to the director **d** (fiber direction unit vector).

Due to strong diffraction it was practically impossible to detect the shear waves at 0 deg using the entire nine inch length specimen. Therefore, after all data were gathered, a short piece of 0.457 in. length was cut from the original block, and shear wave velocities for the 0 deg direction were taken on it. Two different waves were detected, vertical and horizontal shear, with velocity values of V_{vs}(0 deg) = 1.89 mm/us and V_{hs}(0 deg) = 1.95 mm/us, respectively.

For an ideal transversely isotropic material, there is only one shear mode (twice degenerate) in the 0 deg direction, or we may say that the velocities of the vertical and horizontal shear waves must have the same value, coinciding with the vertical shear wave velocity in the 90 deg direction (1.855 mm/us).

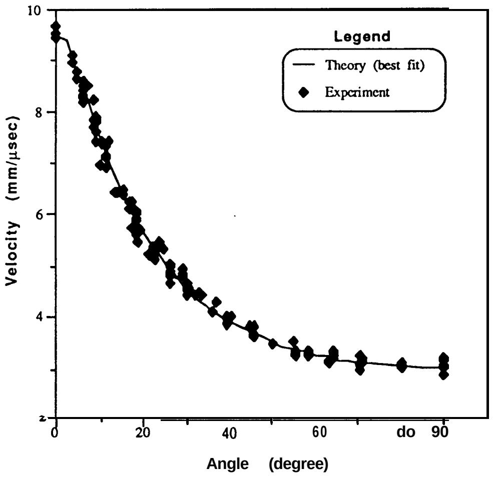

Fig. 2 Experimental data (all combined), and best fit theoretical curve for the energy velocity, obtained from OLGEC bar

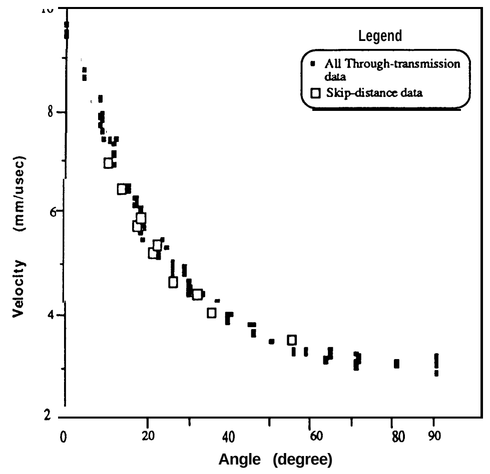

Fig. 3 Comparison of OLGEC data obtained from the through transmission technique with that obtained from the skip distance technique

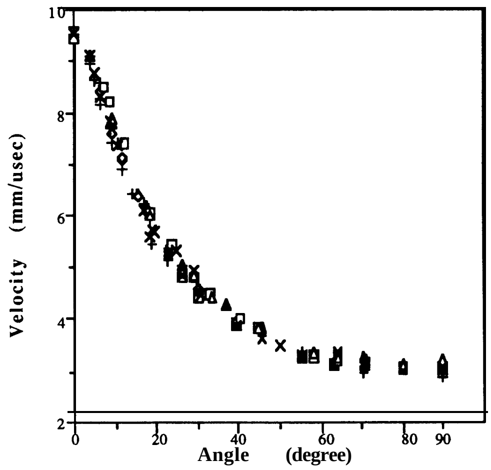

Fig. 4 Through transmission data obtained from the OLGEC bar with various transducer frequency and incident angles. (9 cases in all, frequencies 1.0, 3.5 and 5.0 MHz and L-wave shoe angles from 25 to 45 degrees).

Table 1 Evaluated elastic constants. The stiffness matrix is given in GPA = $10^9 N/m^2$.

Constant	Graphite-Epoxy Specimen
$C_{11} = C_{22}$	14.5
C_{33}	139
$C_{13} = C_{23}$	3.75
$C_{12} = C_{11} - 2C_{66}$	8.08
$C_{44} = C_{55}$	5.33
C_{66}	3.21

Although not exactly the case here, it is strikingly close (~ 3 percent deviation), provided that the longitudinal mode velocity changes by more than three times from the 0 to the 90 deg direction. We take this observation as supporting evidence in favor of the assumed overall transversely isotropic (or unidirectionally anisotropic) nature of the material.

The results of the bulk wave experiments, which were conducted with a variety of different arrangements, as illustrated in Fig. 1, are shown in Fig. 2. Comparison between the through-transmission data and the skip-distance measurement data is presented in Fig. 3. The through-transmission measurement data alone, with different arrangements is shown in Fig. 4.

When plotted together, the data from all of the experimental arrangements form a very smooth curve (see Fig. 2), well matched by the one-parameter ($C_{13} = C_{23}$), best fit theoretical curve for the energy velocity (solid line of Fig. 2, see also Step #5 of the Appendix). We take this as strong evidence that the experimental curve is indeed the energy velocity profile, as would be produced by a point source of quasilongitudinal ultrasonic waves, propagating through an infinite, unidirectionally anisotropic, elastic solid. The phenomenological approach for the processing of the data [1, 20] ultimately yields the values of the five elastic constants that characterize the arbitrary, unidirectionally anisotropic material. These constants are listed in Table 1.

The Surface Wave Technique

B504 Measurements. Surface wave experiments were conducted on specimen B504 with a limited task: to distinguish the columnar side of the specimen from the equiaxed side. The results can be found in reference [20].

Composite Specimens. Small values of the surface wave velocities in graphite-epoxy composite materials have forced us to consider a different surface wave generation procedure. The most popular NDT method for generation and reception of surface waves, and that which was used for the *CCSS* specimen, is known as the resonance technique. This technique utilizes an obliquely incident longitudinal wave from either a liquid or solid upper material, the most commonly used upper materials being plexiglass and water, with longitudinal wave speeds of 1500 m/s and 2700 m/s, respectively. Comparing these velocities with the values obtained from our calculations for the surface wave velocities in composites, one can see from Snell's law, for the combination of plexiglass onto graphite-epoxy, that there does not exist a third critical angle for plexiglass or it is at least very close to the grazing angle. Therefore, the utilization of this very convenient oblique incidence technique is almost impossible.

A modified line source method, similar to that presented in [29], was incorporated with the same differential measuring technique, depicted in Fig. 5. To increase the efficiency of surface wave generation, a solid, sharp edged mediator was used for each probe. The waves were generated along the line contact of the sharp edge mediator, attached to the transmitter, and received at two other line contacts of similar mediators, attached to the receivers and separated by a precisely known distance. The configuration may be called a quasi-point measurement because of the relatively small measurement base of 10 mm. Such a small base was chosen not only due to large attenuation (0.335 dB/mm in the fiber direction and 0.354 dB/mm in the perpendicular direction for 1 MHz), but mainly to avoid any difficulties with the interpretation of the received signals, due to the finite thickness of the composite layer and possible reflected waves from the bottom surface. Two frequencies, 1 MHz and 2 MHz were used in the study.

The surface wave velocity measurements were carried out on three graphite-epoxy composites with unknown material properties. Two of the specimens were unidirectionally reinforced, the third was (0-90)s with 64 plies. The first was the same OLGEC bar (specimen A) used in the bulk wave measurements. The second specimen (B) was plate-like and had dimensions of 157.5 x 94. x 5.1 mm, a density of 1.55 gr/cm^3, and fibers along the width. The thickness of specimen B was not exactly constant but varied up to 15 percent. The third specimen (C), which was also plate-like, had dimensions of 242 x 92.8 x 8 mm and a density of 1.56 gr/cm^3. The specimen was of orthotropic symmetry due to its structure. The principal axes x_1, x_2, were chosen so as to be in the same plane as the surface of the specimen, and x_3 was directed along the length.

The results of surface wave velocity measurements at three different locations and in two perpendicular directions (i.e., c_2, c_3), for each specimen are presented in Table 2. For specimen C, the measurements were performed at one location only.

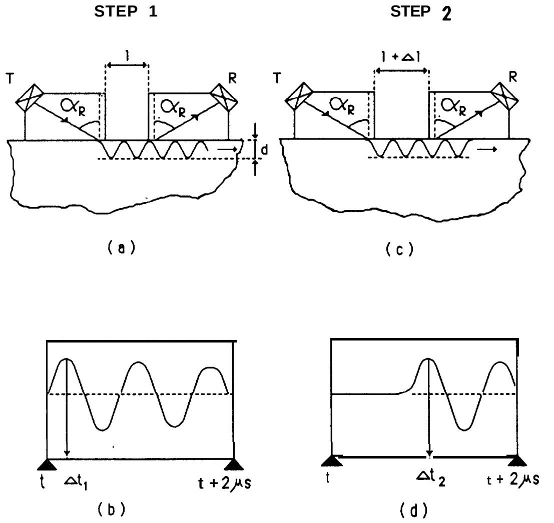

Fig. 5 Differential technique for surface wave velocity measurements:
d Depth of penetration of surface wave;
t Travel time corresponding to distance l between transmitter T and receiver R;
α_R Incident angle (around 62 degrees).

Measurements of the off-axis surface wave phase velocities for specimens B and C at a frequency of 2 MHz was also carried out. The results are plotted in Fig. 6. The reduced anisotropy of specimen C due to the averaging effect of 64 differently oriented laminas (plies) is clearly observed. The values of the surface wave velocity measurements together with some of the bulk wave velocity measurements, were used to evaluate the matrix of elastic constants. The results are given in Table 3.

Theoretical Investigations

Numerical Integration Model. The numerical integration model [27, 30] makes use of the energy flux deviation angle and the resulting group velocity in summing the point source responses over a transmitter or a reflector surface. The Green's function scalar retarded potential serves as a point source inside a surface integral for calculating the superimposed ultrasonic scattering function impinging onto a reflector and/or reflecting from the target. The model is thus capable of handling arbitrary shaped transmitters and reflectors located in three dimensional space, for any generalized phase velocity profile.

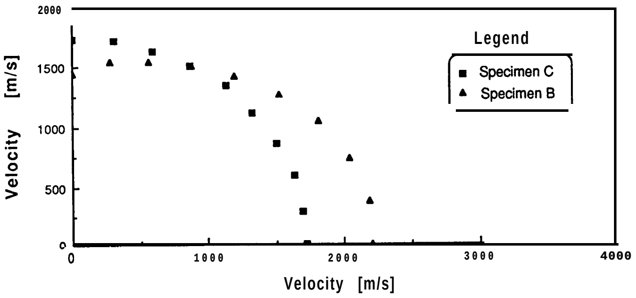

Fig. 6 Off-axis surface wave velocity measurements for specimens B and C. (Nominal frequency = 2.0 Mhz)

Table 3 Elastic constants evaluated with the surface wave technique (GPA)

Constant	Specimen A (transversely	Specimen B isotropic)	Specimen C (orthotropic)
C_{11}	14.5	13.5	68.4
C_{22}	14.5	13.5	75.1
C_{33}	139.0	138.0	71.0
C_{12}	8.1	6.1	57.1
C_{13}	5.6	3.1	55.3
C_{23}	5.6	3.1	8.7
C_{44}	5.3	7.7	12.5
C_{55}	5.3	7.7	5.2
C_{66}	3.2	3.7	5.2

Table 2 Surface wave velocities in two perpendicular directions (along the principal axes) for specimens A, B, and C (m/s)

A				B				C			
1 MHz		2 MHz		1 MHz		2 MHz		1 MHz		2 MHz	
c_3	c_2	c_3	c_2	c_3	c_2	c_3	c_2	c_3	c_2	c_3	c_2
1828	1295	1827	1302	2052	1368	2060	1379	-		-	-
1796	1295	1792	1305	2201	1450	2210	1455	1732	1733	1732	1738
1828	1295	1840	1295	2132	1368	2120	1368	-	-	-	-

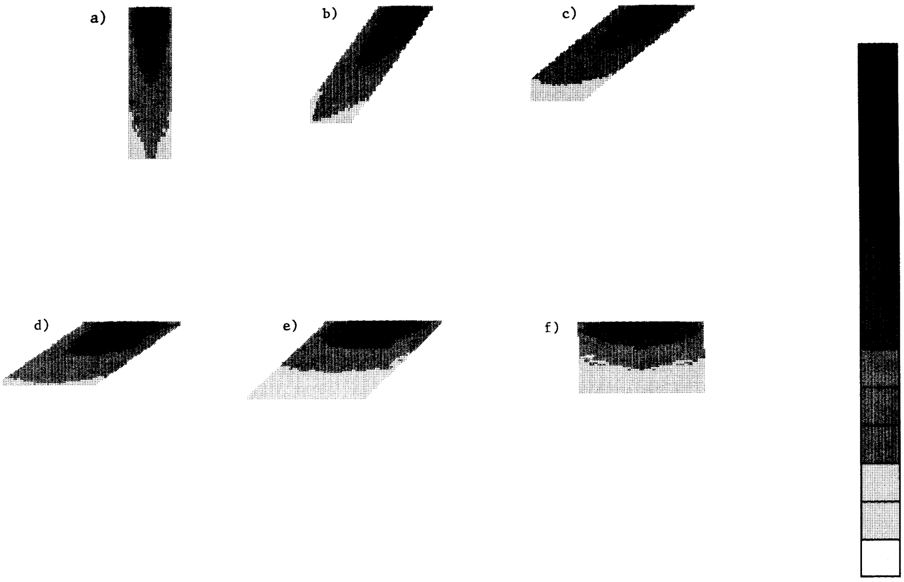

Fig. 7 Ultrasonic field profiles in composite specimen for different orientations of the original phase front to the director (fiber direction). Obtained from numerical integration model with 3.0 MHz. input pulse. (a) 0 deg, (b) 40 deg, (c) 61 deg, (*d*) 72 deg, (e) 61 deg, (*f*) 90 deg.

CCSS Specimen. In reference [10] the beam pattern for a longitudinal wave mode is shown for different angles of entry, again with respect to the director d (in this case the columnar grain direction). The 0 degree incident beam shows a diverging pattern, with a pair of side lobes symmetrically positioned on either side. As the entry angle is varied to 15 degrees, the beam tends to skew in the direction of increasing phase velocity. Skew angles are also observed in the 30 degree and the 65 degree direction diagrams, while in 45 and 90 degree diagrams the waves do not skew at all. The results show that the phase velocity at these angles reaches the maximum and minimum values which is the reason that the energy velocity is identical to phase velocity, and which in turn explains the lack of beam skewing. At 45 degrees there is a natural beam focusing effect which has been experimentally observed [14, 15] and which is the direct consequence of the maximum of the phase velocity being at this angle. At 0 and 90 degrees, where the phase velocity reaches its minimum values, defocusing should be observed.

Graphite-Epoxy Specimen. The generalized numerical model with the scaling transform [30] was applied to the graphite-epoxy composite, and the results for quasi-longitudinal mode propagation are presented in Fig. 7. The transducer arrangement was the same as described above.

Figures 7 *(a-,* show the ultrasonic field profiles for different orientations of the original phase front to the direction of the director d (fiber direction). Hence, the angle is measured between d and the normal to the transducer excitation surface. The moving surface of the transducer is always horizontal and perpendicular to the plane of the drawing, the same as the wave front of the initial excitation.

One may observe the strong focusing effect at 0 deg (the phase and energy velocity are in the same vertical direction along the fibers, so there is no skewing-refer to Figs. 7 and 8) and a strong defocusing effect at 90 deg, when the fibers are in a horizontal orientation. The skewing is well pronounced and approximately equal to 35 deg for a 40 deg orientation, and 57 deg for a 61 deg orientation. It approaches the fiber direction with increasing angle until it reaches 90 deg where, strictly speaking, the skewing is zero. However, due to the strong defocusing, we may just as well say that this latter is the case of 90 deg skewing. From a computational point of view, the very strong overall skewing observed in Fig. 7 is the result mostly of the scaling transform alone, although a mild skewing (~ 8 deg) still exists in the imaginary pre-reverse-scale-transform material.

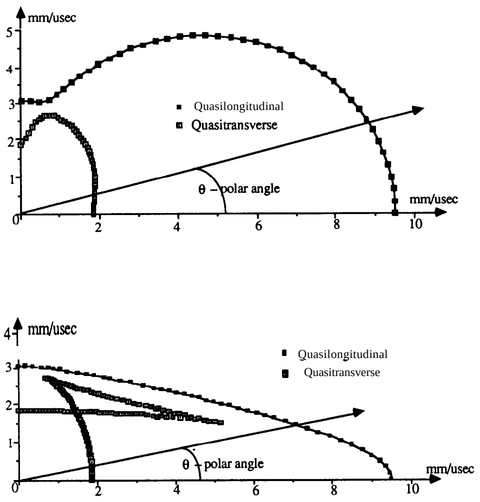

Fig. 8 Phase (a) and Energy (6) velocity profiles for the uni-directional graphite epoxy compsite (polar coordinates). Angle θ is between the fiber direction (horizontal) and the direction of propagation for the given mode.

Evaluation of the Feature Matrix

The theoretical basis and computational procedure for elastic constant evaluation is presented in detail in references [1,301. We shall give here only the results of those procedures, based on the approximate expression for the Green's function [30], which was obtained for the mildly anisotropic medium. Although the graphite-epoxy composite (OLGEC) is certainly not the case of weak anisotropy (Fig. 8 shows that the velocity along the fiber is three to four times the velocity in the perpendicular direction), the special considerations based on properties of the characteristic equation, with respect to the scaling transformation, show that the same approach may be applied

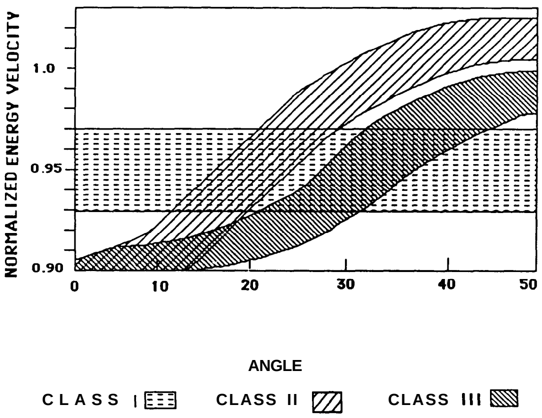

Fig. 9 A possible implementation algorithm concept for material classification

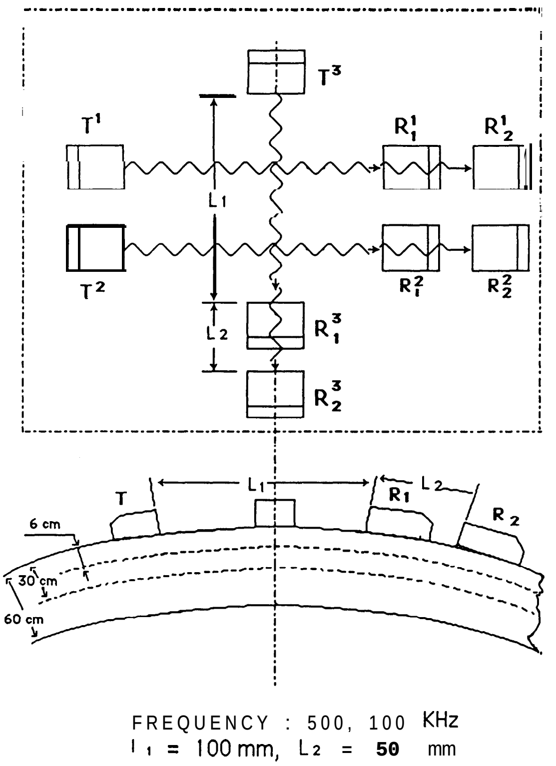

Fig. 10 A surface wave transducer arrangement for material characterization

to the graphite-epoxy composite in spite of its large anisotropy. The idea was mentioned first in reference [30] and then was elaborated in reference [31]. Concisely, a scaling transform along the director d with the scaling factor

$$f = V_1(90\ \mathrm{deg})/\,V_1(0\ \mathrm{deg}).$$

turns the graphite-epoxy composite into the material with very small anisotropy of the quasilongitudinal phase velocity profile. Quantitatively, in a new, scaled system, the graphite-epoxy composite has the anisotropy parameter ∼ 3 percent deviation of the quasilongitudinal velocity from its angular average value.

Briefly, the theoretical analysis leads to the basic statement that the data on ultrasonic pulse velocity, as obtained here, pertains to the energy velocity as opposed to the phase velocity. The results of inverse computations, from energy velocity to phase velocity and finally to the elastic constants, are presented in Table 1 of the bulkwave section.

To determine the elastic constant values from the velocity values the density of the graphite-epoxy composite was estimated as 1.55 $\mathrm{gr/cm^3}$. The procedure for the inverse computation for the surface wave technique can be found in [1]. The results of these computations can be found in Table 3 of the surface wave section of this paper.

Conclusion

The ultimate goal of this work is to produce an expert system for the reliable NDE of anisotropic solids. The methods of material evaluation and transducer selection [32], which are the basic constituent parts of such a system, are outlined very briefly next.

By following a carefully prepared data acquisition protocol (see Appendix A), a series of different velocity measurements can be taken, and from them, a plot of energy velocity as a function of skip-distance (or angle) can be generated (see Figs. 2-4). From this plot, we can obtain the anisotropic material state, as is illustrated in Fig. 9. This material state characterization technique could be implemented by way of a multi-element, electronically phased array of transducers. The surface wave technique may also be used for the determination of the anisotropic material state, as well as the material variations with depth. A suitable surface wave transducer arrangement for carrying this out is illustrated in Fig. 10.

Once the material properties are known, computer runs can be carried out to evaluate the ultrasonic field profiles for arbitrary inspection parameters (i.e., wave modes, frequencies, and incident angles). These profiles will provide us with the necessary information to select the proper parameters which show minimal beam skew and energy velocity variations. We can also, at the same time, explore such characteristics as axial resolution, beam focusing, and lateral resolution for those particular inspection parameters. Side lobe energy, beam splitting, and potential artifacts can also be predicted, and hence avoided in the actual inspection.

All of this is envisioned in an expert system, with rapid computation capability, so that the material characterization results can immediately be used to determine the optimal inspection parameters, hence enabling us to carry out a detailed inspection of the advanced anisotropic materials, widely used in nuclear, aerospace and other leading industries.

Besides being simply a collection of material constants, which are used as inputs to the numerical integration model, in order to generate the ultrasonic field profiles, the overall material stiffness coefficients which are generated can tell us about the reference state of the material in a particular neighborhood and then actually depict changes from the reference state in areas nearby. As a result, such global material property changes as porosity, fiber volume fraction, matrix degradation, etc. will be reflected in the constants of the feature matrix. Such defect types as delaminations, gross defects or through cracking, etc. may also be determined by observations of unusual or bizarre feature values due to the computation process associated with a particular data collection, inspection and analysis protocol. The effects of certain defects on the elements of the feature matrix are reviewed briefly below.

1. Uniform, nondramatic changes in all constants by the same amount in the range of 5 to 10 percent strongly suggests that the density changed by the same amount.
2. The changes in density can be caused by changes in fiber fraction (FF) or porosity (PC), and the discrimination between these two may be done, in principle, by the computer aided decision making procedure.
3. Drastic changes of the elastic constants or bizarre

values (i.e., negative or even complex) indicate the presence of defects. It could mean gross defects (delamination, large voids, cracks in large numbers) or small defects (voids, vertical cracks at various locations, local inhomogeneity or interfacial weakness with depth).

4. If drastic or bizarre results are spotted, bulk and surface wave measurements, at different locations in the neighborhood of the first encountered suspicious spot and at different frequencies, would allow one to discriminate between gross and small defects, and to determine their location and size.

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APPENDIX A

A tentative protocol for anisotropic material evaluation, based on the bulk wave technique, is listed below. Specifically, it is for the elastic constant determination of transversely isotropic graphite-epoxy composites.

Step #	Measurements (velocities)	Techniques	Evaluation (elastic constants)
1.	c_L -longitudinal along the fibers	Pulse-echo, or skip-distance, or transmission	C_{33}
2.	c_L -longitudinal perpendicular to the fibers	Pulse-echo, or skip-distance, or transmission	C_{11}, C_{22}
3.	c_T -vertical shear perpendicular to the fibers	Pulse-echo	C_{44}, C_{55}
4.	c_T-horizontal shear along the fibers	Pulse-echo	C_{66}, $C_{12} = C_{11} - 2C_{66}$
5.	$c_L(\Theta)$-quasi-longitudinal at different angles.	Skip-distance or transmission	C_{13}, C_{23}

Note : With a sufficient number of measurements at different angles, step 5 allows us to eliminate steps 1 and 2, and, therefore, to determine simultaneously the elastic constants C_{11}, C_{22}, C_{33}.