NDE OF ELASTIC PROPERTIES OF FIBER-REINFORCED COMPOSITE MATERIALS USING ULTRASONIC OBLIQUE INSONIFICATION ‘

Yoseph Bar-Cohen, Shyh-Shiuh Lih
JPL, California institute of Technology, 4800 Oak Grove Dr.(125-11 2)
Pasadena, CA 91109, yosi@jpl.nasa.gov

and

Ajit K. Mal
Mechanical and Aerospace Engineering Department
University of California, Los Angeles, CA 90024, ajit@seas.ucla.edu

INTRODUCTION

Fiber-reinforced composites have highly desirable engineering properties that are exploited to design structures with high demands on their performance. Their relatively low weight that is accompanied by high stiffness, strength, fatigue resistance and damage tolerance are making them increasingly selected to fabricate primary aerospace structures. Further, these materials offer unique mix of formability and toughness allowing to imbed sensors and actuators in the material and to form active/adaptive (i.e., smart) structures. However, composites are very sensitive to the details of manufacturing processes and to service conditions, which can induce defects and seriously degrading the material performance.

Composites as multi-layered anisotropic media have posed a challenge to the NDE research community for many years and successful results have been reported in several areas. Particularly, using ultrasonic oblique incident waves, quantitative information can be obtained about defects, adhesion, and the elastic properties [1]. Signals, transmitted either in tone-burst or short pulse form, were used to study the material characteristics. Using tone-burst, the leaky Lamb wave phenomenon was applied to determine the resin dominated constants and to detect a wide range of defects. Recently, reflected signals in the time-domain were tested in different angles of incidence and wave propagation and demonstrated a capability to measure both the fiber and resin dominated stiffness properties. The analysis of reflected ultrasonic waves induced by oblique insonification of composite materials is increasingly recognized as a powerful NDE tool. The theoretical modeling of the wave behavior for tone-burst and pulses has been very successful in accurately corroborating the experimental results. Frequency- and time-domain data and an efficient inversion algorithm are used to determine the stiffness constants of composite laminates. The data repeatability and accuracy makes oblique insonification methods easy to standardize for practical applications. A mechanical scanner in the form of a C-scan attachment was developed to simplify the data acquisition. Using such a scanner and computer software, this method has the potential of becoming a standard NDE technique for composite materials. This paper covers the progress that was made by the authors in applying ultrasonic oblique incidence methods that require access from a single side of test parts using both frequency- and time-domain data.

OBLIQUE INSONIFICATION TECHNIQUES

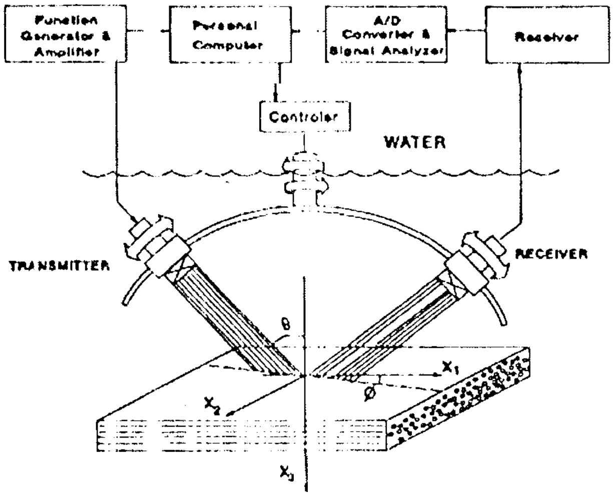
Obliquely insonified ultrasonic waves induce various wave modes at certain frequencies. These modes depend on the material properties and the laminate layup. As describe below, these modes can be analyzed in the frequenc - and time-domain allowing to characterize the materials properties and flaws.

Leaky Lamb Waves (LLW)

in 1983, the leaky Lamb wave phenomenon was observed [2] when a Schlieren imaging system was used to examine the reflected field of continuous wave and tone-bursts at different frequencies. Subsequent studies by various researchers [e.g., 3-5] modeled the phenomena and accurately correlated the results of the analysis. The behavior of LLW was tested for a wide range of' composite materials including polymer matrix composites (PMC) such as graphite/epoxy, glass/epoxy and metal matrix composites (MMC), e.g., graphite/aluminum, graphite/copper and SiC/Ti.

A schematic diagram of the LLW phenomenon excitation for a plate immersed in fluid is shown in Figure 1. The LLW phenomenon is induced when an ultrasonic. wave is obliquely impinging an immersed plate at frequencies that excite plate wave modes. When LLW is generated, the specular reflection (reflection from the composite as a half space) is distorted as a result of a phase cancellation and the excitation of two components with a null between them. The phenomena sensitivity to variations in boundary conditions, elastic properties, thickness and integrity provides detailed information about the material. Using a combination of LLW setup and a C-scan system [1], defects such as delaminations, porosity, ply gaps, matrix cracking and resin content variations were easily detected. Each type of these defects is characterized by a unique spectral response enabling the identification of the defect type.

Figure 1 Schematic description of the leaky Lamb wave phenomenon and the experiment coordinate system.



Ray theory

An alternative method to determine the elastic constants is based on a series of time-domain experiments. The elastic constants are determined separately through experiments in certain directions with the material lay-up. Through this approach the material constants can be determined more accurately and more efficiently than the commonly used nonlinear inversion schemes. Since the wave speed in a composite material is a function of the orientation, it is possible to have critical values. Thus, some of the homogenous waves may become evanescent when the propagation angle is larger or smaller than a certain critical angle. Based on the developed theory [5], an experimental procedure was formulated to determine the five stiffness constants, the procedures are summarized in Reference [1]

THE REFLECTED FIELD AND STIFFNESS MATRIX

The behavior of an ultrasonic wave propagating through a composite material is determined by the stiffness matrix and the wave attenuation. To determine this behavior several assumptions can be made about fiber reinforced composite materials. Since the fiber diameter (e. g., graphite 5-10µm and glass 10-15µ) is significantly smaller than the wavelength (for frequencies up to 20 MHz the wavelength is larger than 100µ), therefore, the material can be treated as homogeneous. Each layer is assumed transversely isotropic bonded with a thin layer of an isotropic resin. The mechanical behavior of an individual lamina is described by an average of the displacements, the stresses and the strains over representative elements.

The average strains are related to the average stresses through the effective elastic moduli. As a transversely isotropic material, unidirectional fiber-reinforced composites are characterized by five independent effective stiffness constants. These constants dependent on the elastic properties of the fiber and matrix materials as well as their volume fraction.

The stress components of the wave are related to the strain through a linear constitutive equation. For a transversely isotropic elastic solid with its symmetry axis along the x_1-axis (Figure 1) this equation can be expressed [5] using the Cauchy's stress tensor, σ_{ij}, the displacement components, u_i, and the five independent stiffness constants of the material are c_{11}, c_{12}, c_{22}, c_{23} and c_{55}. Modeling the effective elastic moduli of composite materials has been the topic of many studies. Extensive discussions of the bounds for the effective elastic moduli of fiber-reinforced composites can be found in Christensen [6] and other associated literature cited therein. For low frequencies and low fiber concentration, the theoretical prediction of the effective elastic constants is in good agreement with experimental results. On the other hand, for high frequencies the theoretical estimates are not satisfactory since the effect of wave scattering by the fibers becomes significant.

The interaction of ultrasonic wave, that obliquely insonifies a composite plate, leads to excitation of various elastic wave modes. These modes are strongly affected by the material integrity as well as the bulk and interface properties. The material characteristics can be extracted from the reflected and transmitted acoustic data that is acquired as a function of frequency and angle of incidence. A pitch-catch setup is assumed to be immersed in water insonifying a fiber-reinforced plate by a plane harmonic acoustic wave. To formulate the wave field, a modified form of the potential function method is used. The field equations incorporate the prescribed conditions at the two fluid-solid interfaces and the continuity conditions at the inner interfaces can be solved by a global matrix method suggested by Mal [5].

INVERSION OF THE ELASTIC CONSTANTS USING LLW DATA

The basic idea behind the inversion is to fit the experiment data to the theoretical model where the stiffness matrix that is obtained represents the properties of the tested composite. A major difficulty in inverting the data is the need to solve a system of nonlinear equations, resulting in non-unique solutions. The authors applied a least square method for the nonlinear equations. The minima in the amplitude spectra of the reflection coefficient R correspond to the modal frequencies of dispersive guided waves in the laminate. The reflection coefficient consists of complex-valued functions of the frequency, laminate thickness and the material properties of both the composite and the surrounding fluid. R is expressed as smooth function and is determined for guided waves in a free plate because the modal frequencies of both free and leaky guided waves are almost identical in a broad frequency range. The real part of R is related to the dispersive guided waves and the imaginary part is contributed by the influence of water loading. The thickness of each lamina, mass densities of specimen and surrounding, fluid as well as the acoustic wave speed are assumed to be constant. The objective of inversion is to find a set of maximum likelihood estimation of c_{ij}. This requires minimization of the root-mean- square of the errors between the modal frequencies obtained from calculations and from the measured data. If the system of equations were linear, it could be directly solved and an exact solution may be obtained. Unfortunately, it is not possible to solve this inversion problem directly since the real part is a strong nonlinear function of the unknowns. An iterative procedure is necessary in seeking convergent solution until a convergence criterion is satisfied.

To determine the capability of the inversion algorithm, the sensitivity of the dispersion curves to variations in the five elastic constants was examined. Figures 2a and 2b are the theoretical symmetric and antisymmetric dispersion curves and the influence of a 20% reduction in each of the five elastic constants on the curves. As can be seen, the constants c_{22}, c_{23} and c_{55} significantly affect the dispersion curves, whereas c_{11} leads to a small change at high phase velocities and c_{12} dots not have any significant effect. Overall, c22, c_{23} and c_{55} are the matrix dominated elastic constants and therefore they are the most sensitive to the manufacturing (e.g. caring) process. Particularly, they are affected by the presence of porosity and variations in resin content. While the above three constants can be accurately inverted for unidirectional laminates, some degree of ill-posedness was observed when multi-orientation laminates were analyzed. For the later, the incorporation of the effect of the interfacial epoxy layer between the various laminae added another degree of freedom to the analysis. A detailed discussion of this issue is given in [5].

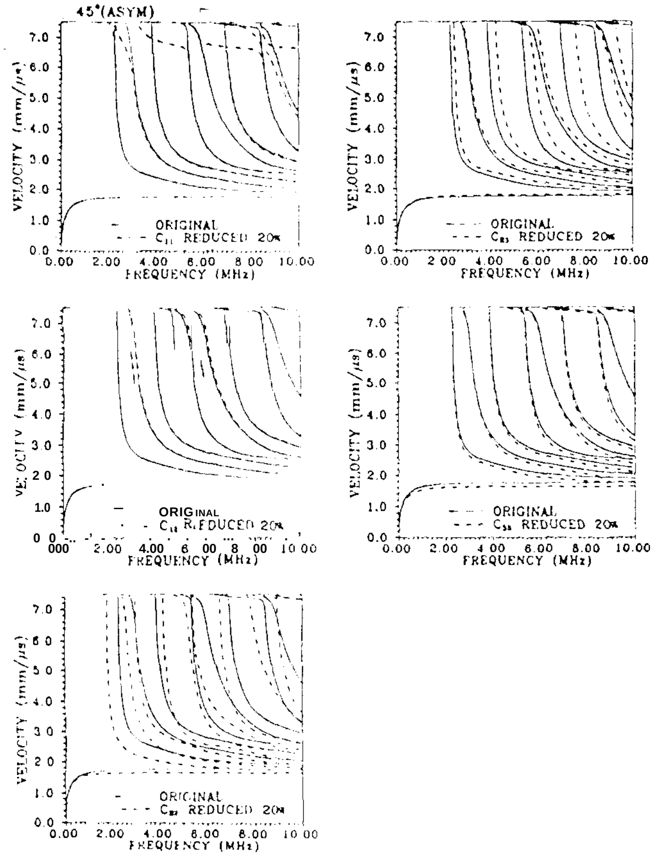


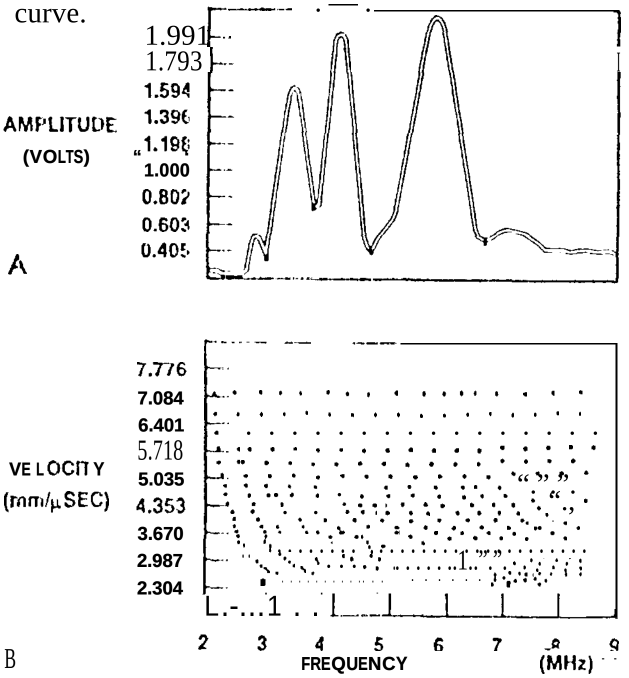
Figure 2: Dispersion curves for the symmetric modes for graphite/epoxy and the influence of 20% reduction in each of the five elastic constants.

EXPERIMENT AND RESULTS

The verification of the theoretical predictions towards practical application of the method discussed herein requires adequate experimental capability, A computer controlled LLW scanner C-scan attachment was developed to support the experimental verification of the predictions. The system was designed to control the polar and incidence angles of the transducers as well as the excitation frequency and can be articulated to position the receiver at the null zone. The transducer pair is controlled in a pitch-catch configuration! orienting the incidence angles from 12 to 75 degrees with minimum increment of 0.05 degrees. Further, the setup can vary the polar angle from O to 360 degrees with increments of.2 degrees. The height of the setup can be controlled within a range of 4.0 inches in increments of 0.5 roil. A description of the electronic setup is given in Reference [1].

A computer code was written to control the incidence and polar angles, the height of the transducers from the sample surface and the transmitted frequency. Signals (tone-burst or pulses) are acquired as a function of the polar and incidence angles and are saved in a file for corroboration with the theoretical predictions. Tone bursts are used to determine the LLW modes and to prepare dispersion curves (phase velocity as a function of frequency). The frequency is varied within the transducer response range (up to 20dB below the maximum amplitude) and the modes are identified for each angle of incidence from 12 to 50 degrees to allow the use of free-plate theoretical calculations. Incrementally, the incident angle is changed within the selected range anti the reflection spectra acquired. At each given incidence angle, the minima are identified and are added to the accumulating dispersion that is plotted simultaneously on the computer display (Figure 3). The acquired minima are uniquely identified on both the spectra and the dispersion curve while the data acquisition is in progress. For a test along the 0^o polar angle (along the fiber direction), Figure 3a is showing the reflection spectra for an arbitrary incidence angle. Whereas, Figure 3b shows the accumulating dispersion curve.

Figure 3: Reflection coefficient and accumulating dispersion curve as presented simultaneously during data acquisition.



Using the LLW inversion algorithm and the experimental setup described earlier, the elastic properties were determined for a wide variety of composite laminates. As an example for a 3.378 mm thick 24-layer unidirectional graphite/epoxy AS4/3501-6 laminate the results are listed in Table 1:

TABLE 1: Inverted stiffness constants for graphite/epoxy AS4/3501-6 $[0]_{24}$ laminate.

ρ(g/cm^2)	c_{11} (GPa)	c_{12} (GPa)	c_{22} (GPa)	c_{23} (GPa)	c_{55} (GPa)
1.578	166.07	7.09	16.19	7.52	7.79

To overcome the deficiency of the LLW method in determining the fiber dominated elastic constant, time-domain experimental data and the analysis obtained from ray theory were used. The time histories of the reflected signals from 8 ply laminates tested at various angles of incidence along, the 0°, 45° and 90° polar Orientations. lamination of the reflected pulses along these orientation with the fibers at fixed angles of incidence identify an angel that can be defined as the polar critical angle. At this angle, a transition is observed in the reflected pulses where the amplitude of the multiple reflections reach a minimum level.

Beside the elastic properties, it was found that the dispersion curves and the reflection coefficient can be used to characterize flaws in the material[1]. These defects include delaminations, fire damage, transverse cracking resulting from both fatigue and static loading. In the analysis, the effect of transverse cracks was determined by assuming the individual lamina is transversely isotropic with lower stiffness. Test results are reported in Ref [1] and showed an excellent agreement with expected behavior of the damaged composite. As expected, the matrix- dominated constants c_{22} and c_{23} decreased and were the most sensitive to the presence of cracking.

DISCUSSION

Theoretical and experimental studies as well as the successful application of oblique insonification of composite materials are increasingly encouraging the practical use of these NDE methods. The authors

studies showed excellent results for unidirectional graphite/epoxy composite. At a lesser degree of **success**, the matrix-dominated elastic properties of multi-orientation laminates were accurately inverted. The need for an access from one side to the test laminate makes these methods attractive for practical **use.** The LLW scanner, that was developed by the authors, provides a high speed data acquisition system **for** the determination of dispersion curves. This device also can be used to acquire pulse data and to **optimize** the test parameters for a C-scan imaging.

For unidirectional fiber-reinforced composite specimens, the important features of the reflected signals in oblique incidence experiments, including the LLW method, were clearly explained through a generalized ray theory. The analysis presented here shows that the overall reflected signal is the result of small number of rays. The irregular behavior of the reflected field is caused by mode-converted waves, many of which are attenuated during the reflection. For waves propagating in the plane parallel or perpendicular to the fibers, the reflected acoustic field from the fiber-reinforced composite is similar to that of the isotropic case in many aspects. However, there are significant differences in certain properties of the field even for propagation perpendicular to the fibers. It is well known that the stiffness constants c_{22}, c_{23} and c55 of the unidirectional composite have a strong influence on the dispersion curves of both leaky and free Lamb waves. Hence, these three constants are determined accurately through appropriate inversion schemes of the LLW data. Due to their weak influence on the dispersion curves, the other two material constants c_{11} and c_{12} must be determined through measurement of critical angles using pulsed oblique incidence ultrasonics and time-of-flight measurements. Pulse-echo is used to determine c_{22} which can also be confirmed by tests at an oblique incidence along the 900 orientation to the fibers. Measurements at this orientation can also be used to determine c_{23}. Tests at off-axis orientations, that are below the critical orientation, θ_c, can be used to determine the third matrix dominated constant c_{55}.

imaging defects using C-scan system combined with an oblique insonification were very successful when unidirectional laminates were tested. Defects such as delamination, porosity anti ply-gaps were easily detected. The acceptance/rejection criteria are well established in a wide range of industry and these standards can be easily applied for angular insonification tests. Porosity rejection criteria, on the other hand, are widely based on volume fraction data where, in most cases, porosity volume fraction below two percent is acceptable. Unfortunately, time is no NDE method which can accurately and reliably determine the volume fraction of porosity. Generally, it is easier to relate to a single parameter that identify porosity, namely volume fraction. However, this parameter does not provide sufficient information to determine the effect on the performance of a structure. Porosity with the same volume fraction but with different characteristic size, location and distribution will have different effect on the mechanical behavior of the laminate. These characteristic parameters may be extracted from oblique incidence C-scan data. Therefore, relevant accept/reject criteria are needed to define limits for the various characteristics of porosity.

In recent years, efforts are being made to apply the oblique insonification techniques to practical composite structures. The detailed inversion of the material properties that is based on the lay-up may require considering the global properties as a laminate.

ACKNOWLEDGMENT

The part of the study that was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), was performed under a contract with the National Aeronautics and Space Administration (NASA).

REFERENCES

1. Y. Bar-Cohen, A. K. Mal and S. -S. Lih, "NDE of Composite Materials Using [Ultrasonic Oblique Insonification," Materials Evaluation, Vol. 51, No. 11, (Nov., 1993) 1285 -1296.

2. Y. Ilar-Cohen and D. E. Chimenti, “Leaky Lamb Waves in Fiber-Reinforced Composite Plates," Review of Progress in Quantitative NDE, Vol. 3B, D. 0. Thompson and D. E. Chimenti (Eds.), Plenum Press, New York and London (1984), pp. 1043-1049,
3. D. E. Chimenti and **R.** W. Martin, "Nondestructive Evaluation of Composite Laminates by Leaky Plate Wave,” Ultrasonics, Vol. 29 (1991) 13-21.
4. V. Dayal and V. K. Kinra, "Leaky Lamb Waves in an Anisotropic Plate. II: Nondestructive Evaluation of Matrix cracks in Fiber-Reinforced Composites," J. Acoustic Society of America, Vol. 89, No. 4 (1991), pp. 1590-1598.
5. A. K. Mal, “Wave Propagation in Layered Composite Laminates Under Periodic Surface Loads." Wave Motion, Vol. 10, (1988), 1’1’.257.166.
6. M. Christensen, "Mechanics of Composite Materials,” Chapter 4, Wiley, New York (1981).