GUIDED PLATE WAVE POTENTIAL FOR DAMAGE ANALYSIS OF COMPOSITE MATERIALS

Krishnan Balasubramaniam and Joseph L. Rose

Department of Mechanical Engineering and Mechanics
Drexel University, Philadelphia, PA 19104

INTRODUCTION

The emergence of plate waves as a functional approach to the evaluation of thin structures, especially composite plates, has been gradual and steady. This statement may be supported by the increasing attention, in the recent publications[1,2], focussed on leaky Lamb waves in composites. The generation and the characteristics of plate wave modes, although using a quasi-local technique, has already been established and the dispersion relationships are being studied in detail, especially for isotropic cases. In practice, the critical drawbacks which have been detrimental in the widespread deployment of these methods are the complicated mode behavior and a lack of complete understanding of the mechanics involved. Thus, to fully exploit the plate waves, it is imperative that the physics of wave propagation within the thin composite structures be fully explored using experimental methods and be backed by a very strong theoretical basis in order to obtain NDE guidelines for fiber reinforced composite materials.

Such attempts have met with varying degrees of success, but in general, a lack of understanding of the basic physics of wave propagation in materials with complex layups and configurations has prevented the systematic development of reliable ultrasonic NDE techniques . In the following sections we shall briefly look at a few of the many recent breakthroughs in the utilization and the understanding of the guided plate waves as applied to the practical composite material damage evaluation problems.

THEORY

A generalized software package for studying the physics as well as the NDE principles of the reflection factor and plate wave dispersion has been recently developed at Drexel University[3]. This software merges the several algorithms already established for modeling damage into the fiber reinforced composite materials[4,5] with models for obtaining plate wave dispersion relationships for generally anisotropic structures. Thus it is possible to analytically study the influence of the various damage states on the ultrasonic phenomena of plate waves and to pick out the most sensitive parameters to be used in experiments.

The generalized model for obtaining plate wave characteristics in free anisotropic composite plates is developed by expanding the generalized Hooke's relationship and obtaining the expressions for stress components (σ_{ij}) in terms of elastic constants and displacement gradients in terms of known parameters and then the boundary conditions at both the plate surfaces is brought into the picture. Such a partial wave technique has been earlier outlined by Solie and Auld[6]. The displacements and the stresses of the six partial

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waves are first written using the exponential representation for displacement. Then the Christofell's equation provides the direction cosines and the polarization for each of the wave modes. Due to the free boundaries, the set of six boundary conditions may be written as

$$\sigma_{33}|_{\pm h/2} = \sigma_{31}|_{\pm h/2} = \sigma_{32}|_{\pm h/2} = 0 \qquad \ldots 1$$

Here 'h' is the thickness of the plate. Taking this set of six boundary conditions as a system of linear equation, and assimilating the corresponding coefficients of amplitudes(A_j) of the various modes within the plate, we obtain a characteristic expression

$$[D]^*\{A\} = 0 \qquad \ldots 2$$

The characteristic dispersion equation is obtain from the non-trivial solution to the above expression by setting the determinant of 'D' to zero.

$$|D| = 0 \qquad \ldots 3$$

There exists many solutions to this equation |D(fd,c)|, by maintaining either frequency-thickness product(fd) or phase velocity(c) as constant, it is possible to determine the roots of the other parameter and the plots for dispersion curves can thus be created.

The anomalies were modeled assuming that the porosity and hydro-thermal effects are purely matrix related while the fiber volume fraction and the fiber misorientation can then be included as building blocks, first for the material property computation of a single laminate and then subsequently for any composite material layup, the laminated plate theory was used. The porosity content can be written as

$$PC = P(1-FF) \qquad \ldots 4$$

where P is the porosity percentage fraction within the matrix and FF is the fiber volume fraction of the composite. This allows the computation of the elastic constants of individual laminates for any given porosity and fiber volume fraction using the theories by Hashin[4] and Behren[5]. The hydrothermal degradation can be modelled, once it is assumed that the polymetric matrix is affected only by such environmental factors such as moisture and temperature. Miller and Adams[7] presented an empirical relationship involving temperature(T) in °K and moisture content (S) in percentage as follows :

$$C_{11} = 5.92 - 0.0041\,T - 1.94\,S \text{ (GPa)} \qquad \ldots 5a$$
$$C_{12} = 3.05 - 0.0021\,T - S \text{ (GPa)} \qquad \ldots 5b$$

with an poisson's ratio assumption of 0.34. Ply orientation anomalies are modeled by transforming the material properties of the individual ply/ply groups to the required orientation before computing the overall effective elastic constants.

EXPERIMENTAL TECHNIQUES

In order to further establish the generalized model the results must correlate with carefully extracted experimental data. This was accomplished using the corner reflector technique on the unidirectional graphite epoxy specimen. For a specific angle of incidence, the frequency spectrum of the corner reflected signal was obtained using a broad banded signal and then the minima of each Fourier spectrum was considered as resonant frequency and related to the presence of a mode. The 'fd' values which constitute the resonant frequencies for that specific angles were then plotted against the phase velocity obtained using the Snell's law relation. In Fig.1, the dispersion curves for this unidirectional graphite-epoxy composite across the fibers is seen to match with reasonable accuracy to the corresponding theoretical curves. Any discrepancy may be attributed to the unavailability of sufficiently accurate elastic parameters describing the structure.

The utility of the dispersion curves and plate waves can be judged only by their

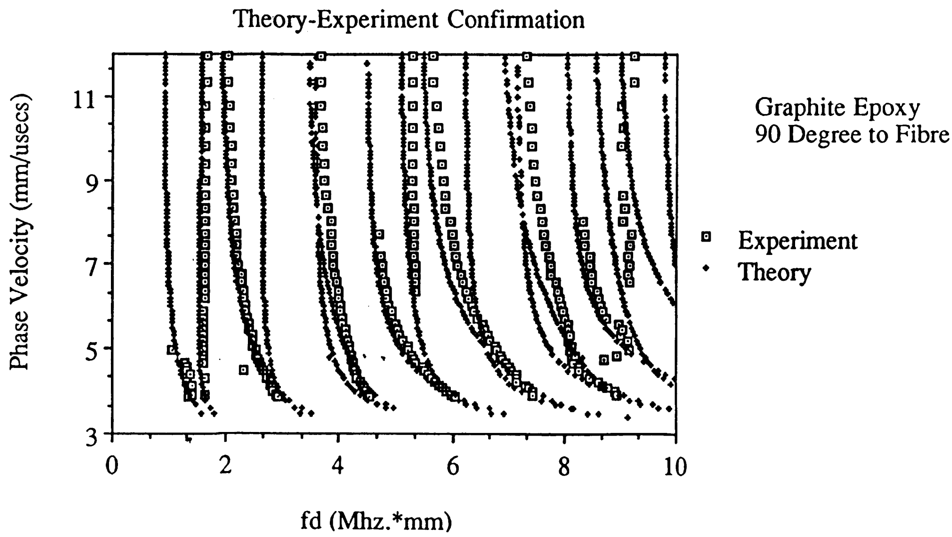

Fig. 1 The dispersion curves for a unidirectional graphite epoxy composite plate, with propagation across the fibers.

application specifically in the field of ultrasonic non-destructive testing. At first, the sensitivity of the technique to the presence of degradation of the material has to be established, followed by the identification of particular features of the wave phenomena and specify their correlation to a quantitative parameter of degradation. Then finally, the practical application possibilities as well as the existing limitations have to be clearly spelled out.

POROSITY ESTIMATION

Porosity is probably the most consummate representative of a global material degradation problem and is of intense concern during the manufacture of composites. It is almost impossible to completely avoid porosity while manufacturing composites, although several new techniques are being tried out in an attempt to keep it to the minimum. Current stringent quality requirements dictate a rigorous inspection for porosity in both a qualitative and a quantitative sense. Estimation of subtle porosity levels is important, especially in critical components and also since most of these have complex contours, the best technique for detection of subtle anomalies seems to be a guided wave approach such as plate waves.

The theoretical model was used to compute the dispersion relationships for the unidirectional composite with degradation due to porosity and changes in fiber volume fraction.It was determined that, as the porosity content increases the modes start to shift to the left. This is an important result since each of the modes may comprise of several data points and even if there are few bad data points, the overall mode behavior would still hold good and an averaged value of the vertical part of the modes will be reliably sensitive to porosity changes. Similar results were obtained for changes in fiber volume fraction. Higher fiber volume fraction makes these curves shift to the higher frequencies. Thus if high fiber fraction and low porosity content can be considered as attributes of a good quality material (potential for excellent performance), then it may be concluded from these studies that poor material quality would shift the dispersion curves to the lower frequency values thus making NDE possible. The sensitivity of the 'fd' shift to porosity was studies using a set of woven PMR-15 specimens with porosity levels up to 12%. The experimental results are plotted in Fig.2 where the first three modes show good sensitivity to porosity levels, even lower than 2% and also that each mode has a unique level of sensitivity to damage. The actual dispersive curves showing the displacement of the modes to the left is provided in Fig.3 .

FIBER MIS-ORIENTATION

The effects of mis-orientation of fibers is a critical problem and is not solvable using normally incident longitudinal waves. This is because of the fact that along this direction, the material properties do not change when a ply is mis-oriented and will have to depend on some other wave mode such as plate waves for detecting the fiber mis-orientation problems.

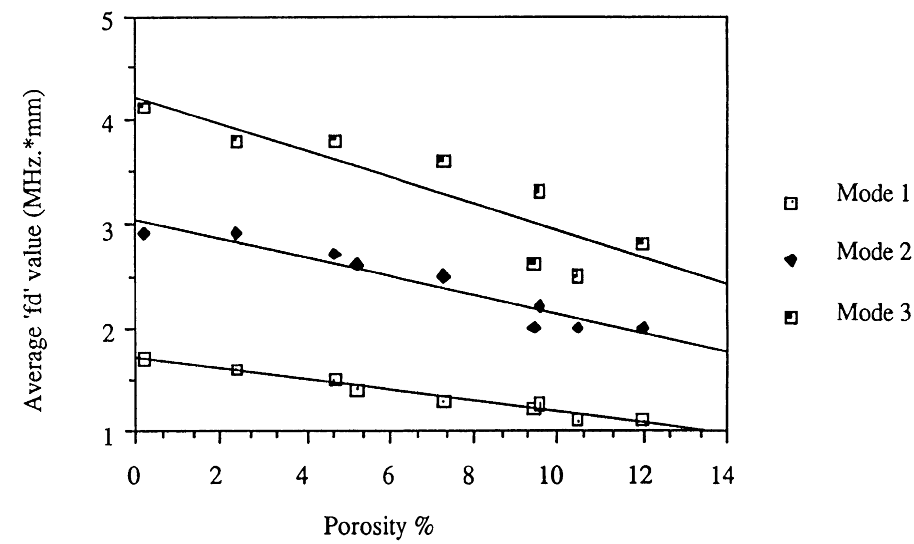

Fig. 2 The sensitivity of 'fd' shift feature to porosity.

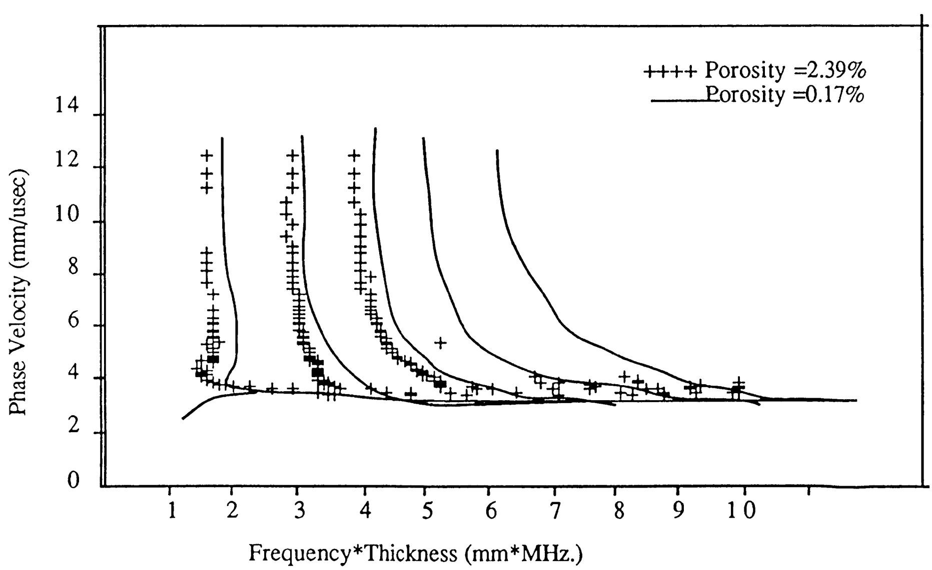

Fig. 3 The experimental dispersion curves for graphite-epoxy composites having two different levels of porosity.

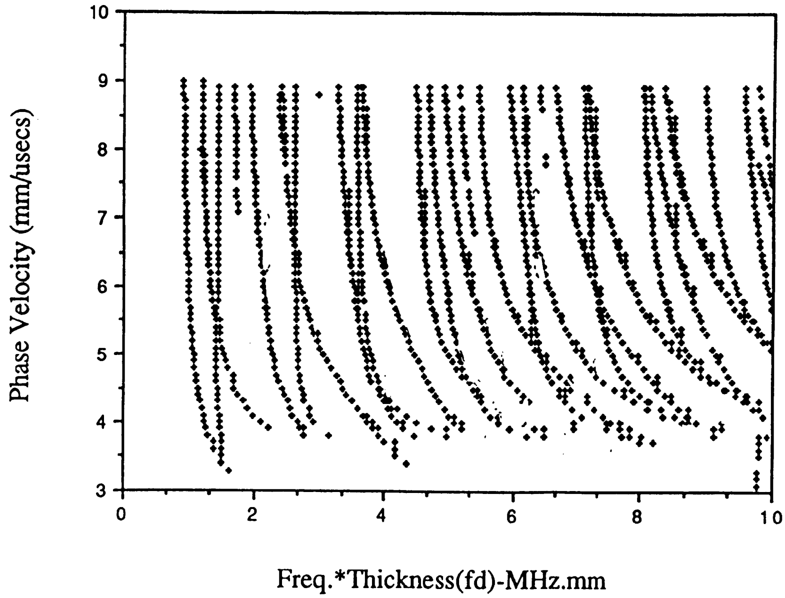

Fig. 4 Dispersion curves for a fiber mis-orientation of 15°

In fact the plate waves are probably the most sensitive wave type to fiber orientation and can be seen from the numerical results obtained for a 75° change in the fiber orientation. Fig.4 shows such results for the 75° must be compared with the 90° shown in Fig.1. The drastic changes in the mode structure and the increase in the number of modes should indicate the sensitivity of the plate wave dispersion to the detection of fiber mis-orientation problems. Here, onlyglobal mis-orientation possibility has been discussed, but it is also possible to show the same for local mis-orientation, where only one ply or ply group among many plies is at the wrong azimuthal angle. Here, of course, the sensitivity of the plate wave dispersion will not so dramatic, but so is the over all material degradation effect due to a local fiber orientation anomaly, relatively less critical.

Other composite material degradation such as hydro-thermal effects, fatigue damage, impact etc. are all factors which change the material state and similar techniques as shown above can be used to provide a qualitative as well as a quantitative insight.

FEATURES FROM THE DISPERSION DIAGRAMS

The utilization of oblique incidence for material characterization uses different wave modes such as the bulk waves (quasi-longitudinal and quasi-shear types), guided surface waves, guided plate waves[8-10]. Such a multi-dimensional approach enhances the feature list for anomaly detection, thus increasing the probability of detection as well as identification, particularly due to the fact that different modes have different sensitivities to different kinds of defects. The most common features which have been found to be useful in an NDE point of view, for anomaly estimation using plate wave dispersion diagrams, can be listed as

* The average <u>shifting of 'fd'</u> for a specific mode within velocity limits.
* The <u>Slope</u> of a section of a specific mode.
* The <u>'fd' value spacing</u> between two modes m_1 and m_2.

The most obvious feature is the shifting of the modes due to material property changes. The slope of the modes corresponding to the group velocity of the mode was shown to be useful through parametric studies in both characterizing the material anomalies as well as assisting the inverse computation of material constants from experiments. The uniqueness of each individual mode is another feature which will might be critical in removing the influence of thickness of the plate. A lot of research needs to be done in identifying additional features and establishing correlation with physical quantities associated with the material.

PLATE WAVE GENERATION

The physics of mode conversion of an obliquely incident ultrasonic wave at an interface between two different medium, in our case liquid/plexiglass and composite, and the presence of another boundary, here the other side of the plate, creates an environment for the several modes to interfere, both constructively and destructively. This provides a somewhat complicated but interesting and useful NDE situation. The process is clearly depicted in Fig.3. Here, the incident longitudinal wave from the liquid side and the specular reflection from the top side of the plate are represented by down and an up going beams respectively. While varying the incident angle, only this specular reflection is initially present while the modes within the plate self-destruct. But at special angles for a particular frequency, the wave modes inside the plates are all in phase and the interference is constructive. This triggers the birth of plate waves. These special angles are the critical angles and the corresponding frequencies represent resonances. Thus, critical angles, resonant frequencies and plate waves are in most cases the manifestation of the same phenomena, which provide accessibility to measure this effect from different perspectives. It is quite possible that any one of the technique may be favored to the others either due to an increased sensitivity or for convenience.

Due to the impedance mismatch between the composite and the encompassing liquid, the plate wave which is being guided by the boundaries of the plate start to leak energy into

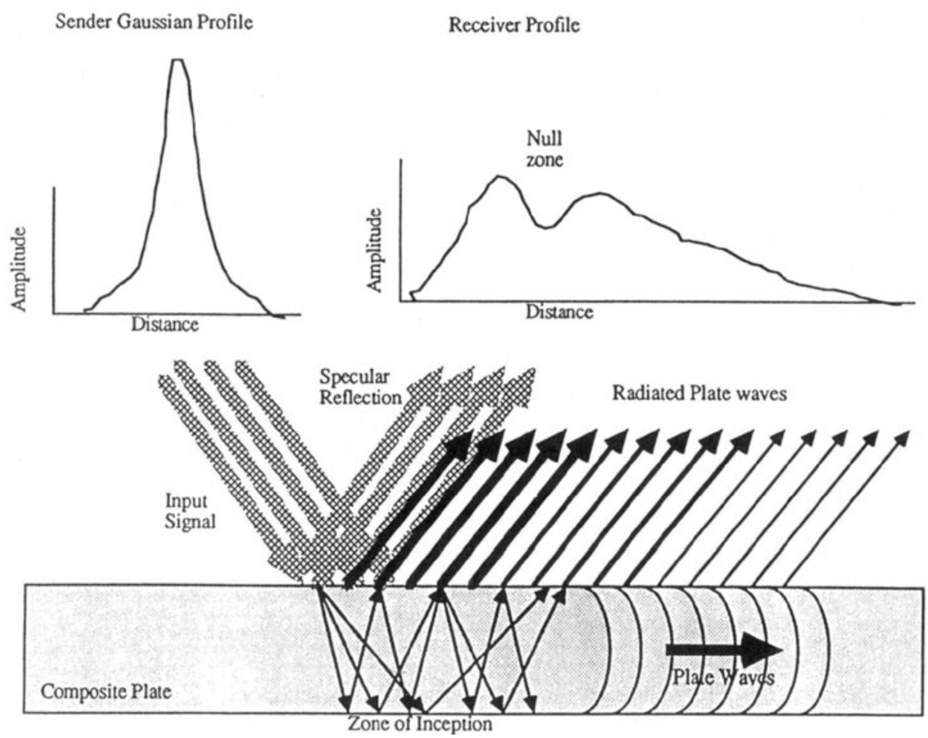

Fig. 5 The plate wave generation and reflection phenomena.

the liquid, from both sides. Due to attenuation, the energy discharged decays with distance of travel. Also, the leaky waves are at a different phase with the specularly reflected longitudinal waves thus resulting in a destructive zone of low amplitude commonly referred to as the null zone, as can be seen from Fig.5. This null region can be monitored for inspection purposes[1,2], since it is sensitive to material state. Thus, several exciting phenomena occur when an obliquely incidence ultrasonic beam strikes a composite plate, and these effects can be monitored by observing changes in reflection factor responses as well as guided plate wave propagation.

CONTACT TECHNIQUES

Contact methods are critical since most in-service inspection is performed in contact mode. A single line scan in contact can effectively replace a point by point grid approach, especially when time constraints demand quick inspection. The purpose behind this study was to gain confidence in the generation, propagation and the presence of sensitivity to anomalies. Several contact transducers were employed and plates of thicknesses 1.0,1.5, and 2.0 millimeters were used in the study. Using several combinations of 'fd' and transducer angles, plate modes were found to generate as well as propagate with sufficient efficiency. To show the sensitivity of the global plate wave technology for determining porosity, the Graphite-Epoxy$(0_4,45,-45,0_4)_s$ specimen having 2% and 4% porosity by volume were taken and plate modes were generated using contact shoes. It was found that the best plate modes could be generated at approximately 10° and 50° for propagation along and across the fibers respectively. A one MHz. probe was used to give a 'fd' product of 3.8 MHz.*mm. Hence a 20° longitudinal and a 70° shear Plexiglass shoes were used for the experiments.The velocity was taken from each side and averaged. The group velocity measurements for the 2% porosity caused a 230 mm/µsecs change in group velocity, which is substantial by current standards of instrumentation having accuracy in nanoseconds. The 4% porosity shows a decrease of up to 1,150 mm/µsecs in group velocity thus illuminating the inherent potential for plate waves as a global inspection means to determine degradation in composite material, all this along with an improve speed of inspection. Thus, the group velocity of plate wave modes is shown to be sensitive to material degradation, especially porosity.

CONCLUDING REMARKS

Notwithstanding any model controversy or inverse solution difficulties due to

- frequency dependent material properties.
- attenuation considerations.
- higher order anisotropy
- non-linear considerations
- non-planar waves etc.

guidelines are being established for data acquisition and feature extraction. Some of the specific contributions from this work can be listed as

1) Quantiative estimation of porosity with good level of confidence.
2) Contact testing potential for global inspection using plate waves demonstrated.
3) New feature based utility of plate wave dispersion diagrams established.
4) Continued feature matrix support based on anisotropy elasticity.

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