ULTRASONIC DISPERSION IN FLUID-COUPLED COMPOSITE PLATES

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INTRODUCTION

Fiber-reinforced composite materials have excited significant interest among industries needing to fabricate structures which are both light in weight and high in stiffness. Therefore, much attention has been paid by researchers over the past decade to composite materials and their properties. One active area of endeavor has been the topic of wave propagation studies [1-8]. Several theoretical approaches have been attempted to render tractable the complicated problem of wave propagation in an anisotropic material with microstructure. Many of these theories are quite useful in their region of applicability. We have reviewed briefly this earlier work in a previous paper [9] and will not recapitulate those comments here. The specific problem with which we are now concerned centers on the role of the structure itself and the influence of its surrounding media on dispersive behavior in guided wave propagation. Since all our measurements have been conducted in a frequency regime where the sound wavelength is much larger than the fiber diameter, we adopt a continuum mixture approach to account for the combined fiber-matrix mechanical properties of the composite. A detailed description of this model is found elsewhere in these Proceedings [10].

When a finite-aperture acoustic wave is incident from a fluid upon a solid plate immersed in the fluid, the sound energy will be mode converted, at appropriate values of the incident angle and frequency, to a guided wave propagating in the plate. The vertically polarized plate wave, very similar to a Lamb wave (free plate wave in vacuum) under most circumstances, is radiation damped by the fluid, and its energy reappears in the fluid as an acoustic mode. The net result of this process is a characteristic distortion and apparent lateral displacement of the reflected beam. The transmitted beam is also displaced, but its distortion has a different appearance. Since the energy can be visualized as leaking from the plate mode to the acoustic mode in the fluid, these excitations are often called "leaky waves".
EXPERIMENTAL TECHNIQUE

In the present study we have made experimental measurements of ultrasonic reflection to infer the dispersion characteristics of vertically polarized plate waves in fluid-coupled plates of unidirectional graphite-fiber reinforced epoxy and compared the results of these measurements to our recent theoretical calculation [10]. The sample used in this investigation is an 8-ply layup of Thornel T300 fibers in a matrix of Ciba-Geigy 914 resin. The plate is approximately 10 x 10 cm, and its thickness varies by no more than 0.5% over the region where measurements have been performed. The elastic constants of the constituents have been derived from our own measurements and other sources [11]. The values used in this study are collected in [12]. Effective composite properties have been calculated from our model [10].

A schematic of the experimental geometry is given in Fig. 1. Damped piston transducers generate and detect acoustic beams in the fluid. At frequencies and incident angles corresponding to the production of guided waves in the plate, the reflected ultrasonic field shows the displacement and distortion characteristic of the presence of propagating waves in the plate, as illustrated schematically in Fig. 1. This phenomenon, which is expected on the basis of the rapid phase variation in the reflection coefficient, is analogous to observations on leaky Rayleigh waves. Not illustrated in Fig. 1 is the transmitted field below the plate. Away from the resonance condition, ultrasonic reflection should be nearly specular. Data are accumulated by stepping the frequency of a 20-microsec rf tone burst, while the receiver position is adjusted to monitor the reflected beam amplitude along the line of the sharp extinction of beam energy denoted by "N" in Fig. 1. This procedure yields plate wave spectra with deep, well defined minima from whose position in frequency the existence of leaky plate waves has been inferred. A more complete description of the experimental details has been given in an earlier paper [9].

An example of the plate wave spectra obtained in these experiments is shown in Fig. 2. The solid curve is the measurement, while the dashed curve is a model prediction based on our recent theoretical analysis [9, 10]. Briefly, this calculation begins with a continuum mixture model.
of the composite. Since the ultrasonic wavelengths involved in the measurements are much larger than the fiber diameter, this approximation is justified. The effect is to homogenize the composite while retaining its anisotropy. Next, the ultrasonic plane-wave reflection coefficient for an anisotropic plate immersed in a fluid is calculated by solving a system of boundary condition equations for the complex reflected wave amplitude. The theory curve of Fig. 2 is obtained by evaluating an integral transform expression for the reflected field which incorporates the reflection coefficient from our analysis [10]. The reflected field is given by

\[ A(Fd) = \int R(Fd, \xi) \phi(\xi) \exp(-i\xi x) d\xi, \]  

where \( R(Fd, \xi) \) is the reflection coefficient from a composite plate, \( \phi(\xi) \) is the spectrum of the incident beam expressed as a Fourier transform of the spatial beam profile, \( \xi \) is the projection of the incident wavevector onto the plate surface, and the last term is a phase factor. The integral is carried over all \( \xi \), or equivalently over angle, and centered on the incident angle. By evaluating the expression in Eq. (1) at many values of \( Fd \), we have constructed the dashed curve of the prediction in Fig. 2. We note the very good agreement between the occurrence of minima in these two curves, where the only scaling involves the height of one of the central peaks. In particular, the line shape of the theory curve follows the experiment closely, especially between 3 and 6 MHz. At higher frequency the amplitude of the measured curves is somewhat lower than the prediction, probably because the model does not include absorptive losses.

Figure 2. Plate wave spectra for graphite/epoxy at 12°. Solid curve is theory; dashed curve is experiment.
RESULTS AND DISCUSSION

The choice of graphite/epoxy as a model composite system has been conditioned by the experimental accessibility of the range of interesting plate wave dispersion behavior and the unusually high degree of elastic anisotropy typical of these materials. Figure 3 presents the results of many measurements on a plate of unidirectional graphite/epoxy, where the plate wave vector is oriented parallel to the fiber direction. The plate thickness is 0.92 mm, and the average fiber diameter is 5 micron with a fiber volume fraction of 0.65. The data are plotted as discrete points in Fig. 3, while the results of the model calculation are shown as solid curves. In this presentation of the data we have implicitly assumed that the plate phase velocity is given by the quotient of the fluid wavespeed over the sine of the incident angle. We observe good agreement between the data and theory in all regimes of leaky plate wave propagation studied (see further graphite/epoxy data in [10]).

The behavior at higher phase velocity is, in general, very similar to that predicted for Lamb waves in anisotropic plates, except in the vicinity of the Rayleigh wavespeed near $F_d=2$ for the two fundamental modes. Here, as detailed in Fig. 3, the inferred dispersion deviates appreciably from the Lamb wave case. The data curve changes slope abruptly at an implied phase velocity of about 2.5 km/sec and proceeds continuously toward the ordinate below that point. The numerical prediction, deduced by examining the behavior of the reflection coefficient, models this curve quite accurately. An investigation of the solutions of the characteristic equation derived from our theoretical analysis suggests that the pole of the reflection coefficient lies at a value different from the reflection minimum in this anomalous region. A similar theoretical observation concerning the behavior of poles and zeros of the reflection coefficient in isotropic plates was made by Pitts, et al. [13]. Much earlier Schoch [14] had also considered the question of total sound transmission through a fluid-coupled isotropic...
The theory curve of Fig. 3 has been constructed by searching the reflection coefficient as a function of incident angle and Fd, taken as real variables, for those points where $R(Fd, \xi)$ undergoes rapid phase reversals indicative of singular behavior in the reflection coefficient and, by inference, of the generation of guided waves in the plate. These calculated curves also correspond to the occurrence of total transmission (i.e., zero reflection), with one exception. The branch leaving the main curve discontinuously to the right with a small slope becomes equivalent to a surface wave at large Fd and instead yields an asymptotically decreasing value of sound transmission, as anticipated for leaky Rayleigh wave generation on a fluid-coupled half-space. In the upper right corner of Fig. 3 the first antisymmetric higher order mode is just visible.

The source of this unexpected variation of phase velocity with frequency is seen in Fig. 4. A family of theoretical curves is plotted here, each calculated for a different value of fluid density from 1.0 to essentially zero. As the density of the fluid approaches zero, the dispersion typical of Lamb waves in vacuum is recovered. A similar anomaly occurs when the plate wave phase velocity is near the longitudinal wavespeed. A representation of that behavior calculated for graphite/epoxy is shown in Fig. 5. Here also, the predictions have been plotted for decreasing fluid density to indicate the strong influence of the fluid in this region. Only the antisymmetric branches survive in this vicinity, as we have observed experimentally in glass epoxy composites [9]. Such an interpretation could be inferred from the work of Schoch [14].

As an additional aid to the understanding of this complicated phenomena, we have calculated particle displacements from our exact mechanical model for an anisotropic composite plate in a fluid. In particular, we have examined the character of the displacements at
Figure 5. Dispersion as a function of fluid density near longitudinal wavespeed.

several points in the anomalous region. Figure 6 displays the particle displacements versus coordinate through the plate thickness parallel to the wavevector, labeled $u$, and normal to both the wavevector and the plate surface, labeled $w$. The values of the phase velocity and $F_d$ are given on each plot. In Fig. 6(a) the behavior closely resembles a fundamental symmetric mode in the plate. An indeterminate aspect of the phenomenon is seen in Fig. 6(b) for the displacements calculated at the junction point of the two curves. However, for large values of $F_d$, the surfacelike branch indeed corresponds to a Rayleigh wave, as shown in Fig. 6(c).

Figure 6(a). Particle displacements as a function of coordinate through the plate thickness. Real part on fundamental symmetric branch.
Figure 6(b). Particle displacements as a function of coordinate. Real part at junction between flexural and surface branches.

Figure 6(c). Particle displacements as a function of coordinate. Magnitude on surface branch.
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REFERENCES

12. Fiber: $c_{11}=235$, $c_{22}=c_{33}=26.0$, $c_{12}=c_{13}=3.69$, $c_{23}=3.72$, $c_{44}=5.52$, $c_{55}=c_{66}=28.2$ GPa; $\rho=1.79$ g/cm$^3$. Matrix: $c_{11}=c_{22}=c_{33}=7.27$, $c_{12}=c_{13}=c_{23}=3.75$, $c_{44}=c_{55}=c_{66}=1.95$ GPa; $\rho=1.26$ g/cm$^3$, $v_f=0.65$.