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Plate Wave Flow Patterns for Ply Orientation Imaging in Fiber Reinforced Composties*

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Abstract

Fiber orientations in graphite epoxy laminates of various configurations are investigated by imaging flow patterns of leaky guided plate waves. The plate wave flow pattern (PWFP) technique shows that the guided plate waves in laminated fiber reinforced composites tend to travel along the preferred fiber directions, rather than in the direction of impingement, especially for inhomogeneous ply layups. This method utilizes two transducers, a transmitter and receiver in a pitch-catch mode, fixed at the same oblique angle. The flow patterns for multi-ply laminates were mapped, and a global view of the ply directions was obtained. A frequency analysis of the ensuing signal showed that selective imaging of the fiber orientations in a multi-layered composite is feasible.
Keywords: aerospace, composite material, fiber reinforced composites, imaging, nondestructive examination, ultrasonic testing.

INTRODUCTION

The overall properties of a laminated composite structure depend on the fiber directions and their stacking sequence. This study focuses on a technique by which the fiber directions can be extracted. Since the layup of a composite part is still an extremely labor-intensive process, there is a high probability of ply misorientation. Even with the automation of the process, fiber misalignment can occur. This is due to the thermal stresses encountered during manufacture and also to complexly shaped structures. Fiber waviness is another fabrication anomaly which must be imaged and characterized to ensure structural reliability Incorrect stacking sequence is another likely possibility A part's desired strength can be considerably decreased with just a small variation in the ply orientation. For instance, with a variation of 10 degrees, the stiffness of a composite laminate can be reduced by 30 percent (Tsai, 1980). With an incorrect stacking sequence, a critical part's designed load carrying capability can be severely altered. As a quality assurance procedure, it would be of great value to verify the fiber directions and stacking sequence in order to evaluate the overall properties of a composite structure.

In this paper, a new imaging technique based on guided plate waves is discussed. The plate wave flow pattern technique utilizes two transducers fixed at the same oblique angle with the first being the transmitter and the second the receiver. This technique, which takes advantage of the flow patterns of leaky plate waves along fiber directions, is based on the fact that guided plate waves tend to travel along the preferred fiber directions, rather than the direction of impingement, even in multi-ply fiber reinforced composites (Sullivan, 1993). Also, due to the multi-mode nature of plate waves, several modes can be simultaneously or selectively generated and, by using a mode-by-mode analysis, it is possible to locate the depth of different ply groups.

Backscatter was successfully applied to map fiber directions, ply gaps, and fiber misalignments by using a polar C-scan system (Bar-Cohen and Crane, 1982; Johnston et al., 1994). Without scanning, the fiber directions can be locally determined by simply rotating the laminate using the backscatter technique. For laminates having many fiber directions, this can become extremely time consuming. Although this technique is a useful tool, a correlation between the layup sequence and the backscatter data has not yet been satisfactorily established. Also, use of polar backscattering to image the fibers has encountered some problems in inhomogeneous plates (Sullivan, 1993). An optical technique has been illustrated which utilizes optical backscatter from the fibers using a probe which is inserted into a hole drilled through the composite (Buijsen et al., 1993). Even though this is a reliable method for ensuring correct lay-up sequence, this technique is extremely localized (will not be useful to evaluate fiber waviness or regions of fiber misorientation) and requires drilling a hole, which is not always feasible in realistic structures. A normal incidence contact technique to determine fiber orientations using shear waves has also been investigated (Komsky 1992).

The theory of plate waves is well established and verified by experimental methods. General theories of plate wave (Lamb wave mode) propagation in multi-layered composite laminates to analyze leaky plate wave behavior have been published (Mal, 1988; Nayfeh and Chimenti, 1989). Because of the complex interaction of the wave field, leaky plate waves were not commonly used in the past. With the progress in the understanding of plate wave theory, these waves are recently finding applications for detecting delaminations, porosity, and other discontinuities in composites (Bar-Cohen, 1987). By developing models which predict wave characteristics, and substantiating the results with experimental measurements, considerable efforts have been made to interpret the behavior of leaky plate waves in anisotropic media (Bar-Cohen and Mal, 1990). Even so, very little work in the imaging and study of plate wave flow patterns has been accomplished for anisotropic and multi-layered composite materials.

BACKGROUND ON PLATE WAVES

In order to choose suitable parameters for generating plate waves (often called Lamb waves), the concept of dispersion must be understood. In plate waves, the variation of the phase velocity with the frequency is known as geometric dispersion. Geometric dispersion is a function of the frequency multiplied by the thickness ('fd') value, whereas anisotropic dispersion is dependent on the orientation of the ultrasonic wave front relative to the material symmetry In Figure 1, the relationship between the 'fd' value and the phase velocity is shown for plate waves in an aluminum plate in air, and is known as dispersion curves (Pilarski and Rose, 1988).

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As previously stated, plate waves are commonly used in evaluating “thin structures. A quick look at the dispersion curves shows that modes with finite phase velocities exist at any frequency. From Equation 1, it is noted that for the appropriate frequency, the wavelength can be made as large or as small as necessary, and still generate Lamb waves. This implies that modes of any frequency can be propagated in a layer of any thickness and hence the ratio of thickness to wavelength or its reciprocal can be made any value whatsoever.

$$\lambda = \frac{v_p}{f'} \tag{1}$$

Since Lamb waves are essentially an interference phenomenon of upward and downward propagating bulk waves, the duration of the incident pulse (which is used to generate the Lamb waves) must be long enough to allow interference between the reflections from both the bottom and the top of the layer. For larger frequencies and smaller wavelengths, more cycles will be needed.

In plate waves, because of dispersion, the phase velocity can no longer be regarded to be the same as the group velocity. The phase velocity is the rate at which a point of constant phase moves along the direction of the wave vector of the plate wave. The group velocity is defined for both a packet of waves of similar frequency and also for waves of a single frequency as well. The group velocity can be defined by the following relation.

$$v_g = \frac{d\omega}{dk} \tag{2}$$

where ω = angular frequency ($2\pi f$) and k = wave number.

The group velocity, so defined, can be shown to equal the more physical quantity known as the energy velocity (Auld, 1990). Several useful relations between phase and group velocity can be found (Achenbach, 1990). A differentiation of the phase velocity with respect to frequency can be obtained from the following relationship.

$$v_g = \frac{v_p^2}{v_p - f\frac{dv_p}{df}} \tag{3}$$

where v_g = group velocity, v_p = phase velocity, and f = frequency.

Dispersion curves are generated to view the possible modes which arise for a particular material at various ‘fd’ values. For a plate immersed in water at a particular value of ‘fd,’ a value of phase velocity is selected. The angle which generates this particular plate wave mode can then be found by satisfying Equation 4. Using 1,480 m/s (4,855 ft/s) for v_w (the sound velocity in water), and the selected phase velocity (v_p), θ_i can be calculated.

$$\frac{v_p}{v_p} = \frac{\sin 90°}{\sin \theta_i} \tag{4}$$

For a particular point on the dispersion curve, the particle displacements in the x and z direction can be plotted. This graph is useful for discerning the depth information in a layered specimen. Figure 2 is a model of a laminate which consists of three layers. Each mode in the sample dispersion curve shown in Figure 2 is either symmetrical or asymmetrical. In the symmetrical mode, the x displacement curve shows that the received ultrasonic plate wave signal is more influenced by the outer layers, when compared to the inner layer. The asymmetrical mode shows that the signal carries more information about the inner layer. Hence, by selectively generating the appropriate plate wave modes, selective imaging of the material state of an individual ply or ply group is potentially feasible.

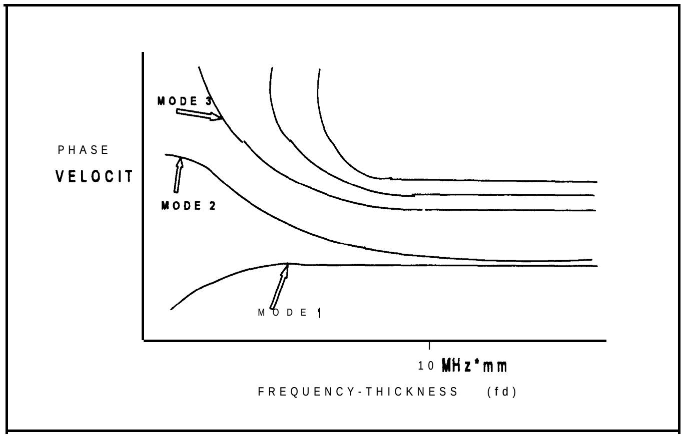

Figure 1 — Sample dispersion curve showing possible plate wave modes.

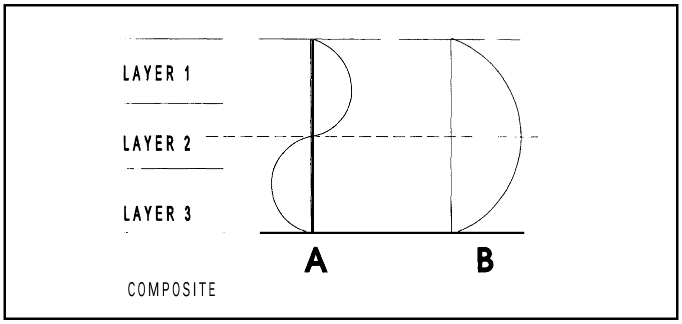

Figure 2 Types of plate wave modes: (a) symmetrical and (b) asymmetrical.

Fabrication of Composite Specimen

Fiberite HYe 1034C prepreg unidirectional tape was used in the fabrication of all test specimens. Table 1 shows the specimens used in the study and the dimensions of each laminate. During the layup, the laminates were vacuum bagged after every ten plies to relieve entrapped air. For the final bag, an aluminum pressure plate of 5 mm (0.2 in.) thickness was placed on the laminates to obtain a polished surface to alleviate scatter caused by surface roughness. During the cure cycle, the laminates underwent maximum pressure and temperature of 586 kPa (85 lb/in.^{2}) and 176 °C (350 °F) respectively A vacuum environment was maintained throughout the cure cycle to eliminate porosity in the resin. After cure, the laminates were cut in 75 by 230 mm (3 by 9 in.) sections with a diamond tip grinder blade. All laminates were weighed and measured, and the thickness of each test piece was gaged at nine different locations and averaged. As listed in Table 1, with the exception of laminates J, G, and I, the laminates consisted of 20 plies, and consistent values for densities were experimentally obtained for all the laminates.

The Plate Wave Flow Pattern Technique

Plate wave modes were generated to image the flow patterns of ultrasonic waves in multiple laminates of various fiber directions. In this technique, one transducer transmits the ultrasonic wave into the specimen, while the receiving transducer captures the leaky plate waves which emanate from the top surface of the laminate (Figure 3). Figure 4 shows the schematic representation for this technique. The transmitter is fixed such that the transmitting probe insonified the test piece at one end, while the receiving transducer scanned the laminate. Both transducers were maintained at the same height from the laminates, and the same angle of incidence was used for both transducers.

A trial and error procedure was used to determine the best incidence angle for generating plate waves. The idea was to use a wide range of angles and a broad range of frequencies in order to generate a set of plate wave modes in any layered specimen. Therefore, the same setup could be employed for any laminate fabricated for

Table 1 Physical characteristics of laminates

Group	Laminate	L (mm)	W (mm)	t (mm)	Wt (kg)	Density 10^{6}*kg/mm^3
I	J $\{0_{40}\}_T$	191.5	75.4	5.72	0.128	1.55
	B $\{0_5/90_5\}_S$	200.0	75.0	2.90	0.066	1.52
	C $\{135_5/45_5\}_S$	200.5	75.0	2.85	0.067	1.56
	D $\{60_5/150_5\}_S$	201.0	74.5	2.90	0.067	1.54
	E $\{20_5/110_5\}_S$	200.7	74.7	2.88	0.067	1.55
	H $\{0_4/90_4/135/45\}_S$	201.0	75.0	3.00	0.066	1.46
II	F $\{0_2/45_4/135_4\}_S$	200.8	74.5	2.76	0.066	1.60
	G $\{0/135/45\}_S$	200.5	74.5	0.84	0.020	1.59
	I $\{0_{10}\}_T$	144.0	74.5	1.50	0.024	1.50

this study The criteria used was to be able to generate plate wave modes which can travel at least 152.4 mm (6 in.). Using the setup shown in Figure 4, the distance between the probes was fixed at 152.4 mm (6 in.). At all times, the same angle of incidence was used for both the transmitter and the receiver. As the angle of incidence was varied, the amplitude of the received signal was observed. At the small angle of incidence of 10 degrees, an acceptable signal was obtained by the receiving probe and hence was selected for all of the experiments.

The optimum range of the frequency thickness product (‘fd’ < 10 MHz*mm) was kept in mind to generate plate waves. A 5 MHz transducer with a focal length of 50.8 mm (2 in.) was used in the initial studies. A thin, transversely isotropic laminate fabricated from 121 °C (250 °F) graphite epoxy prepreg was used for the determination of the incidence angle. This laminate’s ply pattern, $\{0_8\}_T$, resulted in an average thickness of 1 mm (0.04 in.). The thickness of 1 mm and the frequency of 5 MHz resulted in an ‘fd’ value of 5 MHz*mm.

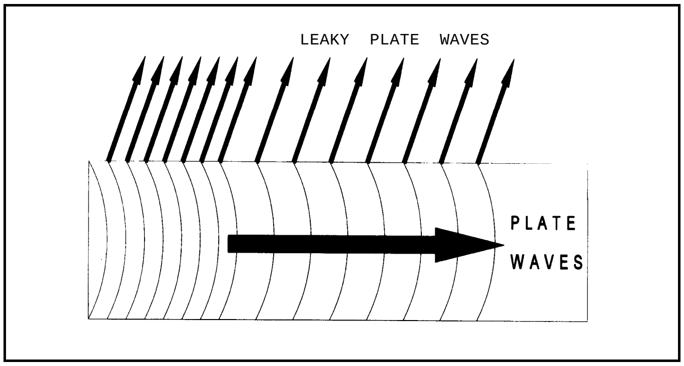

Figure 3 — Schematic representation of plate wave generation and leakage to the substrate media.

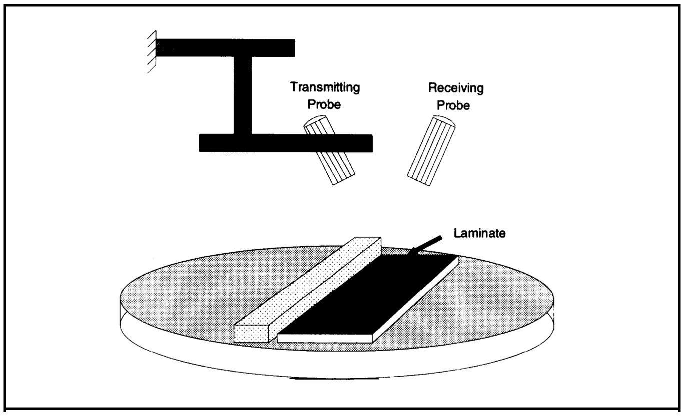

Figure 4 Setup for plate wave flow pattern method.

The incident angle of 10 degrees was used for generating plate waves, and the ultrasonic wave modes traveling along the various preferred fiber directions were detected by the receiver and imaged in grey scale based on peak amplitude. The lighter colors indicate high values of peak amplitude, while the dark regions represent the low received amplitudes (an absence of wave mode). The laminate described above was used for the initial testing for generating plate waves. This specimen was scanned with the fiber direction at 0 degrees, 90 degrees, and 60 degrees, with respect to the trajectory of the transmitter’s sound beam. Figure 5a shows the received signal amplitude when the laminate’s fiber direction is perpendicular to the transmitter. As can be seen, the peak amplitude is concentrated close to the transmitter. Figure 5b shows the scan with the fiber orientation along the transmitted beam. This scan shows that the signal is traveling along the fibers. When the test piece is turned 60 degrees to the transmitter (T), Figure 5c is obtained. This portion of the experiment established the fact that the incident angle of 10 degrees was generating plate waves, and that the sound beam was propagating along the preferred fiber direction. The reason this is not apparent in Figure 5a, where the laminate’s fiber direction is perpendicular to the transmitted sound beam, is that it was physically impossible for the receiver to scan the area immediately under the transmitter. Therefore, the fibers along which the signal was propagating could not be traversed. The question now was, “Could this technique be used to discern the fiber orientations of a multi-directional laminate?”

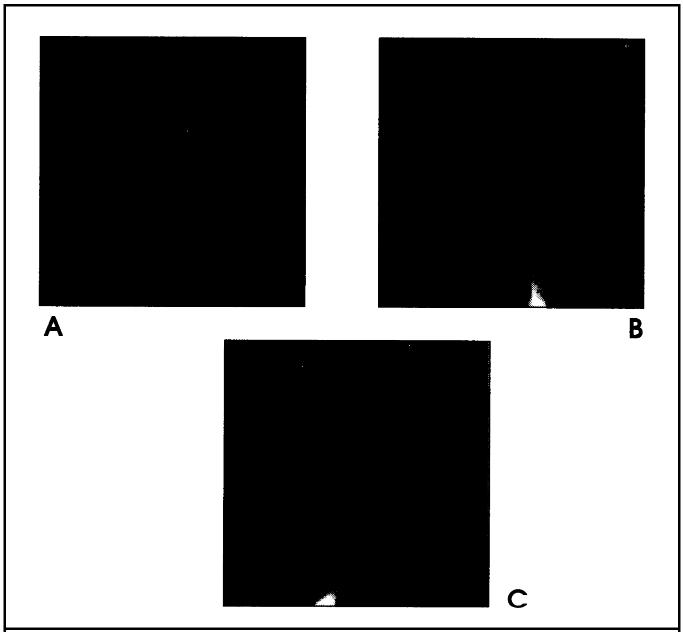

Figure 5 -Thin laminate plate wave flow pattern results using a 5 MHz broad banded transducer. (a) Fiber direction at 0 degrees to transmitter, (b) at 90 degrees to transmitter, (c) at 60 degrees to transmitter.

The experiment above was repeated for the thicker specimen set listed in Table 1. A lower frequency of 1 MHz. was used in order to maintain the frequency*thickness product in the plate wave regime. Typical results are shown in Figures 6a–f. The first two images are the plate wave flow pattern for the unidirectional specimen $J(\{0_{40}\}_T)$ along and across the fiber direction. It is clearly seen that the waves propagate long distances along the fibers (Figure 6a) when compared with Figure 6b (90 degrees to fiber direction). Also, the beam spreading is more noticeable when plate waves propagate across the fiber. When this method is used on cross-ply specimens B (Figure 6c) and C (Figure 6d), the late wave flow patterns are observed along the outer, as well as the inner plies. These figures clearly demonstrate that the coupling between the inner and outer plies do not significantly affect the flow patterns even when more than one ply orientation exists in a laminated structure. The energy propagates along all fibers directions even in cases of specimens with fibers in many directions (Figures 6e, 6f, 6g). Table 2 and Table 3 summarize the results obtained from these scans.

FREQUENCY ANALYSIS OF PLATE WAVE FLOW PATTERNS

Since the fiber directions of the laminates were being successfully mapped, it was decided to investigate the possibility of studying the response to different frequencies. A frequency analysis was conducted based on the principle that there are several modes which are simultaneously generated, and each mode has a unique displacement and stress profile across the thickness of the laminate. Hence, if individual modes are isolated, especially ones which have concentrated displacement/stress values across specific ply groups, and knowing the mode shape of the displacement/stress, individual ply groups can be located. In this paper, the results obtained from specimen C using a 1 MHz frequency broadband transducer will be presented. Figure 7a shows a typical signal from a single point in laminate C; the frequency spectrum of this signal is shown in Figure 7b. From this figure, the frequency bandwidth of the transmitted signal was determined to be from 0.7 MHz to 1.35 MHz. Therefore, small increments in this frequency range were selected and the energy in the frequency band was extracted and mapped as shown in Figure 8. The mapping of the peak amplitude

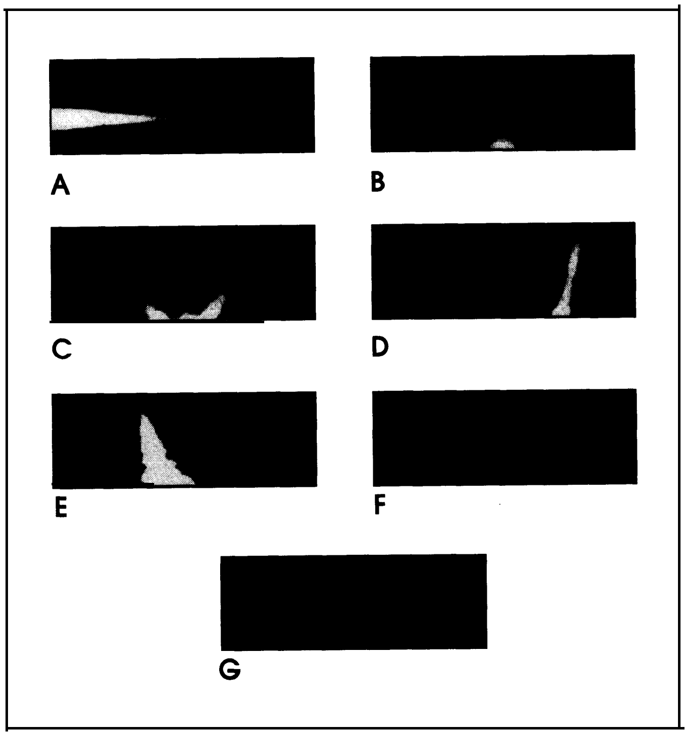

Figure 6 —Plate wave flow patterns for (a) specimen J along 0 degrees, (b) J at 90 degrees, (c) specimen C, (d) specimen D, (e) specimen E, (f) specimen F, and (g) specimen H.

Table 2 Results of plate wave flow pattern testing for laminates J, B, C, D, & E

Specimen	Orientation	Observations
$J\{0_{40}\}_T$	90”	Signal concentrated close to the transmitter.
	0	Clear signal received along the fibers to the end of the laminate.
$B\{0_5/90_5\}_S$	90”	Received signal from the 90” fibers located in the center of the laminate.
	0”	Main signal received from the 0” fibers along the length of the laminate.
c $\{45_5/\text{-}45_5\}_S$	90”	Signal definitely propagates along both the +45 and -45 directions. Comparison of actual data showed that the stronger signal is received from the inner layers.
	0"	Signal is concentrated around the transmitter. Some fiber direction is apparent. Since the width of the test piece (75 mm) is not large enough, fiber direction is not clearly seen.
D $\{60_5/150_5\}_S$	90”	Both fiber directions apparent; the dominant signal is received from the upper 60” plies.
	0"	Although both fiber directions are seen, the strong signal shown is received from the inner layers. Since the width of the laminate constrained the signal, nothing can be said about the strength of the signal from the outer layer.
E $\{20_5/110_5\}_S$	90”	Strongest signal captured from center plies. The top fibers are also observed.
	0"	Top fiber direction is clearly seen; center plies are too short in this configuration to be mapped.

Table 3 Results of plate wave flow pattern testing for laminates F, G, & H

Specimen	Orientation	Observations
$F\{0_2/45_4/135_4\}_S$	90”	All three fiber directions are observed. The stronger signal on the RHS of this figure is received from the fibers in the +45 direction.
	0°*	Some fiber directions seen. On the RHS of this figure, the observed fiber directions are from the 135” plies.
$G\{0/135/45\}_S$	90”	Broad signal; more influence seen from the 135° plies.
	0°*	Signal is received over the entire length of the specimen. The +45 plies are seen better than their counterpart.
H $\{0_4/90_4/45/\text{-}45\}_S$	90”	Top fiber direction seen clearly.
	0°*	Very broad signal; top fiber direction predominant. Other fiber directions are not clear.

* Laminate positioned 0” to the transmitter implies that the length of the beam is along the length of the specimen.

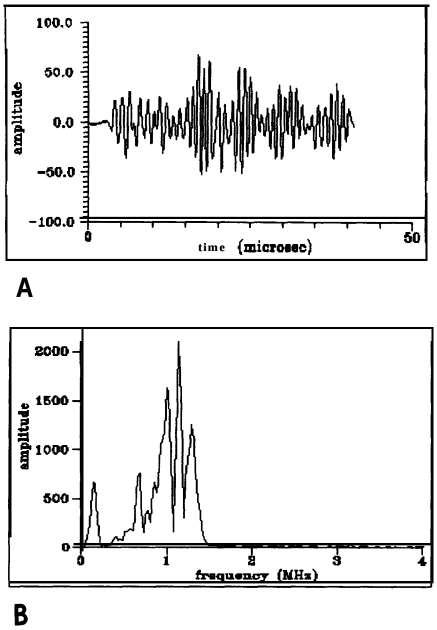

Figure 7 — (a) Typical waveform in main signal in laminate C at coordinate (30,30); (b) typical power spectrum from laminate C.

and the peak frequency is shown in Figure 8a and Figure 8b, respectively There is no additional information obtained from Figure 8c. The energy in the frequency band of 0.81–1.0 MHz, shown in Figure 8d, is similar to the image obtained of the peak amplitude scan (Figure 8a). This was expected since the resonant frequency of the transducer is 1 MHz. The most interesting results are seen in Figure 8e and Figure 8f. In the former, it is observed that this mode is clearly more sensitive to the outer layer (135 degrees fiber direction), rather than the inner layers. In Figure 8f, the next higher mode shows dominance of the signal from the inner plies. Depending on the frequency band, information specific to ply groups from various depths was obtained. This portion of the study established that selective imaging of individual ply orientations using narrowband frequency analysis is possible, and depending on the desired depth, appropriate plate wave modes can be generated.

DISCUSSION AND CONCLUSIONS

For the plate wave flow pattern technique, it was found that the waves travel along preferred fiber directions. It is known that in anisotropic media, such as fiber reinforced composites, there is not a single set of dispersion curves; rather, the dispersion curves are a function of propagation direction. Therefore, when comparing the "flow patterns" for incidence in different angles with respect to fiber directions, it is possible that different modes are being generated. This may also contribute to some of the observations such as the small propagation length when propagating across the fibers.

The plate wave flow pattern technique is successful in mapping the fiber directions of a multi-ply laminate. A frequency based analysis method was developed to analyze the experimental plate wave flow pattern data. Using the frequency filtering method, it was shown that the potential for a ply-by-ply fiber orientation analysis exists, if suitable parameters are selected. Further theoretical background based on plate wave generation and propagation of plate waves in inhomogeneous plates must be developed and correlated with experimental data. Once this is accomplished, a heuristic algorithm can be developed for a reliable method for ply orientation imaging.

This technique can be used either as a local method, as has been demonstrated in this paper, or as a global scanning technique where the ultrasonic plate wave generator and the receiver are fixed at specific azimuthal angles and a x–y raster scan can be designed to image fiber waviness of a specific ply group in a multilayered structure. However, for the single point local technique, more than one fiber direction is determined from a single evaluation scan. By using a highly focused probe, a range of angles can be determined, and by using a broadband transducer, a range of frequencies can be obtained. Therefore, a variety of layups can be evaluated using the same setup. This is the main advantage of this technique over several other methods such as the polar technique. Also, more thorough analysis of the obtained signal is possible because of the already established theoretical basis of plate waves.

While developing the raster scanning methods, optimal parameters such as angle of incidence, separation distance between the transducers, etc., can be obtained to image fiber waviness, and local fiber n&orientation. Attention must also be given to the frequency of the transducers and the thickness of the material under test. Calculation and determination of phase velocities and incident angles must be made. The plate wave flow pattern technique needs to be evaluated as a nondestructive tool for determination of other characteristics and defects which are unique in composites. Porosity, delaminations, voids, and improper cure are just a few of the defects which can be investigated. This research examined laminates fabricated from unidirectional tape. The same technique can be implemented to resolve the fiber directions for hybrid laminates and also for laminates composed of bidirectional fabric material.

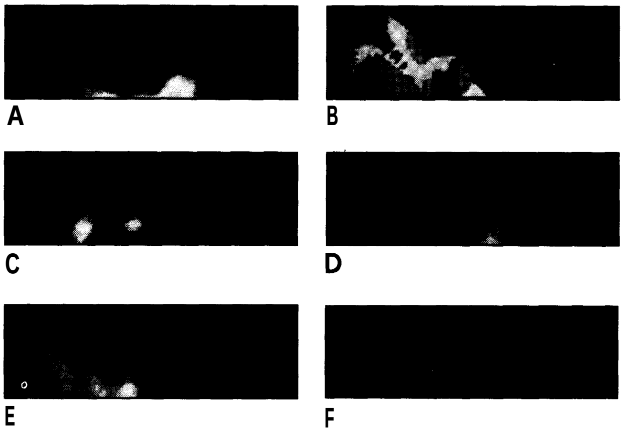

Figure 8 -Laminate C frequency imaging. (a) Peak amplitude, (b) peak frequency, (c) f = 0.7–0.8 MHz, (d) f = 0.81-1.0 MHz, (e) f = 1.1-1.2 MHz, (f) f = 1.21-1.35 MHz.

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