ANALYSIS OF DETECTION OF DELAMINATIONS IN FIBER REINFORCED COMPOSITE TUBES USING AXIALLY SYMMETRIC GUIDED WAVES

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INTRODUCTION

The current and proposed use of fiber reinforced composite tubes in a number of aerospace structural applications is well established. The most serious hindrance to acceptance of composites, in general, is the need to certify non-destructively the integrity of the material [1]. The modes of damage in a composite are varied and complex. Delaminations are particularly important, representing an advanced state of damage in the material [2,3].

The conventional method of inspection for delaminations is immersion C-scan type imaging [4]. As applied to tubes, the interrogating waves would propagate through the wall thickness along the radial direction and the mode of inspection is pulse-echo. This type of inspection has several inherent problems and limitations. These include noise resulting from scattering of the interrogating waves with internal structure (i.e. fibers, porosity and "good" laminations) stemming from the requirement that high frequency waves be used for thin walled specimens, relatively long scanning times, and the unsuitability of immersion testing for many applications [4,5]. An additional artifact of this propagation direction, is the insensitivity of such waves to the longitudinal modulus in the axial direction. Degradation in this modulus has been linked with a variety of composite damage states, particularly those resulting from fatigue [6].

In the method introduced here, the propagation characteristics of axially symmetric longitudinal guided waves are proposed for use in evaluating the material. Because of the propagation direction, lower frequency ultrasound can be utilized, avoiding unwanted interaction with the internal structure. In addition, as the method is experimentally developed it should be possible to achieve much faster scanning rates because of a larger effective tube volume each sample within the scan can potentially evaluate. Furthermore,

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the testing configuration will permit simultaneous monitoring of material properties, including axial longitudinal modulus, through measurement of the dispersion of the guided waves.

PHYSICAL PROBLEM DESCRIPTION AND MODELING

The physical problem being modeled is axially symmetric pulse propagation in a fiber reinforced laminated tube containing an idealized delamination, due to butt or smooth contact with a P-wave ultrasonic transducer given a burst type excitation. The source of the pulse, therefore, is a uniformly distributed time varying pressure (σ_{zz}) acting on the end surface of the tube being modeled. Since the contact is seen as smooth, shear stresses $\sigma_{\theta z}$ and σ_{rz} are taken as zero on this surface. The contact of the transducer and tube and the resulting imposed boundary conditions are depicted in Figure 1. The pulse propagates through a section of "undamaged" tube (20 cm. in all the examples considered here) before encountering the leading edge of an idealized delamination. The delamination is idealized as axisymmetric or circular (extending around entire tube circumference) and semi-infinite in the axial direction. The delaminated section of tube is treated as two independent waveguides, each with stress free inner and outer walls, which implies that normal stresses acting at the delamination surfaces (radial direction normal) are neglected and no shear stresses are transmitted. At the interface between the undamaged and delaminated tube sections (surface normal in the axial direction), continuity of stress and displacement is enforced. The geometry and boundary conditions pertinent to the delamination modeling are summarized in Figure 1. The receiver, which measures outer surface displacement in the radial direction and is taken to be a point receiver, is shown schematically as an arrow in Figure 1.

Despite the idealized nature of the delamination, it is believed that the results of this modeling will be applicable to non-circular delaminations, particularly when the circumferential length of the delamination is greater than the axial length. In addition, results are applicable to finite delaminations provided that backscatter from the trailing edge of a finite delamination is negligible and reflections from the tube end can be suppressed. The neglect of normal stress at the delamination surface is a good approximation, particularly for thin walled tubes. Perhaps the most troubling aspect of the idealized delamination assumptions is that the leading edge of the delamination lies completely in the plane of tube cross section with axial normal direction. Experimental testing will be required to examine the effect of delamination orientation on propagation behavior and the error associated with the assumptions of the model.

Graphite epoxy tubes with ply lay-ups (stacked from inner wall to outer wall) of $[15,-15]_a^4$ and $[(15,-15)_a^4,90]$ were considered in this investigation, where the a subscript indicates anti-symmetric ply stacking with respect to the tube mid-surface. The lamina were all of equal thickness, the total thickness of each tube was 1.27 mm (50 mil), and the thickness to wall midplane radius ratio was 1/10. Material properties used were E_{LL}=137.9 GPa, E_{TT}=6.9 GPa, G_{LT}=4.1 GPa, G_{TT}=3.4 GPa, ν_{LT}=0.25 and ρ=1671 kg/m^3, where L refers to the fiber direction and T is transverse. The delamination in all cases begins at z=20 cm. (transducer/tube interface is at z=0). A "near surface" delamination between lamina 6 and 7 (from the inside of the tube), and a "buried" delamination between lamina 3 and 4 were considered for each tube.

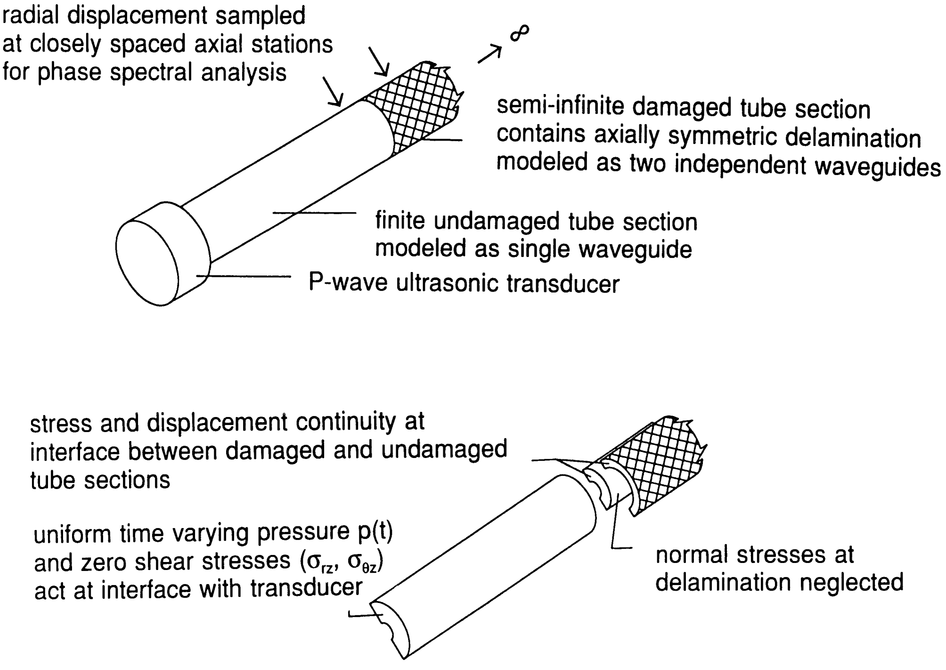


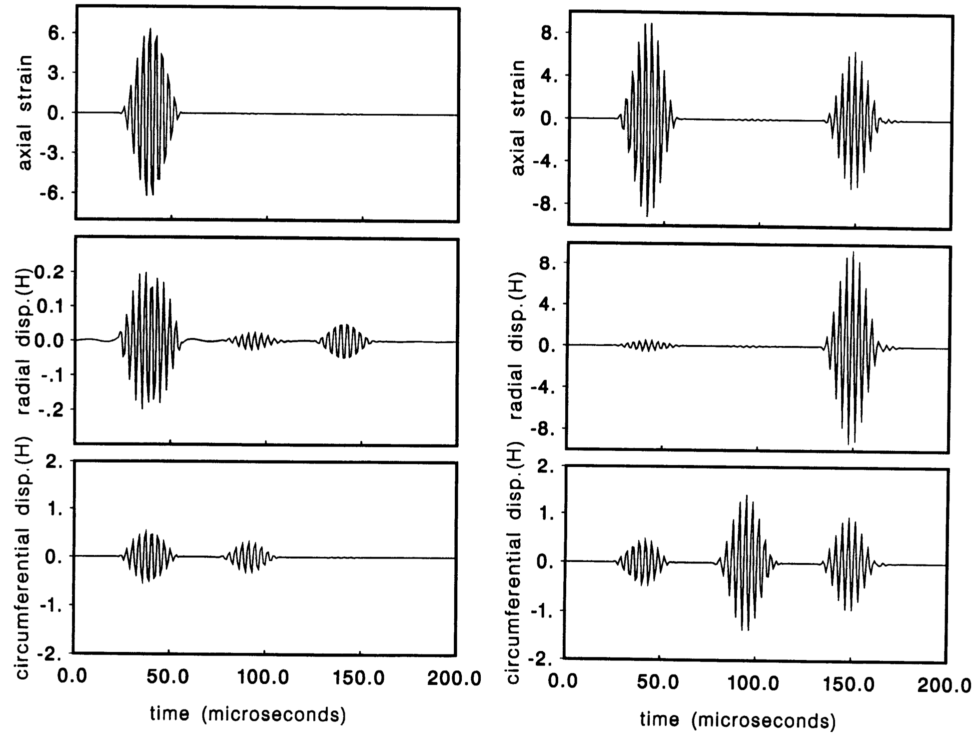
Figure 1. Geometry and boundary conditions of pulse propagation model for composite tubes with idealized delamination. Tube section with cross-hatching on outer surface contains delamination.

The pulse propagation is modeled using an analytical method which is far too lengthy to give here. However, the combined finite element and wave propagation method follows much of the treatment given by Kohl, Datta and Shah [7]. Details of the particular equations extending this work, which treats pulse propagation in composite tubes without delaminations, to the problem being addressed herein is forthcoming [8].

RESULTS

The analytical model was used to predict the three dimensional dynamic response at specified axial stations, given a pressure pulse excitation in the form of a 10 cycle, 300 kHz, Hanning window modified toneburst. For the example tubes considered, 300 kHz is above the cut-off frequency of the 2nd quasi-longitudinal mode, and the excitation is sufficiently narrow banded so that little dispersion is present [7]. Figure 2a illustrates the general features of the response. All three propagating modes which occur at 300 kHz for these tubes are excited to varying extent, as may be discerned by inspection of the radial displacement (Fig. 2a). The first wave packet is due to the primarily axial quasi-longitudinal (axial q-l) mode, the second to the quasi-torsional (q-t) mode, and the third to the primarily radial quasi-longitudinal (radial q-l) mode. Referring to the radial displacement response, there exists some pulse distortion in the first arriving axial q-l wave packet. This is due to backscatter, rather than dispersion, as will be discussed later. The effect of the addition of the 90° outer ply on the response is depicted in Figure 2b. The excitation of the radial q-l mode is significantly increased and that of the axial q-l mode is slightly decreased. Phase and group velocities of the modes are also affected. The axial station in Figures 2a and 2b is prior to the beginning of the delamination. A short distance past the leading edge of the delamination, there are still three distinct wave packets, however, there is noticeable pulse distortion and change in amplitude for the wave packet associated with the axial q-l mode, as shown in Figure 3. Here, radial displacement response for the same tube as used for Figure 2a, but after propagating through some delamination is shown.

Radial displacement is the easiest ultrasonic field to measure on the outer surface of the tube, and consequently, it was radial displacement that was investigated for use in delamination characterization. Hypothetical measurements of the phase velocities at 300 kHz of the two q-l modes using the predicted waveforms was performed by phase spectral analysis [9]. The wave packets associated with these modes have temporally seperated at axial stations near the delamination as seen in Figures 2a and 2b. Each quasi-longitudinal mode wave packet is windowed in order to isolate the desired mode. Responses sampled at two axial locations are required for application of phase spectral analysis. The method yields the effective single mode phase velocity between the sampling points. This test configuration is shown schematically in Figure 1. The primary interest was the effect upon "measured" velocities of the proportion of delaminated tube section within the tube length between the sampling points. A procedure for quantifying the results of this type of examination was required. It was decided to hold the receiver (sample point with greater axial coordinate) fixed and move the source (sample point with lesser axial coordinate)



(a) (b)

Figure 2. Multi-mode excitation due to smoothed 300 kHz pressure pulse toneburst in (a) $[15,-15]_a^4$ ply GPE tube; (b) $[(15,-15)_a^4,90]$ ply GPE tube. All responses are at z=19.125 cm for tubes with buried delaminations and equivalent pulse excitations.

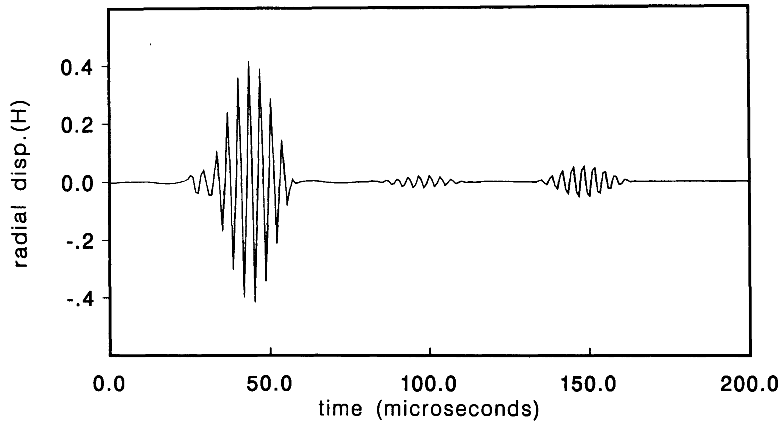


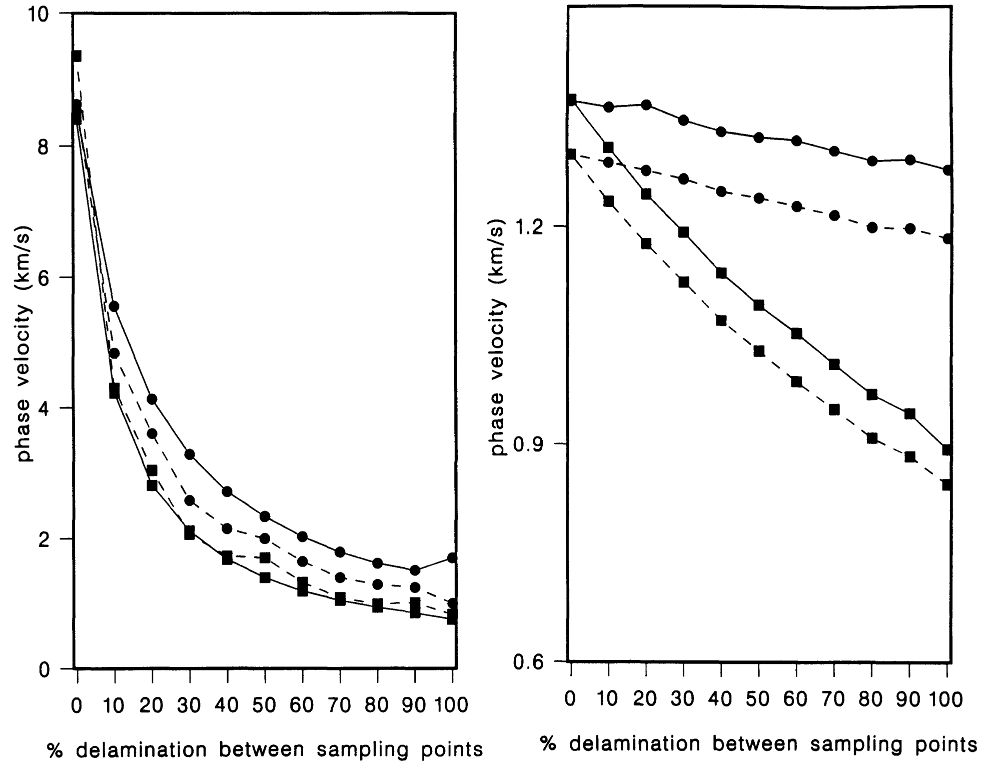
Figure 3. Axial quasi-longitudinal mode wave packet distortion due to mode conversion at delamination. Response at z = 20.375 cm. for $[15,-15]_a^4$ ply GPE tube with buried delamination.

from within the delamination (100 % delamination between sampling points) to various stations with axial coordinates lesser than the beginning of the delamination. These axial coordinates were selected to yield 10% increments in the proportion of "undamaged" tube section to total tube length between the two sampling points. Since detection of relatively small delaminations is of considerable importance, the receiver was fixed at 0.375 cm. from the edge of the delamination. Of course, to obtain a 0% delamination between sampling points, both points had to be moved to outside the delaminated section.

Figures 4a and 4b show the results of the phase spectral analysis for axial q-l and radial q-l modes, respectively. The physical mechanisms by which the measured phase velocities of the axial q-l and radial q-l modes are affected are identical in all four cases (2 ply lay-ups, 2 delamination radial locations) shown in each of these figures. The axial q-l mode shows a marked decrease in measured phase velocity with increasing percentage of delamination, as shown in Figure 4a. This is due to some mode conversion to radial q-l motion when the axial q-l wave is incident on the delaminated tube section. Figure 3 shows the radial displacement at the fixed receiver (z=20.375 cm.) for the same pulse shown in Figure 2. Note how the pulse appears to be lengthening after propagating through .375 cm. of delamination as the mode converted radial q-l mode propagates much more slowly than the axial q-l mode. The .375 cm. length of propagation within the delaminated tube section is not sufficiently long for the two coupled q-l modes propagating at different velocities to seperate completely in time.

The measured phase velocity of the radial q-l mode is not similarly affected by mode conversion with incidence upon the delamination. Comparison of Figure 3 and the radial displacement response of Figure 2a shows little apparent pulse distortion for the radial q-l mode (third wave packet). However, the radial q-l mode phase velocity is affected by the thickness of the waveguide. The decreased effective wall thickness in the delaminated tube section produces a decrease in radial q-l mode phase velocity. As the percentage of delamination in the section between sampling points increases, the effective phase velocity decreases, as shown in Figure 4b.

There exist two complicating factors which may lead to anomolous behavior. First, there exists some influence of non-propagating modes when a station is very close to the delamination edge. In addition, there is some backscatter from the edge of the delamination predicted (propagating in the negative axial direction). Anomaly due to



(a) (b)

Figure 4. Phase velocity by phase spectral analysis for (a) axial q-1 mode; (b) radial q-1 mode. Solid and dashed lines are for $[15,-15]_a^4$ and $[(15,-15)_a^4,90]$ ply lay-up tubes respectively. Circle and square markers are for "buried" delaminations (between lamina 3 and 4) and "near surface" delaminations (between lamina 7 and 8) respectively.

backscatter is worst at axial stations where the backscatter begins to emerge from the tail end of the incident pulse, but has not emerged sufficiently to seperate the incident and backscattered pulses through windowing. Generally, this problem was confined to axial q-l mode measurements, where the incident axial q-l mode converts not only to a forward propagating radial q-l mode, but also to the backscattered radial q-l mode. The appearance of such backscatter is shown in Figure 5. Note that the tail of the pulse at greater axial coordinate has seperated completely from the forward propagating pulse at lesser axial coordinate. Examples of the effect of these anomalies can be most easily discerned in Figure 4a. For instance, the results for the $[15,-15]_a^4$ ply tube with buried delamination indicate that there is an increase in phase velocity of the axial q-l mode with increasing percentages of delamination present. An additional example of such anomolous behavior is the substantially higher phase velocity found for the $[(15,-15)_a^4,90]$ ply tube with near surface delamination for 0% delamination between the sampling points. Clearly, since none of the delamination is contained within the section between sampling points, the phase velocity should be identical to that for a tube with the same ply lay-up and a buried delamination.

As might be expected, near surface delaminations were predicted to be more easily detected than delaminations further from the outer tube surface, as may be seen in examining Figures 4a and 4b. In particular, the greater reduction in effective wall

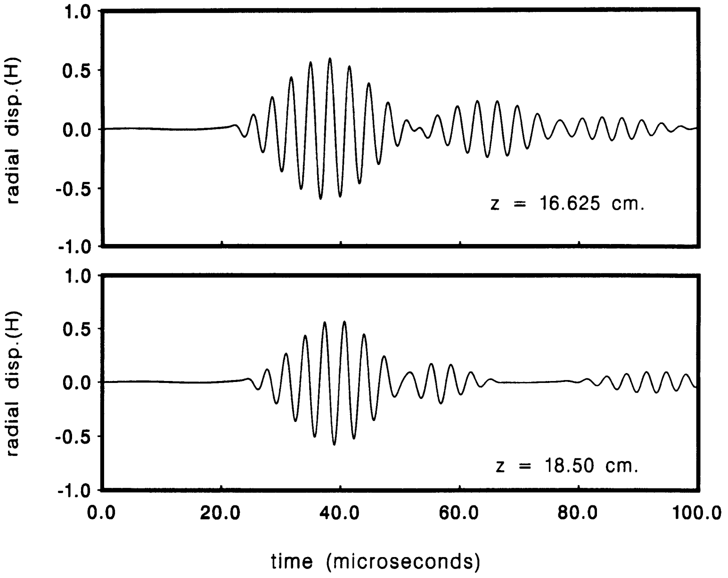


Figure 5. Backscatter from the delamination edge in a [(15,-15)$_a^4$,90] ply tube with buried delamination.

thickness for the delaminated region for the near surface delamination produces greater contrast between radial q-1 mode phase velocities between damaged and undamaged section, thereby improving detection potential using the radial q-1 mode measurements.

As discussed previously, the effect of using a 90° outer ply was to increase coupling of the excitation of axial and radial q-1 modes. The primary benefit of this type of lay-up is expected to be improvement in signal to noise in radial q-1 mode measurement. Hopes that inclusion of this axially soft lamina would otherwise improve inspectability of the sample by increasing contrast in velocities between damaged and undamaged sections proved to be only minimally served. Furthermore, because of the increased coupling between excitation of axial q-1 and radial q-1 modes for the tube with 90° outer ply, the backscatter problem appears to be exacerbated.

CONCLUSION

A method for the analytical investigation of axially symmetric pulse propagation in fiber reinforced composite tubes with delaminations has been demonstrated. This method was used to examine the potential use of axially symmetric guided waves in detecting delaminations by measuring mode phase velocities. Reduction in measured axial mode phase velocity due to radial mode coupling in the delaminated region and the reduced velocity of the radial mode phase velocity due to reduced effective thickness of the delaminated region have been identified as mechanisms for delamination detection.

ACKNOWLEDGMENT

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REFERENCES

1. A.J. Rogovsky, in New Directions in the Non-destructive Evaluation of Advanced Materials, edited by J.L. Rose and A.A. Tseng (ASME, N.Y., 1988) p. 45.
2. D.J. Wilkins, in Characterization, Analysis and Significance of Defects AGARD Conference Proceedings no 355 (1983), paper 20.
3. R.T. Potter, in Characterization, Analysis and Signficance of Defects AGARD Conference Proceedings no 355 (1983), paper 17.
4. P.A. Lloyd, Ultrasonics, Vol. 27 (1989), p. 8.
5. S.C. Wooh and I.M. Daniel, in New Directions in the Non-destructive Evaluation of Advanced Materials, edited by J.L. Rose and A.A. Tseng (ASME, N.Y., 1988) p. 53.
6. E.T. Camponeschi and W.W. Stinchomb, in Composite Materials: testing and design (6th conference), edited by I.M. Daniel (ASTM, Philadelphia, 1982), p. 225.
7. T. Kohl, S.K. Datta and A.H. Shah, AIAA Journal, Vol. 30 (1992), p. 1617.
8. T. Kohl, W.P. Rogers and S.K. Datta, "Axially Symmetric Pulse Propagation in Composite Tubes with Localized Delaminations", to be submitted.
9. W. Sachse and Y.H. Pao, Journal of Applied Physics, Vol. 49 (1978), p. 4320.