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Acousto-Ultrasonic Characterization of Fiber Reinforced Composites

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ABSTRACT

The acousto-ultrasonic technique combines advantageous aspects of acoustic emission and ultrasonic methodologies. Acousto-ultrasonics operates by introducing a repeating series of ultrasonic pulses into a material. The waves introduced simulate the spontaneous stress waves that would arise if the material were put under stress as in the case of acoustic emission measurements. These benign stress waves are detected by an acoustic emission sensor. The physical arrangement of the ultrasonic (input) transducer and acoustic emission (output) sensor is such that the resultant waveform carries an imprint of morphological factors that govern or contribute to material performance. The output waveform is quite complex, but it can be quantitized in terms of a "stress wave factor." The stress wave factor, which can be defined in a number of ways, is essentially a relative measure of the efficiency of energy dissipation in a material. If flaws or other material anomalies exist in the volume being examined, their combined effect will appear in the stress wave factor.

INTRODUCTION

The acousto-ultrasonic approach provides a potential alternative to widely used acoustic emission and ultrasonic techniques for verification of composite integrity and strength as well as degradation due to service conditions. Although conventional pulse-echo ultrasonics readily detects flaws, it is often difficult to correlate a detected flaw to overall performance. Additionally, evaluation of strength loss after use may depend on sensing subtle changes that are distributed throughout the material rather than isolated flaws. Acoustic emission techniques can be used to evaluate the integrity of a material as a whole. The problem with acoustic emission is that the material structure must be put under stress to produce spontaneous emissions from induced flaw growth. It is difficult to predict what such application of stress does to the life of the item being tested especially in the case of composites.

Laboratory studies have uncovered strong correlations between the acousto-ultrasonic stress wave factor and ultimate and interlaminar shear strength in composite laminates. This is in addition to the technique's ability to locate overt defects. Studies are underway to define the full application spectrum of the technique especially relative to measurements of material strength, impact damage, and degradation from thermal and chemical exposure. This report highlights salient aspects of the acousto-ultrasonic technique, the nature of the equipment used, and typical results obtained with composite laminates.

BACKGROUND

Fiber reinforced composite laminates exhibit a variety of failure modes due to their complex, anisotropic nature. The initial stage of failure can be explained in terms of three fundamental modes: tensile, shear, or compressive failure of the matrix; tensile or compressive failure of the fibers; or fiber/matrix interface failure. Subsequent to the occurence of any of these modes, ultimate failure will tend to involve complicated interactions of all three. Governing factors include variations in fiber fraction, microvoid content, matrix material condition, etc. (Ref. 1).

The most widely used nondestructive evaluation (NDE) techniques, i.e., pulse-echo ultrasonics, C-scan ultrasonics, acoustic emission, etc., do not provide a clear correlation between the presence of overt defects and their effects on the failure of fiber reinforced composites. Attempts to relate defects to fracture mechanisms have met with mixed results. When artificial defects are introduced in laboratory specimens, they may exhibit failure modes unrelated to these intentional flaws. Moreover, adverse effects of many naturally-occuring defects cannot be accurately predicted in all cases and their presence may often be ignored (Ref. 2).

Conditions that predispose composite structures to eventual failure can consist of dispersed microstructural irregularities that surround larger, discrete, and readily-detectable flaws. Even when these overt flaws are quite large, as in the case of significant delaminations, the entire integrated defect state should be considered. As illustrated in Fig. 1, a holistic approach combines nondestructive characterization of defects with characterization of material environments in which the defects reside. There is a need for NDE techniques that provide information on how defects, both maroscopic and microscopic, are likely to interact in the material as a whole (Ref. 3). Even in the absence of these types of defects appropriate NDE techniques are still needed to verify that a composite has the strength and endurance properties intended by the designer.

The acousto-ultrasonic approach described herein is aimed at characterization of composite laminates in accordance with the above-mentioned needs. The novel approach described addresses problems peculiar to highly attenuating, anisotropic materials such as fiber reinforced composites. It will be shown that this approach does yield information on the integrated defect condition in such materials. In the cases cited the integrated defect condition is associated with anomalous distributions of microvoids, global variations in fiber/resin ratio, and fiber orientation.

ACOUSTO-ULTRASONIC CONCEPT

The acousto-ultrasonic technique is predicated on the concept that during failure, spontaneously-generated stress waves interact with material morphology and contribute to microcracking and catastrophic crack extension (Refs. 3 and 4). This stress wave interaction is governed by factors such as scattering, dispersion, and reflection due to microstructure and boundary conditions. As indicated in Fig. 2, the same factors modulate ultrasonic signals used in NDE. It is natural to expect that because of their similarity to spontaneous stress waves, artificially introduced ultrasonic waves simulate the way stress waves respond to material conditions. By use of benign ultrasonic interrogation it should be possible to determine a modulation transfer function that describes the behavior of actual stress waves. This would reveal the character and magnitude of stress wave energy transfer during failure processes, at least during initial stages.

The technique described herein affords an indirect but effective means for characterizing the stress wave energy propagation characteristics of composite laminates. The procedure and apparatus are designed to evoke wave interactions that mimic acoustic emission (stress) waves in a material undergoing deformation or experiencing microcracking (Refs. 5 and 6). It will be seen that measurement of these simulated acoustic emission waves correlates strongly with material microstructure and mechanical strength in the case of composite laminates.

Correlations with material properties are obtained by measurement of a "stress wave factor" (Refs. 7 and 8). The stress wave factor may be defined as a measure of the efficiency of stress wave energy transmission. The factor provides a means for rating the efficiency of dynamic strain energy transfer. In unidirectional composite laminates tested thus far (Ref. 9), the stress wave factor is greatest along the fiber direction which is also the direction of maximum strength.

Once microcracking starts in the brittle matrix or fibers, it is to be expected that prompt dissipation of stress wave energy away from crack initiation sites contributes to dynamic integrity and ultimate strength. Regions of small values of the stress wave factor are regions of higher ultrasonic attenuation (Ref. 10). These are also observed to be weaker regions where dynamic strain energy is likely to concentrate and promote further microcracking and failure (Ref. 9).

APPARATUS AND OPERATIONAL FACTORS

Apparatus for making acousto-ultrasonic measurements is shown in Fig. 3 and a block diagram appears in Fig. 4. The acousto-ultrasonic wave is generated by means of a series of broadband ultrasonic pulses. The pulses are introduced into the material of normal incidence by means of an ultrasonic transducer directly coupled to the surface. A fixed distance away an acoustic emission receiving transducer is coupled to the surface. The simulated stress wave sensed by the receiving transducer consists of a large number of oscillations due to multiple reverberations within the material specimen.

Typical waveforms for the ultrasonic input and acousto-ultrasonic output are illustrated in Fig. 5. On the right-hand side of Fig. 5 are the echoes that rebound from the back surface of the specimen opposite the input transducer. For each pulse of the input transducer there will be a set of discrete back surface echoes. The left-hand side of Fig. 5 shows a typical signal sensed by the receiving transducer. The received signal is complex because it consists of the superposition of a large number of reflected signals as indicated by the ray traces in Fig. 6. Each ray represents a unique portion of a reflected wavefront and each has a unique arrival time, depending on the number of reflections from the boundary surfaces of the material.

The acousto-ultrasonic waveform is a "composite" waveform and its characteristics depend on a number of factors: constructive/destructive interference between individual wavefronts, angle of incidence of the individual reflections, mode conversions, etc. Because of these factors the composite waveform will be influenced by material density, tensile modulus, Poisson's ratio, and other material properties. The character of the acousto-ultrasonic waveform will also be influenced by ultrasonic velocity, attenuation, and frequency bandpass properties peculiar to the material macro- and micro-structure.

It is possible to compare different materials by analyzing the acousto-ultrasonic waveform provided other test conditions are reproduced exactly, e.g., thickness, spacing, coupling. As indicated in Fig. 5 the analysis of the acousto-ultrasonic waveform can proceed by measuring its acoustic energy or spectral signature. Variations in acoustic energy or spectral signature will arise from variations in the material properties, macro- and micro-structure, flaws, etc.

STRESS WAVE FACTOR

There are several ways to measure the energy content of the acousto-ultrasonic waveform: peak detection, decay or attenuation slope, root-mean-square, or a simple ring-down count. This latter method borrowed from acoustic emission technology is illustrated in Fig. 4.

After the pulse repetition rate (R) is set, a reset timer in the receiver circuit is set to a predetermined interval (T). The acousto-ultrasonic signal is fed to a counter-totalizer that counts the number (C) of oscillations that exceed a voltage threshold just above the noise level for a given amplification setting appropriate to the material and transducer spacing conditions. The product (R) (T) (C) is taken as the "stress wave factor" E_{SW} which in this case is the ring-down count for a standard number of identical waveforms.

With above-described method the stress wave factor can be used to rank a series of material specimens according to the stress wave energy intensity transmitted. Higher values for E_{SW} correspond to higher intensities (longer ring-down) which correspond, in turn, to materials that transmit acousto-ultrasonic stress wave energy more efficiently.

An alternative method for assigning a numerical value to the stress wave factor is that of first generating an energy envelope for the stress waveform and assigning the peak value to E_{SW}. A further alternative is to perform a spectrum analysis of the stress waveform and assigning the peak value of a particular spectral component to E_{SW}. It is true that each method for evaluating a stress wave factor will give a different numerical result. Each method will also highlight a particular aspect of the stress waveform and yield information on a different aspect of a material's characteristics. The idea is to choose a consistent method to rank a series of specimens. Illustrative examples of methods for analyzing acousto-ultrasonic waveforms are presented in the next section.

EXPERIMENTAL CORRELATIONS

Examples of acousto-ultrasonic waveforms their energy curves and frequency spectra appear in Figs. 7 and 8. The effect of increasing microvoid content and corresponding decrease in transmitted energy in a unidirectional fiber composite laminate is apparent in Fig. 7. In these graphite/polyimide composites strength decreases rapidly as microvoid content rises above approximately 3 percent. The effect of laminate ply orientation on spectral signature is evident in Fig. 8. The frequency spectra were made with acousto-ultrasonic waves propagating parallel to the major axis of tensile specimens (Ref. 9). For both the graphite/epoxy and glass/epoxy specimens there is an obvious decrease in spectral peak energy corresponding to the decrease in plys with fibers running in the 0-degree or axial direction. These specimens exhibited a corresponding decrease in ultimate tensile strength, Fig. 9.

Figure 10 shows the stress wave factor, E_{SW}, plotted against the cure pressures used in making a series of graphite/polyimide 12-ply unidirectional laminates. Higher cure pressure is expected to yield higher-quality, higher-strength panels. The acousto-ultrasonic measurements revealed, however, that even when a key processing variable like cure pressure is controlled, inferior material can still result. In Fig. 10 the upper bound curve shown represents optimum stress wave transmission and, hence, optimum quality for a given cure pressure. Stress wave factor data appearing below the curve are for panels that exhibited higher void content and erratic fiber/resin ratio.

Figure 11 shows that increases in the value of the stress wave factor correspond to increases in interlaminar shear strength for the graphite/polyimide laminates. The interlaminar shear strength measurements were made with short beam shear specimens cut from composite panels made with a range of cure pressures. The data in Figs. 9 through 11 were all obtained using the previously-described ring-down method for evaluating E_{SW}. In the case of Figs. 9 and 11 a normalized stress wave factor N_{SW} is plotted against material strength. The normalization is based on the observation that for each class of composite structure there is a maximum E_{SW} ($= E_{max}$) for a given set of operational conditions. This corresponds to a maximum strength that can be realized for that structure. It is convenient, therefore, to plot a normalized stress wave factor, $N_{SW} = (E_{SW}/E_{max})$ versus a normalized strength, as in Fig. 11.

DISCUSSION

Acousto-ultrasonics is an unconventional approach to nondestructive evaluation of material properties. Nevertheless, it has clearly demonstrated potentials for assessing variations in mechanical strength and performance due to flaws and macro- and micro-structural anomalies in composite laminates.

In acousto-ultrasonics broadband pulses (typically 0.1 to 2 megahertz) are introduced and allowed to interact repeatedly within the material boundaries. When the resultant signal is finally extracted, it carries an imprint of numerous factors that govern or contribute to material performance. In many ways the acousto-ultrasonic waveform resembles the burst-type acoustic emission waveform that arises spontaneously in a material undergoing microcracking or crack extension. This similarity to spontaneous stress waves is the key to inferring material behavior and response to dynamic loading.

Although the acousto-ultrasonic waveform is quite complex it is susceptible to analysis by a variety of straightforward methods. It can be quantitized in terms of a "stress wave factor" which is essentially a relative measure of the efficiency of energy dissipation in a material. If flaws or other anomalies exist in the volume being examined, their combined effect will be reflected in the stress wave factor. The stress wave factor can be readily evaluated in a number of different ways to give numerical ratings of the relative strength of a series of material specimens.

It should be noted that correlations between ultrasonic measurements and material strength have been obtained by other techniques (Ref. 11). For example, measurements of ultrasonic attenuation through the thickness of composite laminates have been correlated with interlaminar shear strength. Ultimate tensile strengths of composite specimens have been correlated with ultrasonic moduli based on combining density and velocity measurements. Although in execution these techniques are more complicated they are complementary to acousto-ultrasonics. Obviously, there will be situations in which one of these techniques is the preferred one for assessing relative variations in composite strength.

One of the advantages of the acousto-ultrasonic method described herein and depicted in Figs. 4 and 6 is that the stress wave signal propagates in a direction parallel to the bounding surfaces of laminate panels. This is significant because the signal can run parallel to a major fiber direction or the direction that actual loads assume in use. Note also that the method requires only one side access and, in principle, accomodates a range of curvatures since the laminate surfaces will act as waveguides.

Alternate send-receive transducer arrangements can, of course, be employed. Certainly, the proximity of the transducers can be modified for best effect in a given composite structure. Or the transducers can be deployed on opposite sides of an article, possibly in exact opposition. This latter transducer arrangement would resemble that used in pulse transmission ultrasonics. The principal difference between acousto-ultrasonics and conventional ultrasonics, regardless of transducer arrangement, is in the manner of sensing and handling signals.

Perhaps the most advantageous aspect of acousto-ultrasonics relative to the more conventional techniques such as those mentioned previously is in overcoming the high attenuation common to most composite structures. It is often difficult to recover a set of undistorted echoes needed for velocity or attenuation measurements. As an alternative, acousto-ultrasonics affords a method for sensing and measuring the results of introducing discrete ultrasonic pulses after pronounced attenuation and dispersion by material factors. The acoustic emission sensor and circuitry provide the necessary sensitivity and amplification. In addition, acoustic emission processing tactics such as ring-down counting provide excellent methods for analysis of the resultant signals (Ref. 6).

Studies are progressing to define the operational spectrum and to examine other potential applications of the acousto-ultrasonic and stress wave factor concepts. For example, preliminary tests show that acousto-ultrasonics is a viable inspection tool for bonded structures like composite skin bonded to honeycomb reinforcement. Other preliminary tests currently in progress demonstrate the utility of acousto-ultrasonics in monitoring degradation of composite laminates due to thermal exposure and impact damage (Ref. 8).

It is apparent from a consideration of results obtained thus far that the acousto-ultrasonic approach can operate on three levels of sophisticaton: Firstly, as a coarse, go-no-go indicator of serious flaws or discontinuities. Secondly, as a means for ranking essentially defect-free materials according to inherent strength. Thirdly, as an investigative tool for identification of factors that govern or contribute to material property variations. This latter aspect of acousto-ultrasonics, similarly with acoustic emission, depends on improving the understanding of waveform and frequency modifications induced by stress wave propagation in various composite media (Ref. 12).

Except in the first sense mentioned above, i.e., as an indicator of flawed regions in composite structures, current versions of the acousto-ultrasonic technique are essentially laboratory oriented. Accomplishment of the more sophisticated measurements suggested and illustrated herein is currently confined to laboratory specimens. In these latter cases careful control must be maintained over transducer positioning, coupling mode, pressure, etc. to achieve reproducible results. Possible field applications of the acousto-ultrasonic technique can be realized only if the necessary accomodations between the apparatus and test article are recognized and employed.

SUMMARY AND CONCLUSION

Acousto-ultrasonics combines complementary aspects of acoustic emission and ultrasonic technology. Acousto-ultrasonics provides an alternative that overcomes problems of conventional acoustic emission and ultrasonic techniques for the nondestructive evaluation of fiber reinforced composite laminates.

The inspection of this class of materials can benefit from the sensitivity and signal processing methods of acousto-ultrasonics.

Examples given herein demonstrate the acousto-ultrasonic methodology and its viability for ranking composite laminates according to their mechanical strength as influenced by local flaws and anomalies in fiber content, fiber orientation, and microvoids. Although adaptable to field use for indicating serious flaws in composite structures the more sophisticated uses demonstrated for the technique have thus far been based on experiments conducted under laboratory conditions.

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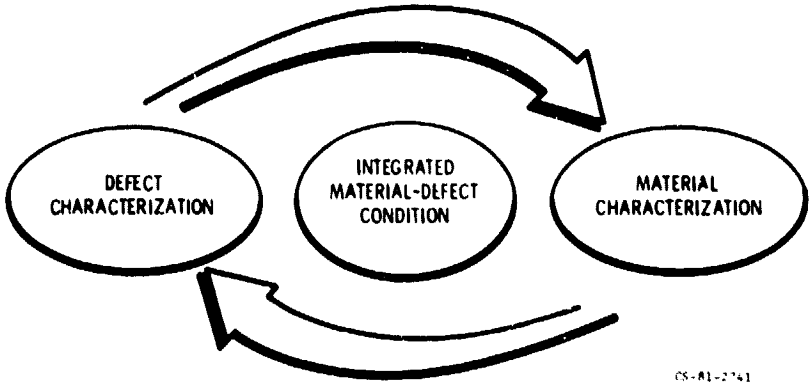

Figure 1. - Diagram illustrating the relation of defect and material characterization to defining the integrated effect of the material-defect state on stuctural integrity and life.

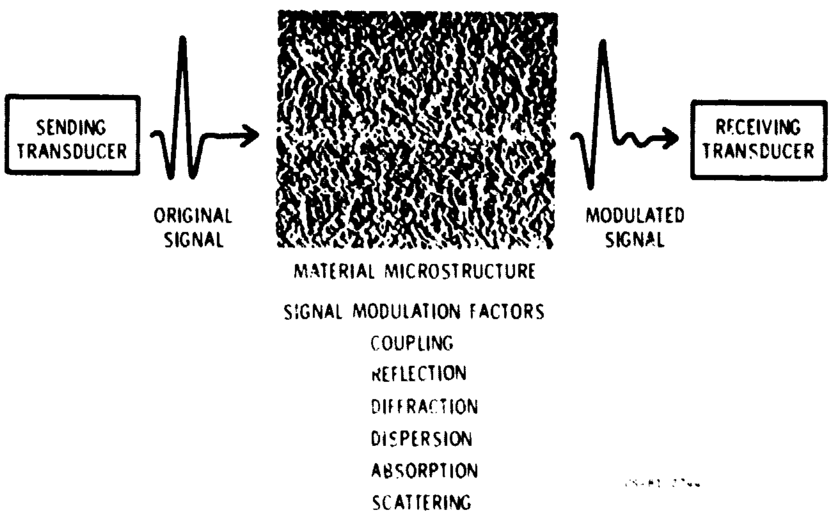

Figure 2. - Depiction of material microstructure as an ultrasonic wave filter in which a standard reference signal becomes modulated according to a definable transfer function.

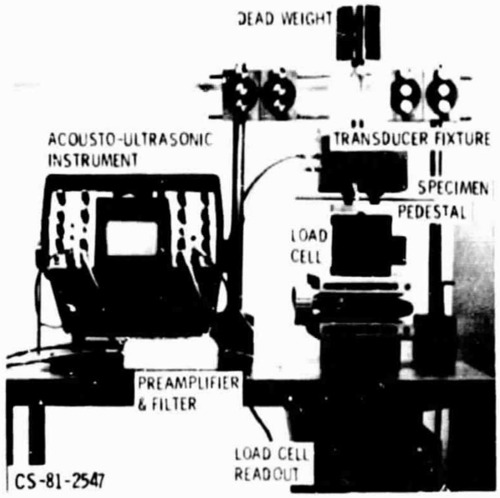

Figure 3. - Apparatus for measuring acousto-ultrasonic stress wave factor. The transducer fixture houses the sending and receiving transducers shown coupled to a composite laminate panel. The weight and load cell readout serve to assure reproducible coupling forces. The equipment shown is intended only to typify one of the numerous alternative arrangements possible, it should not be inferred that data presented herein was obtained with this particular arrangment.

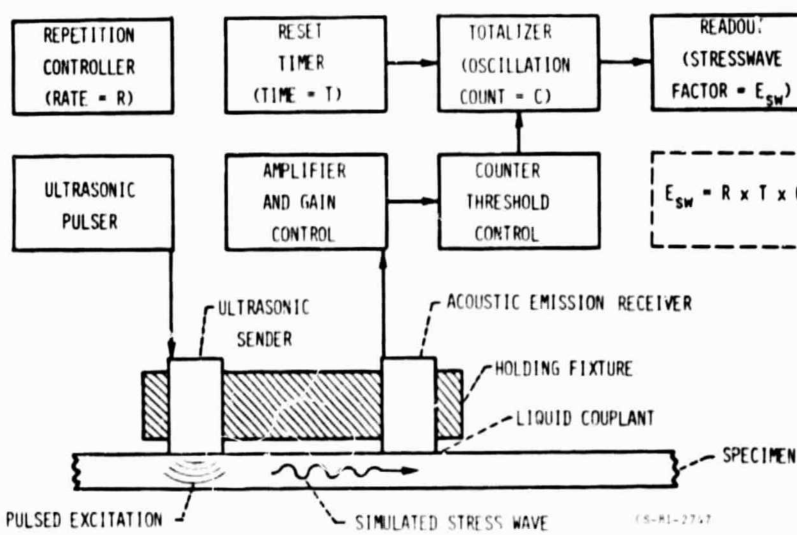

Figure 4. - Diagram of acousto-ultrasonic apparatus for measurement of the stress wave factor E_{SW} = (R)(T)(C). The quantity C is the number of "ringdown" oscillations exceeding a preset threshold voltage as in the acousto-ultrasonic waveform shown in figure 5.

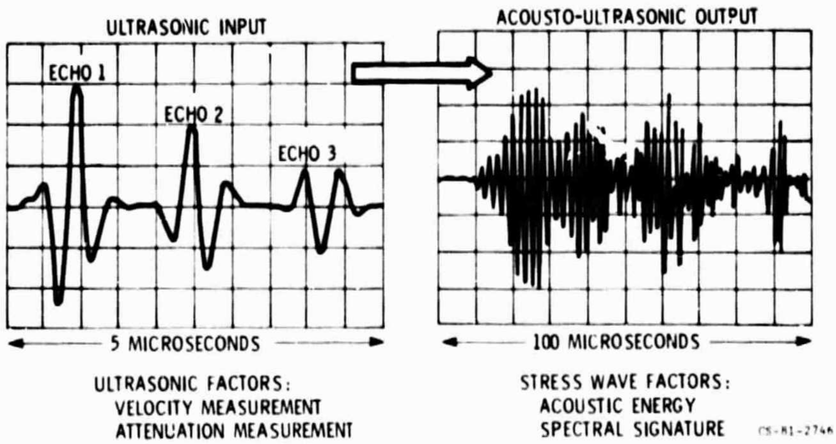

Figure 5. - An ultrasonic plused input (left) is used to excite the acousto-ultrasonic output waveform (right) from which the stress wave factor, E_{SW}, is measured. Both the ultrasonic input pulse echoes and acousto-ultrasonic output can be measured by means of the factors indicated: velocity, attenuation for through-transmission pulse echoes; acoustic energy, spectral signature for the acousto-ultrasonic stress waveform.

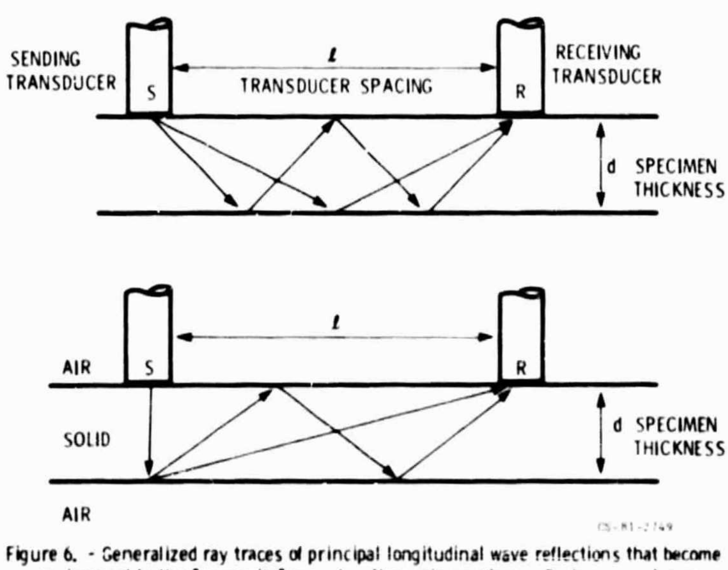

Figure 6. - Generalized ray traces of principal longitudinal wave reflections that become superimposed in the "composite" acousto-ultrasonic waveform. Each successive ray will be delayed by some multiple of the "round-trip" travel time associated with the specimen thickness. The amplitude of each successive wavefront will depend on its particular angle of incidence during reflections. These factors contribute to constructive and destructive interference effects that determine the complex character of the resultant acousto-ultrasonic waveform as in figures 5 and 7.

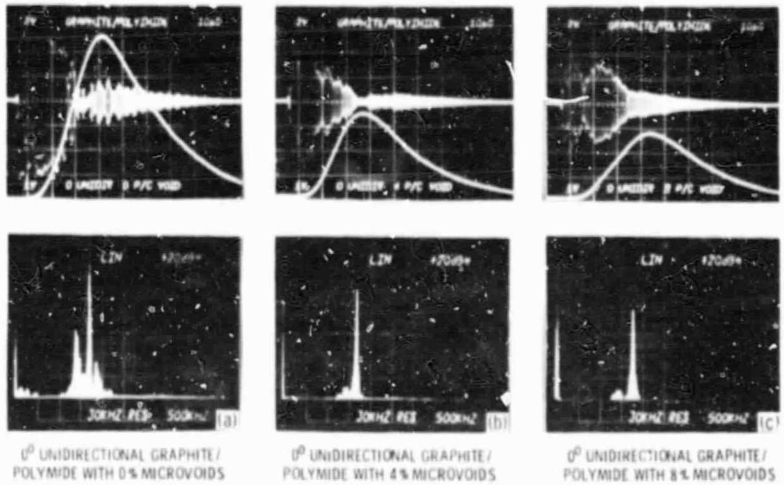

Figure 7. - Effect of microvoid content in fiber composite laminate. At the top are CRT traces of typical acousto-ultrasonic waveforms for graphite/polyimide samples with 0, 4, and 8 percent microvoid content. Superimposed are energy curves corresponding to the individual waveforms. Decreasing stress wave energy with increasing void content is also evident from the frequency spectra below the waveforms.

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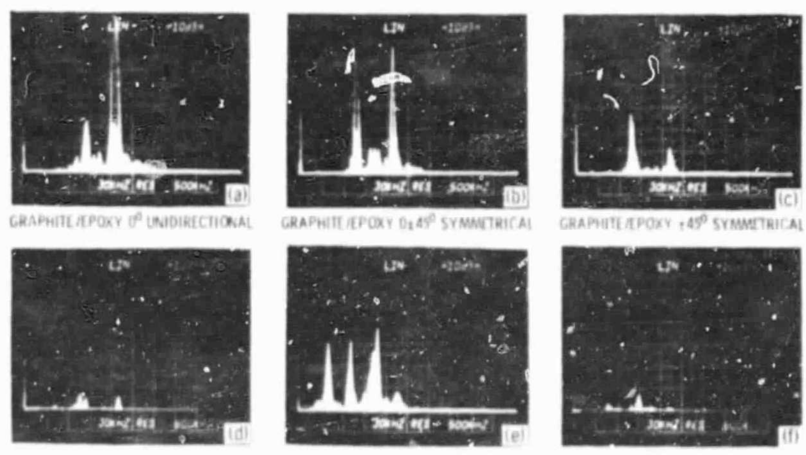

Figure 8. - Effect of various ply orientations in graphite/epoxy and glass/epoxy laminates. Results obtained with 5-ply tensile specimens. Frequency spectra shown are for typical acousto-ultrasonic waveforms obtained under standardized conditions. Spectral signatures, location of peaks, are functions of material thickness and also transducer and instrument bandpass characteristics.

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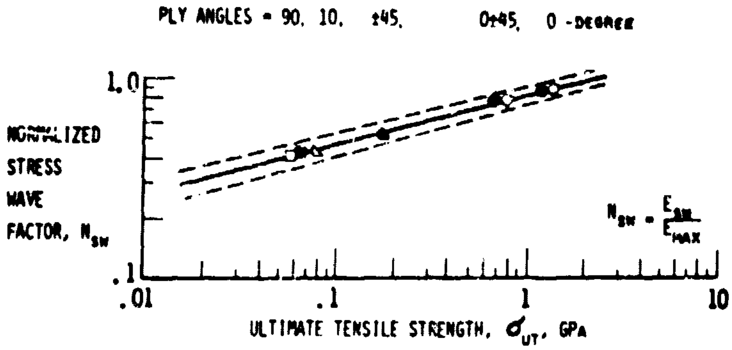

Figure 9. - Stress wave factor as a function of ultimate tensile strength for graphite/epoxy fiber composite laminates. Stress wave factor is normalized relative to its maximum value for the particular material specimens tested. The specimens were eight ply thick and the ply angles given are relative to the tensile loading axis (from ref. 9).

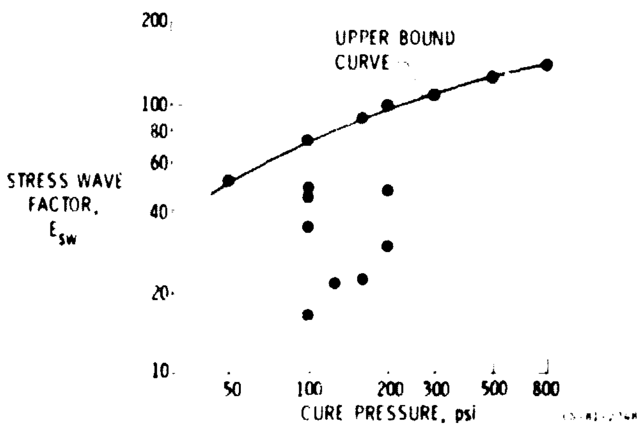

Figure 10. - Stress wave factor as a function of cure pressure applied during thermal forming of fiber composite laminates. The laminate panels were all 12-ply unidirectional. Upper bound curve represents highest quality panel for the indicated cure pressure. Data points below the curve have lower quality as indicated by stress wave factor and confirmed by other tests. Each data point represents 90 uniformly-spaced stress wave factor measurements per panel (from ref. 7).

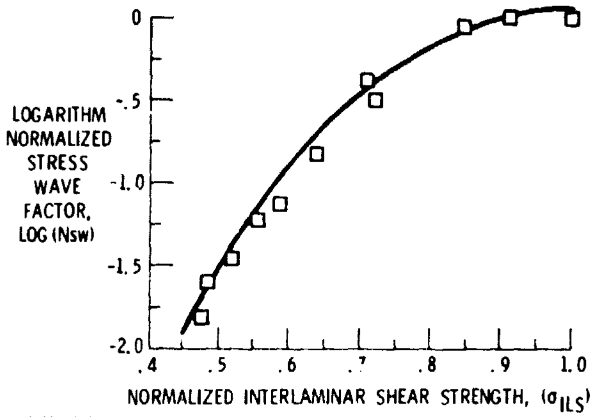

Figure 11. - Variation of acousto-ultrasonic stress wave factor with interlaminar shear strength in a 12-ply unidirectional fiber compostie laminate (ref. 10).