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# Wave Propagation and Acoustic Emission in Layered Composites

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# Wave Propagation and Acoustic Emission in Layered Composites

## **Abstract**

I will be presenting two different phases of our NDT composites program. The first of these, an in-house effort, is on the use of ultrasonic techniques, including spectrum analysis, for the nondestructive testing of composite materials. The second part of the presentation will be on characterization of acoustic emissions for boron/aluminum. This latter program is a joint effort between NADC and the University of Delaware. By way of background, Fig. 1 shows a diagram of an apparatus used for ultrasonic detection and mapping of flaws in composites. This is quite a conventional apparatus with the possible exception of the incorporation of the spectrum analysis capability.

## **Keywords**

nondestructive testing, nondestructive evaluation

## **Disciplines**

Materials Science and Engineering | Structures and Materials

WAVE PROPAGATION AND ACOUSTIC EMISSION  
IN LAYERED COMPOSITED

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I will be presenting two different phases of our NDT composites program. The first of these, an in-house effort, is on the use of ultrasonic techniques, including spectrum analysis, for the non-destructive testing of composite materials. The second part of the presentation will be on characterization of acoustic emissions for boron/aluminum. This latter program is a joint effort between NADC and the University of Delaware. By way of background, Fig. 1 shows a diagram of an apparatus used for ultrasonic detection and mapping of flaws in composites. This is quite a conventional apparatus with the possible exception of the incorporation of the spectrum analysis capability.

SCHEMATIC DIAGRAM OF ULTRASONIC TESTING APPARATUS

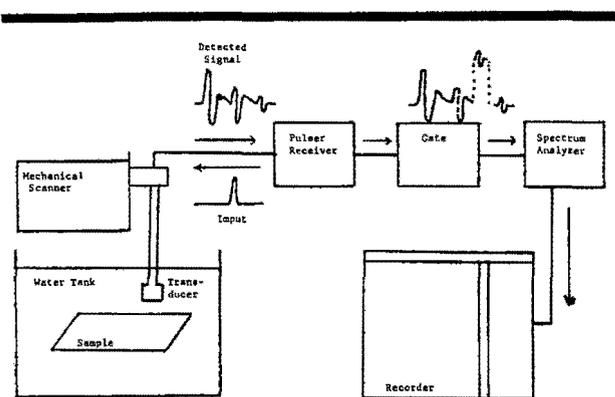


Figure 1. Schematic of Ultrasonic Testing Apparatus

An ultrasonic transducer projects a short duration pulse of broadband ultrasound onto a sample, which returns a decaying transient response due to the multiple echoes and reflections within the sample. The returning stress wave is detected, amplified, and a given time slice from the returning echo is gated and put through a spectrum analyzer. The resulting signal can be used to drive the intensity of a C-scan recorder, thereby producing flaw maps like the one shown in Fig. 2a.

There are several ways in which the effect of gating on flaw detection can be seen. One of these is to look at the displaced superposition of all the A-scans formed by scanning linearly once through a given region. The multiple A-scan of Fig. 2b was taken over a region containing a tight delamination. Between the interface and back echoes there is very little change in the echo due to the presence of the defect. However, the second multiple echo and the third multiple echo show perturbations of the pulse which give more sensitivity for detecting the flaw than could be obtained with just a first echo.

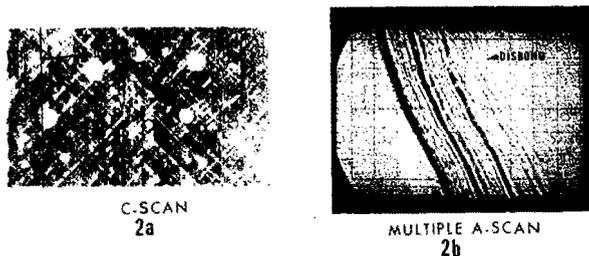


Figure 2. Presentations of Flaws in Graphite Epoxy Panel. White circles are prefabricated flaws.

Figure 3 illustrates another application of multiple echoes for detecting flaws in boron/aluminum. For these C-scans, 10th and higher order multiple echoes were needed to provide the sensitivity necessary to find very small strength-limiting flaws. Clearly the light areas in the C-scans correspond to the areas where the samples failed in the tensile tests.

NDT FOR ADVANCED COMPOSITES

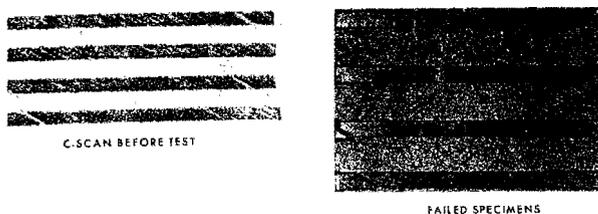


Figure 3. C-Scan detection of strength limiting flaws (fiber density variations) for B/Al composite. Detected flaws correspond to less than 10% reduction in theoretical strength.

Figure 4 illustrates the use of spectrum analysis for C-scan mapping of particular material properties such as thickness. For example, the scan in Fig. 4 used a frequency filter set at the half power point frequency of a transmission thickness resonance. Such resonances are frequencies for which multiple echoes passing through a sample, constructively reinforce each other producing a peak in transmission.

These resonances have been utilized by a number of investigators for making accurate thickness and velocity measurements. In this case, variations in sample thickness effect a motion of the resonance peak, which causes darkening in thicker areas of the sample and lightening in thinner areas of the sample, producing a thickness map of the sample.

In addition, the sensitivity of this technique can be changed by using either a narrow gate or a wide gate, the wide gate yielding a sharper peak and high sensitivity; the narrow gate yielding a broader peak and less sensitivity.

Because of the potential utility of spectrum analysis, not only in C-scanning but as a tool for flaw detection, a model is being developed to mathematically predict or characterize the nature of spectra from layered composites. One reason for doing this is to avoid cataloging different spectra ad infinitum for all of the different possible layups and flaws in a composite sample.

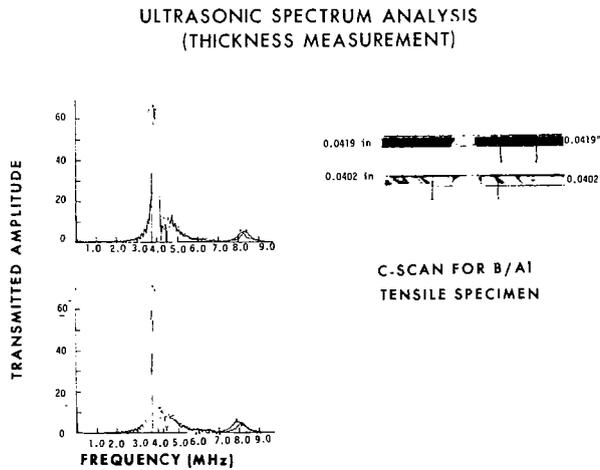


Figure 4. Ultrasonic Thickness Mapping

In Fig. 5 it is shown that the spectrum of a composite material differs somewhat from that of a monolithic plate in that the features corresponding to thickness resonances are not evenly spaced and vary somewhat in sharpness. In addition, the spectral features are found empirically to vary with fatigue, composite layup and environmental exposure.

In an attempt to understand composite spectra, we have been investigating a simple linear model in which the transmission and reflection coefficients of layered media are built up from the known responses of individual layers.

Equations (1a) and (1b) give the expression used to compute the Fourier transform for the transmission (T') and reflection (R') response functions for a layered medium when an additional monolithic medium is joined.

$$T'(w) = \frac{t T(w) \exp(-iwd/c)}{1 + r R(w) \exp(-2iwd/c)} \quad (1a)$$

$$R'(w) = \frac{r + R(w) \exp(-2iwd/c)}{1 + r R(w) \exp(-2iwd/c)} \quad (1b)$$

The lower case t and r can be either computed reflection and transmission coefficients or tabulated experimental data. d and c are respectively the thickness and velocity of sound in the appended medium and T(w) and R(w) are transmission and reflection coefficients before adding on the additional medium. By making d/c complex, damping may be introduced into the model.

To describe non-normal incidence, a matrix quantity may be used for these variables, and in that way the effects of coupling between shear and longitudinal waves may be introduced.

FREQUENCY SPECTRA FROM MATERIALS OF FINITE THICKNESS

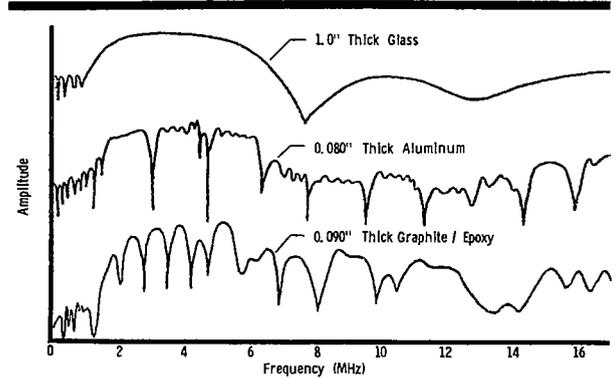


Figure 5. Ultrasonic Frequency Spectra

Figure 6 is a comparison between a frequency spectrum calculated from equation 1 and a measured spectrum. Clearly, all the essential features are predicted. The difference in the peak magnitudes is due to the fact that there was not a perfectly flat frequency envelope in the pulses of ultrasound that were used.

ULTRASONIC SPECTRUM ANALYSIS (SPECTRUM OF 3 LAYER LAMINATE)

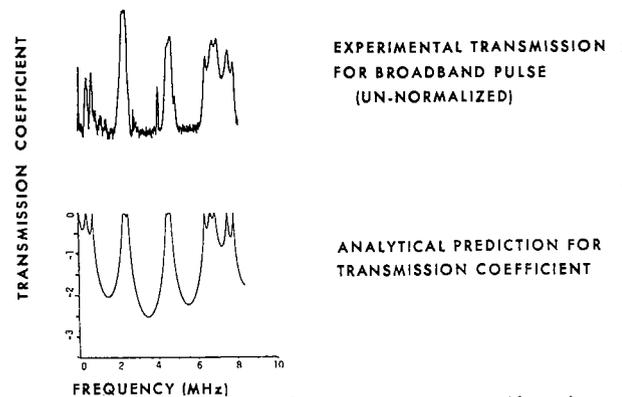


Figure 6. Comparison of Measured and Predicted Frequency Spectra

Figure 7 shows the predicted effect on spectra of adding increasing numbers of layers to a laminate starting with a two-layer laminate and going to a five-layer one. These laminates have very strong reflection coefficients at interfaces thereby emphasizing the effects of the interface.

The closely spaced thickness resonances clustered at low frequencies correspond roughly to thickness resonances for the entire laminate. Between the clusters of thickness resonances are broad minima. These minima deepen rapidly with increasing thickness and in the limit of an infinitely thick laminate, they form bands of frequencies for which traveling waves will not propagate.

The locations of these bands for infinitely thick laminates have been verified independently by utilizing Floquet's theorem which predicts that in such forbidden regions there will be no wave propagation in the infinite laminate limit. An additional prediction is that in the vicinity of these forbidden regions discontinuities in phase velocity occur. In a limit of very weak interface reflections these regions of forbidden transmission get narrow and the whole spectrum merges into the spectrum of a monolithic laminate.

It follows that if, by analogy, with monolithic materials the phase velocities are computed from the positions of thickness resonances, a measure of reflection strength at interfaces can be related to discontinuities in phase velocity.

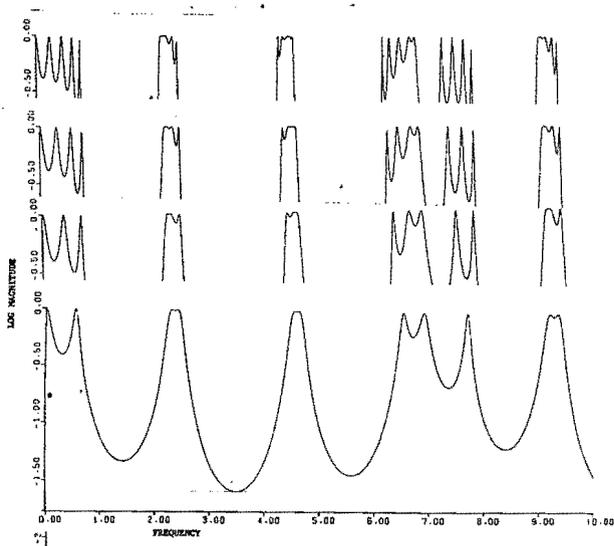


Figure 7. The Effect of Layering on Frequency Spectra

Figure 8 shows dispersion relations obtained from a graphite epoxy laminate having considerable interface porosity, and this material shows considerable variation in velocity of sound and sizeable discontinuities in phase velocity near the predicted forbidden transmission regions.

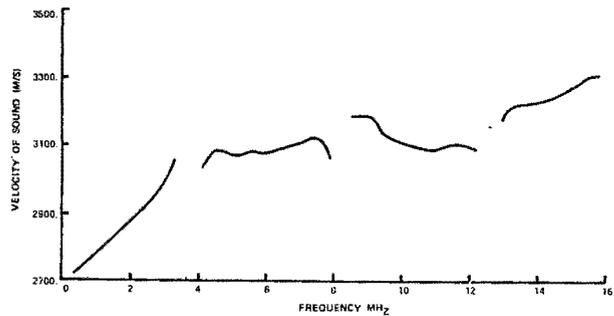


Figure 8. Measured Dispersion Curve for Graphite Epoxy with Porous Interfaces

Figure 9 shows dispersion relations of somewhat higher quality laminates. The T300/5208 material exhibits almost no dispersion below 10 MHz. And all the  $0^\circ$  material, which in theory would be most like monolithic material, shows almost no velocity discontinuity at the predicted forbidden frequency. However, there probably would be a sizeable discontinuity in the group velocity for waves around that frequency.

Dispersion has been observed qualitatively conforming to our model in a number of graphite reinforced resin systems, and variations in this dispersion have been correlated with fatigue, changes in layup, and environmental exposure. The model is less useful for describing materials such as boron/aluminum, since their fiber size gives them a two-dimensional periodic structure which cannot be approximated very accurately by monolithic layers.

Our future work will be directed towards improving quantitative predictions for real laminates, qualitatively and quantitatively correlating dispersion with material degradation and predicting spectra for waves obliquely incident upon laminates. Initial indications are that the oblique incidence results will give much more sensitivity than normal incidence measurements.

The second part of this presentation deals with the work that was done on acoustic emission from boron/aluminum carried out jointly by the University of Delaware and the Naval Air Development Center.

The objective of this research is to characterize acoustic emission signatures from boron/aluminum under various conditions of biaxial loading which might be present in a laminate, in particular, the loading conditions of in-plane shear, fiber tension and transverse tension. The conditions were produced experimentally through the use of off-axis unidirectionally tensile specimens in which the fibers for different specimens presented different angles to the applied load.

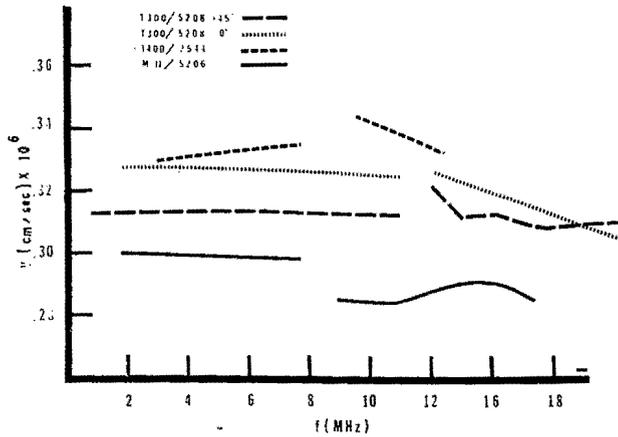


Figure 9. Dispersion Curves for Graphite Epoxy Laminates

Figures 10a and 10b show acoustic emission rate versus strain curves taken for two different frequency regions for a 0° tensile specimen. Figure 10a was taken with peak sensitivity in the frequency region from 0.1 to 0.3 MHz. Figure 10b was taken with maximum sensitivity in the region 0.3 MHz to 1.5 MHz. For the 0° mode of loading the fibers are by far the dominant load bearers and the sample ultimately fails due to fiber breakage.

The rapid peaking of the emission rate at low frequencies (Figure 10a) accompanied by a low emission rate at high frequencies (Figure 10b) is characteristic of this mode of loading.

Preliminary results of spectrum analysis done on tape recordings of these acoustic emissions seem to reveal two kinds of events: a low frequency event at high amplitude and somewhat higher frequency event at a lower amplitude.

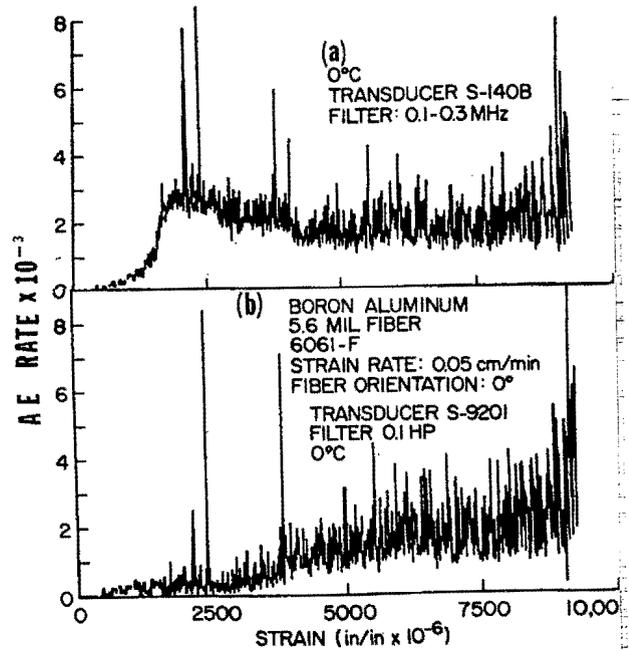


Figure 10. Acoustic Emission from 0° Boron/Aluminum Tensile Specimen, (a) low frequency, (b) high frequency

For off-axis tensile specimens with fiber to load angles greater than 0° and less than 60°, in-plane shear becomes a dominant load bearing mechanism and the sample fails when its in-plane shear strength is exceeded. However, there still exists a large component of fiber tension for angles up to 45°, and the emissions from this fiber tension loading, dominate those emissions resulting from the much quieter in-plane shear mode (see Figure 11).

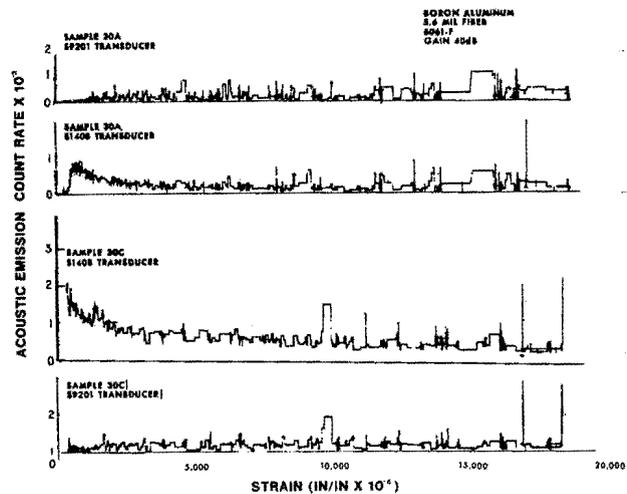


Figure 11. Acoustic Emission from 30° Boron/Aluminum Tensile Specimens

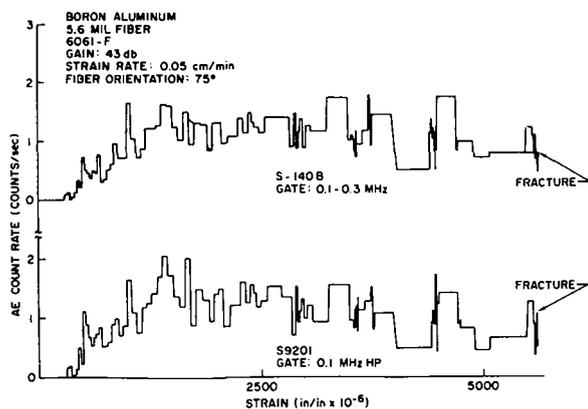


Figure 12. Acoustic Emission Spectra from 75° Boron/Aluminum Tensile Specimen (upper curve-low frequency), (lower curve-high frequency)

The 60° specimen (Fig. 13) has a mixed mode of failure (i.e. it is not clear whether we have failure due to transverse tension or in-plane shear) and since the in-plane mode of acoustic emission is very weak, we have the 60° specimen acoustic emissions dominated by the same type of signature seen in transverse tension.

The signature for the in-plane shear mode was measured in separate rail shear tests and was found to be of a low level, peaking only near failure.

For samples with fiber angles greater than 60° the primary load applied is transverse tension, which is also the failure mode of the specimen. And the AE signatures for this mode of loading are essentially identical at high and low frequencies, differentiating them from fiber tension signatures which are different at high and low frequencies (see Fig. 12).

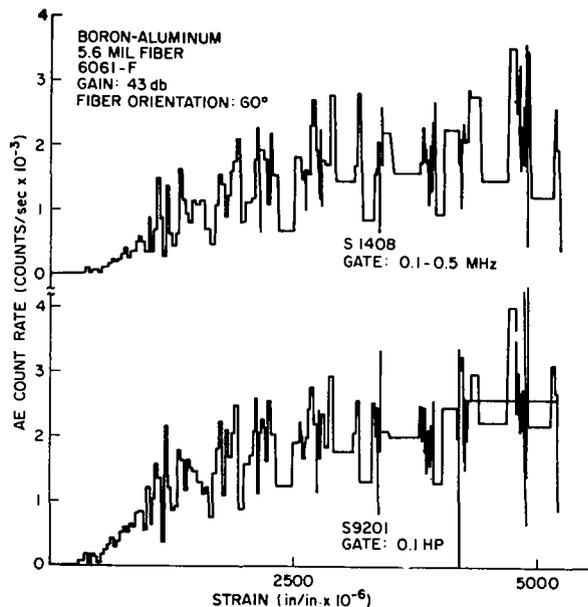


Figure 13. Acoustic Emission from 60° Boron/Aluminum Tensile Specimen

## DISCUSSION

PROF. JOHN TIEN (Columbia University): I must have missed the punch line to your first part. Is that a feasible technique for determining defects or not? I mean all the spectrum analysis.

DR. SCOTT: Yes, it definitely is sensitive to defects. Now we are trying to do more than just say something changed; we're trying to find out what changed. As I said, we have empirical measurements of changes in the spectra due to fatigue and environmental exposure of specimens, and also we can to some extent recognize a layup which is very often important because many times after someone makes a layup, he is not sure what he put in it.

DR. JIM DOHERTY (Pratt Whitney Aircraft): On a system like this with the spectrum analysis you showed us, (the scanning system), what kind of scanning rates in the sense of lines per square foot can you use to get reasonably small spatial resolution for these kinds of defects you're looking at?

DR. SCOTT: The work that I've reported here has been done mostly in the laboratory and I haven't tried to push the speed. So I really don't know.

DR. EMMANUEL PAPADAKIS (Ford Motor Company): In the same vein, were the transmission pictures obtained with two transducers or one, or is it just a multiple echo?

- DR. SCOTT: Instead of using two transducers I just used a reflector plate, which essentially gives you very much the same sort of thing as transmissions.
- MR. DAVE CARVER (Lockheed): In the first section do you do repetitive scans with transducers of different frequencies?
- DR. SCOTT: No. I use a transducer that puts out a very narrow pulse and therefore has a broad frequency spectrum, and then I select the frequencies that I want. You can even pick out combinations of frequencies to enhance particular features.
- DR. PAUL FLYNN (General Dynamics): You said that the lower frequency resonances correspond to the thickness resonances. Would the higher frequency resonances be due to ply thicknesses or interply adhesive thicknesses, or what?
- DR. SCOTT: Well, they really are all thickness resonances. It's just that you get that big discontinuity due to the periodicity of the laminate, and you get so much dispersion at the higher frequencies, and it's really difficult to recognize that what you are seeing are thickness resonances, at least in the example I showed you. However, in something like graphite epoxy, for example, where the interface isn't all that strong, they are really all thickness resonances.
- DR. FLYNN: Do both 0° and 45° plies show resonances?
- DR. SCOTT: Yes. In that first slide I showed for graphite epoxy, (Fig. 2) some discontinuities were due to the fact that we had two periodicities: one layer to layer and the other from one 0°/45° pair to the next.
- MR. B. G. MARTIN (Douglas Aircraft): I understand that in your calculations you took into account attenuation. I was wondering what value you used.
- DR. SCOTT: In the particular calculations which I showed, which were just examples of the model, I did not take attenuation into account. If you wanted to take attenuation into account, you would have to measure it.
- MR. MARTIN: That was exactly my question. Thank you.
- PROF. MAX WILLIAMS (University of Pittsburgh): Let me conclude, then, by one question for clarification. Do I understand that you get very distinct and recognizable signals that permit you to distinguish in-plane shear from direct stress? And that there is no question in your mind about the product mix and the content of the signals for those two loadings; is that correct?
- DR. SCOTT: Well, this seems to be the case when we're just using unidirectional material. Now, I don't know what's going to happen when we start getting into laminated material. For example, in the transverse tension mode, there was some localized yielding and when the material is laminated that localized yielding seems to be arrested somewhat: that may change the signature of the material and this is something we are currently trying to determine.
- PROF. WILLIAMS: You've recognized that you can distinguish between in-plane shear and direct tension. Can you separate out the energy content, for example, as well?
- DR. SCOTT: It may be possible, but I'm not sure. This was our ultimate goal of approaching research in this way, to break the response up into components. We haven't done it yet.
- PROF. WILLIAMS: I understand that you must tolerate impatient engineers.