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# The Use of Continuous Wave Ultrasonic Spectroscopy for Adhesive-Bond Evaluation

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# The Use of Continuous Wave Ultrasonic Spectroscopy for Adhesive-Bond Evaluation

## **Abstract**

The program to be described here was initiated during the past year at the Air Force Materials Laboratory. The problem of determining adhesive bond strength was undertaken with a rather brute-force approach of simply collecting the best possible data, utilizing existing ultrasonic plane-wave theory for layered structures to calculate ultrasonic spectra, and then attempting the inversion of the data to obtain the acoustic properties of the material or structure. An empirical correlation of these acoustic properties with the destructively measured bond strength is planned.

## **Keywords**

nondestructive testing, nondestructive evaluation

## **Disciplines**

Materials Science and Engineering | Structures and Materials

THE USE OF CONTINUOUS WAVE ULTRASONIC  
SPECTROSCOPY FOR ADHESIVE-BOND EVALUATION

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The program to be described here was initiated during the past year at the Air Force Materials Laboratory. The problem of determining adhesive bond strength was undertaken with a rather brute-force approach of simply collecting the best possible data, utilizing existing ultrasonic plane-wave theory for layered structures to calculate ultrasonic spectra, and then attempting the inversion of the data to obtain the acoustic properties of the material or structure. An empirical correlation of these acoustic properties with the destructively measured bond strength is planned.

This research was initiated to determine whether, in general, continuous-wave ultrasonic techniques would provide more accurate data than conventional pulse techniques. Adhesively bonded structures were examined because they are representative of a class of inspection problems for which this technique appears particularly well suited. With this technique, the sample is considered to be a black box, just as it is in the performance of a network analysis on an electronic device. Data were collected by establishing standing waves and measuring the amplitude and phase of the transmitted or reflected ultrasound at each frequency point. The sample spectra were deconvolved with the transducer spectra to reduce the influence of the particular ultrasonic transducers on the spectra.

The experimental system is very straightforward and, in principal, much simpler than a pulse system, although this particular system is more sophisticated than absolutely necessary. As shown in Fig. 1, a signal averager is used to step a synthesizer which drives a broad-band transducer (Panametrics Model V111-HD, 1/4-in. diam.). The through transmission is measured with a Hewlett-Packard gain/phase meter. The analog output of the gain/phase meter is recorded by the signal averager and then is recorded on magnetic tape for further off-line processing. The gain/phase-meter output is the log of the signal amplitude which compresses the spectra and increases the dynamic range.

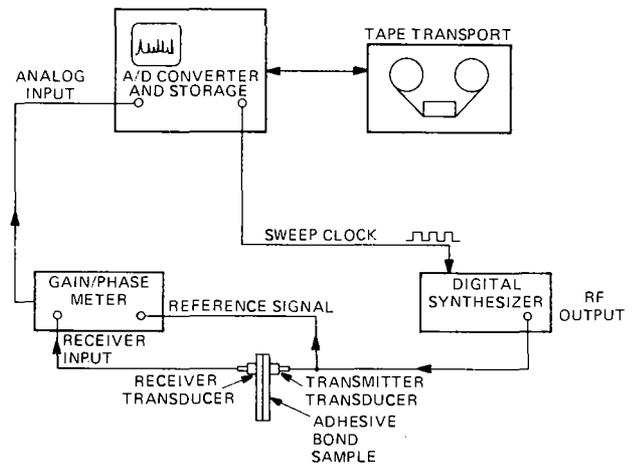


Figure 1. Continuous wave acoustic spectroscopy system diagram.

In summary, the primary advantage of this technique is that the data are taken directly in the frequency domain--the same domain in which the theoretical calculations are performed. The significant improvement in signal-to-noise ratio over that possible with pulse techniques is based upon the same premise as Vernon Newhouse's work with random signal noise methods (i.e., improvement in the on-off ratio through the use of CW versus pulse techniques may, in turn, improve the signal-to-noise ratio by as much as a factor of 1000.)<sup>1</sup> In addition, the frequency resolution is basically unlimited since with a synthesizer any part of the spectra can be expanded easily. Finally, the system utilizes very low power levels to excite the transducer (~ 1 V RMS), and as a result the transducer is not shock excited; therefore, less nonlinear behavior is expected.

Figure 2 shows some preliminary data taken with a solid bond. This sample, which has been used for several months, is composed of two aluminum plates, about 1/16 in. thick, bonded together with an adhesive utilizing a cloth carrier. The bond-line thickness is roughly 0.008 in. The bond-line thickness varies considerably resulting in significant changes in the spectra across the sample as the bond thickness varies. As indicated by the arrows in Fig. 2, the bond resonance occurs periodically. This spectrum has already been corrected for the transducer response by deconvolution with the transducer spectra.

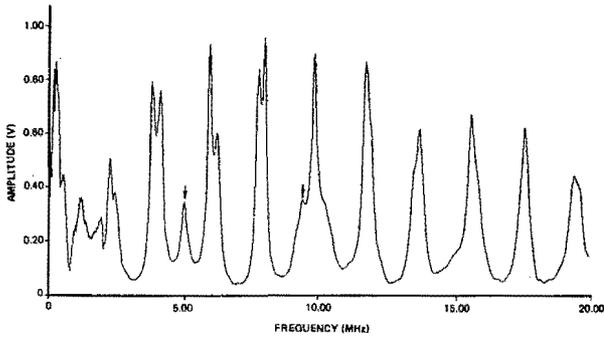


Figure 2. Deconvolved amplitude spectrum for an adhesive bond sample--data taken using oil couplant.

Figure 3 is a phase spectrum of the same sample, which by itself is not very interesting. However, the measurement of amplitude and phase response allows calculation of the real and imaginary spectra as shown in Fig. 4a and 4b.

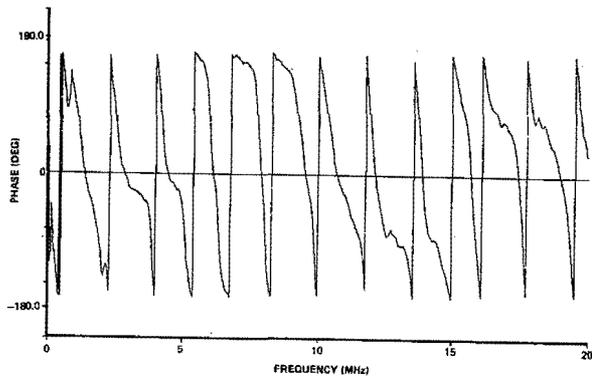


Figure 3. Deconvolved phase spectrum for an adhesive bond sample--data taken using oil couplant.

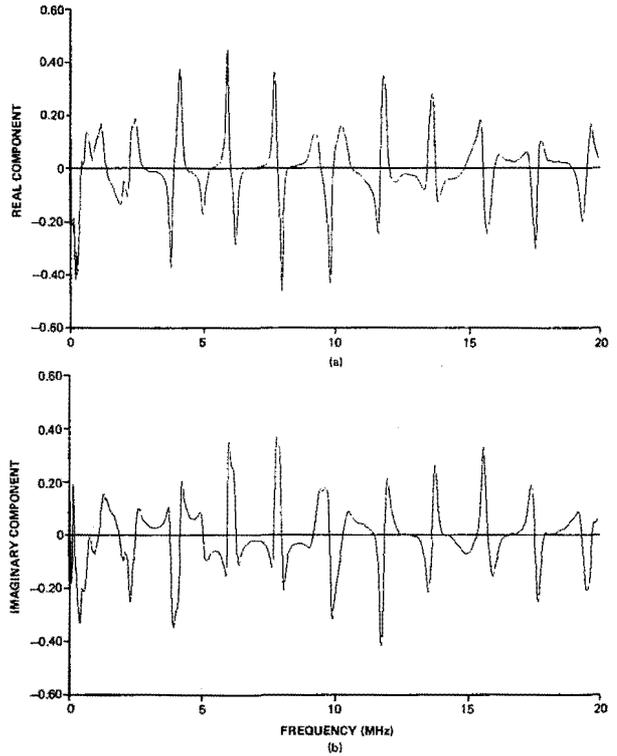


Figure 4. (a) Real component and (b) imaginary component of the complex transmitted amplitude--computed from amp/phase data.

In order to demonstrate that frequency-domain data is equivalent to time data, an inverse Fourier transform was performed, and Fig. 5 shows the type of time data obtained. These spectra actually extend to 50 $\mu$ sec; however, only the first 10 $\mu$ sec are plotted in this figure. This time spectrum has better resolution than that obtainable with the same transducers and a commercial pulse echo system.

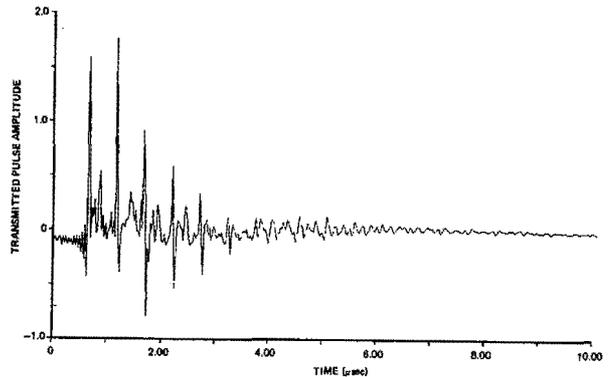


Figure 5. Inverse Fourier transform of deconvolved amp/phase data.

After a water tank was obtained, additional data were taken. Figure 6a is a nondeconvolved spectrum of an aluminum plate in water. The standing waves in the water (on the order of 3-4 kHz) were small compared to the synthesizer step size of 20 kHz and, therefore, appeared to be noise. After

FM modulation of the synthesizer signal, with a maximum frequency excursion which was less than the step size, the water peaks averaged out, leaving only the aluminum resonances, as shown in Fig. 6b.

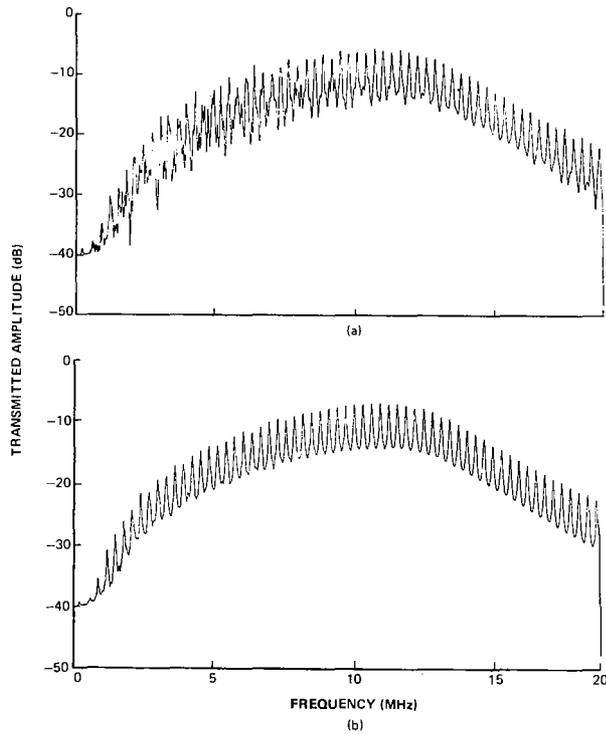


Figure 6. Logarithm (dB) of nondeconvolved transmitted amplitude spectrum for a 3/8 in. aluminum plate in water, without FM modulation (a) and with FM modulation (b).

Figure 7a shows an adhesive-bond water spectrum without deconvolution. With a correction for transducer response the spectra shown in Fig. 7b resulted. One peak goes off scale, and at first there seems to be no reason for that one line to have a transmission coefficient greater than 1. Since, in general, the aluminum plate should attenuate the sound, there should be a gain of less than one. Apparently very good impedance matching exists at this frequency, and the sound is transmitted at that frequency better than through the water bath only.

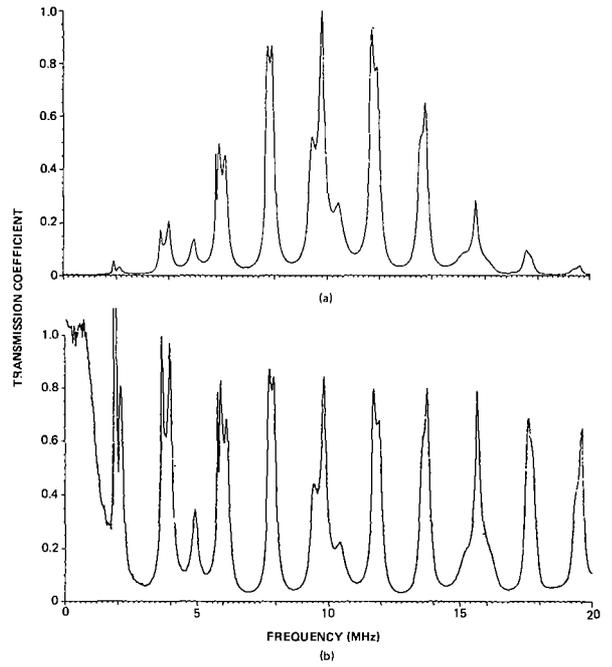


Figure 7. Transmitted amplitude spectrum at normal incidence for an adhesive bond sample in water with FM modulation, without deconvolution (a) and with deconvolution (b).

In general, although some instrumentation should be improved, we are quite satisfied with the quality of the data being obtained with the techniques. Brekhovshikh's n-layered model<sup>2</sup> was used for interpreting the data. Frequency-dependent attenuation terms were added to this model and necessary programming accomplished to calculate and plot the theoretical spectra. The transmission and the reflection coefficients could then be calculated for an n-layered solid in water for any frequency and angle of incidence. Each layer was characterized by seven parameters: thickness, density, longitudinal and transverse phase velocity, and three terms for attenuation--quadratic ( $a_2$ ) and linear ( $a_1$ ) frequency dependence as well as a constant term ( $a_0$ ).

The type of transmission spectra calculated are shown in Figs. 8a through 8d. When compared with the experimental spectra in Figs. 2 through 4b, it is clear that the general features of the data have been obtained. Reflection coefficients were calculated, and the results are shown in Figs. 8e through 8h. The reflection data are theoretically "cleaner" than transmission data. Modification of the experimental system is planned in order to obtain reflection data.

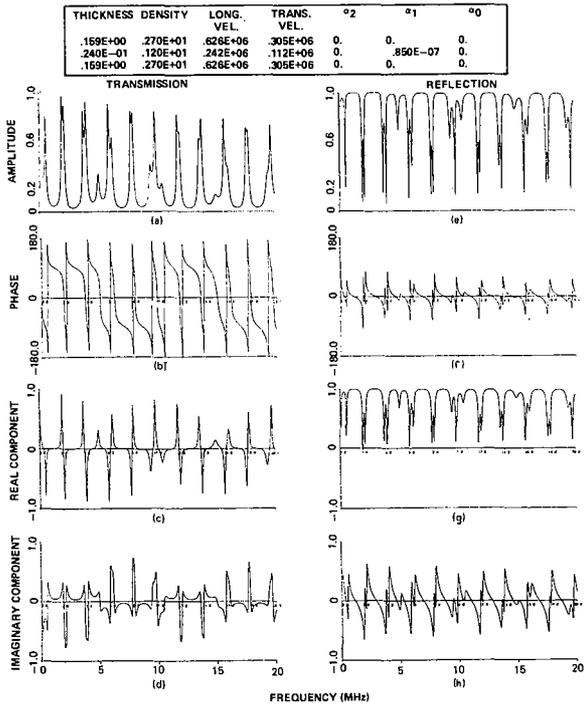


Figure 8. Theoretical spectra for a three-layer system in water. The table shows the acoustic parameters for each layer with thickness in cm, velocities in cm/sec., and linear attenuation in nepers/cm/ $2\pi$  Hz. Figures (a) through (d) are a transmission series and (e) through (h) are a reflection series.

Another interesting theoretical result can be seen in Fig. 9, which is a plot of the sum of the energy-reflection and transmission coefficients. This calculation indicates where energy is lost through attenuation. This theoretical plot includes losses in the adhesive bond only. The variation in the spectrum due to attenuation in the aluminum was very small compared to that due to the attenuation in the adhesive. The bond line peak, being a major source of loss, is accentuated significantly.

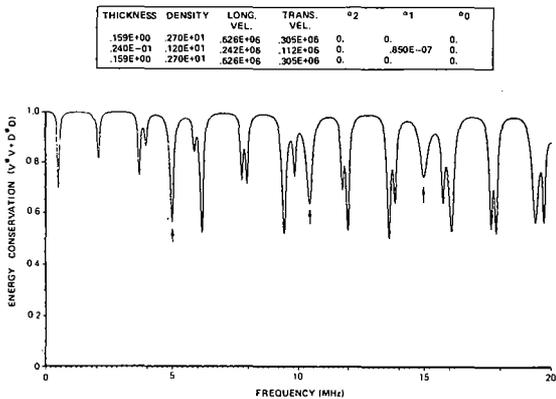


Figure 9.  $V*V$  and  $D*D$  are the energy reflection and transmission coefficients, respectively. For a conservative system the sum of  $V*V$  and  $D*D$  would be identically one, but for a lossy system this is not the case. The arrows indicate the bond line resonances.

Figure 10b is the inverse Fourier transform of the theoretical spectrum shown in Fig. 10a. Here again, the same type of time response was obtained theoretically and experimentally.

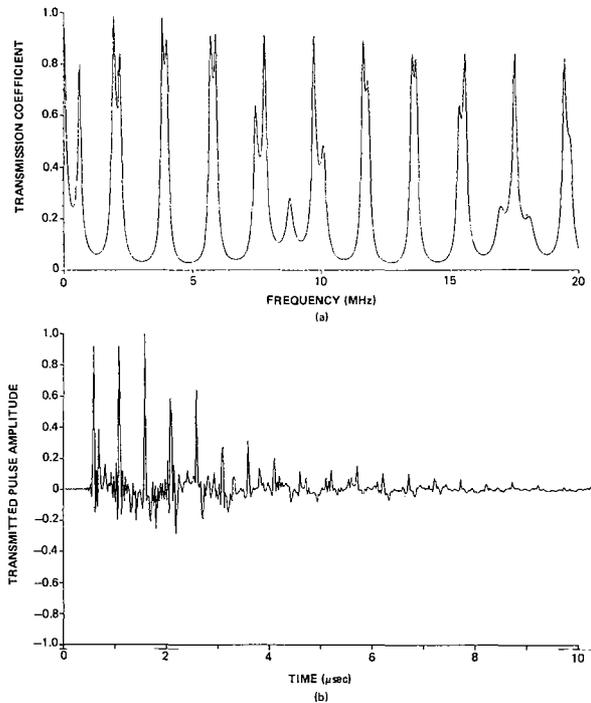


Figure 10. (a) Theoretical transmitted amplitude spectrum. (b) Time domain response resulting from the inverse Fourier transform of the theoretical frequency domain spectrum shown in (a).

Figure 11 is a sequence of transmission spectra where the bond-line thickness was the only parameter varied. Figure 11a has a bond-line thickness of  $\sim 0.009$  in. or  $0.0216$  cm. The first bond-line standing-wave peak should occur at  $5.4$  MHz. As the bond thickness is decreased as in Fig. 11b to  $0.004$  in., the first resonance should occur at  $\sim 11.5$  MHz; as can be seen additional fine structure is also calculated. A further reduction in bond-line thickness to  $0.001$  in., as in Fig. 11c, shifts the resonance to  $23$  MHz which is outside the bandwidth of this spectrum. However, at low frequency a portion of the spectra begins to resemble the spectra that would be obtained for a single plate twice as thick. Therefore, twice as many peaks are observed. Figure 11d is an extreme case for a  $0.0005$ -in. bond line. For this bond-line thickness the first bond-line resonance would be at  $92$  MHz. As can be seen, it resembles a continuous structure with no bond-line resonance. Although the resonance is occurring at  $92$  MHz, it appears that the bond-line resonance frequency could be extracted from these data based on the trends in the spectra. The critical problem of inverting the experimental data to obtain the physical acoustic properties of the structure remains.

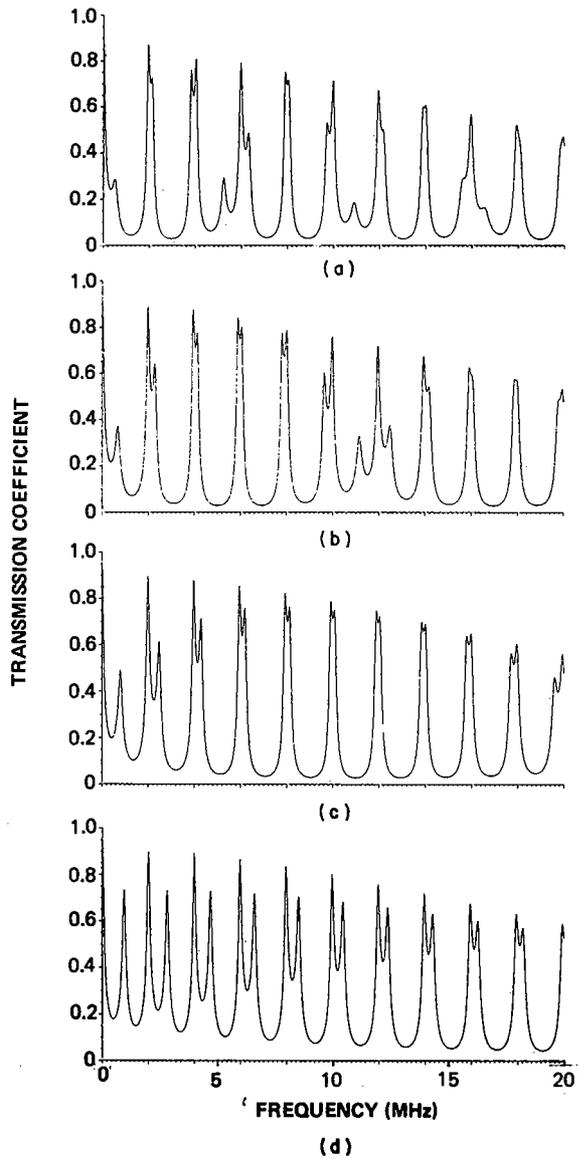


Figure 11. A sequence of theoretical spectra where only the bond line thickness is being varied. The thickness in (a) is .009 in., (b) .004 in., (c) .001 in., and (d) .0005 in.

The result of attempts to make a rough fit to experimental data is shown in Fig. 12. This fit was obtained by trial and error; however, a non-linear least-squares program is being written to

accomplish this more accurately. If the least-squares inversion is successful, the result will be a system which will allow the physical acoustic parameters for an entire layered structure to be obtained. This reduced set of acoustic properties of the structure will then be empirically correlated with bond strength, a residual life, or some other engineering parameters of interest. Appropriate destructive tests for bond strength will also be performed.

THICKNESS	DENSITY	LONG. VEL.	TRANS. VEL.	"2	"1	"0
159E+00	.270E+01	.626E+06	.305E+06	0.	0.	0.
240E-01	.120E+01	242E+06	.112E+06	0.	.850E-07	0.
159E+00	.270E+01	.626E+06	.305E+06	0.	0.	0.

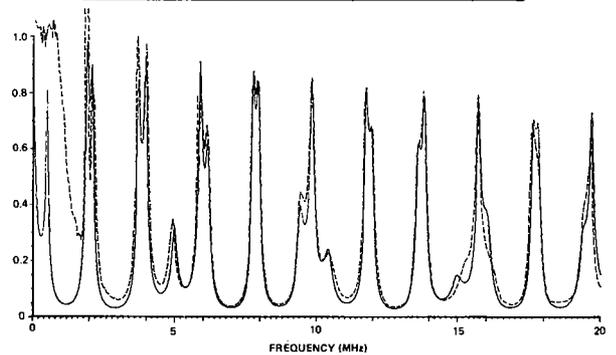


Figure 12. The dotted line indicates an experimentally obtained amplitude spectrum for a bond line sample in water. The solid line is a theoretical plot of a hand estimated fit to the data.

#### REFERENCES

1. V. L. Newhouse, N. M. Bilgutay, and E. S. Furgason, "Random Noise Signal Processing," in *Proceedings of the ARPA/AFML Review of Quantitative NDE*, AFML-TR-75-212 (Air Force Materials Laboratory, WPAFB, OH, Jan 1976), p. 343.
2. L.M. Brekhovskikh, *Waves in Layered Media* (Academic Press, New York, 1960), p. 61.

#### DISCUSSION

PROF. MAX WILLIAMS (Univ. of Pittsburgh): That was perfect. May I ask if Dr. Raney has any comments to add? Are there any questions from the audience?

DR. PAUL FLYNN (General Dynamics): You talked about that first resonance. I think that is what George called the dumbbell mode, because we have a code that deals with 6 layers. It doesn't include the attenuation but the same peaks end up in the same place; they're just in different shapes.

DR. BUCKLEY: Right.

- DR. FLYNN: We have done a parametric study to look at that particular mode, and you can approximate that with spring and mass type stuff and it follows the same type of relationship. And if you bring your bond line down to zero, then you end up with just a sort of organ-type resonance-type thing.
- PROF. WILLIAMS: Mike, will you handle your own questions while there is time, please.
- DR. FRANCIS CHANG (General Dynamics): About the first peak, the value we calculated is different from the dumbbell model that George had, and we did those studies similar to what you did there. In other words, we changed the density of the material, changed the bond line thickness, and changed the combination of layers of bond line thickness, and we actually plot our curves showing how all those parameter changes affect that frequency of the curve peak.
- DR. BUCKLEY: Well, the first peak I don't think is the dumbbell mode; I think the splitting is a function of the dumbbell mode. The first peak is a standing wave I'm talking about. And George isn't talking about the normal standing wave.
- DR. GEORGE ALERS (Science Center): Yes.
- DR. BUCKLEY: You are? At 300 KHz?
- DR. ALERS: Right.
- DR. BUCKLEY: That's a thick bond, then. Okay.
- DR. CHANG: That sort of describes the difference between the dumbbell model and the layered wave calculations.
- DR. BUCKLEY: I'm impressed.
- DR. GEORGE ALERS: Bruce Thompson and Dick Elsley attacked this problem which we called the dumbbell mode, and Bruce calculated the stress distributions throughout the whole sandwich structure, and it's an approximation to say that the aluminum moves as a rigid body. And if you do the back of the envelope calculations for the masses and springs, you only get close to the right answer. But Dick and Bruce's programs, two different programs, predicted what that mode was and I think they came right on. Now maybe we weren't very critical about what we meant by agreement, but it is a standing wave in the total thickness, and the stress distribution in that standing wave-- all the stretch-is in the adhesive and very little in the bonds, and it is the first mode you run into as you come up from zero.
- DR. BUCKLEY: Okay.
- DR. ALERS: I might ask Dick if he wanted to add any comments on that splitting and stuff. He has looked into that a lot more than any of us.
- DR. RICHARD ELSLEY (Science Center): The usual adhesively bonded structure can be viewed as a simple harmonic oscillator at the lowest frequency with the metal adherends acting as masses and the adhesive layer as a spring. At higher frequencies, each individual layer can be viewed as an individual standing wave resonator, generating harmonically related "lines" in any graph of frequency dependent properties. However, because the layers are mechanically joined, these resonators represent coupled oscillators and each resonance then appears as a split pair of "lines". We have found it to be very instructive to graph the frequencies of all the resonant "lines" as a function of the adhesive layer parameters to display what happens when the adhesive resonances cross or interfere with the aluminum plate resonance. The result is like an energy level diagram in solid state physics complete with not-allowed level crossings and the resulting distortion of the mode frequencies in the vicinity of the crossings.
- DR. BUCKLEY: Empirically you can see that and you're giving a simple explanation for a spectra that sometimes seems fairly complicated.
- DR. JERRY TIEMANN (General Electric): It seems to me that when you're doing this inversion operation you should consider doing it in the time domain rather than the frequency domain, because in the time domain you don't have these subtle questions of what's causing a splitting or what mode is this or what mode is that. Each reflection comes from one well-defined surface that you can really relate to what you know about the physical shape of the object you're looking at. And if you go one layer at a time down through there, you can actually separate the problem into a whole sequence of small dimensional fits instead of one great big N dimensional fit all at once as you would have to do if you did it in the frequency domain.

DR. BUCKLEY: That's what I don't agree with. At least from our work if you take that layer and try to separate it out from the rest of the structure, i.e. make it an infinitely thick aluminum structure, that affects the time spectra, too, theoretically. It is coupled, and I don't know to what degree of subtlety we have to go in this spectra to extract the information of interest. So, again, we did take a brute force approach because it does affect it. It isn't completely separated, it does traverse the other material in going through the bond line. So, we decided okay, it does do that, we'll just handle it and avoid that problem or that question. Additionally, the question of how you set a window in the time domain and the subtleties of that to avoid any disturbances of the frequency spectra are kind of involved, at least to me they were kind of involved. So, we just said we'll just avoid that problem, also.

PROF. WILLIAMS: Thank you very much, Mike.

In concluding the Session II here, as an interloper, it's very pleasant for me to listen to the path of progress presented by you all this morning and this afternoon. However, I would like to compliment the members of the NDE community for what is a tremendous amount of progress since the last time I had an occasion to participate, like three or four years ago. Perhaps there are a few new members, and I would like to warn that there are a few alligators in the swamp. If I may be permitted the chairman's prerogative for just a few minutes, I would like to remind you of a few of these, and I don't mean to imply that there are too many and we cannot live with them.

The first goes back to a comment made last night, relating to human factors. These human factors relate to such things as we've heard recently in the Alaskan pipeline where, for one reason or another, various measurements that were thought to have been made were not made. The economic difficulty has been rather large.

A second area in human factors is more or less an apocryphal story that was told to me when I had my first baptism to the NDE fire. Measurements using ultrasonics were made on flat plates by men in the laboratory running the gauges across the flat plates watching for the perturbation of the needle. And it was told to me at that time that they had a human factor difficulty because at the time this was first introduced, the ladies in the plant were still walking through in dresses and skirts. It was quite frequent, it is alleged, that sometimes the inspectors reading the needle took their eyes off the needle giving omissions at sometimes critical points.

Now, in a serious aspect of that, that same kind of steel plate was put into a 260 inch rocket motor case at Newport News for a very large rocket motor. When it finally failed due to hydrostatic testing there was a crack one and one half inches long in a plate of MAR 18 steel over an inch thick. There was human error involved, partly due to specifications, partly due to plain missing the crack because of its orientation with respect to the ultrasonic device used. Now, these are the human factors.

The second comment I would like to make concerns the importance of the interpretation of the end result, fracture and structural integrity, the purpose for much of the work being done. I think it's extremely important that the members of the NDE community recognize that there are some alligators in the fracture mechanics swamp, too. I'll mention one. There has been much glib comment about the use of, say, Griffith's theory to determine critical flaw size. There is a dicotomy with respect to measurements and understanding of fracture in metals and to some extent polymers using the Griffith energy theory, which is supposedly straightforward.

It occurs to relatively few people that, in the ceramics business (of which we are going to hear in the next talk) the ceramics community generally speaking does not use Griffith energy theory for failure; they use vital statistics. And there's not a priori fundamental reason why fracture is fracture and a rose is a rose. Why should one not be able to interchange fracture theory energy and fracture theory statistics? But if the members of the NDE community do not appreciate that there are different interpretations and different reasons for those interpretations, you could, perhaps, get bitten by one of these alligators.

The third and last comment I would like to make is that I don't disagree with the present interpretations and procedures at all. But I would like to stress very strongly the importance that you all and we all attach to and utilize in the premise of linearity in the interpretations that we make. It's important in understanding the material behavior which most of the time is assumed to be linear and elastic. It is not linear and elastic and that affects many of the estimates that are made. It affects whether you are, perhaps, concerned with a resin, which is, first, linearly viscoelastic if you're lucky, and perhaps, if you're somewhat lucky, subject to a time and temperature shift so the temperature and frequency effects can be interchanged in an ad hoc but reasonably satisfactory region, or if you're very unlucky, a completely nonlinear material where the effects are felt most at the lower frequencies or at the higher temperature.

So, from first material aspects there are nonlinearities that bite you. There are nonlinearities that I don't know how to handle when we deal with Fourier transforms and other transforms that are bandied about in making the calculations to interpret the experimental data that will then be used as a judge on the engineering results.

So, in times of this type of difficulty, or this alligator in my analogy, I would summarize by suggesting serious consideration be given to human factors, to the proper incorporation of fracture analysis by the NDE community and third, the very proper use of linearity where justified, but to consider as a possible difficulty that introduced by nonlinearities of material and geometric types.