

APPLICABILITY OF ULTRASONIC RESONANCE
SPECTROSCOPY TO NDE OF ADHESIVE BONDS

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What I will talk about is the work we have been doing on ultrasonic spectroscopy and its potential application to the NDE of adhesively bonded structures. One potential application is in measuring the aging process of adhesive bonds, a problem that was described in an earlier paper this morning.

Figure 1 shows the experimental setup we used. A Hewlett-Packard 2100A computer is the heart of the system. The Hewlett-Packard and Tektronix scopes are used mainly as a delay and as a scanner. A Mosley X-Y recorder is connected to the computer via the D to A. We have used several different types of pulsers, all with several degrees of success. We have used an Automation UM 771 reflectoscope, a Hewlett-Packard 214A pulser, and a Panametric pulser in our work.

The desired RF waveform of the ultrasonic signals are displayed on the scope. A voltage from the D to A sweeps the horizontal sweep in the scope in 256 equal steps. The amplitude of the digitized waveform goes to the computer via the A to D. The computer computes the Fourier transform analytically, and plots the result directly on the Mosley X-Y recorder.

The second figure shows a typical pulse we are using, very short in duration. The reprocessed pulse shown on the left, is the pulse that has been digitized and replotted out for the purpose of comparing whether or not there has been any distortion introduced during digitization. On the right is shown the reference pulse. We generally use the first reflection from the top surface of a specimen as the reference. This series of pulses represents the reflected sound energy from the first top surface, the first bottom, and second bottom surface from a quarter of an inch aluminum plate.

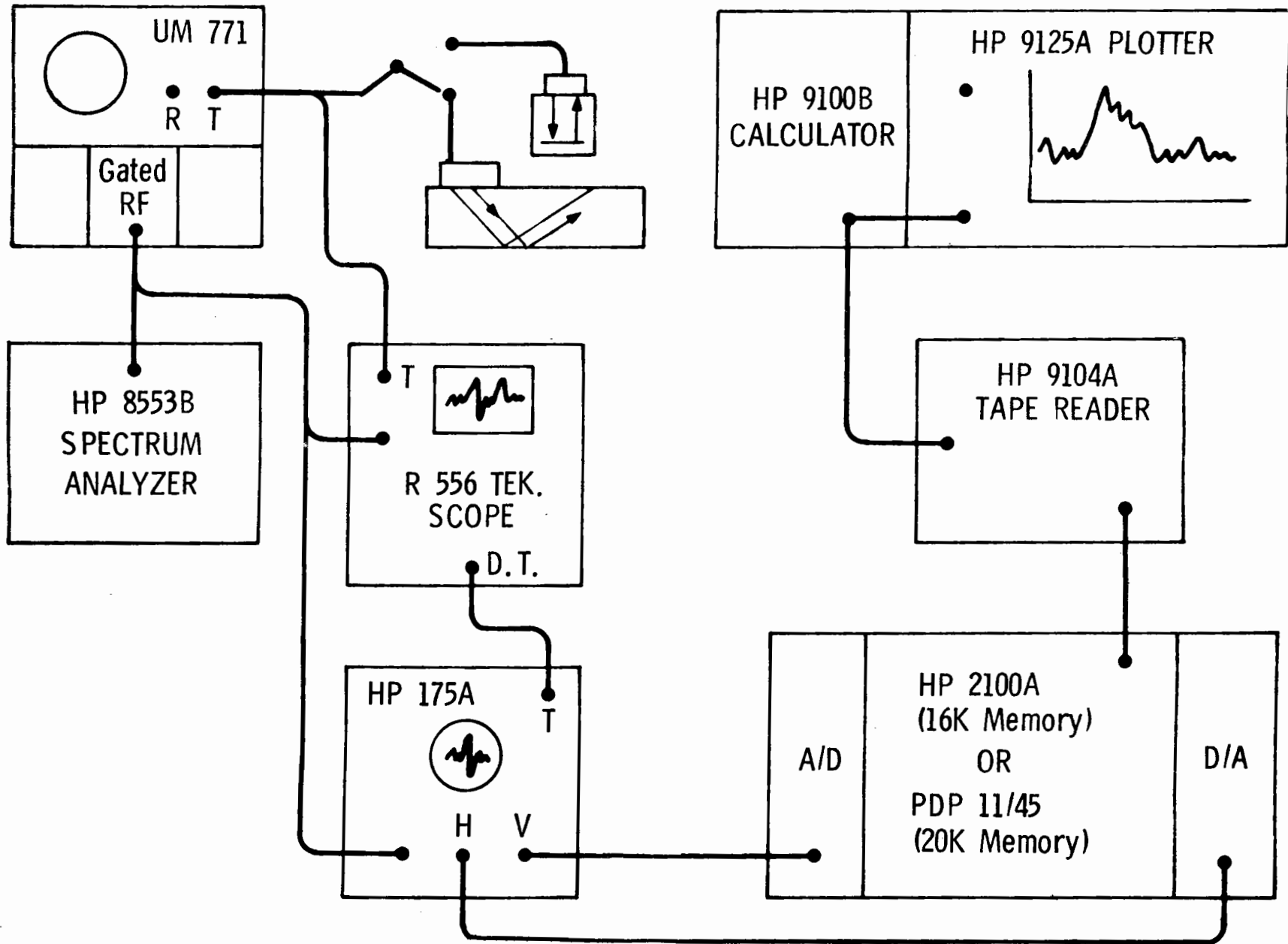


Fig. 1 Block Diagram of Experimental Setup For Signal Processing

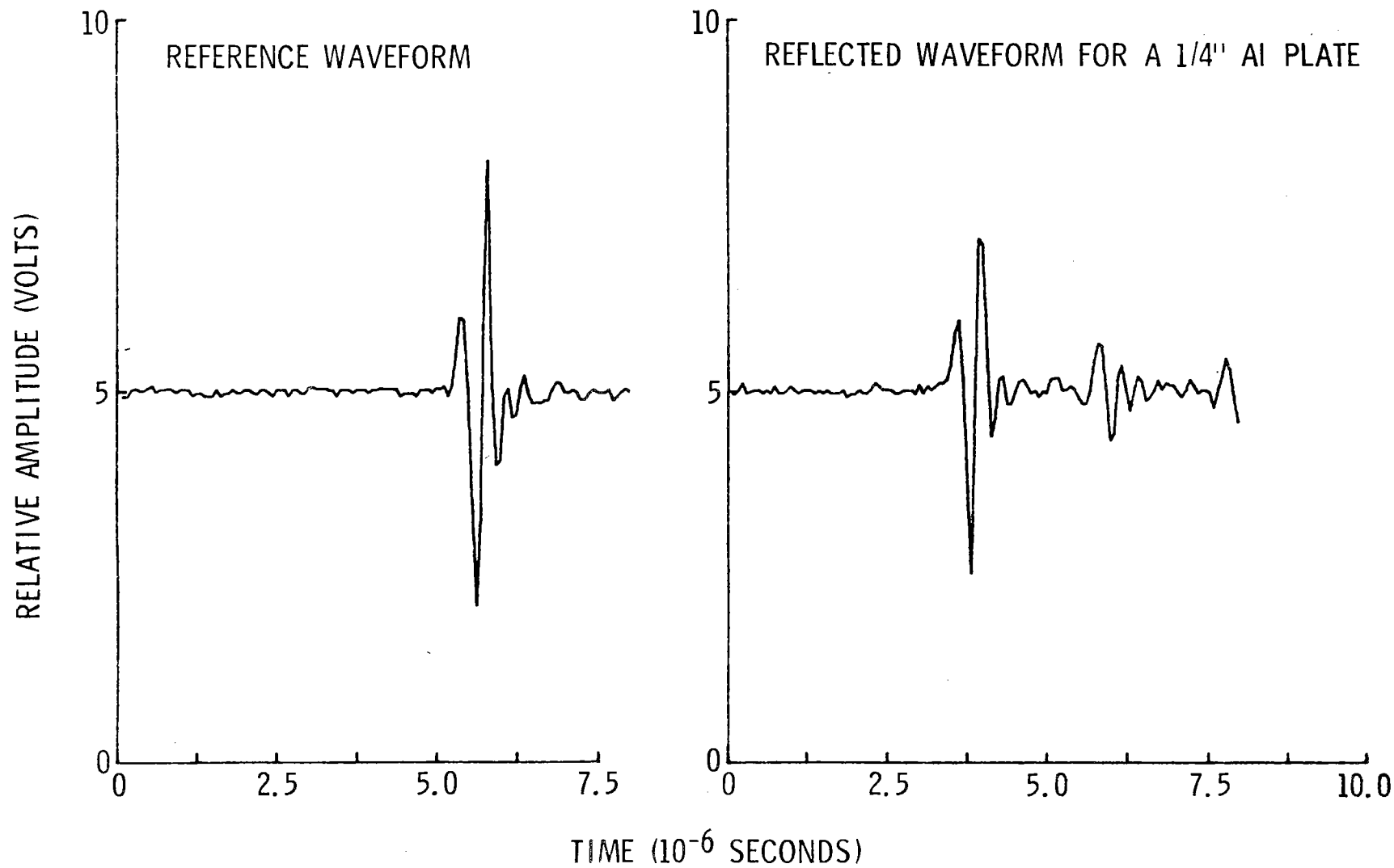


Fig. 2 RF Waveforms Of The Reference And
A 1/4 Inch Al Plate

Typical transformed results are given in Fig. 3. These results were obtained in aluminum while operating in the reflection mode. The upper curve is the reference spectrum. It is obtained by transformation of the top surface pulse. The lower curves are Fourier frequency spectra for an eighth, quarter, and a half of an inch aluminum plate. Each spectrum shows a series of resonant dips. These resonant dips are set up whenever there are integral half wavelengths of sound within the plate thickness. The relationship is given by

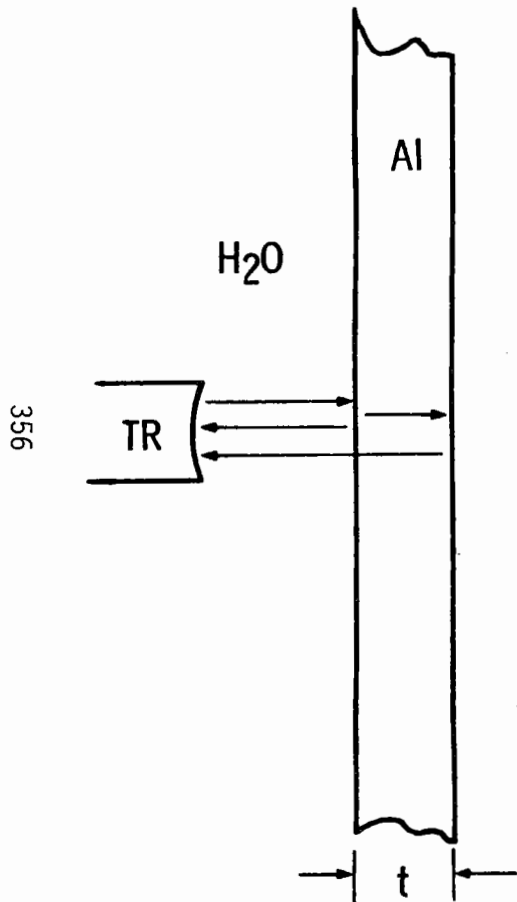
$$t \text{ (plate thickness)} = n \text{ (integer)} \frac{\lambda \text{ (wavelength)}}{2} \quad (1)$$

You can obtain the thickness of the plate by knowing the frequency spacing between resonant dips, provided you know the velocity of sound within the medium. On the other hand, if you know the plate thickness and the frequency period, you can measure the velocity of sound within the medium.

Figure 4 shows the results obtained in the through transmission mode. It uses two transducers instead of one. The difference here is that these are the normalized frequency spectra obtained by dividing the spectrum by the reference spectrum. Normalization minimizes the effect of transducer and electronic frequency bandwidth limitations. These spectra are also plotted on a linear scale as compared to a log scale. Unlike the reflection mode, the sound energy is at a maximum at resonance for the through transmission mode. The resonant peaks are much sharper and the spacing between peaks are more distinguishable in these normalized spectra. As in the case of the reflection mode, you can obtain the plate thickness from the period of resonance.

You not only can obtain Fourier spectrum with compressional waves at perpendicular incidence, you can set up resonance and measure the plate thickness using shear wave at many angles of incidence. Figure 5 shows an application of a shear wave using one transducer incident on a plate at an angle of 45 degrees, and again you get a series of resonance dips because we are operating in reflection. Again, from the resonant periods you can measure the plate thickness. The relationship will be a little more complicated because of the angle, and you now have to use the relationship shown on the figure in order to obtain the plate thickness.

- PULSE ECHO
- LONGITUDINAL WAVES
- NORMAL INCIDENCE



$$t = \frac{C}{2 \Delta f} \quad \text{or}$$

$$C = 2t \Delta f$$

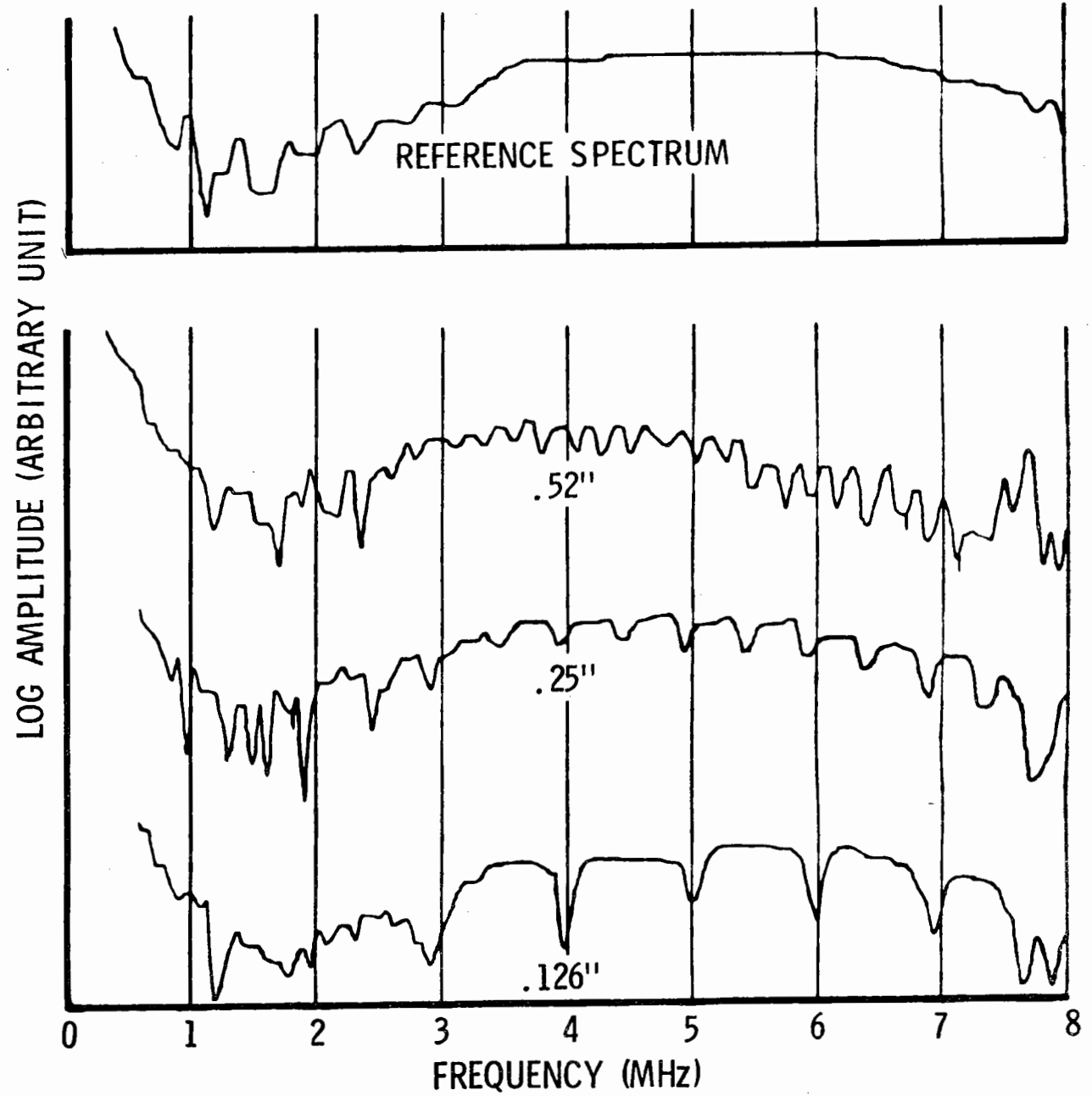
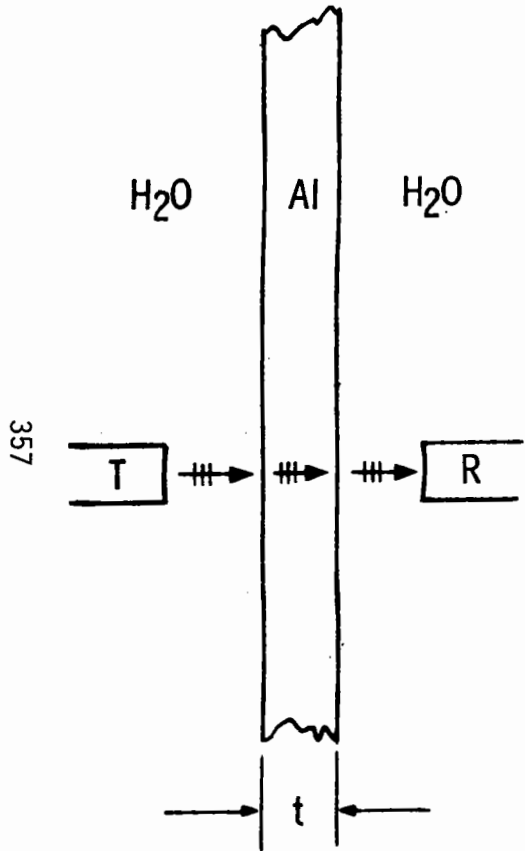


Fig. 3 Measuring Plate Thickness Or Compressional Wave Velocity

- THROUGH TRANSMISSION
- LONGITUDINAL WAVES



$$\Delta f = \frac{C}{2t}$$

NORMALIZED LINEAR AMPLITUDE (ARBITRARY UNIT)

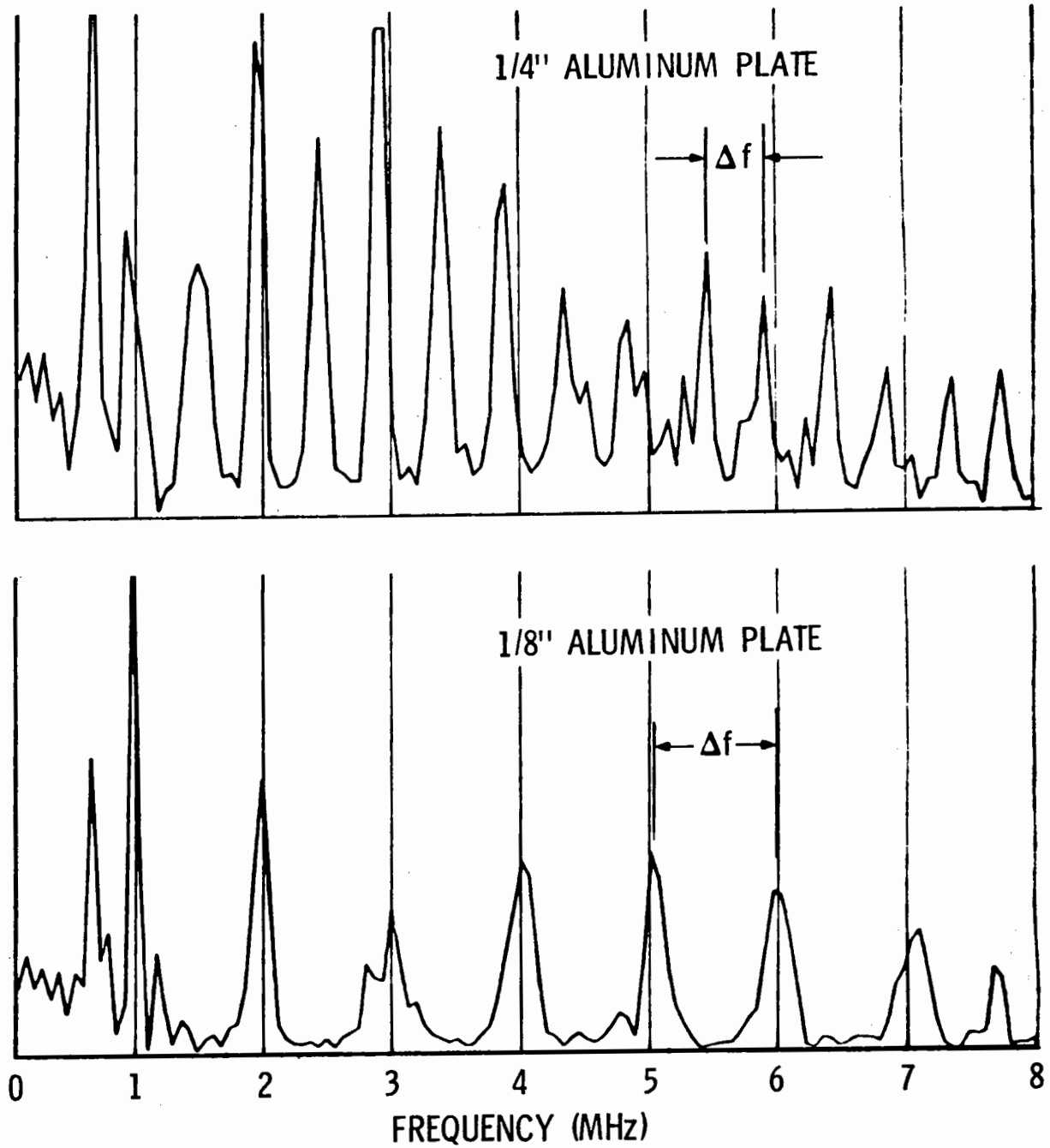
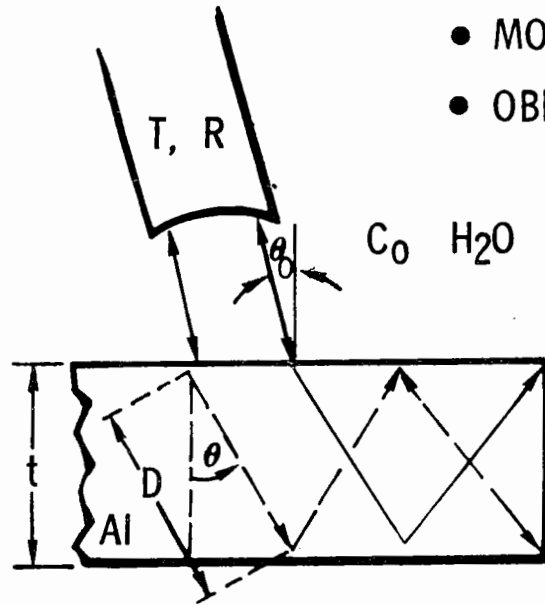


Fig. 4 Measuring Plate Thickness Or Compressional Wave Velocity

- PULSE ECHO
- MODE CONVERTED SHEAR WAVES
- OBLIQUE INCIDENCE



$$t = \frac{b}{2 \Delta f \cos \theta}$$

$$b = \frac{C_0}{\sqrt{\sin^2 \theta_0 + \frac{C_0^2}{4t^2 \Delta F^2}}}$$

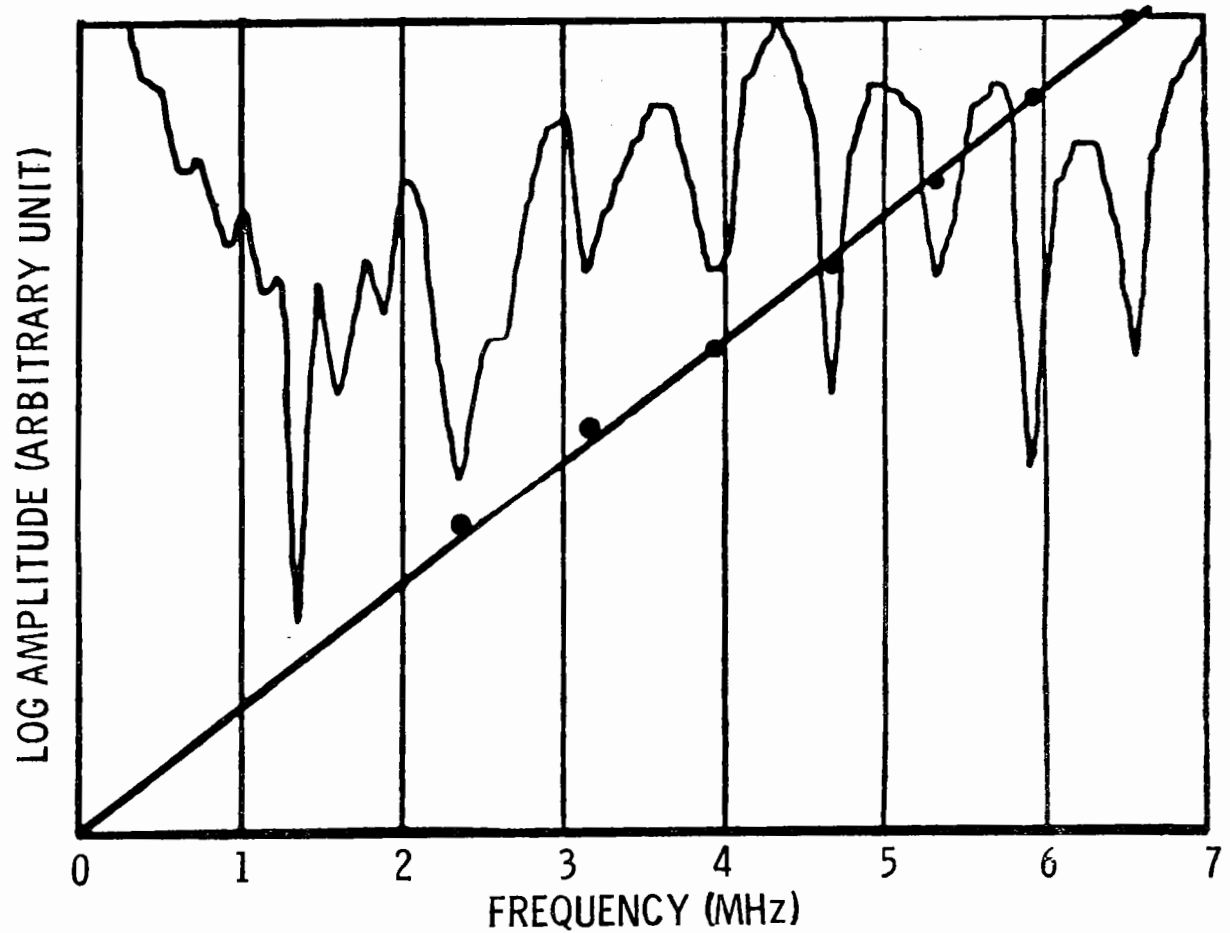


Fig. 5 Measuring Plate Thickness Or Shear Wave Velocity

Well, measuring the plate thickness really isn't our goal. Our objective is to measure the opening of a slot, or eventually, a more natural type of discontinuity such as a fatigue crack. In Fig. 6 are shown some results we obtained using a slot about 23 and 43 mils by about 50 mils deep, and again using shear wave operating at 45 degrees. Now, we gated and digitized the wave form pertaining only to the signal caused by this discontinuity or this slot. The top curve is the reference spectrum. Along with it are shown the spectra obtained from a 23 mil slot from the 43 mil slot. Again, you can use the relationship shown previously to obtain the width of the slot. So, by this method, you can measure the gap opening. Potentially, you can measure the depth of this slot as well as the orientation. We have not had any luck in measuring the depth from this type of approach, but potentially or theoretically, you should be able to measure the depth.

One of the more interesting cases we have studied is the multi-layer case. Here we have a system of an aluminum plate 50 mils, a water gap of 9 mils, and an aluminum plate of 50 mils. This was done as a prelude to the adhesive problems we are attacking at the present. The theoretical calculation given in the upper curve of Fig. 7 shows that you have a series of resonance peaks as you would expect from resonance in the aluminum and the water gap line. One thing that we noticed that is interesting is that there is a line that does not belong to either the aluminum or water series. It appears that there is a line split. From a series of parametric theoretical studies involving different gap thicknesses and acoustic impedances of the material in the gap, we have found that the amount of splitting depends on, first, the difference in acoustic impedance between the parent material and the discontinuity and, second, the dependence on the proximity of the two lines to each other. In other words, if the discontinuity line is far away from the aluminum line, the splitting is very little, if any at all, but if the water line is close to it, the splitting is considerable.

These calculations were obtained using a continuous infinite plane wave model, one of the simplest models you can use. Of course, the first

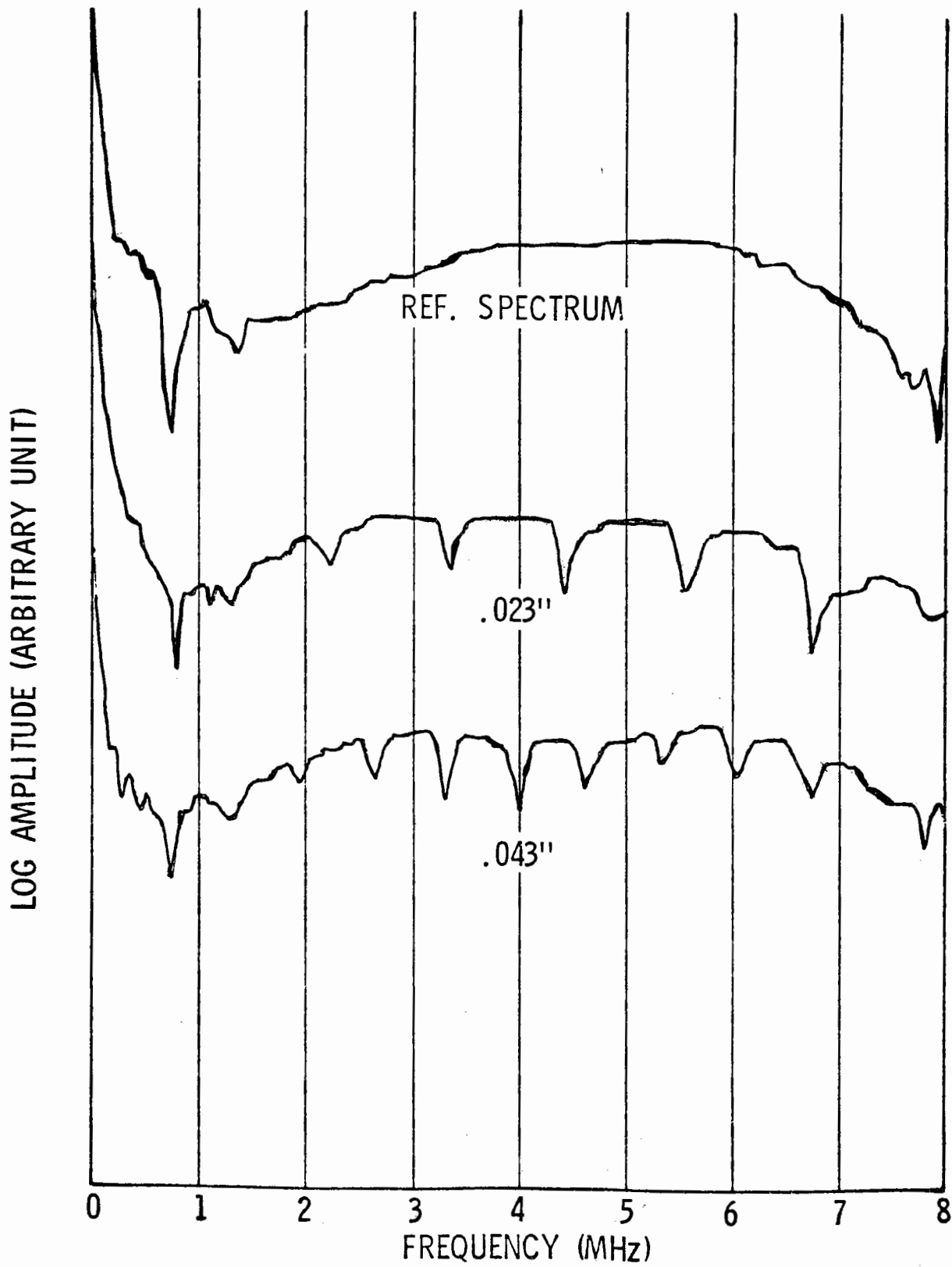


Fig. 6 Frequency Spectra Of The Reference, 0.023 Inch, And .043 Inch Water Filled Slots In A 1/2 Inch Al Plate In Shear Wave

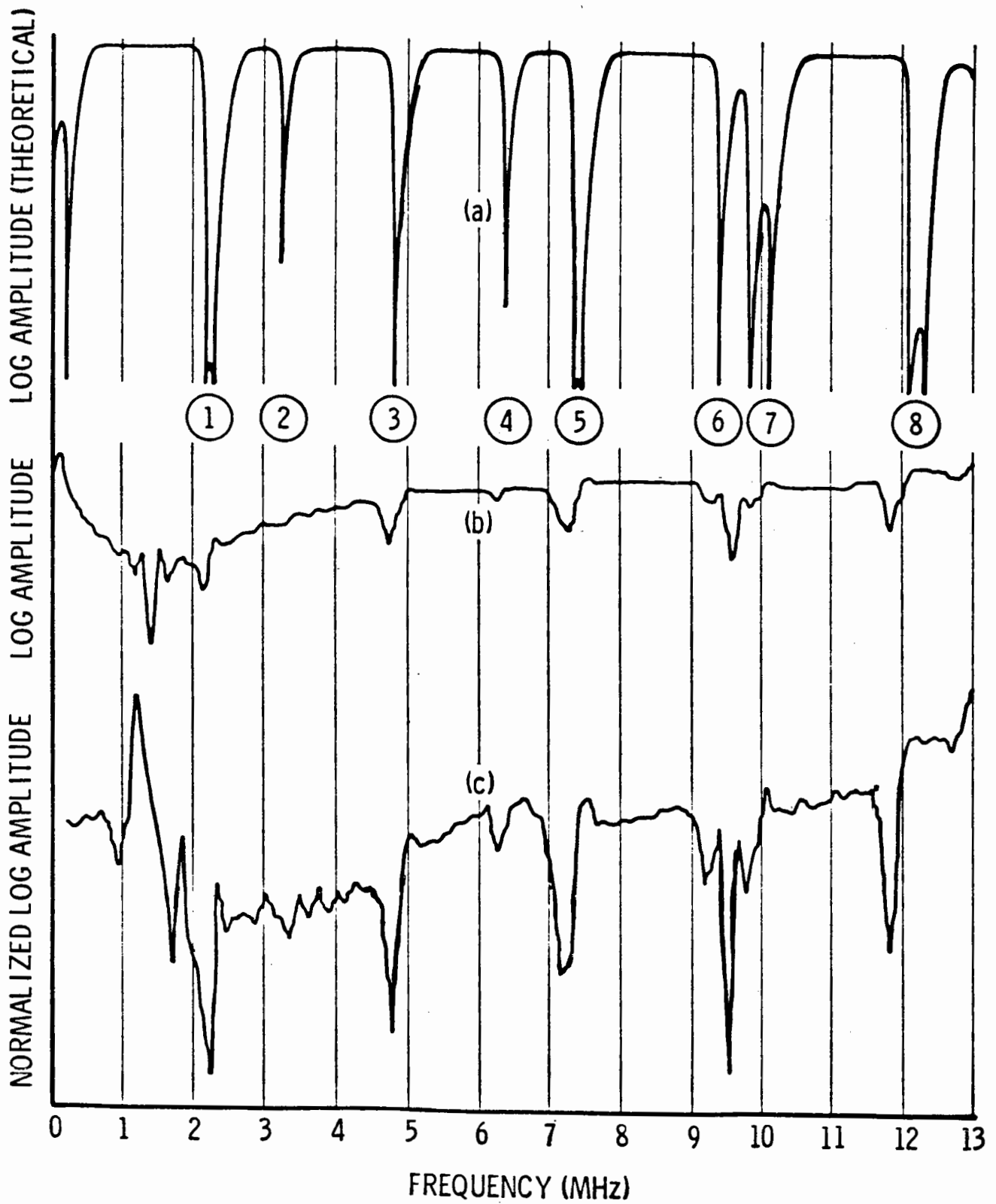


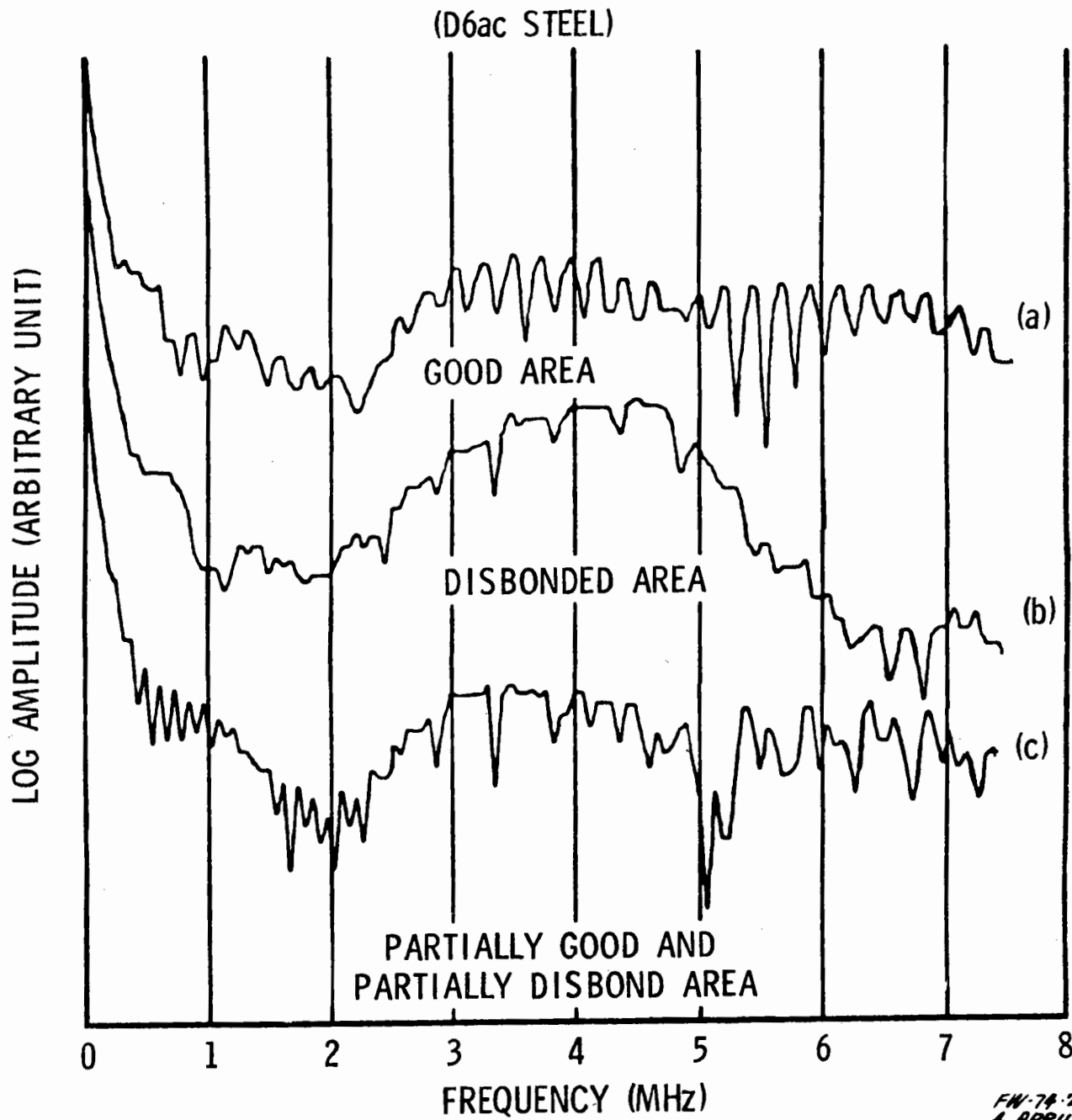
Fig. 7 Theoretical, Experimental, And
 Normalized Experimental Spectrum
 of A 0.05" A1-0.009" Water Gap-0.05"
 A1 Assembly

question we asked is, "How would this be related to the frequency spectrum in which we use very short pulses?" Well, actually, they are related because the short pulses contain many continuous wave components and the aluminum plate and water gap select the resonant frequency components from the components within the pulses. When we did the experiment, we did find the aluminum line, the water line, the aluminum line, and the splitting in good agreement with the continuous wave theory. The second curve in Fig. 7 shows the experimental results in log amplitude, and the bottom curve shows the normalized spectrum. The normalized spectrum enhances the line splitting and brings out the water lines considerably more than in the unnormalized case.

What these results promise to do is to permit you to monitor the change in the acoustic impedance of the material in the discontinuity, thereby providing you with a tool to monitor the thermal and environmental aging process in adhesive bonds.

A potential application of this work to the real world problem is to diffusion bonds, adhesive bonds, and braze bonds. Figure 8 shows the frequency spectrum from a diffusion bonded specimen. This was a specimen that was bonded from two, quarter-of-an-inch thick plates to give you a total of a half-inch thick on a well-bonded area. So, on a well bonded area, you have a resonance period corresponding to a half-inch thick plate. In a nonbonded area we have a resonance period corresponding to a quarter-of-an-inch plate, and the frequency spacing is twice that of the half-inch plate. When you place the transducer partially over a good and partially over a bad area, you get two resonance periods. You get a resonance corresponding to a bad bond and a resonance corresponding to a good bond.

Now, a more interesting application of resonance spectroscopy is to measure the acoustic impedance of a material. You can do this either using a compressional wave at normal incidence or a shear wave at oblique incidence. The results shown in Fig. 9 are those for a shear wave at 45 degrees. We cut a slot in the material, as shown in the inset, and we fill the slot up with



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Fig. 8 Detecting Partial Diffusion Bonds

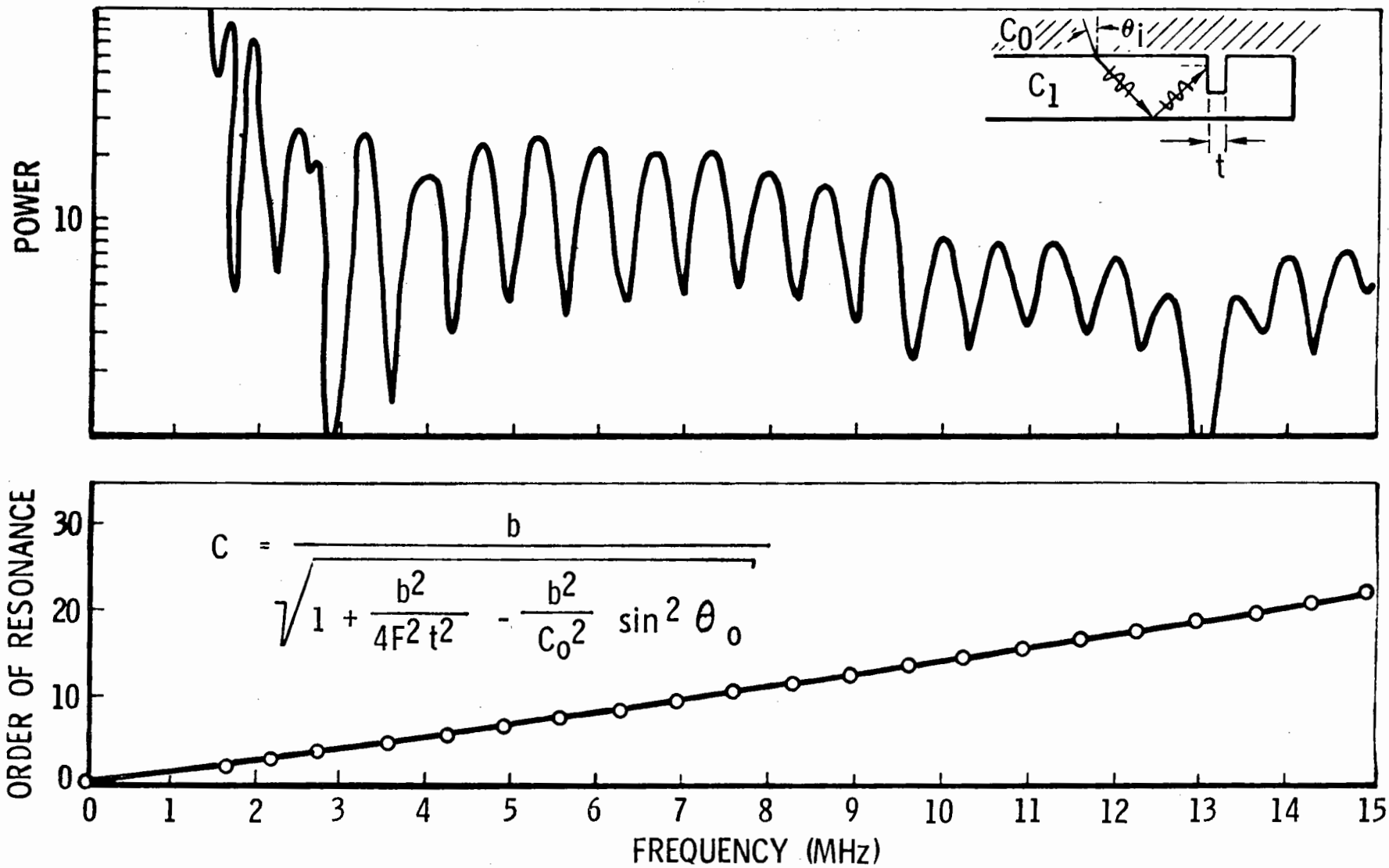


Fig. 9. Measuring Velocity Of Sound In Mercury

different materials; in this case, it is mercury. The results show a series of resonances, and you can measure the width of the gap by knowing the resonant period. More importantly, you can measure the acoustic impedance by measuring the Q of the resonance. We have developed a relationship which I won't have time to go into, to determine the acoustic impedance from the measured Q. The experimentally measured Q for mercury is around 5. The Q for mercury is low and is pretty broad and not that well defined. In the case of water, however, the Q is 17.7. It is much better defined. These results are given in Fig. 10.

The data we have shown here is still in a rather elementary stage. We are continuously refining the system and hopefully, we will be able to get the scattering of the data down to a smaller degree so we can get a more well-defined curve for the acoustic impedance.

So potentially, you can apply ultrasonic spectroscopy to measure the acoustic impedance of a discontinuity by measuring the Q of the resonance or monitor the aging process in adhesives and composite materials by measuring either the change in the acoustic impedance or resonant line shift.

$$P(Q, t/\lambda) = \frac{\sin^2(\pi/Q)}{\sin^2(\pi/Q) + \sin^2(2\pi t/\lambda)}$$

$$Q = \frac{\pi}{\sin^{-1}\left(\frac{2r}{r^2 - 1}\right)}$$

$$r = \frac{\rho_1 c_1}{\rho_2 c_2}$$

Q
=

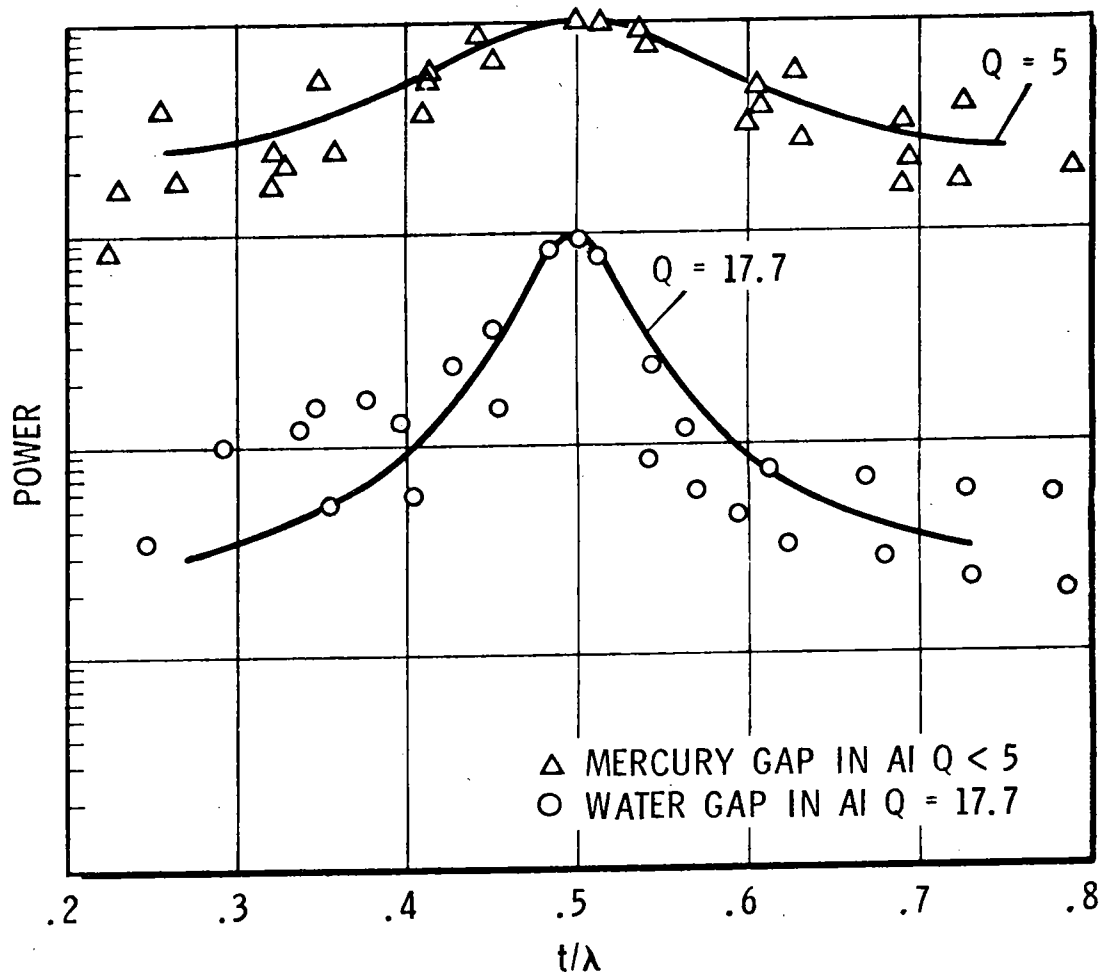


Fig. 10 Measuring Acoustic Impedance Of Materials

DISCUSSION

LIEUTENANT MICHAEL BUCKLEY (Air Force Materials Laboratory, WPAFB): Bill, this technique results in very short pulses which you described initially as interfering and causing the spacing due to the thickness of the material?

DR. YEE: Right.

LIEUTENANT BUCKLEY: This isn't really fair because you didn't hear Dennis' talk, but he didn't observe that phenomenon, if I am correct, with a short pulse, and I am curious to resolve this.

MR. DENNIS CORBLY (Air Force Materials Laboratory, WPAFB): Let's meet in a bar someplace. I think Bill will agree with me that it is just a question of a pulse duration that may be less than the travel time through the plate.

DR. YEE: Right.

MR. CORBLY: If we take and gate the series of reflections into a spectrum analyzer and through a Fourier transformer, we are naturally going to see the product spectrum of the number of echoes, and if there is a group of them in the gated area, they are going to undergo more constructive or destructive interference depending upon the more repetitions you let in there.

LIEUTENANT BUCKLEY: But that standing wave would depend on repetition, too?

DR. YEE: No. I wasn't here but maybe you are talking about gating to one pulse only. Right?

MR. CORBLY: Right.

DR. YEE: Gating to one pulse, we find the information is there. We have found that you could obtain periodic interference patterns. You can get a resonance gating to one pulse provided you gate it on the 10th or 20th pulse. The information is there because the waves have been bounced back and forth, and when you gate on the 10th or 20th echo, it is kind of like a filtering effect, but you could get resonance and thereby a

plate thickness by gating to one pulse. You don't have to gate to two pulses to get the plate thickness. However, you have to gate it to the 10th or 20th reflection before you can get it. We have observed that, but if you gate it on the first few, you won't see it.

DR. ROD PANOS (Air Force Materials Laboratory, WPAFB): I am interested in what you are talking about on the line splitting. You observed it whenever the water interference signal became very close to the substrate interference signal?

DR. YEE: Right.

DR. PANOS: I'm sorry, I just don't understand exactly what is going to cause that splitting. I would like to know more about that.

DR. YEE: We have gone back, first, to the theory to see what gives rise to this resonance, and we have gone back term by term and found the different terms that contribute to this interference resonance and to the splitting. So theoretically, you know, it is there. Physically, we have not been able to come up with a satisfactory model or an analogue to describe this. We have thought about three models. The first one involves two electrical signals beating together in the case of a mixer. Then you will have, as you know, side bands of different frequencies. Maybe a better analogy is two spring-loaded systems with mass and with different spring constants. If you set them in motion, you will get these other side bands.

DR. PANOS: What you are talking about isn't a true frequency causing a beat, you are seeing the interference signal. Now, you have got two interference signals that are in proximity with each other.

DR. YEE: Right.

DR. PANOS: I don't quite see how that analogy fits. I don't see that that analogy follows from one interference signal next to another interference signal and a beat causing a splitting due to the difference between those.

- DR. YEE: All right, there is another way of explaining this line splitting. If you take the thickness of the plate and the thickness of the water and assume that it is one system, you can also show that you can get a resonance line corresponding to that total sum thickness of one plate and one water line.
- DR. DON THOMPSON (Science Center, Rockwell International): Without going into your modeling, Bill, do the attenuations add in this system?
- DR. YEE: You mean the line splitting?
- DR. DON THOMPSON: No, with respect to the Q's. Are they additive?
- DR. YEE: We are only gating to the signal at the discontinuity so the attenuation of the parent material does not enter into the calculation of the Q of the discontinuity resonance.
- DR. DON THOMPSON: You see one Q factor because of the mismatch between the material and there must be another. Is there not another Q that you see due to the layered material itself?
- DR. YEE: We gate out the resonance only corresponding to the discontinuity. So the Q we get is only from the material at the discontinuity and has nothing to do with the metal substrate.
- DR. GEORGE ALERS (Science Center, Rockwell International): Have you taken into account any of the damping that might be in the metal, the slot, or the water?
- DR. YEE: No, damping has not been taken into consideration.
- PROF. GORDON KINO (Stanford University): What are you using for the transducers over this very wide frequency range? Are you using a series of them?
- DR. YEE: No, we are just using a single transducer. We have tried transducers made by Automation and Panametrics. We find those by Panametric generally give us the better result, but we don't use specialized transducers.
- DR. KINO: You just compensate for the differences in the amplitude?

DR. YEE: Well, you have to have a pretty short pulse.

DR. KINO: You are going from about two to eleven megahertz?

DR. YEE: One to fifty.

DR. KINO: It works?

DR. YEE: It is not very difficult. You can get a 15 megahertz transducer and it will go up that high.

LIEUTENANT BUCKLEY: Is there any constant phase relationship in the way you excite the system?

DR. YEE: We have done two things, Mike. We have done it using a short pulse excitation of an L-C circuit which is tuned to some frequency. We also just send a pulse in, a square wave pulse, and shock excite the transducer.

LIEUTENANT BUCKLEY: We will have to talk about this at another time. I don't understand the interference effects if you don't have definite phase relationships.

DR. YEE: The easiest way to look at that is that each of those spikes from the bottom surface reflection corresponds, let's say, to many continuous waves components. The plate or water gap acts as a resonator and selects a frequency component to set up resonance.

DR. MEL LINZER (National Bureau of Standards): Do you find any power dependence on the splitting of the spectra? The other question I have is, if you consider a system of coupled resonators, which is what this is, can you get that same type of a splitting?

DR. YEE: I cannot give you the answer to that question at this time. We are just starting to do work with a coupled oscillator system. It is just two mechanical springs and the mass, but we haven't got to the point yet to be able to say, "Yes," but to me that should be the case. It is a linear system and the equations governing the wave propagation, whether it is ultrasonic or electromagnetic waves, are quite similar. I can't see any difference.

DR. LINZER: Maybe you can get that type of spectrum in the microwave categories.

PROF. HENRY BERTONI (Polytechnic Institute of New York): I just mention that what you really have when pulsing and taking the Fourier transform is equivalent to making reflection measurements in CW and then plotting results as a function of frequency. You are doing it at a lot of different frequencies and then you get a filter characteristic. It would be the same thing as the transmission line problem if you use a lot of line segments and the multiple reflection that would interfere would give you the same kind of response.

DR. BERNARD TITTMANN (Science Center, Rockwell International): Have you considered at all a slot with a strong taper as a function of the depth?

DR. YEE: Yes, but we just haven't done it yet. We have some data on tapered composite plates and still obtain resonance.