The NDT Program at Stanford University

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Jerry Tiemann talked this morning about various ways of giving a paper. I was undecided what to talk about, so I thought I would tell you a little about a lot instead of a lot about a little.

Some of the things that are going on at Stanford include my own, Shaw's, Auld's and Quate's work. In particular, one of the things that was mentioned this morning which I think is very exciting, is Shaw's work on PVF2 plastic transducers. He is obtaining very broad bandwidths of the order of 10 MHz with absolutely flat responses. These are very impressive transducers, and I think they are going to be very important in the future.

We are also carrying out a great deal of research on acoustic imaging in various frequency ranges. Some examples are the Fresnel lens of Auld, the acoustic microscope with 1 micron definition of Quate, and the electronically scanned acoustic imaging arrays by Shaw, Waugh, and Kino. In this work, we have, perforce, been very much involved in how to make transducers for imaging systems. So, I will spend the first part of my talk discussing transducers, and try to relate this to some of the things we have heard in other talks on aircraft materials.

We are basically concerned with various kinds of signal processing techniques. These are the kinds of things that an electrical engineer, when he first meets NDT, says, "Oh, this looks interesting, why aren't they doing more signal processing?" So, we come along and we try to do more signal processing. Some of the signal processing is aimed at imaging, and using some of it for improving the signal to noise ratio and some for pattern recognition.

One obvious approach is to say, "Phased arrays ought to be good; we ought to be able to use, instead of one transducer, a large number of transducers. If we can do that we can gather information much more quickly." Mucciardi talked about one aspect of this. He usually moves one transducer to several places; but he ultimately talks about using several transducers, and then use signal processing to essentially deal with that information at a relatively high speed. Here we shall talk about other techniques.

If one wants to make a transducer array, one must have a large number of separate elements. Some of the problems and structure are illustrated in Fig. 1. Typically, they are put on a backing medium which is, in our case, tungsten powder in epoxy. They may have matching on the front with matching layers and so on, and they have to have slots cut between them to separate them, so that there is not too much coupling between them. The immediate problem is to learn to make one transducer correctly, because, with an array, one needs N identical transducers. If one cannot make single transducers correctly and reproducibly, then the problem of making N transducers in an array is infeasible.

**Acoustic Transducer Array Design**

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**Figure 1.** Acoustic transducer array design.

So, we have been dealing with that problem and it was very interesting to me to listen to the people talking about composites yesterday, because the story is much the same with our tungsten epoxy backing. In our case, we want a tungsten epoxy backing, because it is about the only material that one can use which has a high impedance and a high loss to match the impedance of the ceramics typically used in a transducer. When we first started in this field, we tested a number of commercial transducers. They vary, one from another, quite rapidly. The reason is that it is very difficult to make the tungsten epoxy uniform. So it was very interesting to hear what the composite people were saying, for they use just the same tricks as we do. We are very careful about sputter cleaning the back of the PZT in a press so that it is pressed uniformly; we vary the pressure to vary the packing density of the tungsten powder, and then we vacuum impregnate the epoxy. In this way, we get very uniform characteristics.
Figure 2 shows the calculated impedance of a slotted transducer element, and you can see that the calculated and the experimental results are in excellent agreement. There are some slight differences, but most of them are explainable. It will be seen that one can get the order of an octave bandwidth with these devices. We can also predict their frequency, which can be a problem with rectangular resonators. But they are very inefficient for exciting an acoustic wave in water. One of the things that would be desirable is an efficient transducer: for this one wants matching on the front rather than on the back, so that most of the power goes into the water rather than into the backing.

Now, Jerry Tiemann will differ with me, obviously on this, but we are not interested in looking at objects 1/8" away. We are interested in imaging systems where we might get 10 cm or more away, so our problems are different.

We have been working to get the bonding technology right for the λ/4 matching layers we require. We have been successful and have used multiple layers to match from water to PZT. And, again, we think the technology is in pretty good shape, although we have only done this so far with half inch diameter transducers. A result for a PZT5A transducer with two λ/4 matching layers of glass and epoxy is shown in Fig. 3. We have obtained about an octave bandwidth with a net return loss from transmit to receive and back again of about 3½ dB’s. The theory, in fact, predicts about 4½ dB’s, but we haven’t taken losses in the transformer and the matching network into account. Otherwise, theory and experiment are in very good agreement.

Now, what do we use these transducer arrays for? Last year and the year before I described the basic imaging system that we have been working with, which, of course, uses an acoustic array. So, I am not going to give a long description of this imaging system. I will just refresh your memories slightly.

In Fig. 4 is shown a transducer array used as a receiver. Each element of the transducer is connected to a mixer which mixes a signal from an element with a signal from a tap on an acoustic surface wave delay line. The whole point of this operation is to synthesize the action of a lens by signal processing. The wave front emitted from a single point is spherical; this implies that it will have a parabolic variation of phase along the transducer array. When a signal from an element of the array of frequency $w_s$ is mixed with a signal of frequency $w$ from the corresponding tap on the ASW delay line, a product of the two is formed. The output at the sum frequency $w + w_s$ will also be the sum of their phases. And, if you now sum all the phases from all the mixers, you can cancel out the parabolic variation of phase by using a signal on the delay line with the correct parabolic phase variation. But from a different point source the phase variation will be different, and so the system will not respond in the same way. Thus, we have made a matched filter for a particular point source in space.

The way we do this is very simple. You put in a signal that has a linear variation of frequency along the delay line. In other words, a linear variation of frequency going in that becomes a linear variation of frequency spatially, becomes a parabolic variation of phase. The basic signal needed on the delay line is just a so-called linear fm chirp. This produces a parabolic variation of phase along the delay line which matches the parabolic variation of phase from the array; the sum of the two is a constant. When we insert this signal into the delay line, it travels along it and gives a linear scan along a
line parallel to the array automatically. In addition, by varying the so-called chirp rate, the rate at which the frequency varies in time, you can, in fact, vary the focal length. So, it is an electronically variable focusing system.

In a reflection mode, one can use this system as a transmitter or receiver. In essence, the chirp system acts like a lens which is moving along, and it moves fast. It moves at essentially acoustic wave velocity on the acoustic surface wave delay line, which is comparable to the acoustic wave velocity, say, in water.

In a B mode reflector imaging system, as illustrated in Fig. 5, we send out a transmitted signal which is focused on a particular point and then, as the lens moves, the point scans along a line. After the appropriate time delay, we turn the array into a receiver, and pick up a signal from the same point. Thus, the lens is opposite the point at the appropriate moment and picks up a signal from it. We obtain a definition appropriate to the transverse definition of the lens, but we also get a good range definition, because if a signal from the wrong range reaches the array, the lens has moved past by the time the signal reaches the array.

In practice, we focus on one line, and scan along it with the appropriate time delay between transmit and receive. Then we change the time delays and the focal length of the lens to the next line and scan out a raster, as shown in Fig. 6, perpendicular to the array. We display images in the usual way by using the amplitudes of the received signal to modulate the intensity of the cathode ray tube which is being scanned in synchronism with the acoustic scan.

Last year I talked about the reflection we obtained in water. I also talked about transmission images in bonded epoxy samples and boron fiber reinforced epoxy samples. This year I will show you some of the kinds of things we have done in metals; this is basically an illustration of what real time imaging systems can do.
Now, to obtain images from the interior of a metal sample, we have been using shear waves. We have cut a block in the appropriate way, as shown in Fig. 7, and insert the beam at the right angle to excite a shear wave propagating along the metal parallel to its surface. If the beam is properly focused in water, it will focus and scan, in fact, in the metal.

![Figure 7](image1)

Figure 7. Schematic of setup to excite Rayleigh waves and Lamb waves in target plates. For Rayleigh waves in aluminum $\theta_1 = 28^\circ$.

Two sets of results from a series of holes drilled in a piece of metal are shown in Fig. 8. The top set is taken at 1.7 MHz; the bottom set at 2.75 MHz. You can see that we can delineate very closely both the transverse position and the distance away from the array of the holes.

Now, we can use the same system to excite surface waves or Lamb waves by coming in at the appropriate angle, as shown in Fig. 9, and we can get focused surface waves, Rayleigh waves, or Lamb waves, as the case may be.

If you want to look at cracks, the problem is more difficult, because they are specular reflectors. So, the problem with an imaging system in the present form is that the return signal only comes from a limited range of angles. So, unless the crack is normal or essentially parallel to the surface of the transducer array, one really has trouble obtaining a good image of the crack. However, one might expect that the ends of the cracks, according to the Keller theory, would, in fact, radiate. We have been able to illustrate this effect by showing that, as the crack is rotated, an image of the end of the crack is still seen. The point about such a result is that one does see the ends of a crack with this kind of technique. But, I don't know really how reliable it is, because the basic problem is that small nicks also show up the same way, at least with surface waves, and this experiment was carried out with surface waves. But it is an indication that you do, in fact, see the direct scattering from the ends of the cracks.

Now, I want to talk about another signal processing technique. Some people have been talking about correlation; I want to show you another type of device that carries out that kind of operation. I won't go into the details of how this device works other than to say it is a surface wave delay line in which there is interaction of the waves with silicon. By reading a signal into...
this delay line, in an appropriate way, it can be stored in PN diodes laid down in the silicon. Later, another signal can be read into the device; the output is then the correlation between the original signal and the later signal. This, we believe, will become a very powerful tool for this kind of work. A schematic diagram is shown in Fig. 10.

Figure 10. Schematic of the acoustical pulse echo system.

We carried out an experiment to demonstrate how to use this surface wave correlation device in an A scan system. We took an acoustic transducer and read it into storage, as shown in Fig. 11. The whole point about this operation is that we can store such a reference echo on the device then correlate it with a later echo. If the acoustic transducer distorts these echoes, the reference and a later echo will both be distorted the same way. If the distortion is basically phase distortion, the correlation output will eliminate the phase distortion and a short pulse obtained. Alternatively, if one of the references echoes is a known defect, we can correlate it with the signal from an unknown defect to see if they are the same. The experiment here was to compensate for a poor transducer, somewhat like White's experiment carried out earlier in a different way.

We took a good transducer with a good impulse response; we read an FM chirp into it, about 6 usec long, and the first echo stored on the storage devices. We then correlated it with a later echo and we obtained a correlation peak which, in fact, is a bit wider than the original good impulse response of the transducer, as shown in Fig. 11a and b. But then we took a poor transducer with a bad impulse response and did the same thing. You can see that, essentially, by using this adaptive device we obtained a correlation peak which is much narrower than the response of the transducer, Fig. 11c, d and e.

This is an adaptive system; a very crude system, as yet. But the basic idea here is to use signal processing to clean up the response of a transducer or to use it for pattern recognition by using correlation techniques. Such devices, we believe, can make a great deal of difference to this field and, in particular, to pattern recognition. Thus, we have demonstrated that by using various kinds of signal processing techniques, it is possible to do something about speed recognition of flaws and location and determine the size, and so on, of flaws.

Thank you.
DISCUSSION

DR. EMMANUEL PAPADAKIS (Ford Motor Company): Good. Questions?

DR. JERRY TIEMANN (General Electric Company): Gordon, why does an almost periodic impulse response give a single peak and a correlation function? On the last slide, the right-hand side. I just think your student had the knobs turned wrong.

DR. KINO: No way. First of all he's transferring it up to a carrier and you are always taking the product. A minus times a minus really gives you a plus, and a plus times a plus gives you a plus also, and so you tend to get a positive--

DR. TIEMANN: But then, when you shift it by one half wavelength, you get a minus, and an almost periodic function has an almost periodic correlation function.

DR. KINO: But what we're using is a long chirp, in fact, so we're getting some more averaging.

DR. TIEMANN: -- you get the impulse response of the transducer back?

DR. KINO: No, not if you're correlating chirps.

DR. TIEMANN: Oh, yes.

DR. KINO: Only if you were inserting the chirp through the transducer and the correct matched filter for the chirp itself. Then you get the response of the transducer. That's not what we're doing; we are using the response of the transducer as a calibration, and by correlating two echoes we are removing all phase distortion.