TRANSDUCERS APPLIED TO MEASUREMENTS OF VELOCITY DISPERSION OF ACOUSTIC SURFACE WAVES

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This talk concerns two new acoustic surface wave (SAW) transducer units developed and applied to the field of nondestructive testing. We confine ourselves here to tone burst transduction of Rayleigh waves (at MHz frequencies), although CW operation and (for example) Lamb and bulk waves are also possible.

One of these new units is an array of three comb transducers and the other an electromagnetic transducer (EMT) of new design. Instead of printed circuit board or wire technology for the EMT, we used flat cable. A third transducer type - the conventional wedge - is included for comparison. We will show that the comb and electromagnetic transducers we've developed have significant advantages over the wedge. Directly below we describe our EMT's; later on in this talk we'll describe in detail the new comb design involving one transmitter transducer and two receivers.

The transducer medley in Fig. 1 shows various wedge transducers on the top row. On the bottom row from left to right are the three-comb transducer unit, a flat cable EMT, and an EMT wound from wire. A closeup of a flat cable transducer as shown in Fig. 2 shows a commercially available flat cable section with ends soldered in a meander fashion. The conductor pattern so obtained is more uniform than typically realizable with wire, as seen by the photo in Fig. 3 for an early fabrication attempt. One thing that's easy to do is to have nonuniform wire spacing. We've operated the flat cable transducers in (Rayleigh wave) transmitter-receiver delay lines. The one shown in Fig. 2 is resonant about 1.15 MHz on Al. We've obtained two-way insertion losses of 90 dB while using magnetic fields of 5 kilogauss, a single winding of 15 conductor pairs, simple matching networks, and aluminum as a SAW substrate.

Shown in Fig. 4 is a photo of a self-contained, compact electromagnetic transducer with commercially available flat cable conductors between flexible plastic backings. On aluminum the fundamental resonance is 2.2 MHz. The cable is mounted on a permanent magnet with magnetic axis normal to the flat cable surface. There was a question earlier in this conference on whether electromagnetic transducers can replace conventional ones. I'm not going to answer that completely in the affirmative, but I can say that this transducer can be hand-held and moved over a test surface at will just as one can with a wedge transducer, while avoiding the serious problems of the wedge (to be described later.)

The permanent magnet partially shown in Fig. 4 consists of a Co-Sm alloy with a maximum field of about 3 kilogauss. The field is normal to the SAW

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Fig. 1. Various SAW transducers for NDE. Top Row: Wedge Transducers, Bottom Row, left to right: Comb array, flat cable electromagnetic transducer (EMT), and wire EMT.
Fig. 2. Closeup of EMT made from flat cable with flat conductors. A uniform meander conductor pattern is formed between the two leads through appropriately soldered connections on the cable ends. Conductor center-to-center spacing is 0.050 in.
Fig. 3. Closeup of a wirewound EMT with meander conductor pattern. Note the non-uniform spacing between the wires. Spacing between holes in the circuit board is 0.050 inches.
Fig. 4. Compact hand-held EMT unit consisting of a flat cable with 0.025 inch center-to-center conductor spacing bonded onto a 1 inch long Co-Sm permanent magnet (partially visible) and electrically connected to an OSM connector. The magnet axis is normal to the cable surface.
surface as opposed to earlier, much more bulky magnet designs with the field parallel to it. With either perpendicular or parallel fields, SAW's can be generated, although acoustically somewhat more efficiently in the parallel case.

The reason why we chose the perpendicular design is that magnetically it's much more efficient. The entire magnet in Fig. 4 is less than an inch long—much smaller than the permanent magnet units used to get a parallel magnetic field close to the surface. A lot of magnet and a lot of flux return path material is needed in order to crowd a parallel magnetic field down close to the SAW surface.

The schematic in Fig. 5 illustrates some of the principles involved with wedge transducers. A wedge basically consists of a longitudinal wave transducer mounted on the sloping face of a plastic wedge (of angle θ). The coupling fluid required for acoustic contact between wedge and SAW substrate is of variable thickness and introduces velocity dispersion. Phase distortion also occurs because the bulk waves reflecting from the coupling interface are not adequately absorbed within the wedge and hence return and interfere with the surface waves.

The comb transducer involves a periodic array of rectangular teeth held in contact with the SAW substrate, as shown in Fig. 6. The teeth are vibrated into the surface by means of a piezoelectric transducer for longitudinal waves. The Rayleigh wavelength is the center-to-center spacing of the teeth. One problem with the comb transducer is that a lot of spurious bulk waves are generated. One advantage is that the insertion loss is quite low.

Now, in Fig. 7, very briefly again, we illustrate the concept of a meander EMT with magnetic field B parallel to the SAW surface. The EMT has flat conductors as opposed to round ones, and is held contactlessly above the surface with a given liftoff. The Rayleigh wavelength here is twice the center-to-center spacing so that we have less bulk wave generation than with comb transducers. The meander conductor pattern induces a corresponding pattern of eddy currents in the SAW substrate that, in the presence of B, lead to Lorentz forces which produce the SAW's. The transduction process for the EMT is reciprocal (as it is for the wedge and comb).

Table I summarizes some of the features of the wedge, comb, and EMT. Because of its requirement for a liquid coupling layer, the wedge yields distorted frequency spectra or time responses when the layer thickness changes either through evaporation or movement of the transducer along the surface. One big advantage of the wedge, of course, is that it's commercially available, although flat cable for the EMT's enjoys the same advantage. The comb can be used on any flat solid, whereas for the wedge, the angle has to be chosen for a particular medium.

The electromagnetic transducer being contactless in nature, avoid the contact problems inherent in the wedge and (to a lesser extent) in the comb. With also a simpler design, the EMT has more reproducible and simpler impulse responses. So, if we want to look at frequency signatures of small defects in materials, the EMT will mask these effects less. The flat cable EMT's are
Fig. 5. Concept of a conventional wedge transducer. A piezoelectric transducer mounted on the sloping face of a plastic wedge generates bulk longitudinal waves of velocity $V_L$ which travel through the plastic and convert at the coupling interface into Rayleigh waves (for ex.) of velocity $V_R > V_L$ on the underlying substrate. Transduction is reciprocal. Substantial coupling liquid is required.
Fig. 6. Concept of a comb transducer. A piezoelectric transducer mounted on top of a periodic set of comb teeth generates longitudinal waves of velocity $V_L$ which cause the teeth to vibrate normally to the SAW substrate, setting up Rayleigh waves (for ex.) of velocity $V_R$. Transduction is reciprocal. Clamping pressure and some coupling liquid required. Rayleigh wavelength is the center-to-center spacing of adjacent teeth.
Fig. 7. Concept of a meander electromagnetic transducer. Current $I$ sent through a periodic, meander pattern of conductors pictured here with rectangular cross sections) induces eddy currents in the surface of a nearby conducting or ground plane. A Lorentz force interaction between the eddy current and an external magnetic field $B$ generates Rayleigh waves (for ex.) on the ground plane. Transduction is reciprocal. Coupling is contactless. Rayleigh wavelength is twice the center-to-center spacing of adjacent conductors.
### Table I. Some Transducers for NDE

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<th>Transducer Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>Wedge</td>
<td>Commercially available; Available in many frequencies &amp; large bandwidth; Low insertion loss</td>
<td>Coupling fluid needed; Phase and amplitude distortion; Transducer position uncertain; Wedge angle requirement</td>
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<tr>
<td>Comb</td>
<td>Lowest insertion loss; Usable on any flat solid; Transducer position well known</td>
<td>Difficult to machine uniformly; Single phase; Requires contact force; Not translatable</td>
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<tr>
<td>EMT</td>
<td>Contactless; Simple design; Transducer position known; Easily used on curved surfaces; Design versatility</td>
<td>'High' insertion loss; Needs magnetic field</td>
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relatively easy to make and being flexible, can be placed on curved surfaces. This access to curved surfaces, of course, is quite important in NDE. As an example of curved surface use, we taped a couple of cable EMT's onto an aluminum cylinder to obtain a circulating delay line that worked when first set up.

Another advantage of the cable EMT's is that their flat insulation provides a standard liftoff of a few mils from the SAW surface. Since the cable is also fairly thin, it is ideal for the perpendicular magnetic field design illustrated in Fig. 4: the closer the magnet to the SAW surface, the greater the field and hence, transducer efficiency. The EMT design is also versatile in that the conductor pattern can be tailored to give desired transducer characteristics such as beam profiles. The transducer position on the SAW surface is well-defined, in contradiction to the case of the wedge. So, with the distance between two transducers well known, absolute velocity measurements can be accurately made.

The EMT does have a high insertion loss and needs a magnetic field. The compact EMT unit in Fig. 4 shows, however, that this magnetic field requirement is not really a disadvantage. Adequate signal-to-noise ratios can also be obtained with EMT's.

We measured impulse responses of all three transducer types. In Fig. 8 are shown responses for a couple of wedge transmitter-receiver pairs. Note not only the differences between the first and second pairs (both on Al) but also the lack of reproducibility when the first pair is removed and then reapplied to the Al. The biggest signals in these photos are due to the response of the piezoelectric element on top of the wedge. Most of the other signals are probably spurious, due for example to multiple internal reflections within the plastic wedge blocks.

Now, in Fig. 9 we see things are a little better. The bottom photo gives part of the impulse response for the comb transducers. With one transmitter and two receiver transducers in the comb array, we have a pair of SAW delay lines. The responses of both pairs are combined in the photo by a pulse overlap method, which I will describe a little later. Although care was taken to make identical receivers on this comb unit, the responses are not exactly the same. However, the responses were found to be much more reproducible than those obtainable with wedges.

To measure the impulse response of the EMT, we used a single wedge as transmitter and different EMT units (such as in Fig. 4) as receivers. Photos for two such arrangements, as shown in the top of Fig. 9, show simple and nearly identical responses. Although a wedge is involved, the responses are characteristic of the EMT's because the bandwidths of the latter are much less than those of the former. So, if we want to look at small changes in SAW velocity due for example to surface roughness, then the simpler the transducer response, the easier it is to separate out material effects from those of the transducer. And, of course, if the time response is well behaved, then so is the spectral response.

The emphasis in this talk so far has been on transducer characteristics. We'll now describe the electromagnetic transducer unit and the comb array.
Fig. 8. Impulse responses of wedge-wedge pairs or delay lines. Time scale is 0.5 μsec. Note the lack of reproducibility and the complicated structure of the wedge responses.
Fig. 9. Impulse responses of two comb pairs (lower) and two wedge-EMT arrangements (upper). These responses are quite reproducible. Note the relative simplicity of the structure of each cycle in the wedge-EMT response.
Figure 10 depicts our scheme for differential velocity measurements. One transducer, the wedge, is fixed in position. The moveable transducer is chosen to be electromagnetic (Fig. 4) because it doesn't have to touch the surface. The EMT is mounted on a micrometer head with a positioning precision of plus or minus 1 micron. Care was taken to avoid the problem of backlash on the screw adjustment of the micrometer.

The heart of the electronics in Fig. 10 is an intervalometer developed by Panametrics with an ultimate time resolution of about 0.2 nanosecond. In practice we obtained a couple of nanoseconds resolution when measuring SAW time-of-flight. An attenuated feedthrough signal and another delayed signal which comes through the SAW delay line can, by feeding a sinusoidal sweep into the oscilloscope be superimposed. The frequency of this sinusoidal sweep is divided down from the higher frequency of a stable oscillator within the intervalometer. We thus can make comparisons of one cycle within one pulse with another cycle in another pulse. This cycle-by-cycle comparison can provide more sensitive and more informative measurements than possible with just the video envelope of a SAW signal.

Time-of-flight data for the SAW's were taken for various wedge-EMT separations to yield the positron vs. time plot in Fig. 11. The dashed line is a best straight-line fit to data plotted as dots for an aluminum sample with an rms roughness of 64 microinches. Note the expanded time scale on the graph, with a displacement increment of 1/2 mm. The SAW velocity, taken as the slope, is found to be quite reproducible. We made another velocity measurement run and found a fractional difference between the two runs of 0.13 percent. With wedge-wedge delay lines we obtained typical precisions of 2 to 3%. With wedge-EMT delay lines, precisions better than the 0.1% mentioned above should be realizable through increasing the signal-to-noise ratio, such as by use of a low-noise preamplifier for the EMT receiver.

We used our SAW velocity measurement setup to characterize surface finish conditions on an aluminum alloy, starting with roughness of just a few microinches. We then removed the transducers from that sample and placed them on another with a rms roughness of 64 microinches. Finally, we set back up on the more highly polished material. In our results the difference in the average SAW velocities between the series of runs on the highly polished sample was 0.02 percent. Also, in comparison with the above mentioned 0.13% precision for the roughly polished sample, the fractional difference between the velocities for the highly and roughly polished materials was 0.65 percent, i.e. larger by a factor of 5. In all cases, calculated phase changes due to diffraction affected SAW velocities by less than 0.01%. So, we were indeed discriminating between various conditions of surface roughness.

We now describe some of the results obtained with a comb transducer array similar to one shown in Fig. 12. This array consists of receiver transducers on either end and a transmitter between them but offset from their midpoint. Each transducer consists of a quarter-wavelength thick, high coupling barium sodium niobate (Ba2NaNb5O15) crystal mounted directly above a set of comb teeth and with a fundamental resonance of 3 MHz. Each comb set consists of six teeth with uniform spacing. Comb-comb separations were 1 to 2 inches and insertion losses typically 35 dB without too much care taken in matching diffraction phase changes were again negligible.
Fig. 10. Differential velocity measurement scheme, with a SAW transmitter-receiver pair. The movable transducer (depicted as receiver) was a contactless EMT; its displacement along the axis of SAW propagation thus did not affect the impulse or phase responses of the transducers alone. The electronic 'heart' of the setup is the intervalometer, which provides the necessary sync and driving signals. Data taken were SAW times-of-flight vs. EMT position.
Fig. 11. Velocity of SAW's on polycrystalline aluminum, determined as the slope of a lot of position vs. time-of-flight data taken by the setup shown in Fig. 10. The Rayleigh wave velocity $V_R$ shown here for a typical run is $2.973 \times 10^5$ cm/sec. Experimental precision was sufficient to distinguish between different types of surface finish.
Fig. 12. Closeup of the three transducer comb unit shown in Fig. 1. Each transducer consists of a crystal 'square' of barium sodium niobate mounted above a set of comb teeth machined on the lower surface of a metal bar. Each crystal is connected to an OSM connector. Fundamental resonance is 3 MHz, with useable harmonics at 9 and 15 MHz.
The concept for the three-transducer method is shown in Fig. 13. Two SAW pulses with a relative time delay difference $\Delta t$ are obtained by means of the three transducer array. The phases shown for the two received SAW's include, for completeness, the diffraction contributions $\Delta D_1$ and $\Delta D_2$. Two received pulses superimposed by the pulse overlap method are partially shown in Fig. 14. The envelope shape is very much the same for both pulses, as would be expected for nearly identical comb transducers. This similarity facilitates very precise time measurements made by matching individual cycles on an expanded time scale. The SAW substrate for the pulses in Fig. 14 was 4340 steel. Temperature dependence measurements of SAW attenuation is also greatly facilitated by a three-transducer design.

In addition to the fundamental frequency of 3 MHz, we also operated the Comb unit at the third and fifth harmonics of 9 and 15 MHz. The comb thus appears well-suited for velocity dispersion measurements. We, in fact, measured fractional differences of 0.01% between velocities at 9 and 15 MHz for 4340 steel that had been either gently or abusively ground.

Summarized in Table II are the three pulse methods for NDE that we've presented here. The comparison method simply involves obtaining the differences of data for both reference and test samples. In this respect, the differential displacement or velocity measurements made on aluminum with different surface finishes involved the comparison method. Judicious choice of both the transducer type and the pulse method can provide, for a given application, a powerful tool for NDE.

References
Fig. 13. Three transducer method, involving two received SAW's with a relative time delay $\Delta t$. 

$$\Delta t = \left( \frac{x_2 - x_1}{v} \right) + \sqrt{V_{D1}V_{D2}}$$
Fig. 14. "Overlap" of the two 9 MHz SAW pulses obtained from the three-transducer unit illustrated in Figs. 12-13 and used with the intervalometer represented in Fig. 10. Note the similarity in pulse shapes. SAW substrate: 4340 steel. Such SAW pulses were used to measure velocity dispersions on steel of one part in 10,000.
Table II. Some Pulse Methods for NDE

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<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>Comparison</td>
<td>'Independent' of setup variables; Reference state; Versatile</td>
<td>Precisely known transducer properties (incl. alignment) needed.</td>
</tr>
<tr>
<td>Differential displacement</td>
<td>Independent of setup variables; Amenable to statistical analysis</td>
<td>Controlled displacement critical; time-consuming</td>
</tr>
<tr>
<td>Three transducer</td>
<td>Facilitates pulse comparison; Interferometry possible; Facilitates temperature dependence measurements</td>
<td>Identical transducers required</td>
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DISCUSSION

DR. YIH PAO (Cornell University): Can you generate surface waves on the ferrous metals?

DR. FROST: Yes, in principle we can. We didn't do that ourselves, because there you have two effects - magnetostriction as well as Lorentz force transduction. You get a large magnetostriction response in ferrous materials at relatively low magnetic fields. As the fields increase, the response drops off and then gradually rises again as the Lorentz force interaction taken over?

DR. BRUCE THOMPSON (Rockwell International Science Center): In regard to your comment I'll discuss that tomorrow afternoon in my paper.

DR. WOLFGANG SACHSE (Cornell University): How do you know when you have correct cycle-by-cycle matching in your overlap technique?

DR. FROST: Well, one of the advantages of the differential displacement method with the overlap technique is that you eliminate the response to spurious phase effects from the transducers and electronics. The only thing you are changing is the EMT displacement. So, as long as you are consistent, it doesn't really matter which cycles you match up, because the spurious time delays do not change with displacement. It's a relative measurement. Basically the same argument applies to the three-transducer method.

DR. BERTONI: Any other questions?

I have one brief question. On the wedges, did you do anything to try and control the thickness of the liquid, i.e., the coupling layer?

DR. FROST: No. And that's a good point because you can expand the capability of the wedges possibly by using some very rigid fixture to maintain a constant thickness of liquid. But from the standpoint of the simplicity of transducer design and the amount of work involved, you would have to do more to set that up and actually get it to work, compared to the efforts involved with an EMT setup.

DR. BERTONI: Any other questions?

DR. JOSEPH MOTZ (National Bureau of Standards): Is there any electromagnetic leakage that would affect the safety of the operator of these transducers?

DR. FROST: No, not at these frequencies. There is some leakage, but as far as I know it comes mostly from the leads. Now, I did want to mention one thing that your question indirectly brings up. The connections on the ends of our cable EMT's were made by soldering, but possibly very rugged, reliable and safer conditions could be made by use of commercially available flat cable connectors.