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Optimization of Electromagnetic Transducer Systems

Abstract

Electromagnetic transducers have a number of inherent advantages, some of which have been touched on by other speakers. Historically, their major disadvantage has been their high insertion loss. We have undertaken a project which has been designed to explore techniques for optimizing transducer efficiencies and increasing the dynamic response of ultrasonic systems which use electromagnetic transducers. Today, we would like to report the results of that project.

Disciplines

Materials Science and Engineering

OPTIMIZATION OF ELECTROMAGNETIC TRANSDUCER SYSTEMS

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Electromagnetic transducers have a number of inherent advantages, some of which have been touched on by other speakers. Historically, their major disadvantage has been their high insertion loss. We have undertaken a project which has been designed to explore techniques for optimizing transducer efficiencies and increasing the dynamic response of ultrasonic systems which use electromagnetic transducers. Today, we would like to report the results of that project.

Figure 1 reviews different electromagnetic transducer (EMAT) configurations. On the right-hand side is shown the surface wave transducer configuration, which has been discussed in previous papers.^{1,2} Here we have shown a transducer configuration which uses a normally polarized permanent magnet. The meander coil is placed directly beneath the magnet. When this transducer is placed near a metal part and the coil is driven at the desired frequency, ultrasonic waves are launched in the metal through the reaction of the eddy currents induced in the metal and the static magnetic bias field. Maximum conversion efficiency is obtained when the spatial distribution of the driving stresses corresponds to the spatial period of the propagating ultrasonic signals.

transducer produces a radial distribution of stresses in the metal surface which generates a radially polarized shear wave having an on-axis null in the radiation pattern. This is an unusual and sometimes undesirable feature of this type of a transducer. For flaw detection, one would prefer to excite an ultrasonic signal with an unambiguous direction of polarization and uniform beam profile. A modified bulk wave transducer for exciting a linearly polarized, normally directed shear wave is shown in the center of Fig. 1. This transducer is made up of two co-planar, counterwound spiral coils and a conductive shield to mask the outer portions of the coils and to reduce transducer inductance. The resultant time harmonic stress distribution is essentially spatially uniform and possesses only one direction of polarization, perpendicular to the windings in the center of the transducer and parallel to the surface of the metal part. An essential feature of this transducer configuration is the permanent magnet which concentrates the magnetic field in the region where the currents are flowing in a uniform direction. The magnetic field is quite weak in other regions where the fringing currents deviate from the desired direction, and hence, generation of signals of unwanted polarizations is minimized.

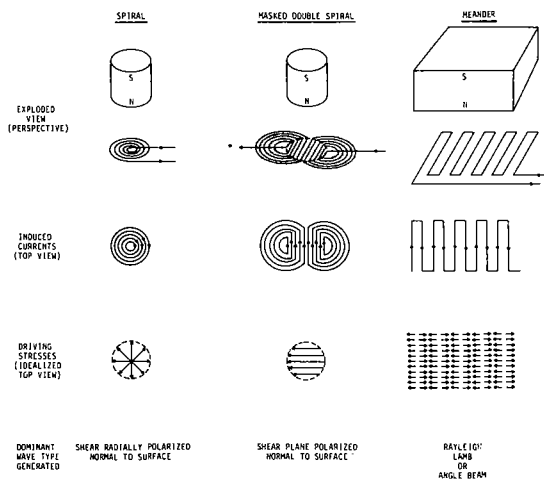


Figure 1. Electromagnetic Transducer configurations.

Bulk wave transducers are shown in the center and the left-hand side of Fig. 1. These are configured differently than surface wave transducers.³ The induced eddy currents result in time harmonic stress distributions which are essentially spatially uniform so that ultrasonic waves are propagated away normal to the surface. The left-hand side shows a spiral coil transducer configuration. This

One of the important common features of EMATS is that they can be packaged for hand-held use. Figure 2 shows both a bulk wave transducer and a surface wave transducer. These units were designed primarily for H.V. operation, but they could easily be adapted for hand-held use by insulating the H.V. terminals. The bulk wave transducer, shown at the left of the slide, uses a spiral transducer coil and a cylindrically shaped samarium-cobalt magnet. The unit at the right of the slide is a surface wave transducer, which under certain conditions can also be used to generate angled shear waves. The magnet is shown slightly offset with respect to the meander line coil. Both transducers have been used to launch ultrasonic waves on aluminum and other metals.

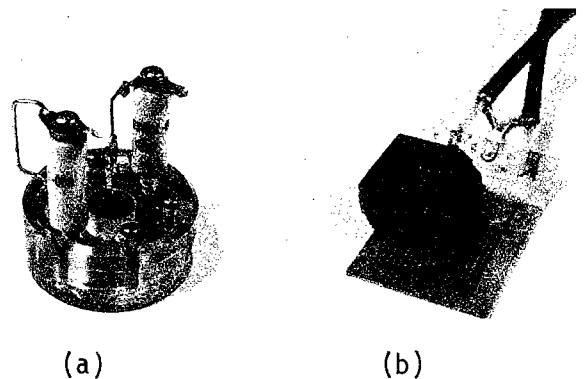


Figure 2. Photograph of lightweight transducers. (a) spiral (b) meander

Our primary concern has been to optimize the signal-to-noise performance of actual systems which use transducers such as these. The effort has been primarily concentrated on the design of electronic assemblies optimized for maximum transmission and detection efficiency when operated in conjunction with electromagnetic transducers. This was done because commercial NDE instrumentation is, in general, designed for operation with piezoelectric transducer loads. Because electromagnetic transducers exhibit different electrical characteristics than piezoelectric transducers, the performance of commercial NDE receiver and transmitter can be severely degraded.

Figure 3 shows a schematic diagram of a "double-ended" ultrasonic inspection system which uses electromagnetic transducers. The dynamic response of such systems has been greatly increased under this program by constructing special purpose electronic equipment for transmission and reception of ultrasonic signals. Because the amplitude of ultrasonic waves generated by electromagnetic transducers is directly proportional to the input current, it is desirable to increase the current drive to the transducer to as high a value as possible. We have done this with high voltage pulse generation using spark gaps for switching. Pulse forming has been accomplished with distributed (coaxial) and lumped (LC) elements. Using such equipment, we have generated short current pulses similar in shape to output pulses of many commercial NDE instruments. The difference is in the magnitude of the pulses. Using our instrumentation, critically damped pulses in excess of several hundred amperes have been observed compared to several amperes available from commercial NDE instrumentation operating under the same loading conditions. Tone burst operation has also been demonstrated with highly dampened electromagnetic transducer systems. We found no difficulty in passing these high current pulses through coils such as those shown in Fig. 2.

On the receiver side of the system we have been able to achieve significant improvements in sensitivity by proper electrical design of new impedance matching networks for coupling the electromagnetic transducers to amplifiers. This was done in order to transform the generally low impedance of electromagnetic transducers to the optimum source resistance of the amplifier. As a part of this effort, we have constructed special purpose, high input impedance receivers for sensing the open circuit voltage of the output transducer and novel broadband impedance transformers in order to transform the 1 to 2 ohm impedance levels of typical transducers up to impedances of approximately 200 ohms, which are necessary for low-noise operation of the amplifier. For surface wave transducers, we have also used a tunable bandpass filter in order to limit the bandwidth of the received signal to the actual bandwidth of the transmitted signal. In this way we were able to further increase our sensitivity by eliminating unneeded bandwidth. The filter is placed directly before the cathode ray oscilloscope used for display of the bandlimited but unrectified signal.

We would next like to compare the results we have obtained when standard NDE instrumentation was used with the electromagnetic transducers to those obtained with our new instrumentation. The signals shown in Fig. 4 were transmitted through 2 inches (5 cm) of aluminum. The signal shown at the top was obtained with an Immerscope 725 connected directly to the transducer. It is not a very clean signal. At the bottom of this slide we show the same signal when the transmitter transducer was connected directly to the high voltage pulse forming circuit. This photo clearly demonstrates the rather significant improvement in the signal-to-noise performance of the system.

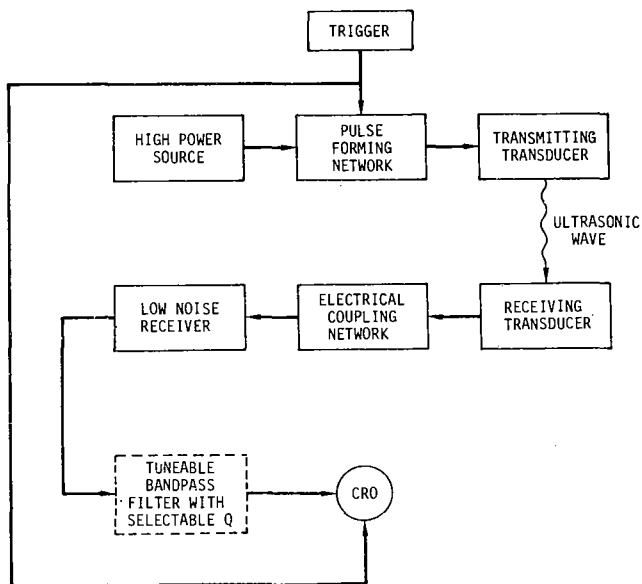
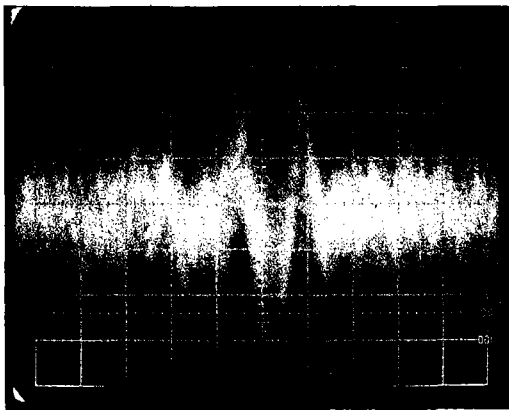
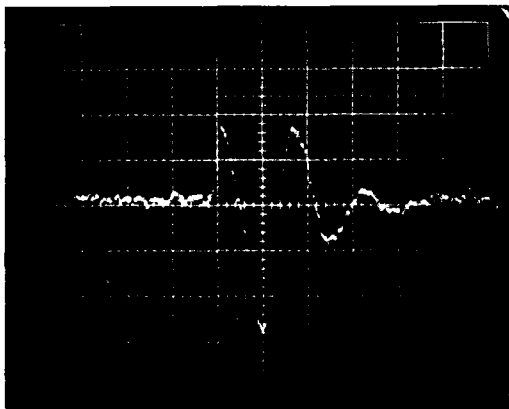


Figure 3. Block diagram of electromagnetic transducer system.



(a)



(b)

Figure 4. Broadband transmission of shear wave between two spiral coils through 5 cm of aluminum ($0.2\mu\text{sec}/\text{DIV}$)
 (a) commercially available search unit
 (b) newly designed electronics

We have also considered signal averaging techniques, since it is always possible to use such techniques in order to improve the signal-to-noise ratios of signals such as those shown at the top of Fig. 4. In this program we have used rather simple techniques; the analog waveform is digitized and several successive signals are digitally added together. Figure 5 shows the result when the same ultrasonic signal is averaged 10, 100 and 1,000 times. We have recently achieved essentially real time operation in this mode. By limiting our processing time to approximately 10msec per signal we are able to average over about 100 successive signals in one second.

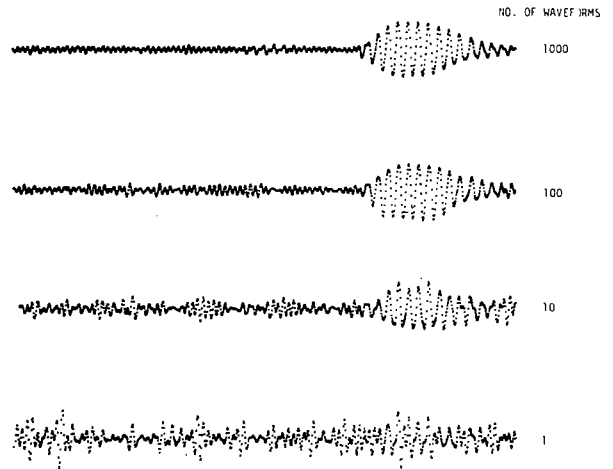


Figure 5. Signal-to-noise improvement of a 5 MHz burst by signal averaging.

As mentioned before, the spiral coils generate radially polarized shear waves which have some disadvantage for flaw detection. However, they do have one intriguing feature. In acoustic media with some shear wave birefringence, the radial distribution of stresses will couple to both polarizations of the shear wave. Part (a) of Fig. 6 shows the input current waveform used to excite one such transducer. Part (b) is a display of the received echo train on a $3/4$ in. thick piece of rolled aluminum. One can see that each echo is broken up into two distinct signals. This is caused by the birefringence effect induced by the rolling texture. This effect is better illustrated in part (c), where the expanded time scale makes it easier to see the time separation between the arrival of the slow and fast shear wave signals. One present application of the shear wave birefringence effect is in the measurement of residual stresses. The ability of the spiral coil to couple to both polarizations with no contact may make these tests more easy to apply.

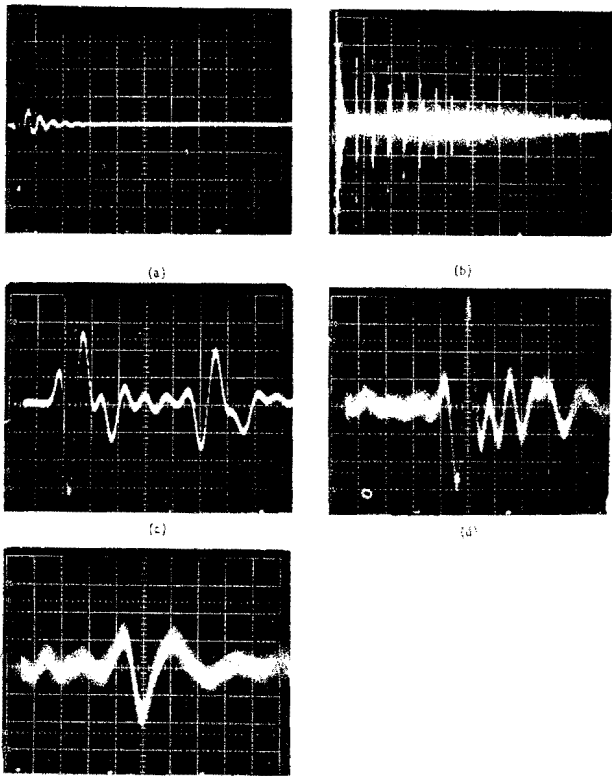


Figure 6. Transmission echoes through 3/4 in. aluminum plate.
 (a) drive current (2 amp/div., 2 μ sec/DIV)
 (b) echoes (0.1V/DIV, 20 μ sec/DIV)
 (c) expanded view of echoes after 5 transits (0.1V/DIV, 0.2 μ sec/DIV)
 (d) expanded view of faster shear wave after 19 transits (0.02 μ V/DIV, 0.2 μ sec/DIV)
 (e) expanded view of slower shear wave after 19 transits (0.02 V/DIV, 0.2 μ sec/DIV)

Parts (d) and (e) of Fig. 6 reveal another interesting phenomenon observed in this rolled aluminum sample. These show separately the individual fast and slow shear wave signals which have each passed through the sample 19 times. Although the difference in their velocities is only 4%, they have propagated a sufficient distance that the pulses are well separated in time. It will be noted that the two signals do not have the same shape as they did in part (c) of this figure. Instead, the slow shear wave has been distorted and decreased in amplitude indicating a strong preferential attenuation of its high frequency components. This is clearly indicative of the microstructure of the material. Since shear waves propagating normal to surfaces are rather difficult to excite with piezoelectric transducers, such effects have not yet been explored for possible NDE application. The electromagnetic transducer removes this limitation and may open a new area of study.

Let us now turn to systems for generating surface waves, with which we have obtained by far the best signals. One reason for this is that the meander coil surface wave transducers exhibit very low inductances due to effective magnetic field cancellation by the adjacent, oppositely flowing currents. The low inductance inherent in these configurations makes it easy to drive large amounts of current through the transducers. The top trace of Fig. 7 shows the input current tone burst at 2.25 MHz with peak amplitude exceeding 150 amperes. Trace b shows the received ultrasonic signal transmitted over 7 inches of aluminum between a pair of 2.25 MHz transducers such as were shown in Fig. 2, and having dimensions 2.54 cm by 2.54 cm. The thickness of the trace does not indicate the electronic noise of the system. In fact, the dynamic range obtained in this experiment was in excess of 80 dB as demonstrated in the bottom trace, which shows the received signal on an expanded scale when 60 dB of attenuation has been inserted between the transducer and the receiver. This clearly demonstrates the potential of these transducers with permanent magnet biasing for hand-held ultrasonic applications.

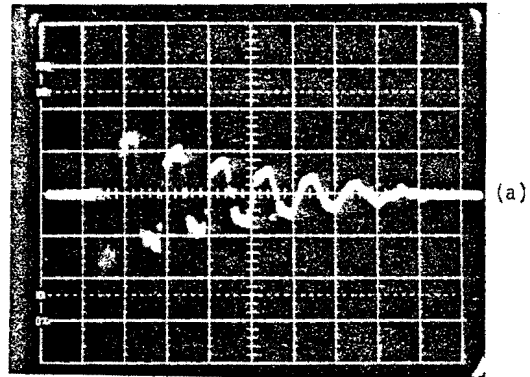


Figure 7a.

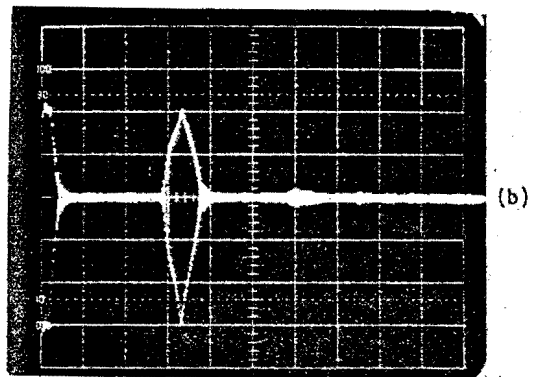


Figure 7b.

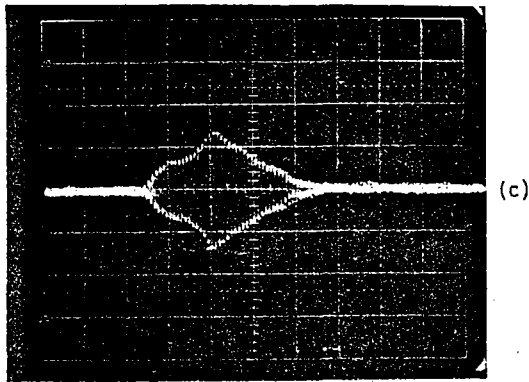


Figure 7c.

Figure 7. 2.25 MHz surface wave transmission over 7 inches of aluminum.
 (a) drive current (100 amp/DIV, 0.5 μ sec/DIV)
 (b) ultrasonic signal (2V/DIV, 20 μ sec/DIV)
 (c) expanded view of ultrasonic signal with 60 dB of attenuation inserted between transducer and receiver (5mV/DIV, 5 μ sec/DIV)

The high dynamic range of these signals suggests that the EMAT's might be useful for the detection of flaws by using surface waves. Szabo has recently used EMAT's to measure the ultrasonic reflection from a step in a surface.⁴ We have recently carried out some similar reflection experiments. In our work, the reflections were saw slits used to simulate cracks. These data are presented in Fig. 8 and are compared to a theoretical curve for step reflectors due to Munasinghe and Farnell.⁵ The reason for making this comparison was that the reflection from slits should be quantitatively similar to that from a step discontinuity, and this was, in fact, observed. The surface wave reflection coefficient is plotted as a function of the ratio of the depth of the slot to the ultrasonic wavelength. The most striking feature of this plot is the relatively large reflection coefficient obtained from a discontinuity whose depth is only 1/10th that of the ultrasonic wavelength. In fact, the reflected signal from this slot is only -26 dB. So, if we have a system with an 80 dB dynamic range, the reflected signal has a 55 dB signal-to-noise ratio. At a frequency of 1 MHz the slit depth is only 0.100 in. (0.025 cm). We are very encouraged by these results.

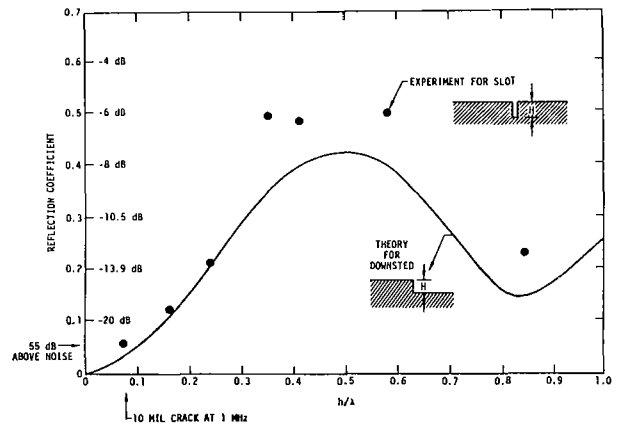


Figure 8. Reflection coefficient of surface waves from EDM slots in steel plate. No theory is available for the slot reflection so the data is compared to theory for a single downstep.

The saw slits used in these experiments were much wider than the elastic beam. Of course, real cracks would be much less wide and would have a non-uniform cross section. We are presently in the process of fabricating a set of such defects for further experiments. We have also seen reflected signals from slots 0.029 inch deep with a 1/2 inch surface length fabricated in steel projectiles. The signals from such defects were well above the noise level. We have not yet performed a full set of experiments necessary to completely define the system sensitivity.

We are now working at the Science Center on two applications programs which I do not have time to describe in detail at this meeting. One of these is a feasibility study of a system for rapid inspection of 155 inch artillery projectiles.⁶ Let me just mention that this project involves magnetizing the whole projectile with an external electromagnet in order to take advantage of magnetostrictive effects which enhance transduction efficiency, and using moveable transducers to accomplish the inspection as shown in Fig. 9. We are also involved in a program for the Electric Power Research Institute.⁷ This is intended to develop techniques for inspecting the interior of nuclear reactor steam generator tubes. The major difficulty here is that these tubes are very small in diameter, about 7/8 inch wide. However, preliminary experiments indicate that useable signal levels can be obtained here too, making it possible to design a successful inspection system.

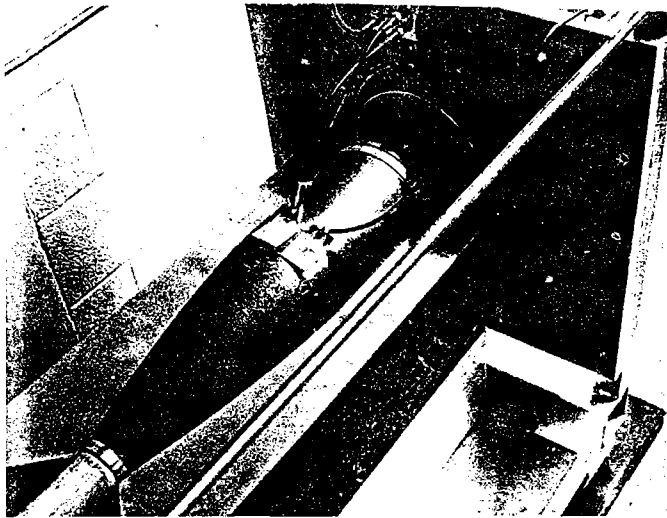


Figure 9. Inspection of 155mm artillery projectiles using EMAT's. The entire projectile is magnetized to the proper bias point by the electromagnet mounted underneath it, and the small surface wave coils are then rapidly scanned over the surface.

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DISCUSSION

PROF. VERNON NEWHOUSE (Purdue University): Are there any questions?

DR. JIM DOHERTY (Pratt/Whitney Aircraft): A simple comment. Slots do not behave like cracks.

DR. THOMPSON: Agreed.

DR. DOHERTY: They really do not. There is a very significant difference. What you see with cracks and what you see with your slots probably won't be similar.

DR. THOMPSON: I agree with that. This is just the first step. There is a question of closure and there's a question of the roughness of the surface, both of which clearly are going to influence the ultrasonic response. I don't know whether you'd like to comment further.

DR. DOHERTY: I think the closure is probably the most significant one. It's been our experience that cracks tend to be rather invisible to the surface waves unless they're very large.

DR. THOMPSON: I think that might be controversial. We certainly have to start somewhere in characterizing EMAT sensitivity, and the slot is a logical point. The next thing to do is look at some real cracks and see what the ultrasonic levels are. I certainly agree with that 100 percent.

PROF. NEWHOUSE: One more question.

DR. P. J. MCKINLEY (University of California): A question about why would you use a surface wave as opposed to an eddy current inspection?

DR. THOMPSON: There are a number of answers to that. In an eddy current inspection, of course, you have to scan your eddy current probe point by point over the surface of the part. In a surface wave inspection you can let the ultrasonic beam propagate over a large area and it will reflect from any defect within this region. Hence, one achieves higher scanning speeds using the surface waves because of the high speed of sound.

Secondly, the surface wave will interrogate the material to a depth equal to the wavelength of the ultrasound, which is, in general, much greater than the electromagnetic skin depth which governs the depth of eddy current inspection. So, you're going to get a much deeper look at the material for subsurface defects using the surface wave. I think those are two good reasons.