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Abstract
In the program description Don Thompson mentioned that one of the overall objectives was to try to increase the communication between the basic research community and the NDE user, and I'd like to mention that my own involvement in NDE did not come from a specific problem oriented research project in NDE. In fact, my interest in electromagnetic generation began from some physics problems, particularly with studies of the electronic properties of potassium single crystals at liquid helium temperature where the contactless feature of electromagnetic transducers was a useful advantage.

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ACOUSTIC SURFACE WAVE GENERATION WITH ELECTROMAGNETIC TRANSDUCERS*

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In the program description Don Thompson mentioned that one of the overall objectives was to try to increase the communication between the basic research community and the NDE user, and I'd like to mention that my own involvement in NDE did not come from a specific problem oriented research project in NDE. In fact, my interest in electromagnetic generation began from some physics problems, particularly with studies of the electronic properties of potassium single crystals at liquid helium temperature where the contactless feature of electromagnetic transducers was a useful advantage.

At last year's workshop my colleague, Tom Moran, outlined some of the advantages of using these EM transducers. Bruce Maxfield has described some of those, and as has been indicated elsewhere, the development of bulk wave EM transducers has been developed literally to a fine art.

In this talk, however, I'd like to extend the discussion and describe two variations of surface wave transducers. Then I'll show some recent examples of applications of surface wave transducers both to attenuation and to velocity scans in aluminum plates, investigating some simple point and crack flaws.

A few years ago Bruce Thompson and George Alers did a rather thorough experimental as well as theoretical study of the EM generation of Rayleigh waves and also of Lamb waves at frequencies of the order of 100 KHz. The geometry of this is outlined in Fig. 1. The direction of the induced eddy currents in the skin depth is denoted by J, the static field direction by $B_0$, and the Lorentz force by $F$. One can either generate longitudinal bulk waves or shear bulk waves by rotating the direction of the static magnetic field. If one uses a wire wound meander coil, such as Thompson and Alers have done, then it's possible to have alternating eddy currents induced under the meander coil, as shown schematically in Fig. 1. Hence, the Lorentz force alternates in direction into and out of the surface underneath the coil and a Rayleigh wave is generated.

We have extended this technique to frequencies in the MHz range, typically from 4.5 MHz up to about 10 MHz. It soon became obvious to us that as the frequency is increased, one has to take considerable pains to keep the geometry of the meander line accurate. Otherwise, one gets serious phase cancellation.

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Bulk Waves

Surface Waves

Eddy current distribution in metal surface due to rf field produced by generation coil

Longitudinal

Rayleigh

Shear

Lorentz forces on eddy currents

Fig. 1. Geometry of electromagnetic generation of ultrasonic waves.
effects, and this becomes very pronounced at 10 MHz. Our approach to the problem was to use standard photographic printed circuit techniques with commercially available flexible printed circuit material. The spacing of the meander line is made to be 1/2 the Rayleigh wavelength. In the case of a 4.5 MHz transducer, the spacing is something of the order of a third of a millimeter, and by using 32 turn meander coils as shown in Fig. 2, we get reasonably good signals. The insertion loss, using small permanent magnets, is something of the order of 80 dB for two conversions over the frequency range from 4.5 MHz to 10 MHz.

In Fig. 3 we see an illustration of a transmitted surface wave signal. The first pulse is the electromagnetic leakage and the second pulse is the transmitted Rayleigh wave signal. The two following smaller echos are reflections from edges of the metal plate. Figure 3 shows that the Rayleigh wave has run around the corner, and reflected from a top edge and returned to the receiving transducer, so it's clearly a surface wave that we're studying.

In examining point flaws and cracks with the plane Rayleigh wave transducer, we didn't have tremendously good sensitivity, but because of the fact that we're dealing with surface waves and we have printed circuit technology, it was quite easy to fabricate a focused wave transducer. In Fig. 4 is shown such a transducer. The spacing is still the same, so that it's a 4.5 MHz transducer, but now we've made the elements of the meander coil successive sections of concentric circles. Thus, the wave that is launched comes to a focus about 2.5 inches away from the edge of the coil, and we arrange two such coils in a confocal arrangement on the test stand. It then becomes possible to scan the focal point over the sample. It's something like the bulk wave C-scan in a confocal arrangement, but now with Rayleigh waves, so that one can look at surface defects. The first such defect that we studied using this technique was a 1.6 mm diameter by 0.9 mm deep hole in a plate of aluminum. The hole was drilled using a standard drill, and hence, it had an irregular shape. Roughly speaking it could be described as a round bottom hole. We did a mechanical scan of the focal point in 1 mm steps in the x-y plane and the results are displayed in Fig. 5. The hole is clearly delineated by the highest 1 mm by 1 mm column in the plot, with a peak attenuation of the focused Rayleigh wave beam of 27.5 dB. Thus, a hole whose size is of the order of the wavelength has a considerable effect on the focused Rayleigh wave beam, even though with the plane Rayleigh wave beam, the hole is barely discernable.

The next surface flaw that we examined was a closed crack in an aluminum plate which Mike Buckley sent us. This crack, if I understand it correctly, was initiated by drilling a hole with a laser in the surface and then bending the plate. A small crack 2 cm long then propagated, essentially symmetrically about the center of the hole. Figure 6 shows the results of a focused wave scan. The crack lies along the x axis in this plot, and the Rayleigh wave beam is sent along y. As you can see, the scan picks out the crack. It's not completely obvious in this perspective that it's a crack and not a point, but plots from different perspectives easily confirm this. Again, using plane Rayleigh waves which you would imagine would be quite sensitive to a linear fault such as a closed crack, we're not able to see a crack of this size, perhaps because it's a closed crack and fairly narrow. As we have demonstrated,
Fig. 2. Photograph of electrode pattern for meander coil.
Attenuates signal 3
Attenuates signals 2 and 3

Signal 1 - SAW from T to R
Signal 2 - Reflection from edge A.
Signal 3 - Reflection from edge B.

Fig. 3. Oscilloscope tracer of transmitted surface wave signal.
Fig. 4. Photograph of electrode pattern for focused wave transducer meander coil.
Fig. 5. Two-dimensional attenuation plot for an aluminum plate with 1.6 mm diameter x 0.9 mm deep hole.
Fig. 6. Two-dimensional attenuation plot for an aluminum plate with a small hole and a 2 cm long closed crack.
however, by scanning the focused Rayleigh wave beam along the same crack it is very easily seen, and we can determine its length.

In Fig. 7 is shown a series of plots of scans along the crack line. The top plot is a plot of a scan along x, that is, scanning the focal point along the length of the crack starting beyond the initiation point. You can see that the change in signal starts at an x position of about 0.4 and then is finished, essentially, at a position of 1.2 inches. Thus, the extent of the crack, which was originally measured to be 0.8 inch visually is clearly detected. In addition there is a 25 dB attenuation peak corresponding to the hole which initiated the crack.

We wanted to get rid of the hole and to try to get some idea as to how deep the crack was, so we started milling the surface. The crack was just barely discernable to the eye when we started, and as soon as we removed the first layer, including the hole (~30 mils), the flaw could no longer be seen at all visually. As shown in Fig. 7, the attenuation clearly picks up the beginning and trailing edge of the crack, and now we start to see some fine structure inside the crack, the origin of which is not obvious. It could be a resonance of the crack opening and closing, for example. We continued to remove layers to see when the crack would disappear, removing 30 mils or about one sound wavelength at a time. The crack is still evident, although the fine structure changes (see Fig. 7).

I will next describe another technique that one can use for surface flaw testing which makes use of the fact that the EM transducers are contactless, namely a study of changes in the relative sound velocity. In this case, changes in the velocity of focused Rayleigh waves are measured as a function of position along the surface of the metal. This is not at all easy to do with conventional transducers because of the fact that one has phase shifts through any bonding material that is used to couple a standard piezoelectric transducer to the metal, but it's quite trivial when using EM transducers, because the phase shifts are fairly insensitive to coil liftoff. The measurement is a phase comparison technique. We start with a stable CW-RF source monitored by a frequency counter. We gate out a 1 usec pulse of that CW signal, amplify it through a wide band power amplifier, and generate an echo train in the conventional way. Then, using a common local oscillator, we heterodyne both the original CW-RF signal and the corresponding RF pulse train to the IF frequency, in this case, 30 MHz. After amplification, the signals are recombined in a phase detector followed by a video amplifier, and the video output is monitored on an oscilloscope, as well as by a boxcar integrator. By adjusting the frequency you can get phase cancellation as displayed by the video output. That in turn is monitored by the boxcar, and one maintains the null by making small adjustments in the frequency of the stable RF source. Fractional changes in transit time, which are a combination of length changes and velocity changes, are given by fractional changes in the frequency as read by the frequency counter.

We applied this technique after milling another 30 mils off of the sample. We still hadn't gotten to the bottom of the crack before I had to leave to come out here, but it can be seen in Fig. 8 that the attenuation is still very much evident. In fact, if anything, it's a little bit larger.
Fig. 7. Scans of sample with crack as received and with 0.03 and 0.06 inch of surface material removed.
Fig. 8. Scan of sample with crack with 0.09 inch of surface material removed.
larger in the region of the crack. One can see the crack by monitoring changes in sound velocity as shown in Fig. 8. The changes are of the order of 4 parts in $10^4$, where the resolution of the phase comparison technique is something like a part in $10^6$. The background changes in the velocity measurement are due mostly, I believe, to small variations in path length from the milling grooves on the surface of the metal.

At the San Antonio conference this spring, Tom Moran presented some data showing the application of the EM technique to bulk wave generation and transmission through an aluminum block. Linearly polarized EM transducers were used to generate either compressional bulk waves or shear bulk waves. Velocity scans were made of a 1 inch by 1 inch bar for both bulk acoustic modes. For longitudinal waves the signal is fairly uniform in the absence of any stress (see Fig. 9). After placing the bar in a 3 point bending press the maximum stress point is identifiable by the increase in velocity. As the load is increased, one can clearly see where the bar is going to fail, and just before failure there is a decrease in the sound velocity as the strains begin to relieve.

From measurement of the relative changes in shear wave sound velocity on the same bar, as shown in Fig. 10, it is evident that even in the absence of stress there is a variation in sound velocity across the sample. We believe that this is indicative of some residual strain fields in this sample of bar stock, which we just picked off the shelf. In fact, this particular sample did fail at a considerably lower stress than subsequent samples which did not show such variations in the absence of a load.

A possible generalization of these results is that the measurement of sound velocity and attenuation in either the bulk wave or the surface wave configuration complement one another. That is, the sound velocity changes are more sensitive to residual internal strains in the sample and not terribly sensitive to small flaws, whereas the attenuation is not as sensitive to residual strains, but it is quite sensitive for point or line flaws. As a corollary to this generalization one can imagine that the sound velocity data could be inverted, so that if one had a good standard material in which the velocity is uniform and the sample is unstrained, a knowledge of the sound velocity could be used to look at variations in thickness of a sample, i.e. one could make a thickness monitor from this scheme by making measurements of relative transit time in the phase comparison velocity technique.
Fig. 9. Velocity scans for longitudinal waves in sample under varying load conditions.
Fig. 10. Velocity scans for shear waves in sample under varying load conditions.
DISCUSSION

DR. BERTONI: Are there any questions on this paper?

PROF. BRUCE MAXFIELD (Cornell University): Do you find that there's an optimum separation distance between the coil and the surface? That is, does your signal level improve as you move the coil slightly away from the surface and then diminish?

DR. THOMAS: I think we have seen some small changes in that, as the sample is pressed up against the coil, we can see it relaxed. It relaxes to a smaller signal as the pressure increases, as it's closer to the surface.

PROF. MAXFIELD: What, then, is the minimum distance that you can get?

DR. THOMAS: Well, that's very much a function of the kind of insulating material that you use on the coil. Now, at 10 MHz it becomes very, very crucial to be close to the sample, because, as Bruce Thompson pointed out, the liftoff effects are exponential on the scale of the sound wavelength.

PROF. MAXFIELD: Right.

DR. THOMAS: One tries to be as close as possible. In this case I guess we were within a few mils of the surface as we scanned across.

PROF. MAXFIELD: We found with bulk transducers that there are capacitive loading effects that they reduce your signal level by 50%.

DR. THOMAS: I don't think we saw anything quite as large as that, but we did see some effects.

DR. BERNIE TITTMANN (Rockwell International Science Center): How high in frequency do you think you can push your present approach?

DR. THOMAS: On the surface waves?

DR. TITTMANN: Yes.

DR. THOMAS: Well, at the moment we're very crude in making our masks and in our printed circuit techniques, but we're already past the official limitations of the printed circuit specifications. Clearly the way to go is to use the technology that's already been developed in the SAW business for making interdigital transducers. I don't see any limitation in pushing the coils probably up to 40 MHz or so. The real problem is getting insulating material thin enough so that you can get the sample close enough to the surface, remembering that your wavelength is decreasing. A frequency of 10 MHz is dead easy.

DR. BERTONI: Another question?

DR. GARY DAU (Electric Power Research Institute): I would like to offer a comment. I believe Mr. Nagel asked about when these could be expected
to be put into service. We have put out an RFP, with the deadline this Friday, looking at this particular process for a backup for eddy current inspection of steam generator tubing in the nuclear power system for PWR reactors. So, we're hoping to get some of the answers that he was asking in that program. It is really just a proof of principle in the laboratory working with real samples but will not be a field system.

DR. BERTONI: I have a question. What's the fundamental limit, or is there a fundamental limitation that gives you such a high insertion loss? What's the cause of that, and can you reduce it by some other process?

DR. THOMAS: Well, of course, you can always reduce the insertion loss by going to higher magnetic fields. The fields that we used here were of the order of 5 kgauss, and the reason that we did that was to try to make a portable device. Now, clearly you can do a lot better than that if you want to go to superconducting coils or laboratory coils, but the feeling was that for a field device, one has sufficient signal to noise ratio already. In my experience, the signal to noise ratio on the surface wave transducers is considerably better than we have achieved with bulk wave transducers using permanent magnets. It's a real fight for us to use bulk wave coils in permanent magnets, but very easy with surface wave transducers at these frequencies.

DR. BERTONI: One other question. In the same vein, will this limit your high frequency response? How high in frequency can you go? The small wires may limit the response.

DR. THOMAS: Well, of course, the technology for developing the wires is well known. These combs for surface wave devices on lithium niobate substrates run up to about 1 GHz. So, it's not the fabrication of the meander line that's the problem. It's the fact that you're working with a fringing field from those coils, and the fringing field is decaying exponentially away from the coil into the metal.

DR. BERTONI: One more question.

PROF. MAXFIELD: Have you tried overtone operation of these surface wave transducers?

DR. THOMAS: No. But I'm sure it will work. We've shock excited them, and they work fine on the fundamental. I just haven't gotten to that as yet. I'm sure they will work on old harmonics.

PROF. MAXFIELD: There's no reason why they shouldn't.

DR. THOMAS: No.