OPTIMIZATION & APPLICATION OF ELECTRO-DYNAMIC ULTRASONIC WAVE TRANSDUCERS*

Bruce Maxfield
Cornell University
Ithaca, New York

First, let me describe briefly what I have in mind when I talk about electrodynamic ultrasonic wave transducers. There are a number of transducers which I would put in this class including the capacitive microphone-type transducers, which are based on an electrodynamic phenomenon as opposed to piezoelectric phenomena. However, I am going to focus my attention on a particular type of electrodynamic device, the electromagnetic acoustic wave transducer or EMAT for short. I will describe electromagnetic acoustic wave generation and, hopefully, will show you how transducers based on this phenomenon have been understood in rather great detail. It is then up to all of us to try and apply this information to solve NDE problems. With this background information, I hope that you will feed back to me ideas so that we can work together on applications.

Figure 1 shows a typical measurement setup when using an electromagnetic acoustic wave transducer or EMAT. One takes a pulse of radio frequency current, at a frequency of a few megahertz and having an amplitude of a few amps peak to peak. That's the typical sort of frequency range that one is working with in NDE problems, although the frequency is by no means limited to this range. They have been used from below a 100 kHz to well over 500 MHz. Clearly, that full frequency range isn't useful to NDE problems.

This RF current (I wish to emphasize that an EMAT is a current, not a voltage, driven device) passes through a coil that is placed near a conducting surface and in the presence of a steady magnetic field, $B_0$. These are the important ingredients. When placed near a metal surface the coil induces eddy currents in the surface. The magnetic field produces a magnetic force, known as the Lorentz force, on those eddy currents, and it's this Lorentz force which couples into the ion lattice and produces the driving force to generate the ultrasonic wave. By varying the directions of the induced current (by having different coil geometries) and the steady magnetic field, you can determine whether shear waves, compressional waves, or a mixture of shear and compressional waves are generated. In addition, you can determine the shear wave polarization. I will not take the time to go into the various possibilities that exist here.

As far as reception goes, there is an inverse process. When an ultrasonic wave is reflected from a surface, currents are established in that surface. The external electromagnetic field, associated with this time varying surface current, is detected by a coil, again, placed in proximity to the surface. Thus, an EMAT provides a means of both generating and detecting an ultrasonic wave in conducting material. (It must be conducting in order to establish

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Fig. 1. Pictorial representation of a typical EMAT measurement setup with coil and field orientation so as to generate shear waves polarized parallel to the y direction. (h is the distance between the coil and the surface). In practice, it is more common to use planar coils rather than the rectangular solenoid shown here.
Eddy currents, and a magnetic field is needed to give the Lorentz force. Since only electromagnetic fields are used to couple into and out of the material that is being studied, you have a completely noncontact device. It is this noncontact feature that has attracted attention to EMATS as far as NDE is concerned.

As is often the case, this advantage costs something; there are always disadvantages that must be weighed against the advantages since Mother Nature is seldom kind to us. The main disadvantage that you have with EMATS is the relatively large insertion loss. In an unoptimized system, the insertion loss will be typically 50 or 60 dB; that is, the output voltage will be down by 100 to 120 dB from the input voltage. Much of the discussion about insertion loss, particularly regarding EMATS, is misleading. A much better term, I think, is the transfer impedance which gives you the output voltage per unit input current. With most present systems the generator is current limited. It is the voltage that you can couple into your receiver system that is important. Thus, the transfer impedance gives you directly the output signal.

Despite the fact that the insertion loss is large, it is still possible to realize acceptable signal-to-noise ratios; values of up to 50 or a 100 can be achieved easily. Hence, we are usually not talking about dealing with small signal-to-noise (S/N) ratios but instead, only small signals. These do have their problems, and one of the goals that we set in this program was to see what we could do in terms of improving the conversion efficiency or raising the output signal level. Most of our attention has focused on various aspects of coil geometry. In most situations, the magnetic field that can be produced is determined by other criteria, probably either the upper field limit of an electromagnet or permanent magnet that can be used. The coil current will be limited by characteristics of generators that you either have available or can design. Our main contribution would seem to be in the area of finding coil geometries that minimize this insertion loss (maximize the transfer impedance). However, in trying to minimize the insertion loss, you don't want to keep your eyes closed to the other important problems that are around. Particularly, I refer to the influence of fringing fields around the coils and diffraction effects that are associated with the ultrasonic wave that is generated by one of these electromagnetic devices. The details of these effects are different for each coil configuration.

Fringing field and diffraction effects are going to be with us even when EMATS prove to be useful electromechanical transducers. At some point they must be understood. For reasons that I don't want to take the time to go into here, it is useful to study simultaneously the problems of optimizing the coil geometry and understanding the origins of and problems caused by fringing fields and the diffraction effects. Figure 2 shows the system that we have assembled to permit all these measurements to be made. We've chosen to study the displacement field that is generated by an EMAT on a spatial scale that is small compared to the spatial extent of the generator, a spiral-wound coil about 19 mm in diameter confined to a plane and placed just above the test specimen. The pressure level or displacement field produced by the generator is probed using a small rectangular coil about 2 by 2 mm. Thus, the probe coil samples roughly 1 percent of generator coil surface area.
Fig. 2. Apparatus for scanning a small receiver coil across the front surface of a metal plate on the back of which is mounted the transmitting coil or other electromagnetic transducer.
The receiver coil is mechanically scanned in the vertical direction and stepped manually in the horizontal. This results in a series of traces, the amplitude of which represents the displacement of the sound wave that was reflected off the surface beneath the receiver coil. As shown by the dashed circles in Fig. 2, the spiral generator coil is on the back surface of a 5 mm thick aluminum plate. Ultrasonic waves produced by this coil are reflected off the front surface, which is scanned by the receiver coil. Since a rectangular coil is used, only one component of the displacement is measured. Thus, as you scan across, at those positions where the generator and receiver coil windings are parallel, you expect a maximum response and at those positions near the center where the coil windings are perpendicular, you expect a null or minimum response.

Figure 3 shows a series of such tracings obtained by putting the signal received by the rectangular coil through a conventional set of pulse-echo ultrasonics and gating out the first echo. This is a quasi-three-dimensional representation of the spatial distribution of one component of the radial displacement generated by a spiral coil. Different sweeps correspond to manually stepping the horizontal position to cover the entire surface beneath the generator coil. Each step corresponds to about 2 mm of displacement. Note that there is one line which goes through the center that has almost no signal. This will be clearer in later figures showing more detail.

Figure 4 is a calculation for exactly the same conditions under which the experimental results of Fig. 3 were taken. I will go into the details of the calculations later. For the moment, I want you to see the results and how well, in general, they compare with experiment. These calculations show some small ripples at the edges as well as peaking in the central region, however, these features are smeared to some extent in Fig. 3 due to the finite receiver coil resolution. The outer circular ridge is an artifact due to the finite cutoff in the numerical integration. The ripples are diffraction effects analogous to the knife edge diffraction in optics. They arise because of the very rapid change (with distance) in the driving force. Comparison of Fig. 4 with Fig. 3 will show that the general calculated effects are evident in the measurements.

I now want to describe briefly how the calculations were done. The problem is readily divided into two parts: the first involves calculating the current distribution in a conductor due to a coil placed near it, and the second involves calculating the displacement at the receiver surface due to the shear stress that is produced by the Lorentz force on the induced currents in the transmitter surface.

In general, it is very difficult to calculate the current distribution in closed form, or at least in useful form, for any arbitrary coil geometry. There is, however, one special case that has been solved by Dodd and Deeds, that of circular loop placed a given distance, h, above a conducting plane. A moment
Fig. 3. Result of a sequence of vertical scans using the apparatus shown in Fig. 2. For each scan, the receiver coil is displaced horizontally by about 2 mm from the previous scan. The display is skewed by 45° so as to make more features clearly evident. These results are for a 19 mm diameter, spiral coil wound of #36 SWG copper wire and placed 0.25 mm above the surface of an aluminum plate. Ripples near the center and periphery are due to diffraction effects.
Fig. 4. Calculated response for the conditions given in Fig. 3. Here, as in Fig. 3, the response is zero along a line through the center because of the polarization sensitivity of the receiver coil.

Fig. 5. Calculated radial displacement as a function of position over the front surface. This is obtained by removing the polarization sensitivity of the receiver coil from the calculations, and gives a better feeling for what the displacement field of a spiral coil looks like. For this calculation, \( h = 0.025 \text{ mm} \), diffraction effects are very strong near the center and periphery.
of reflection should convince you that a sequence of circular loops connected in series is a reasonable approximation to a spiral coil of small pitch. The smaller the pitch, the better the approximation. What we have done is take the analytic solution that was obtained for a single loop placed at a constant distance above a conducting plane and sum all contributions over a series of loops to obtain the current distribution for any particular spiral coil. This gives the current distribution in the surface of the conductor.

The cylindrical symmetry is extremely important in making this whole problem tractable. For this reason we have chosen to study the spiral coil rather extensively to see how well we actually understand the influence of fringing fields, coil liftoff effects (that is, the influence of changes in the separation between the coil and the metal surface), and diffraction effects associated with the spiral coil. I think that further details of these calculations are best left to publications, some of which have already appeared and others will appear soon.

A much better idea of the displacement field is obtained by eliminating the polarization sensitivity of the receiver coil. This can be done very easily in the calculations. An example is shown in Fig. 5 for a coil surface separation, $h = 0.025$ mm. Figures 6 and 7 show quite clearly what happens when $h$ increases. In particular, compare the behavior near the coil circumference. With $h = 0.025$ mm Fig. 6, have a decreased response and some washing out of the diffraction effects. At 1 mm from the surface, Fig. 7, diffraction effects are mostly washed out, and the intensity is reduced still more.

I want to spend the remainder of my time describing the agreement that we have obtained between the measurements and calculations. If you take a section through the center (along a diameter) with the rectangular receiver coil in the direction such that at the edges the winding direction of the two coils are parallel, or as close to parallel as you can realize, and you compare these measurements with calculations for the identical case, you obtain the solid curve in Fig. 8. The measured displacement is given by the circles. The only major difference is on the right hand side where the amplitude is larger and more rounded than expected from the calculations. At the moment, I think this is caused by a small difference in the coil-to-sample spacing for a few windings. Indications are that this is only a coil construction problem and not a calculation problem.

Figure 9 shows the effect of the coil liftoff for a 19 mm diameter transmitter coil. This is the amplitude, that is, the millivolts for some particular coil as a function of distance away from the surface. Close to the surface you have an exponential dropoff, and further away it decreases as $1/n$. The signal at something like 2 or $2\pi$ mm is down by 50 percent of what it would be if the coil were right on the surface.

In summary, I feel that we have demonstrated good quantitative agreement between calculations and measurements for the one coil geometry for which such
Fig. 6. Same as Fig. 5, but $h = 0.25$ mm; note that diffraction effects are weaker and the amplitude is smaller.

Fig. 7. Same as Fig. 5, but $h = 1.0$ mm; diffraction effects are still weaker and the amplitude smaller.
Fig. 8. Comparison between the measured (open circles) and calculated (solid line) response for the conditions described in Fig. 3. The two arrows denoted \( r_0 \) delineate the coil boundary and the symbol \( \cdots \) denotes the square receiver coil dimensions. The rounded region on the right hand side is probably due to a few very slightly misplaced wires; more recent measurements have eliminated this asymmetry.
Fig. 9. Calculated response in the central region of a spiral coil as a function of the coil-to-surface separation distance, $h$. Beyond about 0.25 mm the amplitude decreases about as $1/h$. Measurements show the same general behavior.
comparisons are relatively easy. Our program is now to do approximate
calculations for other coil geometries and to do measurements of the response
generated by other geometries with the confidence that we understand the
influence of diffraction and fringing field effects and can measure them with
some accuracy.

References

DISCUSSION

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

DR. SY FRIEDMAN (NSRDC): These calculations assume that the coil was mounted on an infinitely rigid structure?

DR. MAXFIELD: They assume the coil was mounted on a rigid structure, yes.

DR. FRIEDMAN: Fixed in space, such that the coil itself would not move when the current was put through it?

DR. MAXFIELD: That's correct.

DR. FRIEDMAN: Because in reality it will, you know.

DR. MAXFIELD: Right. Up to current levels of a few amps, the reaction force between the coil and the surface is extremely small. If you get up to coil currents of a few hundred amperes, then you can actually see reaction force effects in the results, sometimes in the form of high frequency chatter. This causes a change in the coil-surface separation distance and is therefore a noise source.

DR. FRIEDMAN: Thank you.

DR. BERTONI: Are there any other questions?

DR. HAROLD FROST (AFCRL): If I understand it correctly, in your calculations involving the spiral arrangement, you took the solution that was essentially a single coil and then used a superposition principle to get the total effect?

DR. MAXFIELD: Yes.

DR. FROST: Did you give any consideration to the effect of the conductors, the wires themselves, in distorting the electromagnetic field on the surface?

DR. MAXFIELD: That was not included in the calculation. The magnitude of this distortion can be estimated and we find it to be very small. Also, you can make coils of different diameter, or you can use printed circuit coils and wire-wound coils and you get the same results. This is another indication that field distortion effects are small since the distortion effects are different in each case, particularly between printed circuit and wire-wound coils.

DR. BERTONI: One way of saying that may be that you're coupling very weakly, in a sense, to the current in the metal, and so its coupling back to the other turns of the coil is probably going to be small.
DR. MAXFIELD: That's not hard to estimate. The reaction of the induced current back on the coil itself is a second order effect which is way, way down.

DR. BERTONI: Any other questions?

MR. WILL NAGEL (Atomics International): I'd like to know your assessment of using a coil transducer of this type as a possible direct replacement for current state-of-the-art piezoelectric transducers, say, flat surface transducers roughly an inch in diameter.

DR. MAXFIELD: I don't think it's a direct replacement at the moment at all. There has been very little in the way of development work going into these transducers. I mean they have been around for years, whereas piezoelectrics have been around for decades. The work that has gone into piezoelectrics is, my guess would be, factors of thousands above that which has gone into the electromagnetic transducer. However, I think they hold a great deal of potential. My own feeling is that their immediate use is going to be in areas such as verifying the various models for scattering theory that have been developed or applications where you need the inherent broadband response. Those are the general areas where I think EMATS will be useful in the very near term. As we understand how to work with them better, particularly to be able to work with smaller signal levels, it will be possible for small, very portable permanent magnets to be used. That's where you're going to get into the real direct replacement for piezoelectric transducers.

DR. BERTONI: Thank you.