Surface Acoustic Wave Electromagnetic Transducer Modeling and Design for NDE Applications

T. L. Szabo
United States Air Force

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I'll be talking mainly about surface acoustic wave electromagnetic transducers, EMT's. These are useful for examining near surface flaws, defects or stress gradients, and they are also very useful for examining rough or painted, or dirty, or hot, or curved surfaces, not necessarily in that order. Recently, this technology has developed to the point where it's possible to fabricate identical transducers. What I'd like to show this morning is that it's also very straightforward to design them. There is quite a large flexibility in the design of these transducers, and they give very clean, reproducible and predictable characteristics, which are, of course, what you need for reproducible quantitative NDE measurements. I'll be describing the work we did last year, the development of a model for these transducers. This work was done by myself, Harold Frost, and Jim Sethares.

Now, I assume that you know how electromagnetic transducers work. The kind I'll be talking about is shown in Fig. 1; it's basically a meander geometry. A large current flows through the meander geometry and produces eddy currents in the surface which produce the periodic stresses that generate surface acoustic waves in both directions. Other modified geometries are possible, including modifications obtained by varying the periodicity of the conductors and also by changing their length.

Figure 1. Schematic diagram for meander coil surface wave Transducer

The type of conductors I'll be talking about are flat conductors because they are very easy to fabricate reproducibly and uniformly in production as Fig. 2 shows. These are different kinds of electromagnetic transducers. On the upper left is a five period wire transducer of the type that has been made in the past. On the right are three 10 MHz printed circuit board transducers. This kind of fabrication technique was developed by Moran and Thomas. On the top we have a multiconductor flat cable EMT, in which the conductor length varies along with the direction of propagation, and I'll be describing that in more detail later.

Figure 2. Various forms of surface wave Transducers

Figure 3 shows the EMT equivalent circuit model. Basically, what we've done is to completely characterize the electrical and acoustical properties of the transducer. This circuit is very useful for design and also, knowing the electrical properties, you can develop better matching techniques. For example, we found theoretically and experimentally that shunt capacitance matching is the best kind to use here because electrically the EMT is mainly an inductor and a resistor. Here $R_E$ is just the normal resistance of the fingers. $L_E$ is the inductance of the transducer. $R_{EC}$ is the new loss mechanism that we identified as eddy current resistance, $X_A$ is the acoustic reactance, and $R_A$ is the acoustic radiation resistance.

Figure 3. EMT Equivalent Circuit
In Fig. 4 we see that both the inductance and the eddy current resistance are functions of the gap. These are some measurements we took at 10 MHz.

We can see that the inductance is almost zero when the transducer is very close to the ground plane, and then when the transducer is removed from the surface, it assumes its free space value; whereas, the eddy current resistance (which is proportional to the square root of the frequency) is largest for small gaps and then decreases as you move the transducer away from the surface.

Figure 4. Eddy current resistance and inductance of EMT as function of lift-off.

Now, we will go to the acoustic properties in Fig. 5. This is the acoustic radiation resistance for a four period transducer plotted versus normalized frequency.

Figure 5. Acoustic radiation resistance as function of normalized frequency.

Now, in developing this model we started out from scratch—from first principles—and worked our way to this result. This response has a \((\sin x)^2\) shape which will seem familiar to those of you that know about interdigital transducers, because both transducers have the same type of response. In developing this model, we found that, in addition to the \((\sin x)^2\) dependence, there is also a skewing term, so that, as you see here, the left side lobe is lower than the right one. We can show simply the similarity between the radiation conductance of an interdigital transducer (IDT) including the skewing term and the radiation resistance for an electromagnetic transducer.

If we define a parameter,

\[
\chi = \pi N \left( \frac{\omega - \omega_b}{\omega_b} \right)
\]

in which \(N\) is the number of periods in the transducer, \(\omega\) is the angular frequency and \(\omega_b\) is the angular center frequency of the transducer, then for the IDT radiation conductance we have

\[
G_A(\omega) = \frac{\omega}{\omega_b} G_A(\omega_b) (\frac{\sin x}{x})^2.
\]

Similarly, for the EMT radiation resistance, we get

\[
R_A(\omega) = \frac{\omega}{\omega_b} R_A(\omega_b) (\frac{\sin x}{x})^2.
\]

And now I'll show some experimental results. In Fig. 6 the insertion loss for two 15 period electromagnetic transducers is plotted as a function of normalized frequency. The insertion loss is 90 dB with a modest input signal of 1 amp peak. We have quite a large range of sensitivity which is adequate for many applications, and you can see that in the pass band there's excellent agreement with the theory. The bandwidth here is simply related to one over the number of periods, so it's very easy to change your bandwidth.

Figure 6. Insertion loss as a function of normalized frequency.
Figure 7 shows the insertion loss for one four period electromagnetic transducer. In this case the experimental data were plotted against a theory in which the radiation resistance was just $\left(\sin x\right)^2$. You can see that within the pass band some of the data points fall below the theory on the left side and above on the right side.


Figure 7. Insertion loss for four period EMT as a function of normalized frequency.

Figure 8 shows that better agreement is obtained with the skewing term included in the theory especially for the passband and on the right side-lobe.

Now, since there is a similarity between the interdigital transducer and the electromagnetic surface wave transducer, naturally, we can draw on the wealth of information on IDT design. We can try some of the same tricks with electromagnetic transducers to obtain not only transduction capability but also a signal processing capability.


Figure 8. Comparison of experimental and theoretical insertion losses with skewing term included.

I will now describe the frequency response of an apodized transducer, which is the one on the upper right of Fig. 2, in which the length of the fingers varies linearly towards the center of the transducer. Shown in the left side of Fig. 9 is the insertion loss of two uniform length transducers, one with 7 periods and one with 15 periods, and on the right we have, again, the insertion loss of the same 7 period transducer in conjunction with the apodized transducer. And you see that good agreement is obtained with the theory. The effect of apodization is to widen the passband and to lower the sidelobes.


Figure 9. Insertion loss of apodized transducer as function of normalized frequency.

Later, Tom Moran will be talking about another way you can change the frequency response of the transducer by varying the periodicity. So, you can see now that you have a tremendous capability here in design flexibility for NDE applications.

And now I'll go into an application that uses a transducer we reported on last year. The transducer shown in Fig. 10 is made out of multi-conductor flat cable bonded onto a samarium cobalt magnet which all results in a very compact package.


Figure 10. Photograph of EMT using multi-conductor flat cable configuration.
Figure 11 shows this transducer being applied. Here is an aerospace part, and on the right side a wedge transducer is used to launch a surface wave which travels up around the curvature of the part. The surface wave is picked up by the electromagnetic transducer shown in Fig. 10. On the top surface there is a scratch which could be either a forging lap or a deep crack. We want to discriminate between these defect types quantitatively. We designed the next experiment shown in Fig. 12 to simulate a forging lap. This is an aluminum downstep made very precisely with a step height of h. On the left we have a wedge transducer launching the surface wave, and the same type of electromagnetic transducer receiving the incident and reflected waves.\(^2,4\) In Fig. 13 we show the theoretical curve for the reflection coefficient from a downstep and our data. This is the reflection coefficient versus the step height divided by wave length; alternatively, you may consider this curve to be the spectrum of the downstep. Here you see that the significant features of this curve are a maximum at .5 and a minimum at around .8. We were able to discriminate between these features using the single transducer for each step shown.\(^4\)

**Figure 11. Application of EMT to complex shaped part**

**Figure 12. Setup for measuring saw transmission and reflection coefficients for a step**

**Figure 13. Comparison of theory and experiment for reflection coefficient for downstep**

You might consider this problem an ideal case. These transducers may be designed to either filter out defects of certain sizes or, since their responses are very clean and well described, it's easy to remove their response from the defect spectra that you are examining.

Other work that we've done includes the successful generation of surface waves on insulators in a non-contact configuration by using these transducers and placing metal tape on the insulator.\(^4\) We've also designed a very sensitive rotation angle sensor using curved electromagnetic transducers.\(^4\)

So, in summary, these transducers are easy to design; they have very reproducible and predictable responses, and there's a lot of design flexibility for NDE applications.

**REFERENCES**


7. T. J. Moran, this proceedings.


DISCUSSION

PROF. VERNON NEWHOUSE (Purdue University): Are there any questions or comments? Would you announce your name and organization, please, and I have been asked by our reporter that the speakers speak up. Otherwise, not only will their remarks be anonymous but there won't even be any remarks.

PROF. MACK BREAZEALE (University of Tennessee): I'm curious to know the reason for stopping with the apodized transducer in the configuration that you used. It seems to me that you can make the additional step of going to a Gaussian function and get rid of the sidelobes completely. Was there a fabrication reason for that?

DR. SZABO: We had considered that and Tom Moran has actually made transducers which do give a Gaussian acoustic beam. In this talk I described how we apodized the transducer to give a certain frequency response. You can also apodize the transducer to give a certain beam shape, and this has been done. And you're right, the Gaussian beam you've described is the best sort of a shape to use for NDE applications rather than a rectangular shape.

PROF. JOHN SHAW (Stanford University): In acoustic IDTs there is an optimum number of fingers. Is that true also for these?

DR. SZABO: It is, that's right. And our model will give you that result, but it's not as straightforward as it is for IDTs. It usually has to be done numerically.

MR. BOB IRWIN (Northrop): In comparative analysis of conventional systems with your EMT device, do you have any data on that as far as sensitivity and resolution?

DR. SZABO: What do you mean by sensitivity and resolution?

MR. IRWIN: Is it more sensitive and does it provide more resolution for near surface defects than immersion systems?

DR. SZABO: Well, this talk has been about surface waves. In an immersion system, you can launch a beam so it will mode convert to a surface wave, but most people just use wedge transducers. An EMT has slightly less sensitivity than a wedge transducer, but it has many other advantages because you are able to place the transducer very precisely and you are able to define its characteristics very well. Does that answer your question?

MR. IRWIN: Somewhat.

PROF. NEWHOUSE: Well, thank you.