A PRACTICAL APPROACH TO FABRICATING IDEAL TRANSDUCERS

J. J. Tiemann
General Electric Corporate Research and Development
Schenectady, New York 12301

A 20 minute talk is something like the well known definition of an expert. One can choose a very narrow subject and say all there is to say about it, or choose a broad one and say very little about any one part. And there is presumably an optimum choice of material and treatment somewhere between these extremes. But I'm going to try a new approach this morning. I'm going to take an extremely narrow subject and say essentially nothing about it. Part of this is a prejudice on my part that it's not very easy to communicate technical details in a meeting like this, and the other part is that I noticed just last night that I left about two-thirds of my figures at home. And so, I'm going to fill up most of the time that would otherwise be my speech with some comments. Since some of these may be controversial, I plan to have substantial time at the end, or even during my talk, if you wish, to pursue whatever questions come up.

I was invited here to come to talk about transducers, and I'd like to tell you how that came about. It came about because the General Electric Jet Engine Dept. has been trying to perform water immersion ultrasonic inspection of engine forgings with commercially available inspection equipment and has found that this equipment is ill suited to the task. I would guess that most of these instruments were designed 5 or 10 years ago for applications in the steel industry. In any case, they do not have enough dynamic range to accommodate the large acoustic attenuation encountered in Jet Engine alloys, and they do not have adequate resolution. But above all, it seems to be impossible to purchase reliable transducers whose characteristics are reproducible and well specified.

This brings me to what I'd like to call the "Frequency Domain Delusion". In part, this is the idea that the transducers used for pulse echo inspection can be meaningfully characterized in the frequency domain. Pulse echo inspection is basically and inherently a time domain phenomenon. There is a one-to-one relationship between the physical location of a scattering center (defect) and the time when the echo returns to the transducer. In the inspection process, the peak amplitude of this highly localized energy pulse is measured, and the part is rejected if it is larger than a predetermined minimum. In the frequency domain, the basis vectors are continuous sine waves, and the descriptors are the amplitude and phase. This basis is inappropriate for describing pulses localized in time because time delay is a global property of the entire frequency domain representation rather than a property of a specific component. What the frequency domain describes is the resonant frequencies and damping factors of the normal modes of vibration of the transducer.

As we shall see, the characterization of a transducer by its resonance and Q factor presumes a structural simplicity that is not true. The implicit assumption of structural simplicity that hides within a frequency characterization can lead to grief.

Since the pulse echo inspection technique is a time domain problem, the entire system should be characterized, specified and analyzed in the time domain. The time domain characterization of a transducer is, of course, its impulse response, and many of us are used to seeing a scope trace of the impulse response of a transducer pasted onto the purchase sheet that comes with it. But this scope trace is not really an adequate document, because it hides a fatal problem that is often encountered when inspecting for flaws near the surface. Furthermore, I'm going to talk only about the longitudinal mode inspection problem which comes about because the reflection of the sound beam from the front surface comes right back into the transducer again. (Top of Fig. 1). Thus, unless the impulse response of that transducer is extremely clean the reflection from that front surface masks the echoes from the subsurface defects. There are two reasons for this. One of them is that the entire beam hits the front surface, and since it's flat, it's all coherently reflected back to the transducer. The defect, on the other hand, is very small so it intercepts less energy, and this energy is scattered in all directions. This accounts for a factor of about 100 (or 40 dB). The other reason is that the defect material is often very similar in acoustic impedance to the matrix, whereas the impedance mismatch at the front surface is very large. (Center of Fig. 1.). So, we're generally trying to look for things that are anywhere from 60 dB to 100 dB down from the reflection of the front surface, and we'd like to see them right under the surface. So, there's a big problem. In fact, if you look at the impulse response of a transducer such as the previous speaker showed in the frequency domain, it looks sort of like what I've shown in the lower part of Fig. 1 labeled "Front Reflection". It has sort of an ideal 3 1/2 cycle response followed by some junk; and this junk, which doesn't show up very well on the purchase sheet scope trace, is what does you in. Note that the relative amplitude of the "junk" will swamp out the defect indications close to the surface as shown in Fig.1. If you turn the gain up high enough to be able to see the defects you are looking for, the actual ringing time of commercial transducers is typically 1 μsec before the defects can be reliably perceived. This 1 μsec ringing time is essentially independent of the center frequency of the transducer and independent of its Q factor. This delayed emission never shows up in the frequency specification or on the purchase sheet scope trace because, first of all, the frequency content of this delayed emission is the same as the main pulse and second, because the total energy is usually less than 1 percent of the energy in the main pulse.

Thus, the fact that there is a problem here would show up in the frequency domain only as an extremely subtle change in the phase characteristic (which is never presented), and is totally beyond the ability of any present spectrum analyzer to detect anyway. Nonetheless, this delayed energy makes the detection of near surface defects impossible.

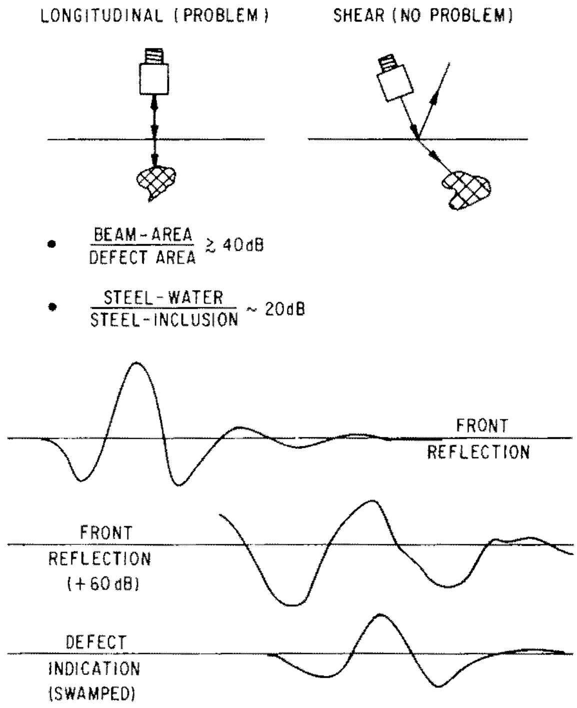


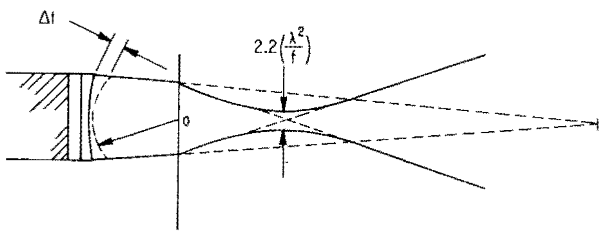
Figure 1. Near surface inspection.

Well, its one thing to argue about how transducers should be measured, and it's admittedly frustrating that commercial transducers aren't the best, but from a physicist's viewpoint, it should be possible to make transducers that do not have a delayed output, and there must be some specific reasons as to why transducers are bad. So, we took some of them apart; I could spend the whole morning on the chamber of horrors we found: things like being glued together with Eastman 910 cement, which is fine for a half a year, but this material continues cross linking and gets more and more brittle as time goes on. It's not surprising, then, that Q factors change with time: after a year or so, the transducers fall off the backing material! We also found electrode films that had completely flaked off and in many cases we found that the material used for the backing simply did not match the acoustic impedance of the transducer slab. In short, we found that the transducer manufacturers do not have the same perceptions as we do concerning the necessary attributes of a pulse echo transducer.

At this point we decided to make some transducers. We would use well characterized materials with uniform properties and well controlled dimensions, and we would use reliable bonding agents, and we would simply insist that they perform the way they were supposed to.

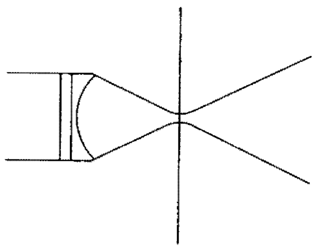
First, we studied some computer models. We took slabs of different materials-with different densities, sound velocities, piezo-electric coupling constants, etc., and predicted transducer parameters such as insertion loss, Q factor, impulse response, etc. (These were some of the figures I left home). And we looked into other design considerations such as the optimum focal length. For deep penetration it's desirable to have a transducer that focuses two or three inches within the material, and since there's a 4 to 1 speed change compared to water, there's actually a foreshortening of the focus. So, the transducer should have a focal length of about 12 inches in order to focus 2 or 3 inches below the surface. This is shown at the top of Fig. 2. Now, such a transducer will enable you to see a defect a couple of inches in, but a defect that is near the surface will have a time dispersion shown by Δt in Fig. 2,, due to the fact that the defect is not equidistant from all points on the transducer surface. Thus, the round-trip time is not unique and you get a time dispersion which corresponds to a loss of resolution. There is no way to make a high resolution, near surface transducer that also has deep penetration. Conversely, if you focus on the front surface, as shown at the bottom of Fig. 2, then the time dispersion at the surface goes away, but the beam diverges and you don't get good penetration. So, you have to optimize the focus of the transducer depending on what the application is.

1. DEEP PENETRATION TRANSDUCER



- LOW ENERGY DENSITY AT FRONT SURFACE
- TIME DISPERSION (LOSS OF RESOLUTION)

2. NEAR SURFACE TRANSDUCER



- HIGHER ENERGY DENSITY
- BETTER RESOLUTION NEAR SURFACE
- POOR PENETRATION

Figure 2. Transducer focal length.

On the other hand, if you put a lens in front, you blow it. There is no way you can put a lens in front of a transducer without destroying the impulse response. The problem is that the lens is usually plastic and has a different impedance from both the transducer and the water. Since both of the lens surfaces have reflections, the acoustic energy bounces back and forth several times as shown at the top of Fig. 3, and this represents a cause of delayed energy emission.

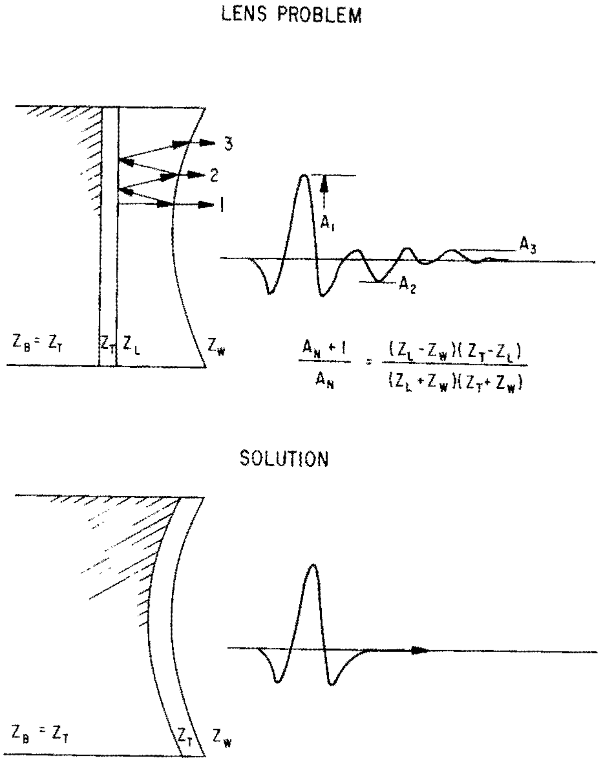


Figure 3. Lens Problem.

The problem is shown quantitatively in Fig. 4 which is a plot of round trip reflection loss and insertion loss as a function of lens impedance. Note that there is less than 10 dB round trip loss for the impedance range corresponding to most plastics. Thus, if you want to have an attenuation of 60 dB, (as is required to see a near surface defect), something like 6 round trips are needed. The time delay for these 6 round trips is unacceptable for near surface inspection.

We have investigated another approach as an alternative to a lens, namely to make the transducer in the form of a thin spherical shell instead of a plane slab. This approach, which is shown at the bottom of Fig 3, is actually quite practical, since spherical lapping tools are available with almost any radius of curvature (thanks to the optical industry). So, it's actually no more difficult to grind a spherical shell of material than it is to grind a flat slab.

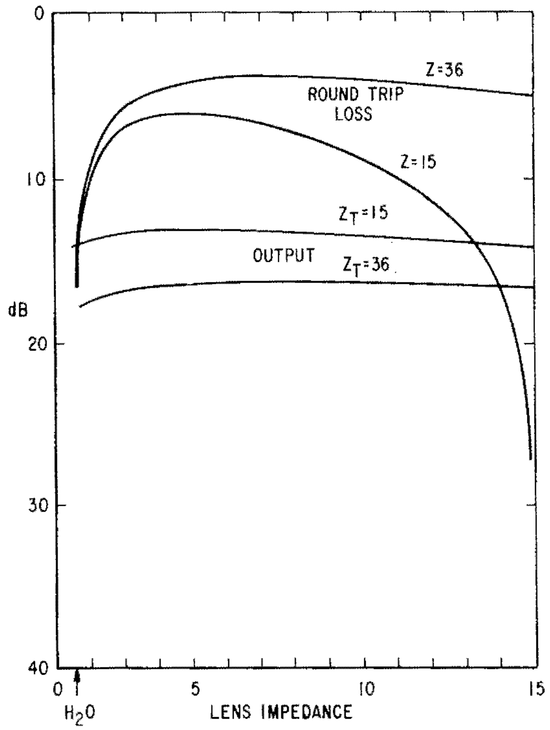


Figure 4. Plot of round trip reflection loss and insertion loss as a function of lens impedance.

We identified another problem which is a sneak path caused by the Poisson's ratio coupling of the transducer, namely, when the transducer squeezes in longitudinally, (indicated by horizontal arrows at the top of Fig. 5) it squeezes out laterally, (indicated by vertical arrows). The way commercially available transducers are made, the laterally directed energy just goes right out into the case and comes out about an eighth of an inch later at the edges of the case. (Shown by dotted path.) This was the source, by the way, of the delayed energy from the commercial transducers to be shown later. We identified that by putting a ring of plasticine clay (shown as dotted material) around the case and around the front of the transducer so as to hide the end of the case, and sure enough, the delayed energy went away. (That didn't completely solve the problem for that transducer because that particular transducer also had a lens on it.) Our approach to the sneak path problem was to not let the transducer edge have any contact with the case. Instead of continuing laterally, we want any energy that is emitted laterally to be converted into a backward motion which then enters the backing. The construction shown at the bottom of Fig. 5 apparently does work. It does cut down the delayed energy, and eliminates the sneak path to the transducer case.

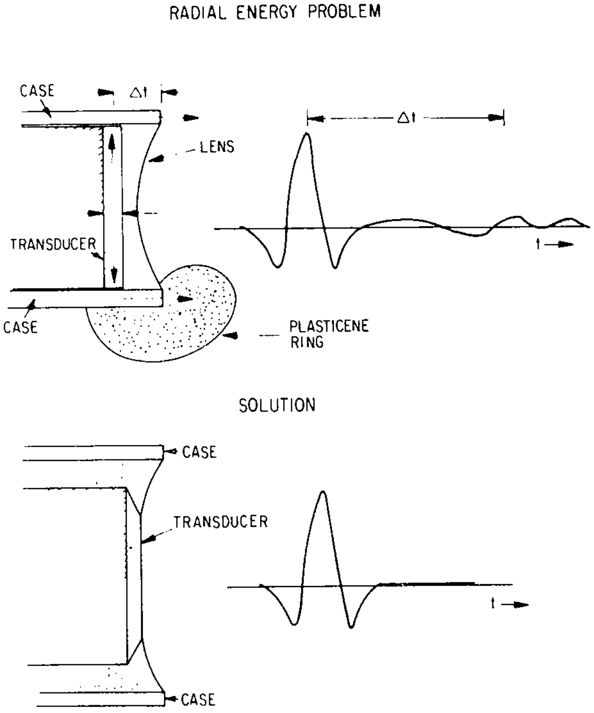


Figure 5. Radial energy problem.

There are other questions, such as the choice of transducer material. There is a figure of merit, for example, which is essentially the output voltage ratio. In other words, let's say I put one volt on the transducer; it emits some sound which then reflects back, and I measure the output pulse amplitude. The combination of material properties that gives the output voltage ratio is the acoustic impedance times the sound velocity times the dielectric constant times k^2, divided by an acoustic mismatch factor to take into account the mismatch between the front surface of the transducer and the water. Figures of merit for some commonly used transducer materials are shown in Table 1.

Table I

TRANSDUCER MATERIALS

FIGURE OF MERIT

- FIXED EXCITATION VOLTAGE
- UMATCHED AMPLIFIER

MATERIAL	k^2	ϵ_{33}^{S}	V	ζ	Z	$\frac{Z V \epsilon k^2}{\left(\frac{Z}{Z_w}+1\right)}$
PZT-2	.26	260	4.41	7.6	33.5	18.4
PZT-4	.26	635	4.6	7.5	34.5	45.5
PZT-5A	.24	830	4.35	7.75	33.7	53.0
PZT-5H	.26	1470	4.56	7.5	34.2	105.2
PZT-6A	.15	730	4.56	7.45	34.1	30.3
PZT-7A	.25	235	4.8	7.6	36.5	16.0
$BaTiO_3$	.14	1260	5.47	5.7	31.2	63.4
$Li_2SO_4 \cdot H_2O$	.09	9	5.47	2.06	11.3	0.7
$PbNb_2O_6$ LM278	.16	225	2.54	5.8	14.7	11.5
K-81	.14	300	3.25	6.0	19.5	13.6
K-83	.14	175	5.33	4.3	22.9	11.3
K-85	.18	800	3.30	5.5	18.2	50.2
$NaKNbO_3$	.28	450	6.2	4.45	27.6	57.3

Finally, I'll make a few comments about anti-reflection coatings. We put an anti-reflection coating on a transducer under the delusion that we were going to improve the output voltage, but it turns out that the best you can do with an anti-reflection coating is about 2 or 3 dB; that's when the impedance of the anti-reflector equals the square root of the product of water impedance and transducer impedance. The improvement in insertion loss achieved by an anti-reflection layer is shown quantitatively in Fig. 4 for two values of transducer impedance. The impedance values shown correspond to lead metaniobate (z = 15) and PZT (z = 35). But what you pay for that is the round trip loss problem of the energy trapped in the anti-reflection layer. It's absolutely clear that you're better off with 2 or 3 dB more insertion loss than to fight with this delayed energy emission.

DISCUSSION

PROF. VERNON NEWHOUSE (Purdue University): Well, I'll take the first stab.

DR. TIEMANN: Great.

PROF. NEWHOUSE: Stab is the wrong word. Jerry and I have known each other for 20 years.

A few years ago, unfortunately, I don't remember the name of the contributor, maybe he's here in the audience, but somebody published a very impressive paper on being able to detect the coating on teeth, which is only a few microns thick using very long bursts of waves. And we this afternoon — if there is time, if Dr. Papadakis gives us the time — hope to present some preliminary results on the use of computer processing to get very high resolution results even from low band width systems. So, I don't think that it's an open and shut case that you need that ideal simple δ function to get high resolution.

DR. TIEMMANN: I agree with that, but let me put this in the context of the Jet Engine Department trying to inspect parts on the factory floor with a pulse echo technique. And in that context there's only one way I can see to be helpful, and that's to make better tools.

MR. DICK BUCKROP (Alcoa): Were you successful in coming up with transducers which have measurably better resolution at equal penetration to those commercially available?

DR. TIEMANN: I have to answer that with a waffle, and the problem is that we're just making these now and the answer is sort of yes or no. I will say that the transducers that we have made do behave the way they're supposed to. When we get the impedance of the backing to equal the impedance of the transducer, there will be no reflection from the backing, and they will either have the ideal impulse response, or we'll have to figure out the reason why. From the mathematics and the physics of it we must get three half cycles and nothing else.

DR. PAPADAKIS: Are you going to generate durable transducers with no wear plates?

DR. TIEMANN: I can't answer that right now, but I feel that there is no possibility of putting a wear plate on unless it matches the impedance of the transducer, in which case it's essentially not there. So there could be a wear plate, but you should not put an immediate impedance in. It should be the impedance of water or it should be the impedance of the transducer. There must be only one reflecting surface. There can be one reflection off the front surface provided it's never heard from again. The fatal problem comes when you have two surfaces that reflect.

PROF. J. SHAW (Stanford University): There's a relatively new material in the transducer art, poly (vinylidene) fluoride, a piezoelectric plastic, and if one makes a simple transducer using films of this material bonded onto backing rods, you can very easily realize a clean impulse response. It consists of a single bipolar pulse form. And also, being flexible, it perhaps--well, it's easy to think of making lenses and perhaps even variable focus lenses.

DR. TIEMANN: The comment is that there's a piezoelectric plastic which can be used to fabricate a very good looking transducer. I consider that kind of research to be extremely valuable potentially for use on the factory floor. I would encourage further work on that.

PROF. NEWHOUSE: One last question.

PROF. R. E. GREEN (Johns Hopkins): I happen to be working with some of this material myself, and I think it's hopeful that something will come out of it, but at the present time the melting point of poly(vinylidene) fluoride and the other type polymers that are piezoelectric, is not optimum for working around jet engines.

DR. TIEMANN: Oh, no, we do these inspections in water at the factory.

PROF. GREEN: But the response is very weak. I would say it's comparable to the EMAT. So, I don't know what its order of magnitude is, but it's two or three times from the common piezoelectric material; but these developments are going on all the time. So, it is interesting.

DR. TIEMANN: Yes. You can see from this figure of merit that unless you have a high impedance, a high velocity and a high dielectric constant, it's very hard to get a good figure of merit.

PROF. NEWHOUSE: One last question from Professor Shaw, then we'll go for coffee.

PROF. SHAW: Well, one advantage of poly(vinylidene) fluoride is in radiating into water it matches very well into water, and that goes a long way to compensating for the relatively lower piezoelectric constant.

DR. TIEMANN: It also has a relatively high velocity, and both of these factors help.

PROF. NEWHOUSE: Thank you.