

SIGNAL PROCESSING WITH SURFACE ACOUSTIC WAVE DEVICES

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Our interest is in analog signal processing as it might be applied to NDE, carrying out some sophisticated signal processing using an inexpensive, real-time analog system based on the surface acoustic-wave technology, or perhaps the CCD technology.

To date we have considered an inverse filter for correcting for the frequency response of an NDT transducer: we have shown the feasibility of making such a device and will show some experimental results here. We are making and testing some filters that have been designed to go with a commercial NDT transducer that we have purchased. We are also looking at the possibility of realizing the same sort of filter with a charge-coupled device.

In the next year we should like to look at a more complicated analog signal processor - the convolver or correlator - to see how it can be realized and applied to defect signature recognition. At the end of my talk I'd like just to mention some work being done by another faculty member at Berkeley on an interesting receiving transducer which I don't think has come to the attention of this particular audience.

NDE Inverse Filter

As outlined last year, we are using as a test object a block having regions of different acoustic impedance (Fig. 1). When we send in a pulse it would be nice if our system produced nearly delta-function waveforms indicative of the presence of planar discontinuities of impedance. In our actual system (5 MHz PZT transducer bonded to an aluminum block), ringing of the transducer results in a distorted output which is not easy to interpret. So the idea is that we might design a simple filter for the system to correct for the frequency response of the NDT transducer and give us, in this case, a delta-function like output.

Initially, we followed the work of Seydel and Frederick¹ who have shown that you can make a digital inverse filter that will do this. Instead, we're using a surface wave filter. The output SAW transducer is designed to have a response which is inverse to the response of our NDT sending and receiving transducer; ideally, we should get some output that looks something like that sketched in the figure.

The design of this filter is based on the impulse response of the NDT transducer. In our case we get this by driving the transducer, letting the acoustic pulse reflect from the reflector, photographing the waveform of the reflection and then scanning that into a computer system.

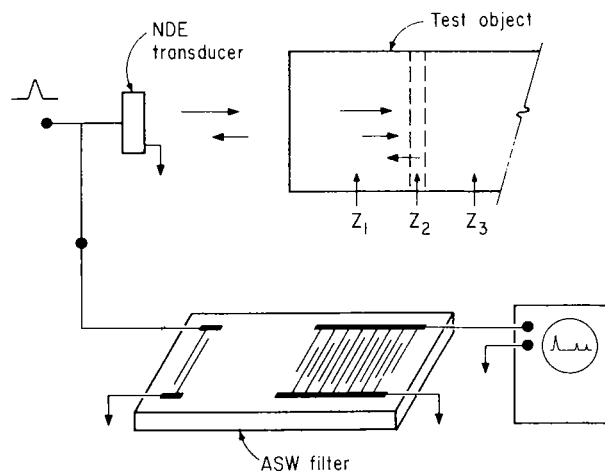


Figure 1. Schematic illustration of simulated NDE system with transducer, test block, filter, and indication of desired output on oscilloscope screen.

We take the impulse response as our reference function, the starting point for the design. We use Fourier transform that to get the true inverse filter characteristic that we would like to have. We also do some weighting on the edges of that response so it doesn't go to infinity where our NDT transducer has no output. We then take an inverse Fourier transform to get the impulse response of our filter. It's the impulse response of the device we're trying to make.

In order to make the device easier to build, we would like to truncate that response somewhat, but not truncate it so much that it ruins the results. We have used both a mean square error criterion and a visual comparison of full and truncated impulse responses in order to determine how much truncation was permissible.

For design of the output transducer of our filter, we have recently implemented the Parks-McClellan finite impulse response (FIR) computer programs to tell us what the tap weights for our filter transducer electrodes should be. I think this is important because we can use that information in the design of either a charge-coupled or surface-wave filter, and we're building some actual filters so as to compare the results of these two designs and see which is best.

The other point here is that in principle, as I think I said last year, the artwork could be produced on a digital computer system. This is a fact now: we are cutting rubyliths for our filter on a digitized (Gerber) plotter (in our Mechanical Engineering Department) and find that this is a great improvement over doing it by hand.

Figure 2 shows a layout of one of the filters with its input transducer and output transducer designed to have the desired inverse response, and a multi-strip coupler to take care of incidental bulk waves. Our first filter had a rather simple input with only one set of fingers for broadbandedness. Later filters have more input electrodes for more efficient transduction.

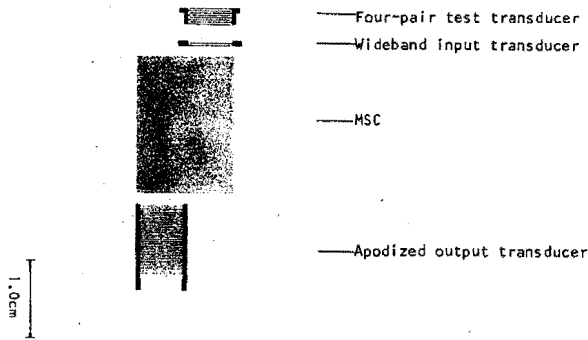


Figure 2. Layout of SAW inverse filter with input transducer(s) at left side and output transducer at right, separated by multistrip coupler for suppression of bulk waves.

In our test setup a PZT transducer is mounted on an aluminum block which is oil-coupled to a thin glass slide: the bottom surface of that glass slide is coupled by an oil film to another aluminum block, making a sandwich structure which produces reflections. On the oscilloscope trace (Fig. 3) are the unprocessed responses from the back of the test block and the output of our inverse filter. Comparing the responses, one sees that it is possible to resolve the separate peaks in the filtered output only.

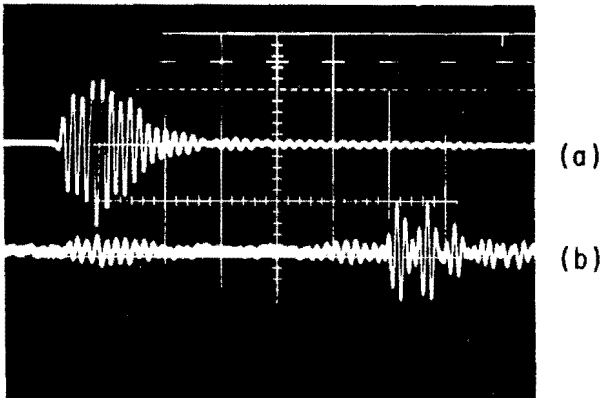


Figure 3. Reflections from test block. (a) Unfiltered return. (b) Return filtered with SAW inverse filter, showing resolved separate reflections from different layers at end of test block.

We made other measurements, trying to correlate the amplitudes of the peaks in the output with the magnitude of the impedance discontinuity, and found that the properties of the oil film dominate in the reflections. Since we didn't know how thick the film was, we set up instead a water bath system (Fig. 4) to permit measurement of resolution. The bottom end of the aluminum block is in a water bath; a (water-filled) gap between the bottom end of that block and another aluminum block in the water bath forms our impedance discontinuity. We can move the test block up and down (measuring the distance with a dial indicator) and measure the spatial resolution. We have shown that inverse filtering can improve the spatial resolution of our test transducer, which has lots of ringing. Now we are seeing to what extent it can improve the response of a purchased commercial transducer.

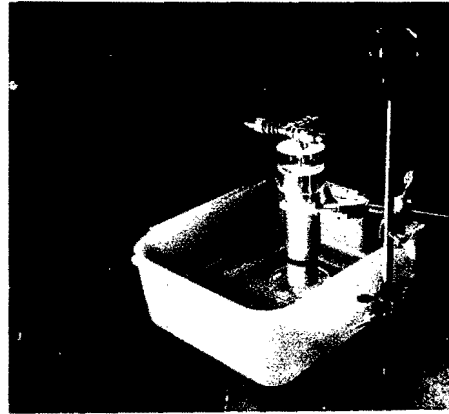


Figure 4. Photograph of test block in resolution test setup. Block can be moved known amounts vertically to vary width of gap in water bath between it and a second metal cylinder located in the bath.

As mentioned earlier, the starting point in the filter design is the impulse response of the NDE transducer. The impulse response of one purchased commercial transducer, driven by a rectangular pulse (from a commercial pulser that is nominally identical to the one used by the manufacturer of this transducer), is shown in Fig. 5. One realizes that if one were making an inverse filter to go with a particular transducer, one would not like to have the impulse response of the system (composed of pulser and NDE transducer) change; if the pulse duration of the drive pulser changes, then the impulse response of the system changes and the filter isn't as good. For this reason, it is advantageous to drive the transducer rather with a single step² that then very gradually decays away to zero voltage sometime later. When our commercial transducer is driven with a single step, we get what most people would agree is a more nearly ideal response (Fig. 6). It is also interesting to note that with the same step voltage one obtains about 3.5 times the acoustic output amplitude as when one drives with a rectangular pulse.

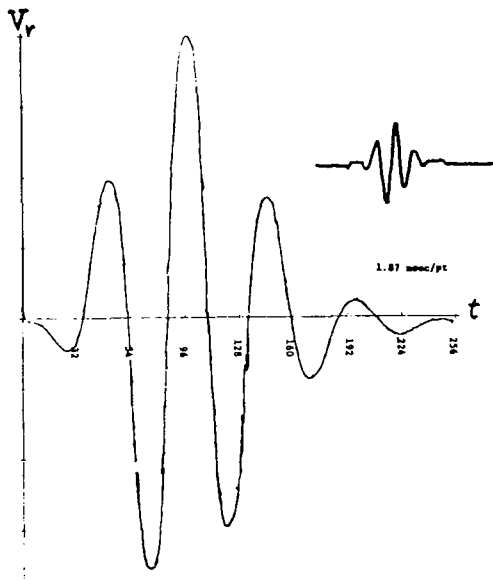


Figure 5. Impulse response (output voltage V_r versus time t when acoustic pulse reflects from a plane reflector in water bath) of commercial NDT transducer driven by rectangular pulse supplied by pulser made by same manufacturer. Inset shows tracing of impulse response as supplied by manufacturer with transducer.

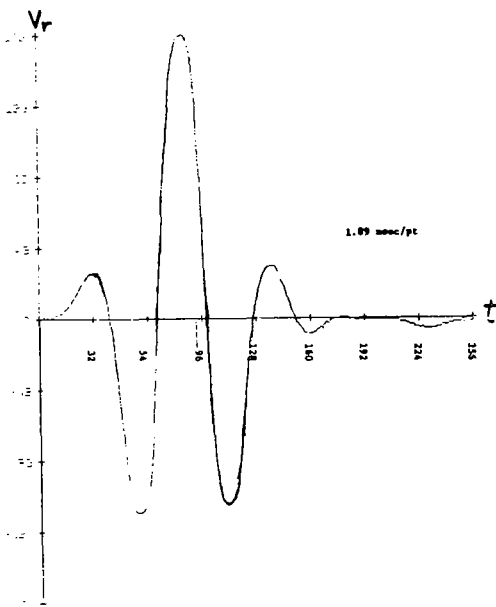


Figure 6. Transducer of Fig. 5 driven with single step to obtain impulse response. Note that response is more nearly symmetrical and of somewhat shorter duration.

Of course, one could generate such a step drive with solid-state circuitry, but we did it with a commercial (SKL) delay line pulse generator which is normally used for the generation of short duration rectangular pulses. The device operates by slowly charging a coaxial cable to a constant potential and then discharging it suddenly upon closure of a relay having mercury-wetted contacts. When the relay closes, disturbances travel in both directions along the coaxial line; the load sees, first of all, a rise in voltage when the disturbance reaches it, and then a fall back to zero when the disturbance reflecting from the open end of the coaxial line reaches the load.

All we want is the fast voltage rise at our load (NDT transducer). So we terminated the charging cable in a DC-blocking capacitor and a resistor equal in value to the characteristic impedance of the cable. Although this may seem crude because it involves a mechanical element, namely, the relay, the rise time of the step that we get out of this was as short as 0.4 nanosecond, showing this to be a very practical type of step pulse generator.

Piezoelectric field-effect Transducer

I would like to change now to a different topic -- a receiving transducer being developed by Prof. Muller and his students at Berkeley. The transducer is a combination of a standard silicon device, a field effect transistor, with a piezoelectric film.³ The important characteristics of the transducer are that it's a very sensitive transducer having a large bandwidth and a very small active area; that it makes a very natural interface between acoustics and signal processing because one obtains an electrical signal in a silicon integrated circuit ready for additional processing as needed.

Figure 7 is a cross-section through the device showing a silicon wafer and the conventional source and drain electrodes. Normally the current which flows from the source to the drain electrode depends only upon the potential applied to the gate electrode. To this standard field effect transistor has been added a thin rf sputtered layer of piezoelectric zinc oxide. When this film is strained, it produces an additional potential in the gate region which has a large effect on the current that flows from the source to drain. Because this film is very close to the flowing carriers, it has a very large effect, making a very sensitive device. (In the devices that have been made, the gate width is only one micron, so, one has a very well localized transducer also.)

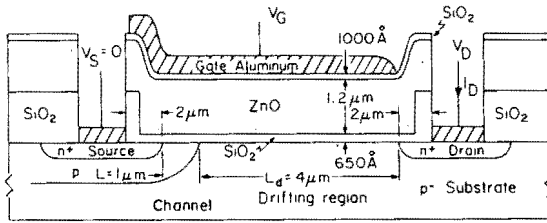


Figure 7. Schematic cross-section of piezoelectric field-effect transistor transducer, showing conventional source, drain, and gate electrodes of aluminum, together with film of piezoelectric zinc oxide (ZnO) underneath gate electrode. (From Yeh and Muller, Ref. 3)

The sensitivity is indicated by static measurements, shown in Fig. 8, where source-to-drain current is plotted against source-to-drain voltage, with gate bias as parameter. The amount of source-to-drain current flowing depends upon the magnitude of the strain. One can define something equivalent to a conventional gauge factor as the fractional change in this source-drain current divided by the strain. Static gauge factors as high as 160,000 have been measured, showing this is indeed a very sensitive device. More measurements of dynamic properties are probably needed, but the transducer has been shown to respond to bulk compressional waves up to about 20 MHz, to surface waves as high as 15 MHz, and there is no apparent reason for these to be upper limits; thus the transducer is expected to respond from DC up to many hundreds of megahertz.

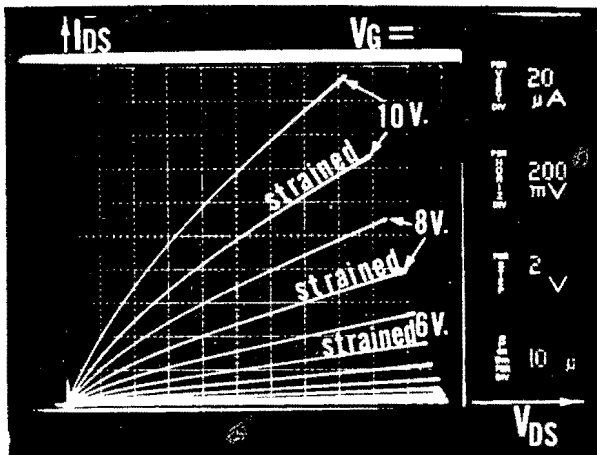


Figure 8. Source-drain current vs. source-drain voltage of transducer in unstrained and strained conditions (strain is 1.8×10^{-6}). (From Yeh and Muller, Ref. 3)

At this conference yesterday, somebody mentioned the need, in the field of acoustic emission, for a wideband transducer that can be located close to the sources of sound. Figure 9 suggests how this field-effect transducer might meet this need. The figure shows a mockup including a conventional transistor header on which the field effect transducer can be mounted. Small coaxial cables connect to the transducer. Some standard transistor headers have a ceramic post coming out of the bottom which can be used to couple sound into the transducer very conveniently. So one can obtain a very small receiving transducer which is well shielded and which has a nice coupling port for sound waves. Incidentally, we have compared the response of one of these FET transducers with the response of a 5 MHz PZT transducer, using a breaking glass capillary as sound source, and find we observe about the same output voltage from both transducers.

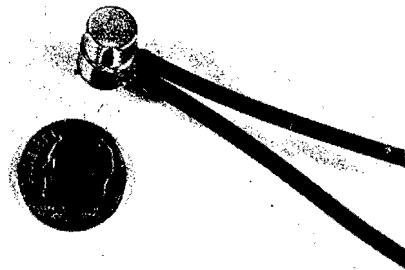


Figure 9. Mockup of piezoelectric field-effect transistor transducer in slightly modified transistor header package. Flexible miniature coaxial cables shown are for bias and output.

I will conclude by saying that I think we have demonstrated the feasibility of making an analog signal processor, namely, the inverse filter using acoustic surface wave technology. We are characterizing these filters, and have designed and are testing one for use with a commercial NDT transducer.

REFERENCES

1. J.A. Seydel, "Computerized Enhancement of Ultrasonic Non-destructive Testing Data," Doctoral Dissertation, University of Michigan, 1973.
2. E.G. Cook, "Transient and Steady-state Response of Ultrasonic Piezoelectric Transducers," Convention Record, I.R.E., Pt. 9, pp. 61-69, 1956; H.E. Van Valkenburg, "Note on 'Sources of Sound in Piezoelectric Crystals'," J. Acoust. Soc. Am., 32, No. 11, p. 1468, 1960.
3. K.W. Yeh and R.S. Muller, "Piezoelectric DMOS Strain Transducers," Appl. Phys. Letters 29, No. 9, 521-522, 1 Nov., 1976.

DISCUSSION

DR. PAUL FLYNN (General Dynamics): Your SAW filter application that you showed might be of interest in an adhesive bar problem. I would like you to comment on possible applications of this inverse filter to signal processing to resolve out adhesive bond-type signals. Do you think it would be applicable?

PROF. WHITE: Possibly so. When people were talking yesterday about the adhesive bond problems and the difficulty of knowing the properties and the thickness, I was thinking about oil films where we had essentially the same problem.

DR. JERRY TIEMANN (General Electric): What is the order of magnitude of the output impedance relative to PZTs?

PROF. WHITE: The output impedance is typically around 15 kilohms, but good electrical response into the very high megahertz region can be observed, if that's what you were worried about.

DR. CHRIS FORTUNKO (Rockwell Science Center): I wanted to point out that it's possible to synthesize this signal like this with two transmission lines. We changed the amplitude and the pulse length and you can synthesize an input signal which will drive the transducer so as to minimize the ring out. This has been done in Berkeley in the 50s, around 55 or so.

PROF. VERNON NEWHOUSE (Purdue): Yes, Dr. Fortunko has pointed out that you can synthesize signals which will produce an ideal transducer response, and we've heard a talk by Dick White which has given some very beautiful results on designing surface acoustic wave devices to essentially deconvolve the outputs of these transducer systems. Would anybody who represents the computer area perhaps like to comment on this? (No comment.)

Well, in that case, I'll jump into the breach and point out that, as Dr. White pointed out, you are going to have different signals with different transducers, so you would have to design a different inverse filter for each transducer, and the computer or microprocessor might have an advantage there insofar as it's more easily changeable.

DR. JERRY TIEMANN: The problem with using a computer to do all of this is one of the digitization or quantization dynamic range that you have available. In order to preserve the accuracy you need to actually perform these deconvolutions, you require something like 14 to 16 bytes accuracy in the A to D conversion. Furthermore, to preserve the band widths, you have to have sampling rates up into the 20 or 30 megasamples per second range. And the expense and problems of getting these extremely accurate, very high speed A to D conversions, is beyond the state of the art.

PROF. NEWHOUSE: We are going to talk about that this afternoon using a correlation-type system which produces nice slow outputs which overcome the sampling rate problem and also refer to computer processing techniques which smear things out so as to overcome that other problem you mentioned.

DR. KEN LAKIN (USC): I have a comment regarding the inverse filter. There has been considerable work done on adaptive transversal filters wherein you are allowed to change the response of the filter. So, even if you have a transducer that is drifting with time conceivably recorrect on the adaptive basis, an electrical adjustment. There was a paper given at the '74 Sonics-Ultrasonics symposium on that and Tom Bristol of Hughes Aircraft might be able to comment on current work done on adaptive transverse filters. Do you care to comment, Tom?

DR. THOMAS BRISTOL (Hughes Aircraft): We're working on a surface wave tap delay line implementation of an adaptive filter, but it has to be a closed loop type of algorithm. And the point is, one has to have some kind of an error criterion to form an error. It's certainly conceivable if we could somehow have an evaluation criteria or some way to establish an error signal, it would be feasible.

PROF. NEWHOUSE: You do need a procedure which is adaptive and can change from instant to instant.

PROF. GORDON KINO (Stanford): We have tried a procedure with that. It's not an inverse filter, it's a correlation filter. But I merely describe it so that basically you can read a signal into a storage device, correlate the weighted signal, use one angle to calibrate the exponent. And that works quite well.

PROF. NEWHOUSE: We hope to describe a procedure using the computer to do exactly the same thing. If anybody would like to get into the subject of piezoelectric transducers versus acoustoelectric transducers, because one thing that hasn't been brought out is that the terrible problem with piezoelectric transducers is that if you change the orientation of your target by just a smidgen, your spectrum changes completely, whereas these phase insensitive transducers that Dr. Heyman talked about don't have that problem. Should we throw away our piezoelectric transducers immediately?

DR. JOSEPH HEYMAN (NASA, Langley Research Center): No.

PROF. MACK BREAZEALE (University of Tennessee): Unless we all throw them away, I would like to ask about the sensitivity of the alternatives to the piezoelectric transducer.

DR. HEYMAN: The power detector is less sensitive than, say, a quartz or even a PZT type of transducer. However, it is not a limiting factor. I'm talking of maybe two orders of magnitude less sensitive.

PROF. R. E. GREEN (Johns Hopkins University): Can you also generate sound waves with the power transducers?

DR. HEYMAN: Well, it is piezoelectric, so you certainly can generate sound waves, but it's not as efficient as some other technique. We're working on a combination of transmit and receive detector which would marry optimum conditions.

PROF. GREEN: Do you think the generated mode will be as sensitive as the receiver mode?

DR. HEYMAN: The only loss in combining the two is going to be in the relative impedance difference between the material.

DR. ROD PANOS (Air Force Systems Command, Materials Lab): I would like to have Dr. Heyman explain a little more in detail this new technique.

DR. HEYMAN: The power detector as it currently stands now is a cadmium sulphide acoustoelectric cell, and the conversion of the acoustic wave to the electrical signal is via phonon carrier coupling in the material itself. So that when an acoustic wave enters the cadmium sulphide cell, it creates an electric field in the cell which couples to the electrons. This leads to a loss of energy in the acoustic wave and a corresponding momentum transfer to the electrons in the cell. This in turn leads to a net charge flow in the cell which results in the whole picture which can be measured. At present we're trying to optimize some of the rise times associated with this phenomena and hope to be able to achieve rise times that would make it very suitable for pulse echo work. I must admit my bag is CW ultrasonics, and I have found it to be very valuable in that area.