

SURFACE ACOUSTIC WAVE FILTERS FOR REAL
TIME PROCESSING OF ULTRASONIC SIGNALS*

Richard White
University of California
Berkeley, California

We shall discuss using surface elastic wave device to do analog signal processing that is applicable to NDE problems. I'm going to talk today about one specific device which we have looked at which can be used with a conventional NDE system to improve resolution.

It's really brave to remain analog in an increasingly digital world, but I think there are some advantages that analog devices can have. The advantages I am referring to are speed of operation (real time operation), and the simplicity of the device, which translates, in part, into low cost.

The applications that I am thinking of here are the taking of returns from an ultrasonic NDE system and preprocessing them for a data collection system, or perhaps just real-time processing for simple display on an oscilloscope. The sort of experimental situation that we might consider is sketched in Fig. 1. It is a very simple system where we have an NDE transducer, perhaps in a water bath or, as in our experiment, actually fastened onto a test block composed of regions of different acoustic impedance.

When we pulse the NDT transducer with a short electrical pulse, ideally we would like to get back a sort of delta function return from each reflecting surface. If you actually perform this experiment with a transducer which has a reasonably narrow bandwidth, what you get back instead of delta functions is a sequence of waveforms as shown in Fig. 2 - you have poor temporal and spatial resolution. So, what we would like to do is to look at a simple way of filtering this output and obtaining a real time output having a delta function character which represents the reflecting surfaces somewhat better.

A way to achieve this was shown by Seydel and Frederick¹ at the University of Michigan. They modelled the system as shown in Fig. 3. A pulser drives the transducer, generating an acoustic pulse which propagates through the test medium and encounters a discontinuity which is what you would like to study. The pulse reflects and perhaps is also partially transmitted. The reflected pulse passes through the test medium again, excites the transducer and produces an output.

The problem is to get information about this unknown - this discontinuity - and to eliminate the distortions due to the other elements in the system. What you are really after is the frequency or

* Research sponsored by ARPA/AFML Center for Advanced NDE

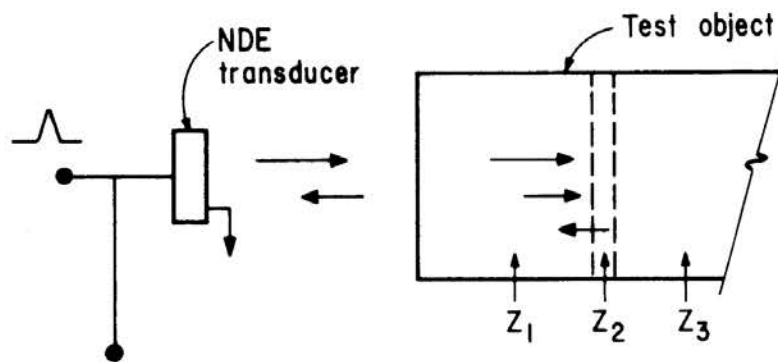
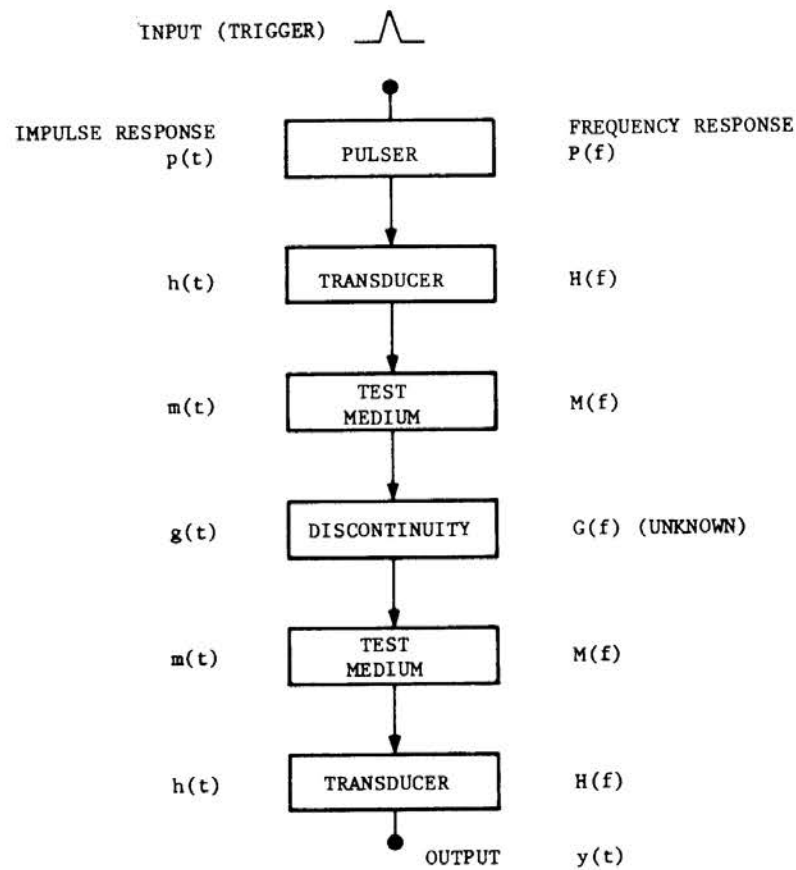


Fig. 1 Experimental ultrasonic NDE arrangement



Fig. 2 Output (voltage vs. time) from relatively narrowband NDE transducer showing ringing



Output (impulse response of entire system)

$$\begin{aligned}
 y(t) &= p(t) * h(t) * m(t) * m(t) * h(t) * g(t) \\
 &= \tilde{s}(t) * g(t), \text{ where } * \text{ denotes convolution,} \\
 a(t) * b(t) &= \int_{-\infty}^{\infty} a(t') b(t-t') dt'.
 \end{aligned}$$

Seek inverse $\tilde{s}^{-1}(t)$. Then can obtain characteristic $g(t)$ from $y(t)$.

Fig. 3. Mathematical model of a pulse-echo ultrasonic nondestructive testing system. Each physical function is represented by a linear, time invariant system.

(From Seydel 1973)

impulse response of the discontinuity; but the output signal is the impulse response of the entire system, which is the convolution of all the impulse responses with the unknown $g(t)$.

All of these other impulses can be combined in an $\tilde{s}(t)$ convolved with $g(t)$. In order to unravel this you look for an inverse function $\tilde{s}^{-1}(t)$ which will enable you to get $g(t)$ from the output signal. Seydel and Frederick did this in a combined analog-digital system which worked well. We're trying to do the same thing in a simple analog system.

To set up their digital inverse filter, Seydel and Frederick used as a reference function the output from a stress-free, planar reflecting surface. This reference function was digitized and the computer was programmed to determine a filter characteristic which would convert the return signal into a delta function representative of the planar reflector. Once the digital filter characteristic has been determined it is used to filter the actual output - including reflections from defects. Then one should be able to resolve the various reflections or reflecting surfaces.

This is really just a filtering problem, and surface waves can be used to make filters. So, the device that we're considering, and the output we would hope to obtain are as sketched in Fig. 4. The acoustic surface wave (ASW) filter consists simply of some properly dimensioned electrodes on a piezoelectric substrate. The return from the NDE transducer produces surface waves at the left hand broadband surface wave transducer, and these waves propagate through the other transducer to produce an electrical output. If the ASW transducers are designed to do the inverse filtering operation that is appropriate for this NDE transducer, then we should get a display on the scope consisting of (nearly) delta functions; this display is more easily interpretable than is a display of the raw return itself.

ASW Filter Design Procedure

The design process is outlined in Fig. 5. First we obtain the response of the NDE transducer fastened onto a cylindrical test block. When the transducer is pulsed we get back a reflection, as Seydel and Frederick did, for use as a reference function. This waveform is photographed and scanned into a computer used by the picture-processing group at Berkeley. From this we can obtain the frequency response of the NDE transducer. We can then determine the true inverse filter characteristic.

Figure 6 shows on a linear scale the frequency response of one of the NDE transducers. The center frequency was near 5 MHz. The true inverse filter will have very large transmission on the edges of this response curve, but these will not be useful in the actual experiment since there is only noise power present at those frequencies; hence, one conventionally weights the inverse filter response in those regions to maintain a good signal-to-noise ratio. A Hanning weighting was used.

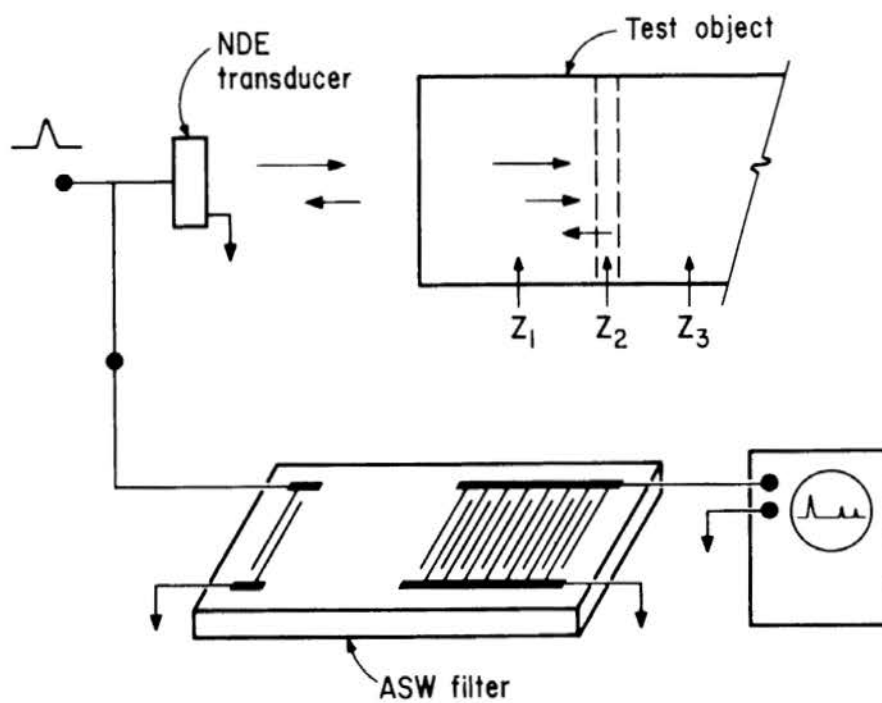


Fig. 4 Experimental ultrasonic NDE arrangement showing use of acoustic surface wave (ASW) inverse filter and hypothetical oscilloscope presentation

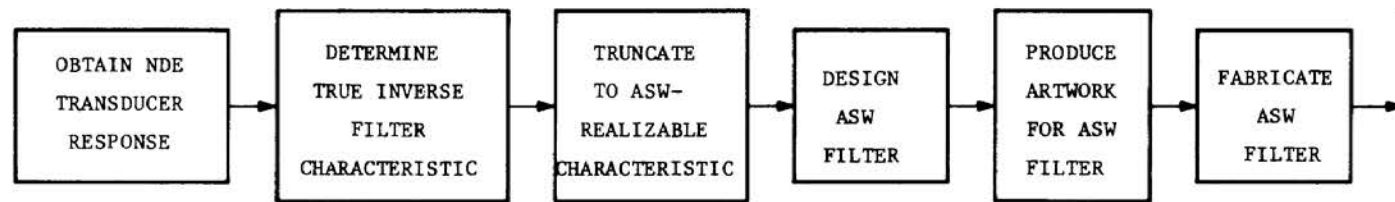


Fig. 5 Procedure for design of ASW inverse filter

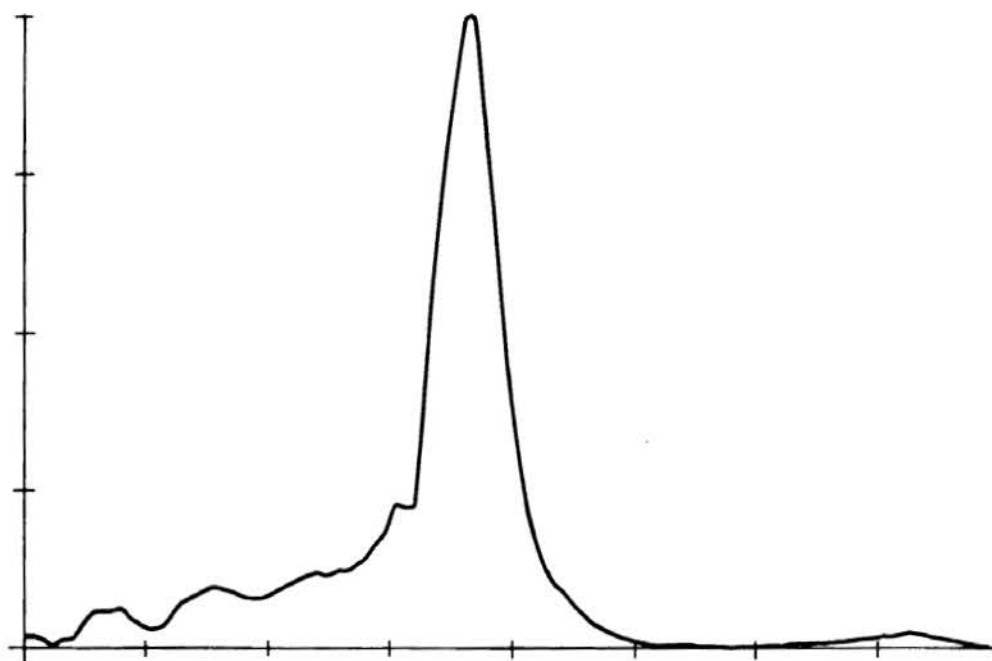


Fig. 6 Frequency response of pulser, NDE transducer, and medium (amplitude of response vs. frequency). The center frequency of the system is about 5.7 MHz.

In addition, it is convenient to truncate the impulse response of the inverse filter, so as to simplify obtaining an ASW inverse filter. (We shall see that there is a simple correspondence between the length of the impulse response and the length of the ASW transducer.) In the computer simulation, we have truncated the impulse response until distortion of the deconvolved reference function was just noticeable; in this way it was possible to reduce the requisite number of ASW transducer finger pairs from 250 down to only 20 pairs.

Figure 7 shows the frequency response of the Hanning weighted inverse filter, as determined by the computer from the full reference function. The arrow marks the center frequency of the NDE transducer itself, at approximately 5.7 MHz. Figure 8a shows the reconstructed impulse response corresponding to the inverse filter frequency response in Fig. 7; Fig. 8b shows the output versus time that would be obtained from the full weighted inverse filter when the reference function was input to it. Figure 9a shows the impulse response for a truncated inverse filter (i.e., one which is easier to realize in ASW form), and Fig. 9b shows the computer-simulated output of the truncated filter when the reference function was input to it. Note that only slight distortion of the waveform has resulted from the rather severe truncation of the impulse response of the inverse filter. We have assumed that this output is adequate, and have designed the ASW filter to have the impulse response of Fig. 9a.

Design of the ASW filter output transducer to yield this impulse response is straightforward (Fig. 10). This figure shows the output transducer electrode pattern superimposed on the truncated impulse response.

The overlap of adjacent electrodes is made to correspond to the impulse response at each point where the response has a relative maximum or minimum. It can be shown, and it is intuitively reasonable, that the impulse response of such an ASW transducer would be just the design impulse response. The photolithography is then carried out to produce the ASW filter. Note that the middle four steps of the design process outlined in Fig. 5 can be carried out easily on a computer with an attached plotter.

Experimental Device and Results

The electrode layout of the ASW inverse filter is shown in Fig. 11. The wideband input transducer is at the left. The output transducer, designed as indicated in Fig. 10, is at the right. Between them is a multistrip coupler whose function is to prevent bulk waves which might be set up at the input from reaching the output transducers: the multistrip coupler (MSC) transfers the surface waves to the lower path and leaves the bulk waves unaffected. The electrodes were made of aluminum evaporated onto YZ lithium niobate. (The filter could be made instead with PZT, at lower cost.)

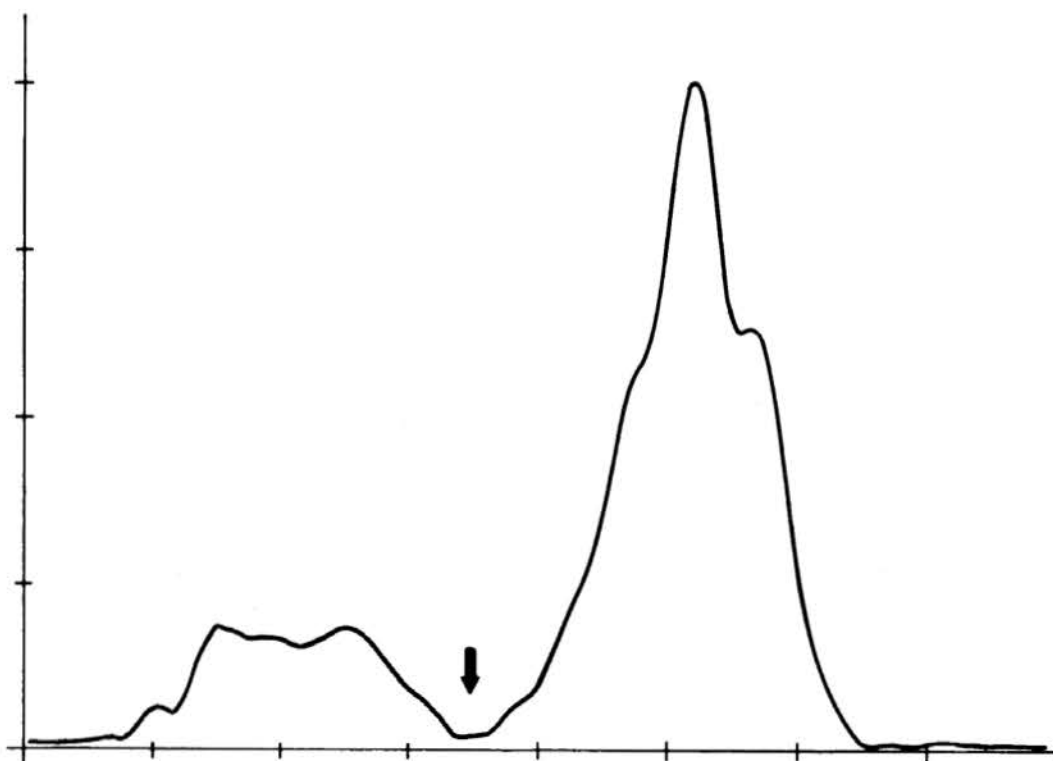


Fig. 7 Frequency response of Hanning-weighted inverse filter, as determined by computer from full reference function. Arrow is approximately 5.7 MHz.

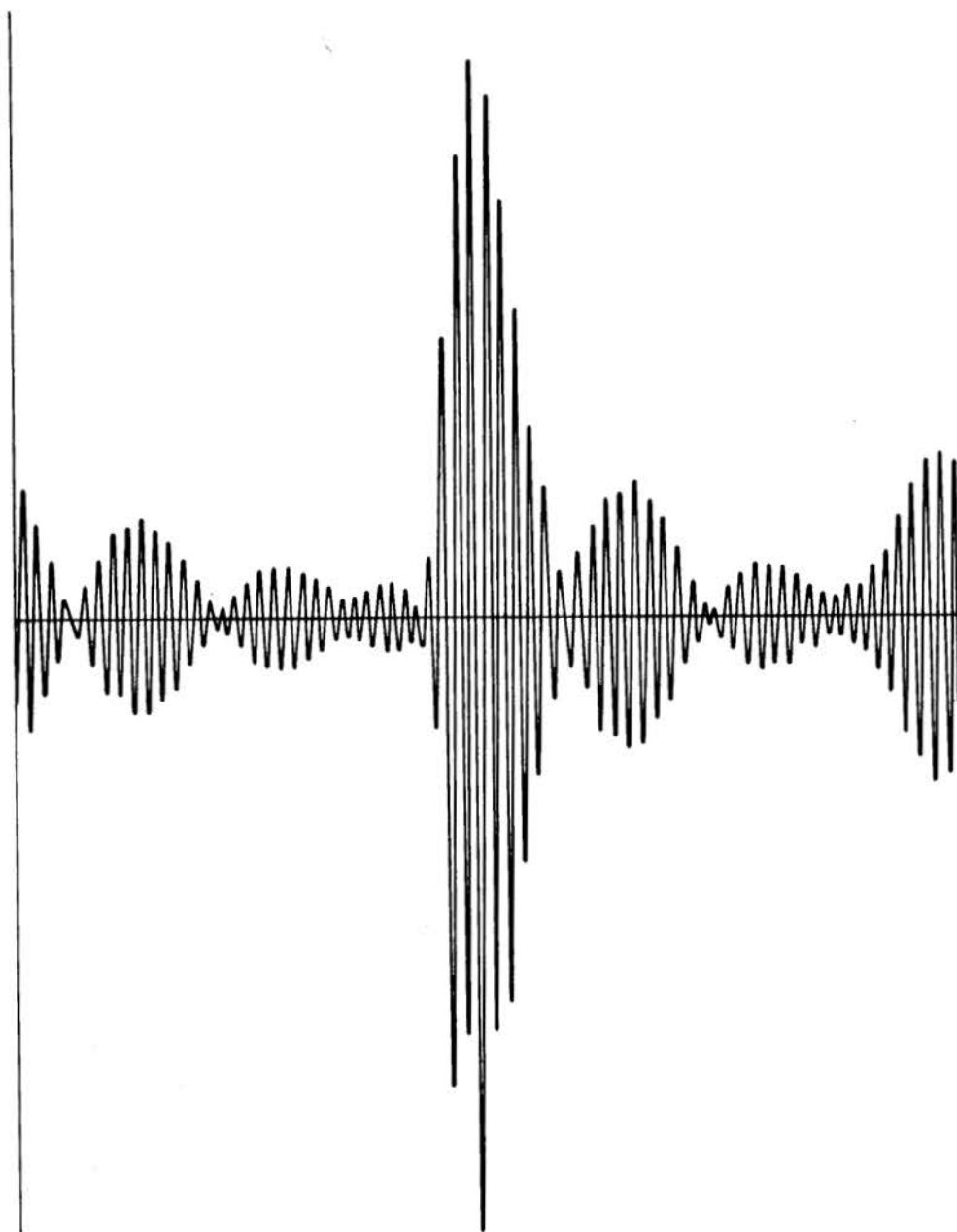


Fig. 8a. Impulse response (amplitude vs. time) for weighted inverse filter. Note: the time origin is arbitrarily shifted in this presentation; the impulse response time axis essentially wraps around on itself.

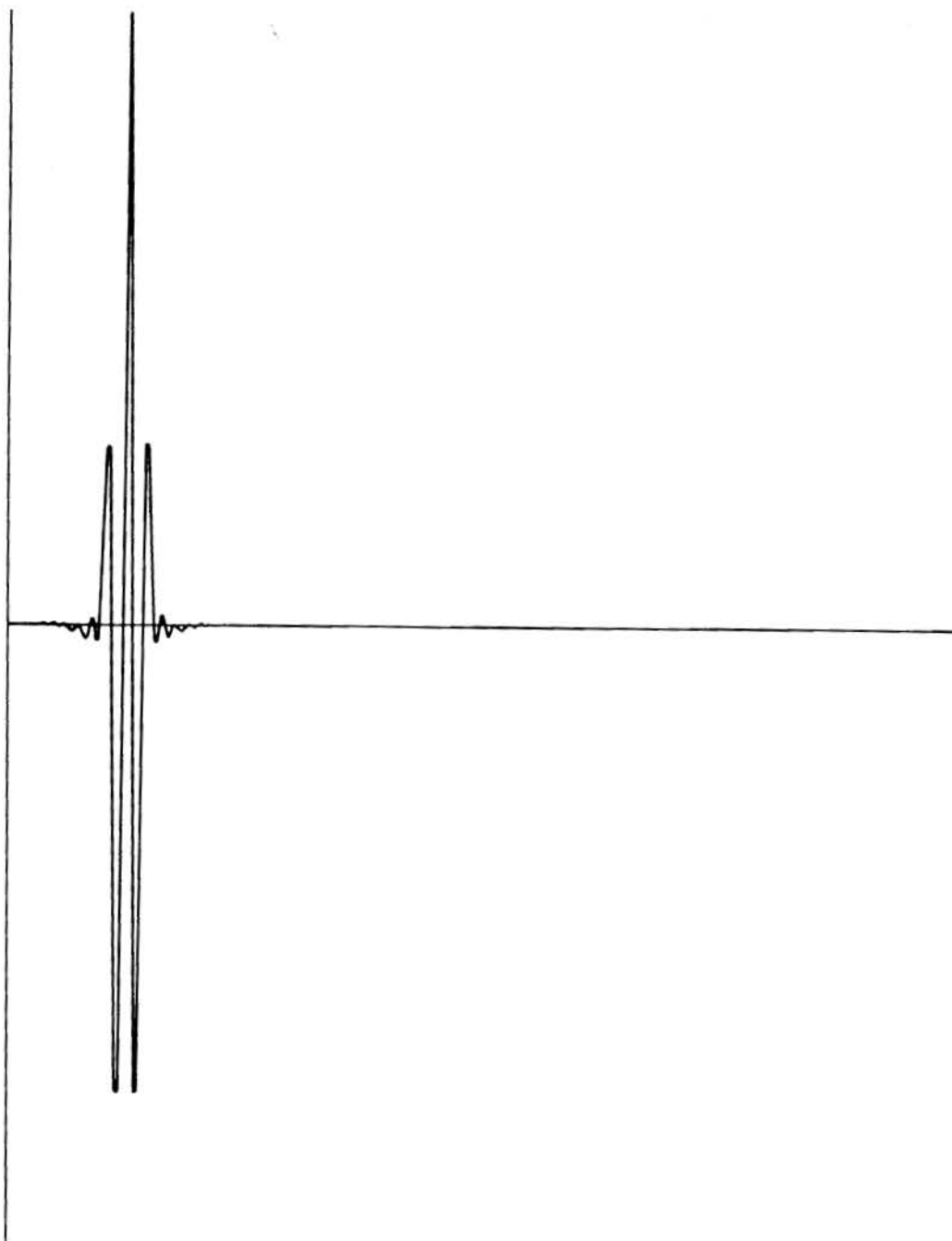


Fig. 8b Calculated output (amplitude vs. time) for full weighted inverse filter with reference function as input

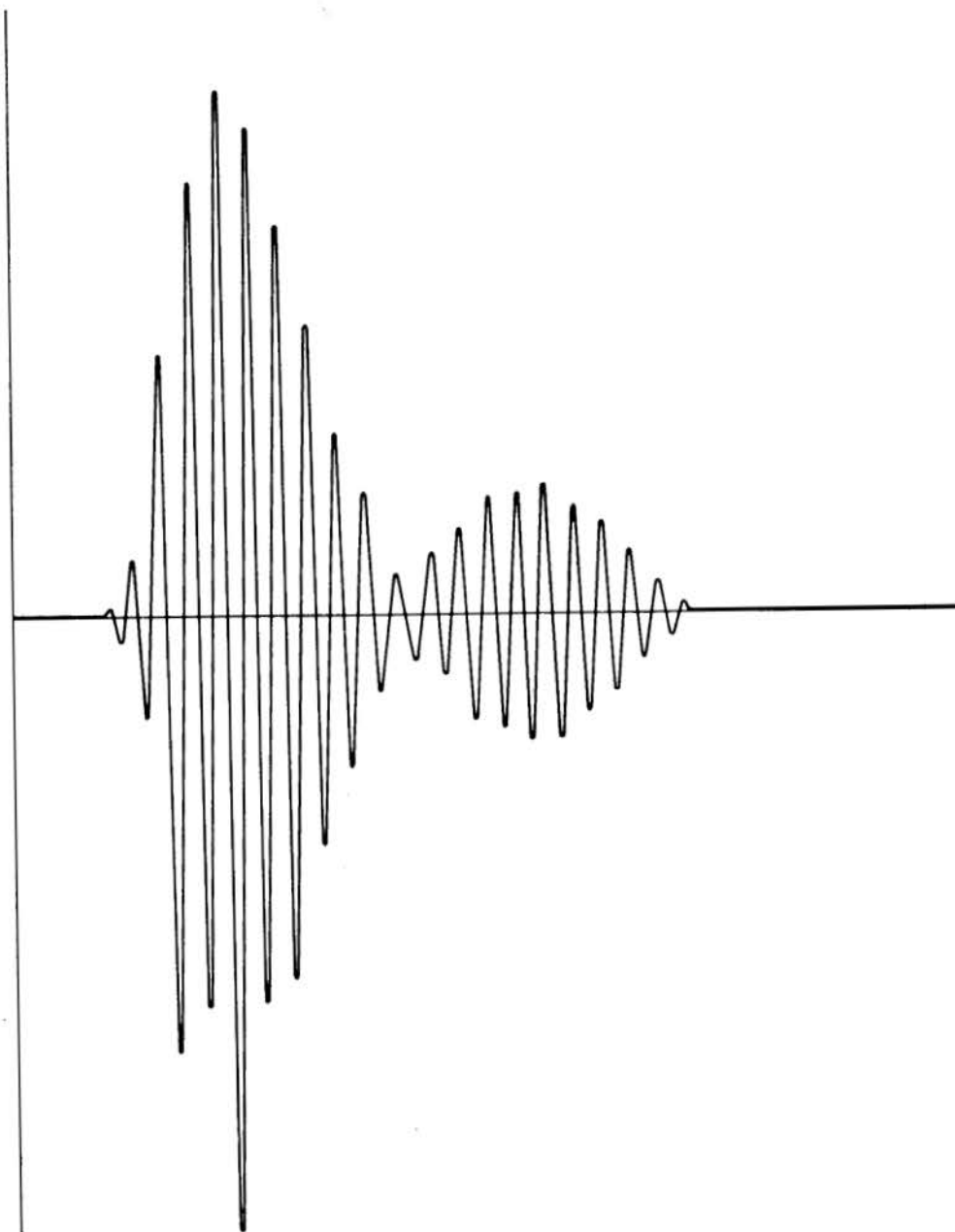


Fig. 9a. Truncated impulse response.

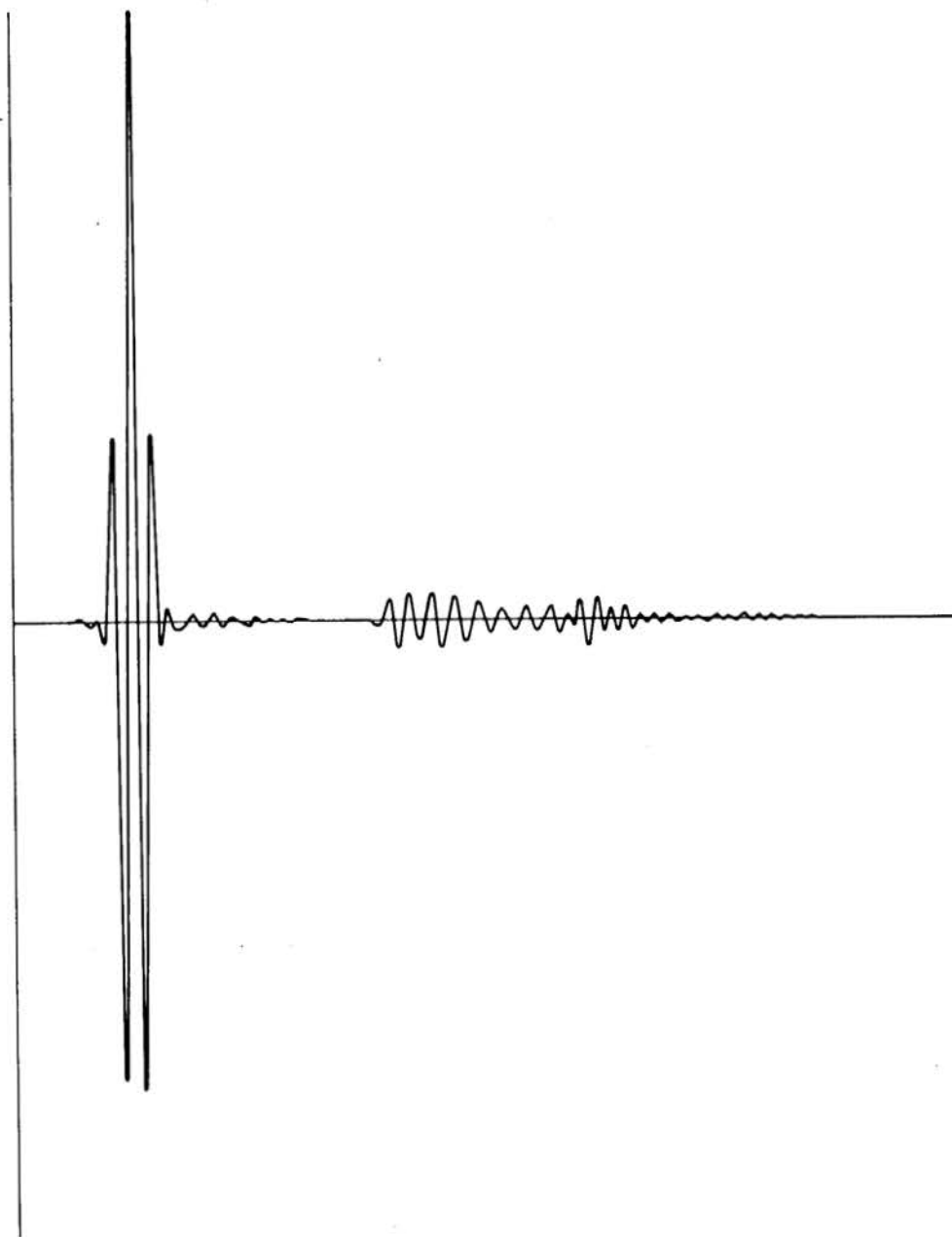


Fig. 9b. Calculated output of weighted and truncated inverse filter with reference function as input.

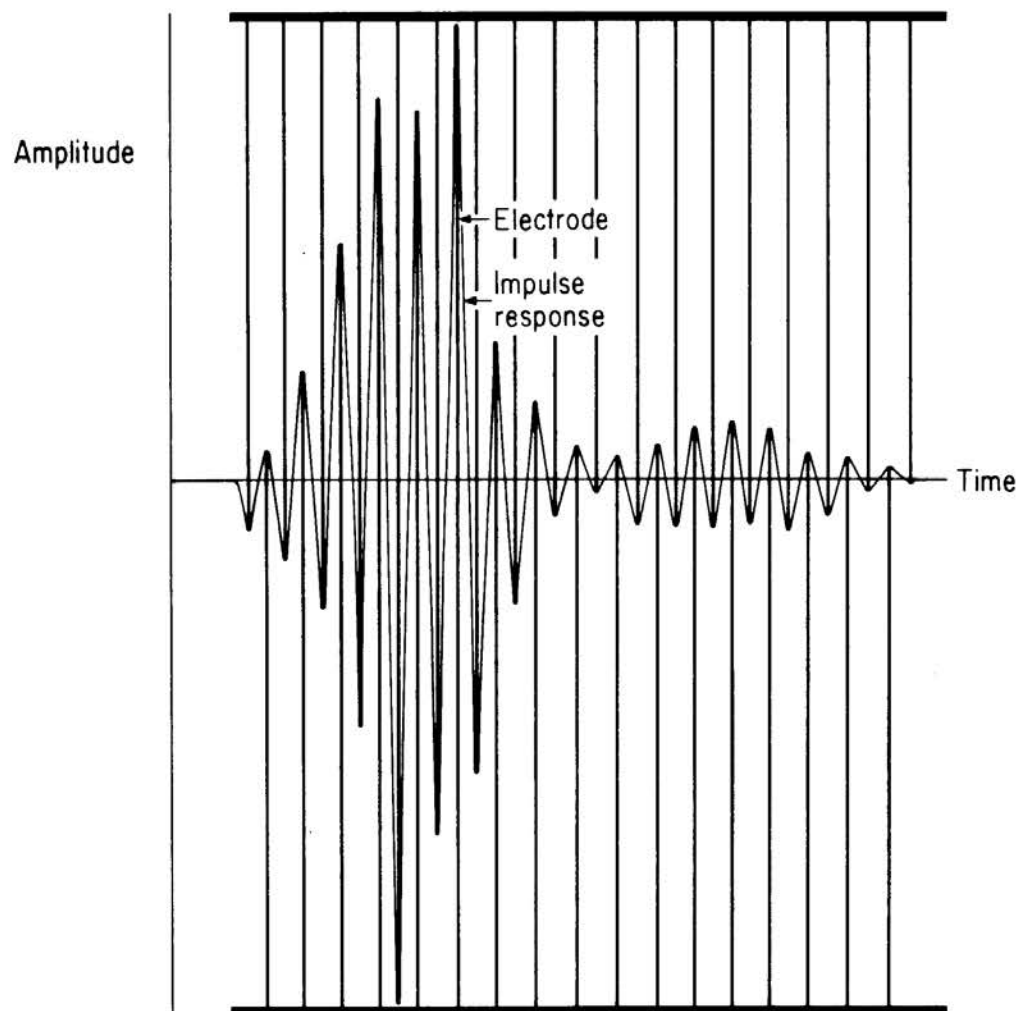


Fig. 10. Impulse response and output transducer electrodes superimposed. The respective fingers of the electrodes correspond to the impulse response function amplitudes and their times of occurrence.

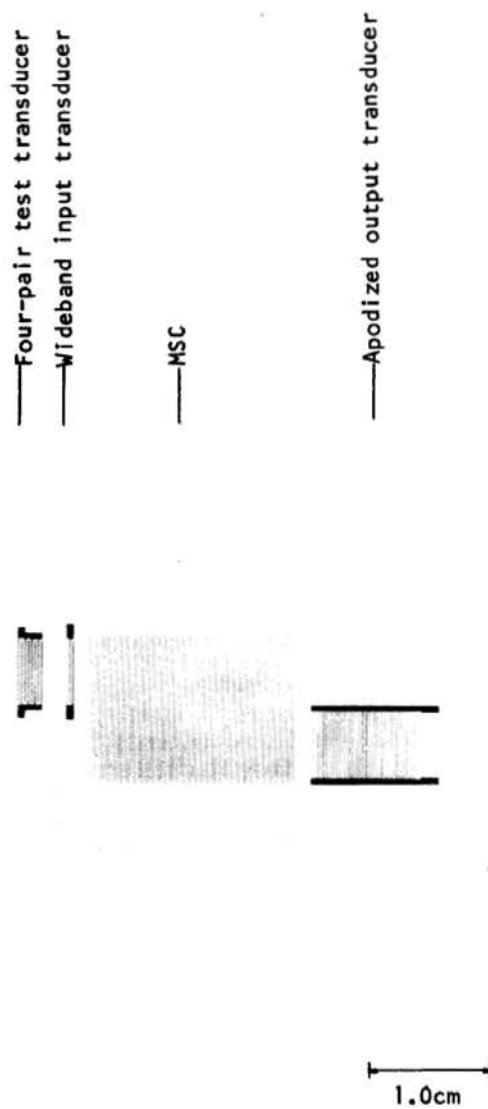


Fig. 11. Acoustic surface wave inverse filter with impulse response $\bar{r}(t)$.

Some results are shown in the remaining figures. Figure 12 shows the response of the ASW filter to the reference reflection signal as input. The reference function is shown at top, and the output of the filter is shown at bottom. The output is quite similar to the expected output as given by the computer simulation. One notes some electrical feedthrough at the left side of the output waveform (which can be greatly reduced with proper shielding of leads); the presence of some bulk wave interference on the output is also seen (this can be greatly reduced by incorporation of a multi-finger input surface wave transducer in the design).

Figure 13 shows the impulse response of the ASW filter designed according to the principle illustrated in Fig. 10. Figure 14 shows the design of an absolute value and lowpass filter which was used in our later experiments at the output of the ASW filter. Figure 15 shows the effect of this filter when the reference reflection signal was used as input to the ASW filter.

Finally, Fig. 16 shows a block diagram of the experimental arrangement used, together with a photograph of the equipment and test block. The lower trace on the oscilloscope shows real-time delta function output resulting from use of a test block corresponding approximately to the hypothetical arrangement sketched in Figs. 1 and 4.

Conclusions

We claimed at the beginning that this analog technique would provide real time output, and indeed it does. We said the device was simple; possibly the design road map obscures the simplicity. The ASW filter measures about three or four inches on a side. The lithium niobate crystal itself measures only about 2 cm x 5 cm. Small balanced-to-unbalanced transformers are mounted on the board to help out with the bulk wave problem. The filter is very compact and simple.

We have clearly only indicated feasibility here. We need to use a multi-finger input on our next device to reduce the insertion loss and the bulk wave interference. We also will test this filter with other NDE transducers to see the degree to which the design needs to be modified for each transducer. It appears from talking with people who do photolithography, that if one can do most of the art work in a computerized fashion, one could make many filters, each of which was different to match a given NDE transducer, essentially all on one computer plot, and the cost per filter is then very low. Finally, it might be interesting to think about including such a filter in the same package as the NDE transducer.

Reference

1. J. A. Seydel and J. R. Frederick, Material Evaluation, Vol. XXXI, 223 (1973).

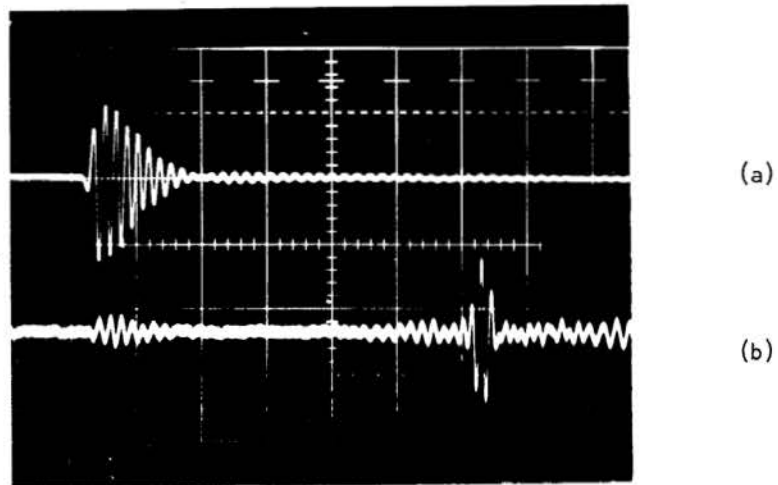


Fig. 12. ASW filter response to the reference reflection signal. (a) Reference reflection signal, and (b) ASW filter output. $1\mu\text{s}/\text{div}$.

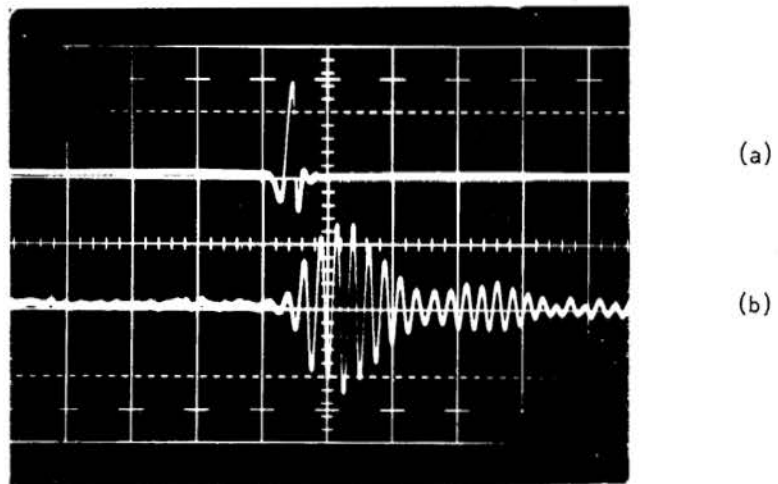
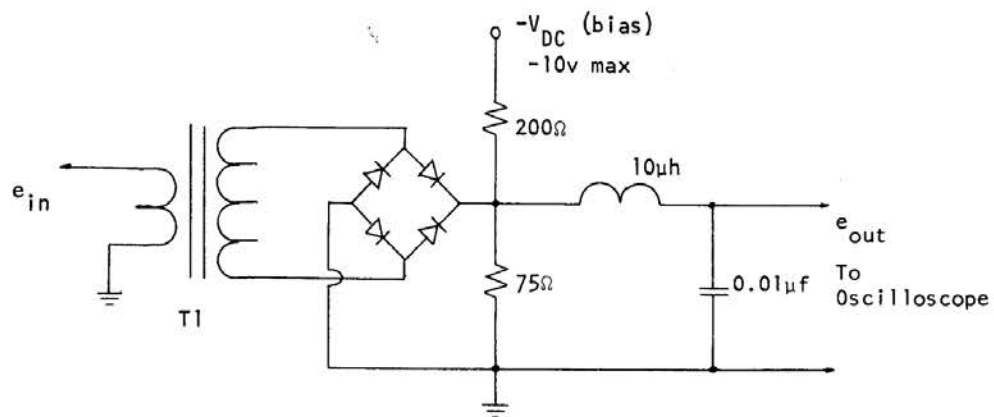


Fig. 13. Impulse response of the ASW filter. (a) Exciting pulse, and (b) ASW filter impulse response. $0.5\mu\text{s}/\text{div}$.



All diodes: HP 5082-2800
 T1: 50Ω to 200Ω wideband transformer
 Mini-Circuits Laboratory Model T4-1

Fig. 14. Absolute value and lowpass filter circuit schematic.

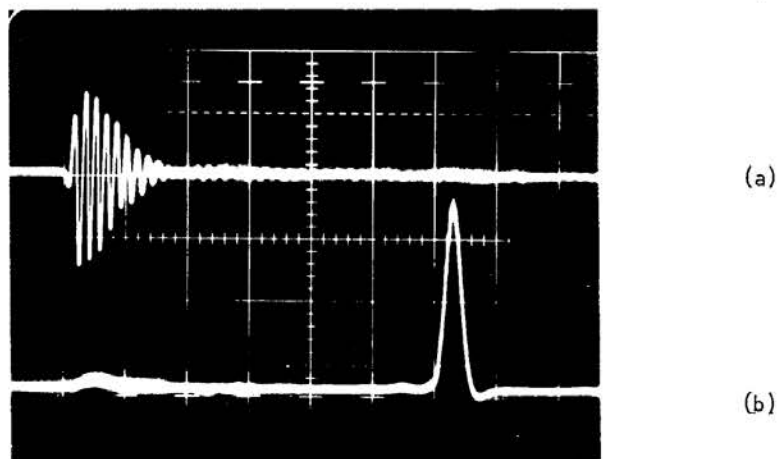
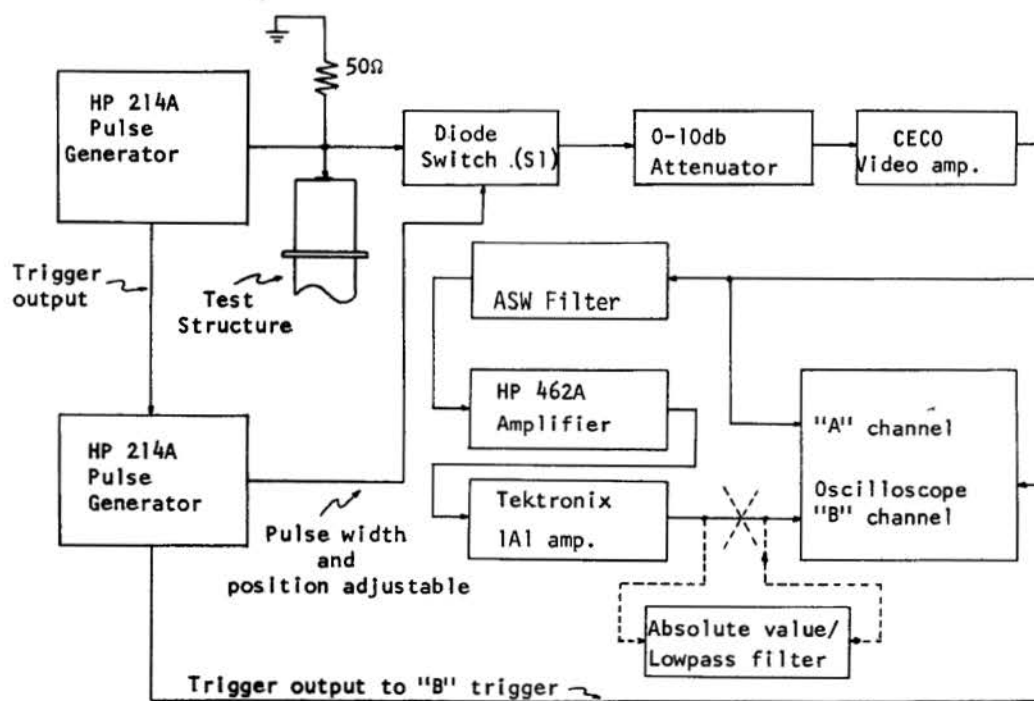
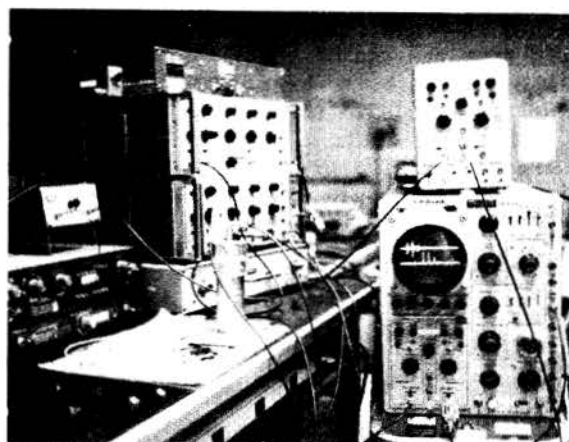


Fig. 15. Deconvolved, demodulated, and smoothed reference signal.
 (a) Reference reflection signal input to ASW filter, and
 (b) Output of the absolute value-lowpass filter circuit.
 1μs/div.



(a)



(b)

Fig. 16. Electronic equipment of the pulse-echo NDE system. (a) Block diagram, and (b) Photograph of the actual system.

DISCUSSION

- DR. STEVE CARPENTER (University of Denver): You say you got the response using a test block. If that test block is a different material you get a different response for the NDT transducer?
- DR. WHITE: This is something we don't really know about yet, and this is something we would have to check out. Maybe Seydel has some comments on that. He has probably done that experiment.
- DR. JIM SEYDEL (University of Michigan): Yes, there are some minor differences you have to take into account. I think the whole thing is going to depend on what you were talking about: doing the A experiment with the B transducer. You have to do that experiment to find out how critical that is. There's no doubt you are going to lose some resolution.
- MR. SY FRIEDMAN (NRDC): Do I understand it correctly that one would have to build an individual filter for each individual transducer in this system?
- DR. WHITE: That's true. On the other hand I tried to indicate this is not as formidable as it might sound. For example, if you simply read in the response of the various transducers you want to apply a filter to, you could produce one piece of art work on a computerized plotter which would make a number of these things at once. And this, of course, brings your cost down.
- DR. HARRY F. TIERSTEN (Rensselaer Polytechnical Institute): Why did you use the coupler to change the path on the multistrips?
- DR. WHITE: In principle the multistrip coupler will shift the track of the surface waves from the top of the filter (Fig. 11) to the bottom of the filter, whereas the bulk waves, hopefully, continue going on through it and do not couple to the output transducer.
- DR. VERNON NEWHOUSE (Purdue University): The particular computer results weren't quite as good as I would have expected from the computer deconvolution process. Is that because you cannot realize physically a perfect deconvolution filter whether you use surface wave devices or anything else as opposed to what you would do in the computer?
- DR. WHITE: No, I think it's because of the weighting functions that we chose for that. I think by using different weighting functions we would have gotten a different output.
- DR. NEWHOUSE: Also, it would appear that you are going to have to have a different filter for different ranges when there is a strong frequency dependent absorption, but you might be able to overcome that by having a kind of weighted filter --

DR. WHITE: Right.

DR. NEWHOUSE: --where you can electronically change the wave.

DR. LARRY KESSLER (Sonoscan, Incorporated): In your inverse filter you showed a zero response to the center frequency of the transducer.

DR. WHITE: It wasn't quite zero. It was low relative to higher frequencies but it was not zero.

DR. KESSLER: Do you expect some notable decrease in sensitivity as a result of that?

DR. WHITE: I guess we really haven't looked at it that carefully yet. Again, maybe Jim Seydel has a comment on that.

DR. SEYDEL: Any deconvolution procedure increases the noise, and so you will get a decrease in sensitivity. But typically speaking there are other ways of making this up.

DR. KESSLER: Do you have any idea of the order of magnitude?

DR. SEYDEL: I'm afraid not. I wish we did. I have never seen anybody that's analyzed that problem.