

# DIGITAL SYNTHETIC-APERTURE ACOUSTIC IMAGING SYSTEM

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## ABSTRACT

A real-time 32-element synthetic aperture acoustic imaging system has been developed. We can test new ideas for the system by using an acoustic array and carrying out image reconstruction on a computer. Contour plots of simple images are shown to illustrate the resolution (0.4 - 0.5 mm in range and transverse resolution) and sidelobe levels obtained with this synthetic-aperture technique. Rayleigh wave images of surface cracks and holes in metal samples have been obtained and a new type of monolithic edge-bonded acoustic transducer array has been developed for use in Rayleigh wave imaging. A number of techniques for reducing the sidelobe levels and improving the resolution have been investigated. The results obtained with a new 32-tap digital delay line for deconvolving the pulse response of a transducer in real time are described.

## INTRODUCTION

This project has as its aim the development of a real-time synthetic-aperture acoustic imaging system for use in nondestructive evaluation. Last year we described a hardware implementation of such a system which makes use of digital electronics in order to obtain real-time images using an 8-element acoustic transducer array and we also described the results obtained with computer reconstruction of images using a 32-element array. Since that time, we have made a number of significant advances which we will describe in this paper.

Our work during the past year has had four main thrusts:

(1) The construction of a second generation synthetic aperture acoustic imaging system. This new system incorporates a number of improvements over our previous system and it is designed to produce real-time images using a 32-element transducer array. This system is currently in the debugging stage, and based on past experience, we expect to obtain our first experimental results in the very near future;

(2) The use of computer processing techniques for displaying quantitative image information. We have recently investigated the use of contour plotting for the display of quantitative image information. This contour plotting technique has been employed to study in detail the point spread function of our imaging system, and in the future, we intend to use this method, as well as other techniques such as pseudo-color images, in order to display quantitative information about actual flaws;

(3) The development of new types of transducers for acoustic imaging. This work is described in greater detail in a companion paper. The technology for constructing reliable high-efficiency broadband transducer arrays for the excitation of bulk waves in water has made considerable progress and we believe that most of the construction difficulties have been overcome. A major breakthrough has been achieved in the design of a new type of transducer array for the excitation of Rayleigh waves in solids, the edge-bonded transducer. Using this edge-bonded transducer array, Rayleigh wave images of both real and simulated flaws in

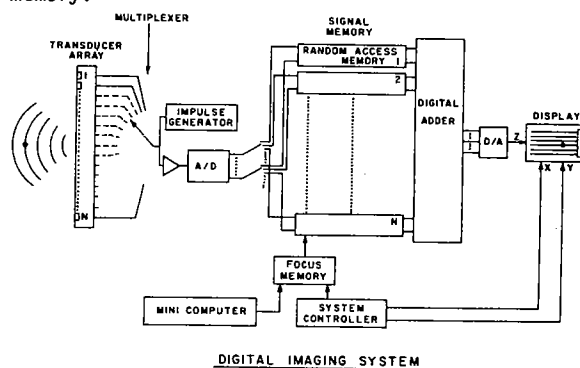
aluminum samples have been obtained;

(4) The demonstration of a real-time programmable filter. We have constructed a 32-tap real-time programmable filter which makes use of a novel digital-analog technique in order to achieve a wide bandwidth (DC to 5 MHz) from a reliable low-cost design. There are a number of potential uses for this filter in acoustic imaging and other signal processing applications, a few of which will be illustrated in this paper.

## REAL-TIME IMAGING SYSTEM

Last year we reported the results obtained with our first generation 8-element transducer array hardware system. This year we have constructed a new synthetic aperture acoustic imaging system which is designed to utilize a 32-element transducer array in order to produce real-time images. The theory of synthetic-aperture imaging has been described in detail in our previous paper.<sup>1</sup> Here we will briefly review the basic principles of operation of this system.

A block diagram of the actual hardware system is shown in Fig. 1. This new system incorporates a number of design improvements over our previous hardware system and it contains 80 kilo-bytes of high-speed (50 nsec cycle time) memory as well as all of the electronics required for computer interfacing, display control, and array multiplexing. The memory is partitioned as thirty-two 1 kilo-byte blocks of signal memory and 48 kilo-bytes of focus memory.



The construction of this system has been hampered by delays in the delivery of a number of key components. The system is now completed and we are currently in the process of debugging the circuitry. Based on past experience with our first generation hardware system and our computer reconstruction techniques, we are confident that this new system will perform as expected, and we anticipate obtaining real-time images from this system within the next month.

The operation of this system consists of two phases: the signal acquisition phase and the image reconstruction phase. During the signal acquisition phase, an analog multiplexer selects a single element of the transducer array. This element is excited with an impulse from the impulse generator and an acoustic signal propagates out into the medium. The return echoes are received by that same transducer element, and after passing through the multiplexer and input amplifier, the signal is digitized by a high-speed analog-to-digital converter and stored in a digital memory. This process is repeated for successive elements of the transducer array, with each of the signals being stored in a corresponding memory. During the image reconstruction phase, the focus memory controls the addressing of the signal memories. The outputs of the signal memories are summed together in the digital adder and converted to an analog voltage which modulates the intensity of a raster scanned display in order to produce a two-dimensional image. This entire process is accomplished in approximately 30 msec, with about 10 msec for signal acquisition and 20 msec for image reconstruction, resulting in a frame rate of approximately 30 Hz, well above the rate required for real-time imaging.

#### COMPUTER PROCESSING

Last year, using our real-time hardware system as well as computer processing techniques, images of wires in a water tank were produced and it was demonstrated that low sidelobe levels could be obtained. As this work has progressed, we have realized that there are serious limitations to the use of intensity display of images obtained from a high-quality imaging system. One problem is the limited grey scale range of an intensity image which makes it difficult to observe a weak reflector in the vicinity of a strong reflector. This method of display also makes it hard to obtain quantitative information about the image, and we expect that as the NDE field progresses, more quantitative information will be required from our images in order to make a better determination of the shape, size and nature of a flaw.

There are a number of simple examples which can be used to illustrate how quantitative measurements can help us interpret the image obtained from a flaw. First, consider a point defect which gives rise to a scattered field that falls off inversely as the distance from the flaw. If the defect has a higher impedance than the surrounding medium, the reflected signal will have the same sign as the incident signal. In the case of a low-impedance defect, such as a void, the reflected signal will be opposite in sign to the incident signal. Now, consider the case of a wave scattered from a crack which is aligned at an angle to the wave so that the specular reflection cannot return to the transducer array. In this case, only the two ends of the

crack are observed and they appear in the image as two isolated points.<sup>2,3</sup> However, the fields associated with these two radiating points fall off inversely as the square root of the distance from the end of the crack, and furthermore, the scattered signals from the two ends of the crack are of opposite sign. It can be seen that there is quantitative information available from this imaging technique which, if adequately displayed, could be utilized to aid in the interpretation of the images produced.

Accordingly, we have written a contour plotting program which at the present time gives us magnitude plots of an image, but which at a later time might give us plots of both amplitude and phase. This contour plotting technique has proven to be extremely useful in making quantitative measurements of our imaging system performance.

In order to measure the point-spread function of our imaging system, a small (.25 mm diameter) wire was placed in a water tank at a range of 3.2 cm from a 32-element transducer array having a 1.6 cm aperture and a 3.3 MHz center frequency. By using computer reconstruction techniques, images of this wire were produced from both real data and from artificially constructed theoretical data. From these images, a set of contour plots were obtained which show lines of constant amplitude around the wire. Due to space limitations, only two of these plots will be shown. It suffices to say that there were no great differences between the experimental and theoretical plots, which, of course, is very encouraging. The results shown in Fig. 2 were obtained using 32 transducer elements with linear processing, and we see here a 3 dB resolution of .5 mm in the transverse direction, and .4 mm in the range direction. These results are essentially in agreement with the theoretical predictions of about .5 mm resolution in both the range and transverse directions. This contour plot shows the sharp fall-off from the main lobe down to a background sidelobe level of about -24 dB. It is important to note the smooth contours around the main lobe; others have predicted that there might be higher sidelobe levels at a 45° angle to the axis of the array,<sup>4</sup> but it is apparent from our results that there is no such problem with this system. Figure 3 shows a similar contour plot obtained using the nonlinear processing technique which has been discussed in the past.<sup>1</sup> As described last year, this technique, using square root gain compression, is expected to give a significant reduction in the sidelobe levels. This can be seen quite clearly in the contour plot, with the background sidelobe level reduced to about -36 dB. Again, there is a sharp fall-off from the main lobe and with this nonlinear processing technique, the resolution in both the range and transverse directions is actually somewhat improved over that obtained with linear processing. Knowing that there are no anomalous directions where the sidelobe levels are particularly high, it is convenient to describe the resolution of this system by showing a pair of slices through the point spread function, one in the range direction and one in the transverse direction, as shown in Fig. 4.

With this contour plotting technique, we have been able to obtain accurate measurements of the performance of our imaging system. The sidelobe levels and resolution obtained with this synthetic

aperture technique are far better than those obtained with any comparable imaging system we have worked with in the past, or seen in the literature.

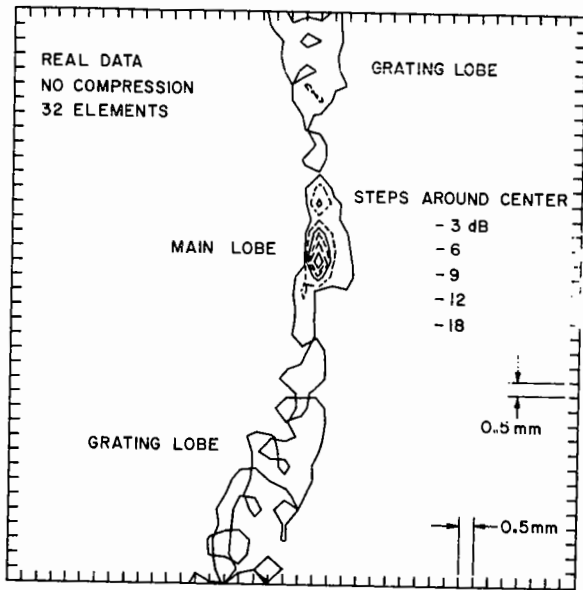


Fig. 2. Contour plot of the image of a small wire obtained with linear processing.

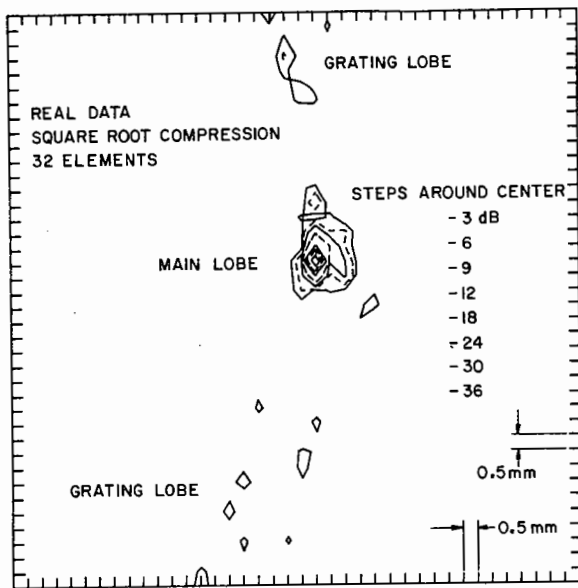


Fig. 3. Contour plot of the image of a small wire obtained with nonlinear processing.

#### RAYLEIGH WAVE IMAGING

Because of our interest in NDE, we have recently investigated a number of techniques for the excitation of Rayleigh waves (surface waves) in solids. Looking at wires in a water tank, as we have done in the past, is very convenient during the early stages of development of an imaging system, but for NDE applications, we are more likely to be interested in using bulk (longitudinal

and shear) waves in solids or Rayleigh waves, as well as other types of Lamb waves. We have recently developed a new type of array, the edge bonded transducer array, which is a major breakthrough for the excitation of Rayleigh waves and several computer reconstructed images obtained using this array will be shown.

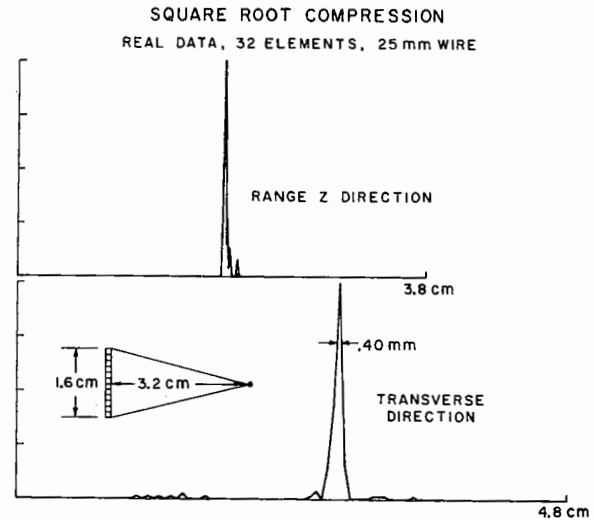


Fig. 4. Range and transverse resolution with nonlinear processing.

Several years ago, Kino and his colleagues developed an acoustic imaging system based on a phased array technique which used chirp-focusing.<sup>2,5</sup> With this system, it was demonstrated that various types of waves, including shear, Lamé, and Rayleigh waves could be excited using mode conversion from a longitudinal wave array and that imaging could be performed using these types of acoustic waves. All of these techniques are applicable to our synthetic aperture imaging system and the wedge coupling technique has been used with our system in order to obtain Rayleigh wave images of both real and simulated flaws in aluminum samples.<sup>6</sup> One drawback to this technique is that it introduces aberrations due to the compound angles involved, which in turn lead to a degradation in the performance of our imaging system. In the past, this degradation was not noticeable, but as the performance of our imaging systems has improved from a resolution of 2 mm to a resolution of better than 0.5 mm, this effect has become significant.

Therefore, a new type of array, the edge-bonded transducer (EBT) array has been developed to eliminate these problems. This transducer has a number of important advantages over other techniques used for the excitation of Rayleigh waves. First of all, the array is very simple to construct and it gives both high efficiency and broad bandwidth. Secondly, because it is used in a configuration where a Rayleigh wave on a solid substrate excites a Rayleigh wave on a test object of the same material, the EBT array is free from the aberrations introduced by the wedge coupler formerly employed. This is because there is no difference in the acoustic velocity of the two substrates. The array is shown schematically in Fig. 5, and it is described

in detail in a companion paper.<sup>7</sup> The array is constructed by epoxy-bonding a slab of piezoelectric ceramic onto an aluminum substrate. Thin film electrodes are deposited on the back of the ceramic which is one-half of a Rayleigh wavelength in thickness. The electrodes are approximately one wavelength long in the direction perpendicular to the surface of the substrate; therefore they efficiently excite a Rayleigh wave whose penetration depth is on the order of a wavelength. Each element is approximately one wavelength wide and the individual elements are shielded from one another by ground strips. Our first edge-bonded transducer array has exhibited high-efficiency (7 dB round trip insertion loss), broad bandwidth (about an octave) and wide angle of acceptance ( $\pm 35^\circ$ ). The spurious modes excited by this first array are quite high, but we have already developed a number of techniques for reducing these spurious signals to negligible levels in our future arrays.

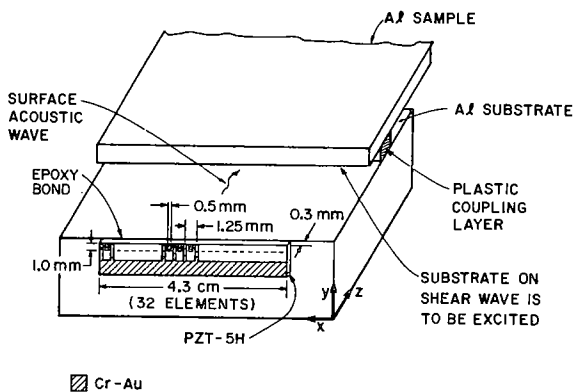


Fig. 5. Edge bonded transducer array.

The edge-bonded transducer array can be used to excite Rayleigh waves in a test sample by placing the test sample on top of the array substrate with a thin strip of coupling material (typically plastic or rubber) placed between them as shown in Fig. 5. The loss in going from one substrate to the other has been measured to be approximately 2 dB, which adds another 4 dB to the round trip insertion loss. Computer reconstructed images of several test objects were obtained using this EBT array. Figure 6 shows an image of four center-punch marks and one drilled hole on the surface of the array substrate. This image was obtained using square root gain compression to reduce the sidelobes from the end of the block. Three of the defects show up quite clearly, while the last two defects are difficult to see amidst the clutter from the end of the substrate. Figures 7 and 8 show images obtained using the EBT array to look at an electron discharge machined (EDM) slot in a separate test sample. In Fig. 7, the slot was placed parallel to the transducer array and it shows up quite clearly over its entire length. In Fig. 8, the slot was placed at a  $25^\circ$  angle to the array and once again the slot shows up quite clearly over its entire length, since the array was able to receive the specular reflection from the slot. This illustrates the width of the aperture and large angle of acceptance which can be used with this imaging system. In the future, we intend to place the slot at an even steeper angle to

the array so that only the ends of the slot will be observed. The clutter in this image is due mainly to the spurious modes which are excited by the EBT array, which will be eliminated in a later version of the array.

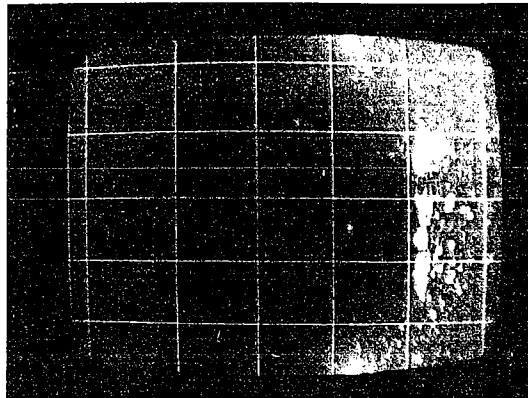


Fig. 6. Rayleigh wave image of center-punch marks in aluminum substrate (1 cm squares).

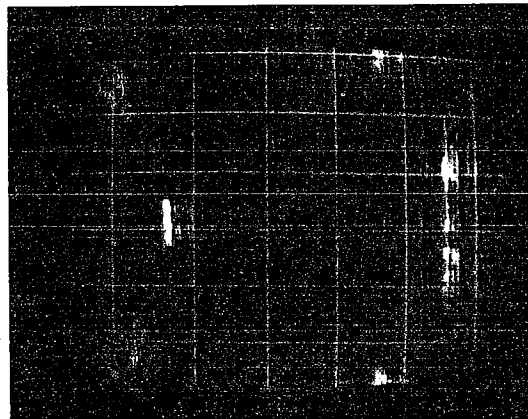


Fig. 7. Rayleigh wave image of an EDM slot placed parallel to the transducer array (1 cm squares).

In the near future we plan to look at these images in detail using our contour plotting program to see if any of the predicted features in these images, namely the  $1/\sqrt{R}$  fall-off from the end of the crack can be observed. Because of the success of our Rayleigh wave imaging experiments, we intend to continue the development of the EBT array and to use this array in most of our future imaging experiments. The limited number of images so far obtained illustrates one of the disadvantages of computer reconstruction: it is very slow (up to 1 hour). The real time system eliminates this difficulty and makes adjustments to obtain the optimum images relatively simply.

#### REAL-TIME PROGRAMMABLE FILTER

We have developed a real-time programmable filter for use with our synthetic aperture acoustic imaging system. This programmable filter

is an extremely flexible signal processing element which can be employed for inverse filtering, real time deconvolution, matched filtering or any number of other applications. The basic idea here is to use the filter to compensate for deficiencies in the transducer so as to obtain as compact an impulse response as possible within the bandwidth limitations of the system. Another potential application of great importance in imaging systems is to remove distortion which is introduced by propagation through an inhomogeneous medium, or poor contact between the transducer array and substrate.

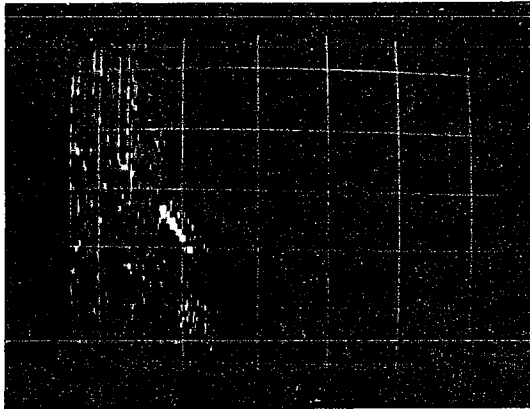


Fig. 8. Rayleigh wave image of an EDM slot placed at 25° to the transducer array (1 cm squares).

It has been demonstrated earlier by White that a surface acoustic wave (SAW)<sup>8</sup> filter could be designed for this type of application, and we have demonstrated a programmable charge-coupled device filter.<sup>9</sup> There are a number of limitations to these techniques: the SAW filter is not programmable; rather it must be tailored to a specific application, while the CCD filter has a limited bandwidth, much less than 1 MHz. In order to overcome these limitations, we have developed a new type of programmable filter which makes use of a hybrid digital-analog approach in order to achieve a 5 MHz bandwidth from a reliable low-cost design.

A block diagram of the actual hardware is shown in Fig. 9. The filter makes use of a high-speed analog-to-digital converter which samples the input signal and converts it into 8-bit digital words which are sequentially loaded into an 8-bit wide digital shift register. This shift register acts as a tapped delay line and at each stage of the shift register, a multiplying digital-to-analog converter (MDAC) is used to multiply the digital word by an analog tap weight reference voltage to produce an analog current output. The outputs of all the MDAC's are tied together on a common output bus where all the currents are summed to produce the filter output. The tap weight reference voltages are established by a set of latching digital-to-analog converters which are programmed by the computer.

In operation, the digital signal at the input to the filter is inserted into a computer. By using Fourier transform techniques or an iterative technique, such as the LMS algorithm, the computer calculates the time response of the filter required to transform the input signal into the desired

output. We currently favor the use of the Fourier transform technique to calculate the Wiener filter solution because of its high speed (a few seconds) and the fact that it gives us a picture of how the filter is performing in both the frequency domain and the time domain. Suppose the spectra of the input signal and the desired output signal are  $X(\omega)$  and  $D(\omega)$  respectively. The frequency response of the filter which gives the least mean-squared fit to the desired output signal in the presence of noise is given by the Wiener solution

$$H(\omega) = \frac{D(\omega)X^*(\omega)}{X(\omega)X^*(\omega) + N^2(\omega)} \quad (1)$$

Here,  $X^*(\omega)$  is the complex conjugate of  $X(\omega)$  and  $N^2(\omega)$  is the noise power. If the noise level is low, optimum use of the available bandwidth can be made in order to sharpen a transducer impulse response or to remove distortion from an acoustic signal. Once the required filter response has been calculated, by whatever means, the filter is programmed and it then operates in real time with a 5 MHz bandwidth and a 40 dB dynamic range.

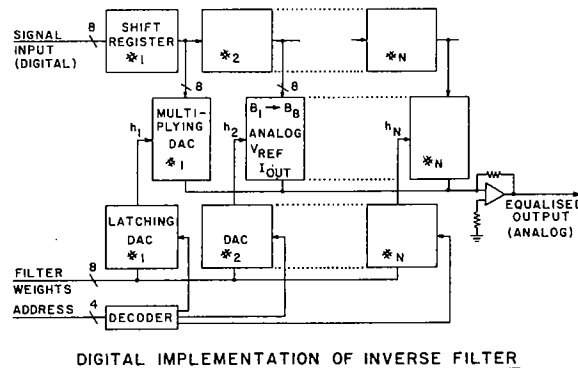


Fig. 9. Hardware implementation of a real-time programmable filter.

A number of experiments have been performed to illustrate potential applications of this filter, two of which will be shown here. One application of this filter is to improve the impulse response of an acoustic transducer. Theoretical calculations have been done which indicate that the optimum tradeoff between range resolution and transverse resolution is obtained with approximately a single sinusoid transducer impulse response. Figure 10(a) shows an actual impulse response of a commercial 2.25 MHz transducer in both the time and frequency domains, while Fig. 10(b) shows the desired signal, a single sinusoid. Fourier transform techniques are employed to calculate the frequency response, Fig. 10(c) and time response, Fig. 10(d), of the filter required to transform the input signal into the desired output. Figure 10(e) shows the results obtained with our real-time hardware. The top trace shows the actual transducer impulse response at the input to the filter, while the bottom trace shows the filter output, a good approximation of a single sinusoid.

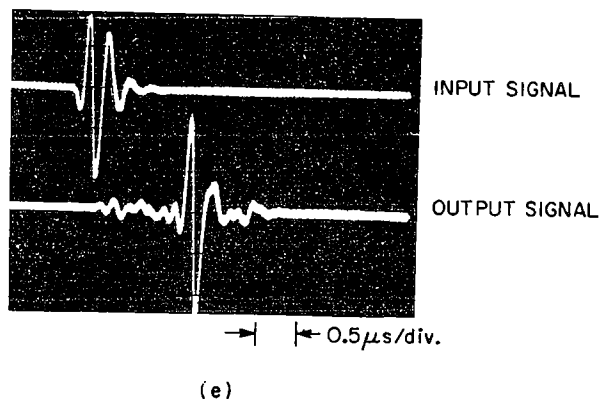
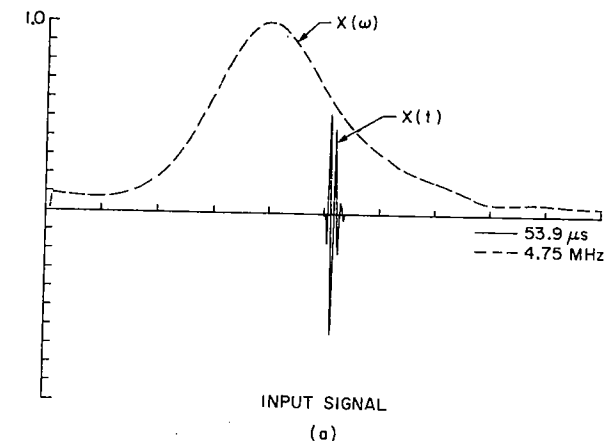
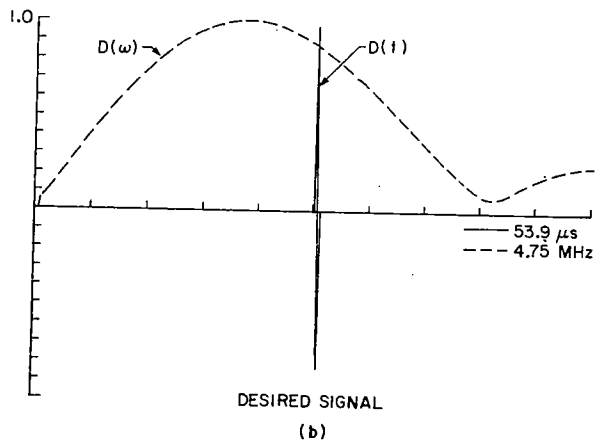
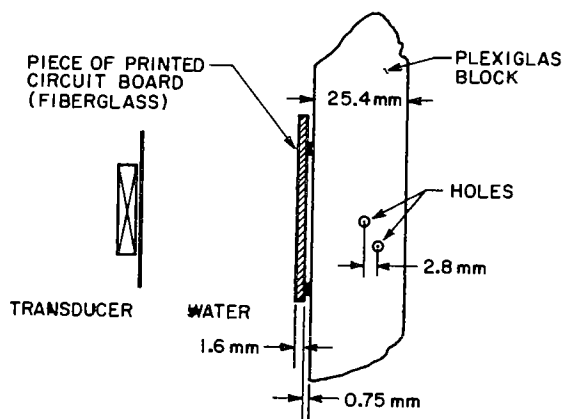
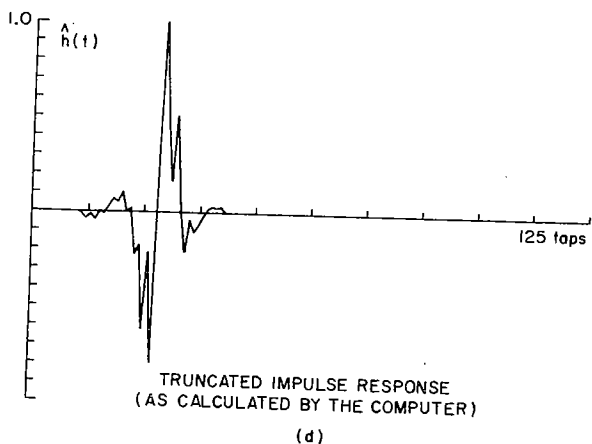
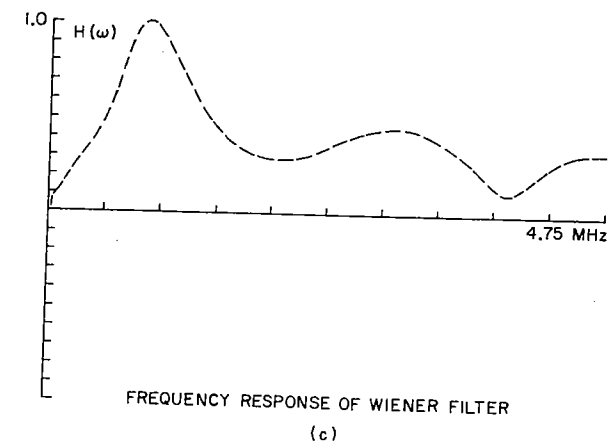


Fig. 10. Shaping of the transducer impulse response using a real-time programmable filter.



Another application for this filter is to remove distortion introduced by propagation through an inhomogeneous medium. Figure 11 is a schematic of the experimental set-up. While looking at the echoes from two small holes in a plastic block, a sheet of fiberglass printed circuit board was placed in front of the plastic block, causing reverberations which distorted the echoes, as would a poor contact between a transducer and a substrate. Figure 12(a) shows the undistorted signal. Here, the echoes from the two holes and from the back-face of the plastic block can be picked out quite clearly. At the top of Fig. 12(b), the distorted echoes can be seen; the individual echoes from the two holes are now difficult to distinguish from one another. The object of this experiment was to use the back-face echo to train the filter to remove the distortion. If the distortion can be removed from the back-face echo, then presumably, the same filter will remove the distortion from the other echoes as well. In the bottom trace of Fig. 12(b), it can be seen that the filter has been quite successful in removing the distortion, and it is once again possible to distinguish the individual echoes from the two holes.



EXPERIMENTAL SET-UP FOR DISTORTION DECONVOLUTION

Fig. 11.

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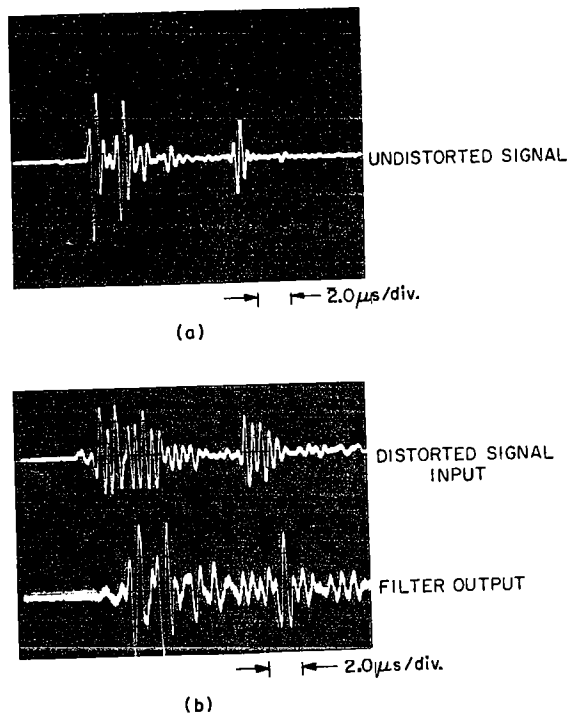


Fig. 12. Experimental results of distortion deconvolution.

## CONCLUSIONS

We have continued to make advances in a number of areas related to our work with digital synthetic-aperture acoustic imaging. Our second generation hardware system is currently under test and preliminary experimental results are expected in the near future. Computer processing techniques for the display of quantitative image information are being investigated and a contour plotting program has already been used to help characterize the performance of our imaging system.

A significant breakthrough has been achieved in the design of a new type of transducer array for the excitation of Rayleigh waves (the edge-bonded transducer array) and this new array has been used to obtain Rayleigh wave images of surface defects in aluminum samples. A new real-time programmable filter has been developed which shows a great deal of promise for use in imaging as well as other signal processing applications.

## ACKNOWLEDGMENTS

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SUMMARY DISCUSSION  
(Doug Corl)

Jerry Posakony (Session Chairman - Battelle Northwest): Is there a question? We can handle one right now.

Vicki Panhuise (General Electric): I am used to looking at graphic systems, and I realize you studied your images and especially your punched holes. Have you tried taking an unknown sample where you had no idea what the indication was in trying to pick it out of your displays?

Doug Corl: No, we haven't done that. If you punched a hole similar to the ones that I have in an aluminum block and gave me that sample, I could easily find the location of it. But if I didn't know it was a punched hole--for example, if it was a scratch or something like that--it would be difficult to pick it out. A single isolated flaw in a clean surface I can find, and then I can see the general shape of it or something like that, get some more information. But if the flaw is in a complicated object, it would be difficult to get a good image of it.

Vicki Panhuise: Is that your ultimate goal?

Doug Corl: The problem with the complicated object is the sidelobes from one object might appear--you don't really know whether they are another object or just sidelobes. Using more transducer elements, for example, to reduce the side-lobe level, makes it easier to distinguish an actual object from a sidelobe. If you can get the sidelobe level down to minus 36 db, it's much easier to distinguish a sidelobe from an actual signal than in the case where you have a minus 12 db sidelobe.

Jerry Posakony: One more question.

Paul Holler (Inst. fur Zerstorungsfreie Prufverfahren): I wonder if you have a special reason not to excite the Rayleigh wave by just putting the array on the specimen and matching the wave by your array control. Is there any reason not to do it that way? You know what I mean? Just put the plane array on your specimen, no edge or nothing, and simulate a wedge by the array control. I think that's the normal way to use for things like that.

Doug Corl: I understand the question. You're suggesting using a linear phase across the array to excite a Rayleigh wave.

Gordon Kino (Stanford University): Now you're really asking for two-dimensional array.

Paul Holler: It's a one-dimensional array.

Gordon Kino: One dimension to simulate the wedge and another to do the focusing that's across the wave.

Paul Holler: It's because you want to do focusing.

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