

## A SHEAR WAVE TRANSDUCER ARRAY FOR REAL-TIME IMAGING

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### INTRODUCTION

In this paper we describe a contacting shear wave array which we have used to characterize flaws in aluminum samples. By using shear waves instead of longitudinal waves, this array has doubled the resolution of our real-time synthetic aperture imaging system. The images we have obtained are significantly better than those obtained with longitudinal or surface wave arrays.

The array is built on a buffer rod of the same material as the test specimen. Consequently there is no refraction, and aberrations are not introduced at the interface. Coupling loss, which is typically large with shear wave transducers, is negligible in this array. Off-normal wave incidence at the buffer rod-specimen interface is utilized to couple shear waves from the array to the specimen through longitudinal waves in the fluid couplant. The geometry of the array causes reflections from the end of the buffer rod and the back of the specimen to be eliminated from the image. This simplifies the task of isolating the reflections of flaws from the larger reflections of surfaces.

### THEORY AND DESIGN

We have developed a contacting shear wave array<sup>1</sup> for use with our real-time digital synthetic aperture imaging system.<sup>2</sup> The images obtained with this array have been used to characterize flaws in aluminum samples. The location, width, and in some cases depth, of cracks have been clearly indicated. In all cases, the image of the crack has been free from obscuring front-wall and back-wall echoes. Currently, we are developing techniques to estimate crack size from echo data obtained with this array.

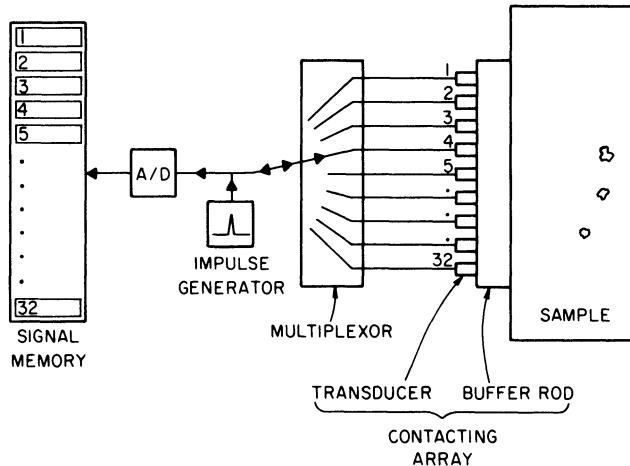


Fig. 1. Relevant features of the digital synthetic aperture imaging system.

The relevant features of our synthetic aperture imaging system are presented in Fig. 1. The system pulses each of the 32 array elements individually and then digitizes the received signal. These digitized signals are stored in an electronic memory and are used to synthesize an image based on the acoustic echoes. This type of imaging system places special requirements on the array. The digitization rate of the A/D converter limits the operating frequency. In order to achieve at least three samples per cycle, the center frequency of the array is limited to 3 MHz. Only one element is operated at a time; hence, the elements must be highly efficient. The impulse response must be narrow, as this determines the depth resolution of the image. In addition, the angular spectrum must be as broad as possible, allowing each element to illuminate the entire target field. These criteria imply that cross-coupling in the array must be minimized, as cross-coupling adversely affects the impulse response and angular spectrum of an array.

In order to satisfy these requirements, our array is designed to be placed in direct contact with the target specimen. By doing so, we avoid the high losses and aberrations associated with immersion techniques. Direct contact permits the use of shear waves. The reduced wavelength of shear waves provides our array with twice the resolution of a comparable longitudinal wave array. This is achieved without having to raise the operating frequency, which has been shown to be limited. Since we are using direct contact, the array is constructed on a buffer rod. The acoustic impedance of the buffer rod heavily loads the array elements, providing high efficiency and a good impulse response. It also eliminates the need for a backing. The buffer rod is composed of aluminum and the array elements of PZT-5H. This ceramic has a high electromechanical

coupling constant for shear wave operation. The elements are separated by sawing to inhibit cross-coupling.

The dimensions of the array for 3 MHz operation appear in Fig. 2. The maximum resolution obtainable at this frequency is about one wavelength, or 1 mm using shear waves in an aluminum test specimen. In order to provide a broad angular response, the individual elements are a half wavelength wide (0.5 mm). This width was also chosen so as to achieve an acceptable electrical input impedance of about 300 ohms. The spacing between elements is one wavelength. In their longest dimension, the array elements are 12 mm. This allows the array to focus through more than 5 cm of aluminum without significant beam diffraction in the transverse direction.

Aberrations are caused by refraction at the buffer rod-specimen interface. Refraction occurs when the velocities of the buffer rod and specimen are dissimilar. Under these circumstances, the transit time between an array element and a point in the specimen is a function of relative position as well as spacing. The reconstruction algorithm used by the imaging system assumes that the transit time is only a function of spacing. Aberrations may be eliminated by choosing the buffer rod velocity to be the same as that of the specimen. For this reason we have chosen to use a buffer rod composed of the same material as the specimen, to provide aberration-free images.

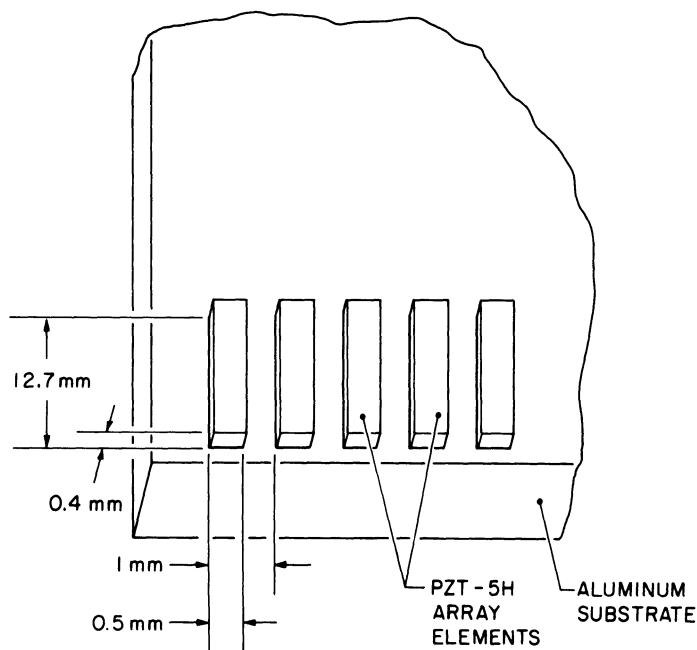


Fig. 2. Array dimensions.

This solution to the problem of aberrations cannot be adopted in arrays designed for immersion, which suffer from aberrations at the fluid-specimen interface.

In order to achieve high efficiency, losses at the buffer rod-specimen interface must be considered. Contact between the two is accomplished by using a thin layer of fluid couplant. Figure 3 plots the transmission through such a buffer rod-couplant-specimen interface as a function of incidence angle. In this case, an aluminum buffer rod and specimen are assumed, as well as  $.04 \lambda$  of water couplant. The wave incidence is shear vertical, as used in our array design. The transmission is zero for normal incidence. This occurs because the shear wave has no component of particle motion normal to the surface. Even when viscous fluid couplants are used, the transmission is very low. Beyond  $28^\circ$ , the longitudinal wave exceeds its critical angle and does not propagate in either the buffer rod or specimen. This eliminates a potential source of spurious echoes which would clutter the image. Finally, the transmission is near its maximum at  $45^\circ$  incidence. This is the value we have chosen for our array.

For comparison, transmission through the same interface, with longitudinal wave incidence instead of shear, is plotted in Fig. 4. In this case, the transmission has its maximum at normal incidence. For all values of incidence angle other than  $0^\circ$ , shear waves are excited. These waves would create additional echoes, and interfere with the imaging process. Hence, the comparable longitudinal wave array design is optimized at normal incidence, rather than  $45^\circ$  incidence.

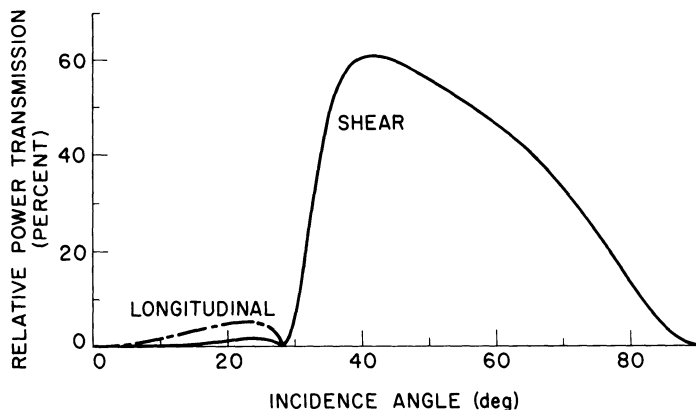


Fig. 3. Transmission vs. incidence angle at the buffer rod-specimen interface: shear vertical incidence.

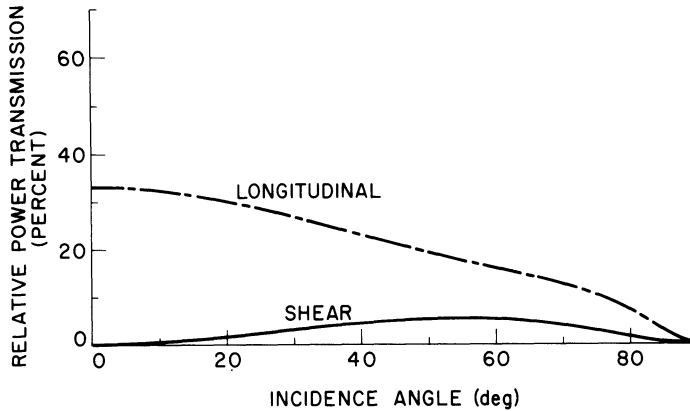


Fig. 4. Transmission vs. incidence angle at the buffer rod-specimen interface: longitudinal incidence.

The efficiency of the two optimized designs is compared in Fig. 5. Transmission loss through the interface is plotted as a function of couplant layer thickness. As the figure shows, the 45° SV incidence design is considerably more efficient than the normal incidence longitudinal design over a wide range of couplant thicknesses. At the couplant thickness we generally operate with  $0.04 \lambda$ ; the shear wave design is 5 dB more efficient in round-trip travel. In addition, it is 17 dB more efficient than an immersion design, which would suffer an 11 dB one-way loss at the fluid-specimen interface. The surprising conclusion, which applies to single transducers as well as arrays, is that the use of shear waves and off-normal incidence, with direct contact, is the most efficient technique for exciting an acoustic wave in a solid sample.

The choice of 45° incidence provides several advantages other than efficiency, which are depicted in Fig. 6. Longitudinal waves are not excited, as they are beyond their critical angle. Shear waves which reflect off the interface between the buffer rod and specimen reflect away from the array at an angle of 90° and do not return to complicate the image. In the same fashion, waves reflecting off the back wall of the specimen continue to propagate in the specimen and do not return to the array. Such echoes typically overwhelm and obscure the reflections from flaws in arrays which utilize normal incidence. Forty-five degrees incidence makes the array a very sensitive detector of flaws which run normal to the back wall of the sample. These flaws combine with the back wall to form corner reflectors of large effective aperture to the incident acoustic wave. Echoes from these reflectors are much greater in magnitude than those emanating from crack tips (which have a smaller effective aperture). With normal incidence, only the crack tips are visible. Consequently an array utilizing normal incidence is much less sensitive to these sorts of cracks.

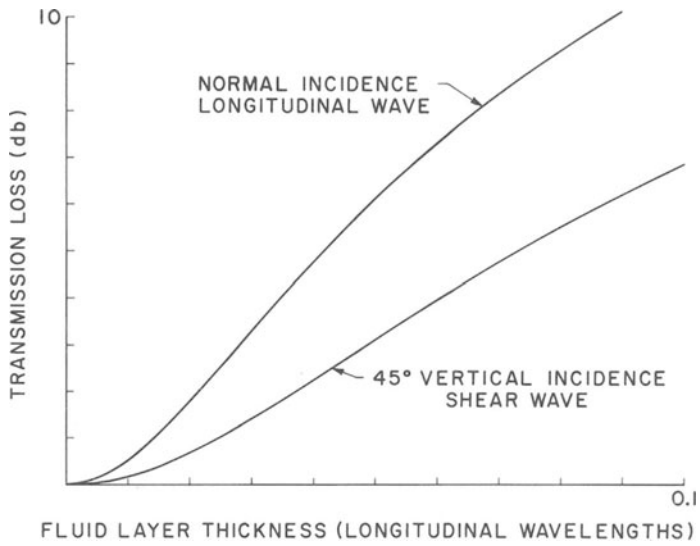


Fig. 5. Transmission loss vs. layer thickness at the buffer rod-specimen interface.

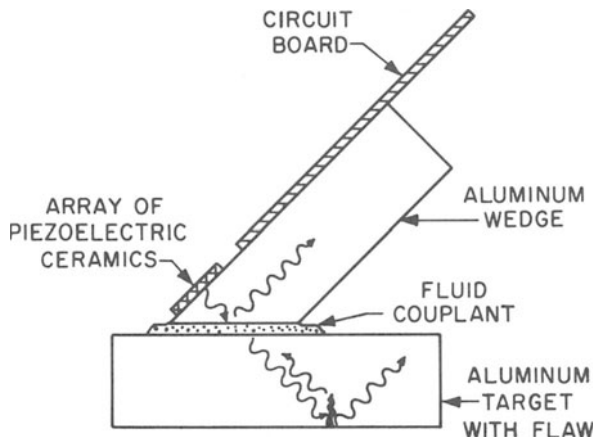


Fig. 6. Array coupled to specimen.

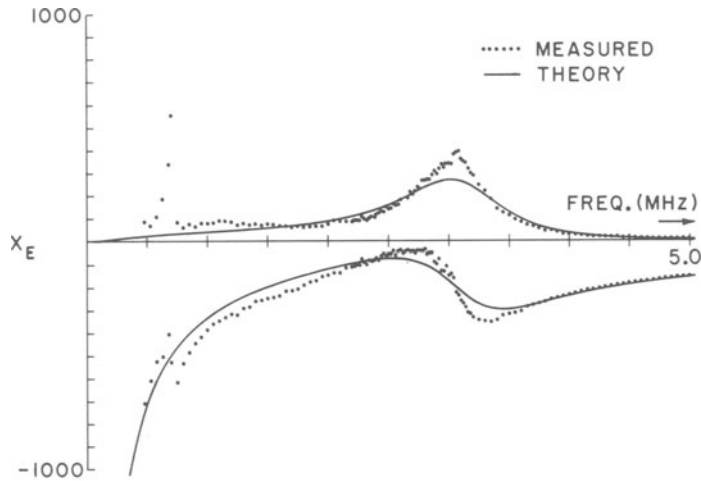


Fig. 7. Electrical input impedance of a single array element.

#### EXPERIMENTAL RESULTS

The electrical input impedance of a single array element is compared to theory in Fig. 7. There is reasonable agreement around the 3 MHz resonant frequency. At 0.7 MHz there is a significant disparity due to acoustic cross-coupling. Cross-coupling manifests itself most strongly in the impulse response, which appears in Fig. 8. The theoretical impulse response is approximately four half-cycles long. The measured response parallels the theoretical response for the first four half-cycles, but extends for another five half-cycles beyond that and possesses a long tail which is 20 dB below the amplitude of the main pulse. As a consequence of this extended impulse response, our depth resolution is only half of what we predicted. In addition, the long tail of the response obscures small features, such as crack tip echoes, which we wish to observe.

As the elements are separated by sawing, and there is no acoustic backing, the only path available for cross-coupling is the buffer rod. Surface skimming SH waves propagate along the surface of the buffer rod, coupling the elements. The existence of this wave is allowed by the placement of the elements themselves, which serve as periodic mass loads.<sup>3</sup> These waves are strongly excited by the narrow array elements and decay slowly. We view the elimination of this cross-coupling mechanism as being the most important improvement which could be made on the array.

We have obtained excellent images of EDM slots and cracks on the back side of aluminum samples using this array. These images were very easy to obtain. A few drops of fluid couplant were applied to the buffer rod, and the sample was placed on top. No pressure

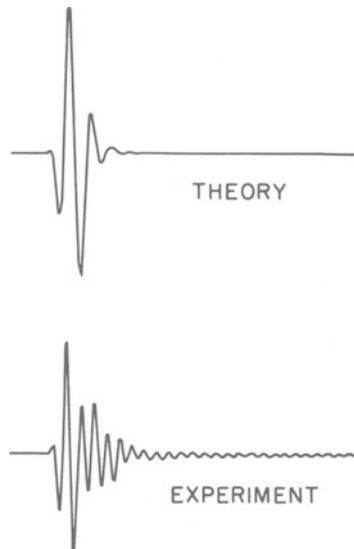


Fig. 8. Theoretical and measured impulse responses.

was required, due to the high transmission at the interface. The images appeared as soon as the target entered the field of view of the array. Figure 9 is an image of an EDM slot 5 mm long and 2 mm deep. In this image, the vertical axis represents lateral position in the sample, and the horizontal axis represents depth. The depth increases to the right, starting from the right-hand side of the series of bars which appears in the image. Note the absence of back wall and interface reflections. Figure 10 is an image of a crack which was created with a three-point bending jig. The irregular shape of the crack is visible in the image. The intensity of the image varies with the crack depth, being most intense at the center. In some cases, we have been able to estimate crack depth based on the time difference between the crack tip echo and the crack base echo. Unfortunately, the tip echo is much weaker, often rendering it invisible.

#### CONCLUSIONS

Several important conclusions can be drawn from the design and operation of this array. The most significant, which applies to single transducers as well as arrays, is that shear waves may be



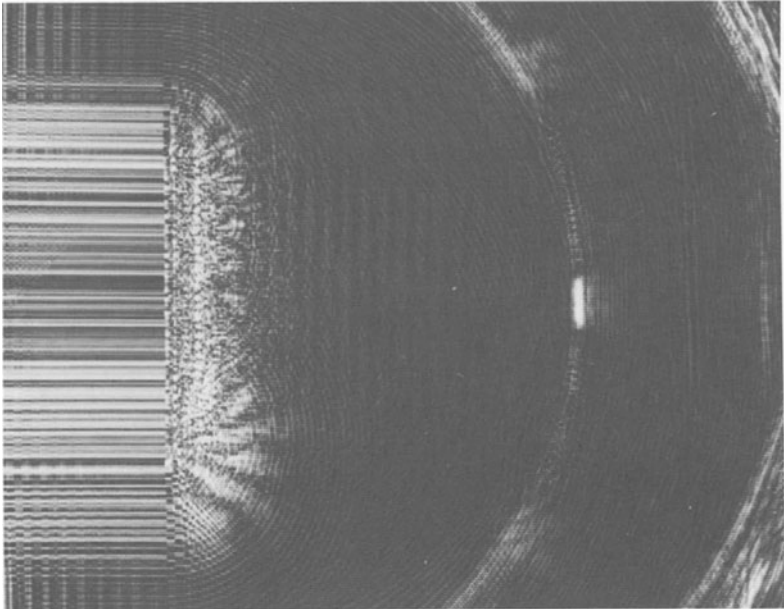


Fig. 9. Image of an EDM slot.

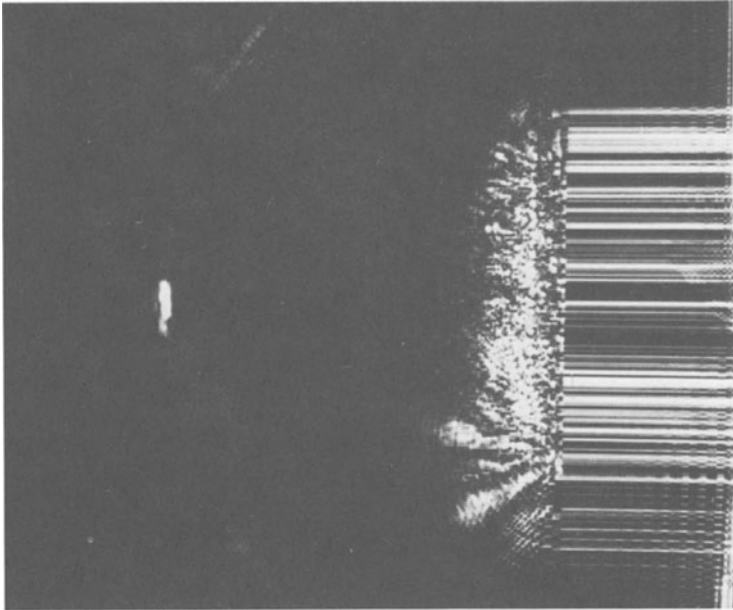


Fig. 10. Image of a crack.

excited in solid samples with greater efficiency than is possible with longitudinal waves. This is accomplished by using off-normal wave incidence, and direct contact. A second conclusion which applies specifically to arrays is that aberrations may be eliminated by using direct contact, and choosing a buffer rod composed of the same material and specimen. The third conclusion is that 45° incidence increases sensitivity to cracks which run normal to the back surface of the array, and at the same time eliminates spurious echoes from the buffer rod-specimen interface, and the back wall of the specimen. Finally, we believe that we can double the depth resolution of this array by using techniques that we have developed to eliminate cross-coupling. This will increase the utility of this tool in quantitative NDE.

#### ACKNOWLEDGEMENT

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