CONTACTING TRANSDUCERS AND TRANSDUCER ARRAYS FOR NDE

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Abstract

We have designed and built a longitudinal wave and several shear wave contacting arrays for the nondestructive evaluation of aluminum. The arrays each have 32 elements and operate at a center frequency of 3 MHz. Side drilled holes and EDM slots of different orientations (all of which are in aluminum sample blocks) are imaged using these arrays in a real-time synthetic aperture imaging system.

Following a suggestion of H. D. Williams of the CEGB (England), the coupling problem between the arrays and the aluminum block under test has been alleviated by using natural bee honey with bulk wave transducers in the frequency range of 3 MHz to 300 MHz. Our initial experiments indicate that honey is a superior couplant to any of the other available couplants.

1. Introduction

We have developed several novel contacting transducer arrays. The arrays were designed to operate in direct contact with test specimens rather than through a liquid bath. They have been used with our synthetic aperture imaging system[1] to image cracks, EDM slots, and holes in aluminum target blocks. One of the arrays utilized longitudinal waves, and the other three utilized shear waves. The arrays each had 32 active elements and center frequencies in the 2.5-3.5 MHz range.

The parameters of greatest concern to us in our array designs were: 1) time duration of the impulse response; (2) efficiency; (3) width of the angular response from a single element; (4) cross-coupling between elements, and (5) uniformity of response from element to element. The task of obtaining a short impulse response with high efficiency is somewhat simpler in a contacting array than in an array designed to operate through water. The impedance of the load material (aluminum or steel) is sufficiently high that high impedance backings are not required. In addition, there is little to be gained from the use of matching layers. Therefore, all that is required to get a short impulse response and high efficiency is good coupling to the load medium.

The cross-coupling between elements was minimized by sawing the ceramic into separate pieces. This eliminated cross-coupling through the ceramic itself. However, there was still some cross-coupling between elements through the load medium.

The angular response was maximized by making the individual array elements narrow. The array elements were about a half wavelength wide, measured in wavelengths of the load medium. In the other dimension the elements were greater than $10\ \lambda$ long. This assured us of having a flat, fan-shaped beam.

Uniformity of response from element to element depends mostly on the fabrication procedure. The two steps in this procedure which are most critical are: (1) obtaining a uniformly thin glue bond between the ceramic and the faceplate; and (2) sawing the ceramic into separate array elements without causing them to be damaged. We achieved a fair degree of success in this area by carefully cleaning the surfaces before bonding the ceramic, and by using narrow saw blades.

2. Longitudinal Contacting Array

For our first contacting array we chose to use longitudinal waves (longitudinal waves are much easier to couple than shear waves). This array had a center frequency of about 3 MHz. Coupling between the array elements, and the object under test was accomplished through a $1/4\ \lambda$ aluminum faceplate which was built into the array. The details of the construction appear in Fig. 1.

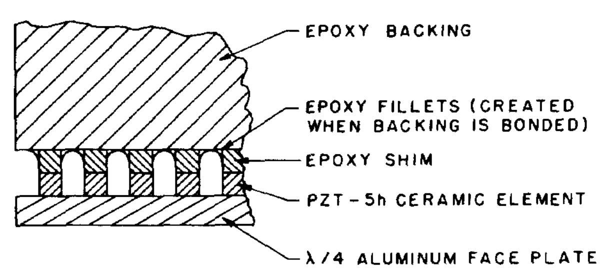

Fig. 1. Cross-section of the longitudinal contacting array with quarter-wave faceplate.

A light epoxy backing was used, but more for structural reasons than for acoustic reasons.

The backing was required so that pressure could be applied to the array in order to couple it to the target medium. The epoxy strips on the back of each ceramic element were used to keep epoxy fillets from coming between the elements. It was feared that such fillets might introduce cross-coupling.

The first step in constructing the array was to lap the faceplate to 1/4 λ thickness, while it was bonded by wax to a thick aluminum block for support. The PZT-5H ceramic (.40 mm x .125 cm x 5 cm) was then bonded to the faceplate with room temperature curing epoxy. A gold foil strip was then soldered to the PZT to serve as the electrical contact (the other contact was the faceplate itself). An epoxy shim was then glued to the ceramic and the ceramic and shim were sawed into array elements. Finally the backing was glued to the array. With the backing in place, the array was structurally sound and the aluminum block upon which the array was built could be removed. A circuit board was attached to the backing and connections were made to the individual array elements. Transformers were soldered to the circuit board in order to provide electrical matching to the elements.

Fig. 2. Image of three 1/16" drill holes in an aluminum block, taken with longitudinal contacting array.

The images in Figs. 2 and 3 were made using this array. These are imaged of side drilled holes in an aluminum block. The configuration used in this experiment is depicted in Fig. 4.

The round trip insertion loss for the array was about 14 dB at center frequency with a 3 dB bandwidth of 66% . Ten elements were connected in parallel in order to remove the effects of diffraction from this measurement. Coupling to the target was accomplished with the aid of a medical ultrasound couplant with properties like those of water. Even with the couplant, a moderate amount of pressure was required in order to get good images with this array. The impulse response and efficiency were adversely affected by the weak coupling between the array and the load.

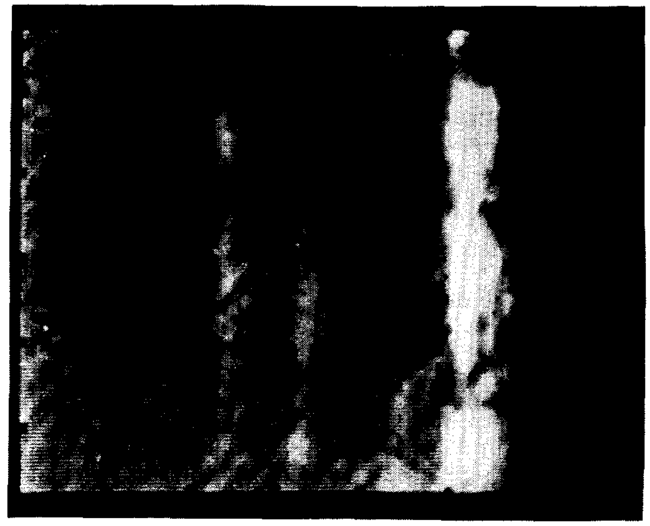

Fig. 3. Image of three 1/16" drill holes with array rotated through 90^0 from orientation used in Fig. 2.

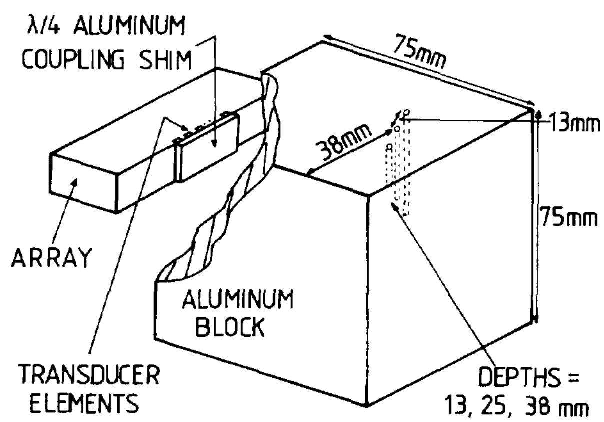

Fig. 4. Longitudinal contacting array and aluminum target block.

3. Shear Transducers

In order to improve the resolution of our imaging system, we constructed several shear wave arrays. At a given frequency (in metals and ceramics) the wavelength of a shear wave is only about half that of a longitudinal wave. Consequently, by using a shear wave array in our 3 MHz imaging system, we were able to double the resolution.

In the past we have excited shear waves in metal targets by utilizing mode conversion techniques.[2] In this approach a longitudinal wave array is used to excite a longitudinal wave in water. This wave then converts to a shear wave at the interface with the target. The disadvantage of this approach is that it causes abberations, which make the image reconstruction difficult. Therefore, we decided to develop contacting shear arrays to avoid the abberation problem.

The first shear array which we constructed was assembled in the same fashion as the longitudinal array. The array had a 1/4 λ thick aluminum faceplate, and a light epoxy backing (refer to Fig. 1 and details of longitudinal array construction). The problem of achieving good contact between the array and the target was never surmounted with this device. Since the array was 12.5 mm tall by 50 mm wide, the total contact area was almost 7 cm^2. The material that functioned best as a couplant was natural bee honey, due to the high shear viscosity of that fluid. Other couplants were tried but proved ineffective (the subject of couplants will be raised in more detail in the next section). With honey as a couplant, and the use of extreme pressure to force the array to the target, a round trip insertion loss of 14 dB was measured with a 3 dB bandwidth of 69% . Other sets of elements in the array produced weaker responses (twelve elements were connected in parallel to make this measurement). The impulse response of the array was predictably poor. Without the benefit of good coupling, there was little to damp the ringing of the elements. This array was used in the imaging system. However, it was difficult to discern the back wall of the target block, let alone flaws inside it. Because of the coupling problem, we abandoned this particular approach to the design of the shear array.

Our second shear array was constructed in such a fashion as to eliminate the coupling problem. In this case, the PZT ceramic was bonded directly to the object that we desired to test (refer to Fig. 5 for more detail). After being bonded to the target block, the ceramic was slotted with a 0.5 mm saw blade into separate array elements. Each element was then connected to a separate circuit board trace, using a ball bond. No backing was required for this array as the target block provided structural integrity.

As might be expected, this array functioned very well. Figure 6 is an image of three saw cuts, each about .2 mm wide and ranging in depth from 1 mm to 5 mm . Even the shallowest cut (1 mm) is resolvable with this array. The round trip insertion loss at center frequency was 7 dB (measured with 11 elements in parallel). This approaches the theoretical minimum, as 3 dB are accounted for by the sparseness of the array, leaving only 4 dB to account for. The element-to-element variations in impedance were also very small. The 3 dB bandwidth was 63% .

The undesirable features that were present in this array were high cross-coupling between elements and an impulse response with a long ring-down time. Since the array had no backing and the ceramic had been sawed into separate elements, the only remaining mechanism for acoustic cross-coupling was coupling through the target block itself. This same coupling may have been responsible for the long ringdown time. In any case, the cross-coupling caused by the load medium cannot be eliminated in a contacting shear array, and represents a fundamental limitation.

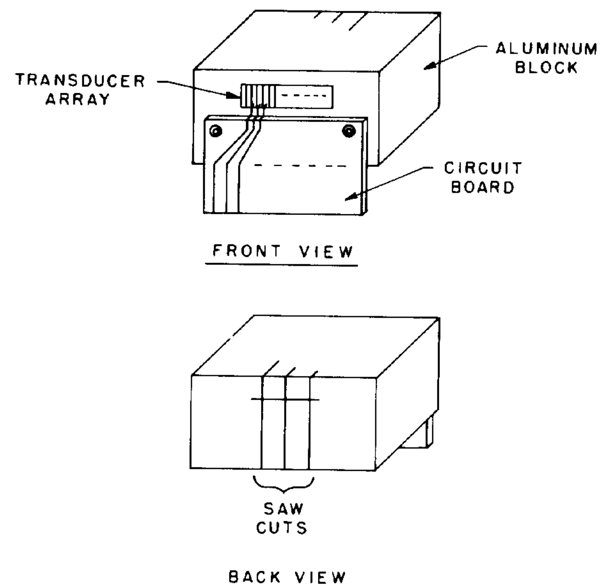

Fig. 5. Shear array bonded directly to an aluminum target block.

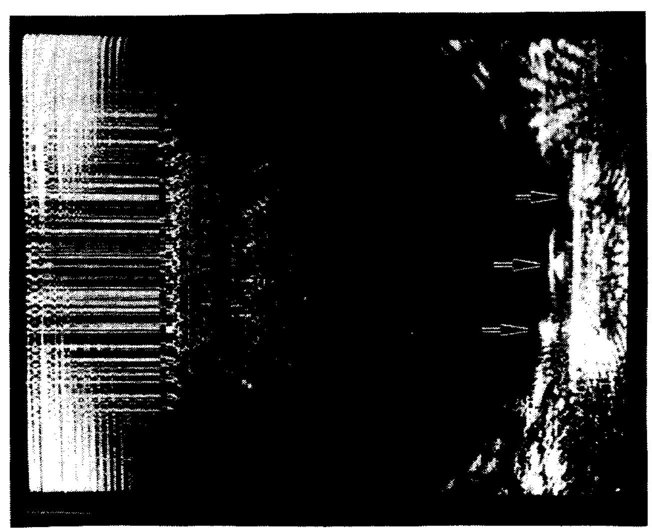

Fig. 6. Image of three saw cuts (1 mm, 3 mm, and 5 mm deep) made with shear array bonded to target block.

Aside from the difficulty involved in bonding a transducer array to an object under test, there are also functional disadvantages to this scheme. Foremost, there is the fact that the transducer cannot be moved to examine flaws in other regions of the object. Therefore, our third shear wave array was developed in order to avoid the problems of coupling we faced with our first array, and the limitations of immobility we faced with our second array. In this array, we decided to utilize longitudinal wave propagation through the layer of couplant instead of depending on the shear viscosity of the couplant to allow shear wave propagation. The acoustic beam from the array was converted from a shear wave to a longitudinal wave on one side of the interface and vice versa on the other. Since the process was symmetric, no abberations were introduced.

The geometry of this interface is depicted in Fig. 7. A shear wave is launched at an angle of 45^0 with respect to the interface in a block of aluminum. Longitudinal waves are cut off (beyond their critical angle) in the block. At the interface the shear wave, which has vertical polarization, mode converts into a longitudinal wave. The longitudinal wave propagates across the layer of couplant where it re-converts into a shear wave at the other interface. No longitudinal waves are excited in the aluminum target block, as they too are beyond cut-off. The one-way loss through such an interface has been measured to be less than 2.5 dB .

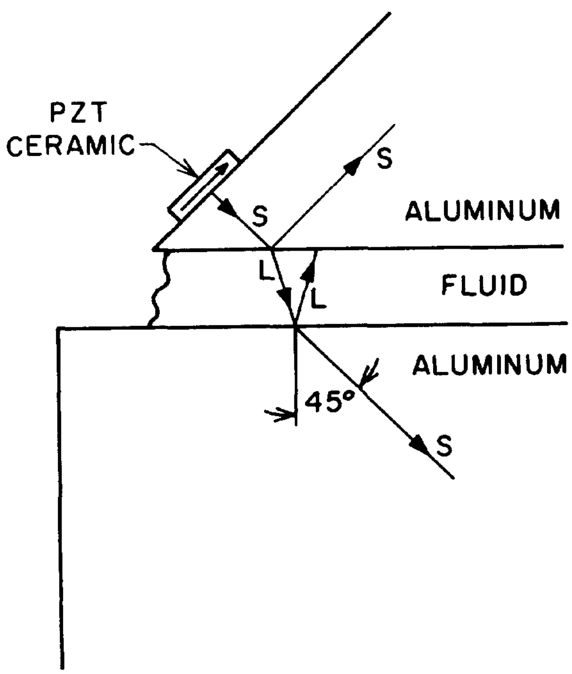

Fig. 7. Geometry for a shear array utilizing mode conversion at the target interface.

An array was constructed using these principles (refer to Fig. 8 for details of the construction). The ceramic was bonded to the aluminum wedge with epoxy. It was then sawed into separate elements, each 0.5 mm wide, spaced 1 mm apart. These elements were connected to the circuit board traces with ball bonds.

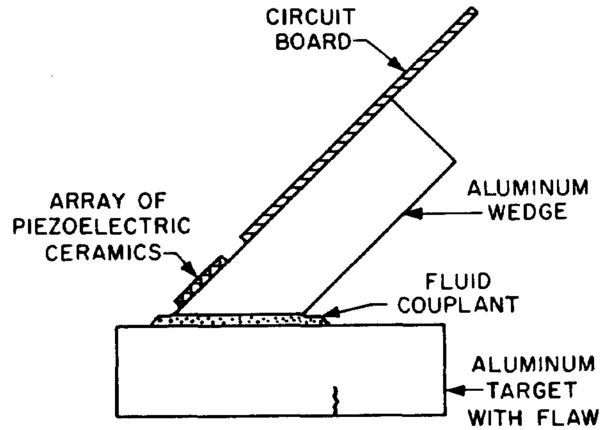

Fig. 8. Shear array configuration used to obtain image in Fig. 9.

The performance of this array in our imaging system was excellent. Figure 9 is an image of a narrow EDM slot cut in a block of aluminum (the configuration is like that in Fig. 8). The round trip insertion loss at center frequency was 19 dB , with a 3 dB bandwidth of 50% . The impulse response was acceptable, although the ringdown time was long (perhaps due to cross-coupling). A drawback with this array was that the variation in impedance from element to element was considerable. This must have been caused by either faults in the epoxy bond or damage to the ceramic due to sawing. We are in the process of constructing the second of these devices with more uniform element-to-element response. We will use transformers in this next array in order to improve the electrical match to the elements, and hopefully improve the impulse response.

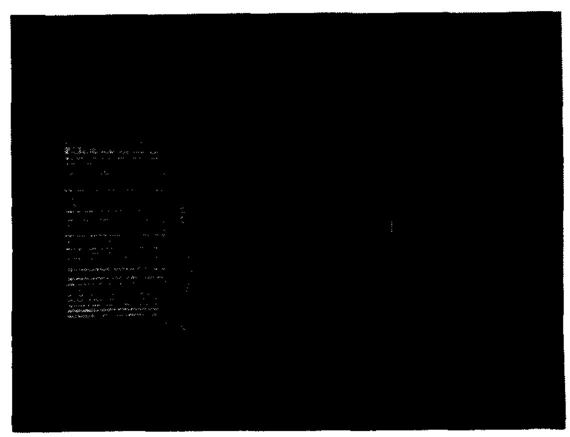

Fig. 9. Image of an EDM slot in an aluminum block, taken with 45^0 incidence shear array.

An additional advantage to this design for a shear array is that it generates a beam at a 45^0 angle with respect to the surface of the object under test. Cracks on the far side of the object, which run normal to the surface, will then combine with the surface to form an edge reflector to the 45^0 beam. Echoes from the front and back faces of the object do not appear in the image, and therefore do not mask the flaw.

4. Couplants

In order for a contacting transducer to be effective, it is important to use a good couplant between the transducer and the object under test. Couplants for longitudinal waves are readily available. Most of these couplants have an impedance like that of water. This is quite low compared to the impedance of the metals and ceramics we would like to test, but as the layer becomes very thin, the impedance difference becomes less important.

Liquid couplants will also allow shear waves to propagate, but with much less ease than longitudinal waves. The shear waves decay in the liquid within a depth which is proportional to the shear viscosity. This is analogous to the "skin effect" of electric fields in metals.

We have made measurements of insertion loss with several different couplants to try and determine which ones are best in these applications. The choice of couplant was of little significance with the longitudinal array. A viscous fluid couplant like honey led to the same loss at the interface as with a couplant like water. However, with the shear array, the two way loss at the interface was 15 dB lower with honey used as a couplant than with a water-like couplant.

At very high frequencies, the attenuation of honey is less than what one would predict based on an f^2 law. In our 300 MHz longitudinal wave flaw detection system (ZnO on a sapphire buffer rod), honey has surpassed all other couplants. This includes viscous resins and various liquids other than liquid metals. The reflection coefficient for the sapphire-honey-ceramic interface was the same as for the sapphire-ceramic hertzian contact. Thus, we were able to scan the sample with excellent transmission. We are in the process of studying this unusual behavior of viscous fluids at high frequencies.

5. Conclusions

We have described four novel contacting arrays for use in nondestructive testing. The primary obstacle to the use of these arrays is loss at the array-sample interface. We have successfully used natural bee honey as a shear wave couplant at low frequencies and a longitudinal wave couplant at high frequencies. Further investigation into the subject of viscous fluid couplants is required.

References

1. G. S. Kino, D. Corl, S. Bennett, and K. Peterson, "Real-Time Synthetic Aperture Imaging System," 1980 Ultrasonics Symposium Proceedings, November, 1980.
2. T. M. Waugh and G. S. Kino, "Real-Time Imaging with Shear Waves and Surface Waves," Acoustical Holography, 7, 103-115, Plenum Publishing Corp, 1977.

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