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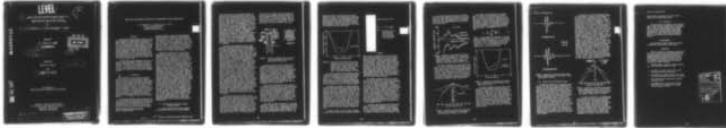
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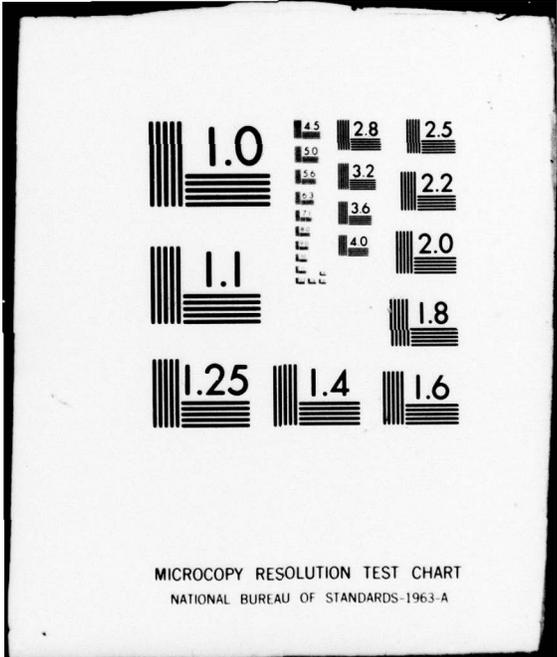
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C. S. DeSilets, A. R. Selfridge, and G. S. Kino

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HIGHLY EFFICIENT TRANSDUCER ARRAYS USEFUL IN NONDESTRUCTIVE TESTING APPLICATIONS*

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Abstract

Two types of highly efficient transducer arrays are described which couple acoustic energy into the samples imaged in nondestructive testing applications. The first type of array utilizes fully slotted, double quarter-wave matched elements to couple the acoustic energy from the high impedance ceramic to water, which is used as the transmitting medium. One such 180 element linear array operating at a center frequency of 3.5 MHz has 11 dB return loss, 45% 3 dB bandwidth, and $\pm 13^\circ$ 3 dB acceptance angle. Experimental results with an improved double quarter-wave matched, fully slotted array are described including 9 dB return loss, 65% 3 dB bandwidth, and $\pm 44^\circ$ 3 dB acceptance angle.

A second type of high efficiency array uses unslotted ceramic permanently attached to a high impedance buffer block which is coupled directly to the load. Individual array elements are formed by deposition of electrodes on the monolithic slab of ceramic. One longitudinal wave test array mounted on aluminum is reported with a half power beamwidth of $\pm 37^\circ$.

I. Introduction

The development of two types of transducer arrays for use in a synthetic aperture digital acoustic imaging system is described in this paper.¹ One type of array using narrow slotted piezoelectric elements is most suitable when the acoustic impedance of the load medium is low with respect to that of the piezoelectric ceramic. A second type of array of monolithic construction is useful when the acoustic impedance of the load medium is similar to that of the ceramic, as would be useful for a contacting transducer for nondestructive testing of metals and ceramics. The theory of operation of both types of arrays has been described in previous papers.²

The synthetic aperture imaging system requires very high transduction efficiency and bandwidth, so double quarter-wave matching layers to a water load were employed in the slotted array design. The transducer elements and layers are all slotted to minimize acoustic cross-coupling between elements

and thus achieve as broad an angular beamwidth from each element as possible. The design and characteristics of a 180 element double quarter-wave matched array will be discussed. This array has 11 dB return loss and operates in the 2.7-4.3 MHz frequency range with concomitant 5 half cycle impulse response. The angular 3 dB beamwidth is only $\pm 13^\circ$, however. Results with a test array designed for more optimal response will be shown. This array has an angular beamwidth of $\pm 44^\circ$, 65% bandwidth, and 9 dB return loss response.

Monolithic arrays have been constructed by depositing metal electrodes, by standard photolithographic techniques, onto a slab of piezoelectric ceramic.² Acoustic matching techniques, either using quarter-wave layers or a lossy backing, yield broad bandwidth arrays. However, the beam pattern from an individual element is too narrow and nonuniform for use in most imaging systems when loaded with a low impedance medium like water.³ In the case where high impedance, high velocity loads, like steel or ceramics, are to be imaged, monolithic arrays can be quite useful. By coupling a ceramic slab directly to the sample, or alternatively, through a buffer medium, excellent array characteristics can be obtained. High efficiency and broad bandwidth are obtained since the array is well matched acoustically by the sample or the buffer medium. No backing is employed. Broad, uniform beam patterns are obtained since the longitudinal velocity match between the load and the ceramic is good and high angle longitudinal wave critical angles are obtained. In fact, if the longitudinal velocity of the load is greater than that of the ceramic, which would usually be the case in practice, there is no longitudinal critical angle. Test results with a monolithic longitudinal wave array mounted on an aluminum sample will be presented. A 3 dB angular beamwidth of $\pm 37^\circ$ has been obtained by this technique. This type of array should prove to be useful in nondestructive testing applications. Shear wave monolithic arrays could also be constructed by employing ceramic with the poling axis along the element axis.

II. Slotted Double Quarter-Wave Matched Transducer Arrays

In order to achieve the desired transducer array characteristics, that is, array elements

with high efficiency, short duration impulse response, and broad angular beamwidth, quarter-wave acoustic matching techniques were used in conjunction with tall, narrow, piezoelectric ceramic elements.² Proper application of quarter-wave acoustic matching allows highly efficient transduction of acoustic energy into the low impedance load medium, typically water ($Z = 1.5 \times 10^6 \text{ kg/m}^2\text{-sec}$), from the high acoustic impedance PZT-5A ceramic ($Z = 29.7 \times 10^6$) over octave frequency bandwidths. Short duration impulse response, which is essential for good range resolution, is obtained by designing the transducer to achieve as nearly as possible a Gaussian-shaped passband.⁴ Elements with a height-to-width ratio on the order of two-to-one allow the excitation of a pure, piston-like extensional mode with a very high electromechanical coupling coefficient ($k^2 = 0.47$ for PZT-5A).² Broad angular beamwidth is achieved by using narrow elements and by reducing the element-to-element cross-coupling to a minimum.

With these characteristics in mind, a 180-element quarter-wave matched array was designed and built to operate with fully-slotted elements at a 3.8 MHz center frequency, Fig. 1. The array was fabricated by epoxying a 0.46 mm thick \times 10 cm long \times 1.25 cm wide slab of PZT-5A with 2000 Å thick chrome nickel electrodes to 0.305 mm \times 10 cm \times 1.16 cm piece of borosilicate glass, which formed the first matching layer. The extra width of PZT-5A was included in order to make electrical connection. This slab was then bonded to a backing of silicon carbide loaded epoxy ($Z = 9.4 \times 10^6$) formed into a long wedge shape (6.35 cm \times 1.27 cm) with a lossy flexible epoxy coat around the edge to eliminate reflected signals from the backing. Electrical connection was made with 0.025 mm thick brass leads, 0.25 mm wide on 0.51 mm centers soldered to both edges of the ceramic. A 0.10 mm thick piece of Dow 332 epoxy was then cast onto the front of the glass to make the outer quarter-wave plate, Fig. 1. The electrical connections were brought down the sides of the backing by leads on printed circuit boards. The individual elements were cut with a 0.15 mm diamond saw blade. With a 0.20 mm saw kerf the elements were 0.305 mm wide on 0.51 mm centers. These elements were 0.05 mm wider than expected, which had some deleterious effects on the response of the array. For this reason, the slotted epoxy matching section mode-hopped to a higher order mode which affected the impedance matching property of the section. Therefore, an additional 0.10 mm thick layer of epoxy was glued onto the face of the array so that the total thickness of the epoxy was 0.2 mm.

The addition of the extra layer of epoxy smoothed out the frequency response of the elements. The match between theory and experiment is not good, especially at the high frequency end where the theory does not predict the low radiation resistance observed in the experimental data. The complicated nature of the modes excited in the slotted epoxy matching section precludes a better prediction of the transducer characteristics. However, the smooth frequency response of the element does yield a short duration impulse response, and the insertion loss is low. In addition, before

this layer was attached, a mixture of highly absorptive silicon carbide loaded polyurethane was vacuum impregnated into the grooves between the array elements. This measure served to damp out the lateral resonance of the transducer elements which resulted from their excess width. It also gave greater structural rigidity to the array.

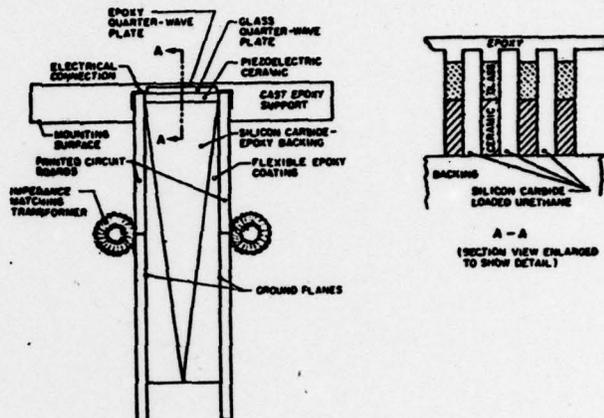


FIGURE 1. Schematic showing details of construction of 180 element, double quarter-wave matched slotted array.

The insertion loss of the transducer array elements was determined by first connecting 14 elements in parallel (to eliminate the diffraction loss in the following reflection mode experiment). This procedure gave an input impedance of 52 ohms at -45° measured at 3.5 MHz permitting matching to a 50-ohm generator. The transmitted signal was reflected off an air-water interface approximately 0.5 cm away, and the received signal measured with a high impedance probe. The total 14-element length was 0.7 cm making the path length in water well within the Fresnel zone (approximately 10 cm in this case).

The round-trip insertion loss as a function of frequency is shown in Fig. 2. Its maximum value is 11 dB at 3.85 MHz when an additional 2.2 dB was subtracted from the experimental data to account for the reflected signal which was incident upon the gaps between the elements. The bandwidth between 3 dB points was 45%. For comparison, the theoretical insertion loss of an element is shown in Fig. 2. The theoretical case shows 6 dB round-trip insertion loss and an 82% 3 dB bandwidth. This extra 5 dB loss in the experimental data has not been explained.

Since each transducer element has a very high impedance, 750 ohms, it is necessary to transformer match into a 50-ohm cable. Transformers were wound with an 8:31 turns ratio on high permeability ferrite cores (Indiana General 7704) so that the impedance of an element was 50 ohm at 3.5 MHz. The

transformers take 50 V impulses on the primary without saturation. The large number of turns was necessary to increase the parasitic parallel inductance and resistance in the transformer to large enough values so that they had minimal effects on the bandshape and insertion loss of the elements. This introduces a slight tuning effect which lowers the insertion loss by a small amount.

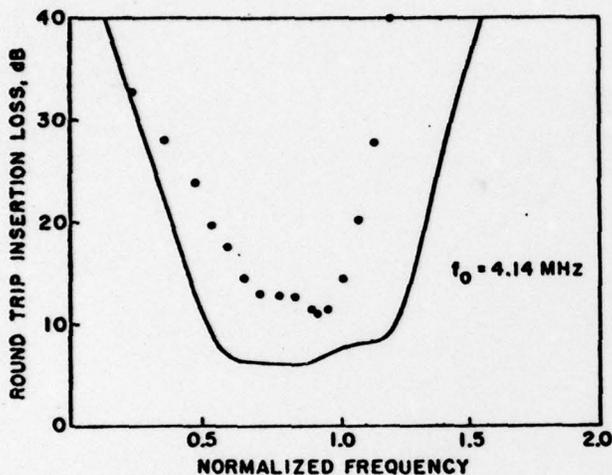


FIGURE 2. Comparison of theoretical with experimental round-trip insertion loss of 14 elements connected in parallel of 180 element array. Element size is 0.46 mm high \times 0.305 mm wide \times 1.25 cm long. Glass quarter-wave plate is 0.305 mm high. Total epoxy thickness is 0.20 mm.

The impulse responses of 32 impedance matched elements were measured by reflecting a signal off a thin 0.18 mm diameter wire target and are shown in Fig. 3. The excitation was a 0.17 μ sec wide square pulse. A 3.5 MHz 5 half-cycle impulse response, consistent with the measured 45% bandwidth was observed for each of the connected 32 elements which are observed to have a very uniform response.

The angular acceptance of a single impedance matched element was measured by rotating the array about the long axis of the element while insonified by plane waves from a transmitting transducer. Acceptance angles were measured over a range of frequencies and were much lower than expected, ranging from $\pm 24^\circ$ at 2.5 MHz to only $\pm 6.5^\circ$ at 4 MHz. The expected values calculated from a simple $\sin x/x$ response where $x = (\pi d \sin \theta)/\lambda$ were $\pm 61^\circ$ and $\pm 31^\circ$ respectively. The low acceptance angles were attributed to acoustic cross-coupling in the unslotted epoxy matching section/face plate, in the backing and in the urethane material between the elements. Nevertheless, the array has yielded excellent results in a synthetic aperture imaging system.

In order to obtain a better angular response, a test array was built with much narrower elements.



TRANSDUCER RESPONSES TO SINGLE TARGET

TRACE 1 INPUT IMPULSE (VERTICAL SCALE 50 V/DIV)

TRACES 7 to 33

SIGNAL RETURNS ON INDIVIDUAL TRANSDUCER ELEMENTS FROM A SINGLE 0.18 mm DIAMETER WIRE TARGET LOCATED NORMAL TO TRANSDUCER CENTER AT RANGE $Z = 70$ mm. RECEIVED SIGNALS AMPLIFIED BY 20 dB AND DELAYED BY 92 ns PRIOR TO DISPLAY.

FIGURE 3

This was done to eliminate the lateral resonance seen in the 180 element array and to allow the epoxy quarter-wave section to be narrow enough to function properly. Many technological changes were introduced in the design to improve the ease of construction. PZT-5H ceramic with its high dielectric constant ($1508\epsilon_0$) was used as the active material to keep the electrical impedance as low as possible. The circuit boards were beveled so that direct indium solder connections could be made between the ceramic and the leads on the PC board, eliminating the brass combs used previously. The backing was cast in place onto the ceramic eliminating the need to make a thin epoxy bond between the ceramic and the backing.

The ceramic, 0.476 mm thick \times 1.27 cm wide \times 3.2 cm long, was epoxied to a glass slab 0.305 mm thick \times 1.19 cm wide \times 3.2 cm long as done previously. A 5.7 cm deep silicon carbide/epoxy backing ($Z = 8.7 \times 10^6$ kg/m²-sec) was cast onto the back of the ceramic by vacuum impregnation. A beveled circuit board was glued to one side of the backing and indium solder was used to make connection to the ceramic. Epoxy 0.109 mm thick was then cast onto the front of the glass as was done previously. A 0.254 mm wide diamond saw was used to dice the array on 0.508 mm centers. Elements 0.180 mm wide were obtained in this manner. A 0.0127 mm thick Mylar sheet was vacuum suctioned onto the front of the array using ethylene glycol as a couplant. A 8:30 turn transformer was used to match the electrical impedance to 50 Ω .

Excellent results were obtained with this design. The electrical impedance of an unmatched element is shown in comparison to the theory in Fig. 4. Fairly good agreement between experiment and theory is obtained, and no lateral resonance is observed for these very narrow elements. There

is a 10% down shift from the theory of the impedance at the high frequency end, which is as yet unexplained. This could be the effect of the change in the effective load impedance from the longitudinal plane wave impedance which is not accounted for in the theory.⁵

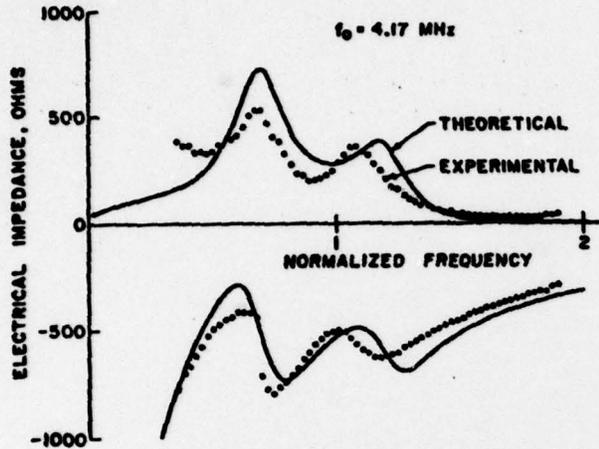


FIGURE 4. Comparison of theoretical and experimental electrical impedance of one element of double quarter-wave test array. Element dimensions are 0.476 mm x 0.18 mm x 1.27 cm. Glass thickness is 0.305 mm. Epoxy thickness is 0.109 mm. Mylar face plate is 0.0127 mm thick.

The angular acceptance was measured as before at 3.5, 4, and 4.5 MHz and much wider angular bandwidths than in the previous array were observed as can be seen in Fig. 5. The 3 dB acceptance angles were $\pm 44^\circ$ at 3.5 MHz, $\pm 34^\circ$ at 4.0 MHz, and $\pm 37^\circ$ at 4.5 MHz. Thinner elements and the lack of a thick full face layer on the front of the array helped bring about these results. Thus, the construction of efficient, broadband, high angular acceptance, slotted array elements has been demonstrated.

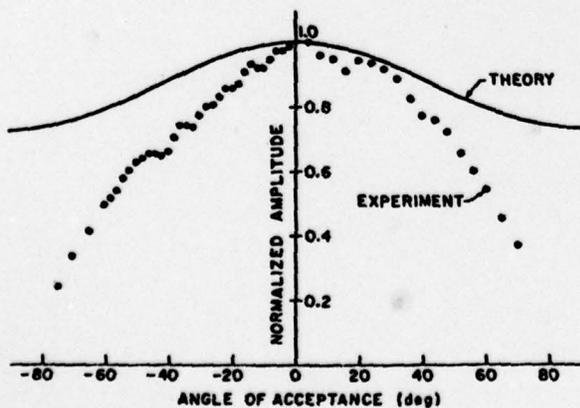


FIGURE 5. Comparison of theoretical and experimental angular acceptance of one element of same test array as in Fig. 4 at 3.5 MHz.

The round trip insertion loss of a single matched element is shown compared to theory in Fig. 6. The data was taken by exciting the element with an RF tone burst and reflecting the signal off an air-water interface 4.58 mm away from the element. The data was corrected for far field diffraction spreading by calculating the directivity of the radiation. This was done by measuring the beam pattern of the element and integrating under the curve. The diffraction loss, η , is then

$$\eta = \frac{d}{2Z} \int_{-\pi/2}^{\pi/2} \frac{I(\theta)}{I_0} d\theta \quad (1)$$

where d is the width of the element, Z is the reflector-element distance, $I(\theta)$ is the radiated power as a function of angle, and I_0 is the radiated power at 0° . The measured, corrected insertion loss is 9 dB at 3 MHz compared to the theoretical 6 dB. The 3 dB bandwidth is 65% which compares well to the theoretical 66%.

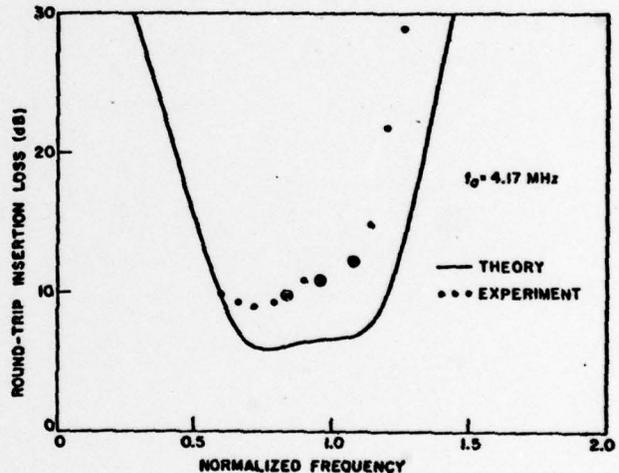


FIGURE 6. Comparison of theoretical and experimental insertion loss of one element of same test array as in Fig. 4.

The impulse response is shown in Fig. 7 and shows excellent agreement with the theoretical prediction. This data was taken by exciting the transducer element with a 50 V short pulse and reflecting the signal off an air-water interface 4.58 mm away. The basic 1-1/2 cycle response is seen, but additional ringing is observed after the main response. This is mainly a result of too square a bandshape and could be improved with the use of a lower impedance material for the second quarter-wave plate, a higher impedance material for the first quarter-wave plate, or possibly a higher impedance backing at the cost of increased insertion loss.

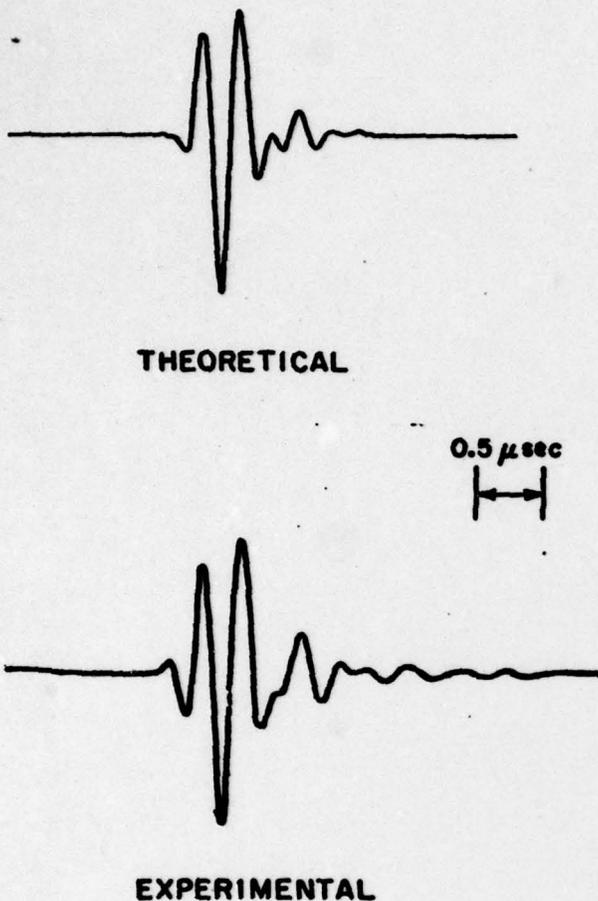


FIGURE 7. Comparison of theoretical and experimental impulse response of one element of same test array as in Fig. 4.

III. Ceramic on Metal Monolithic Arrays

An important application of monolithic transducer arrays lies in the area of nondestructive testing. In this case, images of flaws can be produced by directly coupling the acoustic energy generated by the transducers into the sample to be imaged instead of using an intervening low impedance coupling medium like water. A longitudinal or shear wave array of high impedance ceramic like lead zirconate titanate can be directly coupled into a high impedance sample or attached to a buffer material which is then directly coupled to the sample. The advantage of this technique is two-fold. First, a high efficiency, broad bandwidth array can be easily produced without the use of quarter-wave matching layers. Also, since the acoustic velocities of these materials are as large or larger than those of the transducer material, there are no longitudinal-longitudinal or shear-shear critical angles, thus allowing broad, uniform spatial frequency responses for monolithic array elements.

To demonstrate the use of monolithic arrays for this purpose, a longitudinal monolithic array was constructed by epoxying a slab of PZT-5A ceramic onto an aluminum buffer block. Theoretical curves were computed and compared to experimental values for the same configuration. The experimental data were taken by epoxying a $1.27 \text{ cm} \times 0.79 \text{ mm}$ slab of PZT-5A ceramic onto the edge of an aluminum plate 5 cm thick. Sixty array elements were defined on the ceramic by etching away a $1 \mu\text{m}$ thick Cr-Au film on the top surface of the ceramic. The elements were $0.51 \text{ mm wide} \times 1.143 \text{ cm long}$, and the area around the elements was left covered with gold and grounded to form a shield. The radiation pattern of the center element was determined by machining the plate in a cylindrical surface of 7.62 cm radius around the center of the array. A 1.90 cm diameter, 2 MHz thin disc transducer was bonded to a block of aluminum with a front surface matching that of the plate. The angular response was easily checked by moving the transmitting plane wave transducer around the surface and receiving the signal with the center monolithic array element as a function of angle. The angular responses for $f = f_0$ is shown in Fig. 8 and compared to theory. Excellent agreement between theory and experiment is demonstrated in this figure, and an acceptance angle of $\pm 37^\circ$ is shown. Little evidence of excitation of shear waves is seen, although the small peaks at $\pm 40^\circ$ could be caused by this effect.

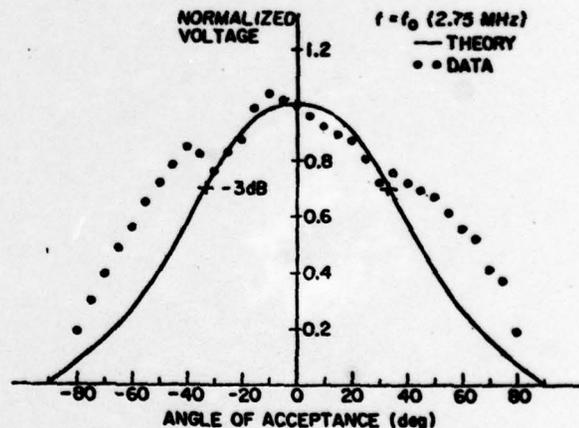


FIGURE 8. Comparison of theoretical and experimental angular acceptance of one element of 60 element monolithic test array at $f_0 = 2.75 \text{ MHz}$. Piezoelectric ceramic is PZT-5A; load is aluminum. Element width is 0.508 mm.

As can be seen from Fig. 8, excellent monolithic transducer arrays can be constructed for this important area of application in nondestructive testing. The excellent impedance match between metals and piezoelectric ceramics allows the simple construction of extremely efficient transducer arrays with 50 to 100% bandwidths depending on the exact properties of the metal and ceramic used. In addition, broad and uniform spatial frequency responses are automatically obtained since critical angle phenomena are eliminated. Monolithic arrays

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should become an important part of future non-destructive testing imaging systems.

IV. Conclusion

The construction of broadband, wide acceptance angle, highly efficient slotted arrays for exciting waves in water has been demonstrated. Broadband wide acceptance angle monolithic ceramic arrays can also be used to excite waves in high impedance materials. Monolithic PVF₂ arrays might be expected to be used to excite waves in water because of the relatively good match between PVF₂ and water.

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References

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