AN EDGE-BONDED SURFACE ACOUSTIC WAVE TRANSDUCER ARRAY

H. C. Tuan, A. R. Selfridge, J. Bowers, B. T. Khuri-Yakub, and G. S. Kino

Ginzton Laboratory
Stanford University
Stanford, CA. 94305

Abstract

A new type of transducer array has been designed and built for imaging surface defect in metals such as aluminum. The array is formed by edge-bonding a piece of piezoelectric material to a substrate of the same material as the sample to be tested. The individual elements in the array are formed by photolithography, and each element acts as an edge-bonded surface wave transducer. The array has 32 elements resonant at a center frequency of 3.1 MHz with a round trip 6 dB and a ±35°, 3 dB acceptance angle at its center frequency. A theory has been developed which predicts the angular response of the array accurately.

1. Introduction

Several years ago, Kino and his colleagues developed an acoustic imaging system for NDE based on a phased array technique which used chirp-focusing.[1] With this system, it was demonstrated that various types of waves, including shear, Lamb, and Rayleigh waves, could be excited by mode conversion from a longitudinal wave array in water, and that imaging could be performed using these types of acoustic waves. Normally the array is held at an angle to the surface of interest, longitudinal waves are excited in water, and with the correct choice of angle, Rayleigh waves or other modes of interest may be excited and focused in the substrate.

The problems of mode conversion have become more severe as we have improved our imaging systems. The difficulty is that the mode conversion process introduces aberrations into the image because of the differences in velocity between the waves in water and the waves in the metal so that as angle of attach of beam entering the metal is changed, the time and phase delays of the rays change slightly. It was not a problem in our earlier systems with definitions of the order of 2 mm; aberrations of this type have only become a problem now that the imaging systems have definitions of the order of .5 mm.

Accordingly, we have constructed a new type of array especially designed for exciting acoustic surface waves in NDE applications. This array consists of a piezoelectric ceramic slab bonded to a metal substrate of the same material that it is desired to examine. The principle of operation combines some of the earlier ideas on monolithic transducers with that of the edge-bonded transducer.[2-5] Thin film electrodes are deposited on the back of the ceramic, which is itself approximately a half Rayleigh wavelength thick. The ceramic is poled in a direction perpendicular to the surface of the substrate, so as to excite a strong SV component. The electrodes are themselves approximately one wavelength long in the direction perpendicular to the top surface of the metal and ceramic. These electrodes, therefore, efficiently excite a Rayleigh wave whose penetration depth is of the order of one wavelength. The individual electrodes themselves are approximately one wavelength wide and are separated from each other by a gap of the order of a wavelength in which a grounding strip is deposited, to shield the individual array elements, one from the other.

The PZT-5H ceramic is epoxy-bonded to the aluminum substrate using the Papadakis method of thin bonding.[6] The back side of the array is metallized to achieve good grounding and to minimize the variation of electrical impedance from element-to-element due to nonuniformity of the epoxy bond. Individual elements of the array are accessed by ball bonding 2-mil gold wire to the electrodes. PZT-5H was chosen for the piezoelectric material because of its high dielectric constant in this application ($\epsilon_{11} = 3000$) and large coupling coefficient ($k_{15}^2 \approx 0.65$). This makes it possible to obtain transducer elements with a low enough value of impedance for transformer matching to a 50 ohm load. Because the impedance match between the ceramic and the metal is fairly close, a wave excited by a single electrode, which forms the array element, does not reflect back and forth in the ceramic, thus avoiding coupling the elements together. So the elements do not need to be slotted. Furthermore, because the Rayleigh wave velocity in the ceramic (2.05×10^5 cm/sec) is lower than that in most metals (2.85×10^5 cm/sec in Al), it follows from Snell's law that a ray excited in the metal substrate will emerge at a larger angle to the axis than the corresponding ray in the ceramic.

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By using the array in the coupling configuration shown in Fig. 1[5,7] it is possible to transfer energy from the substrate in which the wave is excited to a neighboring identical substrate material. The two substrates are placed parallel to each other, with a thin layer of plastic between them, the layer of plastic being of the order of 5 mm to 1 cm long. No aberrations in the focusing are introduced by this coupling technique, because the wave velocities in the two substrates are identical.

2. Theoretical Analysis

A theoretical analysis of the transducer has been developed, based on the edge-bonded transducer theory given at this conference last year. This theory has had to be modified to take account of the finite width of the array elements and the fact that the rays can be emitted at large angles to the transducer axis.

We therefore considered the excitation of a straight crested wave in the ceramic at an angle θ to the x axis, shown in Fig. 1. This gives rise to a plane wave in the metal at an angle θ_M to the axis, where by Snell's law

$$\frac{\sin\theta_M}{\sin\theta} = \frac{v_M}{v_0} \tag{1}$$

where v_M and v_0 are the wave velocities in the metal and ceramic, respectively.

We use the normal mode equations and notation given in Ref. 5 and write, for a wave propagating at an angle to the axis:

$$\frac{\partial a}{\partial z'} + j\beta a = \frac{j\omega}{4P}\int \rho(x',y'z')\phi_n^*(x',y')dx'dy' \tag{2}$$

where

$$\beta = k\cos \tag{3}$$

$$z' = z\cos\theta + x\sin\theta \tag{4}$$

$$x' = x\cos\theta - z\sin\theta \tag{5}$$

and $k = \omega/v_0$.

We assume that the charge on an electrode of width w and height h is Q so the charge density is uniform and of value $\sigma = Q/wh$. The charge on the front electrode is more spread out due to fringing effects, and its distribution is taken account of in the theory. We assume a perfect reflection at the back surface of the wave generated in the backward direction.

We also treat the reflection at the front surface of an SV wave with only a v_y component. We find that the reflection coefficient at the front surface is

$$\Gamma = \frac{Z_M' - Z_0'}{Z_M' + Z_0'} \tag{6}$$

where $Z_M' = Z_M\cos\theta_M$, $Z_0' = Z_0\cos\theta$, and Z_M and Z_0 are quasi Rayleigh wave impedances defined as $Z_M = \rho_M v_M$, $Z_0 = \rho_0 v_0$, and ρ_M and ρ_0 are the mass densities of the metal and piezoelectric material, respectively.

With the use of these assumptions we calculate the amplitude $|a(\ell,\theta,k)|$ of the excited wave to be of the form

$$|a| = K(k,\ell)\sqrt{1 + \operatorname{sech}^2\gamma\ell - \frac{\cos(k\ell\cos\theta)}{\cosh\gamma\ell}} \cdot \left[\sin\left(\frac{k\ell\cos\theta}{2}\right)\right]\left[\frac{\sin(kw\sin\theta/2)}{kw\sin\theta/2}\right] \left[\frac{\dfrac{Z_M'}{Z_0'}}{\left(\dfrac{Z_M'}{Z_0'}\right)^2\cos^2(k\ell\cos\theta) + \sin^2(k\ell\cos\theta)}\right]^{1/2} \tag{7}$$

where $K(k,\ell)$ is a parameter which can be calculated from the edge-bonded transducer theory[5] and

$$\gamma = (\varepsilon_{33}^T/\varepsilon_{11}^T)^{1/2}k\sin\theta . \tag{8}$$

The first square bracket in Eq. (7) accounts for the fringing field effect and gives the basic excitation of the plane crested wave. The second term accounts for reflection at the back surface. The third term accounts for the width of the transducer element, and the fourth term accounts for the reflection at the front surface.

We note that the effective propagation constant in the Z direction is $k\cos\theta$. This serves to peak up the response for off axis rays at higher frequencies where there is a half wave resonance, i.e., where $k\ell\cos\theta \approx \pi$. On the other hand, the fringing field effect tends to lower the large angle response at higher frequencies, as does the effect of the finite width array element.

The radiation resistance R_a of the transducer can be calculated from the original theory of the infinite width edge-bonded transducer by putting $R_a = \mathscr{R}e P/2I^2$, where P is the radiated power and $I = j\omega Q$ is the current entering the transducer element. This in turn implies that the original edge-bonded transducer formulation must be modified by multiplying the expression for R_a by a term proportional to $\int|a^2(\theta)|d\theta$. The normalization required is obtained by matching both theories, analytically, for the situation when $kd \to \infty$.

3. Experimental Results

The transducer elements of the array were tested by exciting them with a narrow pulse and receiving the returning echo from the far corner of the aluminum block. The maximum amplitude of the returning echo from the far corner were within ±1.0 dB of each other for all the elements. Figure 2 shows the measured impulse response of 22 elements of the array, connected in parallel, and the Fourier transform of this response. We note that this result corresponds to normal incidence. The elements have a center frequency for normal incidence of 3.1 MHz and a 6 dB bandwidth of 65%. The insertion loss of each element was determined by exciting the element with an rf tone burst and measuring the amplitude of the reflected wave from the far end of the aluminum block. After correcting for both the reflection coefficient of a 90° corner in aluminum[8] and the diffraction loss, the measured two-way insertion loss of each element is 14 dB.

The acceptance angle of an individual element was measured by exciting it with a tone burst and receiving the signal with a wedge transducer that is moved along a 6-cm circle, facing the element. The maximum amplitude of the signal receive by the wedge transducer versus angle is plotted in Figs. 3, 4, 5, and 6 for 4 different frequencies, $f = 0.4\ f_0$, $f = 0.8f_0$, $f = f_0$, and $f = 1.2f_0$ where $f_0 = 3.5$ MHz , and compared to the theoretical result given by Eq. (7). It will be seen that the agreement between theory and experiment is excellent. The angle of acceptance at the 3 dB points is approximately ±35° at the center frequency. It will be noted that there is some evidence of cross-coupling in the response at $1.2f_0$.

The input impedance of 16 elements of the array, placed in parallel, was measured and is shown as a function of frequency in Fig. 7. The insertion loss of these elements corresponds within 2 dB to the electrical mismatch loss when measured into a 50 Ω load. The theoretical plot is not given as we have still to finish the complete numerical analysis, using Eq. (7), along with the results of the edge-bonded transducer theory. We now have calculated v_0 for PZT-5H and find that $v_0 = 2.03 \times 10^5$ cm/sec . This is in good agreement with measurements carried out by Yu with interdigital transducers on PZT-5H which gave a value of $v_0 = 2.05 \times 10^5$ cm/sec . The measured impedance has a peak at 3.9 MHz rather than 3.5 MHz. This is due to the excitation of waves at an angle to the axis. The results of Eq. (7) when used to perform the integration of $a^2(\theta)$, do in fact, tend to make the impedance have a peak value at a higher frequency than 3.5 MHz. The minimum insertion loss occurs at a lower frequency (3.1 MHz) due to the fact that the reactance has a minimum below 3.9 MHz.

The surface wave generated in the substrate has been coupled onto a substrate under test by holding the two pieces parallel to each other and using a thin film of water or plastic approximately 5 mm long as the coupling medium. For aluminum-aluminum coupling, it has been calculated that at a center frequency of 3.5 MHz, the transfer loss is 2.7 dB with an optimum coupling length of 4.5 mm. Experimentally, the one-way transfer loss is measured to be 3 dB.

4. Conclusions

A new type of edge-bonded surface acoustic wave transducer has been built. The array has the advantages of simpler construction and use than the conventional slotted array, and furthermore should not give rise to aberrations in a focused surface wave image. High efficiency, broad bandwidth, and wide acceptance angles for the individual elements have been obtained. A theory has been developed to predict the angle of acceptance of the individual elements, which is in excellent agreement with the experiments. The theory should lead to complete predictions of the impedance of the transducer elements as a function of frequency.

Acknowledgment

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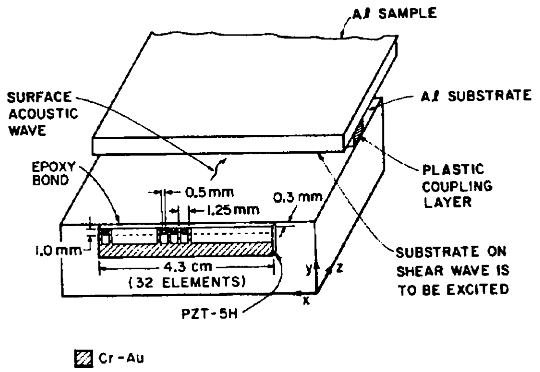

Fig. 1. The edge-bonded 32-element surface acoustic wave transducer array.

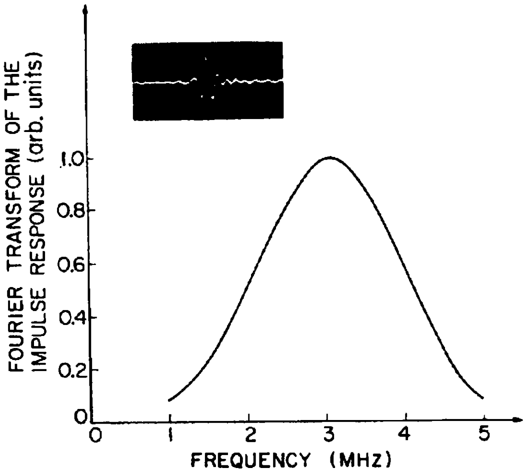

Fig. 2. The impulse response and its Fourier transform of 22 elements of the array, excited in parallel 0.5 μsec/Div for the impulse response.

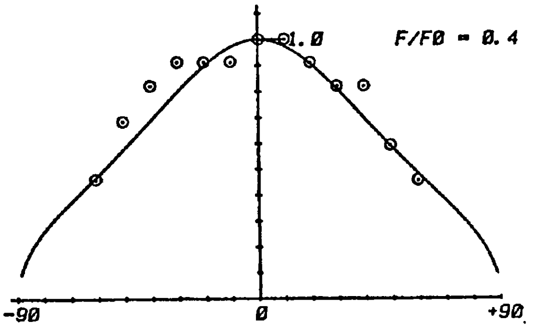

Fig. 3. The experimental and theoretical angular response of the transducer array at $f/f_0=0.4$.

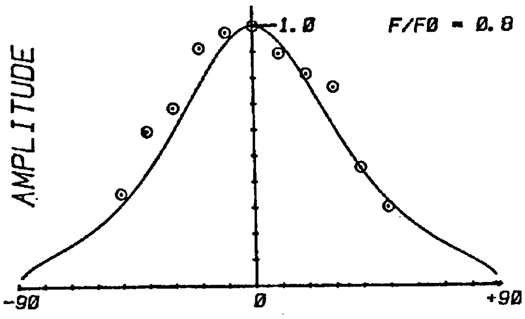

Fig. 4. The experimental and theoretical angular responses of the transducer array at $f/f_0 = 0.8$.

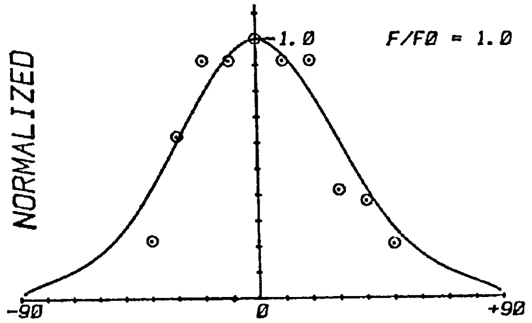

Fig. 5. The experimental and theoretical angular response of the transducer array at $f/f_0 = 1.0$.

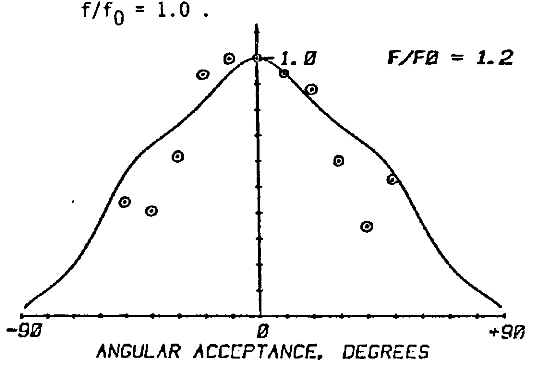

Fig. 6. The experimental and theoretical angular responses of the transducer array at $f/f_0 = 1.2$.

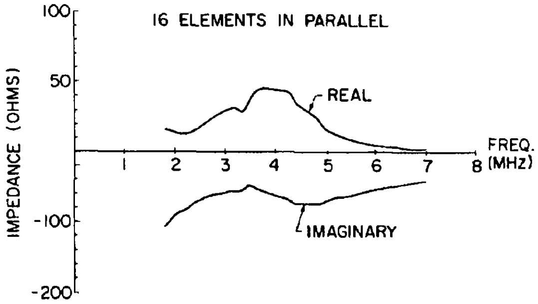

Fig. 7. The measured input impedance of 16 elements placed in parallel.