Development of a Dual Element Ultrasonic Transducer

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Abstract

We construct dual element ultrasonic angle beam transducers suited for NDT applications, based on the previous theoretical work, Ref. 2. Construction procedure includes analysis of characteristics of each component, fabrication, and performance verification of the probe. Comparison of experimental results with those of theoretical caluculation shows good agreement with each other. Overall performance of the transducer is concluded to function well enough to be implemented in practical applications overcoming the problems encountered with a single element transducer.

요약

이미 발간된 바 있는 이론적 결과를 바탕으로 비파괴 검사용 분할형 초음파 탐촉자를 개발하였다. 개발과정은 각 부품의 제작, 조립, 그리고 성능평가 등을 거쳤고, 실험 결과는 이론치들과 잘 일치하였다. 본 연구에서 개발된 탐촉자는 실현장에서 요구하는 기준치를 충분히 만족시킬정도로 우수한 성능을 보였다.

I. Introduction

In order to consider requirements for NDT transducers, it is important to define the kind of work for which the transducers may be employed. Dual element transducers are designed to overcome problems come across by single element transducers when measuring very thin materials or when detecting near surface discontinuities[1]. When a piezoelectric crystal inside the probe is excited, it vibrates and generates an elastic wave. The crystal vibration has a finite duration or ringing time. During this time, the crystal can not act as a receiver for the reflected echo, and the receiver amplifier may be saturated by the transmitted pulse. This is called a dead zone and may extend several millimeters into the test object for a low frequency transducer. When using single crystal normal beam probes, the subsurface resolution is often not satisfactory because of the dead zone. For locating and characterizing near surface anomalies, the ringing time is a critical problem. In addition, if the test surface is rough, it may produce long ringing interface echoes. The sue of a dual element transducer overcomes these disadvantages because the receiver can sense the reflected signal even before the transmitter has ceased transmitting. Due to its high signal to noise ratio, the dual element probe performs well for detecting discontinuities in highly attenuative ma-

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접수일자 : 1993. 4. 17

terials like concrete and stainless steel weld metal.

A dual element transducer consists of two transducers(a transmitter of longitudinal waves and a receiver)mounted on delay lines side by side and separated by an acoustic barrier(Fig. 1).

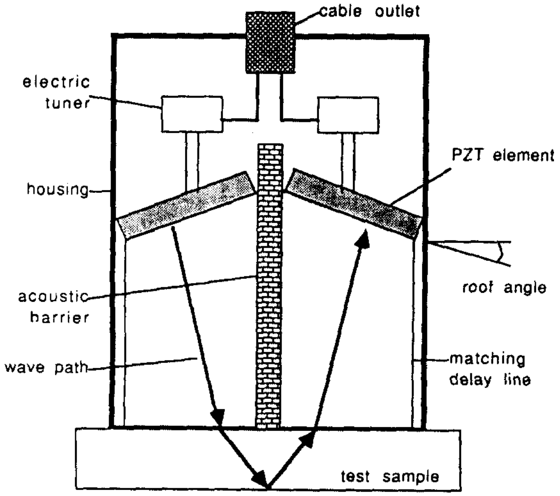


Fig 1. Schematic diagram of a dual element angle beam transducer

One element is purely the transmitter and the other purely the receiver. In the last paper[2], the author investigated the structure and properties of a dual element transducer in a theoretical manner. The results provided the optimum transducer structure for the widest operating bandwidth, the best linearity of phase variation, the shortest ringdown time, and the highest sensitivity. On the basis of it, this paper describes construction of the dual element transducer suited for non-destructive test applications. The construction process includes development and manufacture of each component, assembling, and calibration to meet given specifications, as mentioned in Secs. 2 and 3. Section 4 conducts summary of the work and assesses remaining problems.

Ⅱ. Components manufacturing

Figure 1 is a schematic diagram of the transducer under study. The crystals are cemented to the delay lines and are very carefully shielded from each other, both electrically and acoustically. They are mounted in a common housing with two separate connectors and linked to a flaw detector by twin cables. Components composing the probe are housing, front matching layers, piezoceramic elements, a backing material, electric tuning circuits, and cables for external measurement. In this section, each of the components is developed and calibrated to be suitable for our purpose. Table 1 shows representative material properties of the components.

Table 1. Material properties of each component composing the probe

Housing	density velocity	2750 $\mathrm{kg/m^3}$ 5150 m/sec
Matching delay line	density velocity	1680 $\mathrm{kg/m^3}$ 2628 m/sec
Piezoelectric ceramic	density velocity d_{33} g_{33}	7600 $\mathrm{kg/m^3}$ 3390 m/sec 285×10^{-12} m/V 24.9×10^{-3} Vm/N
Backing material	density velocity	3490 $\mathrm{kg/m^3}$ 929 m/sec
Matching circuit	inductor	8 μH

The housing is made of Aluminum alloy with inclusion of Magnesium[3]. The alloy is chosen for its good mechanical strength and shapability. It measures 34.0mm(diameter)×30.0mm(height)

The matching delay line is made of Acryl. The choice of a suitable material for the layer can be a critical factor in probe performance. The matching layer reflects the impedance of a piezoceramic to an acoustic load in a more acceptable form[4]. It also serves as an acoustic window to protect the ceramic element form wearing and fracture. In this study, we put more emphasis on the shapability in selection of the material due to the nature of the dual element transducer. The unit is supposed to take a higher priority to function as a mechanical protector and an acoustic delay line rather than as an impedance matching layer. Acryl is fairly strong and is easily worked into an arbitrary form. It also has an appropriate acoustic impedance value for our purpose(4.4 Mrayl). Complete isolation of the transmitting and receiveing transducers enables the crystal to be mounted in the probe far away from the surface of the test specimen, which results in long delay lines. The two transducers are pitched at an angle to the verical plane dividing them, called the roof angle or squint angle, around 8 degrees. Therefore in strict terminology, it is called a dual angle beam transducer to be differentiated form a dual normal beam probe. The angle causes the longitudinal wave beams of the two transducers to overlap, creating a pseudo focusing effect in the focal zone and increasing the signal-to-noise ratio. The probe under development is for scanning steel samples whose longitudinal wave velocity is about 5400 m/sec. The value of 8 degrees is chosen to make the focal point inside a steel plate 8mm away from the Acryl surface. The focal point of 8mm is the requirement given by consumers. Form the Snell's law, the critical angle for total internal reflection of longitudinal waves is 29.1 degrees at the boundary between Acryl and steel. Hence, the roof angle of 8 degrees is small enough to prevent the generation of lateral waves at the boundary. However, in practice, due to multiple refection inside the Acryl delay line, a surface echo may be still present, even thogh small. Depending on material properties of test samples, the roof angle can be varied to focus the ultrasonic beam at a desired postion. Side surfaces of the delay lines are scratched to prevent undesirable uniform reflection of the waves. Size of each unit is 26.0mm × 13.1mm × 4.2mm.

For the piezoceramic element, we choose the commercially known material PZT-4[5] following the results in Ref. 6. It has quite good durability along with excellent sound generation and reception efficiency. Each PZT unit measures 4.0mm × 24.0mm × 0.4mm. The ceramic element is bonded to the Acrylic layer with an adhesive of epoxy type resin. The process of mounting requires the insertion of a thin bonding layer between the PZT and the delay line. The thickness of the bonding layer affects the performance of the transducer markedly, and thus must be taken into account[7]. A more severs case that is not modeled using the one dimensional calculation in Ref. 8 is that of a poor or patchy bond. In such a bond, the reflectivity may vary form point to point across the bond. The practical effect of such a patchy bond is that a greater proportion of energy is reflected from the bond line than should normally be expected. With the patchy bond line, some regions of the piezoelectric will be loaded by the designed acoustic impedance while others may be, in effect, air backed. Hence great care is undertaken to control the bond line thickness.

At this point, each half of the dual element transducer is ready, which is the Acrylic delay line with a PZT crystal. The two halves are bonde together using fast curing low viscosity epoxy. To prevent interference of transmitted and received signals with each other, we place a lossy wall in the middle of the two ports as shown in Fog.1. A cork plate takes the role of the wall, which has a high acoustic attenuation coefficient and low moisture absorbability. In addition, in the neighborhood of the crystals, the plate is fitted with electrical screening to prevent electric cross coupling. The bonded unit is now seated in the housing and is prepared to be coupled with a backing material.

The backing material is a composite of silicon rubber and tungsten powder. The composite is the suspension of the tungsten powder in the rubber. Ultrasonic enegy, once in the backing, should be rapidly absorbed or attenuated so that the backing material does not act as a source of delayed ultrasound. Rubber materials are usually very good absorbers of ultrasound in the megahertz range, due to interactions between the sonic energy and side chains in the polymers. For proper acoustic impedance, several mixing ratios of the two materials are tried. When various experimental error factors are taken into account, the best ratio for our purpose is determined to be two weight of the silicon rubber to three of the tungsten powder. It corresponds to the characteristic impedance of 4.6 Mrayl. Much of work has been done, both theoretically and experimentally, to analyze the effect of the mixing ratio on acoustic properties of the composite[9]. Although the calculation is expected to be accurate, the accuracy of the result will depend on the precision with which the elasitic constants of the components are defined. Tungsten may be thought of as an element with better defined properties but its commonly quoted maximum density of 19.3×10^4 kg/m^3 is only achieved by careful working of the material. The tungsten powder used in probe construction is almost certainly lower in density than this. These low values are presumably not to be attributed to the presence of oxide or impurities. It must be linked to some degree of porosity that may be enhanced in mixing by any tendency of the rubber not wet the powder completely. These factors limit the accuracy of the theoretical prediction. In processing, the tungsten powder is mixed with the rubber by means of Toluene, and the composite is vacuumed to eliminate air bubbles. Once the backing composite gets ready, it is cast directly onto the back of the piezoelectric so that the bond between the two materials is formed as part of the setting process. It is assumed that this method of construction avoids bond line problems, but experience suggests that the probe behaves as though there is a bond line still present. This is due to the difficulty of closely aligning a collection of randomly shaped particles against a flat surface, causing patchiness of the bond. In some sense, bond problems are inevitable with these materials, but are usually less severe and these backings are thus common.

As a final step in the construction, the probe unit is electrically matched and linked to a flaw detector. The electrical matching of a dual element probe differs in principle from that of a single crystal probe. It is no longer necessary to compromise between matching sigle crystal as both transmitter and receive. Each crystal can be matched separately and even different types of piezoelectric materials can be used to obtain an optimum performance[6]. In this form, several inductors are connected in parallel and series to the transmitting and receiveing ports of the transducer. The inductance is used to improve the efficiency of the ultrasonic transducer at the expense of some reduction in bandwidth[10]. Use of additional capacitors is avoided to prevent the ringing of the L-C circuit. Optimum Value of the inductance is determined through simulation with the equivalent circuit model in Ref. 2. The criteria used in the optimization is(1) to minimize the reactance of the probe, and(2) to match the impedance of each side of the probe to that of a corresponding port of a pulser receiver(Panametrics 5055PR) so that maximum power transfer can occur. Inductors are fabricated in the laboratory with ferrite cores(D3B DR, Korea TDK), ferrite caps(M8C THP, Korea TDK), and enamel-coated copper wires(diameter : 0.33mm). The process on the transmission side is matched on the receiving side where apporopriate electronic or digital filtering techniques can be used to pro-

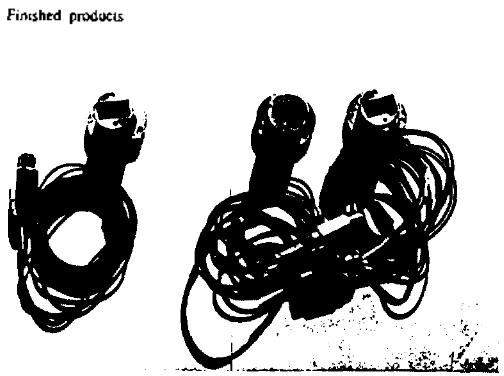


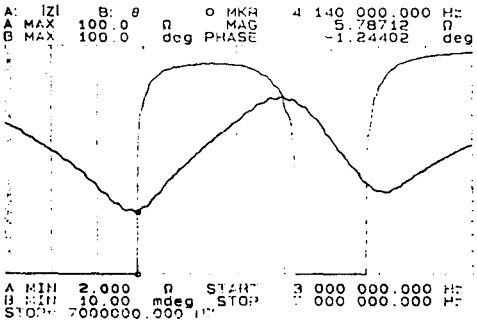
Fig 2. Photograph of finished dual angle beam transducers

duce equivalent changes in the overall response. Figure 2 shows completely finished transducers.

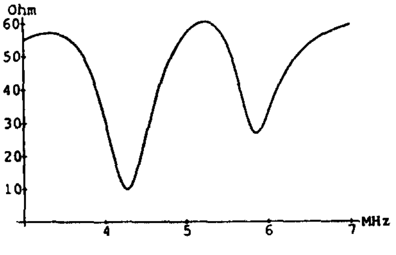
Ⅲ. Characterization

The assembled transducer is analyzed with an Impedance Analyer (HP 4194A). The bare PZT element is prepared to resonate at 5.4 MHz in its series-branch thickness mode. Figure 3 is ths measured result with corresponding theoretical data calculated with the model in Ref. 2. Attachment of layers causes variance of the crystal impedance with frequency, while broadening its operation bandwidth. Properties of the matching layers were not chosen to be optimum in consideration of the bandwidth. Matching layers of higher acoustic impedance will provide a more flat variation. It is observed that there is good correspondence between the two sets of data. Nonlinear factors and experimental error factors are considered to cause the quantitative discrepancy.

To check generation of appropriate waveforms, we perform a preliminary direct contact pulse-echo test with an Acryl plate as a test specimen. The Acrylic plate is 10mm thick, a little bit less than the focal distance of the probe inside the plate. A Panametrics Pulser-Receiver(5055PR) and a Philips Oscilloscope (PM3340) constitutes the test equipment, Fig. 4 a. For the use of these probes, the equipment must have the means of separating the transmitter from the amplifier with a minimum of cross coupling so that the receiver can start detecing echoes before the transmitter ends transmission. Figure 5 is ths impulse response of the transducer. The main echo is from the reflection at bottom of the test plate. The waveform is quite clear and has high enough signal-to-noise ratio. The delay line(matching layer) keeps the transmission pulse away from the sur-

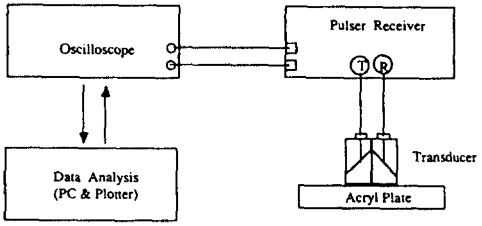


(a) experimental

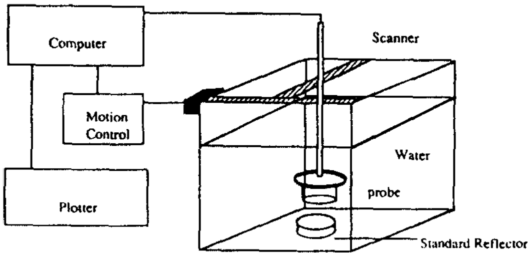


(b) theoretical

Fig 3. Frequency dependence of the probe impedance (transmitter part)



(a) manual test



(b) auto test (Ultra Pack II)

Fig 4. System set-up for ultrasonic probe characterization face so that it can no longer have an interfering effect on the flaw detection. In an ideal design, sound can only reach the receiver by way of the specimen. In practice, a residual cross coupling can not be completely avoided because some energy will find its way directly across the contact surface, called surface echoes[11] as described in Sec. 2. The practical quality of the dual type probe depends on the extent of this cross coupling surface echo. A good value is regarded in the range of more than 30 dB below the back echo, as evidenced in the Fig. 5.

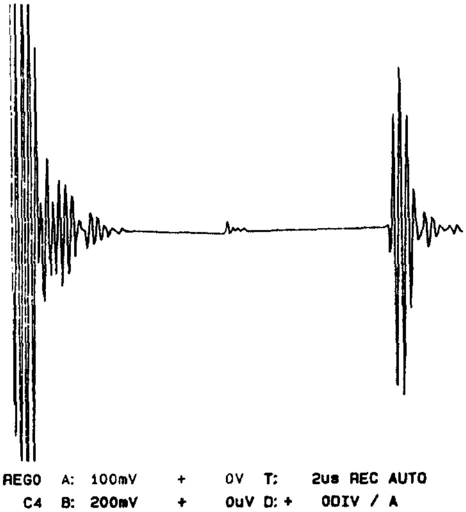


Fig 5. Waveforms from a prototype dual element transducer

For full characterization of the transducer, the probe is immersed in a standard water bath system. Performance of the transducer is checked in both time and frequency domains with the Ultra PAC II system of Physical Acoustics. The system consists of PC hardwares and an immersion tank with associated bridge and carriage assembly, Fig. 4-b. The transducer mounting has independent angular adjustment in two orthogonal planes. Figure 6 shows distance-amplitude characteristic (DAC) variation of the transducer in water. Focal distance is 27.1mm(1.07 inch in the figure) in water, and range of -3dB reduction is 24.6mm(0.97 inch). As evidenced in the figure, the transducer has excellent distance-amplitude variation properties, which is quite beneficial in detecting defects over a wide depth span. Now a standard carbon block reflector is placed at the focal point of the transducer, and a tone burst signal of 250 V is fed to the probe. Figure 7 is the representative experimental pulse echo response and Fig. 8 is the corresponding theoretical result obtained in Ref. 2. They show fairly good agreement with each other, which verifies the validity of the theorotical model. In the figure, center frequecy is 4.9 MHz, peak frequency is 3.9 MHz, operation bandwidth at-3dB range is 2.4 MHz (41%), bandwidth at-6dB range is 2.9 MHz (59%), peak-to-peak voltage is 1.3 V, number of cycles is 7, rise time is 0.13 μsec, and fall time is 0.72 μsec.

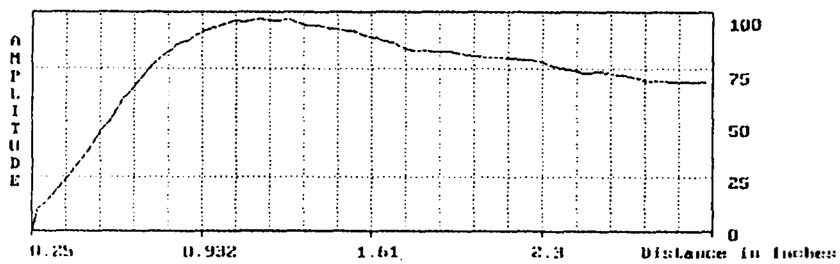
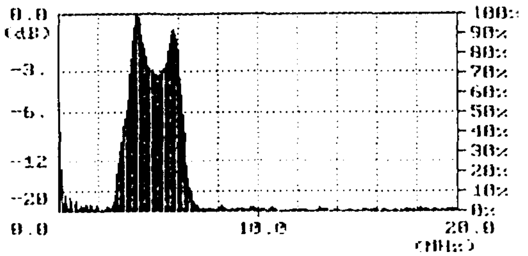
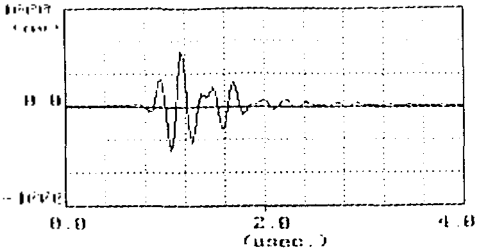


Fig 6. Distance-amplitude characteristic curve of the dual element transducer

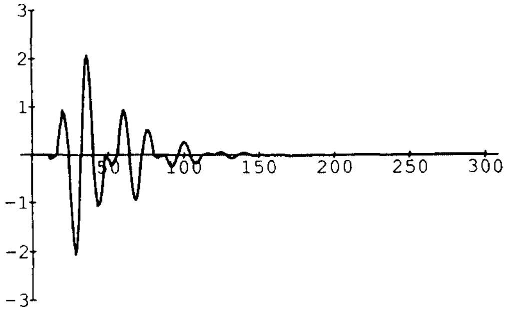


(b) frequency domain

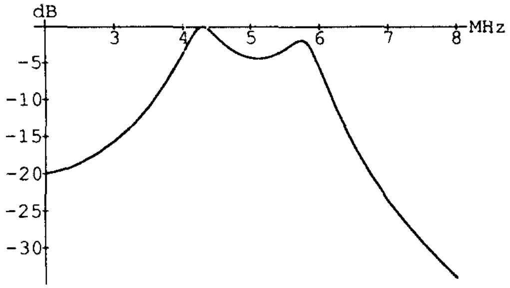


(a) time domain

Fig 7. Experimental characteristics of the dual element transducer



(a) time domain



(b) frequency domain

Fig 8. Theoretical characteristics of the dual element transducer calculated with the model in Ref. 2.

The transducer developed in this study is supposed to work as in-situ diagnostic tools. Hence, practical operation conditions are applied to the probe and its performance is analyzed with a standard stepped(N1) sample following the rule JIS G0901. Overall results are as summarized in Table 2. Most of commercially available probes go through the same N1 sample calibration process. Hence, results from the stepped sample test will be a good indication of how good is our transducer in comparison with commercially accepted criteria. The Table 2 lists major items of both the criteria and performance of the probe developed in the present work. From the comparison, our

Table 2. Test criteria and performance of the developed probe

Type of test	Items		Criteria	Performance
Manual	focal point		8±2 mm	8 mm
	DAC	3 mm	≥-8 dB	5 dB
		19 mm	≥ 6 dB	-3 dB
	N1 sensitivity		10±2 dB	10.5 dB
	S/N ratio		≥30 dB	47 dB
	effective beam width		≥20 mm	21 mm
Auto UST	Gain calibration		≥10 dB	16 dB
	Gate calibration		±14 x 1/32 μsec	15 x 1/32 μsec
	DAC calibration		30±3 dB	30 dB

transducer is concluded to function well enough to be implemented in practical applications.

Ⅳ. Conclusion

On the basis of the theoretical results in Ref. 2, we constructed a dual element ultrasonic angle beam transducer suited for NDT applications. Construction procedure included analysis of characteristics of each component of the probe, fabrication, and verification of its performance. Comparison of the experimental results with those of theoretical calculation showed good agreement. Overall performance of the transducer is concluded to be so good as to meet the criteria of commercially available transducers. The developed probe can be a useful tool to diagnose both in-depth and subsurface defects of various structures, overcoming the problems encountered with a single element transducer.

In real situations, however, nominally identical transducers may produce quite different responses in terms of frequency, relative efficiency, pulse length, or some other important parameters. This level of variability appears to have been inherent in the piezoelectric transducer from its earliest use[12]. In assessing the variability, many factors extraneous to the transducer itself can affect the measured performance. These factors include the character of the excitation, pulse, the bandwidth of the amplification sysem, the nature of the reflector, the acoustic properties of couplant or specimen, and the length of cable connecting the transducer to the driver and amplifier. None of these factors is negligible. Hence, future work should concern better quality control and standardization of probe performance.

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