Characteristics Evaluation for a PZT Transducer with a Cylindrical Rear Surface

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Abstract

The characteristics of a PZT transducer with a cylindrical rear surface were investigated theoretically and experimentally. The transducer was assumed as a set of finite rectangular ceramic elements for applying the staircase model to the theoretical analysis and the KLM equivalent circuit model was modified for analyzing its electric impedance and pulse-echo response. All results were compared with those of a conventional plane transducer which has a constant thickness of average value for the cylindrical arc. It was noted that the transducer with a cylindrical rear surface has several subsidiary resonant frequencies which are able to widen bandwidth.

Keywords: *PZT transducer, Cylindrical Rear Surface, Staircase Model, Electric Impedance, Pulse-Echo Response*

I. Introduction

In recent decades, industrial nondestructive evaluation or medical diagnosis technique has been remarkably developed, especially for providing high quality acoustic images. For all ultrasonic imaging systems, the axial and lateral spatial resolutions related to the characteristics of an employed transducer are usually crucial to determine a system performance. The axial spatial resolution which is one of the most important parameters for acoustic B-mode imaging depends on the frequency bandwidth of pulses radiated from an ultrasonic transducer. The short pulse with broad frequency bandwidth is necessary for high axial resolution.

The techniques using two or three acoustic matching layers and attenuative backing layers of high impedances have conventionally been employed to design broad bandwidth transducers [1-3]. Even though an acceptable bandwidth was achieved by the techniques, the fabricating process is still complicated and the backing layers cause poor sensitivity. As one of many techniques to accomplish a broader bandwidth with high sensitivity, the shape modification from a plane transducer was introduced by Volpkin et al. [4]. Barth et al. then proposed the staircase model to analyze the characteristics of a transducer with thickness variation [5]. Hanafy developed a PZT transducer with a cylindrical front surface and evaluated its performance by suggesting that the thickness variation in a transducer can widen bandwidth [6].

The objective of this study is to confirm the effects of thickness variation in a PZT transducer with a cylindrical rear surface on its performance. In an effort to do so the transducer with a cylindrical rear surface which is newly designed for this study was considered as a set of finite rectangular ceramic elements to apply the staircase model and the KLM equivalent circuit model [7] was modified appropriately. The electric impedances and pulse-echo

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responses were obtained by theoretical analysis using those models and by an experiments. The results were compared with those of a conventional plane transducer with similar size.

II. Structure and Modeling

Figure 1 shows the structure of the designed piezoelectric PZT ceramic. It has a plane radiating surface and a cylindrical rear surface. The rear surface of the ceramic was ground into the cylindrical curvature of R=67.7mm. The electrode was subsequently sputtered and evaporated along with chrome, copper and nickel in order to form approximately 2㎛ in total thickness. As shown in the figure, the thickness of the ceramic varies according to its arc from the minimal 0.46㎜ at the center to the maximal 0.64㎜ at the edges, respectively.

Applying the staircase model given by Barth et al. [5] to the case of our transducer, the ceramic was assumed a set of finite rectangular elements which have different thickness as shown in Fig. 2. In that case, the thickness of an element at the i-th section is given as following:

$$T_i = T_{\min} + R\left(1 - \sqrt{1-\left(\frac{X_i}{R}\right)^2}\right) \approx T_{\min} + \frac{X_i^2}{2R} \quad (1)$$

where

$X_i = (i-1)\frac{L}{N}$; $i = 1, 2, \cdots, N-1, N$

R : curvature of a cylindrical surface.

L : half length of a cylindrical rear surface ceramic

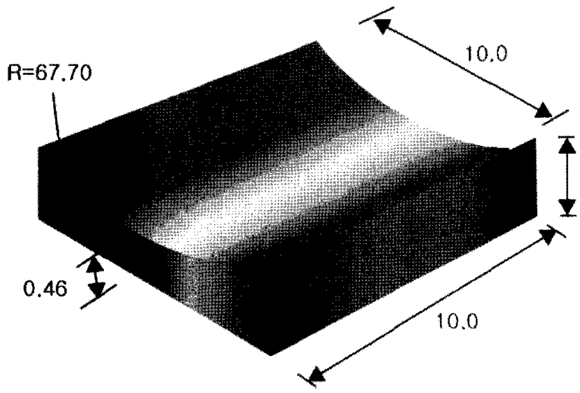


Fig. 1. Dimension of the piezoelectric PZT ceramic with a cylindrical rear surface.

From equation (1), the thickness of each section is calculated using the minimum thickness of the ceramic and the increment according to location and curvature.

III. Electroacoustic Characteristics Analysis

3.1. Electric Impedances of the PZT Ceramics

The electric free impedance Z_F of a piezoelectric transducer can be represented by clamped and motional impedances. In KLM model, the equivalent circuit of an end-electroded bar transducer, like an element in the staircase model shown in Fig. 2, involves a clamped capacitance and a serial electrical network of frequency

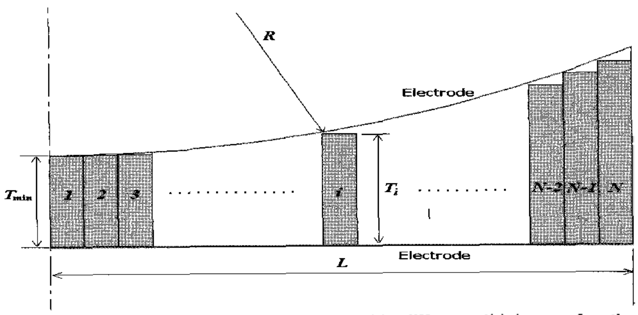


Fig. 2. A set of ceramic elements with different thickness for the staircase model.

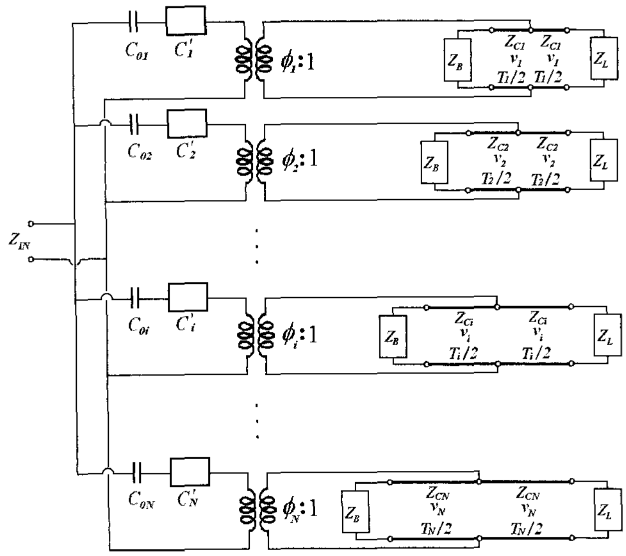


Fig. 3. A modified KLM equivalent circuit model and its parameters.

T_i : thickness of i-th element,

v : longitudinal velocity of PZT ceramic,

Z_{ci} : acoustic impedance of PZT ceramic,

Z_B : acoustic impedance of backing,

Z_L : acoustic impedance of medium,

ϕ_i : electro-mechanical turing ratio of i-th element,

C_{0i} : clamped capacitance of i-th element,

C_i': motional capacitance of i-th element.

dependent components connected to the centre of an acoustic transmission line. Using the staircase and KLM models, the effect of the cylindrical rear surface on electric input impedance and subsequent pulse−echo response can be calculated by assuming the ceramic as a parallel connection of the individual rectangular elements. Considering the parallel connection, the total electric input impedance of the ceramic, Z_{IN}, can be obtained by following equation:

$$\frac{1}{Z_{IN}} = \frac{1}{Z_{F1}} + \frac{1}{Z_{F2}} + \cdots + \frac{1}{Z_{FN}} = \sum_{i=1}^{N} \frac{1}{Z_{Fi}} \tag{2}$$

To calculate the free impedance of i−th element Z_{Fi} and consequently Z_{IN}, the KLM model was modified with parallel connection as shown in Fig. 3. The individual element was represented as a branch in the modified KLM model. The element thickness T_i varies according to number of division N and i. The acoustic impedance of PZT ceramic Z_{ci} is given by $Z_{ci} = Z_{0i}A$ using the specific acoustic impedance $Z_{0i} = \rho v$ (ρ: density, v: sound speed) and the radiating area A. The clamped capacitance of the i−th element in all cases is given by the equation (3)

$$C_{0i} = \frac{\epsilon^s A}{T_i} \tag{3}$$

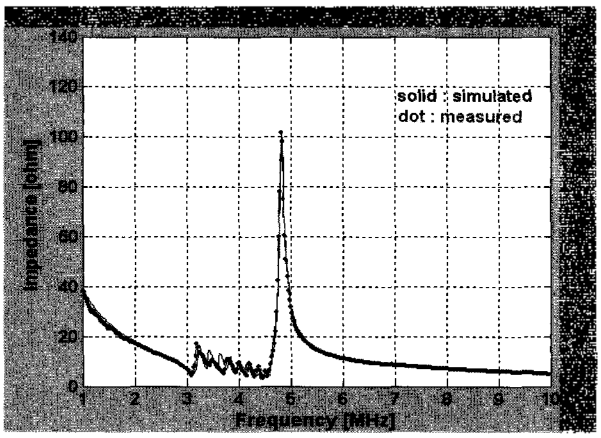
where the ϵ^s is the permittivity of PZT at constant strain.

The electro−mechanical turning ratio of the i−th element ϕ_i and the motional capacitance C_i' are given by following equations (4) and (5).

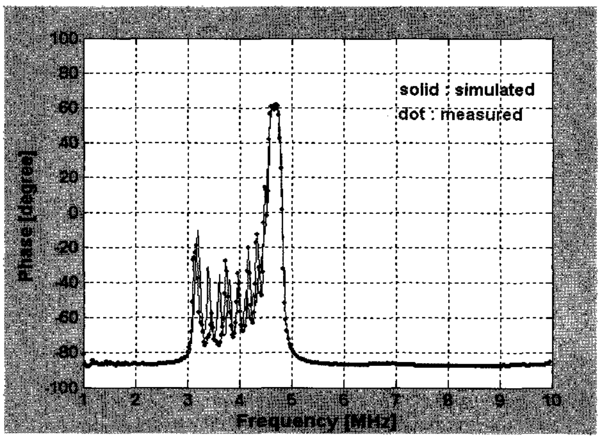
$$\phi_i = k_{ti}\sqrt{\frac{\pi}{\omega_{0i} C_{0i} Z_{ci}}}\,\sin\left(\frac{\omega}{2\omega_{0i}}\right) \Big/ \left(\frac{\omega}{2\omega_{0i}}\right) \tag{4}$$

$$C_i' = \frac{-C_{0i}}{k_{ti}^2 \sin\left(\frac{\omega}{2\omega_{0i}}\right) \Big/ \left(\frac{\omega}{2\omega_{0i}}\right)} \tag{5}$$

where k_{ti} and ω_{0i} are the electro−mechanical coupling

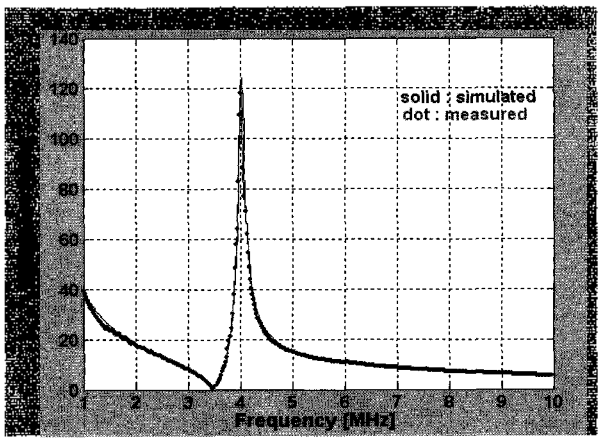


(a) magnitude



(b) phase

Fig. 4. Impedance of the ceramic with a cylindrical rear surface.



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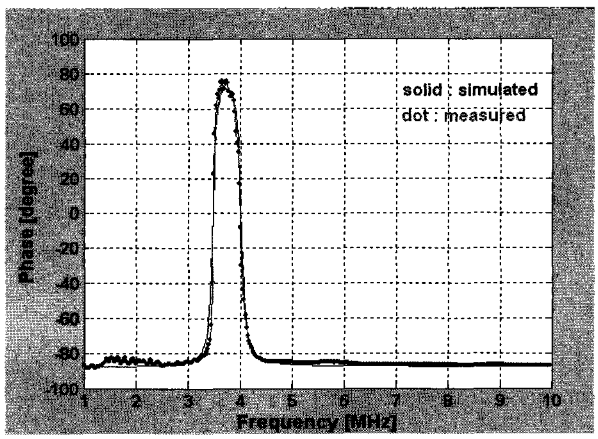


(b) phase

Fig. 5. Impedance of the ceramic with constant thickness.

Table 1. Physical properties for the PZT ceramic.

Impedance [$Mrayl$]	35
Density [Kg/m^3]	7800
Electromechanical coupling coefficient	0.55
relative dielectric permittivity	3800

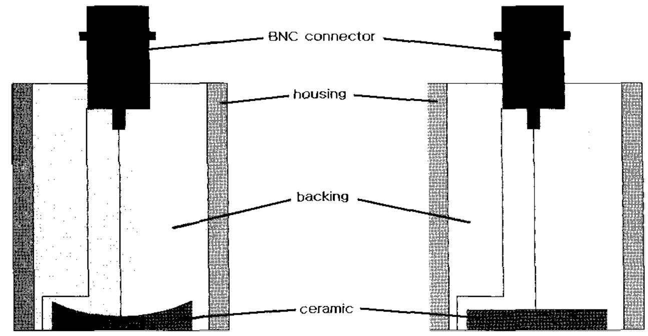


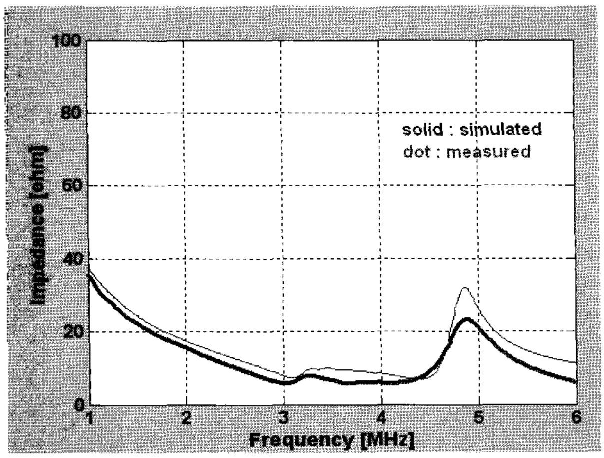
Fig. 6. The probes made of the PZT ceramics.

coefficient and the resonant angular frequency of the i-th element, respectively.

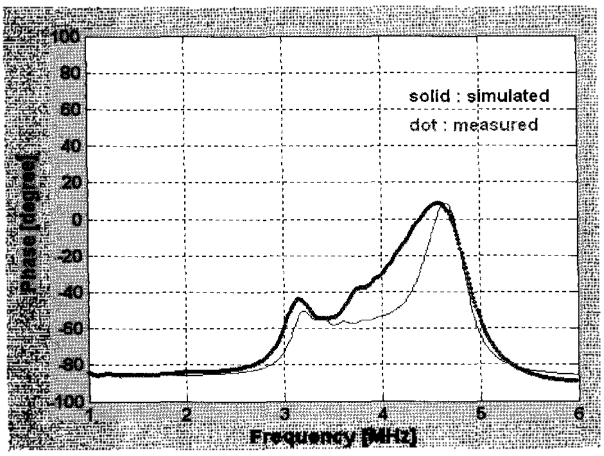
In calculation, the resonant frequency ω_{0i} was properly estimated by considering the thickness T_i and the boundary condition for the acoustic impedance difference between an element and the backing and medium in advance. The frequency dependent input impedance for an element is obtained according to the variation of ω. The computer program for calculating Z_{IN} is easily obtained from the well known conventional KLM model analysis program for a single element transducer.

Figure 4 shows the calculated and measured impedances of the PZT ceramic with a cylindrical rear surface. The impedance / gain-phase analyzer, HP4194A (Agilent Technologies, USA), was used to measure impedances. The physical properties of the ceramic used in calculation were given in Table 1. It is noted that the transducer with a cylindrical rear surface has many subsidiary resonant and anti-resonant frequencies in the calculation as well as in measurement. The calculated results of magnitude and phase are in good agreement with the measured ones when the number of segment N is greater than or equal to 16.

For comparison and verification, a plane transducer was

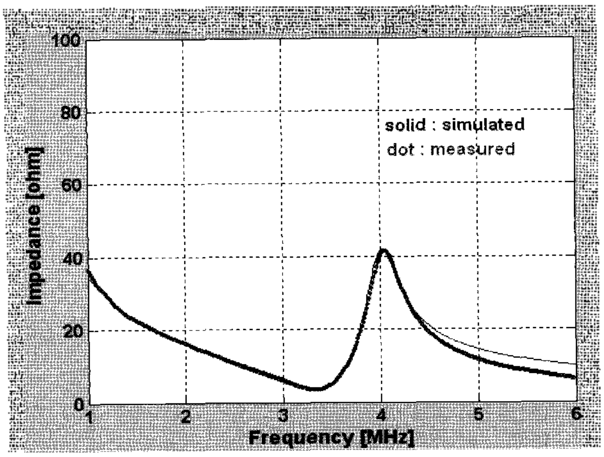


(a) magnitude

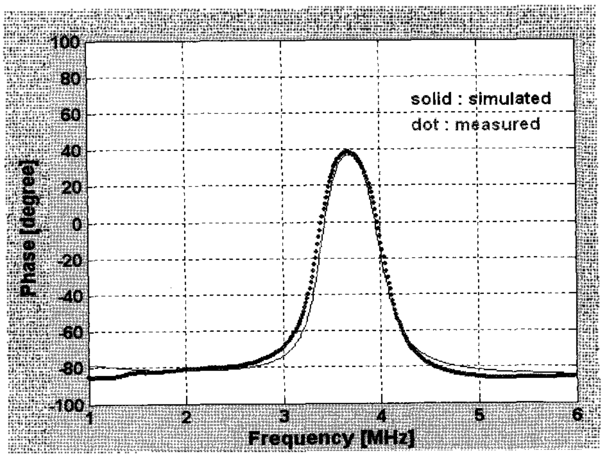


(b) phase

Fig. 7. Impedance of the probe made of the ceramic with a cylindrical rear surface.



(a) magnitude



(b) phase

Fig. 8. Impedance of the probe made of the ceramic with constant thickness.

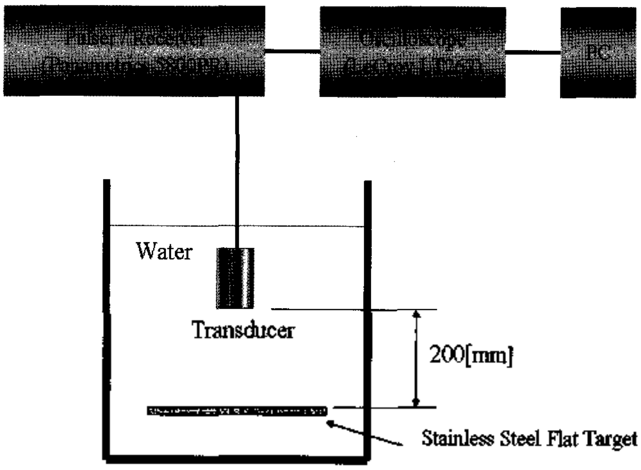


Fig. 9. Block diagram for pulse echo measurement system.

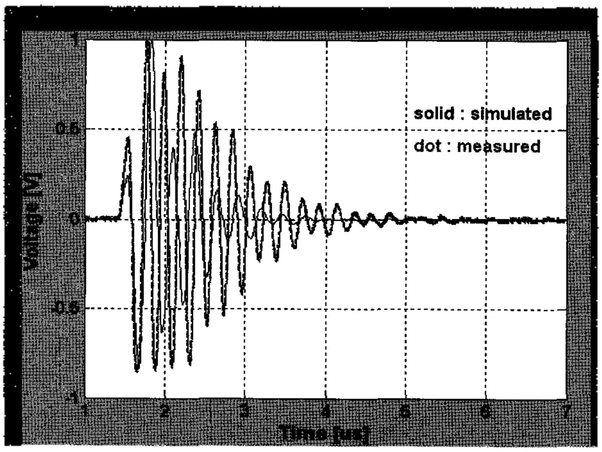
made with a constant thickness of approximately $(T_{max}+T_{min})/2$. Figure 5 shows the calculated and measured impedances. The results were similar as the typical pattern of a conventional plane transducer with $3.4MHz$ center frequency. It was revealed that the transducer with a cylindrical rear surface has a peculiar impedance pattern which is quite different from the one of general plane transducers. The transducer operates with the most effective at about 4.5MHz, which is the resonant frequency for minimum thickness of the transducer. The reason is not clear, but we guess, it is because the poling voltage was adjusted to the minimum thickness and the thickness variation was very small near the thickness.

The resonant frequency, f_{si}, and anti-resonant frequency, f_{ai}, for i-th element under the boundary condition of free-free on both sides can be given by following equations [8]

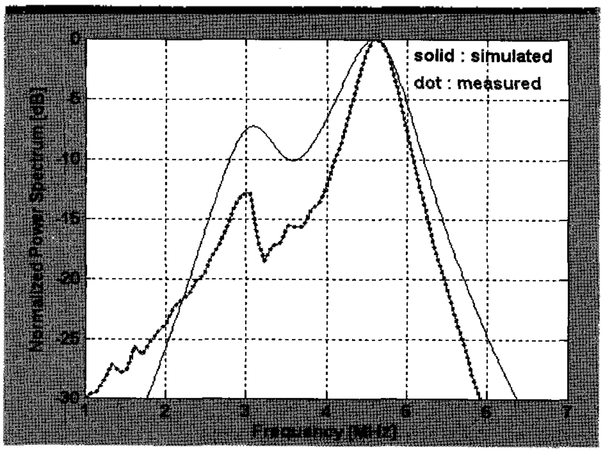
$$f_{ai} = v/\,2T_i, \tag{6}$$

$$f_{si} = \frac{v\sqrt{1-8k_t^2/\pi^2}}{2T_i} \tag{7}$$

From equations (6) and (7), it is easy to know that the resonant frequencies depend on the thickness of each element, and that the resonant frequency decreases if the

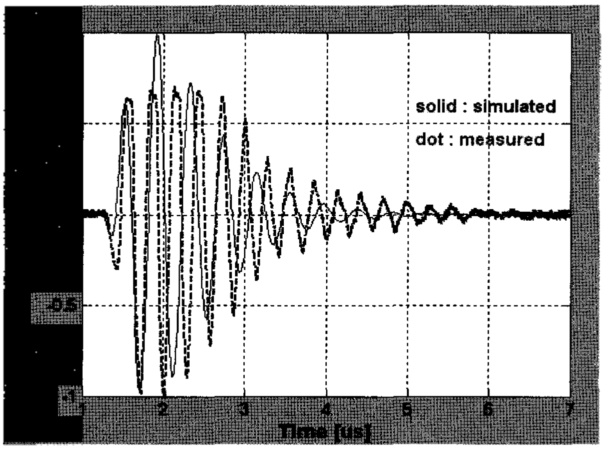


(a) waveform

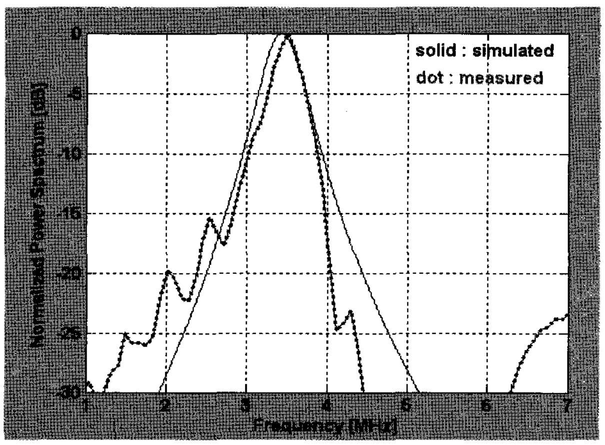


(b) power spectrum

Fig. 10. Pulse-echo response of the probe made of the ceramic with a cylindrical rear surface.



(a) waveform



(b) power spectrum

Fig. 11. Pulse-echo response of the probe made of the ceramic with constant thickness.

distance of a segment from the center of the transducer increases. It makes multi-resonant and multi-anti-resonant frequencies for combined whole segments.

3.2. Electric Impedances and Pulse-Echo Responses of the Probes

In order to investigate the acoustic wave radiating performance of transducers, those two PZT ceramics were manufactured into probes by placing them within electrically shielded plastic housings as shown in Fig. 6. Each probe has very simple structure with only one backing layer. The backing layer was made of Epoxy and #220 Al2O3 powder to achieve the acoustic impedance of 3 Mrayls.

3.2-1. Electric Impedances

The electric input impedances of the probes are shown in Fig. 7 and 8. Even if the fluctuations in input impedance at resonant and anti-resonant frequencies were blunted by mass loading effect of the backing, it is possible to know that those frequencies are widely distributed over frequency range from 3MHz to 5MHz for the probe with a cylindrical rear surface. The distribution implies broad bandwidth characteristics for the probe. On the other hand, the probe with constant thickness shows the typical impedance pattern of a conventional plane transducer of which center frequency is about 3.4MHz.

3.2-2. Pulse-Echo Response

Figure 9 shows the measurement system for pulse-echo responses of the probes. The 5800PR pulser/receiver (Panametrics, USA) and LT262 digital oscilloscope (LeCroy, Switzerland) were used in this system. The data acquisited by the oscilloscope were transferred to a personal computer using GPIB for FFT analysis. A stainless steel flat target was set to parallel with the radiating surface of the transducer at 200mm intervals to avoid annoying near-field effects. Because the transducers were directly contacted with water without any acoustic matching layers, high fractional bandwidth was not expected. It is shown that the waveform obtained by calculation and experiment show long ringings and that the theoretical and experimental results are in good agreement as shown in Fig. 10 and Fig. 11. The difference between calculation and measurement for the probe with a cylindrical rear surface was considered as machining error of the cylindrical surface and electrical mismatch between the transducer and the pulser/receiver, which could not be considered in measurement..

Table 2. Pulse-echo response characteristics of the probes.

Parameters			Constant Thickness	Cylindrical Rear Surface
Center Frequency [MHz]		cal.	3.4	4.6
		mea.	3.5	4.8
Fractional Bandwidth [%]	-6dB	cal.	19.9	21.3
		mea.	15.4	13.8
	-20dB	cal.	19.3	85.4
		mea.	15.4	76.0

From Table 2, it is noted that the center frequency of the cylindrical rear surface probe is higher than the constant thickness probe. Even though the fractional bandwidths for −6dB were similar in both probes, those for −20dB were quite different. The bandwidth of the probe with a cylindrical rear surface was broader than the constant thickness probe by more than 4 times.

IV. Conclusion

The electroacoustic characteristics for the PZT ceramic transducer with a cylindrical rear surface were investigated theoretically and experimentally to confirm and understand the effect of thickness variation on its performance. The staircase model was applied and the KLM equivalent circuit model was properly modified for analyzing the electric input impedance of the transducer. The results were compared with those of a conventional plane transducer with similar size. From the impedance results, it was noted that the transducer with a cylindrical rear surface has several distributed subsidiary resonant and anti-resonant frequencies. Comparison of pulse-echo response of the two probes revealed that the cylindrical rear surface is able to widen frequency bandwidth.

References

1. C. S. Desilets, J.D. Fraser and G. S. Kino, "The Design of Efficient Broad-band Piezoelectric Transducers," IEEE Trans. Sonics Ultrason.

SU-25 (3), 115-125, 1978.
2. C. H. Chou, J. E. Bowers, A. R. Selfridge, B. T. Khuri-Yakub and G. S. Kino, "The Design of Broadband and Efficient Acoustic Wave Transducers," 1980 IEEE Trans. Ultrason. Symp. Proc. 2, 984-988, 1980.
3. J. H. Goll, "The Design of Broad-Band Fluid-Loaded Ultrasonic Transducers," IEEE Trans. Sonics Ultrason. SU-26 (6), 386-393, 1979.
4. A. V. Vopilkin, "Wide-band Ultrasonic Transducer and its uses," U.S. Patent 3, 968,680, 1976.
5. P.G. Barthe and P. J. Benkeser, "A Staircase Model of Tapered-thickness Piezo-electric Ceramics," J. Acoust. Soc. Amer. 89, 1434-1442, 1991.
6. A. M. Hanafy, "Broadband Phased Array Transducer Design with Frequency-Controlled Two-Dimensional Capability," SPIE 3341, 64-82, 1998.
7. R. Krimholtz, D. A. Leedom and G. L. Mattheat, "New Equivalent Circuits for Elementary Piezoelectric Transducers," Electron. Lett. 6, 398-399, 1970.
8. V. M. Ristic, *Principle of Acoustic devices* (John Wiley & Sons, New York, 1983), Chap. 5, pp.117-159.

[Profile]

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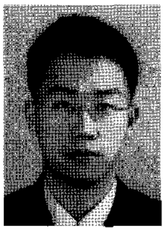

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