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Minimization of thickness of ultrasonic transducer by using piezoelectric backing layer

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1. Introduction

Ultrasonic transducers have been used in various fields, such as medical diagnosis and Nondestructive Test. Generally, the transducers have suitable matching layer and absorptive backing layer for broadband characteristic[1)]. Even though the backing layer should be thick enough to have sufficient absorption, the transducer needs to have thin thickness when it has to be inserted in a narrow place such as the transesophageal echocardiogram. There are many studies on the reduction of backing layer thickness by means of metal composite materials[2)]. In this study, we propose a method to minimize the thickness of transducer by using a piezoelectric backing layer. The backing layer converts the acoustic energy generated from the driving piezoelectric vibrator into electrical energy, and the impedance connected to the electrical terminals of the backing layer can make an absorption effectively by changing the phase of or consuming the electrical energy. Using the piezoelectric backing layer, the transducer with broadband charateristic could be designed in relatively thin thickness.

2. Transducer configuration and equivalent circuit

Figure 1 shows the structure of the broadband ultrasonic transducer with a piezoelectric backing layer. The proposed transducer consists of the driving piezoelectric vibrator, the piezoelectric backing layer that has electrical impedance Z_e, the matching layer, and the composite backing layer. The equivalent circuit of the proposed transducer is shown in **Fig. 2**. In this figure, Z_{b0} and Z_{md} are the characteristic impedance of each acoustic medium, and the impedances of each layer are as follows.

$$Z_1 = jZ_{p1}\tan\frac{\gamma_{p1}l_{p1}}{2}\ ,\quad Z_2 = -jZ_{p1}\csc\gamma_{p1}l_{p1}\ ,\quad \phi_1 = \frac{eS}{l_{p1}}\ ,$$

$$Z_3 = jZ_{p2}\tan\frac{\gamma_{p2}l_{p2}}{2}\ ,\quad Z_4 = -jZ_{p2}\csc\gamma_{p2}l_{p2}\ ,\quad \phi_2 = \frac{eS}{l_{p2}}\ ,$$

$$Z_{b1} = jZ_b\tan\frac{\gamma_b l_b}{2}\ ,\quad Z_{b2} = -jZ_b\csc\gamma_b l_b\ ,\quad C_{10} = \frac{\varepsilon S}{l_{p1}}\ ,$$

$$Z_{m1} = jZ_m\tan\frac{\gamma_m l_m}{2}\ ,\quad Z_{m2} = -jZ_m\csc\gamma_m l_m\ ,\quad C_{20} = \frac{\varepsilon S}{l_{p2}}\ ,$$

$$Z_{p1} = \rho_{p1}c_{p1}S\ ,\quad \gamma_{p1} = \frac{\omega}{c_{p1}}\ ,\quad Z_{p2} = \rho_{p2}c_{p2}S\ ,\quad \gamma_{p2} = \frac{\omega}{c_{p2}}\ ,$$

$$Z_b = \rho_b c_b S\ ,\quad \gamma_b = \frac{\omega}{c_b}\ ,\quad Z_m = \rho_m c_m S\ ,\quad \gamma_m = \frac{\omega}{c_m}\ .$$

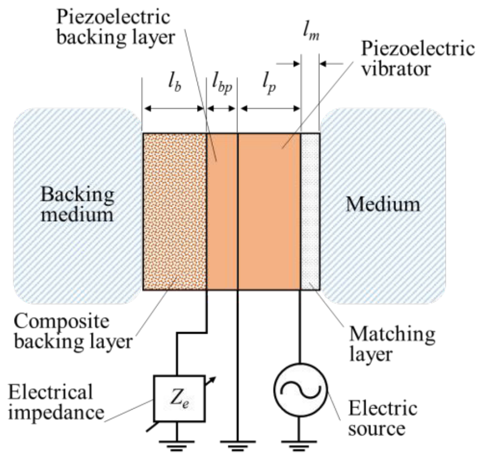

Fig. 1 Structure of proposed transducer.

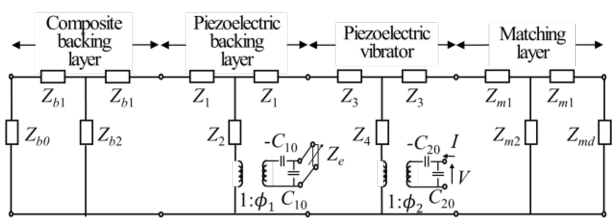

Fig. 2 Equivalent circuit of the transducer.

Here, γ, l, ρ, and c denote the wave number, the thickness, the density, and the sound velocity, respectively, and the subscripts p_1, p_2, b, and m refer to the piezoelectric backing layer, the driving piezoelectric vibrator, the backing layer, and the matching layer, respectively. The permittivity, the piezoelectric stress constant, the cross-sectional area, and the angular frequency are denoted by ε, e, S, and ω, respectively. The transfer function of the proposed transducer can be obtained by the analysis of the equivalent circuit of Fig. 2[3)].

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3. Determination of electrical impedance

In this study, the driving piezoelectric vibrator and the piezoelectric backing layer are the thickness of 1.0 mm and 0.5 mm, respectively. The matching layer of the thickness 0.3 mm and the impedance 4.5 Mralys is placed in front surface of the driving piezoelectric vibrator so that the sound waves generated from the vibrator are easily transmitted to the medium. The composite backing layer with a thickness of 1.0 mm is placed on the rear surface of the piezoelectric backing layer to provide more effective absorption and the waterproof effect. The total thickness of the designed transducer is within 2.8 mm and it corresponds to about 2.8-fold thickness of the driving piezoelectric vibrator. The transfer function for the designed transducer was calculated under the condition that the inductor as electrical impedance is connected to the piezoelectric backing layer, as shown in Fig. 1. **Figure 3** shows the change of the transfer function with the inductance. The transfer function shows the maximum bandwidth when the inductance is about 0.21 μH.

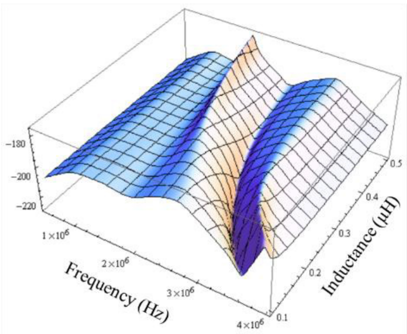

Fig. 3 Transfer function change with electrical inductance.

Figure 4 shows the change of the calculation result of the transfer function with different resistance values when an inductor of 0.21 μH and a resistor are connected to the electrical terminals. In this case, the maximum bandwidth appears in the resistance of 3 Ω.

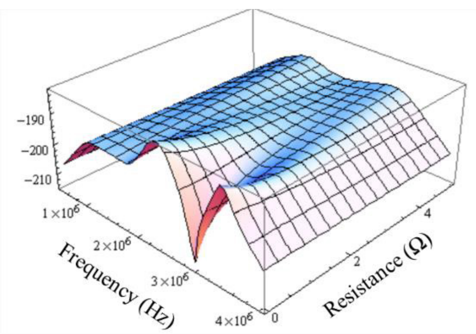

Fig. 4 Transfer function change with resistance when inductance is 0.21 μH.

4. Transfer function

The transfer functions of the transducer for different states of the backing layer are shown in **Fig. 5**. The -6 dB bandwidth of the transducer is 114.80% when the resistance and the inductance are 3 Ω and 0.21 μH, respectively (solid line). The bandwidth decreases to 28.57% when the electrical terminals are open circuit (dash line). For comparison, the bandwidth is also calculated when an alumina-epoxy composite backing layer is used instead of the piezoelectric backing layer (dot line). The result shows that the -6 dB bandwidth is 64.91%.

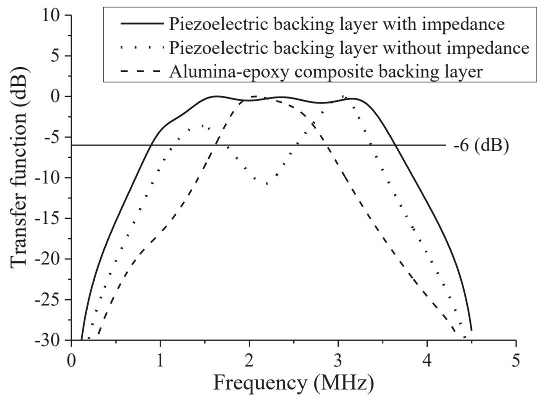

Fig. 5 Bandwidth of transducers for different backing layer states.

5. Summary

To minimize the thickness of transducer, a piezoelectric backing layer was adopted which an electrical impedance was connected. When the electrical impedance consists of the inductance of 0.21 μH and the resistance of 3 Ω, the maximum bandwidth of the ultrasonic transducer was 114.80%. When the thickness of the piezoelectric backing layer is 0.5-fold of the driving piezoelectric vibrator, the maximum bandwidth was calculated. It was confirmed that broadband ultrasonic transducer with thin thickness can be designed by using the proposed piezoelectric backing layer.

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