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Bandwidth control of ultrasonic transducer by shaping piezoelectric ceramic vibrator

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1. Introduction

To control the characteristics of a piezoelectric ultrasonic transducer, backing and maching layer has been suitably designed for the purpose of the transducer. Recently, as one of the frequency bandwidth control method, a layered piezoelectric vibrator has been adopted[1-3]. These methods control the propagating characteristics of the sound wave radiated from the piezoelectric vibrator without controlling the characteristics of the vibrator itself. In this study, it is aimed to fabricate ultrasonic transducer with desired frequency bandwidth characteristics by shaping of piezoelectric ceramic vibrator. The resonant characteristics for the shape of the piezoelectric ceramic vibtator with nonuniform thickness are theoretically examined, and the characteristics of fabricated ultrasonic transducer are experimentally confirmed. To reduce trial and error in manufacturing the proposed transducer, a simulation model is designed based on a finite element method.

2. Theory

For one-dimensional analysis of the piezoelectric vibrator with nonuniform thickness, as shown in **Fig. 1**, it is assumed that each cylindrical piezoelectric vibrating element is connected in parallel mechanically and electrically. The element has the height $l(x)$ and the thickness dx which is the difference of inner radius and outer radius. Here, the dx is infinitesimal value and $l(x)$ is a function of the height depending on the desired frequency bandwidth.

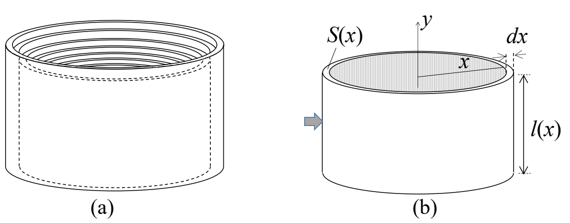

Fig. 1 Theoretical analysis model of piezoelectric vibrator with nonuniform thickness (a) and a cylindrical piezoelectric vibrating element (b).

The input admittance of each piezoelectric element, which is polarized in the y direction, is obtained

$$dY(x) = j\omega \frac{2\pi x \varepsilon^S}{l(x)} dx + \frac{2\pi x}{Z_s(x)\dfrac{l(x)^2}{e^2} - \dfrac{l(x)}{j\omega\varepsilon^S}} dx, \qquad (1)$$

$$Z_s(x) = \frac{(Z_b + Z_t)(Z_f + Z_t)}{Z_f + Z_b + 2Z_t} - Z_c, \quad Z_f = \rho_f c_f, \; \gamma(x) = \frac{\omega}{c} l(x),$$

$$Z_c = jZ_p \csc\gamma(x), \; Z_t = jZ_p \tan\frac{\gamma(x)}{2}, \; Z_b = \rho_b c_b, \; Z_p = \rho c.$$

The ρ, c are the density and the sound speed of piezoelectric vibrator, respectively. The subscripts f and b refer to front and back of the acoustic medium. The ε^S and e are the permittivity and the piezoelectric constant of the vibrator, respectively. The $l(x)$ is the thickness of vibrator. For example, in the case of a piezoelectric vibrator with concave radiation surface, the height function $l(x)$ from the geometry of **Fig. 2** is given by

$$l(x) = l_0 + R - \sqrt{R^2 - x^2}. \qquad (2)$$

Substituting Eq. (2) into Eq. (1), the total admittance of concave surface vibrator with nonuniform thickness can be expressed as

$$Y = \int_0^a dY(x) dx. \qquad (3)$$

Here a is the radius of the vibrator.

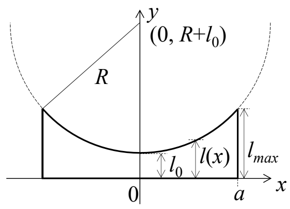

Fig. 2 Geometry of the height for the piezoelectric vibrator with concave surface.

3. Design and fabrication

As an example, a piezoelectric transducer with concave radiation surface was fabricated with CNC milling machine to examine the change of frequency bandwidth by the shape of the transducer. The diameter, the minimum thickness, and the radius of curvature of the concave piezoelectric vibrator are 10.5 mm, 0.985 mm and 7.846 mm, respectively. A PZT-5H plate with 3 mm thickness was processed for 12 hours to make the concave vibrator. Photograph of the fabricated concave vibrator was shown in **Fig. 3(a)**. The processing time was set to be long enough to avoid depolarization loss due to the stress from cutting process. For comparison, a flat type piezoelectric vibrator with the same diameter and a constant thickness of 3 mm was also fabricated. The backing layers of the transducers with the processed

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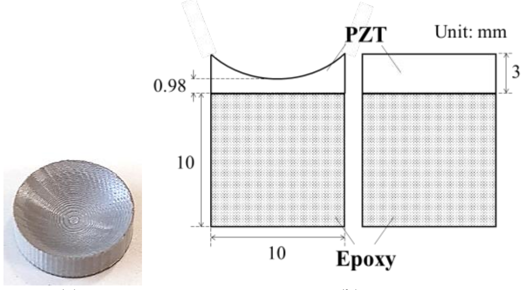
piezoelectric vibrators are made of epoxy resin, as shown in **Fig. 3(b)**.

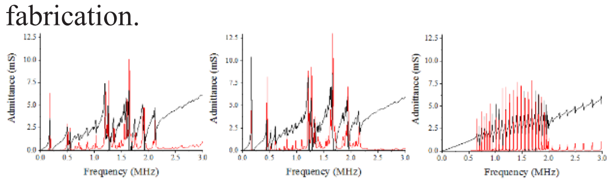


(a) (b)

Fig. 3 Processed PZT-5H ceramic (a) and concave and flat type transducers (b).

4. Results

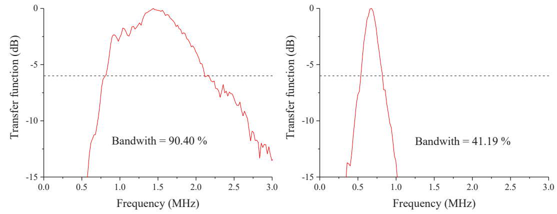
Figure 4 shows the input admittance characteristics of fabricated concave type vibrator. Measurement result, as shown in Fig. 4(a), shows the resonant characteristic in a very wide frequency range owing to the nonuniform thickness of the piezoelectric vibrator. Figure 4(b), which is the simulation result based on a finite element method, is very similar to that of Fig. 4(a). In the result for one dimensional analysis, as shown in Fig. 4(c), although the lateral mode cannot be considered, the thickness mode, which appears in wide frequency range, was in good agreement with the measurement one. From this, the suggested theoretical method could be used in determining the shape of the piezoelectric vibrator having the purposed resonant characteristics. Meanwhile, the simulation method based on a finite element method could be used as the way to reduce trial and error in designing ultrasonic transducers before fabrication.



(a) (b) (c)

Fig. 4 Admittance of concave surface vibrator with air backing layer. (a) Measurement, (b) simulation, and (c) one dimensional analysis.

Figure 5 shows the simulation result of the impulse response to analyze the frequency bandwidth of the concave type ultrasonic transducer. In simulation, the single pulse, which has the pulse width of 0.29 μs and the amplitude of 50 V was applied. The transfer function of the transducer is shown in Fig. 5(a). In this result, the -6 dB bandwidth of the transducer is more than 90%, whereas the result of flat type transducer with 0.66 μs pulse width shows comparatively narrow bandwidth of less than 42%, as shown in Fig. 5(b). The acoustic field distributions of two type ultrasonic transducers were simulated, as shown in **Fig. 6**. The input signals were continuous wave of 1.68 MHz for the concave type transducer and 0.756 MHz for the flat type one respectively.



(a) (b)

Fig. 5 Frequency bandwidth of two type ultrasonic transducers. (a) Concave type transducer and (b) flat type transducer.

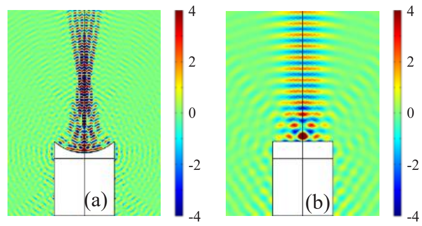


Fig. 6 Acoustic fields of two type ultrasonic transducers. (a) Concave type transducer and (b) flat type transducer.

In the concave type, it could be predicted that the ultrasonic vibration mainly accur at the position with 1.18 mm thickness of the vibrator because the sound speed of the piezoelectric ceramic is 3957 m/s and the driving frequency is 1.68 MHz. However, the vibration accured on the relatively wide area of the surface and the acoustic field was then converged by the concaved radiation surface in the result of Fig. 6(a). Meanwhile, in Fig. 6(b), the acoustic field shows the typical patten by the planner surface of the ultrasonic transducer.

5. Summary

A piezoelectric ceramic vibrator was processed in its shape to control the acoustic characteristics. An ultrasonic transducer with desired frequency characteristics was designed and fabricated by using the vibrator. To estimate the resonant characteristics of the transducer with the shape of the vibrator, a theoretical method was derived. As the simulation results for the concave type ultrasonic transducer with nonuniform thickness, the frequency bandwidth was over than 90%, and the acoustic field from the transducer was focused.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(2018R1D1A1B07047402).

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