Improvement of Low-Frequency Characteristics of Piezoelectric Speakers Based on Acoustic Diaphragms

Hye Jin Kim, Woo Seok Yang, and Kwangsoo No

***Abstract*—The vibrational characteristics of 3 types of the acoustic diaphragms are investigated to enhance the output acoustic performance of the piezoelectric ceramic speaker in a low-frequency range. In other to achieve both a higher output sound pressure level and wider frequency range of the piezoelectric speaker, we have proposed a rubber/resin bi-layer acoustic diaphragm. The theoretical square-root dependence of the fundamental resonant frequency on the thickness and Young's modulus of the acoustic diaphragm was verified by finite-element analysis simulation and laser scanning vibrometer measurement. The simulated resonant frequencies for each diaphragm correspond well to the measured results. From the simulated and measured resonant frequency results, it is found that the fundamental resonant frequency of the piezoelectric ceramic speaker can be designed by adjusting the thickness ratio of the rubber/resin bi-layer acoustic diaphragm. Compared with a commercial piezoelectric speaker, the fabricated piezoelectric ceramic speaker with the rubber/resin bi-layer diaphragm has at least 10 dB higher sound pressures in the low-frequency range of less than 1 kHz.**

I. Introduction

Recently, mobile information technology products have required smaller, slimmer, lighter, and more power-efficient components with the advent of smartphones and tablet PCs. To meet these demands, several investigations into alternatives to traditional acoustic components have been presented [1]–[5]. Especially, piezoelectric acoustic actuators or piezoelectric ceramic speakers have received much attention as the most promising devices to overcome the thickness limitation of the traditional dynamic speakers [6]–[9].

Schematic views illustrating differences between the traditional dynamic and piezoelectric ceramic speakers are shown in Fig. 1. Traditional dynamic (so-called voice-coil) speakers use a lightweight diaphragm connected to a rigid basket via a flexible suspension that constrains the voice coil to move axially through a cylindrical magnet gap. When an electric signal is applied to the voice coil, vertical force is generated in accordance with Fleming's left hand rule and the diaphragm is forced to vibrate. The vibrations of the diaphragm are transferred to the surrounding air where they reproduce an audible sound wave. Because the output sounds of the dynamic speakers are proportional to the vertical force created by the magnet field, the permanent magnet used must be more than 3 mm thick. In contrast, piezoelectric ceramic speakers consist of an acoustic diaphragm fixed to a rigid frame and a piezoelectric ceramic bonded on the diaphragm. When an electric signal is applied to the piezoelectric ceramic sheet, the ceramic membrane generates a mechanical strain by the inverse piezoelectric effect. Because the acoustic diaphragm is bonded to the piezoelectric ceramic sheet, the diaphragm vibrates with the mechanical deformation of the piezoelectric ceramic sheet, creating a sound wave. In contrast to traditional voice-coil speakers, the piezoelectric ceramic speakers can be less than 1 mm thick because they do not need a thick permanent magnet. In addition, piezoelectric ceramic speakers are more power-efficient and lighter than the traditional dynamic speakers.

Despite these many advantages, general piezoelectric ceramic speakers have suffered from a limitation of performance in the low-frequency range. In other words, because fundamental resonant frequencies of piezoelectric ceramic speakers are higher than those of traditional voice-coil speakers, it is hard to implement piezoelectric speakers with high output sound pressure performance even in a low-frequency range of less than 1 kHz. So far, there have been several research efforts to improve the acoustic performance of the piezoelectric ceramic speakers in a low-frequency range [10], [11]. Ohga *et al.* proposed a novel tuck-shaped PVDF piezoelectric diaphragm to enhance the low-frequency performance of the piezoelectric speakers [10]. Chiu *et al.* introduced a signal processing method that combines two techniques—psychoacoustic bass extension and dynamic range compression—to make the low-frequency sound richer in piezoelectric speakers [11]. However, most of these approaches use piezoelectric loudspeakers with large piezoelectric acoustic diaphragms which are not suitable alternatives for traditional voice-coil dynamic speakers being used in portable devices.

To improve the output sound performance of piezoelectric ceramic speakers in the low-frequency range, we focus our attention on smaller acoustic diaphragms which can influence the resonant frequencies of the piezoelectric ceramic speakers by their thickness or material properties. Generally, an acoustic diaphragm made of a material having low stiffness makes it possible to achieve a low fundamental resonant frequency (f_0). Hence, the acoustic diaphragms should be designed to be more flexible

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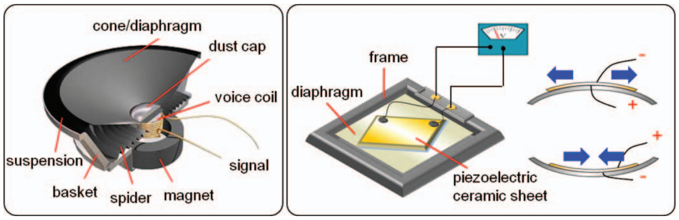

Fig. 1. The schematic view of difference between traditional voice-coil and piezoelectric ceramic speakers.

and soft to achieve the lower fundamental resonant frequency, whereby the output acoustic characteristics of the piezoelectric ceramic speakers in the low-frequency range can be enhanced. To achieve both a higher output sound pressure level and lower resonant frequency of the piezoelectric speaker, this paper proposes a rubber/resin bilayer acoustic diaphragm. For comparison, we simulated and analyzed the vibrational mode characteristics of the piezoelectric ceramic speakers using 3 types of acoustic diaphragms: a rubber single-layer diaphragm, a resin film single-layer diaphragm, and a rubber/resin bi-layer diaphragm. The resonant frequencies and mode shapes for each type of acoustic diaphragm were simulated using the finite-element analysis (FEA) method. Then, the vibrational frequency response characteristics of the piezoelectric ceramic speakers were analyzed to predict the output sound pressures of the piezoelectric speakers for the 3 types of acoustic diaphragms using three-dimensional time harmonic structure–acoustic interaction simulation.

To verify the effect of the acoustic diaphragms on the resonant frequencies and output sound characteristics in a low-frequency range, piezoelectric ceramic speakers with the 3 different types of acoustic diaphragms are fabricated and investigated with the vibrational frequency response characteristics. This paper shows that the experimental resonant frequencies and output sound pressures of the piezoelectric ceramic speakers are in good agreement with the numerical results for 3 types of acoustic diaphragms.

II. Structure and Fabrication

In general, piezoelectric ceramic speakers consist of three components: a piezoelectric ceramic membrane, an acoustic diaphragm, and a rigid frame. In this paper, the fabricated piezoelectric ceramic speakers comprise an acoustic diaphragm fixed to a rigid frame and a lead zirconate titanate (PZT) ceramic membrane bonded on the acoustic diaphragm.

A. Preparation of the PZT Ceramics and Diaphragms

First, the piezoelectric ceramic sheets have been prepared to have the triple-layered multimorph structure by screen printing method and sintering process, for low driving voltage and large acoustic output characteristics [12]. Similar to the triple-layered bimorph piezoelectric ceramic actuators [13]–[15], the triple-layered multimorph ceramics also consisted of three piezoelectric layers: the upper and lower piezoelectric active layers and the piezoelectric dummy layer which is between the upper and lower piezoelectric active layers. Here, each active piezoelectric layer had a triple-layered structure. Fig. 2 shows the cross-sectional SEM image of the fabricated triple-layered multimorph piezoelectric ceramic sheet and the schematic electrical configuration for the multimorph piezoelectric ceramic polarized in parallel direction. P and E indicate the polarization direction and applied electric field in each piezoelectric active layer, respectively. As shown in Fig. 2(b), the triple-layered multimorph piezoelectric ceramics were polarized in parallel direction and electrically connected in parallel because the parallel connection can provide much larger deformation than the series connection for the same electric voltage applied [12]. In other words, this is due to the fact that the parallel triple-layered multimorph piezoelectric ceramics in parallel connection result respectively in shrinkage and expansion at the upper and lower active layers with the applied electric field. The fabricated triple-layered parallel multimorph piezoelectric ceramic sheets were polarized under an electric field of 2.1 kV/mm at 110°C for 3 min. The dimensions and total thickness of the fabricated ceramics were 15 × 14 mm and 110 μm, respectively; the thicknesses of each piezoelectric element in the active layers and the dummy layer were 13 and 25 μm, respectively.

The acoustic diaphragm is a critical component that determines the low-frequency characteristics of the piezoelectric ceramic speakers. In other words, a flexible acoustic diaphragm can make it possible to get a lower fundamental resonant frequency of the piezoelectric ceramic speakers. This means that the output acoustic characteristics of the piezoelectric ceramic speakers such as resonant frequency and frequency response range significantly depends on the vibrational characteristics of the acoustic diaphragms.

The acoustic diaphragms are typically made from lightweight, stiff materials such as coated paper, plastic resin film, or metal. In this paper, we used 3 different types of acoustic diaphragms: a rubber single-layer diaphragm, a resin film single-layer diaphragm, and a rubber/resin bilayer diaphragm. Here, the rubber and resin single-layer diaphragms are silicone rubber and polyethyleneimine (PEI) resin film, respectively. To compare the effect of each acoustic diaphragm on the resonant frequencies and output sound characteristics of the piezoelectric ceramic speakers in a low-frequency range, all diaphragms used in this paper had the same dimensions of 18 × 20 mm.

B. Fabrication of the Piezoelectric Ceramic Speakers

The fabrication process flow of the piezoelectric ceramic speaker is shown in Fig. 3. First, the prepared triple-layered multimorph piezoelectric ceramic sheets were bonded onto each type of acoustic diaphragm by being tilted at an angle of 15° at the center of the diaphragm [Figs. 3(a)

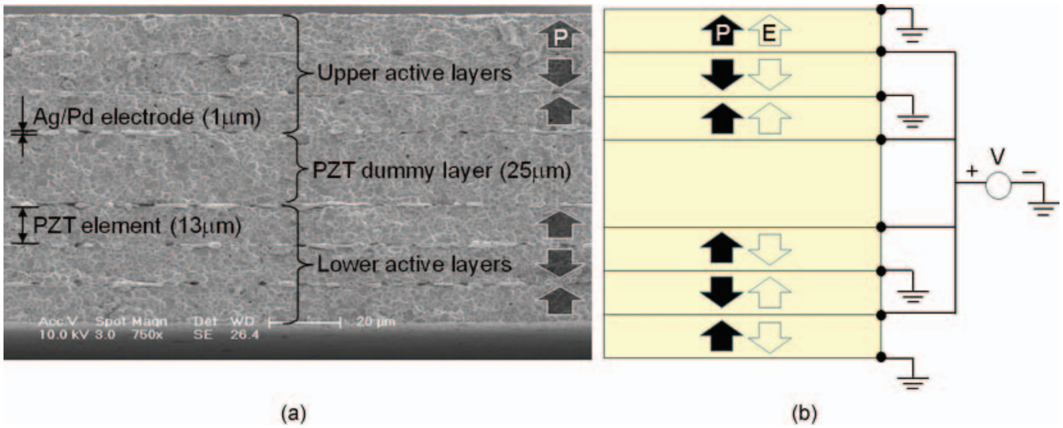

Fig. 2. (a) The cross-sectional scanning electron micrograph image of the fabricated triple-layered multimorph piezoelectric ceramic sheet and (b) the schematic electrical configuration for the multimorph piezoelectric ceramic polarized in parallel direction.

and 3(b)]. The tilted position of the piezoelectric ceramic on a flexural acoustic diaphragm can prevent additional vibrations caused by standing waves generated in a symmetrical assembly [7]. In other words, the tilted position of the PZT ceramic on the diaphragm can provide higher sound quality of the speakers than a symmetrical pattern of a PZT ceramic sheet on a diaphragm. In addition, the highly elastic silicone epoxy used between the ceramic and the acoustic diaphragm helps to obtain stable output sound pressure and lower distortion characteristics of fabricated piezoelectric ceramic speakers. The silicone epoxy used in this work was well cured into a soft, uniform, and stress-relieving material at room temperature for about 10 min.

Next, a 10-μm-thick layer of silicone material was applied on the top of the PZT ceramic sheet using a spin coating method [Fig. 3(c)]. We used a dilute silicone solution with low viscosity of about 0.05 Pa·s to cover all sides of the PZT ceramic sheet. The silicone coating process helps to obtain stable sound pressure characteristics of the fabricated speakers by avoiding the separation of the PZT ceramic sheet and the acoustic diaphragm.

Finally, the piezoelectric ceramic speakers were completed by fixing each acoustic diaphragm bonded with the triple-layered multimorph piezoelectric ceramic sheets into a rigid frame which has large internal absorption loss characteristics, and by electrically connecting them to terminals [Fig. 3(d)] The thickness of the fabricated piezoelectric ceramic speaker was only 1 mm, including the printed circuit board (PCB) frame, and the dimensions of the vibrational active region of the acoustic diaphragms were 18 × 20 mm.

III. Results and Discussion

A. Fundamental Resonant Frequencies

An ideal piezoelectric ceramic speaker can be modeled by the single-resonance system: the output sound pressure of the resonant system is in the stiffness-controlled region below the fundamental resonant frequency and in the mass-controlled region above it [2], [11]. From the frequency response of an ideal piezoelectric speaker, it is shown that the output acoustic performance is approximately independent of the frequency in the mass-controlled region, but is proportional to the square of frequency in the stiffness-controlled region. In other words, below the fundamental resonant frequency (f_0), the output sound pressure level of the piezoelectric ceramic speaker is proportional to f^2 because the displacement of the acoustic diaphragm is inversely proportional to the frequency. Hence, lowering the fundamental resonant frequency of the acoustic diaphragm improves the acoustic performance of the piezoelectric ceramic speakers for a wider frequency range.

Typically, commercial piezoelectric speakers with acoustic diaphragms such as a plastic resin film or metal foil have a fundamental resonant frequency of around 1 kHz because of the stiffness of their diaphragms. In this paper, we use 3 different types of acoustic diaphragms—a rubber single-layer diaphragm, a resin film single-layer diaphragm, and a rubber/resin bi-layer diaphragm—softer than the acoustic diaphragms of the commercial piezoelectric speakers to obtain fundamental resonant frequencies less than 1 kHz.

If the acoustic diaphragm is a simple rectangular vibrating single-layer membrane on the uniform in-plane stress, the resonant frequencies of the rectangular vibrating membrane model can be given as [16]–[18]

$$\omega_{m,n} = \sqrt{\frac{T}{\rho}\left[\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2\right]}, \qquad (1)$$

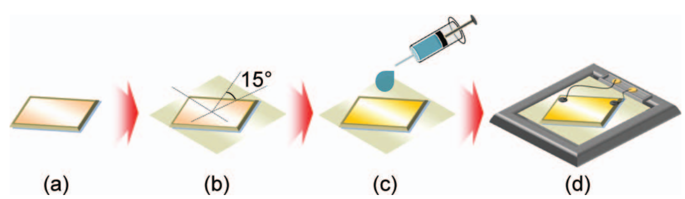

Fig. 3. The fabrication process flow of the piezoelectric ceramic speakers.

where T is the stress, ρ is the density of the vibrating membrane, a and b are the lateral membrane dimensions, and m and n are natural numbers, respectively. When $m = 1$ and $n = 1$, the rectangular vibrating membrane is at the fundamental resonance. Because a and b are given as the dimensions of membrane, the fundamental resonant frequency of the rectangular membrane is proportional to the square root of the stress of the membrane material.

In addition, if the bending of the membrane is uniform and pure, the stress in the membrane at the fundamental resonant frequency is proportional to the strain by the Young's modulus due to Hooke's law:

$$\begin{aligned} T &= E \cdot \varepsilon_{\mathrm{m}} \\ \varepsilon_{\mathrm{m}} &= \frac{d}{R}, \end{aligned} \tag{2}$$

where E and ε_{m} are the Young's modulus and the maximum strain of the membrane, and d and R are the distance from the neutral axis to the surface of membrane and the radius of the curvature of the membrane at its neutral axis, respectively. Then, (1) becomes

$$\omega_{m,n} = \sqrt{\frac{Ed}{\rho R}\left[\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2\right]} \tag{3}$$

Hence, the fundamental resonant frequency of the rectangular vibrating membrane is proportional to the square root of the Young's modulus and thickness of the membrane. In other words, to lower the fundamental resonant frequency of the piezoelectric speakers, the acoustic diaphragm must be thinner and more flexible.

To verify the theoretical square-root dependence of the fundamental resonant frequency $\omega_{1,1}$ on the thickness and Young's modulus of the acoustic diaphragm, we simulated and analyzed the vibrational modal characteristics of the acoustic diaphragms using the FEA method. Then, the fundamental resonant frequencies were determined by measuring the frequency response characteristics of the acoustic diaphragms by laser scanning vibrometer (LSV) equipment. Fig. 4 shows the relationship between the fundamental resonant frequencies and the thicknesses of the acoustic diaphragms. For comparison, the measured results are also plotted in Fig. 4. In the cases of the rubber and resin single-layer diaphragms, the fundamental resonant frequencies increase with the square root of the thicknesses of the acoustic diaphragms. This result indicates that the simulated and experimental results for the fundamental resonant frequencies are in excellent agreement with the theoretical dependence on the thickness according to (3), regardless of the types of the acoustic diaphragms.

However, when the thicknesses of the rubber and resin single-layer diaphragms are equal, the fundamental resonant frequencies of the rubber single-layer diaphragm are much lower than those of the resin single-layer diaphragm, as shown in Figs. 4(a) and 4(b). For example, the fundamental resonant frequencies of the rubber and resin film

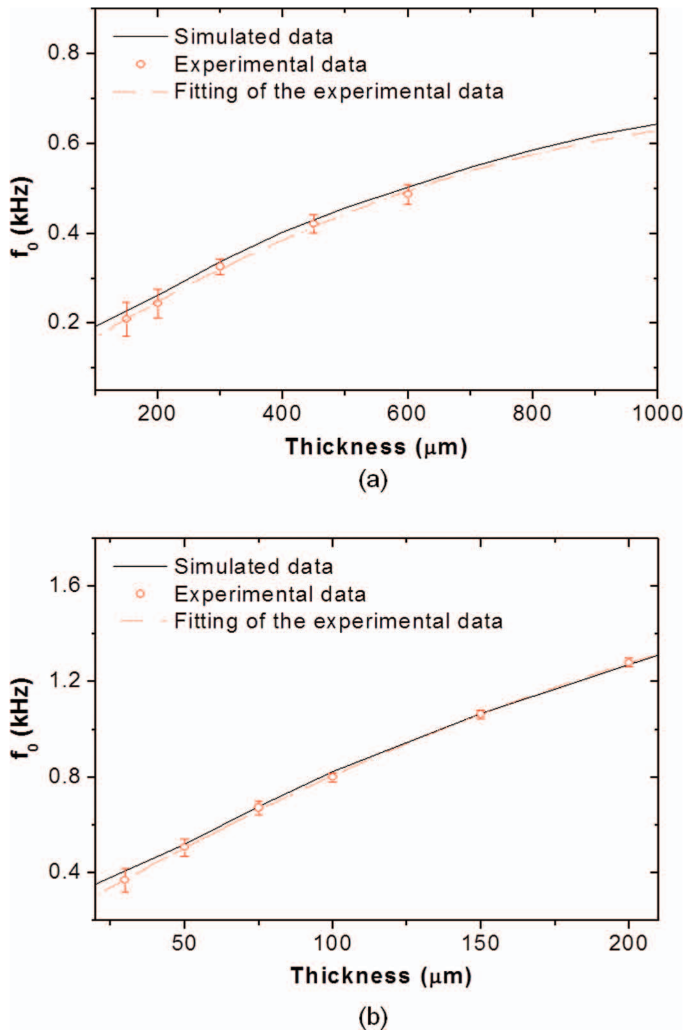

Fig. 4. The fundamental resonant frequencies of (a) the rubber single-layer and (b) the resin film single-layer diaphragms versus the thickness.

single-layer diaphragms were 0.21 and 1.063 kHz, respectively, when they have the same thickness of 150 μm. This means that the fundamental resonant frequency of the diaphragm also depends on the material properties such as the modulus of elasticity, agreeing with the theoretical analysis according to (3). In this paper, other materials with higher Young's modulus than the resin film single-layer were not considered because they obviously result in higher fundamental resonant frequencies than those of the commercial piezoelectric speakers. Instead, we used the rubber/resin bi-layer diaphragm with different thickness ratios of the layers to analyze the dependence of the fundamental resonant frequency on the thickness of each layer.

Fig. 5 shows the dependence of the fundamental resonant frequency on the relative thickness of the resin (or rubber) layer of the rubber/resin bi-layer diaphragms. Here, all of the rubber/resin bi-layer diaphragms had the total thickness of 150 μm. As shown in Fig. 5, the fundamental resonant frequency increases with increasing thickness of the resin layer and decreases with increasing thickness of the rubber layer. Moreover, the fundamental resonant frequencies are proportional to the square root of the thickness of the resin layer. These results mean that the thickness ratio of the layers of the rubber/resin bi-layer diaphragm define the effective Young's modulus of the diaphragm so that the fundamental resonant frequencies of the diaphragm have a square-root dependency on the thickness of the resin layer, according to (3). Therefore, for the single-layer acoustic diaphragms, the soft rubber single-layer acoustic diaphragm has a lower fundamental resonant frequency than the resin film single-layer diaphragm; for the rubber/resin bi-layer acoustic diaphragm, the fundamental resonant frequency can be decreased by increasing the thickness ratio of the rubber layer to the resin layer.

B. Frequency Response Characteristics

To enhance the output acoustic characteristics of the piezoelectric ceramic speakers in the low-frequency range, the fundamental resonant frequencies of the acoustic diaphragms were investigated in the previous section. To verify the effect of the fundamental resonant frequencies of the acoustic diaphragms on the output sound characteristics in the low-frequency range, the vibrational frequency response characteristics of the piezoelectric ceramic speakers with the acoustic diaphragms were analyzed by the three-dimensional time harmonic structure–acoustic interaction simulation using the FEA method. Table I lists the mechanical, electrical, and piezoelectric properties of PZT and diaphragm materials that are used in the simulation. Fig. 6 shows the modeling for simulation of the structure–acoustic interactive frequency response characteristics of the piezoelectric ceramic speakers. To simulate the structure-acoustic interaction under the same condition as the measurement, the piezoelectric ceramic speaker was fixed to a baffle plate of 50 × 50 cm, and we used the perfectly matched layer (PML) to absorb waves from the speaker so sound waves generated by the piezoelectric ceramic speaker can propagate without reflection. For comparison of the frequency response characteristics for the acoustic diaphragms, we selected 3 types of acoustic diaphragms: a 300-μm-thick rubber single-layer diaphragm, a 100-μm-thick resin film single-layer diaphragm, and a 150-μm-thick rubber/resin bi-layer diaphragm. Here, the rubber/resin bi-layer diaphragm consists of a 100-μm-thick rubber layer and 50-μm-thick resin layer. The dimensions of each acoustic diaphragm and the PZT ceramic sheet were 18 × 20 mm and 15 × 14 mm, respectively.

Figs. 7 and 8 show the simulated and measured vibrational mode shapes of the piezoelectric ceramic speakers and the vibrational frequency response characteristics, respectively. We simulated the vibrational resonant characteristics using both the solid and acoustics modules of Comsol Multiphysics finite element analysis software (Comsol Inc., Burlington, MA). As shown in Figs. 7 and 8, the vibrational mode shapes of each diaphragm simulated by solid and acoustics modules are in good agreement with the measured results. Here, the $(2,1)$ mode shape simulated by the acoustics module shows some discrepancy with the other solid simulated and experimental results. It seems to be a $(2,1)$ + $(2,2)$ mode rather than a $(2,1)$ single mode. One explanation for this is that the following $(2,2)$ mode is so close to $(2,1)$ mode and the displacement for the $(2,2)$ mode is much larger than the $(2,1)$ mode, as shown in Fig. 8. Then, the simulated vibrational frequency response characteristics were verified by LSV measurement with an input drive voltage of 0.1 V_{pk}. Table II shows the simulated and measured resonant frequencies of the piezoelectric speakers for the acoustic diaphragms. As shown in Table II, the simulated modes (resonant frequencies) for each diaphragm correspond well to the measured results. The simulated fundamental resonant frequencies were respectively 337, 824, and 675 Hz for a 300-μm-thick rubber single-layer diaphragm, a 100 μm-thick resin film single-layer diaphragm, and a 150-μm-thick rubber/resin bi-layer diaphragm. Similarly, the measured fundamental resonant frequencies of them were 326, 800, and 677 Hz, respectively. As a result, it is obvious that the fundamental resonant frequency of the rubber single-layer diaphragm is lowest compared with those of the other types of diaphragms. In other words, the resonant frequencies of the piezoelectric speakers can be lowered by a flexible acoustic diaphragm, as analyzed in the previous section.

Fig. 9 shows the time harmonic parametric frequency response characteristics of the piezoelectric speakers from the structure-acoustic interactive simulation. The plots indicate the output sound pressure levels at a distance 10 cm away from the exits of the speakers. In common with results from Fig. 8 and Table II, the first resonant mode for the rubber single-layer diaphragm occurs at 337 Hz, which enhances the output sound pressure of the

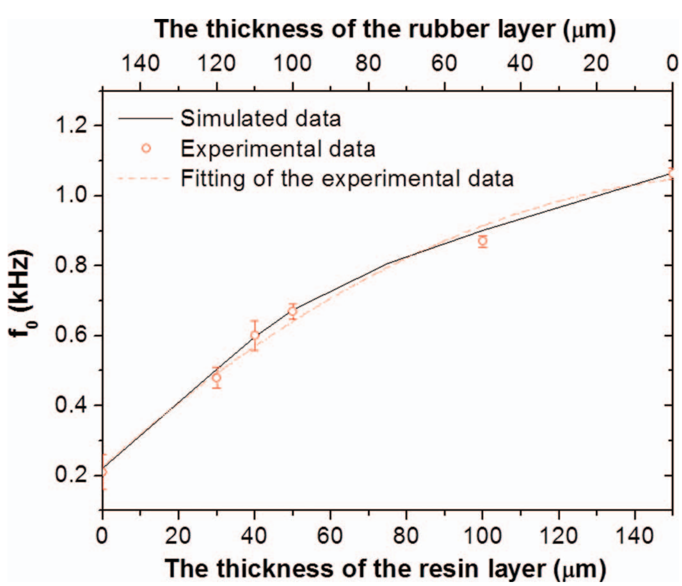

Fig. 5. The dependence of the fundamental resonant frequency on the relative thickness of the resin (or rubber) layer of the rubber/resin bi-layer acoustic diaphragm. The total thickness of the rubber/resin bi-layer diaphragm is 150 μm.

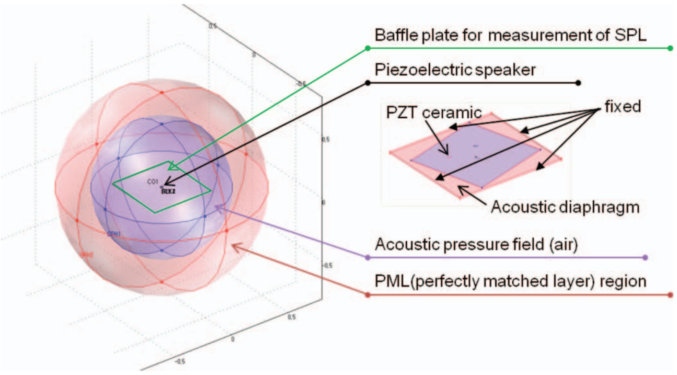

Fig. 6. Modeling for simulation of the structure-acoustic interactive frequency response characteristics of the lead zirconate titanate (PZT) ceramic speakers.

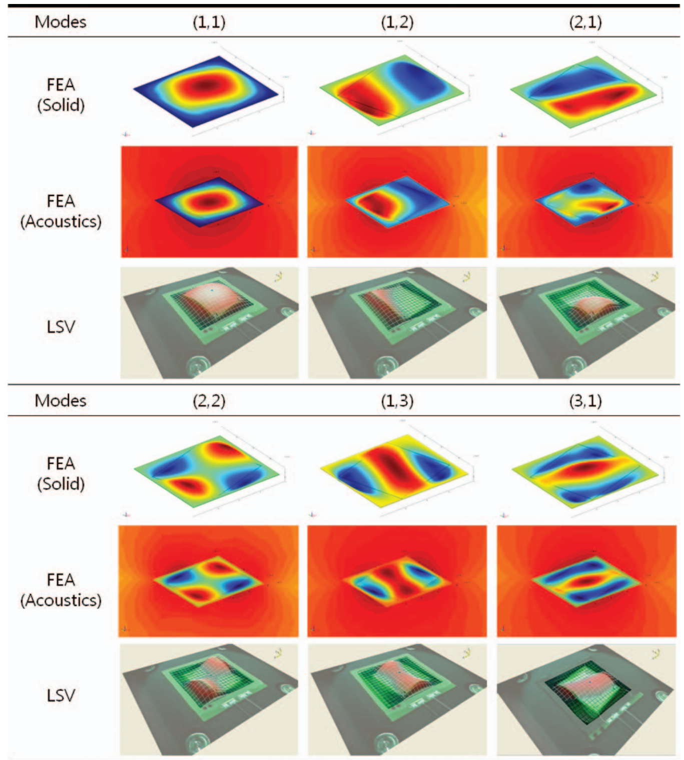

Fig. 7. The simulated and measured vibrational mode shapes of the piezoelectric ceramic speakers obtained from finite element analysis (FEA) and laser scanning vibrometer (LSV).

piezoelectric speaker in the low-frequency range of less than 400 Hz. However, the output sound pressure level for the rubber single-layer diaphragm has poor characteristics compared with the other types of diaphragms above the first resonant frequency. On the other hand, the piezoelectric speaker with the resin film single-layer diaphragm has a higher average sound pressure level above the fundamental resonant frequency of 824 Hz but fails to achieve good acoustic performances in the low-frequency range of less than 824 Hz.

Therefore, to achieve both low fundamental resonant frequency and high output acoustic characteristics in a piezoelectric ceramic speaker, the acoustic diaphragm must be designed to be more flexible than the resin film single-layer diaphragm and stiffer than the rubber single-layer diaphragm. For this reason, the rubber/resin bi-layer acoustic diaphragm is investigated in this study. As shown in Fig. 9, the simulated fundamental resonant frequency and the average sound pressure level of the piezoelectric speaker with the rubber/resin bi-layer diaphragm were 634 Hz and 85 dB at 10 cm, respectively. Compared with the other types of the diaphragms, the fundamental resonant frequency of the rubber/resin bi-layer diaphragm is lower than that of the resin film single-layer diaphragm

TABLE I. Material Properties of the Lead Zirconate Titanate (PZT) Ceramic and Acoustic Diaphragms Used in the Finite Element Analysis Simulation.

Material properties	PZT ceramic	Silicone	PEI resin
Density (kg/m^3)	7840	896	1270
Young's modulus (MPa)	—	10.4	870
Elastic constants (m^2/N)		—	—
$S^E{}_{33}$	2.1×10^{-11}		
$S^E{}_{11}$	1.53×10^{-11}		
$S^E{}_{55}$	4.0×10^{-11}		
Dielectric loss factors (%)	2.4	—	—
Mechanical quality factor	65	—	—
Poisson's ratio	0.33	0.1	0.44
Curie temperature (°C)	300	—	—
Relative dielectric constant		—	—
$\varepsilon^T{}_{33}/\varepsilon_o$	2000		
$\varepsilon^T{}_{11}/\varepsilon_0$	1800		
Piezoelectric constants (C/N)		—	—
d_{33}	3.0×10^{-10}		
d_{31}	-2.1×10^{-10}		
d_{15}	5.5×10^{-10}		
Coupling coefficient		—	—
k_{33}	0.75		
k_{31}	0.4		
k_{15}	0.54		

TABLE II. The Simulated (Sim) and Measured (Meas) Resonant Frequencies of the Piezoelectric Ceramic Speakers With 3 Types of Acoustic Diaphragm.

	Mode resonant frequency (kHz)					
	Rubber single layer		Resin film single layer		Rubber/resin bi-layer	
Modes	Sim	Meas	Sim	Meas	Sim	Meas
(1,1)	0.34	0.33	0.82	0.8	0.68	0.68
(1,2)	0.44	0.43	1.49	1.5	1.19	1.2
(2,1)	0.57	0.58	1.77	1.75	1.61	1.62
(2,2)	0.8	0.78	2.35	2.35	1.79	2.02
(3,1)	1.37	1.32	2.92	2.89	2.32	2.32
(1,3)	1.68	1.55	3.72	3.72	2.54	2.55

but higher than that of the rubber single-layer diaphragm. This is because the resin film layer of the rubber/resin bi-layer diaphragm behaves as a mass applied to the rubber single-layer diaphragm. In other words, because the rubber/resin bi-layer diaphragm is similar to the rubber single-layer diaphragm stressed by added mass, the fundamental resonant frequency of the bi-layer diaphragm is higher than the rubber single-layer diaphragm because of the effect of mass [16].

As mentioned previously, the rubber single-layer diaphragm has the lowest fundamental resonant frequency but has poor acoustic characteristics compared with the other types of diaphragms above the first resonant frequency. For example, at 1 kHz, the sound pressure level for the rubber single-layer diaphragm is around 20 dB lower than the case of the resin film single-layer diaphragm. In addition, the frequency response characteristics for the rubber single-layer diaphragm have severe peaks and dips, compared with the other types of diaphragms. On the other hand, the rubber/resin bi-layer and the resin film single-layer diaphragms provide higher and more stable sound pressure levels than the rubber single-layer diaphragm.

To verify the simulated frequency response characteristics of the acoustic diaphragms, we measured the output acoustic characteristics of the fabricated piezoelectric ceramic speakers with the 3 types of acoustic diaphragms using a pulse analyzer (3560, Brüel & Kjær, Nærum, Denmark). The fabricated piezoelectric speakers were fixed at a baffle plate of 50 × 50 cm for measurement. Fig. 10 shows the fabricated PZT speaker and the output sound pressure measurement setup with a baffle plate. The experimental output sound pressures of the piezoelectric speakers are obtained by the 4191 1/2-in (12.7-mm) reference microphone (Brüel & Kjær, Nærum, Denmark) at a distance of 10 cm from the exits of the speakers.

Fig. 11 shows the output sound pressures of the fabricated piezoelectric ceramic speakers mounted on a 50 × 50 cm baffle plate. The measured frequency response characteristics of the piezoelectric ceramic speakers according to 3 types of the acoustic diaphragms are quite similar to the simulated results shown in Fig. 9. The measured fundamental resonant frequency of the rubber/resin bi-layer diaphragm (677 Hz) is lower than 800 Hz of the resin film single-layer diaphragm but higher than 326 Hz of the rubber single-layer diaphragm, and the rubber/resin bi-layer diaphragm provides higher and stable sound pressure levels than the rubber single-layer diaphragm. Moreover, the piezoelectric speaker with the rubber/resin bi-layer diaphragm produces a sound pressure comparable with that of the resin film single-layer diaphragm even though its

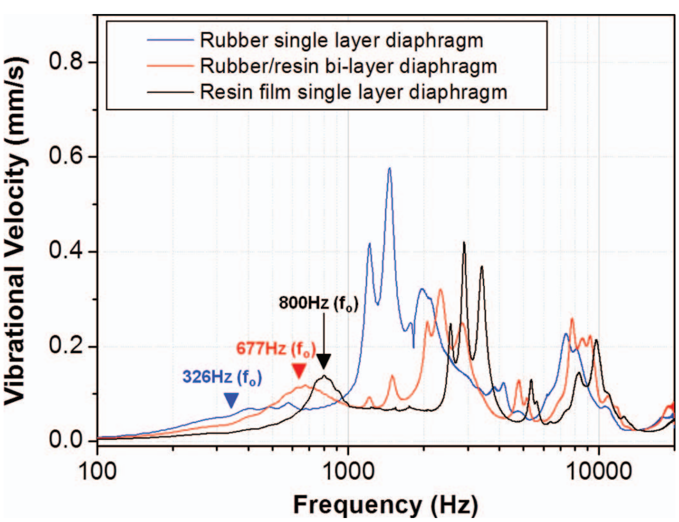

Fig. 8. The vibrational frequency response characteristics of the fabricated piezoelectric speakers with the acoustic diaphragms. The fundamental resonant frequencies for each diaphragm are marked with an inverted triangle in the graph.

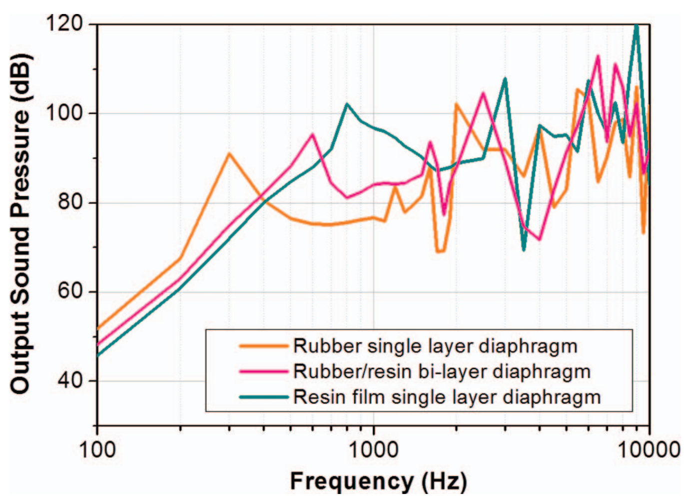

Fig. 9. The simulated frequency response characteristics of the piezoelectric ceramic speakers according to the acoustic diaphragms.

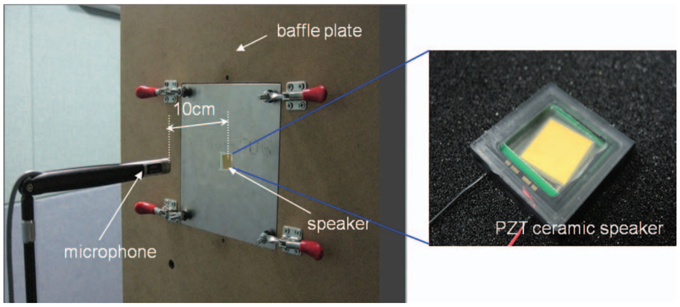

Fig. 10. Images of the fabricated PZT ceramic speaker and the sound pressure measurement setup with a baffle plate.

fundamental resonant frequency (677 Hz) is lower than the 800 Hz of the resin film single-layer diaphragm. From these simulated and measured results, it can be concluded that the rubber/resin bi-layer diaphragm provides not only a fundamental resonant frequency lower than that of the commercial piezoelectric speaker but also high and stable acoustic characteristics. As shown in Fig. 11, the fabricated piezoelectric ceramic speakers with the flexible acoustic diaphragms have superior characteristics in the low-frequency range compared with a commercial piezoelectric speaker. Especially notable, the fabricated piezoelectric speaker with the rubber/resin bi-layer diaphragm has at least 10 dB higher sound pressures than a commercial piezoelectric speaker in the low-frequency range of less than 1 kHz.

IV. Conclusions

In this paper, the vibrational characteristics of 3 different types of acoustic diaphragms were investigated to improve frequency response characteristics of the piezoelectric ceramic speaker in the low-frequency range. The theoretical square-root dependence of the fundamental resonant frequency on the thickness and Young's modulus of the acoustic diaphragm was verified by FEA simulation and LSV measurement. The simulated resonant frequencies for each diaphragm corresponded well to the measured results. The simulated fundamental resonant frequencies were, respectively, 337, 824, and 675 Hz for the rubber single-layer, the resin film single-layer and the rubber/resin bi-layer diaphragms. Similarly, their measured fundamental resonant frequencies were 326, 800, and 677 Hz, respectively. These results indicate that the resonant frequency of the piezoelectric ceramic speaker can be designed by adjusting the thickness ratio of the bi-layer acoustic diaphragm, whereby the output acoustic characteristics of the piezoelectric ceramic speakers in the low-frequency range can be enhanced. Compared with a commercial piezoelectric ceramic speaker, the fabricated piezoelectric speaker with the rubber/resin bi-layer diaphragm has at least 10 dB higher sound pressure in the low-frequency range of less than 1 kHz.

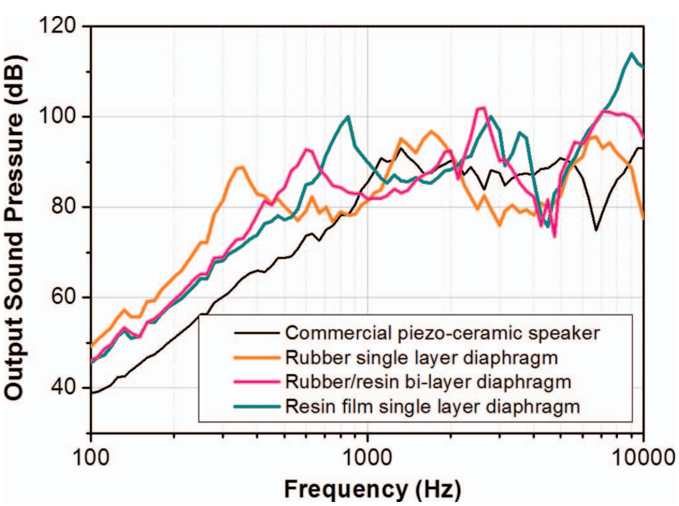

Fig. 11. The output sound pressures of the fabricated piezoelectric ceramic speakers mounted on a 50 × 50 cm baffle plate.

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