High Performance Piezoelectric Microspeakers and Thin Speaker Array System

Hye Jin Kim, Kunmo Koo, Sung Q Lee, Kang-Ho Park, and Jongdae Kim

This paper reports on an improved piezoelectric microspeaker with a high sound pressure level of 90 dB, a total harmonic distortion of less than 15%, and coherence higher than 0.9. The fabricated $Pb(Zr,Ti)O_3$ (PZT) microspeakers have a thickness of only 1 mm including the speaker frame and an active area of 18 mm×20 mm. To achieve higher sound pressure and lower distortion, the PZT piezoelectric microspeaker has a well-designed speaker frame and a piezoelectric diaphragm consisting of a tilted PZT membrane and silicone buffer layer. From the simulation and measurement results, we confirmed that the silicon buffer layer can lower the first resonant frequency, which enhances the microspeaker's sound pressure at a low frequency range and can also reduce useless distortion generated by the harmonics. The fabricated PZT piezoelectric microspeakers are implemented on a multichannel speaker array system for personal acoustical space generation. The output sound pressure at a 30 cm distance away from the center of the speaker line array is 15 dB higher than the sound pressure at the neighboring region 30 degrees from the vertical axis.

Keywords: Piezoelectric, microspeaker, sound pressure level, distortion, directivity.

I. Introduction

As portable devices require smaller, lighter, and more power-efficient components, many devices are being developed to achieve a compact form factor [1], [2]. Traditionally, voice coil motor (VCM) speakers have been used for cellular phones because of their lower price and great performance. However, they have suffered from a limiting factor of their thickness as mobile devices become more compact. Thus far, a number of studies on other type of speakers as alternatives to VCM speakers have been presented [3]-[7]. Among them, ceramic or piezoelectric speakers have received attention as the most remarkable options. While VCM speakers have a 3 mm or greater thickness, piezoelectric speakers are thinner than 1 mm. In addition, piezoelectric speakers are more power-efficient than VCM speakers because of their high impedance characteristics.

To date, piezoelectric speakers have been developed using various piezoelectric materials such as quartz, $BaTiO_3$, ZnO, $Pb(Zr,Ti)O_3$ (PZT) (lead zirconate titanate), PMN-PT (lead magnesium niobate–lead titanate), PZN-PT (lead zinc niobate–lead titanate), and so on [8]-[10]. One of the most widely used types of piezoelectric materials is PZT which has an ABO_3-type complex perovskite structure. PZT piezoelectric materials have higher piezoelectric charge constants (d_{33} or d_{31}) and electromechanical coupling coefficients (k_{33} or k_{31}). These electromechanical coupling coefficients are defined as the numerical measure of the conversion efficiency between electrical and acoustic energy in piezoelectric materials. The piezoelectric charge constants quantify the volume change when a piezoelectric material is subject to an electric field. Thus, a piezoelectric material with a higher piezoelectric charge constant and electromechanical coupling coefficient

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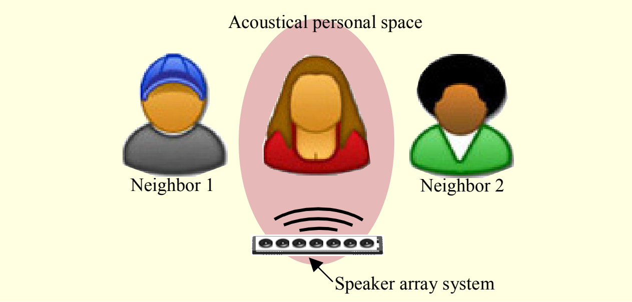


Fig. 1. Schematic conceptual diagram of a personal acoustical space.

produces a higher efficiency in a piezoelectric speaker. A piezoelectric material with a higher piezoelectric and electromechanical coefficient can offer a higher output sound pressure in a piezoelectric speaker.

This paper reports on an improved PZT piezoelectric microspeaker with higher performance than commercial piezoelectric microspeakers. To achieve high performance of PZT microspeakers, the piezoelectric membrane and speaker frame must be well designed and manufactured. In our study, the tilted shape of the PZT membrane and a thick silicone buffer layer were designed to obtain a more flexural and soft membrane which enhances the sound pressure and reduce the distorted sounds of the microspeaker. Also, the speaker membrane was well mounted onto a speaker frame using highly elastic epoxy to absorb vibration by the deflection of the speaker frame and reduce distorted sounds of the speaker.

Recently, an acoustical personal space generation technique has received much attention as a very important and useful technology because it offers a higher acoustical energy area in the target region than in the neighboring regions, which maintains personal privacy and protects neighbors from noise damage [11]-[13]. In particular, the demand for personal acoustical space generation on portable terminal devices has grown because of the noise problem in public spaces which is generated from using portable devices (cellular phones, PDAs, PMPs, handheld PCs, and so on). A conceptual diagram of an acoustical personal space is shown in Fig. 1. To form a personal acoustical space, a multichannel speaker array system can be used as a directivity formation method. Therefore, a speaker array system should be more power-efficient. The multichannel speaker array system for personal acoustical space generation presented in this paper uses a fabricated PZT piezoelectric microspeaker that can offer a thinner, lighter, and more power-efficient array system.

II. Structure and Fabrication

This paper reports on an improved high-performance piezoelectric microspeaker which was fabricated using a well-designed structure and successful manufacturing process. A schematic view of the PZT piezoelectric microspeaker is shown in Fig. 2. Typically, piezoelectric microspeakers consist of a piezoelectric diaphragm and a speaker fixing frame. As shown in Fig. 2, the PZT microspeaker is also comprised of a diaphragm that has a tilted piezoelectric membrane and a silicone buffer layer, as well as a speaker frame that can absorb vibration and reduce undesirable distortions. A cross-sectional structure is shown across the center of the diaphragm.

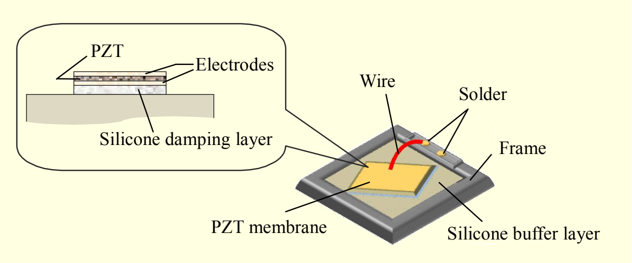


Fig. 2. Schematic view of a PZT piezoelectric microspeaker.

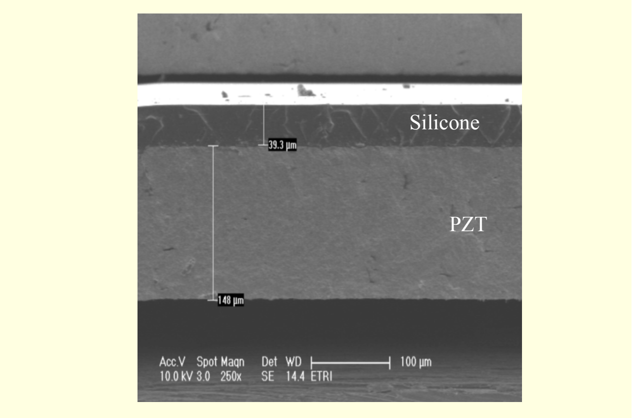


Fig. 3. SEM image of the silicone damping material cured on a PZT membrane with good uniformity.

The PZT piezoelectric microspeakers were successfully fabricated as follows. First, the PZT membrane was thinned down to 40 μm thickness by chemical mechanical polishing of the bulk PZT ceramic film. Au electrodes of 0.2 μm were deposited on the entire surface of both sides of a 40 μm thick PZT membrane using e-beam evaporation equipment. A silicone damping material was then spin-coated on the back of the membrane, and a silicone buffer layer of 0.2 mm was bonded onto the back of the membrane. The silicone damping material helps the uniform bonding between the membrane and a silicone buffer layer so that the sound pressure characteristics of the fabricated speakers are highly reproducible. The silicone damping material is then cured into a 40 μm thick soft, stress-relieving material to obtain higher sound pressure and lower distortion. Figure 3 shows that the silicone damping material was well cured under the appropriate conditions and had good uniformity.

The PZT membrane was designed to have a tilted shape on the silicone buffer layer to prevent standing waves reflected from the rigid speaker frame. The thin and tilted PZT membrane and thick silicone buffer layer allow the diaphragm to be more flexural and soft, enhancing the sound pressure and reducing the distorted sounds of the microspeaker. Finally, the piezoelectric diaphragm was mounted onto a speaker frame using highly elastic epoxy to absorb vibration created by the deflection of the speaker membrane and to reduce the harmonic distortion created by the useless vibration. The thickness of the fabricated piezoelectric microspeaker was only 1 mm including the speaker frame.

III. Numerical Analysis

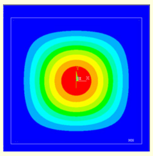
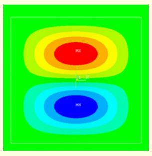
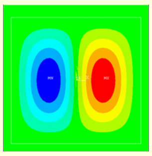
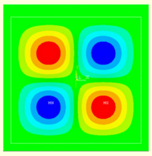
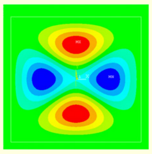
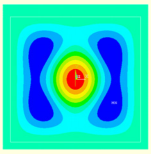
It is well known that the performance of microspeakers is very dependent on the mechanical properties of their diaphragms. To evaluate the mechanical and acoustic performance of the fabricated PZT piezoelectric microspeaker, we simulated and analyzed the modal and harmonic characteristics using the finite-element analysis method.

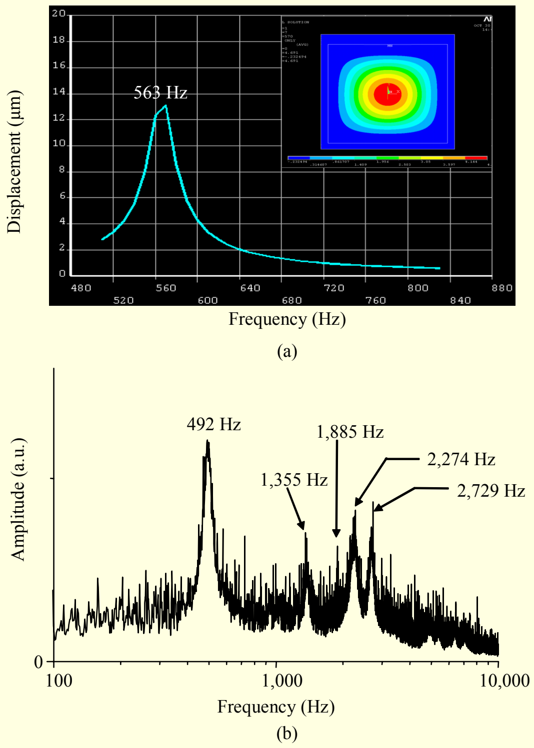
In this paper, we conducted a modal analysis to determine the vibration characteristics of the fabricated PZT piezoelectric microspeaker. Table 1 shows its natural frequencies and mode shapes. The first resonant mode occurs at 563.3 Hz, which enhances the microspeaker's sound pressure even at a low frequency of less than 1 kHz.

To lower the first resonant frequency, the diaphragm of the speaker must be more massive and flexural. For this reason, the thin PZT membrane and thick silicone buffer layer of the diaphragm were designed to improve the speaker's acoustic performance at a low frequency range.

Figure 4(a) shows the simulated vibration characteristics of the PZT piezoelectric microspeaker at the first resonant frequency. The y-axis shows displacements in the center of the membrane as a function of frequency. The size and thickness of the PZT membrane are 14 mm × 13 mm and 40 μm, respectively. The diaphragm of the fabricated microspeaker is 18 mm × 20 mm. With a structural damping factor of 0.02, the displacement at the center of the PZT microspeaker is 13 μm at 1 V.

Table 1. Modal analysis of the fabricated PZT piezoelectric microspeaker.

Mode 1	Mode 2	Mode 3
563.33 Hz	1350.4 Hz	1352.4 Hz
		
Mode 4	Mode 5	Mode 6
1992.9 Hz	2418.9 Hz	2435.2 Hz
		



(a)

(b)

Fig. 4. (a) Simulated displacement characteristics at the first resonant frequency followed by a harmonic analysis and (b) LSV measurement result of the fabricated PZT piezoelectric microspeaker.

Figure 4(b) shows the laser scanning vibrometer (LSV) measurement result to confirm the simulated vibration mode of the speaker. The first resonant frequency was measured to be 492 Hz, which is quite similar to the simulated result. The higher order resonant frequencies are also similar to the simulated results. Therefore, the simulated vibration characteristics correspond to the measured results at each resonant frequency. The measured displacement at the center of the PZT membrane was 11.8 μm at 1 V.

From these simulated and measured results, we confirmed that the diaphragm of the fabricated PZT microspeaker is very flexural and soft. This means that the neutral axis of the diaphragm is shifted by the thick silicone buffer layer so that the deflection of the diaphragm is also increased.

IV. Characteristics of PZT Microspeakers

The PZT piezoelectric microspeaker was successfully fabricated, and the PZT diaphragm was then polarized for domain orientation. The piezoelectric charge constants of the PZT films were measured using a pneumatic loading method [14], [15]. Table 2 shows the measured piezoelectric coefficients of the PZT membranes before and after poling.

Figure 5 shows the measured hysteresis curve of the fabricated piezoelectric microspeaker. The polarization hysteresis loops were obtained using a standardized ferroelectric test system (P-LC100-K, Radient Technologies). The polarization-electric field (P-E) characteristics were well saturated and symmetrical over 5 kV/cm, and then the remnant polarization (Pr) was about 32 μC/cm^2. We polarized the PZT membranes for 20 minutes at 5 kV/cm at 120 °C.

A fabricated PZT piezoelectric microspeaker is shown in Fig. 6. It has a thickness of only 1 mm and an active region of only 18 mm × 20 mm. The speaker has dimensions of 20 mm × 22 mm. The microspeaker was also packaged using an enclosure and a protector.

Table 2. Measured piezoelectric coefficients of the PZT films before and after poling.

		d33 (pC/N, average)		
		PZT film (80 μm-thick)	PZT film (100 μm-thick)	PZT film (150 μm-thick)
Before poling		62	57	53
After poling at 120°C	2 kV/cm	241	223	221
	5 kV/cm	265	256	291
	7 kV/cm	242	259	283

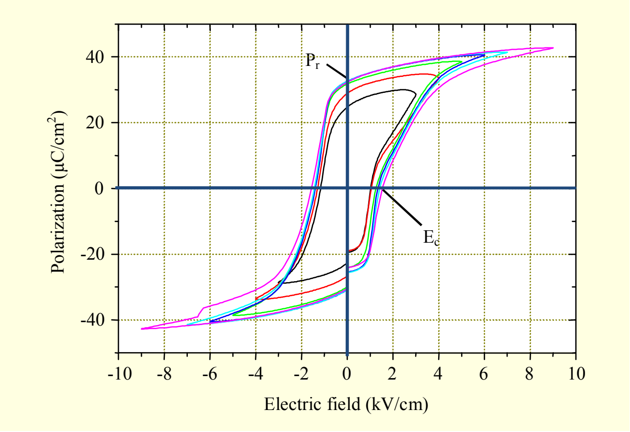


Fig. 5. P-E hysteresis curve of the fabricated PZT microspeaker.

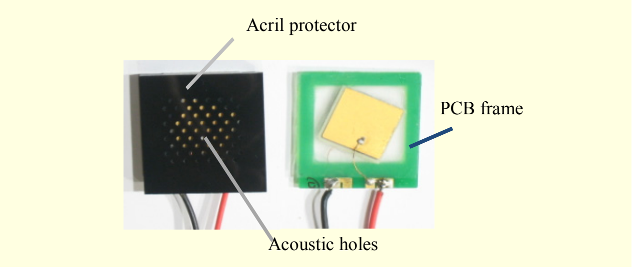


Fig. 6. Photographs of the fabricated PZT piezoelectric microspeaker.

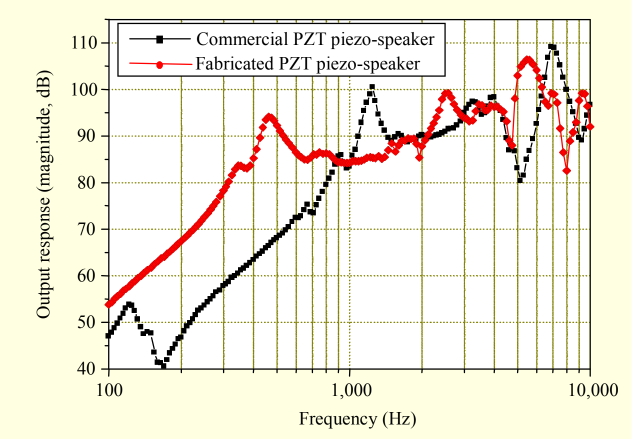
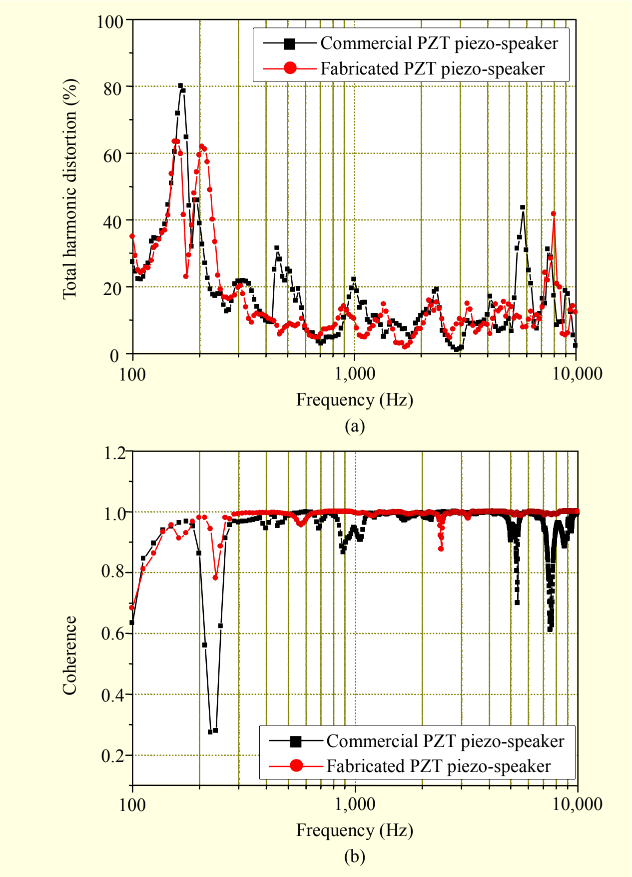


Fig. 7. PZT piezoelectric microspeaker SPL output with 16 $V_{p\text{-}k}$ (zero-peak) at a distance of 1 cm.

The acoustic output sound pressure of the fabricated microspeaker was measured at a distance 1 cm away from the exit of the speaker using a Brüel & Kjær Type 4232 Anechoic Test Box. Figure 7 shows the generated output sound pressure of the microspeaker. The frequency response was measured at 16 $V_{p\text{-}k}$ with a swept sine signal from 100 Hz to 10 kHz.

The output sound pressure level (SPL) of the fabricated microspeaker is about 90 dB (±5 dB), which can deliver a competitive SPL compared to that of a commercial piezoelectric speaker with the same size of 20 mm × 22 mm. The PZT commercial speaker used for comparison was the SPS2220-03 model developed by Sonitron. The frequency response shows that the fabricated microspeaker has very superior characteristics at a low frequency range of less than 1 kHz. Generally, piezoelectric microspeakers are limited in generating a low frequency range. However, the fabricated PZT speakers have an enhanced sound pressure about 20 dB higher than that of commercial PZT speakers at a low frequency range of less than 1 kHz. As shown in the simulated results, this improvement of acoustic performance is caused by the first resonant frequency shifting to a low frequency range due to the thin PZT membrane and thick silicone buffer layer,



(a)

(b)

Fig. 8. (a) Percentage of THD and (b) coherence measurement results of the fabricated PZT piezoelectric microspeaker.

and the deflection of the diaphragm is increased by a neutral axis shift due to the thick silicone buffer layer.

For the harmonic oscillator, the natural frequency is given as $(k/m)^{1/2}$. The thick silicone buffer layer has a large mass and low k compared to that of other metal layers of commercial PZT speakers. We confirmed that the speaker membrane with a thick silicone buffer layer has a lower resonant frequency and lower harmonic distortions than other metal or composite vibrating diaphragms. In addition, it is well known that the stress $\sigma(y)$ in the membrane is proportional to the strain $\varepsilon(y)$, and the normal strain varies linearly with the distance y from the neutral axis. Thus, the neutral axis shift due to the thick silicone buffer layer can produce more mechanical stress in the surfaces of the membrane and helps to obtain a large deflection of the diaphragm.

Figure 8 shows the percentage of total harmonic distortion (THD) and the coherence measurement results of the fabricated PZT piezoelectric microspeaker.

The percentage of THD is defined as

$$\%THD = 100 \times \sqrt{\frac{A_2^2 + A_3^2 + \cdots + A_N^2}{A_1^2 + A_2^2 + A_3^2 + \cdots + A_N^2}}\,, \tag{1}$$

where A_2^2, $\cdots$, A_N^2 are the power levels of the harmonics, and A_1^2 is the power level of the fundamental (pure) tone. In the equation, A denotes the amplitude of the fundamental and harmonic components. Considering the frequency dynamic range from 400 Hz to 8 kHz of the fabricated speaker, the fabricated PZT piezoelectric microspeakers have a THD of less than 15% and a coherence of higher than 0.9, which demonstrates a competitive level of performance compared to commercial piezoelectric speakers.

The tilted shape of the PZT membrane was designed to reduce the THD by preventing additional vibrations due to standing waves generated in a symmetric pattern. Because the standing wave can increase total harmonic distortion, we tilted the PZT membrane on the vibrating diaphragm, avoiding a right angle with the frame. A uniform silicone damping material and a thick buffer layer can also reduce the distorted sounds generated by a rough membrane. Moreover, we used a highly elastic epoxy to minimize the distortions when the diaphragm was mounted onto the speaker frame. The highly elastic epoxy and rigid speaker frame support the speaker membrane with a uniform stress and absorb the vibration by the speaker membrane equally. Therefore, the percentage of THD shows that the tilted PZT membrane, a thick silicone buffer layer, and a proper speaker frame with a highly elastic epoxy help to reduce distorted sounds of the speaker, which enhances the sound quality of the microspeakers.

Figure 8(b) shows that the fabricated microspeakers have a very high coherence higher than 0.9. The coherence $C_{xy}(f)$ is defined by

$$C_{xy}(f) = \frac{\left|P_{xy}(f)\right|^2}{P_{xx}(f)P_{yy}(f)}\,, \tag{2}$$

where x and y are the input and output signal, respectively. The magnitude squared coherence estimate is a function of frequency with values between 0 and 1 that indicates how well x corresponds to y at each frequency. Coherence is a function of the power spectral density (P_{xx} and P_{yy}) of x and y and the cross power spectral density (P_{xy}) of x and y. This high coherence result shows that the fabricated microspeakers can produce a very coherent sound, enabling them to be implemented for sound concentration control of a personal acoustical space.

V. Thin Multichannel Speaker Array System

Personal acoustical space generation requires a multichannel speaker array system as it is more power-efficient. We manufactured a PZT speaker array system using the fabricated PZT piezoelectric microspeakers. Figure 9 shows the manufactured 7-channel microspeaker line array system with a

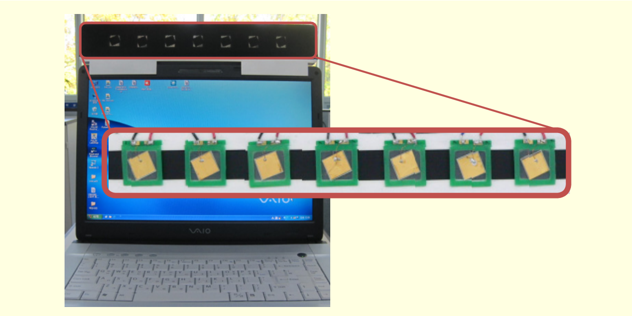


Fig. 9. 7-channel microspeaker array system with the fabricated PZT speakers for personal acoustical space generation.

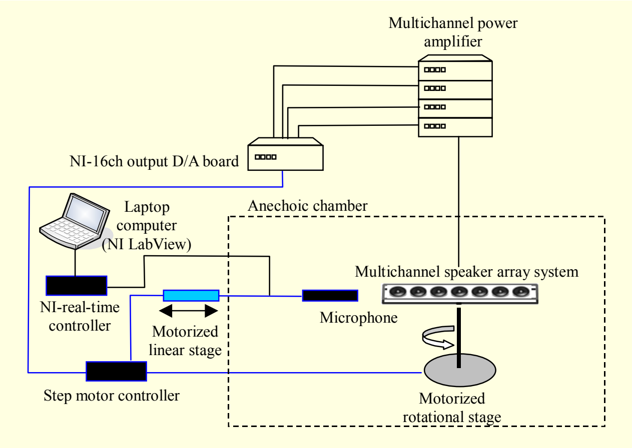


Fig. 10. Schematic configuration of the automatic directivity measurement system for multichannel speaker line array.

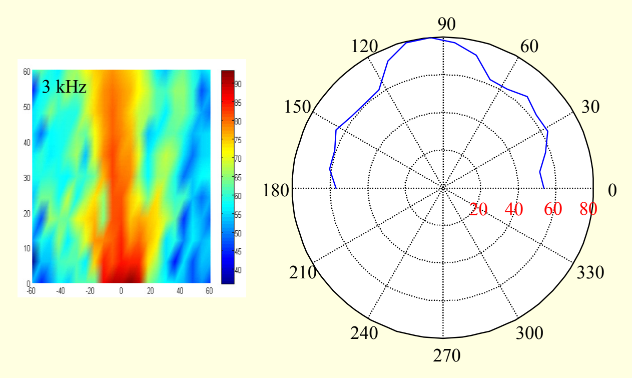


Fig. 11. Directivity measurement results of the speaker array system.

25 cm width and a 4.16 pitch which can be mounted on a laptop computer.

The directivity of the speaker array system was measured in an anechoic chamber. Figure 10 shows a schematic configuration of the automatic measurement system. The volume of the anechoic chamber was 5.6 m × 5.6 m × 2.4 m, and the background noise level was less than 20 dB.

To form personal acoustical space generation with a multichannel speaker array, we must control the magnitude and phase of each speaker independently. In this study, the control solutions are obtained by the conventional source signal control method called the acoustic brightness control method [13]. This method finds the source strength vector that maximizes the acoustic brightness defined as the ratio between acoustic energies in the listening region and acoustic sources. The cost function is given by

$$\alpha = \frac{E_\mathrm{L}}{J_c} = \frac{\mathrm{q}_\mathrm{c}^\mathrm{H}\left[\frac{1}{V}\int_V \mathrm{G}^\mathrm{H}\mathrm{G}\,dV\right]\mathrm{q}_\mathrm{c}}{\mathrm{q}_\mathrm{c}^\mathrm{H}\mathrm{q}_\mathrm{c}}, \tag{3}$$

where J_c and E_L mean the energy of all sources and the acoustic energy in the listening region, respectively; q_c is the source strength vector; G is the vector of acoustic transfer function; and H is the Hermitian operator.

The 7-channel PZT piezoelectric microspeaker array system and its directivity measurement results are shown in Fig. 11. Figure 11 shows the pressure fields and polar radiation pattern of the sound pressure at a radius 30 cm away from the center of the speaker line array. The measurement results were optimized from the transfer functions of each fabricated PZT microspeaker in the target region. The transfer functions were measured at distances 22 cm away from each speaker. As shown in Fig. 11, the output sound pressure at the front and at a distance 30 cm away from the center of the sources is 15 dB higher than the sound pressure at the neighboring region 30 degrees from the vertical axis.

The manufactured speaker line array system has a very thin and light form factor because each piezoelectric microspeaker has a thickness of only 1 mm. Moreover, even though it includes multichannel speakers, power amplifiers, and digital signal processors, the speaker line array system is more power-efficient because the piezoelectric microspeakers are more power-efficient than traditional VCM speakers. Therefore, we confirm that the fabricated piezoelectric microspeakers are suitable for implementation for sound concentration control of personal acoustical space and enable the realization of a thinner, lighter, and more power-efficient directive speaker array system.

VI. Conclusion

This paper presented high-performance piezoelectric microspeakers which have a high SPL of 90 dB (±5 dB), a THD of less than 15%, and a coherence of higher than 0.9. To obtain higher sound pressure and lower distortion, the PZT piezoelectric microspeaker has a well-designed speaker frame and a diaphragm that consists of a tilted PZT membrane and a silicone buffer layer. From the simulation and measurement results, we confirmed that the silicone buffer layer can enhance the sound pressure of the PZT piezoelectric microspeakers at a low frequency range and reduce undesirable harmonic distortions. The fabricated PZT piezoelectric microspeakers achieve a competitive performance compared to other commercial piezoelectric microspeakers of the same size.

The fabricated PZT piezoelectric microspeakers were implemented on a multichannel speaker array system for personal acoustical space generation. The output sound pressure at the front and at a distance 30 cm away from the center of the speaker line array is 15 dB higher than the sound pressure at the neighboring region 30 degrees from the vertical axis. We have confirmed that the fabricated PZT piezoelectric microspeakers can be implemented for sound concentration control of a personal acoustical space and enable the realization of a thinner, lighter, and more power-efficient directive speaker array system.

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