Helmholtz Resonator for Lead Zirconate Titanate Acoustic Energy Harvester

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Abstract. Acoustic energy harvesters that function in environments where sound pressure is extremely high (~150 dB), such as in engine rooms of aircrafts, are expected to be capable of powering wireless health monitoring systems. This paper presents the power generation performances of a lead-zirconate-titanate (PZT) acoustic energy harvester with a vibrating PZT diaphragm. The diaphragm had a diameter of 2 mm, consisting of Al(0.1 µm)/PZT(1 µm)/Pt(0.1 µm)/Ti(0.1 µm)/SiO2(1.5 µm). The harvester generated a power of 1.7x10^-13 W under a sound pressure level of 110 dB at the first resonance frequency of 6.28 kHz. It was found that the generated power was increased to 6.8x10^-13 W using a sound-collecting Helmholtz resonator cone with the height of 60 mm. The cone provided a Helmholtz resonance at 5.8 kHz, and the generated power increased from 3.4x10^-14 W to 1.4x10^-13 W at this frequency. The cone was also effective in increasing the bandwidth of the energy harvester.

1. Introduction

Energy harvesters have attracted considerable attention for possible application to independently operating intelligence systems [1,2]. PZT [Pb(Zr,Ti)O3] is an excellent candidate for harvesting power from ambient vibration sources because it can efficiently convert mechanical strain to electrical charge [3,4]. Several bulk PZT piezoelectric energy harvesters have been reported [5-9]. In addition, currently, energy harvesters using thin PZT films are being extensively studied because they were expected to be integrated into silicon integrated circuits (IC) [10-13].

Acoustic energy harvesters that function in an environment where sound pressure is extremely high (~150 dB) such as in an engine room of an aircraft, are expected to be capable of powering wireless health monitoring systems. Horowitz et al. have recently reported on a microelectromechanical systems (MEMS) acoustic energy harvester that contains a PZT piezoelectric film as a diaphragm [14]. They claimed that their energy harvester with a PZT (0.27-µm thick) diaphragm with a diameter of 2.4 mm should exhibit a power density of 0.34 µW/cm² at a sound pressure level (SPL) of 149 dB under the first resonance vibration mode. Shinoda et al. [15] fabricated PZT energy harvesters with similar sizes to those of Horowitz et al., compared the performances of their energy harvesters with those of Horowitz et al. at SPL of 100 dB, and reported that higher generated power could be realized by vibrating PZT diaphragms at the third-resonance frequency. Kimura et al. reported that PZT acoustic harvesters with non-wet electrode fabrication processes exhibited further improved power density at
the first resonance [16]. However, these previous reports on the PZT acoustic energy harvesters did not utilize the different polarity charges in the central area and the peripheral area of the diaphragms. Tomioka et al. reported on similar PZT acoustic energy harvesters considering to utilization of different polarizations of generated charges on the vibrating diaphragm with a PZT piezoelectric capacitor [17]. Iizumi et al. reported on further improved performances of PZT acoustic energy harvesters that utilized different charge polarizations at the peripheral area and the central area of a PZT diaphragm with a diameter of 2 mm, using a combined device consisting of a peripheral harvester and central harvester [18].

Horowitz et al. also discussed the influences of Helmholtz sound resonator placed in front of the energy harvesters, and suggested an increase of the frequency bandwidth of the harvesters [14]. However, the influences of the Helmholtz sound collecting cones with a trumpet shape have not been reported. In this paper, the power generation of a similar PZT energy harvester equipped with a Helmholtz sound collecting cone with a trumpet shape was investigated.

2. Device Structure

Figure 1(a) shows the top-view design of the PZT energy harvester investigated here. The two top Al electrodes cover the peripheral area and the central area of the PZT diaphragm, respectively. A schematic of a cross-section of the energy harvester is shown in Figure 1(b). A piezoelectric capacitor with the diaphragm structure of Al (0.1 µm)/PZT (1.0 µm)/Pt (0.1 µm)/Ti (0.1 µm) was formed on 1.5-µm-thick SiO₂ substrate. The cavity with a diameter of 2.0 mm was fabricated on a 300-µm-thick silicon wafer. The processing details have been already reported previously [15]-[17].

When sound pressure is applied from above the device, the diaphragm vibrates, resulting in the deflection of the diaphragm. The deflected PZT capacitor generates a voltage difference between the Al electrodes and the Pt/Ti common electrode owing to the polarization of PZT. In the case of exciting the first resonance, in which the entire diaphragm was vibrated in the same phase, the generated charge polarizations were different between the peripheral area and the central area as schematically shown in Figure 1(c). The two energy harvesters were defined between the peripheral electrode and the common electrode. However, only the peripheral harvester was investigated in this work.

The resonance frequencies of the diaphragm under a sound pressure level of 110 dB were measured between 1 kHz and 17 kHz using the characterization system described in previous reports [15], [16]. In order to measure the resonance frequency of the energy harvester, an amplifier with a gain of 10,000 was connected to amplify the output voltage signals from the energy harvester. The measured lowest resonance peak appeared at 6.28 kHz. This suggested that the first resonance occurred at 6.28 kHz. The simulated first resonance frequency obtained using the infinite element method well coincided with the value of 6.28 kHz as previously reported [15]-[18].

In this study, a sound collector cone made of thin paper was attached in front of a speaker (Figure 2). Two sound collector cones with height H of 60 and 70 mm were used here. To ensure that the cone covered the speaker, the diameter of the bottom of the cone was 80 mm. Figure 2(c) shows the sound pressure measured at the top end of the cone as a function of the sound frequency. The sound pressure varied as a function of the sound frequency. When using the cone, the increase of the sound pressure of approximately 15 dB was realized, as seen in Figure 2(c). It should be noted that the resonance peak frequencies can be adjusted by modifying H. The shape of the cone was designed to have a maximum sound pressure at a frequency of approximately 5-7 kHz, to enhance the harvested energy near the first resonance of 6.28 kHz. Frequency positions fn at the peak sound pressure can be explained using a simple Helmholtz resonance theory [14]. The resonance frequency can be obtained by assuming that n-times half of the wavelength of the sound is equal to H. Thus, fn is expressed as shown in Eq. 1;

\[ f_n = \frac{n}{2H} c \quad \text{Eq. (1)}. \]
where \( n \) is an integer, and \( c \) is the velocity of sound at room temperature (345 m/s). The calculated resonance frequencies for the Helmholtz resonance of the cones with \( H \) of 60 and 70 mm are shown in Table 1.

**Figure 1.** Structure of PZT energy harvester; (a) top view, (b) Schematic cross-section, and (c) concept of connected energy harvester.

**Figure 2** Sound pressure measurement setups; (a) without using sound collecting cone, (b) with using sound correcting cone and (c) measured sound pressure at the end of paper cone as function of sound frequency.
Table 1. Calculated resonance frequencies for the Helmholtz resonance with the diameter D of 80 mm and the height H of 60 mm and 70 mm.

| n=1 | H=60mm 2.87 kHz | H=70mm 2.46 kHz |
| n=2 | 5.75 kHz | 4.92 kHz |
| n=3 | 8.62 kHz | 7.39 kHz |
| n=4 | 11.5 kHz | 9.85 kHz |
| n=5 | 14.3 kHz | 12.3 kHz |
| n=6 | 17.2 kHz | 14.7 kHz |

3. Results and Discussion

Figure 3(a) compares the frequency dependencies of the open-circuit output voltages for the peripheral device with and without the sound collector cone with height of 60 mm. The sound pressure was controlled to be 110 dB within the measured frequency range. Sharp peaks for the first resonance for the peripheral device measured with or without the cone were observed at 6.28 kHz. The output voltages for the device measured using the cone showed distinct peaks at 5.8 kHz and 6.28 kHz. The peak at 5.8 kHz corresponds to the Helmholtz resonance (see Table 1, n=2 with H=60 mm). The peak at 6.28 kHz increased by approximately two times. This output voltage seems to increase because of the wide Helmholtz resonance peak at 5.8 kHz. The peak voltage value at 5.8 kHz was increased from 0.0034 to 0.0292 mV, which is an increase in a factor of approximately 8.6. Thus, a significant increase in the generated power can be expected using the sound collector cone. In addition, the bandwidth of the output voltage was increased. Table 2 summarizes these results.

Figure 3(b) shows the relationships between the generated power of the energy harvester and the sound pressure in different cases. The power was measured at a load resistance of 56.8 Ω that was determined by impedance matching between the harvester and the load resistance. The harvester generated the power of $1.7 \times 10^{-13}$ W under the sound pressure level of 110 dB at the first resonance frequency of 6.28 kHz, without using the cone. The harvester generated the power of approximately $3.4 \times 10^{-14}$ W at 5.8 kHz. The measured generated powers for the harvester using the cone with H of 60 mm are also compared in Figure 3(b). A significant increase in the generated power was realized using the cone at the both frequencies. These values of the generated power were $1.4 \times 10^{-13}$ W at 5.8 kHz and $6.8 \times 10^{-13}$ W at 6.28 kHz, respectively.

Figure 3 (a) Frequency dependence of output voltages as measured with or without using the cone (110 dB). (b) Sound pressure dependences of output power as a function of sound pressure at the diaphragm first resonance of 6.28 kHz and the Helmholtz resonance at 5.8 KHz.
Table 2. Comparison of resonance frequencies and open-circuit output voltage using and without using the sound collector cone.

|                  | First resonance | Output voltage Helmholtz resonance | Output Voltage |
|------------------|-----------------|------------------------------------|----------------|
|                  | (kHz)           | (mV)                               | (mV)           |
| Without cone     | 6.28            | 0.0204                             | 0.0034         |
| With cone        | 6.28            | 0.0410                             | 0.0292         |

4. Conclusions
This paper presented an energy harvester with a vibrating PZT diaphragm. The diaphragm had a diameter of 2 mm consisting of Al(0.1 µm)/PZT(1 µm)/Pt(0.1 µm)/Ti(0.1 µm)/SiO$_2$(1.5 µm). The harvester generated a power of $1.7 \times 10^{-13}$ W under a sound pressure level of 110 dB at the first resonance frequency of 6.28 kHz. It was found that the generated power was increased to $6.8 \times 10^{-13}$ W using a sound-collecting Helmholtz resonator cone with the height of 60 mm. The cone provided a Helmholtz resonance at 5.8 kHz, and the generated power increased from $3.4 \times 10^{-14}$ W to $1.4 \times 10^{-13}$ W at this frequency. The cone was also effective to increase the bandwidth of the energy harvester.

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