Output Power of Piezoelectric MEMS Vibration Energy Harvesters Under Random Oscillation

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Abstract. The output characteristics of MEMS piezoelectric vibration energy harvesters (PVEHs) under random oscillations are analysed. We fabricated cantilever-type MEMS-PVEHs using Pb(Zr,Ti)O₃ films. The autocorrelation function of the transient displacement of the cantilever tip under random oscillations features a narrow-band random vibration. From the power spectral density (PSD) of the output voltage of the PVEHs, the resonance frequency decreases and the full-width at half-maximum increases with increasing vibration acceleration. By comparing output properties under various sinusoidal oscillations, nonlinear effects including the soft-spring effect and nonlinear damping effect clearly influence the output characteristics under random oscillations. The power generation is proportional to the square of the vibration acceleration even in the acceleration region where nonlinear effects become conspicuous.

1. Introduction

In recent years, considerable attention has been directed toward vibration energy harvesters (VEHs). The motivation is that electrical energy may be generated from the energy of vibration in the ambient surroundings and exploited as an energy source to power micro-devices, such as small wireless sensor nodes in a sensing network, structural health monitoring systems, biomedical implants, and environmental condition monitoring systems. Vibration energy harvesting is viewed as one of the key technologies in realizing the Internet of Things or the Trillion Sensors Universe [1–3].

Several transduction methods may be used for VEHs including electromagnetic induction, electrostatic induction, anti-magneto restriction effect, and piezoelectricity. Among these methods, piezoelectricity has received much attention owing to the direct conversion of vibration energy into electrical energy with a high-power density and the simplicity of its device structure. Moreover, piezoelectric VEHs (PVEHs), VEHs based on piezoelectricity are suitable for miniaturization and easy to integrate since they are highly compatible with the MEMS process [4–6]. To date, much of the reporting concerns the characteristics of MEMS-PVEHs obtained using sinusoidal oscillations [7–10] but few using random oscillations. For this reason, clarification of the output performance of the MEMS-PVEHs using random oscillations would be useful.
In this study, we fabricated the cantilever-type MEMS-PVEHs employing Pb(Zr,Ti)O$_3$ (PZT) films. The power-generation characteristics were investigated at various accelerations under random oscillations. The PVEHs showed a resultant nonlinear characteristic. We also examined the output performance under sinusoidal oscillations and discuss their nonlinear characteristics.

2. Experiments

2.1. MEMS fabrication process

The structure of the fabricated PVEHs for study (Figure 1) consists of a single cantilever structure, which is composed of a supporting Si membrane, SiO$_2$, Pt/Ti bottom electrode, PZT piezoelectric film, Pt/Ti top electrode, and a Si proof mass. In the MEMS fabrication process of PVEHs (Figure 2), the starting material is a silicon-on-insulator (SOI) wafer of 20-µm-thick Si (device layer), 1-µm-thick SiO$_2$ (insulating layer), and 500-µm-thick Si-bulk. First, an SOI wafer was oxidized on both sides to a thickness of 1.0 µm. We used a Pt/Ti film as a bottom electrode. The Pt/Ti film was deposited with a thickness of 100 nm/10 nm on the front surface by sputtering. Subsequently, a PZT piezoelectric film with a thickness of 3.0 µm was prepared by sputtering [Figure 2(a)].

As a top electrode, a Pt/Ti film was deposited to a thickness of 100 nm/10 nm. We then patterned sequentially a Pt/Ti top electrode, PZT piezoelectric film, and a Pt/Ti bottom electrode by inductive coupled plasma-reactive ion etching (ICP-RIE). An interlayer insulating film (TEOS-SiO$_2$) with a thickness of 0.6 µm was deposited by CVD and patterned by ICP-RIE [Figure 2(b)]. To form electrodes and wires, Pt/Ti was sputter-deposited and patterned by ICP-RIE. Subsequently, we removed the thermally oxidized SiO$_2$ layer, Si device layer, and SiO$_2$ insulating layer on the front surface around the cantilevers. The SiO$_2$ and Si layers were etched by ICP-RIE and deep RIE, respectively [Figure 2(c)].
Figure 4. Transient displacement of the cantilever under random oscillations at acceleration of 1.0 m/s² (RMS).

Figure 5. Autocorrelation function of the displacement of the cantilever at acceleration of 1.0 m/s² (RMS).

The Si bulk was etched from the backside by deep RIE to form the cantilever and a proof mass. We finally fabricated the cantilever-type MEMS-PVEHs with a unimorph structure; see figures 1 and 2(d). The width, length, and thickness of the cantilever were 1.0 mm, 6.0 mm, and 24 µm, respectively. Made from the Si-bulk, the proof mass has dimensions 1.5×1.0×0.5 mm³ and weight 1.8 mg. The fabricated PVEHs were designed to exhibit a resonance frequency of around 195 Hz.

2.2. Evaluation of the characteristics of PVEHs

The experimental setup with a shaker for measuring the displacement of the tip of the cantilever and the power spectral density (PSD) of the output voltage of the PVEHs under random oscillations is shown in figure 3. Random oscillations were generated by a vibration simulator (K2 Sprint; IMV). A load resistor was connected across the bottom and top electrodes. The output voltage across the load resistor was measured, and the PSD of the output voltage was obtained using the vibration simulator.

3. Results and discussion

The transient displacement of the tip of the cantilever under random oscillation was recorded (figure 4); the PSD of the vibration acceleration was constant in the frequency regime between 160 and 220 Hz with 1.0 m/s² (RMS) and an impedance-matched load resistance of 180 kΩ. The cantilever vibrates with a period of around 5.2 ms, i.e., at a frequency near 192 Hz, which is almost the same as the designed resonance frequency. From the transient displacement (figure 4), we determined the autocorrelation function of the displacement (figure 5), which is defined as

\[ R(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t)x(t + \tau) dt, \]

where \( x(t) \) is the transient displacement of the tip of the cantilever. The autocorrelation function is effective in finding periodicities inherent in the random vibration. In figure 5, we found a narrow-band random vibration with a resonance frequency of about 192 Hz as the curve is similar to an attenuated autocorrelation function of the sinusoidal oscillation.

Figure 6 shows the PSD of the output voltage over various vibration accelerations from 0.1 m/s² (RMS) to 22 m/s² (RMS). When the vibration acceleration is less than 3.3 m/s² (RMS), the resonance frequency is about 192.4 Hz, which is almost the same as that obtained from the autocorrelation function of the transient displacement (figure 5). In contrast, the resonance frequency decreases when the vibration acceleration is larger than 3.3 m/s² (RMS). The resonance frequency is 191.8 Hz with a vibration acceleration of 22 m/s² (RMS). The PSD curves are seen to become more asymmetric with the resonance frequency decreasing; conversely, the full-width at half-maximum (FWHM) increases with increasing vibration acceleration when the vibration acceleration is larger than 3.3 m/s² (RMS).
This behaviour seems to be attributable to the soft-spring effect because of nonlinearity in the cantilever vibration. Therefore, to clarify these nonlinear characteristics, we analysed the output properties of the PVEHs under sinusoidal oscillations. We measured the output voltage across the load resistor under sinusoidal oscillations using a lock-in amplifier (LI-5640; NF). These oscillations were generated by the vibration simulator (K2 Sprint; IMV), the frequency being ramped up and down at a rate of 0.01 Hz/s around the resonance frequency of the PVEHs.

The frequency dependence of the output voltage across the 180-kΩ impedance-matched load resistor (figure 7) under a sinusoidal oscillation varying its vibration acceleration from 0.1 m/s² (RMS) to 10 m/s² (RMS). The resonance frequency is seen to remain constant at 192.3 Hz in the frequency regime (≤1.0 m/s² (RMS)). In contrast, the resonance frequency decreases in the frequency regime (> 1.0 m/s² (RMS)) to 191.4 Hz at the vibration acceleration of 10 m/s² (RMS). As in figure 6, the resonant curves become more asymmetric and that the resonance frequency decreases; conversely, the FWHM increases with increasing vibration acceleration in the frequency regime (> 1.0 m/s² (RMS)).

From figure 7, the soft-spring effect becomes conspicuous as the vibration acceleration increases. However, there is little hysteresis when the frequency ramps up and down. Therefore, it is considered that other nonlinear effects are added to the soft-spring effect. Aramaki had found similar output properties and analysed the nonlinear effect using cantilever-type MEMS-PVEHs employing the Pb(Zr,Ti)O₃ (PZT) films [11]. He determined that the nonlinear effect includes not only the soft-spring effect but also a nonlinear damping effect that is proportional to the square of the velocity of the proof mass of the cantilever. Therefore, we infer from the PSD (figure 6) influences by both soft-spring and nonlinear damping effects.

The acceleration dependence of the power generation (figure 8) was determined by integrating the PSD of the output voltage under random oscillations (figure 6) with the frequency and dividing by the

**Figure 6.** PSD of the output voltage for various acceleration from 0.1 m/s² (RMS) to 22 m/s² (RMS) under random oscillations.

**Figure 7.** Frequency dependence of output voltage for various accelerations from 0.1 m/s² (RMS) to 10 m/s² (RMS) under sinusoidal oscillations.

**Figure 8.** Acceleration dependence of the output power under random oscillations at fixed impedance-matched load resistance.
impedance-matched load resistance 180 kΩ. This power generation is proportional to the square of the acceleration also in the acceleration region (> 1.0 m/s² (RMS)) where nonlinearity becomes conspicuous. This aspect is under current scrutiny using a mass-spring-damper system model from the viewpoint of the soft-spring and nonlinear damping effects.

4. Conclusions
We fabricated cantilever-type MEMS-PVEHs using PZT films. We examined the output properties under random oscillations. From the autocorrelation function of the transient displacement of the tip of the cantilever, we found a narrow-band random vibration with a resonance frequency near 192 Hz. The PSD of the output voltage of the PVEHs under random oscillations reveals nonlinearities stemming from the soft-spring and nonlinear damping effects. The power generation is proportional to the square of the acceleration also in the acceleration region where these nonlinearities become conspicuous.

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References
[1] Roundy S, Wright P K and Rabaey J 2013 Comput. Commun. 26 1131
[2] Roundy S and Wright P K 2004 Smart Mater. Struct. 13, 1131
[3] Kim S G, Priya S and Kanno I 2012 MRS Bulletin 37 1039
[4] Mitcheson P D, Reilly E K, Toh T, Wright P K and Yeatman E M 2007 J. Micromech. Microeng. 17 S211
[5] Priya S 2007 J. Electroceram. 19 165
[6] Khan A, Abas Z, Kim H S and Oh I K 2016 Smart Mater. Struct. 25 053002
[7] Minh L V, Hara M and Kuwano H 2013 Jpn. J. Appl. Phys. 52 07HD08
[8] Yoshimura T, Murakami S, Wakazono K, Kariya S and Fujimura N 2013 Appl. Phys. Exp. 6 051501
[9] Murakami S, Yoshimura T, Satoh K, Wakazono K, Kariya K and Fujimura N 2013 J. Phys.: Conf. Ser. 476 012007
[10] Kariya K, Yoshimura T, Murakami S and Fujimura N 2014 J. Phys.: Conf. Ser. 557 012101
[11] Aramaki M, Izumi K, Yoshimura T, Murakami S, Satoh K, Kanda K and Fujimura N 2018 Jpn. J. Appl. Phys. in press