Shoe-mounted vibration energy harvester of PZT piezoelectric thin films on metal foils

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Abstract. This paper describes shoe-mounted piezoelectric vibration energy harvesters (PVEHs). The PVEHs were fabricated from Pb(Zr,Ti)O$_3$ (PZT) thin films which were directly deposited onto Pt/Ti-coated stainless steel foil by rf-magnetron sputtering. We experimentally and theoretically evaluated impulse responses of the PVEHs by applying a simple impulse input on the energy harvesters, typical damped free vibration behaviour was clearly observed, and the output signal was in good agreement with the theoretical value. We measured the output power by applying the impulse input with an optimal load resistance of 33.9 kΩ. The maximum output power was approximately 20 μW, which correspond with the calculated value based on theoretical equation. From these results, the theoretical equation we derived might be helpful for design purposes of the shoe-mounted PVEHs.

1. Introduction
Piezoelectric vibration energy harvesters (PVEHs) have been of great interest as promising power sources for networks of wireless sensor nodes. Among a variety of target applications, shoe-mounted PVEHs have been thought to be promising products as battery-free wearable system because of their high power generation efficiency [1]. To mount the PVEHs on shoes, high flexibility and toughness are strongly required. We have previously fabricated PVEHs of Pb(Zr,Ti)O$_3$ (PZT) thin films on stainless steel foil and confirmed their excellent performance such as flexibility, toughness, and high-efficiency of power generation [2], which would be suitable characteristics for the shoe-mounted PVEHs. However, several technical issues still remain, for example, establishment of design guideline and prediction of power generation on the shoe-mounted PVEHs. The practical design of the PVEHs is based on the experimental results and theoretical calculation of electro-mechanical models. Conventionally PVEHs have been evaluated under continuous sinusoidal excitation. However, the shoe-mounted PVEHs are placed under the periodic impulsive excitation environment and the theoretical evaluation should be considered according to the specific input waveforms including impulse input.

In this study, we fabricated PVEHs composed of PZT thin films on stainless steel foils deposited by rf-magnetron sputtering. We evaluated both of harmonic and impulse response of the PVEHs and compared with the calculation results of impulse response of piezoelectric unimorph cantilevers. Finally, we discussed applicability of PZT thin-film PVEHs for shoe-mounted power generators.
2. Experiments

2.1. Device fabrication

Figure 1 shows a schematic illustration of the PZT thin-film PVEHs, which are mounted in an empty space at heel part. The PZT thin film was deposited on the Pt/Ti-coated stainless steel foil by rf-magnetron sputtering. The thickness of the PZT and stainless steel are 2.5 μm and 40 μm, respectively. After the PZT deposition, post annealing was conducted to ensure the crystallization of perovskite phase. Subsequently, the Pt top electrode was prepared through a shadow mask. To adjust the resonant frequency, we attached the seismic mass of 0.93 g at the tip of cantilever as shown in Fig. 1. We confirmed that the pyrochlore-free polycrystalline PZT thin films were prepared on the stainless steel foils by X-ray diffraction measurement. The measurement values of the relative dielectric constant and dielectric loss were 285 and approximately 5%.

![Figure 1. Schematic illustration of PVEH. 2.5-μm-thick PZT films were deposited on 40 μm-stainless steel foils by rf-magnetron sputtering.](image)

2.2. Frequency response

We measured the frequency response of the tip displacement of the PZT thin films PVEHs to determine the resonance frequency. The PVEH was attached to a vibration exciter and frequency of periodic vibration was swept under the acceleration of 0.1, 0.2 and 0.3 m/s². We also characterized the load resistance dependence of the output power with a variable external load resistance at the resonance frequency.

2.3. Power generation performance

The measurement setup of the power generation performance is shown in Fig. 2. The impulsive force was inputted at the fix end with a hammer. The impulse response of output voltage and tip displacement was measured using an oscilloscope and laser Doppler vibrometer, respectively.

The optimal load resistance is assumed by the following equation,

\[ R_{opt} = \frac{1}{\omega C} \]  

where \( \omega \) and \( C \) denote natural angular frequency and capacitance respectively.
3. Results and discussion

Figure 3 shows the tip displacement as a function of the frequency. We clearly observed non-linear resonances, which is due to large deformation of the PVEHs, in the frequency range from 20 Hz to 30 Hz. Furthermore, the resonance frequency was decreased with increasing the acceleration because of softening spring effect. Before the measurement of impulse response, we applied a negative unipolar electric voltage (1 kHz, 20V\text{p-p}) on the top of electrode for one minute as a polling treatment of the PZT thin films. After that, we measured the impulse response of the output voltage and results are shown in Fig. 4. Typical damped free vibration curve was clearly observed.

We derived the theoretical equation of the impulse response of the piezoelectric cantilever as the following equation,

\[ V = e^{31t} \frac{3w h x_1 (1 - \nu_s) (2l - x_1) \Delta v}{4 l^3 C} e^{-\omega_d t} \sin \omega_d t \]  

(2)

where \( w \), \( h \), \( x_1 \), \( \nu_s \), \( l \), \( C \), \( \Delta v \), \( \omega_n \), \( \omega_d \), \( \zeta \) and \( t \) denote the cantilever width, substrate thickness, distance from fix end to the edge of upper electrode, Poisson’s ratio, cantilever length, capacitance, velocity change before and after impulse, natural angular frequency, damping natural angular frequency, damping and time, respectively. The velocity change after impulse was derived from the curve fitting with the experiments. The values for calculation are listed in Table 1. As shown in Fig. 4, calculated curves are in good agreement with the experimental results. We connected the optimal load resistance of 33.9 kΩ, and measured output power after impulse, and the results are shown in Fig. 5. These results imply that theoretical equation based on the impact model would be applied for the design of the shoe-mounted PVEHs and be helpful to improve the performance of the PVEHs.
Table 1. The input values for calculation.

| Parameter                                      | Value   |
|------------------------------------------------|---------|
| Cantilever width: $w$                          | 15 mm   |
| Substrate thickness: $h_s$                     | 40 μm   |
| Distance from fix end to the edge of upper electrode: $x_1$ | 11.8 mm |
| Poisson’s ratio: $\nu_s$                      | 0.3     |
| Cantilever length: $l$                        | 15 mm   |
| Capacitance: $C$                               | 193.3 nF|
| Velocity change before and after impulse: $\Delta v$ | Open 0.2 m/s$^2$ Short 3.0 m/s$^2$ |
| Damping natural angular frequency: $\omega_d$  | 157 rad/s |
| Natural angular frequency: $\omega_n$         | 157 rad/s |
| Damping: $\zeta$                              | 0.008   |
| Piezoelectric coefficient: $e_{31,f}$          | 1.5 C/m$^2$ |

Figure 3. Displacement of the PVEH in an open-circuit state as a function of frequency. The nonlinear resonance was clearly observed due to the large deflection of the PVEH.

Figure 4. Impulse response of output voltages at the open-circuit state. Theoretical calculation were in good agreement with the experimental result.

Figure 5. Impulse response of output powers connected with the optimal load resistance.

4. Conclusions
In this study, we developed PZT thin films PVEHs, and evaluated impulse response aiming for shoe-mounted PVEHs. We derived the theoretical equation of output power under the impulsive excitation and compared with the experimental results of impulse response of output power. The calculated curves showed good agreement with measured values. The PVEHs of this study is expected to generate power levels enough for the operation of sensor-nodes by heel strikes.

References
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