DEVELOPMENT OF PIEZOELECTRIC VIBRATION ENERGY HARVESTERS FOR BATTERY-LESS SMART SHOES

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Abstract For the purpose of realising the battery-less smart shoes, we have developed piezoelectric vibration energy harvesters (PVEHs), and PVEH-driven sports shoes. The smart shoes are equipped with acceleration sensors in the sole and Bluetooth LE (BLE) modules, which were driven by PVEHs composed of piezoelectric bimorph cantilevers. We have confirmed the capability of the PVEHs to frequently transmit the sensing data from the beacons of BLE when the subjects practically run while wearing shoes.

1. Introduction
Many researchers have published presentations about “smart shoes” equipped with various sensors, radio communication modules and others for commercial uses [1]. However, the components in the smart shoes are usually driven by batteries, which are worried about giving out the power or frequent charging operation. On the other hand, shoe-mounted energy harvesting has attracted attention as a power source for mobile or wearable devices [2]. However, there have been few reports on the battery-less smart shoes in which sensors are driven by vibration energy harvesters. In this study, we have developed high-power piezoelectric vibration energy harvesters (PVEHs), which generate electric power enough to operate wireless modules and insole sensors by impulsive forces on the soles of shoes during walking and running, and test to transmit the sensing data. We demonstrated the capability of the PVEHs for the actual application to battery-free smart shoes.

2. Developments of piezoelectric vibration power device with piezoelectric films
2.1. Fabrications of piezoelectric vibration power device with piezoelectric thick films
In order to produce the PVEHs, we used the growth technique of piezoelectric thick films [3]. This is a revolutionary technique to form piezoelectric films by screen-printing on stainless steel substrates. We can form piezoelectric films with the thickness of 40 μm on both sides of the 100 μm-thick stainless steel by using this technique as shown in figure 1. We have already confirmed the dramatic improvement of the reliability of the fracture strength by the sintering process of the compressive residual stress over 500 MPa in the piezoelectric thick films. The experimental output spectrum of figure 2 has the resonant frequency 59.3 Hz and the maximum generation power 180 μW at the vibrational acceleration 0.98 m/s² and the load resistance 197.8kΩ.

2.2. A design method by the equivalent circuit model
Structure of the PVEH are optimized by theoretical models of equivalent circuit (figure 3) based on the lumped parameter model [4] and the piezoelectric constitutive equations [5]. The equivalent circuit model consists of mechanical and electrical systems, and a transformer connecting these two systems.
The mechanical systems consist of a metallic cantilever beam with piezoelectric films, while the electrical ones are composed of electrode capacitances as shown in figure 1. In the case of sinusoidal excitation, i.e. \( f(t) = F \sin(\omega t) \), we have formulated the output power \( P_{\text{out}} \) as follows.

\[
P_{\text{out}} = 0.5 R v_c^2 \left( R + R_c \right) \left( R + R_c \right)^2 + X_c^2 \right]^{-1}.
\]

\[
V_c = \left[ K^2 + 1 - (\omega/\omega_0)^2 \right] + jD \right]^{-1} \Gamma + K^2 F,
\]

\[
R_c = \left( \omega C \right)^{-1} D K^2 \left[ D^2 + \left[ K^2 + 1 - (\omega/\omega_0)^2 \right] \right]^{-1},
\]

\[
X_c = \left( \omega C \right)^{-1} D K^2 \left[ D^2 + \left[ K^2 + 1 - (\omega/\omega_0)^2 \right] \right]^{-1} + \left[ D^2 + \left[ K^2 + 1 - (\omega/\omega_0)^2 \right] \right]^{-1}.
\]

\[
K = \Gamma / \sqrt{C k},
\]

\[
D = \left( \omega/\omega_0 \right) Q^{-1},
\]

\[
Q = m o_0 c^{-1},
\]

where \( \Gamma \) is the turns ratio of the transformer, \( C \) is the capacitance of electrodes-sandwiched PZT, \( m \) is the tip-mass, and \( k \) is the spring coefficient of the trapezoidal cantilever formulated as follows.

\[
\Gamma = 3(1 - v_s) \left( h_s + h_p \right) L_n \left( 2L - L_n \right) \kappa d^{-1}
\]

\[
C = 0.5 e_{33} L_n \left[ w_o (2L - L_n) + w_i L_n \right] \ell h^{-1}
\]

\[
o_0 = \sqrt{k m^{-1}},
\]

\[
k = k_d \kappa d^{-1}.
\]
\[
\kappa_a = 8Y_p h_p^2 + 12Y_p h_p^2 h_s + 6Y_p h_p h_s^2 + Y_s h_s^2, \\
\kappa_d = 6(w_0 - w_1)^3 L^2 w_0^2 \left[ r^2 - 2(1 - r)(1 - r) \log |1 - r| + r \right], \\
r = (w_0 - w_1) w_0^{-1},
\]

where \( Y_p \) and \( Y_s \) are Young’s modulus of the piezoelectric film and substrate, respectively. To accurately reproduce experimental values of the PVEH, we have performed fitting processes. More specifically, we have calculated the theoretical \( P_{\text{out}} \) spectra by the equation (1) with various \( Q_s \) as shown in figure 2, where the \( Q \) means a mechanical quality factor defined by the equation (7). We can find the \( Q=86 \) spectrum is the best theoretical curve to fit the experimental ones in figure 2. Based on the extracted parameters, we can accurately reproduce output spectra by the theoretical calculations.

3. Harvesting characteristics of PVEHs in shoes

In order to estimate the generating power by PVEHs during running, we attached acceleration sensors in the soles of the prototype shoes as shown in figure 4. We measured the vibrational accelerations while 6 male subjects (21 to 27 years old students) jog on a pavement surface while wearing shoes. Figure 5 shows an example of the time dependent of the acceleration. The acceleration maxima are about 300 m/s\(^2\) when the shoes land on the pavement surface.

![Figure 4](image1.png)

**Figure 4.** A shoe with acceleration sensors in the sole.

![Figure 5](image2.png)

**Figure 5.** An example of the time dependent of the acceleration at a sole.

![Figure 6](image3.png)

**Figure 6.** A time dependent of the output voltage by the reproduced acceleration.

We measured the output generation characteristics of the above-mentioned PVEHs fixed on the vibrator in the excitation of impulses with acceleration maxima about 300 m/s\(^2\). Figure 6 shows an example of the time dependent of the output voltage. We can observe damped trains with voltage maxima about ±50V, which are appeared by impacts when the shoes land on the surface. Based on the measured voltages and the load resistance, we have estimated the ac power generation as 360 to 1200 \( \mu \)J per one step, which is depend heavily on the subjects.
4. **Manufacturing prototype shoes**

We have manufactured prototype sports shoes with a sole containing W20 mm × L60 mm × H14 mm resin housing, which contains two PVEHs with a power supply circuit, controller and Bluetooth LE module, as shown in figure 7. Further, we have incorporated the housing in the arch section of the shoe so as to avoid spoiling the design and the feeling. We have confirmed to be able to frequently transmit the sensing data from the beacons of Bluetooth LE when the subjects practically run while wearing shoes. So we can draw Bluetooth-transmitted foot pressures on a PC as shown in figure 7. Currently, we are applying this technique to the pose recognitions, feedback systems of voice, optical indicators of foot pressures and so on.

![The housing containing two PVEHs](image)

**Figure 7.** A prototype shoe with the PVEH module and Bluetooth-transmitted foot pressures drawn on a PC.

5. **Conclusions**

We have developed PVEHs generated by impulsive forces on the soles of shoes during walking and running. We have also manufactured prototype sports shoes with a sole containing resin housing, which contains two PVEHs, a power supply circuit, controller, Bluetooth LE module, and others. We have confirmed to be able to frequently transmit the sensing data from the beacons of BLE when the subjects practically run while wearing shoes. Currently, we are developing smart shoes that can monitor runners’ postures by using prototype shoes, and designing each device parameters using by equivalent circuit models.

**References**

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