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Designing and manufacturing a piezoelectric tile for harvesting energy from footsteps

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ABSTRACT

The objective of this research is to design a piezoelectric tile for harvesting energy from footsteps and to optimize the system for harvesting maximum energy. Because piezoelectric modules easily break when directly subjected to energy generated by human movements, we designed a tile that employs indirect energy transmission using springs and a tip mass. We aimed at matching the mechanical resonance frequency of the tile with that of the piezoelectric modules. The resonance frequency of a piezoelectric module with a 10-g tip mass was almost similar to the vibration frequency of the tile at 22.5 Hz when we dropped an 80-g steel ball from a 1-m height. We performed impedance matching and realized a matching value of 15 kΩ. Under these optimal mechanical and electrical conditions, we harvested 770-μW RMS and 55-mW peak output power.

1. Introduction

Over the past ten years, research studies on piezoelectric energy harvesting have been extensively conducted [1–18]. Among them, studies on piezoelectric energy harvesting from human force have also been actively conducted. These studies include the energy harvested from the bending of elbow or finger joints [19], implants in the knee joints [20], electricity generated using polyvinylidene difluoride attached to bag straps [21], piezoelectric modules inserted under the soles of shoes [22–25], or motion of the human limbs [26,27].

The power generated from wearable devices such as shoes or backpacks can be utilized as micro-electricity sources for auxiliary power. Although the above mentioned cases cannot be considered as macro-sources because of their limited installation area, independent units such as piezoelectric tiles can be planted over a wider area; thus, they can be used as macro-power sources.

Two ways of generating power from piezoelectric modules are available: hitting [28–31] and vibrating [32–42]. Hitting involves the transfer of energy directly to the piezoelectric modules, and thus, it generates more power than the vibrating method of generating power. However, because the hitting method of generating power can easily break the modules, the vibrating method has been studied more widely. Ceramic piezoelectric modules can be easily broken when directly subjected to energy generated from human movements. Therefore, we developed a piezoelectric tile that employs an indirect method of energy transmission using a spring and a tip mass.

This research is aimed at matching the resonance frequency of a cantilevered piezoelectric module with the frequency of a piezoelectric tile. In addition, we optimize the circuits through impedance matching after mechanical optimization by frequency matching.

2. Method

Fig. 1 shows the piezoelectric tile used in our experiment. Fig. 1(a) shows that it is modeled on a real tile, and its area is $150 \times 150\ mm^2$. Fig. 1(b) shows that the piezoelectric tile consists of an upper plate that has to be directly stepped on, a middle plate where the piezoelectric modules are set up, a bottom plate, and four supporting springs. The middle plate is piezo installed layer

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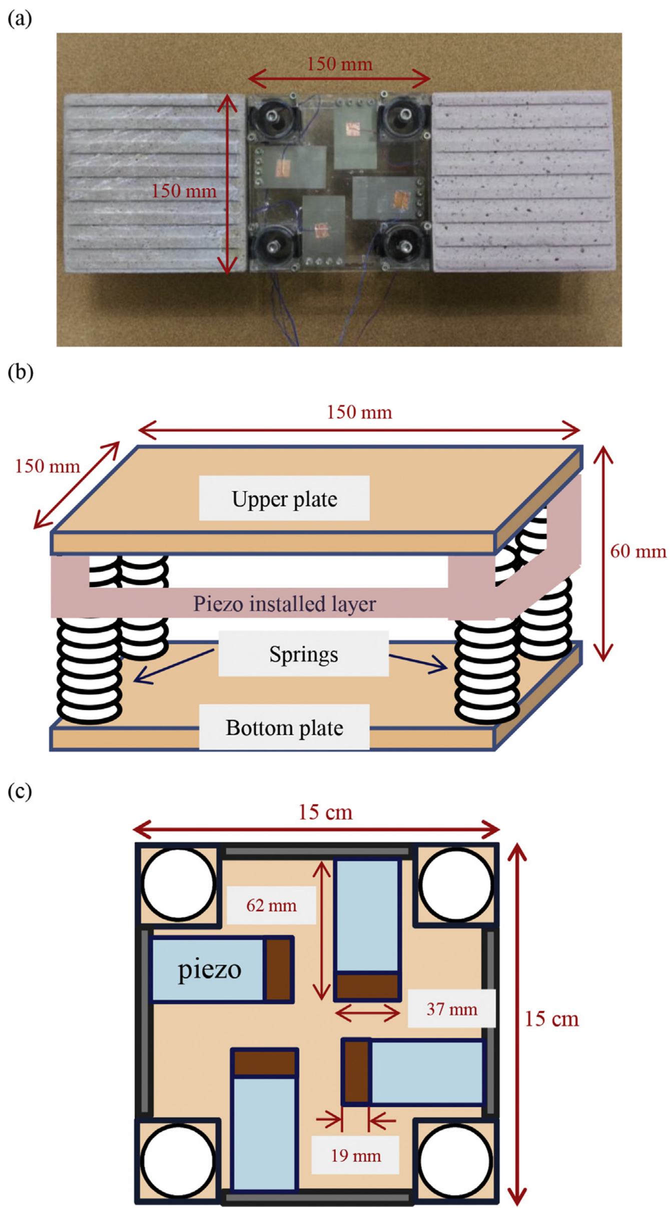

Fig. 1. Conceptual design of the piezoelectric and real tiles. (a) Real piezoelectric tile with a real tile. (b) Illustration of the piezoelectric tile. (c) Piezo-installed layer.

which is attached upper plate. The length of the four springs is 40 mm, and the thickness of the upper and bottom plates is 10 mm each. Fig. 1(c) shows a detailed image of the cross section of the middle part where the modules are placed. The piezoelectric material with the dimension of 47 × 32 × 0.2 mm^3 is placed on a substrate of stainless steel plate having the dimension of 62 × 37 × 0.2 mm^3. The thick film piezoelectric material is PZT-PZNM manufactured by TIOCEAN (Korea). Table 1 lists the properties of the piezoelectric material.

2.1. Frequency matching between the piezoelectric tile and the piezoelectric module

Theoretically, resonance frequency of the cantilever beam relies on effective stiffness of the beam and effective mass of both beam and a tip mass [43].

Table 1
Material properties of the piezoelectric module.

Piezoelectric material	Value
Density (g/cm^3)	7.60
Dielectric constants ($\varepsilon_{33}T/\varepsilon_0$)	21
Piezoelectric charge constants ($\times 10^{-12}$ m/V): d_{33}, d_{31}	450, −200
Piezoelectric voltage constants ($\times 10^{-3}$ V m/N): g_{33},g_{31}	22.1, −11.1
Elastic constants ($\times 10^{-12}$ m^2/N): $S^E{}_{11}$, $S^D{}_{11}$	13.8, 11.8
Stainless steel (SUS-304)	Value
Density (g/cm^3)	8
Young's modulus (GPa)	193

$$\omega_{beam} = \sqrt{\frac{K_{beam}}{m_{eff}}} \tag{1}$$

Effective stiffness (K_{beam}), which can be written as

$$K_{beam} = \frac{b}{4L^3}\left(\sum_{i=1}^{n_1} n_i E_i h_i^3 + \sum_{j=1}^{n_2} n_j E_j h_j^3\right) \tag{2}$$

where b is the width of the beam, L is the length of the beam; n_1 and n_2 are the numbers of piezoelectric and electrode layers; E_i and h_i are the Young's modulus and height of each piezoelectric layer; and E_j and h_j are the Young's modulus and height of electrode layer, respectively. The effective mass of cantilever beam (m_{eff}) with the tip mass can be approximated as

$$m_{eff} = m_t + 0.23bL\left(\sum_{i=1}^{n_1} n_i \rho_i h_i + \sum_{j=1}^{n_2} n_j \rho_j h_j\right) \tag{3}$$

where m_t is tip mass; and ρ_i and ρ_j are the densities of the piezoelectric and electrode plate, respectively [44].

In order to find out the natural frequency of the tile, we dropped an 80-g steel ball from a height of 1 m for equal input energy. The displacement sensor ZS-HLDS10 shown in Fig. 2(a) is manufactured by Omron (Korea), and the DPO-4054B oscilloscope is manufactured by Tektronix (USA). The displacement sensor measured the displacement of the vibrating surface when the steel ball hit the surface under free fall.

Fig. 2(b) shows the experimental tools used for measuring the resonance frequency of the piezoelectric module with a tip mass. The function generator is model 33250A manufactured by Agilent (USA), the vibration exciter is model 4809 manufactured by Brüel & Kjær (Denmark), and the power amplifier is model 2718 manufactured by Brüel & Kjær (Denmark). We used the displacement sensor to measure the vibration displacement on the surface when the 80-g steel ball fell on it.

Using the exciter shown in Fig. 2(b), we determined the different resonance frequencies by varying the tip mass at 0, 10, 30, and 50 g. Subsequently, we checked whether the output voltage was high near the resonance point by measuring the voltage using different tip masses.

From the experiment described, we adopted the tip mass with the most similar resonance frequency to the vibration frequency of the tile.

2.2. Impedance matching using resistive component and application to real conditions

Extracted power from piezoelectric module, which can be written as