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Asymmetric PZT bimorph cantilever for multi-dimensional ambient vibration harvesting

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Abstract

A vibration based piezoelectric cantilever energy harvester was investigated as a power source by generating the electricity from two-dimensional ambient vibrations (less than 1 g and 60 Hz) for mobile handsets, building automation, medical, and defense applications. The proposed energy harvester was designed and fabricated by using a bimorph lead zirconate titanate (PZT) bender and an aluminum inertial mass. In order to harvest the two dimensional vibrations, the fabricated inertial mass was asymmetrically assembled at the end of the PZT bender by adjusting the center of mass. The asymmetric inertial mass contributes to generate power from the vibration applied into the length and thickness directions of PZT bender. The fabricated bimorph PZT bender exhibited a volume of $36 \times 10 \times 0.72$ mm^{3}and capacitance of 7.5 nF. The fabricated device generated the maximum output power at the resonant frequency of 45 Hz and the load impedance of 100 kΩ for input vibrations in the *z*-axis and the *x*-axis. The output powers and voltages were approximately 7.5 mW and 38.5 V for the *z*-axis and 1.4 mW and 16.7 V for the *x*-axis when 10 m/s^2 of acceleration was applied at its resonant frequency.

Keywords: D. PZT; Energy harvesting; Asymmetric mass

1. Introduction

Energy harvesting technologies, which convert the ambient energy of things such as light, heat, and mechanical vibrations into electrical power, have received much attention for micro-power systems. Since the traditional power sources like chemical batteries have some limitations due to their maintenance. These limitations result in considerable problems and costs for the hazardous and harsh environments and autonomous systems. Moreover, the development of low-power integrated circuits (ICs) has reduced power consumption to only tens to hundreds of micro-watts. Therefore, micro-power generators using ambient energy harvesting coupled with low-power ICs have lead to sustainable tiny wireless sensors such as implanted biomedical sensors, intelligent buildings and structures, wearable devices, and wireless sensor networks [1–4].

The vibration energy has great potential for micro-power generation because it has a relatively higher power density than the other types of energy, infinite lifetime, and reliability in harsh environments due to the absence of physical connections to the outside world. Therefore, electromechanical devices have been studied in order to generate power from mechanical vibrations by means of electromagnetic, electrostatic, and piezoelectric principles. Their basic designs utilize a mass spring damper system in which the mechanical parts move in accordance with transducers under the influence of an external vibration. In these electromechanical devices, the maximum output power is achieved at the resonant frequency [3–12].

Many research groups have reported that energy harvesting devices that using ambient vibrations have exhibited output powers ranging from micro- to milli-watts. Bulk-prototype piezoelectric energy harvesters have been developed and demonstrated by using various structures and transduction modes [5–7]. To address the size and volume issues, a few groups have reported micro-machined piezoelectric vibration energy harvesters. In order to present feasibility as a power

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source, they reported the micro-machined power generator which generated several micro-watts of output power from induced vibration [8–12]. While they presented promising results, these devices are limited to generate electrical power from one dimensional vibration source [3–12]. Since the ambient vibrations are existed in two or three dimensional directions, the previously reported devices are limited for practical use.

In this paper, the piezoelectric energy harvesting device was investigated to generate the electricity from two-dimensional vibrations. The proposed device was comprised of the bimorph PZT bender with asymmetrically attached inertial mass. The induced vibration in the length direction of PZT bender could be coupled to the PZT bender in its fundamental mode due to the asymmetric inertial mass. The proposed device was optimally designed, fabricated, and characterized.

2. Design and fabrication

As shown in Fig. 1, the proposed energy harvesting device consists of a bimorph PZT bender and an asymmetric inertial mass. The inertial mass located at the end of PZT bender helps to generate electrical power from the vibration applied through the thickness direction of PZT bender, z-axis [1–3]. The motion of vibration is coupled to generator by means of the inertia of total mass. This mass (m) is suspended by a spring with spring constant (k), while its motion is damped by a parasitic damping (b_m). It is also damped by the generator (P_g). Fig. 2(a) shows a schematic drawing of proposed vibration based piezoelectric energy harvester. The angular displacement of inertial mass is $\theta(t)$ and the induced vibration in the z-axis is represented by $z(t)$. Fig. 2(b) shows the equivalent circuit of vibration energy harvester. The piezoelectric coupling at between electrodes is modeled as a transformer. The dielectric and piezoelectric losses are neglected in this analysis. The detail analysis for the z-axis vibration can be presented at [3].

In order to harvest another vibration which is existed through the length direction of PZT bender, the x-axis, the inertial mass was asymmetrically divided by the PZT

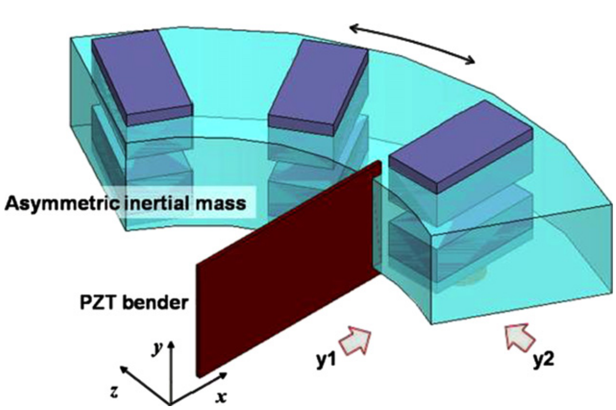

Fig. 1. Conceptual drawing of proposed asymmetric piezoelectric bimorph cantilever for two-dimensional vibration energy harvesting.

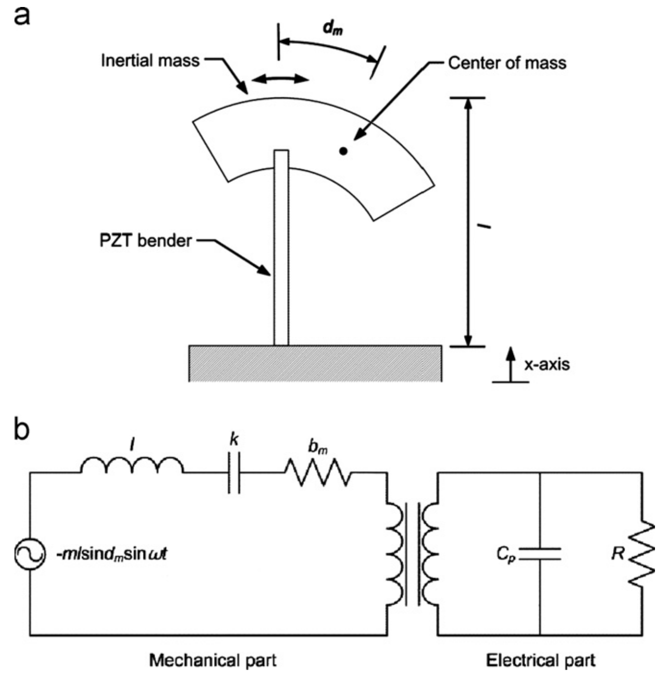

Fig. 2. Schematic drawing (a) and equivalent circuit representation (b) of proposed piezoelectric energy harvester.

bender by adjusting the center of mass. Therefore, the motion of vibration in the x-axis could be coupled to the PZT bender in the fundamental mode. This driving force could be derived by the angular distance from the cantilever tip to the center of effective mass (d_m) as shown in Fig. 2. Hence, the magnitude of external bending momentum (M) at the PZT bender from the induced vibration in the x-axis is given by

$$M = m\ddot{x}l \sin d_m \tag{1}$$

where $\ddot{x}$ is the displacement from the induced vibration in the x-axis of this system and l is the cantilever length.

The external bending momentum is balanced by the toques from the internal stress in the beam. Therefore, the mechanical part in Fig. 2(b) with the vibration in the x-axis can be approximately expressed as

$$m\ddot{x}l \sin d_m = I\ddot{\theta} + b_m\dot{\theta} + k\theta + \frac{k_2 Y_c d_{31}}{t} v \tag{2}$$

where I is the momentum of inertia of PZT bender, d_{31} is the piezoelectric constant, t is the distance between electrode, and k_2 is the transformation factor for piezoelectric power generator.

The generated output voltage across the PZT bender can be described by using electrical part in Fig. 2(b):

$$\dot{v} = N\frac{d_{31}t}{\varepsilon}k_1\dot{\theta} - \frac{1}{RC_p}v \tag{3}$$

where ε is the dielectric constant, C_p is the capacitance of PZT bender, k_1 is the transformation factor for piezoelectric energy harvester, and R is the load resistor.

The analytical expression for power transferred to the load can be derived by taking the Laplace transform of

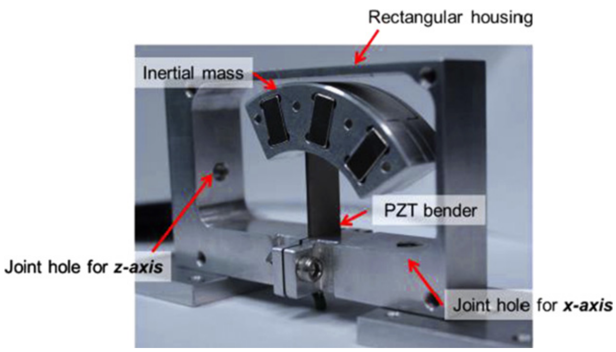

Fig. 3. Photomicrograph of fabricated energy harvester and fixture with a bimorph PZT bender and an asymmetric aluminum inertial mass.

Eqs. (2) and (3) [3]. Therefore, the output voltage is given by

$$v = \frac{-j\omega(d_{31}k_1 t/\varepsilon)\sin d_m \ddot{x}}{1/RC_p\omega_0^2 - ((1/RC_p) + 2\varsigma\omega_0)\omega^2 + j\omega\left[\omega_0^2\left(1+k_p^2\right) + (2\varsigma\omega_0/RC_p) - \omega^2\right]} \quad (4)$$

where k_p represents the electromechanical coupling coefficient.

In order to confirm the proposed device structure, the energy harvesting device was fabricated by using PZT bender, which could convert the vibration of 45 Hz to electrical power.

The utilized bimorph PZT bender exhibited a volume of $36 \times 10 \times 0.72\ \text{mm}^3$. The thickness of each PZT layer was 0.3 mm. The asymmetric aluminum inertial mass was also designed and fabricated by milling machining to scavenge the several tens hertz of low vibrations as shown in Fig. 2. It had inner diameter, outer diameter, thickness, and spread angle of 20 mm, 30 mm, 12 mm, and 90°, respectively. The PZT cantilever had a length of 10 mm and an angular distance from the cantilever tip to the center of mass was approximately 15°. As shown in Fig. 3, the PZT cantilever and inertial mass were fixed to the rectangular housing which has a joint hole in each 90° for mounting the device onto a vibration exciter in the x-axis or the z-axis. The output voltage of the proposed energy harvester for the vibration in the x-axis can be expected to become approximately 25.8% of the output voltage under the vibration in the z-axis from Eq. (4). However, the conventional energy harvester with symmetric inertial mass cannot generate electricity from induced vibration in x-axis because it has an angular distance of 0°, $d_m = 0$. Fig. 3 shows the fabricated piezoelectric cantilever energy harvester by using the PZT bender and asymmetric aluminum inertial mass.

3. Experimental results and discussions

Firstly, the polarization characteristic of the fabricated PZT cantilever bender was measured by using the Sawyer–Tower circuit with triangular waveform. Fig. 4 shows the measured polarization versus the applied voltage hysteresis loop of the bimorph PZT bender. A remanant polarization of $12.5\ \mu\text{C/cm}^2$ and coercive field of 3.5 kV/cm were measured. The capacitance measured using an HP4194A was 7.5 nF. Therefore, the extracted relative dielectric constant was approximately 2952.

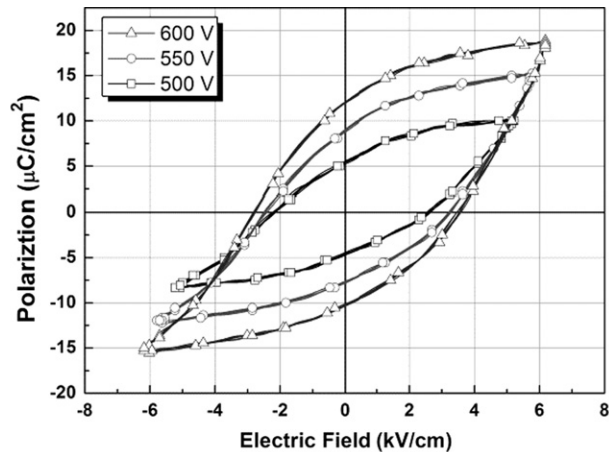

Fig. 4. The measured polarization curve of the fabricated bimorph PZT bender for two-dimensional vibration energy harvesting.

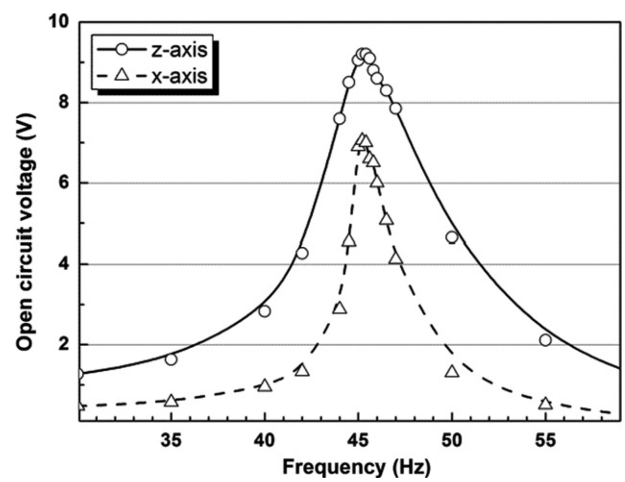

Fig. 5. The measured open circuit voltages of the fabricated harvesting device at induced vibration of $1\ \text{m/s}^2$ of acceleration and frequencies ranged from 30 to 60 Hz.

The device characterization was performed by using vibration exciter, power amplifier, accelerometer, and voltmeter. The fabricated device was connected to the voltmeter and attached on the vibration exciter by using the joint hole for harvesting the x-axis or the z-axis vibration. The input vibration and output voltage were measured by using the 8305 reference accelerometer and voltmeter, respectively. As shown in Fig. 5, the fabricated device installed at the the x-axis and the z-axis exhibited the maximum output voltage at its resonant frequency of 45 Hz.

The optimal load impedance (R_{opt}) for maximum power transfer was found by varying the resistive loads at the $1\ \text{m/s}^2$, $5\ \text{m/s}^2$, and $10\ \text{m/s}^2$ of input vibration and the resonant frequency of 45 Hz. The optimum load

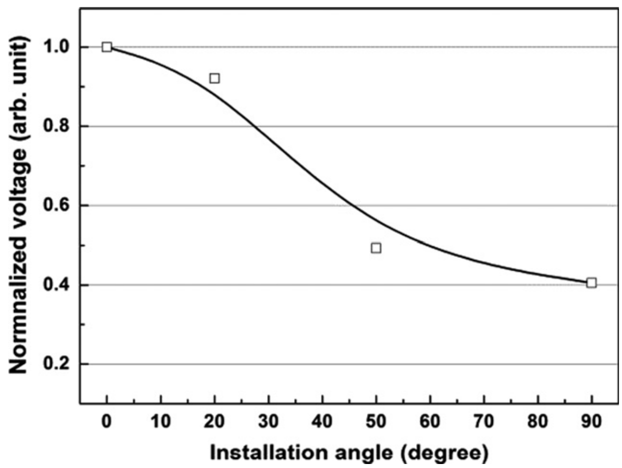

Fig. 6. The normalized output voltages of the fabricated energy harvesting device at various installation angles.

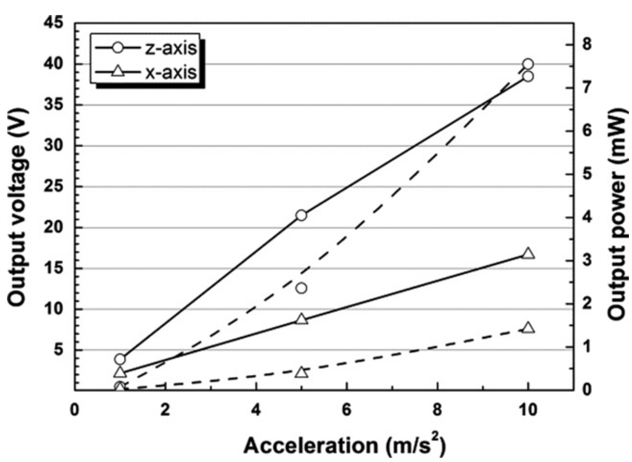

Fig. 7. The measured output load voltages (dotted line) and powers (solid line) of the fabricated harvesting device at its resonant frequency and various accelerations ranged from 1 to 10 m/s^2.

resistances were determined as approximately 100 kΩ for obtaining the maximum output power for the applied vibrations in the x-axis and the z-axis direction. While the conventional device has a limitation for energy harvesting at various installation angles as discussed before, the fabricated device could generate electricity at the installation angles ranging from 0 to 90° as shown in Fig. 6. The generated output voltage in the x-axis vibration (90°) was more than 40% of output voltage from the z-axis vibration (0°).

Fig. 7 shows the measured output voltages and powers at the various accelerations and its resonant frequency. As expected, the output power for the z-axis vibration was much larger than the x-axis vibration due to the large deflection of PZT bender. The obtained output powers and voltages were approximately 7.5 mW and 38.5 V for the z-axis and 1.4 mW and 16.7 V for the x-axis when 10 m/s^2 of acceleration was applied at its resonant frequency (34 Hz for the z-axis and 40.5 Hz for the x-axis).

4. Conclusions

This paper presented a piezoelectric vibration energy harvester to generate the electricity from two-dimensional ambient vibrations (less than 1 g and 60 Hz). The proposed energy harvester was designed and fabricated by using a bimorph lead zirconate titanate (PZT) bender and an inertial mass attached asymmetrically. The asymmetric inertial mass was effective to generate power from the vibration applied into the length and thickness direction of PZT bender. Future work will include the design and fabrication of micro-fabricated piezoelectric power generator with high performances for multi-dimensional ambient vibration harvesting.

Acknowledgments

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