A TWO-DIMENSIONAL VIBRATION ENERGY HARVESTER USING AN PIEZOELECTRIC BIMORPH CANTILEVER WITH AN ASYEMTERIC INERTIAL MASS

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Abstract: A piezoelectric vibration energy harvester was investigated to generate the electricity from two-dimensional ambient vibrations (less than 1g and 60Hz) for mobile handsets, building automation, medical, and defense applications. The proposed energy harvester was designed and fabricated by using a bimorph PZT (lead zirconate titanate) bender and an 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 direction of PZT bender. The fabricated device generated 7.5 mW and 1.4 mW of electrical power from the induced vibration through the thickness and length direction of PZT bender, respectively.

Keywords: energy harvesting, two dimensional vibrations, PZT, ambient vibrations, asymmetric mass

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, because the traditional power sources, e.g., chemical batteries, have 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 ICs (integrated circuits) has reduced power consumption to only tens to hundreds of microwatts. 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, wireless sensor networks, etc [1-4].

The vibration energy has great potential for micro-power generation because it has a relatively higher power density, an 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 harvesting devices, the maximum output power is achieved at their resonant frequencies [3-12].

Energy harvesting devices previously reported that use ambient vibrations have exhibited various output powers ranging from micro- to milliwatts. Bulk-prototype piezoelectric energy harvesters have been researched to improve their performances by varying geometrical structures and transduction modes [5-7]. To reduce their sizes and volumes, a few groups have reported micro-machined piezoelectric vibration energy harvesters. These micro-machined power generators have generated several micro-watts of output power from induced vibrations [8]-[12]. However, 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, a piezoelectric energy harvesting device is newly designed, fabricated, and characterized to generate the useful electricity from two-dimensional ambient vibrations. The proposed device was comprised of the bimorph PZT bender attached with inertial mass asymmetrically. 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.

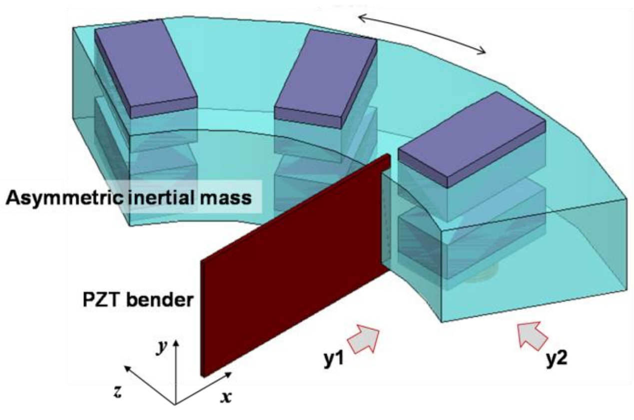
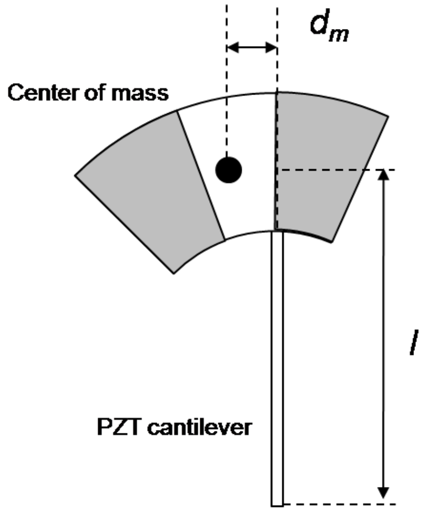
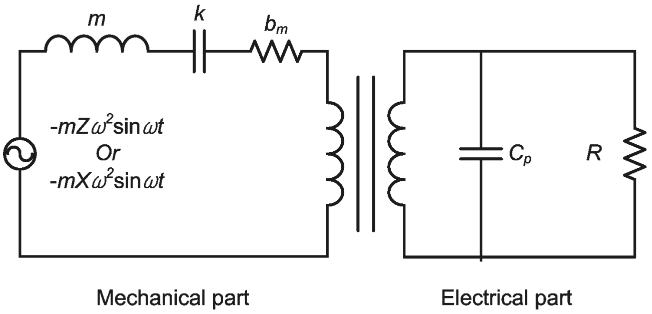


Fig. 1: Conceptual drawing of proposed piezoelectric power generator for two-dimensional vibration energy harvesting.



(a)



(b)

Fig. 2: Schematic drawing (a) and equivalent circuit representation (b) of proposed piezoelectric power generator.

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 one-dimensional vibration which is 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 modeled as being suspended by a spring with spring constant (k), while its motion is damped by a parasitic damping (b_m). This mass also damped by the generator (P_g). Fig. 2 (a) shows a schematic drawing of vibration energy harvester. The displacement of total mass is $\theta(t)$ and the displacement in z-axis of this system 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 mechanical part in Fig. 2 (b) can be obtained by applying Kirchhoff's law as

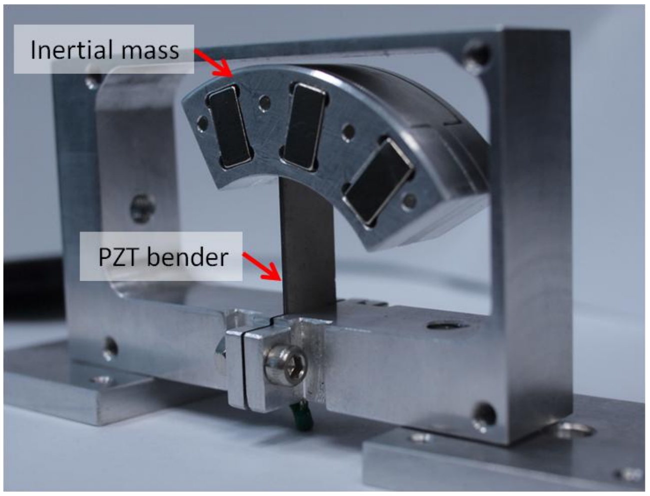


Fig. 3: Photomicrograph of fabricated device and fixture by using a bimorph PZT bender and an asymmetric aluminum inertial mass.

$$m\ddot{z} = m\ddot{\theta} + b_m\dot{\theta} + k\theta + \frac{k_2 Y_c d_{31}}{t}v \qquad (1)$$

where d_{31} is the piezoelectric constant, t is the distance between electrode, and k_2 is the transformation factor for piezoelectric power generator.

The detail analysis for z-axis vibration was well presented in [3]. In order to harvest another vibration which is existed through the length direction of PZT bender, x-axis, the inertial mass was asymmetrically divided by the PZT bender by adjusting the center of mass. Therefore, the motion of vibration in x-axis can be coupled to the PZT bender in fundamental mode. This driving force can be derived by the distance from the cantilever tip to the center of effective mass (d_m) as shown in Fig. 2. Hence, the mechanical part in Fig. 2 (b) with the vibration in x-axis can be approximately expressed as

$$m\frac{d_m}{l}\ddot{x} = m\ddot{\theta} + b_m\dot{\theta} + k\theta + \frac{k_2 Y_c d_{31}}{t}v \qquad (2)$$

where x is the displacement in x-axis of this system and l is the cantilever length.

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

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

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

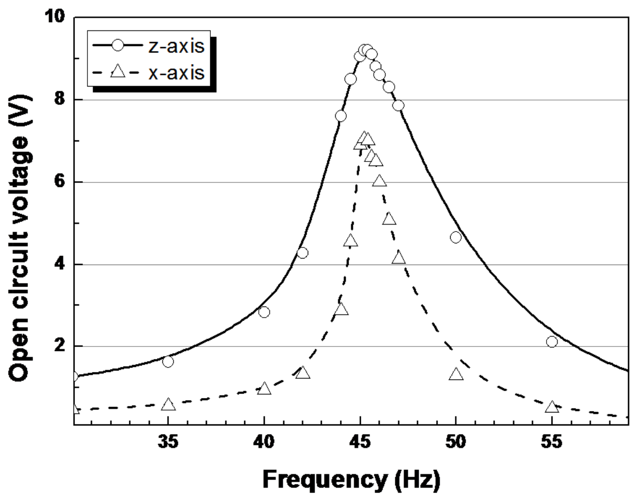


Fig. 4: The measured open circuit voltages of fabricated harvesting devices at induced vibration of 1m/s² of acceleration and frequencies ranged from 30 to 60 Hz.

The analytical expression for power transferred to the load can be derived by taking the Laplace transform of (2) and (3) [3]. Therefore, the output voltage is given by

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

where k_p represents the electro-mechanical coupling coefficient.

In order to verify the effectiveness of the proposed structural geometry, the energy harvesting device was fabricated by using PZT bender to convert the vibration of 50Hz to electrical power. The fabricated bimorph PZT bender exhibited a volume of 36 × 11 × 0.6 mm³ and capacitance of 25 nF. The asymmetric aluminum inertial mass was also designed and fabricated by using a milling machining to scavenge the several tens Hz of low vibrations as shown in Fig. 2. Its inner diameter, outer diameter, thickness, and spread angle are 20 mm, 30 mm, 12 mm, and 90°, respectively. The PZT cantilever had a length of 10 mm and the distance from the cantilever tip to the center of mass was approximately 3.88 mm. Therefore, the output voltage of energy harvester for the vibration in x-axis was expected to become 26% of the output voltage under the vibration in z-axis. This PZT cantilever and inertial mass were fixed at the rectangular housing which has a joint hole in each 90° to attach the PZT cantilever in x-axis and z-axis of vibration exciter. Fig. 3 shows the demonstrated energy harvesting devices by using PZT bender and asymmetric aluminum inertial mass and the rectangular housing.

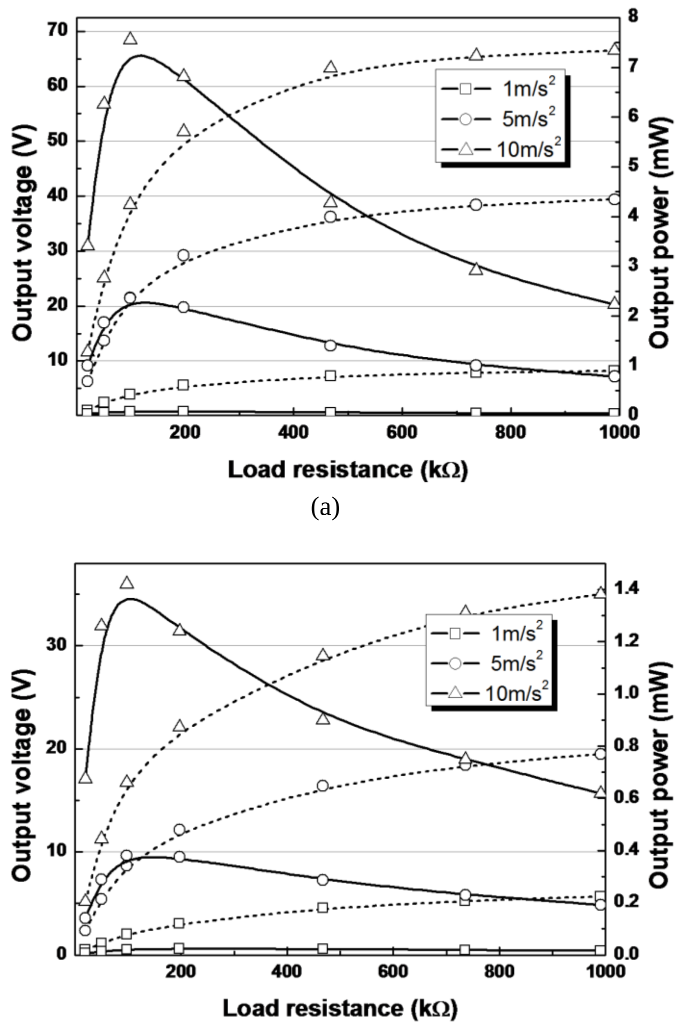


Fig. 5: The measured output load voltages (dotted line) and powers (solid line) of the fabricated harvesting device at various load resistances from z-axis (a) and x-axis (b) vibrations.

EXPERIMENTAL RESULTS

The measuring experiment of harvester was performed by using vibration exciter, power amplifier, accelerometer, and voltmeter. The fabricated device was connected to the voltmeter and attached on the 4809 vibration exciter of Brüel & Kjær. The input vibration was measured by using the 8305 reference accelerometer of Brüel & Kjær.

As shown in Fig. 4, the fabricated device generated the maximum output power at the resonant frequency of 45Hz for input vibrations in z-axis and x-axis. The optimal load impedance (R_{opt}) for maximum power transfer was found by varying the resistive loads at the 1m/s², 5m/s², and 10m/s² of input vibrations and the resonant frequency of 45Hz. The optimum load resistances were determined as approximately 100 kΩ for obtaining the maximum output powers for the applied vibrations in x-axis and z-axis direction, as shown in Fig. 5.

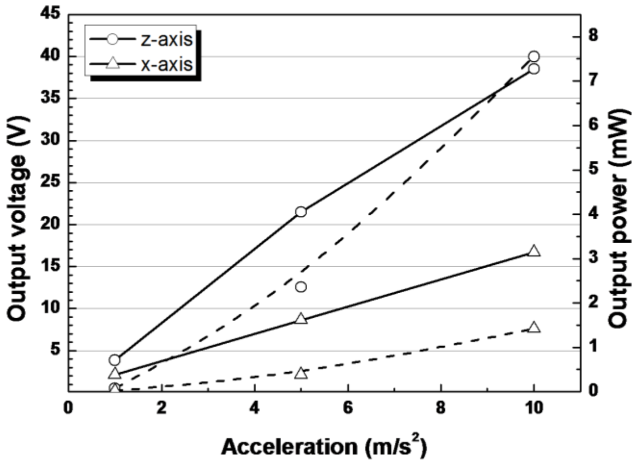


Fig. 6: The measured output load voltages (dotted line) and powers (solid line) of the fabricated harvesting device at its resonant frequency and various accelerations ranged from 1 to 10 m/s^2.

Fig.6 shows the measured output voltages and powers at the various accelerations and its resonant frequency. As expected, the output power for 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 z-axis and 1.4 mW and 16.7 V for x-axis when 10m/s^2 of acceleration was applied at its resonant frequency (34Hz for z-axis and 40.5Hz for x-axis).

CONCLUSION

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

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