Energy harvesting from low-frequency vibration using a shear-mode rectangular cymbal transducer with a piezoelectric array

Wei He¹⁴, Jitao Zhang² and Aichao Yang³

¹ School of Information Engineering, Baise University, Baise 533000, China;
² College of Electric and Information Engineering, Zhengzhou University of Light Industry, Zhengzhou 450002, China;
³ Jiangxi Electric Power Research Institute, Nanchang 330096, China.
⁴ E-mail: weiheky@yeah.net

Abstract. Energy harvesting from ambient environment has become a hot topic in recent years. In this paper, a shear-mode cymbal transducer is proposed to convert vibration energy into electric energy. The harvester is composed of a piezoelectric array, two brass caps, added mass, and an aluminum plate. Shear stress is induced on the piezoelectric array under vibration due to the interaction of the caps and the aluminum plate. The harvester then produces electric power. A prototype is fabricated. The prototype exhibits a flat response at low frequency of 20 Hz - 38 Hz. Under an acceleration of 1.0 g, the shear-mode device can generate a load power of 0.88×10⁻⁹ W with an optimal load resistance of 0.5 MΩ.

1. Introduction

Energy harvesting efficiency is closely related to the ambient available energy sources. Energy sources in the environment, such as light, heat, vibration, and magnetic field, can be used for producing electric power. Among these energy sources, vibration is very common for energy harvesting in our daily life [1-3]. The energy extracting from vibration can be converted to electric energy to power electronic devices (e.g., wireless sensor nodes). In the past few years, researchers have developed a variety of methods to capture vibration energy [4, 5].

Cymbal transducers have been used to harvesting ambient energy due to their simple structures and the capability of withstanding high pressure [6, 7]. A typical generator based on a cymbal transducer is fabricated from brass caps and piezoelectric material, and the piezoelectric material works in d31 mode. However, piezoelectric material works in shear-mode has higher electromechanical coupling coefficient. In this paper, we investigate a modified cymbal transducer operating in shear-mode for low-frequency condition. To produce shear stress and enlarge the capacitance, a rectangular mechanism and a piezoelectric array are adopted. Theoretical analysis and experimental research are carried out on the output characteristics of the proposed device.

2. Structure

Figure 1 shows the structure of the proposed shear-mode scavenger. The device is composed of two brass caps, four PMN-PT plates, a retaining plate, and added mass on the top of the upper cap. Under the action of acceleration (the direction of the acceleration is along 1-direction), shear stress is
produced on the piezoelectric plates due to the interaction between the brass caps and the retaining plate. The PMN-PT plates then produce voltage due to piezoelectric effect. To increase the capacitance of the device, the four piezoelectric plates are connected in parallel (the material of the retaining plate is aluminum), as shown in Figure 1.

Figure 1. Schematic diagram of the proposed shear-mode vibration energy harvester.

3. Analysis of the device

According to the mechanism shown in Figure 1, the piezoelectric constitutive equations [8] in shear-mode can be applied. Based on the structural parameters of the rectangular cymbal transducer [9], the open-circuit output voltage can be deduced when the four PMN-PT plates are connected in parallel, which is calculated by

$$ V_{\text{open-circuit}} = \frac{mah_c d}{4Sc_{55}^\beta} (l_a - l_b) $$

where $m$ is the mass adding on the generator, $a$ is the acceleration, $h_{15}$ represents the piezoelectric stiffness constant (in shear-mode), $d$ is the thickness of each piezoelectric plate, $l_a$ is the length of the cap top, $l_b$ is the length of the retaining plate (exclusive of the bonding part), $S$ is the electrode area of one PMN-PT plate, $c_{55}^\beta$ is the elastic stiffness coefficient, and $l_c$ is given by

$$ l_c = l - d $$

where $l$ is the height of the cavity of the harvester.

When a load resistance $R_{\text{load}}$ is connected to the harvester, the generated current $I$ under $R_{\text{load}}$ can be expressed as [10]

$$ I = \frac{dQ}{dt} $$

where $Q$ is the charge. Assuming that $I = I_0 \cos(\omega t + \theta)$, the time-dependent voltage across $R_{\text{load}}$ is

$$ V_{\text{time-dependent}} = R_{\text{load}} I_0 \cos(\omega t + \theta) = V_0 \cos(\omega t + \theta) $$

where $\omega$ is the angular frequency, and $\theta$ is the initial phase. The effective value of $V_{\text{time-dependent}}$ is

$$ V_{\text{load}} = \frac{\sqrt{2}}{2} V_0 $$

Then, the output power $P_{\text{load}}$ and the optimal load resistance $R_{\text{optimal}}$ can be respectively calculated by

$$ P_{\text{load}} = \frac{V_{\text{load}}^2}{R_{\text{load}}} $$

$$ R_{\text{optimal}} = \frac{V_0^2}{P_{\text{load}}} $$
\[ R_{optimal} = \frac{1}{\omega C_{total}} = \frac{1}{2\pi f C_{total}} \]  

where \( C_{total} \) is the total capacitance of the piezoelectric plates which can be expressed as \( C_{total} = 4C \)  

where \( C \) is the capacitance of each piezoelectric plate.

4. Results and discussions

To investigate the output performance of the proposed structure, experiments have been conducted under low-frequency condition. An acceleration of 0.5 g is applied on the harvester to investigate the low-frequency response (non-resonant condition). Figure 2 shows the output voltage versus the frequency of the prototype. As can be seen from Figure 2, the device has a flat response to the frequency. When the frequency increases from 20 Hz to 38 Hz, the output voltage exhibits a minimum value of 19.44 mV and a maximum value of 19.93 mV. The experimental results of the conventional mode (\( d_{31} \) mode) are also plotted in Figure 2 to validate the performance of the proposed structure. In the same frequency range (20 Hz-38 Hz), the output voltage varies in the range of 11.69 mV and 12.12 mV. A distinct improvement is achieved for the proposed structure. The higher outputs of the proposed device are due to the higher piezoelectric constant and the higher electromechanical coupling coefficient of the shear-mode.

The acceleration on the energy harvesting device is increased to 1.0 g, and the excitation frequency is kept at 30 Hz. Changing the load resistance connected to the generator, the load voltage varies according to the load resistance. The power is then calculated using the square of the load voltage divided by the load resistance, and the results are plotted in Figure 3. It can be seen from Figure 3 that the output power has a maximum value of \( 0.88 \times 10^{-9} \) W, and the corresponding matching load resistance is 0.5 M\( \Omega \). Assuming \( Q = Q_0 \sin(\omega t + \theta) \), \( I_0 \) and \( Q_0 \) can be calculated using equations (3)-(5) after obtaining the load voltage \( V_{load} \). Figure 4 plots the relationship of \( V_{load}, I_0 \), and \( Q_0 \). As can be seen from Figure 4, \( I_0 \) and \( Q_0 \) \((Q_0 = I_0/\omega)\) decrease when the load voltage \( V_{load} \) increases. The load power can attain a maximum value at a certain \( R_{load} \) (0.5 M\( \Omega \) in this paper). In real application, the energy
harvesting device can be connected to a power management circuit to provide larger power for low-power electronics, which can instantaneously discharge after charging.

Figure 3. Output power of the proposed shear-mode device versus load resistance at the frequency of 30 Hz with an acceleration of 1.0 g.

Figure 4. Calculated $I_0$ and $Q_0$ as a function of the load voltage $V_{load}$ at 30 Hz.

5. Conclusions
A shear-mode energy harvester is presented in this paper to extract energy from ambient vibrations. A theoretical analysis is conducted under shear-mode condition, and the experimental results are obtained, which verify the practicability of the proposed shear-mode device. The comparison has been carried out with the conventional $d_{31}$ mode, and an obvious increase of the output voltage is achieved when using $d_{15}$ mode. The device with stable outputs can be applied to low-frequency vibration environment.

Acknowledgment
This work is supported by the National Natural Science Foundation of China (Grant Nos. 61761001 and 61503344).
References

[1] Harne R L and Wang K W 2013 Smart Mater. Struct. 22 023001
[2] Zou H X, Zhang W M, Li W B, Hu K M, Wei K X, Peng Z K and Meng G 2017 Appl. Phys. Lett. 110 163904
[3] Gammaitoni L, Neri I and Vocca H 2009 Appl. Phys. Lett. 94 164102
[4] Wang L and Yuan F G 2008 Smart Mater. Struct. 17 045009
[5] Zhou S, Chen W, Malakooti M H, Cao J and Inman D J 2017 J. Intel. Mat. Syst. Str. 28 367
[6] Palosaari J, Leinonen M, Hannu J, Juuti J and Jantunen H 2012 J. Electroceram. 28 214
[7] Moure A, Rodriguez M I, Rueda S H, Gonzalo A, Rubio-Marcos F, Cuadros D U, Pérez-Lepe A and Fernández J F 2016 Energ. Convers. Manage. 112 246
[8] Ikeda T 1990 Fundamentals of Piezoelectricity (Oxford University Press, Oxford)
[9] He W, Lu Y R, Qu C W and Peng J C 2016 Sens. Actuators A 241 120
[10] Ren B, Or S W, Zhang Y, Zhang Q, Li X, Jiao J, Wang Wei, Liu D, Zhao X, and Luo H 2010 Appl. Phys. Lett. 96 083502