Research Article

Study of the Effect of the Segmentation Method on the Power Generation Performance of Rectangular Piezoelectric Energy Harvester

Xiaochao Tian,1 Jinlong Liu,1 Jiayin Lin,1 Shenfang Li,1 Zhicong Wang,1 Jun Hou,1 Sida Zhang,2 Zhigang Yang,2 and Jinzhi Zhu 1

1School of Mechanical and Vehicle Engineering, Changchun University, Changchun, Jilin, China 130022
2School of Mechanical and Aerospace Engineering, Jilin University, Changchun, Jilin 130025, China

Correspondence should be addressed to Jinzhi Zhu; 805521204@qq.com

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Since the piezoelectric energy harvester will generate strain zero point when it is bent, it will affect the power generation effect. In this paper, the strain zero point of the cantilever beam of the rectangular piezoelectric energy harvester is studied through theoretical analysis. The main analysis is the specific location of the strain zero point in the first-, second-, and third-order modes of the cantilever beam of the energy capturer. The results of the theoretical analysis are verified by experimenting with different segmentation methods of piezoelectric energy harvesters. The experimental results show that the piezoelectric energy harvester is segmented at 0.275 in the length direction of the piezoelectric ceramic in the second-order mode, and the output power is 5 times that of the nonsegmented state. In the third-order mode, the piezoelectric energy harvester is segmented at 0.16 and 0.61 in the length direction of the piezoelectric ceramic, and the output power is 5.83 times that of the nonsegmented state. The research in this paper provides new ideas and methods for improving the power generation capacity of piezoelectric energy harvesters.

1. Introduction

With the rapid development of the Internet of Things, people need electronic devices in more and more places in production and life, but electronic devices are often affected by the performance of battery life, so there is an urgent need for a device that can use external energy to convert into electricity for electronic devices to work. Wind energy from the natural environment [1, 2], solar energy [3, 4], vibration energy [5, 6], geothermal energy [7, 8], etc., can generate energy, of which vibration energy is the most widely distributed; other energy collection methods are limited by the application conditions and difficult to be widely used, so the capture of vibration for microelectronic products and systems is more universal significance [9].

Due to the low conversion rate of the piezoelectric material itself, a lot of research has been done to improve the electromechanical conversion efficiency and power generation performance of piezoelectric energy harvester. Among them, Xie et al. compared the output power of a single piezoelectric energy captor with that of multiple piezoelectric energy captors of different sizes in the frequency domain and demonstrated that the synchronous operation of multiple piezoelectric energy captors of different sizes can effectively increase the output power and frequency band width [10]. By changing the cross-sectional shape of the piezoelectric energy trap, Tan et al. and Shan et al. reduced the intrinsic frequency of the piezoelectric energy trap so that the piezoelectric energy trap could achieve high power generation at a lower excitation frequency [11, 12]. Ma et al. designed a variable cross-sectional circular piezoelectric energy trap that could reduce the intrinsic frequency of the piezoelectric cantilever beam [13]. Jia and Seshia investigated the linear piezoelectric cantilever beam both numerically and experimentally and explored the power maximisation of the ratio of mass to cantilever length [14]. Tian et al. improved the
energy conversion rate of a dual-chip piezoelectric energy trap by rationalising the dimensional ratio between the piezoelectric ceramic and the cantilever beam substrate [15]. Liu proposed a miniature iso-intensity beam piezoelectric vibration energy harvesting structure; the output voltage and output power per unit volume of this iso-intensity beam structure are better than those of the iso-section beam piezoelectric energy trap [16]. Du et al. designed a magnetic frequency modulation piezoelectromagnetic composite energy harvesting device, which adds a magnetic broadening device to collect energy in low frequency vibration environment and improve the energy harvesting efficiency [17].

Other researchers have studied piezoelectric energy harvester in segments to improve the energy conversion efficiency of piezoelectric cantilever beams. Among them, Quan et al. modelled a segmented cantilever beam piezoelectric actuator and analyzed that the tip displacement of the segmented ceramic in the second-order mode of the piezoelectric energy trap was 100% larger than that of a continuous cantilever beam [18]. Hu et al. studied the segmented ceramic of the piezoelectric energy trap to determine the relationship between the effective piezoelectric ceramic coverage of the piezoelectric cantilever beam and the electrical energy output of the piezoelectric cantilever beam [19]. Zizys et al. divided the piezoelectric ceramic into two segments by analyzing the constant cross section and the dimensionless numerical transient analysis of the optimally shaped cantilever beam, and the output voltage of the segmented piezoelectric energy trap was increased by 7% compared to the unsegmented one [20]. However, the above studies did not fully investigate the specific locations of the strain zero point in the first-, second-, and third-order modes of the piezoelectric energy trap, and the effect of the electrical energy output of the piezoelectric energy trap segmented at the strain zero point.

In this paper, the location of the strain node on the piezoelectric cantilever beam is investigated through theoretical analysis. By determining the location of the strain node on the cantilever beam, the piezoelectric ceramic is segmented at the strain node, and it is demonstrated using tests that the segmentation of the piezoelectric ceramic at the strain node can significantly improve the energy conversion capability of the piezoelectric energy trap. This segmentation mode provides a new idea and method for improving the electrical energy output performance of piezoelectric energy harvester.

2. Theoretical Modelling and Analysis

Segmented ceramic means that the entire ceramic surface of the piezoelectric ceramic is divided into multiple segments. As shown in Figure 1, the structure of a single crystal chip piezoelectric trap is shown schematically, which consists of a piezoelectric ceramic and a metal substrate glued together by epoxy resin.

The piezoelectric energy trap as shown in Figure 1 is fixedly supported at one end and free at the other. The piezoelectric energy trap in this fixed manner can be equated to a cantilever beam system.

According to the piezoelectric equation,

\[ D_3 = e_{31}S_1 + e_{33}E_3, \]  

where \( D_3 \) is the potential shift, \( e_{31} \) is the piezoelectric constant, \( S_1 \) is the strain, \( e_{33} \) is the dielectric constant, and \( E_3 \) is the electric field strength.

The strain on the neutral layer at a distance from the captive energy source is

\[ S_1 = -x_3 \frac{\partial^2 \omega}{\partial x^2}, \]

where \( \omega \) is the lateral displacement of the energy capturer with respect to the base.

\[ \omega = \omega(x, t) = \sum_{i=1}^{p} \phi_i(x)r_i(t), \]

where \( \phi_i \) is the modal type function of order \( i \), \( r_i \) is the coordinates at order \( i \) of the modalities, and \( p \) is the number of modalities.

\( \phi_i \) can be found from (2) under the boundary conditions.

\[ \frac{d^4 \phi_i(x)}{dx^4} - \left( \frac{\lambda_i}{l} \right)^4 \phi_i(x) = 0, \]

where \( (\lambda_i/l)^4 = ma^2/EI \), \( \lambda_i \) is the eigenfrequencies at the \( i \)th order mode, \( l \) is the length of the cantilever beam, \( m \) is the mass per unit length of the beam, \( \omega_i \) is the intrinsic frequency at the \( i \)th order mode, and \( EI \) is the flexural strength.

The boundary conditions at the fixed end of the piezoelectric energy trap are

\[ \omega_0 = 0, \]

\[ \omega_o' = 0. \]

The boundary conditions at the free end are

\[ EI\omega'' = \omega^3 I_0 \omega + \omega^2 S_0 \omega, \]

\[ EI\omega'' = -\omega^2 M_0 \omega - \omega^2 S_0 \omega, \]

where \( I_o = J + M_0(\alpha_x^2 + \alpha_y^2), \quad J = (M_0(I_0^2 + l_0^2)/12)S_0 = M_0 \alpha_x = m_0 l_0 \alpha_x. \)
Taking equations (4) and (5) into equation (6) yields that
\[
\phi_i = \cosh \lambda_i \frac{x}{L} \cos \lambda_i \frac{x}{L} - \frac{a_{11}}{a_{12}} \left( \sinh \lambda_i \frac{x}{L} \sin \lambda_i \frac{x}{L} \right),
\]
where
\[
a_{11} = (\cosh \lambda_i + \cos \lambda_i) + \lambda_i^3 (I_2/m^2) (-\sinh \lambda_i + \sin \lambda_i),
\]
\[
a_{12} = (\sinh \lambda_i + \sin \lambda_i) + \lambda_i^3 (S_1/m^2) (-\cosh \lambda_i + \cos \lambda_i) + \lambda_i^5 (S_3/m^2) (-\sin \lambda_i + \sin \lambda_i).
\]

3. Simulation Analysis

Based on the above theoretical analysis, the relationship between strain and beam length ratio is obtained in this paper by MATLAB calculation and normalisation, as shown in Figure 2.

As can be seen from the diagram, the cantilever beam has no strain zeros in the first-order mode, the strain zeros in the second-order mode are at 0.275, and the strain zeros in the third-order mode are at 0.16 and 0.61. We know that when the piezoelectric trap strain is in the same direction, the trap output charge is also in the same direction. When both positive and negative charges are present inside a piezoelectric ceramic, the electrical output of the captor will be reduced.

In order to verify the accuracy of the strain zero position, three sets of piezoelectric energy harvester were selected. The first set did not cut the piezoelectric ceramic; the second set cuts the ceramic into two sections at 0.275 in the length direction of the piezoelectric ceramic; the third set splits the ceramic into three sections at 0.16 and 0.61 in the length direction of the piezoelectric ceramic. The positive and negative output voltages of these three groups of piezoelectric energy harvester in the first-, second-, and third-order modes will be verified by the COMSOL simulation software.

As can be seen from Figure 3, the unsegmented piezoelectric trap produces all positive charges in the first-order mode; as can be seen from Figure 4, in the second-order mode, the piezoelectric ceramic is segmented into two segments at 0.275 in the ceramic length direction, and the piezoelectric ceramic to the left of the segmentation line produces negative charges, and the piezoelectric ceramic to the right of the segmentation line produces positive charges; as can be seen from Figure 5, in the third-order mode, the piezoelectric ceramic is segmented into three segments at 0.16 and 0.61 in the ceramic length direction, and the piezoelectric ceramics to the left and right of the segmentation line produce different positive and negative charges.

From the above theoretical analysis, it can be seen that after reasonable segmentation, the cut piezoelectric ceramics produce isotropic charges at their respective modal frequencies.

4. Experimental Testing and Analysis

In order to verify the results of the theoretical analysis of the zero position of the strain on the piezoelectric energy trap, three groups of piezoelectric energy harvesters were designed and fabricated. The energy harvester substrate material was beryllium bronze, the size was 74 mm × 20 mm × 0.3 mm, and the piezoelectric ceramic material was PZT-5; the size is 60 mm × 20 mm × 0.3 mm. The piezoelectric ceramics of the first group of piezoelectric energy harvesters are not segmented. The second group of piezoelectric energy harvester splits the piezoelectric ceramic into two sections at 60 mm × 0.275 = 16.5 mm in the piezoelectric ceramic length direction; the third group splits the piezoelectric ceramic into three sections at 60 mm × 0.16 = 9.6 mm and 60 mm × 0.61 = 36.6 mm in the ceramic length direction. The free end of each group of energy harvesters is glued with a mass block with a mass of 5 g. The resonance frequencies of the first-, second-, and third-order modes of the three groups of piezoelectric energy harvesters are analyzed by an impedance analyzer, which are 17 Hz, 40 Hz, and 108 Hz.

The experimental test system is shown in Figure 6. The test setup mainly consists of an exciter, power amplifier, oscilloscope, rectangular piezoelectric trap, computer, etc. The tests focus on the output voltage, output current, output power, and capacitor charging time of the three groups of piezoelectric energy harvester in the range of 0 Hz-130 Hz. The piezoelectric ceramics of the second and third sets of energy harvester are connected to the rectifier bridge shown in Figure 7.

According to the formula,
\[
P = I^2R = \left( \frac{E}{R + r} \right)^2,
\]
\[
R = \frac{E^2}{4r + ((R - r)/R)}.
\]
It can be seen that the output power reaches its maximum when the internal resistance in the circuit is equal to the external resistance. Due to the presence of the rectifier bridge, the capacitor, and the piezoelectric trap’s own internal resistance in the charging circuit, some of the output power is consumed, and an external resistance equal to the internal resistance needs to be connected to the charging circuit in order to maximise the output power. The capacitor in Figure 8 has an internal resistance of 40 kΩ, so the external resistance is also 40 kΩ.
The output power and voltage of the power amplifier were kept stable during the test, and the output voltage under various operating conditions was obtained by adjusting the frequency (observed using a digital oscilloscope), and the voltages recorded during the test were all peak voltages, as shown in Figure 8.

The curves in Figure 8 show that the output voltages of the three groups of energy capturers are the same at the first-order resonance frequency. At the second-order resonance frequency, the output voltage of the second group of energy capturers is greater than that of the third group of energy capturers. At third-order resonant frequencies, the output voltage of the third set of captors is greater than that of the second set of captors.

From the curve in Figure 9, it can be seen that at the first-order resonance frequency of 18 Hz, the output current of the three groups of energy capturers is the same; at the second-order resonance frequency of 40 Hz, the output current of the second group of energy capturers is 0.03 mA, which is greater than that of the third group of 0.024 mA and greater than that of the first group of 0.01 mA; at the third-order resonance frequency of 108 Hz, the output current of the third group of energy capturers is 0.035 mA, which is greater than that of 0.02 mA for the second group and 0.01 mA for the first group.

We use the output voltage obtained from Figure 9 and the output current obtained from Figure 10 to obtain the output power using \( P = U \cdot I \) to plot Figure 10.

As can be seen from Figure 10, at the first-order resonance frequency, the output power values of the three groups of energy capturers are close to each other; at the second-order resonance frequency, the output power of the second group of energy capturers is 0.3 mW, which is 1.47 times of the output power of the third group of energy capturers of 0.204 mW and 5 times of the output power of the first group of energy capturers of 0.06 mW. At the third-order resonance frequency, the output power of the third group capturer is 0.42 mW, which is 2.39 times of the output power of the second group 0.176 mW and 5.83 times of the output power of the first group 0.072 mW.

To get a better feel for the magnitude of the power output from the three sets of captors, we charged the external capacitors of the piezoelectric captors and tested the time it took for the capacitors to go from 0 V to 10 V. As can be seen from Figure 10, the output power of the piezoelectric energy harvester is very low at nonresonant frequencies, so we only test the time it takes to fill the capacitors around the first-, second-, and third-order resonant frequencies.

As can be seen from Figure 11, at the first-order resonance frequency, the three groups of piezoelectric energy harvester charge the capacitor in close time; at the second-order resonance frequency, the second group of piezoelectric energy harvester charges the capacitor in the shortest time of 10 min; at the third-order resonance frequency, the third group of piezoelectric energy harvester charges the capacitor in the shortest time of 8 min.

From Figures 8–10 and Figure 11, it can be seen that at the first-order resonant frequency, the output voltage, output current, output power, and capacitor charging time of the three groups of piezoelectric energy capturers are close to each other, and the electrical energy output is close to each other, which proves that there is no strain zero point of the piezoelectric energy capturer at the first-order resonant frequency. At the second-order resonance frequency, the output voltage, output current, and output power of the second group of captors are greater than those of the first and third groups, and the capacitor charging time is less than that of the first and third groups, proving that the piezoelectric captors have a strain zero point at 0.275 in the length direction of the piezoelectric ceramic at the second-
order resonance frequency. At the third-order resonance frequency, the output voltage, output current, and output power of the third group of captors are greater than those of the first and second groups, and the capacitor charging time is less than that of the first and second groups, proving that the zero point of strain of the captors is at 0.16 and 0.61 in the length direction of the piezoelectric ceramic at the third-order resonance frequency of the piezoelectric captors.

5. Conclusion

This paper demonstrates through theoretical analysis and experimental tests that reasonable segmentation of the piezoelectric energy trap in the second and third-order modes can significantly improve the power generation capacity of the trap. In the first-order mode, there is no strain zero point in the piezoelectric energy trap, and segmentation has no effect on the electrical output of the piezoelectric cantilever beam. In the second-order mode, the piezoelectric trap has a strain zero point at 0.275 in the ceramic length direction, and the output power of the piezoelectric trap segmented at 0.275 in the ceramic length direction is five times higher than that of the unsegmented trap. In the third-order mode, the piezoelectric trap has strain zeros at 0.16 and 0.61 in the ceramic length direction, and the output power of the piezoelectric trap at 0.16 and 0.61 in the ceramic length direction segment is 5.83 times higher than that of the unsegmented trap. This method of splitting the piezoelectric ceramic at the strain zero point by finding the strain zero point in the first-, second-, and third-order modes of the piezoelectric energy trap can effectively increase the electrical energy output of the piezoelectric energy trap, providing new ideas and methods for future energy conversion in piezoelectric energy harvester.

Data Availability

Data are available on request to the authors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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