Design and optimization of a broadband piezoelectric energy harvester

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Abstract: The conventional linear cantilever piezoelectric energy harvester has a relatively narrow working frequency range (1-2 Hz) and low energy harvesting performance. Therefore, a new effective host structure needs to be developed. This paper proposes a broadband piezoelectric energy harvesting structure to solve this problem. The proposed structure is composed of three beams. Based on the finite element analysis via ANSYS software, the theoretical model of this structure is established. The response characteristics of the energy harvester are analyzed, and the optimization design strategy is presented. The finite element simulation results show that the working frequency range of the presented harvester can be changed by adjusting the length ratio of each beam. Therefore, the result indicated that the proposed energy harvesting structure can widen the effective bandwidth and improve the energy harvesting performance.

Keywords: Broadband; piezoelectric; cantilever beam; finite element analysis; length ratio

1. Introduction
Chemical batteries are the preferred power supply for integrated circuits, MEMS and portable electronic devices. However, the limited capacity and life of batteries, which need to be replaced regularly, will inevitably bring inconvenience to the application of these systems, especially for the development of the rapidly growing wireless sensor networks and embedded intelligent systems[1]. In order to improve the traditional energy supply system of chemical batteries, the self-powered equipment which harvests mechanical energy into electrical energy has been a research hotpot. Piezoelectric energy harvester is a main way to harvest vibration energy in the environment, compared with other power generation principles, piezoelectric power harvester has many advantages, such as simple structure, no heating, no electromagnetic interference, no pollution, and easy to realize the miniaturization and integration of mechanisms. Thus, Vibration energy harvesters have attached much attention in recent year [2] and widely used to supply power for small electronic devices such as portable micro-power appliances or wireless sensors and it is the best power supply to replace chemical batteries. At present, the developed piezoelectric vibration energy harvester generally has a relatively narrow working frequency range(1-2Hz) and low energy harvesting performance which is not conducive to efficiently harvest and transfer the environmental vibration energy. Improving the energy transferring efficiency and the frequency bandwidth of the piezoelectric energy harvester is the key point in the research field. Literature [3-4] improves the output voltage and widens the working
frequency band of the system by setting permanent magnets on and below the cantilever beam, but this method increases the complexity of the system and is not conducive to system integration. Guangqi Wang[5] proposed a type of broadband piezoelectric cantilever vibration energy harvester with an elastic magnifier to improve the energy transferring efficiency and the frequency bandwidth of the piezoelectric energy harvester. However, the proposed model is not stable and neglects the electromechanical coupling characteristics of the energy harvester and it is difficult to predict and analyze the output characteristics of the energy harvester. Literature[6-8] using a L-type piezoelectric energy harvester to widen the working frequency and energy harvesting performance. Shahruz[9] and Ferrari[10] first proposed the concept of bandwidth filter and the mathematical model of vibration energy filter. The energy filter proposed by Shahruz and Ferrari is a set of piezoelectric cantilevers of different lengths, each of which has a mass block fixed at its free end, the superposition of the resonance frequency between the cantilevers can be changed by adjusting the variables of length and load. These studies show that we can enhance the harvesting performance and widen the working frequency through altering the structures of the piezoelectric energy harvesters.

In this paper, we design and optimization a broadband piezoelectric energy harvester. By adding an auxiliary vertical cantilever beam and a parallel cantilever beam at the end of the horizontal cantilever beam, a Z-type piezoelectric vibration energy harvester is constructed. The working frequency range of the proposed structure can be changed by adjusting the length ratio of each beam. Thus forming a wider working frequency band.

2. Experimental materials and methods

2.1. Overall structure

Some text. According to literature [11-12] the first mode frequency and the second modal frequency spacing of traditional cantilever beam structure is large. Which is not conducive to forming a widen working frequency. In this paper, by adding auxiliary cantilevers which include a auxiliary vertical cantilever beam and a horizontal beam in the end of a traditional cantilever structure, composing a Z-type cantilever structure. By controlling the structural parameters of the three beams, the natural frequency spacing of each mode of the beam is reduced, and the three beams are connected in series to form a broadband resonance band. The structural model of the Z-type broadband piezoelectric vibration energy acquisition device is shown in Figure 1. The structure consists of a base, metal substrates L1, L2, L3, and piezoelectric layers which is separately attached to two horizontal beams.

![Fig.1 Model of the broadband piezoelectric energy harvester](image)

2.2 Finite element model analysis of the piezoelectric energy harvester
Based on Hamilton's principle and the relationship between stress-strain, strain-displacement and potential-electric field, the finite element analysis model of Z-type piezoelectric energy collector can be established\cite{13}:

\[
\begin{bmatrix}
m & 0 \\
0 & 0
\end{bmatrix}\begin{bmatrix}
\dot{u} \\
\dot{v}
\end{bmatrix} + \begin{bmatrix}
c & 0 \\
0 & 0
\end{bmatrix}\begin{bmatrix}
\ddot{u} \\
\ddot{v}
\end{bmatrix} + \begin{bmatrix}
k & -\Theta \\
\Theta^2 & p
\end{bmatrix}\begin{bmatrix}
u \\
v
\end{bmatrix} = \begin{bmatrix}
F \\
Q
\end{bmatrix}
\] (1)

Where \( m \) is the structural mass matrix. \( C \) is the structure damping matrix; \( K \) is stiffness matrix of the structure; \( U \) is the structural displacement vector; \( F \) is the structural force vector; \( V \) is the structural vector. The electric potential vector; \( Q \) is the charge vector; \( \Theta \) is the electromechanical coupling matrix; \( P \) is the electrical capacitance matrix of the piezoelectric energy harvester, \( \dot{u}, \dot{v}, \ddot{u}, \ddot{v} \) represent the displacement vectors and potential vectors of the structure to be one and two derivatives of time \( t \) respectively.

While the electromechanical coupling equation of piezoelectric element is\cite{14-16}:

\[
T = c^E - e^E E
\]
\[
D = e^S + eS
\] (2) (3)

In the equation \( T \) is the stress vector, \( E \) is the electric field intensity vector, \( D \) is the displacement vector, \( S \) is the strain vector, \( e \) is the piezoelectric stress matrix, \( c^E \) is the elastic coefficient matrix of PZT under constant electric field strength; \( e^S \) is the dielectric constant matrix of PZT under constant strain, \( e^T \) is the transpose matrix of the piezoelectric torque matrix \( e \).

According to the equations (1) ,(2), and (3) the model of the broadband piezoelectric energy harvester can be established and the vibration modes and response characteristics of piezoelectric energy harvester under different boundary conditions and constraints can be analyzed by using the finite element analysis software ANSYS\cite{17}. The structural material parameters of the piezoelectric energy harvester are shown in Table 1 and Table 2. The entity model of the piezoelectric energy harvester is shown in the Fig 2.

| Table 1 Parameter of piezoelectric energy harvester |
|-------------------|---------|--------------|-----------------|
| Parameters        | Material| Density/ kg.m\(^3\) | Elastic Modulus/G Pa | Poisson ratio |
| Substrate layer   | Steel   | 7850         | 2.00×1011        | 0.28         |
| Piezoelectric layer | PZT     | 7500         | 7.65×1010        | 0.32         |

| Table 2 Initial geometrical dimensions of the piezoelectric energy harvester |
|------------------|-----------------|-----------------|-----------------|
| Parameters       | Long/mm         | Width/mm        | Thickness/mm    |
| Horizontal layer | substrate       | 30              | 10              | 1              |
| Vertical layer L1| substrate       | 30              | 10              | 1              |
| Horizontal layer L2| substrate    | 30              | 10              | 1              |
| Piezoelectric layer | layer     | 30              | 10              | 0.5            |

Analyzed the system models to obtain the first and second natural frequencies of the piezoelectric energy harvester and get the resonant frequencies of the piezoelectric devices. The purpose of this paper is to narrow the natural frequency spacing between the second-order mode and the first-order mode of Z-type energy harvester, base that the second-order mode frequency is close to the first-order
mode frequency. Therefore, the first-order mode and second-order mode of the system are mainly investigated. The first-order mode and second-order mode obtained by finite element calculation are shown in Figure 3.

Fig. 2 Entity Model

(a) The first order mode shape (b) The second order mode shape

Fig. 3 Model shape of the system

2.3 Effect of mental substrate L1 on the mode of the system

Changing the length of the substrate L1 while keep the length of the substrate layer L2 is 30mm and the length of substrate layer L3 is 30mm. The natural frequency of the piezoelectric energy harvester changes with L1 as shown in Figure 4. The result shows that with the length of substrate layer L1 increasing, the natural frequencies of the first-order mode and second-order mode of the system decrease gradually, and the frequency of the second-order modes of the system decreases faster than that of the first-order mode, but the frequency spacing is basically stable close to a constant.

Fig. 4 Effect of mental substrate L1 on the mode of the system

2.4 Effect of mental substrate L2 on the mode of the system

Changing the length of the substrate L2 while keep the length of the substrate layer L1 is 30mm and the length of substrate layer L3 is 30mm. The natural frequency of the piezoelectric energy
harvester changes with L1 as shown in Figure 5. The result shows that with the length of substrate layer L2 increasing, the natural frequencies of the first-order mode and second-order mode of the system decrease gradually, and the frequency of the second-order modes of the system decreases faster than that of the first-order mode. The result also shows that while the length of L2 is 80mm the natural frequency changes tend to be stable which mean that frequency spacing is decreasing and the second-order frequency close to the first-order frequency.

![Fig.5 Effect of mental substrate L2 on the mode of the system](image1)

2.5 Effect of mental substrate L3 on the mode of the system

Changing the length of the substrate L3 while keep the length of the substrate layer L1 is 30mm and the length of substrate layer L2 is 30mm. The natural frequency of the piezoelectric energy harvester changes with L1 as shown in Figure 6. The result shows that with the length of substrate layer L3 increasing, the natural frequencies of the first-order mode and second-order mode of the system decrease gradually, and the frequency of the second-order modes of the system decreases faster than that of the first-order mode. The result also shows that while the length of L3 is 90mm the natural frequency changes tend to be stable which mean that frequency spacing is decreasing and the second-order frequency close to the first-order frequency.

![Fig.6 Effect of mental substrate L3 on the mode of the system](image2)

According to the analysis results of Fig. 4, Fig. 5 and Fig. 6, the natural frequencies of the first order and second order modes of the system decreased with the increase of the lengths of L1, L2 and L3 while the variation of the frequency spacing tends to be stable. When the length of L1 changes, the frequency spacing of the first mode and the second mode of the piezoelectric energy harvester tends to be stable. When the length of L3 changes, the frequency spacing between the first order mode and the second order mode of the structure decreases rapidly, when the length of L3 is 90 mm, the frequency spacing tends to be stable. Changing the length of L2, the frequency spacing between the first order
and second order modes of the device decreases sharply, and when the length of L2 is 80 mm, the frequency spacing tends to be stable.

Therefore, considering the practical application to optimized the structure of the broadband piezoelectric energy harvester. Finally, the length of L1 is 80 mm, the length of L2 is 80 mm and the length of L3 is 90 mm. After optimizing, the first order and second order mode of the piezoelectric energy harvester are 20.2 Hz and 35.1 Hz.

2.6 Analysis of electrical output response characteristics

In order to improve the output voltage of the piezoelectric sheets and improve the harvesting performance of the piezoelectric cantilever energy harvester established the model of the optimized Z type piezoelectric broadband energy harvester (L1 is 80 mm, L2 is 80 mm, L3 is 90 mm) via ANSYS software. The excitation is applied in the vertical direction of the support and the excitation level is 1 m/s, changing the frequency of the excitation, the relationship between the output voltage of the piezoelectric energy harvester and the frequency of the excitation is shown in Fig 7. The result shows that there are two peak points in the voltage output of the three beams, corresponding to the first and second order resonance points of the system respectively.

![Fig.7 Frequency response characteristics of output voltage of the structure](image)

3. Conclusions

This paper aims at to solve the problems of narrow working frequency band and low energy harvesting performance of conventional linear cantilever piezoelectric energy harvester. Proposed a Z-type piezoelectric cantilever energy harvester and optimized the parameter of the structure via ANSYS software. The finite element modeling and simulation analysis are carried out and the conclusions are as follows:

1. By controlling the structural parameters of Z-type cantilever beam, the first order and second order natural frequency modes of the piezoelectric cantilever energy harvester can be reduced and the spacing of the natural frequencies between the two modes can be also reduced. Thus, the working bandwidth of the piezoelectric cantilever energy harvester can be effectively expanded and the energy harvesting efficiency can be improved.

2. With the increase of the length of L1, L2 and L3, the natural frequency spacing of the first order and second order modes of the piezoelectric energy harvester decrease. When L1 is 80 mm, L2 is 80 mm and L3 is 90 mm, the natural frequency spacing of the first order and second order modes of the system tend to change smoothly and reach to the minimum value. And the two peak corresponds to the frequency ratio is 1.86.

3. The three beams of the Z-type piezoelectric cantilever energy harvester all can be used for harvesting the vibration energy which can effectively expand the working frequency band of the piezoelectric energy harvester and improve the harvesting performance of the device.
References
[1] J.Taneja, A. Krioukov, S. Dawson Haggerty, and D. Culler. Enabling Advanced Environmental Conditioning with a Building Application Stack. In Proc. of the 4th IGCC, 2013.
[2] REN B , OR S W , ZHANG Y ,etc. Piezoelectric energy harvesting using shear mode 0.71Pb(Mg1/3Nb2/3)O3-0.29PbTiO3 single crystal cantilever[J]. Applied Physics Letters ,2010 ,96(8):083502
[3] Shengxi Zhou ,Junyi Cao ,Alper Erturk, J.Appl Phys.102,173901(2013)
[4] Hua’an Ma, Jingquan Liu, etc. A broadband magnetic piezoelectric vibration energy collector [J]. Sensors and Micro-systems, 2011, 30 (04): 66-68.
[5] Guangqing Wang, Yongzheng Zhan, Wenping Jin, etc. Analytical model and experimental study of a broadband piezoelectric vibration energy harvester [J]. Journal of Mechanical Engineering, 2015, 51 (06): 155-164.
[6] Liu Yue, Dong Weijie, Bai Fengxian. Structure and performance of L-type piezoelectric trap based on d15 mode [J]. PIEZOELECTRICSie and ACOUSTOOPTIC, 2017, 39 (06): 848-851.
[7] Zhixiong Zhang ,Xuejun Zheng ,Yong Zhang ,ect. Energy harvesting performance of d15 mode PZT-51 cantilever beam in parallel structure [J]. Chinese Journal of nonferrous metals,2015,25(8):2183-2189
[8] Wei Zhang ,Yueming Lu ,Guangqing Yue, etc. Finite element analysis and characteristic simulation of L-type piezoelectric vibration energy harvester[J].Journal of Materials Science and Engineering, 2016,34(06): 1010-1014.
[9] Shahrzu S M. Design of mechanical band-pass filters with large frequency bands for energy scavenging[J]. Mechatronics, 2006, 16(9): 523-531.
[10] Ferrari M, Ferrari V, Guizzetti M, et al. Piezoelectric multifrequency energy converter for power harvesting in autonomous microsystems[J]. Sensors and Actuators A: Physical, 2008, 142(1): 329-335.
[11] Erturk A, Jamil M R,Daniel J I. Piezoelectric energy harvesting from a L-shaped beam-mass structure with an application to UAVs [J]. Journal of Intelligent Material Systems and Structures, 2009, 20(5):529-544.
[12] Jiejie Zhang, Jun Wang, Weiqing Liu, etc. Prediction and analysis of bending behavior of composite laminated beams with folded section [J]. Journal of Materials Science and Engineering, 2014, 32 (3): 456-460.
[13] Fuxue Zhang, Wang Likun Wang. Modern Piezoelectricity (Volume 1) [M]. Beijing: scientific publishing brake.2002,26–32.
[14] Roundy S, Wright P K , Rabaey J. A study of low level vibration as a power source for wireless sensor nodes [J]. Computer Communication,2003,26:1131-1144.
[15] Sodano H ,Inman D ,Park G. Generation and storage of electricity from power harvesting devices[J]. Journal of Intelligent Material Systems and Structural, 2005,16:67-75.
[16] Triplette A L. Vibration base energy harvesting with essential nonlinearities[J]. Dissertations & These Gradworks,2011:779-786.
[17] Huina Mao, Weiming Tao, etc. Finite element analysis of dynamic coincidence response of Multiferroic composites [J]. Journal of Materials Science and Engineering, 2013, 31 (3): 464-478.