Design and experimental investigation of a T-shaped piezoelectric energy harvester

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Abstract. This paper presents a T-shaped piezoelectric energy harvester (TPEH) by utilizing multimodal techniques. The proposed TPEH is consisted of a clamped-clamped beam and a branched cantilever beam at the center. One end of the clamped-clamped beam could move freely along the axial direction and a piezoelectric wafer is glued at the end. Two operational bandwidths are shown in the experimental results. Moreover, various cantilever beam configurations were investigated. It was found that the first resonance band moves to the low frequency range as the tip mass of the cantilever beam increases. However, the second resonance band accesses to lower frequency range slightly. Finally, it was demonstrated that the presented TPEH can be used in low frequency and low amplitude vibration environment.

1. Introduction
With the development of wireless sensor networks, energy harvesting can be used as an alternative method to power the wireless sensor networks has attracted growing attention from researchers. Many ambient environmental energy sources can be converted to electrical power, including vibration, solar, tide, and wind, etc. Vibration energy is abundant in the ambient environment, therefore many researchers devote to improve the output power and bandwidth of vibration energy harvesting. Piezoelectric [1, 2], electromagnetic [3], electrostatic [4], and triboelectric [5] are the main transduction mechanisms to convert vibration energy to electrical power.

Traditional linear energy harvester can be used to harvest ambient vibration energy with narrow bandwidth. In order to overcome this problem, nonlinear [6, 7], impact [8] and pluck [9] methods have been introduced to design the vibration energy harvester. For the sake of increasing the output power and the operational bandwidth, internal resonance and multimodality have been used. Yang and Towfighian [10] proposed an internal resonance nonlinear vibration energy harvester to enhance the energy harvesting efficiency. Xiong et al. [11] presented an energy harvester with 1:2 internal resonance to widen the bandwidth. Chen et al. [12] developed a 2:1 internal resonance energy harvester to widen the response bandwidth, and the main parameters were investigated. A multimodal and multidirectional vibrational energy harvester was proposed by Deng et al. [13]. Sun and Tse [14] presented a multimodal vibrational energy harvester for machine rotational frequencies. Therefore, it is meaningful to design a piezoelectric energy harvester with multimodal techniques.

In this paper, we proposed a T-shaped piezoelectric energy harvester (TPEH). Multimodal techniques were utilized to increase the response bandwidth of the energy harvester. The electromechanical coupling model of the proposed TPEH was established. The response of the multi-resonance bands
TPEH was studied under different excitation intensities. A series of cantilever beam structures of the TPEH were investigated experimentally. Design and modelling are introduced at Section 2. Section 3 shows the experimental investigation. Finally, Section 4 shows the conclusions.

2. Design and modelling

2.1. Design
The schematic of the proposed TPEH is shown in figure 1. The TPEH compose of a clamped-clamped beam with a mass block which located at the midpoint, and a cantilever beam with a tip mass which is designed at the center of the clamped-clamped beam, and a piezoelectric wafer is attached at the moveable clamped end of the clamped-clamped beam. The output voltage of the piezoelectric wafer is consumed by the loading resistor ($R$). The external excitation direction is perpendicular to the $x$-$z$ plane.

![Figure 1. The schematic of the proposed T-shape piezoelectric energy harvester.](image)

2.2. Modelling
The electromechanical coupling dynamical model can be deduced using the extended Hamilton’s method. The governing equations of the TPEH can be given as

$$
m_1\ddot{y}_1 + c_1\dot{y}_1 + c_3y_1^2 + \gamma_1y_1 + \rho\left(y_1^2\ddot{y}_1 + y_1\dot{y}_1^2\right) + c_2\left(y_1 - \ddot{y}_2\right) + \gamma_2\left(y_1 - y_2\right) = + k_3\left(y_1 - y_2\right) + \frac{dV}{dt} = -m_3\ddot{y}_3
$$

$$
m_3\ddot{y}_3 + c_3\left(\ddot{y}_3 - \dot{y}_1\right) + \gamma_2\left(y_2 - y_1\right) + k_1\left(y_2 - y_1\right) = -m_5\ddot{w}_6
$$

$$
C_p\ddot{V} + V/R - \chi_1 = 0
$$

(1)

3. Experimental Investigation

3.1. Experimental setup
The experimental setup is shown in figure 3. For the sake of analyzing the output performance of the TPEH, a series of experiments were carried out under harmonic excitations. The excitation signal is generated by a vibration control software on the computer, then amplified via a power amplifier, and transferred to the electro-dynamic shaker. An accelerometer is used to acquire the vibration signal, then passed to the vibration controller to achieve the feedback control of the base excitation. The middle point displacement of the clamped-clamped beam is measured through a laser displacement sensor. The generated voltage and the midpoint displacement of the harvester are collected by a NI 6361 data acquisition card, and then transferred to the computer.
3.2. Experimental results and discussions

A series of experiments were conducted to analyze the performance of the presented TPEH in terms of frequency responses. A 5 MΩ loading resistor is used in the following part of the section, which is regarded as open circuit condition of the energy harvester.

Figure 3 shows the experimental voltage and displacement responses for up and down chirp excitations of 2 ms². During the sweep experiments, the sweep ratio is equal to 0.05 Hz/s. The up and down sweep responses of the generated voltage is shown in figure 3(a). It is found that there are two resonance peaks of the developed TPEH. The first resonance band is near 10 Hz, while the second resonance band is near 29 Hz. Figure 3(b) and (c) show the zoom-in figures of the generated voltage of the energy harvester around the first and second resonance peaks, respectively. As shown in figure 3(b), a wide band nonlinear response is observed at the first resonance peak under up and down sweeps. It is a typical characteristic of the nonlinear energy harvesting system. From figure 3(c), it can be observed that the up and down sweep responses of the output voltage are exactly the same at the second resonance peak.
Figure 3. Experimental (a) displacement responses for up and down chirp excitations of 2 ms$^{-2}$, and (b), (c) the zoom-in figures around the first and second resonance peaks.

Figure 4 shows the up and down sinusoidal chirp excitation responses of the generated voltage under different excitation amplitudes (2 ms$^{-2}$, 4 ms$^{-2}$, and 8 ms$^{-2}$). It can be found that the bandwidths of the first and second resonance bands increase as excitation amplitude increases. The frequency response peak of the second resonance band shifts to the low frequency direction when the excitation amplitude is enhanced. However, the trend of the frequency response curves around the first resonance band holds the same as the excitation amplitude increases.

Figure 4. Experimental (a), (b) voltage under various up and down chirp excitations.

The up chirp excitation responses of the displacement with different tip masses (6.9 g, 11.5 g, 16.1 g) of the cantilever part are shown in figure 5. It is observed that the first resonance peak moves to the low frequency range obviously as the tip mass of the cantilever beam increases. However, only slight change occurs to the second resonance peak. The peak value of the first resonance increases firstly and then decreases as the tip mass of the cantilever beam increases. Therefore, the proposed TPEH can be used in the low frequency and widen bandwidth ambient environmental vibration excitation under suitable design.
Figure 5. Experimental displacement for up chirp excitation of 2 ms$^2$ with different tip masses of the cantilever beam.

4. Conclusions
In this paper, a TPEH is developed by using multimodal techniques. The electromechanical coupling model is established. Experimental results demonstrate that the proposed TPEH can operates under two operational frequency bandwidths. The two response bandwidths are improved with the increasing of the excitation amplitude. The first resonance band moves to the low frequency range obviously, nevertheless the second resonance band changes slightly as the tip mass of the cantilever beam increases. Therefore, the proposed TPEH can be applied in the practical environmental vibrations.

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