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Energy harvesting performance of a dandelion-like multi-directional piezoelectric vibration energy harvester

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ABSTRACT

To achieve effective harvesting of ambient vibration energy in different directions, this paper proposes a dandelion-like multi-directional piezoelectric vibration energy harvester (MD-PVEH). After theoretical design, analysis and optimization of the device, validation experiments were carried out, which shows that the dandelion-like MD-PVEH can harvest relatively more energy in different excitations, although it harvests less energy from excitation in individual directions (for example, the angle between excitation direction and X axis is $\pi/2$ in XZ plane). Overall, this dandelion-like MD-PVEH with a load resistor of 8 kΩ can reach its maximum output power of about 0.28 mW and maximum energy conversion efficiency of 3% in the harmonic excitation which the frequency and amplitude are 22 Hz and 0.28 mm, respectively. It can meet the needs of many microelectronic devices.

1. Introduction

With the increasing development of microelectronics technology, electronic products tend to be miniaturized and integrated. The emergence and development of ultra-low-power communication standards as Bluetooth and Zigbee have urged the electronic products to be wireless and portable. However, the key technical problem that needs to be solved is how to adopt relatively easily applicable methods to supply power. Energy harvesting technology has the potential to liberate these low-power products from their traditional power-supply methods such as electric wire and battery, and makes their applications easier and more flexible. What is more, compared with supplying power by chemistry battery, energy harvesting technology is cleaner and more environmental friendly. Compared with harvesting solar energy and thermal energy, harvesting ambient vibration energy is more widespread [1]. Piezoelectric vibration energy harvesters have advantages of high energy density, non-electromagnetic interference, and easy integration with MEMS. Current researches on piezoelectric energy harvesting structures [2–12] are pretty thorough. Cantilevered beam structure has become mostly considered structure for the energy harvesting device because of its low stiffness, high sensitivity, easy calibration, etc. A kind of piezoelectric vibration energy harvester is developed by Shanghai Jiaotong University [13], and its prototype was made in 2007. They made silicon cantilever through MEMS technology, and PZT piezoelectric layers and electrode layers on the surface of cantilevers by Sol-Gel technology. They attached nickel masses to the end of cantilever beams. Under the resonant frequency of 608 Hz, its output power can reach 2.16 μW. Lee and other researchers [14] in National Taiwan University developed a kind of inter-digital electrode MEMS piezoelectric energy harvesting device in 2008. The device has a natural frequency of 214 Hz and can export electric power of 0.352 μW when driven by a sinusoidal acceleration excitation of 1 g.

As can be seen from the above description, most piezoelectric vibration energy harvesters are based on linear single cantilevered beam structure and PZT piezoelectric material. Their structures are simple, and fabrication processes are not complicated. However, sometimes ambient vibration is not only in a single direction and a narrow frequency band. It is noteworthy that Marco Ferrari and Vittorio Ferrari propose a multi-frequency converter array (MFCA), which uses multiple bimorph cantilever beams with different natural frequencies to widen the bandwidth of the vibration energy harvester [15]. Their experiments show that the harvester with MFCA can harvest wideband vibration energy effectively, and supply power for battery-less sensor modules. Marco Ferrari's team also proposed some different approaches to use nonlinear solutions to scavenge energy from wideband vibrations [16–18]. They

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use a piezoelectric beam converter coupled to permanent magnets to create a bistable system. In the excitation of random vibration, the system bounces between two stable states, which significantly improves the energy harvesting efficiency. In their later study, piezoelectric buckled beams are also used as a bistable scavenger structure for vibration energy harvester. Their research shows that the piezoelectric buckled beams exhibit superior power generation over a large interval of resistive load, with gains up to more than a factor of ten compared to unbuckled beams. Their researches greatly improved the frequency adaptation capability of vibration energy harvesters. However, in some cases, ambient vibrations are also in different directions. Traditional single-cantilevered beam structure is only sensitive to excitation in one direction, and is not able to maximize the harvested energy.

This paper aims at designing, characterizing, optimizing and testing a dandelion-like multi-directional piezoelectric vibration energy harvester (MD-PVEH) which can harvest ambient vibration energy in different directions efficiently. This paper is organized as follows. In Section 2, we outline our design concept, theoretical analysis and optimization. In Section 3, we describe the experimental set-up and experiment results of the dandelion-like MD-PVEH, in comparison with the theoretical predictions. Conclusions are finally given in Section 4.

2. Concept design, analysis and optimization

In this section we first propose a concept of MD-PVEH, give its dandelion-like structure design and the corresponding multi-source charging circuit design. The theoretical analysis is then used for acquiring its output performance, and then the structural parameters are optimized.

2.1. Concept design

Most of the vibration energy harvesters can only harvest energy of vibration in single direction efficiently. However, ambient vibrations are complex and usually change their directions, which is difficult for the application of harvesters. Therefore, to find some kinds of harvesting structures that are sensitive to vibration in different directions are significant. We call this kind of environmental adaptive piezoelectric vibration energy harvesters MD-PVEHs. We propose a dandelion-like MD-PVEH. The structure is shown in Fig. 1. As can be seen, the harvester consists of a number of piezoelectric cantilevered beams, multi-faceted support body, upright column and base. Each cantilevered beam is fixed on the multi-faceted support body in different directions, so they are respectively sensitive to vibration in different directions. When harvester is driven by ambient vibration in different directions, the corresponding sensitive piezoelectric cantilevered beams can produce forced vibration, and achieve a full harvesting of energy in ambient vibration.

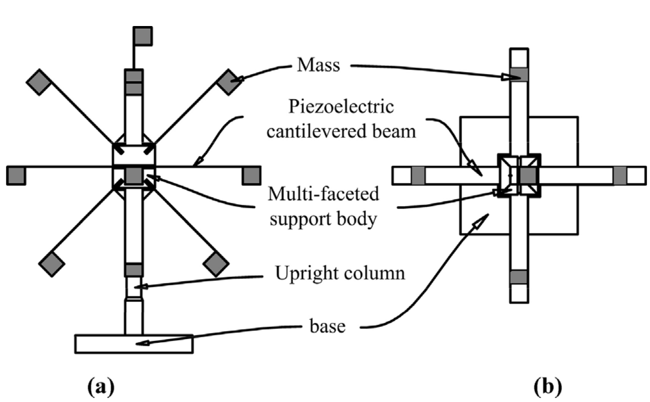

Fig. 1. Dandelion-like multi-directional energy harvesting structure: (a) side view; (b) top view.

This design is simple and easy to manufacture. Moreover, researches on single cantilevered beam piezoelectric energy harvesting structures has accumulated a large number of reliable theoretical and experimental results, which provides a lot of references for the analysis of this structure.

For dandelion-like MD-PVEH, we design a multi-source energy harvesting circuit which can harvest output power from more than one source effectively. Because of their different fabrication positions, each single piezoelectric cantilevered beam structure has different vibration sensitive direction. Therefore, their output voltages are different in amplitude and phase.

Considering diode and its one-way conductive property, we design a kind of poured-type charging circuit. All outputs of individual single piezoelectric cantilevered beam harvesting structure are connected to full-bridge rectifier circuit, to convert bipolar alternating signal to unipolar signal. After that, we use filter capacitors to convert signal to DC signal with smaller ripple, and charge battery through corresponding diodes and current limiting resistor.

2.2. Theoretical analysis

Working process of dandelion-like MD-PVEH can be seen as that each single cantilevered beam is fixed on the multi-faceted support body and harvests vibration energy in different direction. The power harvested by the entire device is equal to the sum of which harvested by each single cantilevered beam. Therefore, we can select one of the single cantilevered beams to analyze. Analysis method for other beams is the same. In this way, we select a single cantilevered beam from the device arbitrarily. The single piezoelectric cantilevered beam and its parameters are shown in Fig. 2.

Assuming the angle between this cantilevered beam and vibration direction is α_i ($i = 1, 2, \ldots, 13$), and vibration excitation is $u\sin\omega t$. According to the theory of synthesis and decomposition, excitation component that perpendicular to the cantilevered beam surface is

$$z_i = u \sin\alpha_i \sin\omega t \tag{1}$$

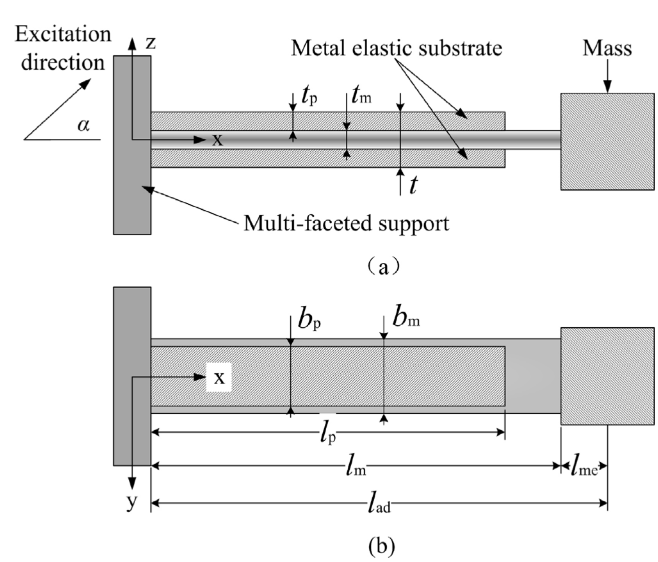

Fig. 2. Structure of the single cantilevered beam and its parameters: (a) side view; (b) top view.