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Design and experimental verification of a bi-directional nonlinear piezoelectric energy harvester

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ABSTRACT

Harvesting energy from ambient vibrations via piezoelectric effect has been considered as a promising solution for implementing self-sustained low-power electronic devices. Most of the proposed piezoelectric energy harvesters (PEHs) are focused on the energy harvesting from uni-directional vibration. This is a strong limitation because the vibration may come from various directions in practical applications. To address this issue, this paper presents a design and experimental verification of a compact bi-directional nonlinear PEH that is sensitive to two orthogonal directions. This nonlinear PEH is composed of two magnetically coupled piezoelectric cantilever beams with orthogonal directions of deflection. Theoretical analysis and experiments reveal that the proposed PEH can not only harvest vibration energy from various directions but also provide an enhanced output voltage as compared to its linear counterpart. The introduction of magnetic coupling also enables the energy transfer between the two beams, which helps to restrain the excessive deflection of the two beams. Moreover, the advantage of nonlinear PEH is found to be highlighted at low-level excitation, whereas the resonant frequency of the nonlinear PEH drops as the excitation level reduces.

1. Introduction

The recent years have witnessed a rapid development of low-power devices that are being powered and sustained by batteries. Since batteries fail to keep pace with the demands of such devices, especially in terms of energy density, life span, and maintenance cost [1–3], the proliferation of low-power devices raises the problem of effective power supply. A promising solution to this issue is harvesting energy from the ambient mechanical vibrations via electrostatic [4], electromagnetic [5], or piezoelectric transductions [6–8]. The piezoelectric transduction has attracted most attention due to its high energy density, strong electromechanical coupling, simple structure, and good compatibility with microelectromechanical systems (MEMS) [9–17].

A conventional piezoelectric energy harvester (PEH) is generally designed as a cantilever beam with piezoelectric patches attached in unimorph or bimorph configuration and a proof mass affixed at the free end. The conventional PEH can efficiently scavenge energy provided that its resonant frequency matches the frequency of the vibration source. Unfortunately, this requirement cannot always be guaranteed since the frequencies of the naturally occurring vibration sources usually vary in a certain range. With a slight drift from the resonance, the efficiency of a conventional PEH will drop remarkably.

In order to overcome this limitation and thus improve the performance of a conventional PEH, researchers have proposed several strategies to realize broadband PEH. The first strategy is to design a PEH with manually or automatically tunable natural frequencies [18–22]. But the complexity and power consumption of the tuning scheme may completely offset any improvement achieved in the performance of a PEH [13,23]. Multimodal energy harvesting is another strategy widely pursued for broadband purpose. This strategy can be achieved by integrating piezoelectric cantilever array in one harvester [24,25], exploiting two degree-of-freedom (DOF) PEH configuration [14,26], or making use of complex multiple-beam configuration [27,28]. Although multimodal energy harvesting schemes have showed improved performances on the bandwidth, they increase the volume, and then reduces the energy density of a PEH.

Nonlinear magnetic coupling is another common technique usually employed to achieve broadband energy harvesting. Cottone et al. [11], using repulsive magnets, developed a piezoelectric inverted pendulum with bistable state to boost energy harvesting

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from stochastic vibrations. Lin et al. [13] and Ferrari et al. [29] proposed empirical models for describing the repulsive magnetic force, and thus facilitated the study on the effect of repulsive magnetic force on the performance of a PEH. Erturk et al. [15,30] reported a bistable piezo-magneto-elastic structure formed by a ferromagnetic cantilever beam and two magnets for broadband energy harvesting. The increased bandwidth of this structure results from the attractive magnetic interaction between the beam and two magnets placed close to the free end of the beam symmetrically. A similar design was also presented by Stanton et al. [12] to harness energy from 11 to 16 Hz under 0.3 g ($g = 9.81\ m/s^2$) excitation acceleration. Later on, Stanton et al. [31] proposed another bistable PEH by employing the magnetic coupling between a piezoelectric cantilever beam and a fixed magnet. An experimental study on this PEH structure with attractive and repulsive configurations was also conducted by Tang et al. [23]. Other researchers also investigated, both analytically and experimentally, the responses of nonlinear PEHs considering various magnetic coupling strengths (by varying the separation distance between magnets) and various excitation levels [32,33].

The aforementioned research works focused primarily on exploiting the magnetic coupling between a fixed magnet and a movable magnet affixed at a piezoelectric cantilever beam. Recent studies indicated that the performance of a PEH can be further improved by using the magnetic coupling between adjustable or movable magnets. For example, by adding a magnetic oscillator to a conventional PEH, Tang and Yang [7] developed a novel nonlinear PEH that can provide a wider bandwidth than the PEH coupled with a fixed magnet. The improved performance of this PEH is attributed to the magnetic oscillator that transfers part of its vibration energy to the PEH via magnetic interaction. Zhou et al. [17] presented a PEH with rotatable external magnets, and found that their PEH can be tuned to match the frequencies of the ambient vibration by regulating the angular orientation of the rotatable magnets. The magnetic coupling dual-cantilever PEH with monostable or bistable configuration has also been proposed by Fan et al. [34] and Su et al. [35] respectively to achieve broadband energy harvesting.

Although magnets have been exploited successfully in expanding the bandwidth, the PEHs still suffer from uni-directional sensitivity. This indicates that the performance improvement of nonlinear PEHs is limited because the naturally occurring vibration may come from various directions. To tackle this issue, Audò et al. [36] proposed a two-dimensional bistable PEH that is realized by introducing the magnetic coupling between two piezoelectric cantilever beams. The two beams are arranged in a line but deflect along two orthogonal directions. Su and Zu [37] developed a tri-directional PEH that includes a main cantilever beam, an auxiliary cantilever beam, and a spring-mass system, with magnets integrated to introduce nonlinear force and couple the three sub-systems. Unlike the two-dimensional PEH in which the two cantilever beams are all designed to conduct piezoelectric conversion, the tri-directional PEH only employs a main cantilever beam to realize piezoelectric conversion. The energy sensed by the spring-mass system and the auxiliary cantilever beam is transferred to the main cantilever beam via magnetic coupling.

In this paper, a novel bi-directional nonlinear PEH is designed and developed. This PEH consists of a primary piezoelectric cantilever beam and an inner piezoelectric cantilever beam with magnets affixed at their free ends. The inner beam is enclosed by the primary beam to form a compact structure. The two beams deflect along two orthogonal directions to achieve bi-directional sensitivity. The proposed PEH is theoretically modeled and experimentally validated. It will be shown that the proposed PEH can achieve multi-directional energy harvesting with improved performance.

2. Theoretical modeling

Fig. 1 illustrates the schematic diagram of the proposed PEH. This PEH consists of a primary beam and an inner beam. The primary beam is a hollowed cantilever beam that encloses the inner cantilever beam to form a compact structure. Each beam is fabricated from two piezoelectric layers and a metal shim. The two beams are clamped at the same side, and two magnets are attached at the free ends to generate repulsive interaction. The primary beam deflects along the z direction, whereas the inner beam moves along the x direction. Each beam extracts the energy from the component of vibration along its sensing direction. As a result, the energy distributed along various directions on the x–z plane can be harvested since the generic vibrations on the x–z plane can be projected to the x and z directions.

In modeling the proposed PEH, each beam can be considered as a mass + spring + damper + piezo structure [35,38,39]. The governing equations of the primary beam can be described by

$$M_1\ddot{z}(t) + \eta_1\dot{z}(t) + K_1 z(t) + \Theta_1 V_{P1}(t) = F_1(t) + F_m(t)z(t)/l(t), \quad (1)$$

$$-\Theta_1\dot{z}(t) + C_{P1}\dot{V}_{P1}(t) = -I_1(t). \quad (2)$$

Similarly, the governing equations of the inner beam can be expressed as

$$M_2\ddot{x}(t) + \eta_2\dot{x}(t) + K_2 x(t) + \Theta_2 V_{P2}(t) = F_2(t) + F_m(t)x(t)/l(t), \quad (3)$$

$$-\Theta_2\dot{x}(t) + C_{P2}\dot{V}_{P2}(t) = -I_2(t). \quad (4)$$

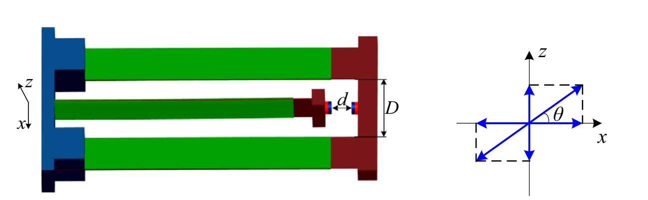
where $z(t)$ and $x(t)$ are the tip displacements of the primary beam and inner beam, respectively; M_i is the equivalent mass; η_i is the equivalent damping; K_i is the equivalent stiffness; Θ_i is the effective piezoelectric coefficient; C_{Pi} is the clamped capacitance of the piezoelectric layers; $V_{Pi}(t)$ and $I_i(t)$ are the voltage output and current output, respectively; $F_i(t)$ is the applied force coming from the mechanical vibration of the base; $F_m(t)$ is the magnetic force; l is the projection of the distance between the two magnets on the x–z plane; the subscripts 1 and 2 in the parameters denote the primary beam and inner beam, respectively. l is obtained as

$$l(t) = \sqrt{x^2(t) + z^2(t)}. \quad (5)$$

For the interaction between two magnets, we assume that the magnetic force acts only in the vibration directions, and the magnetic force in the axial direction has a negligible effect on the beam vibration [13,23,33]. In addition, we assume that the directions of the magnetic moments are always vertically aligned during the vibrations of the two beams. Based on these assumptions, the coupling force between the two magnets can be expressed as [11,23]

$$F_m(t) = \frac{3\mu_0 m_1 m_2}{2\pi}\sqrt{x^2(t) + z^2(t)}[x^2(t) + z^2(t) + d^2]^{-\frac{5}{2}}. \quad (6)$$

where μ_0 is the permeability constant, m_1 and m_2 are the effective magnetic moments of the two magnets, and d is the horizontal distance between the two magnets. The inclusion of repulsive magnets can produce two nonlinear configurations: monostable and bistable



(a) Schematic diagram of the proposed PEH (b) Vibrations on the x- z plane

Fig. 1. Schematic principle of the proposed PEH.