Energy Conversion and Management 148 (2017) 1391–1398

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Design and experimental investigation of a magnetically coupled vibration energy harvester using two inverted piezoelectric cantilever beams for rotational motion

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ARTICLE INFO

Article history:
Received 4 May 2017
Received in revised form 3 July 2017
Accepted 3 July 2017

Keywords:
Vibration
Energy harvesting
Magnetic force

ABSTRACT

Energy can be harvested from rotational motion for powering wireless autonomous electronic devices. The paper presents a magnetically coupled two-degree-of-freedom vibration energy harvester for rotary motion applications. The design consists of two inverted piezoelectric cantilever beams whose free ends point to the rotating shaft. The centrifugal force of the inverted cantilever beam is beneficial to producing large amplitude in a low speed range. The electromechanical coupling dynamical model is developed by the energy method from Hamilton's principle and validated experimentally. The experimental results indicate that the presented harvester is suitable for low speed rotation and can harvest vibration energy in multiple frequency bands. The first and second resonant behaviors of voltage can be obtained at 420 r/min and 550 r/min, and the average output powers are 564 μW and 535.3 μW, respectively.

1. Introduction

Energy harvesting from renewable energy such as mechanical vibration is considered as a promising way to replace or widen the lifespan of the traditional batteries [1]. A variety of vibration energy harvesters have been designed to convert vibration energy into electrical energy [2]. Compared with linear systems, nonlinear energy harvesters work effectively over a wide frequency range [3]. Chen et al. [4] analyzed the effect of internal resonance of two cantilevers elastically connected under magnetic interaction. Then a L-shaped broadband internally resonant vibratory energy harvester was presented by Chen et al. [5]. Yildirim et al. [6] proposed a parametrically excited system for energy harvesting. Wang et al. [7] designed a magnetic-spring based electromagnetic system to harvest vibration energy from human motions.

Specially, bistable energy harvesters moving across two potential wells under the proper conditions can dramatically increase power output [8]. Yang et al. [9] designed a novel energy harvester consisting of two elastic beams and a flextensional transducer, which had two steady states due to pre-compression. Then the nonlinear mechanical and electrical behaviors of the bistable energy harvester were provided by Yang et al. [10]. Cao et al. [11] investigated the nonlinear dynamic characteristics of variable inclination magnetically coupled bistable energy harvesters. In order to improve the efficiency of energy harvesting, Li et al. [12] designed a tristable energy harvester using magnets. In addition, multiple degree-of-freedom (DOF) vibration energy harvesters were investigated to enhance the performance of energy harvesting [13–15]. Fan et al. [13] designed a compact bi-directional nonlinear piezoelectric energy harvester which was comprised of a hollow piezoelectric cantilever beam and an inner piezoelectric cantilever beam. Li et al. [14] presented a piezoelectric energy harvester which consisted of two cantilevers with resonant frequencies of 15 Hz and 22 Hz. Kim et al. [15] presented a magnetically coupled 2-DOF energy harvester and provided physical insight into its nonlinear resonant behavior.

Rotational motion is one of the most common forms of mechanical movement in civil and industrial applications. The continuous oscillations of a cantilever beam can be generated by the gravitational force while the cantilever beam is rotating [16]. Khameneifar et al. [17] presented an energy harvester which consisted of a piezoelectric cantilever beam with tip mass mounted on a rotating hub. Roundy et al. [18] designed an energy harvester using the unique dynamics of an offset pendulum and applied it to a tire pressure monitoring system mounted on a car rim. Gu et al. [19]

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http://dx.doi.org/10.1016/j.enconman.2017.07.005
0196-8904/

and Hsu et al. [20] proposed a piezoelectric energy harvester for rotational vibration applications and its resonance frequencies were tuned passively by the centrifugal force which changed with the rotational speed. Ramezanpour et al. [21] presented a piezoelectric vibration energy harvester which was excited by rotating magnets. Then Ramezanpour et al. [22] proposed a rotary piezoelectric frequency up-converting energy harvester under weak excitation. In order to increase the vibration amplitude of piezoelectric beam, Guan et al. [23] reduced the centrifugal force by shortening the radius of the rotation.

However, the coupled multi-DOF vibration energy harvester for rotational motion was not provided. The paper presents a magnetically coupled 2-DOF bistable energy harvester for rotational motion, which can generate high voltage at low rotating speeds and work effectively in multiple frequency bands. The paper is organized as follows: In Section 2, the design is described. The electromechanical coupling dynamics model is established in Section 3. In Section 4, the experimental procedure is presented and the results are discussed. The summary is concluded in Section 5.

2. Design

The magnetically coupled 2-DOF energy harvester for rotational motion is shown in Fig. 1. There are two inverted piezoelectric cantilever beams installed rigidly with free ends facing each other on a hub. Two permanent magnets with same polarities are mounted on the free ends of the two piezoelectric cantilever beams, respectively. The hub rotates with its central axis which is perpendicular to the direction of gravity.

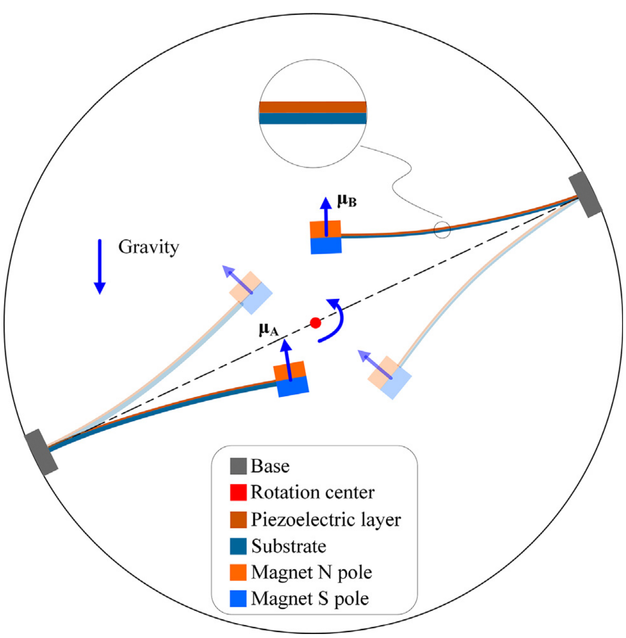

Fig. 1. Schematic of the magnetically coupled energy harvester using two inverted piezoelectric cantilever beams for rotational motion.

The inverted cantilever beam means that the direction of beam's fixed end to its free end is opposite to the direction of the centrifugal force during rotation. This is inspired by the inverted flag in flow [24]. The centrifugal force of the inverted cantilever beam may be beneficial to producing large amplitude in a certain speed range. The behavior of the inverted cantilever beam can be classified into three regimes according to its bending stiffness and rotating speed, straight mode (micro vibration), vibration mode (significant vibration) and deflected mode (may be broken), as shown in Fig. 2. The two tip magnets are mutually exclusive, so that the harvester can have two equilibrium positions. The two natural frequencies of the 2-DOF harvester are designed to be different. And the 2-DOF system possesses two different frequency bands for the first and second primary resonances which produce high power. Thus, it can harvest vibration energy in multiple frequency bands.

3. Modeling and analysis

The dynamic analysis of the magnetically coupled 2-DOF harvester is shown in Fig. 3(a) and the dimensions of the tip magnets are shown in Fig. 3(b). The inverted cantilever beams rotate about the rotation axis which is in the horizontal plane. The gravity force drives the cantilever beams to vibrate. The fixed ends of the two inverted cantilever beams are always relative stationary.

3.1. Modeling

The electromechanical coupling dynamical model can be developed by the energy method based on Hamilton's principle. The kinetic energy of the magnetically coupled 2-DOF harvester can be expressed as

$$\begin{aligned} T = & \frac{1}{2}\sum_{i=1}^{2}\left\{J_{si}\dot{\phi}^2 + \rho_{si}A_{si}\int_0^{L_i}\left[\dot{w}_i^2 + 2\dot{\phi}(L_i + d_i - x_i)\dot{w}_i\right]\mathrm{d}x_i\right\} \\ & + J_p\dot{\phi}^2 + \tfrac{1}{2}\rho_p A_p \sum_{i=1}^{2}\int_0^{L_p}\left[\dot{w}_i^2 + 2\dot{\phi}(L_i + d_i - x_i)\dot{w}_i\right]\mathrm{d}x_i \\ & + \frac{1}{2}\sum_{i=1}^{2} m_i\left[\left(\dot{y}_i + d_i\dot{\phi}\right)^2 + \dot{\phi}^2 y_i^2\right] \end{aligned} \quad (1)$$

where ρ_{si}, A_{si}, L_i and J_{si} are the material density, the cross sectional area, the length and the inertia of the cantilever beams, ρ_p, A_p, L_p and J_p are the material density, the cross sectional area, the length and the inertia of the piezoelectric layers, w_i is the deflection of the beams, d_i is the distance between the center of the tip

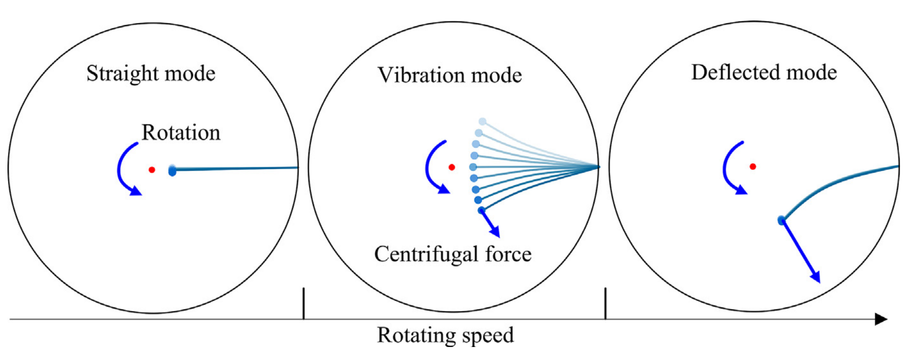

Fig. 2. Schematic of the inverted cantilever beam in rotation.