Mechanical Systems and Signal Processing 110 (2018) 260–272

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Harvesting performance of quad-stable piezoelectric energy harvester: Modeling and experiment

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ARTICLE INFO

Article history:
Received 18 August 2017
Received in revised form 8 March 2018
Accepted 9 March 2018

Keywords:
Piezoelectricity
Quad-stable energy harvester
Random excitation
Interwell motion
Snap-through

ABSTRACT

To overcome the defects of bi-stable energy harvester (BEH) and improve the energy conversion ability under weak stochastic excitation, we developed a novel quad-stable energy harvester (QEH). This configuration is composed of a piezoelectric cantilever beam with a tip magnet and three external fixed magnets. By adjusting positions of the fixed magnets and altering the distances between the tip and the fixed magnets, four stable equilibrium positions (SEPs) can be realized in the static state of QEH. The diagram of potential energy illustrates that QEH has shallower and wider potential wells than BEH at the same separation distance, implying that it can execute jumping across the potential barrier easily. Validation experiment was carried out and the experimental results showed that QEH could create larger deflection and generate higher output voltage than BEH nearly over the whole range of excitation intensity. Furthermore, by controlling the gap and separation distances, the QEH can be optimized to reach the maximum output power for a certain excitation intensity.

1. Introduction

Energy harvesting from ambient vibration has become a promising research field due to the increasing power requirement for wireless sensor networks [1–6]. Among various transduction methods of harvesting energy to power the wireless sensor nodes, piezoelectric energy harvesting has received a great attention in the literature owing to its high power output and easy application [7–11].

Conventional linear piezoelectric energy harvester is not efficient in harvesting vibration energy with a broadband frequency range. However, ambient vibration energy existing in most environments is made up of a number of frequencies. Therefore, the linear energy harvester is inefficient in realistic environments. To solve this problem, a bi-stable energy harvester (BEH) has been proposed to expand the operational bandwidth, which could produce high power output by snap-through phenomenon [12–16]. In BEH, magnetic force has been frequently adopted to realize bi-stable characteristic due to its convenience and better performance [17,18]. Many theoretical and experimental studies have been carried out to investigate the dynamic characteristic and performance of BEH. De Paula et al. [19] investigated the influence of nonlinearities in linear, mono-stable and bi-stable systems subjected to random vibrations. Erturk et al. [20,21] theoretically and experimentally investigated the high-energy orbits of BEH subjected to harmonic excitations. Both mono-stable and bi-stable configurations with magnetic attraction and repulsion effects were studied for sinusoidal and random excitations

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https://doi.org/10.1016/j.ymssp.2018.03.023
0888-3270/

[22]. Some energy harvesters with adjustable or movable magnets were designed to enhance the output electrical power. Lin et al. [23] studied a piezoelectric cantilever beam with moveable external magnets to improve the scavenging efficiency. Zhou et al. [24] experimentally and numerically investigated an energy harvester with rotatable external magnets to broaden the power generation frequency bandwidth. Tang et al. [25] reported a piezoelectric energy harvester with magnetic oscillator. The experimental results showed that the proposed energy harvester had a nearly 41% increase in output power. Gao et al. [26] studied a BEH with elastic external magnet, which was proved to be able to prompt the harvesting performance under low-intensity excitation. Jung et al. [27] theoretically and experimentally investigated the nonlinear dynamic characteristics of a piezoelectric energy harvester. Kwuimy et al. [28] investigated a BEH with fractional order physical properties and the results showed that the fractional power deflection should be reconsidered in the design of nonlinear energy harvester. Kim and Seok [29] analyzed the dynamic and energetic characteristics of a multi-stable energy harvester with a soft tip magnet and two external fixed magnets. Furthermore, in order to promote the harvesting ability, the tri-stable energy harvester with shallower potential wells are designed and investigated. Zhou et al. [30] carried out an investigation on tri-stable energy harvesters at different harmonic excitation levels with the frequency ranging from 1 to 20 Hz. The results verified that the tri-stable one could easily cross the potential barriers to realize snap-through, thereby generating high voltages. The influence of potential well depth on the performance of tri-stable energy harvester were numerically and experimentally investigated by Cao et al. [31]. Zhou et al. [32] proposed an impact-induced method to realize high-energy motions under weak excitation. Zhu et al. [33] and Li et al. [34] studied the coherence resonance of tri-stable energy harvester subjected to Gaussian white noise excitation. On the other hand, Zhou et al. [35] conceived a quad-stable energy harvester (QEH) and the corresponding experimental results showed that it could make improvements in energy harvesting under random excitation.

This paper theoretically and experimentally studied the nonlinear dynamical characteristics of an improved QEH based on the model conceived in [35]. The electromechanical coupling equation was derived by the energy-based method and the Euler-Lagrange equation. The bifurcation diagrams are plotted to show the variation of stability with the separation distance. The results of theoretical analyses and validation experiments prove that QEH can easily realize snap-through motion between potential wells and reach coherence resonance even at weak random excitation. In practical application, the QEH could be optimized by adjusting the gap and separation distances such as to reach the maximum output for a given excitation intensity.

2. Mathematical modeling of QEH

As depicted in Fig. 1(a), a typical BEH is composed of a piezoelectric cantilever beam, a tip magnet and a fixed magnet located opposite the tip one; and the two magnets have the same polarity opposed to each other so as to produce a nonlinear magnetic repulsive force. The piezoelectric layers pasted on the cantilever beam are connected to a circuit with a resistance load R. The separation distance between the two magnets can be controlled such that the ferromagnetic beam could keep a state with two stable equilibrium positions (SEPs). Now to improve the performance of harvesting, we add two other fixed magnets, which are situated near the left and right sides of the original fixed magnet; then by adjusting the gap and separation distances between them, the system could have four SEPs, i.e., it turns to a QEH, as shown in Fig. 1(b).

To derive the electromechanical coupling equations of QEH, the kinetic energy and the potential energy of the system should be calculated first. The total kinetic energy of the system comes from motions of the substrate layer, the piezoelectric layers and the tip magnet, thus it is

$$T_{pb} = \frac{1}{2}\int_0^L m[\dot{w}(x,t) + \dot{z}(t)]^2 dx + \frac{1}{2}m_0[\dot{w}(L,t) + \dot{z}(t)]^2 \tag{1}$$

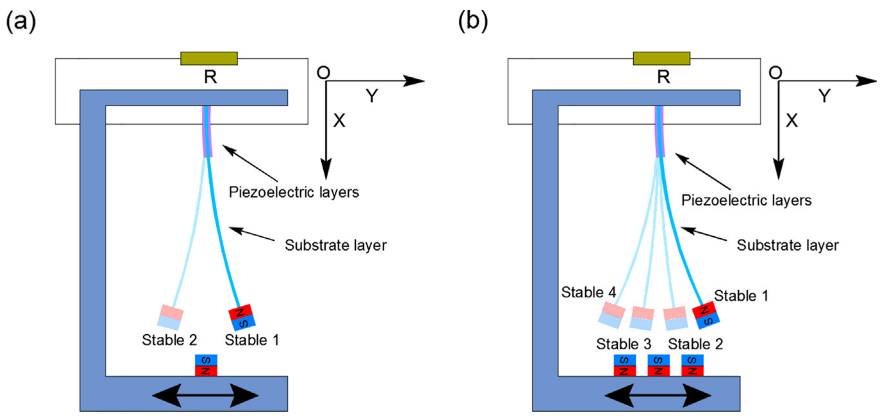

Fig. 1. Schematics of (a) BEH and (b) QEH.