Mechanical Systems and Signal Processing 105 (2018) 427–446

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Dynamic and energetic characteristics of a bistable piezoelectric vibration energy harvester with an elastic magnifier

Guangqing Wang [a,*], Wei-Hsin Liao [b], Binqiang Yang [a], Xuebao Wang [a], Wentan Xu [a], Xiuling Li [a]

[a] School of Information and Electronic Engineering, Zhejiang Gongshang University, Hangzhou 310018, China
[b] Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong, China

ARTICLE INFO

Article history:
Received 16 March 2017
Received in revised form 30 October 2017
Accepted 14 December 2017

Keywords:
Bistable energy harvester
Elastic magnifier
Dynamic behavior
Energetic characteristics
Bifurcation analysis
Distributed parameter model

ABSTRACT

Bistable piezoelectric energy harvesters are being increasingly seen as an alternative to batteries in low-power devices. However, their energy harvesting characteristics are limited. To enhance these, we use a configuration including an elastic magnifier to amplify base excitation and provide sufficient kinetic energy to overcome potential well barriers, thus leading to large-amplitude bistable motion. We derive the distributed parameter mathematical model of this configuration by using Hamilton's principle. We then investigate the nonlinear dynamic behaviors and energetic characteristics and analyze the bifurcation for the equilibrium solution of the model. The simulations and experiments show high electromechanical responses and energy generation characteristics of the proposed system over a broad frequency band. The results suggest that, compared with a typical bistable piezoelectric energy harvester, the proposed energy harvester system with an elastic magnifier can provide higher output over a broader frequency band at lower excitation levels by adjusting the system's mass and stiffness ratios.

1. Introduction

Energy harvesters are a type of electromechanical device that harvest and convert ambient energy into electric energy. They have undergone rapid developments in recent years and drawn the attention of many researchers as an alternative to batteries in some low-power electronic devices [1,2]. This is because the batteries used in such devices have several disadvantages, such as short lifetime, low power density, the production of harmful waste, and high maintenance costs [3,4].

A variety of energy sources, including vibration, wind, sunlight, and heat, can be used in the development of various energy harvesters [1]. However, vibration energy in particular has been considered for its ubiquitous occurrence on Earth and excellent power density [5]. Most of the previously reported vibration energy harvesters have been a type of linear resonator and use their resonant characteristics of a strong resonant peak, which can exhibit satisfactory performance with large vibration amplitude when the ambient excitation frequency matches the system's natural frequencies. The main problem of such a linear energy harvester is that the resonant bandwidth is very narrow, so significantly lowering the harvesting efficiency in the off-resonant frequency region [6–11].

* Corresponding author.
E-mail address: kele76@163.com (G. Wang).

https://doi.org/10.1016/j.ymssp.2017.12.025
0888-3270/

To overcome this issue, researchers have proposed various energy harvesters such as array oscillators, multimodal oscillators, and active or adaptive frequency tuning oscillators [12,13]. A bistable energy harvester has also been recently proposed and proved to be an efficient means to harvest more vibration energy over a broad frequency range [14–22]. In general, a beam-type bistable energy harvester can be realized by imposing an external force on the beam tip using a magnet. Such a bistable energy harvester has a double-well potential, yielding three different dynamic regimes, which are determined by the strength of the excitation applied to the system: (1) a low-amplitude intrawell motion for a small excitation strength, (2) an aperiodic or chaotic motion for a certain amplitude excitation strength, and (3) a large-amplitude periodic interwell motion for a large excitation strength. The interwell motion is known to help the system to harvest more vibration energy over a wide frequency band. However, it requires higher excitation strength. If the excitation strength is low, the bistable energy harvester may exhibit low-energy intrawell motion, and the tip inertial mass oscillates around one of the stable equilibria with small strokes per period [16–18], which greatly reduces the output performance. In spite of this limitation, the abovementioned merits of bistable energy harvester are accelerating their development using various structures and methods.

To enhance the output performance of bistable energy harvesters under low-level excitation, researchers have attempted to make them oscillate with large-amplitude interwell motion. Masuda et al. [19] and Sebald et al. [20] found that an external intervention can help bistable energy harvesters return to a large-amplitude motion state. Sebald et al. [21] found that increasing the excitation amplitude can help them jump from low-amplitude motion to large-amplitude motion. Erturk and Inman [22] found that increasing the excitation amplitude or applying an initial velocity to the bistable harvesters may lead to large-amplitude motion [23,24]. Recently, Kim and Seok [25,26] proposed tristable or multistable energy harvesters, which, compared with bistable energy harvesters, have shallower and wider potential wells, thus enabling them to extract vibration energy in a wider frequency range, even under a relative low excitation level. However, the magnetic field arrangements for tristable or multistable energy harvesters are much more complex.

Unlike the abovementioned methods, the present paper focuses mainly on the enhancement of a bistable piezoelectric energy harvester (BPEH) with an elastic magnifier (EM) for large-amplitude periodic interwell motion. The EM is composed of a block mass, and a spring element was placed between the BPEH and the base. By adjusting the system parameters, such as the mass ratio and stiffness ratio between the EM and BPEH, the base excitation should be greatly amplified to provide the BPEH with large accelerating energy, so as to cause the BPEH to oscillate with large-amplitude interwell motion, resulting in a high electromechanical response and energetic generation over a broad frequency band. Although numerous studies have investigated the effects of a linear piezoelectric energy harvester with an EM, few have investigated a BPEH with an EM. Wang and Liao [27] studied a lumped parameter model of a BPEH with an EM (BPEH+EM), and obtained some promising results, where the exciting frequency was less than the fundamental resonant frequency of the cantilevered structure. However, their lumped parameter model may yield inaccurate results due to the contribution of the distributed mass of the cantilevered structure to the exciting amplitude. In addition, the dynamic and energetic characteristics where the exciting frequency is larger than the fundamental resonant frequency would be of great interest for further investigation. Therefore, the main objective of the present study is to theoretically and experimentally investigate the dynamic behaviors and energetic characteristics of BPEH+EM to obtain more physical insights. We develop a distributed parameter mathematical model of the BPEH+EM system based on Hamilton's principle and linear piezoelectricity. Using the dipole–dipole magnetic model, we formulate the magnetic repulse force acting on the beam tip in terms of several parameters, which we incorporate into the governing differential equation obtained using the variation principle. We then analyze the dynamic characteristics and energy harvesting performances of the BPEH+EM system by numerical simulation and experiments, respectively, and compare the results with those of a conventional BPEH system.

2. BPEH+EM configuration and mathematical modeling

The BPEH+EM configuration considered in this study is schematically shown in Fig. 1. The BPEH comprises a bimorph beam cantilevered at the left wall of a U-shaped block and two permanent magnets, one of which is attached to the tip of the cantilever beam (called the tip magnet), and the other one is fixed at the right wall of the U-shaped block (called the external magnet). The magnetic field orientation of the tip magnet is of opposite polarity to that of the external magnet, as shown in Fig. 1a. The cantilever beam is composed of a central substrate layer, covered with two identical thin piezoelectric layers (PZT_1 and PZT_2) on both of its surfaces. The surfaces of each piezoelectric layer are fully covered with thin electrode. The two piezoelectric layers are polarized oppositely in the thickness direction and are electrically connected in series with an external load resistance, denoted by R, representing the equivalent resistance of an electronic device that is electrically connected to the energy harvester system. The EM comprises a U-shaped block and a spring element, and the U-shaped block is mechanically connected in series with the spring element. The EM is positioned between the BPEH and the base, as shown in Fig. 1b. To model the system shown in Fig. 1b, the BPEH+EM system can be simplified as a two-degrees-of-freedom (2-DOF) nonlinear vibration model, as shown in Fig. 1c, in which M_b, K_b, and C_b denote the equivalent mass, stiffness, and damping of the EM, respectively; L and b are the length and width of the beam; h_s and h_p are the heights of the central substrate and the piezoelectric layers, respectively; and z_b and z_m are the vibration levels of the base and the EM, respectively. The tip magnet and the external magnet are separated by a distance (d) measured in the x-direction based on the undeformed state of the beam. In this situation, the magnetic repulsion force applied to the tip beam tends to depend strongly