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Magnetically coupled flextensional transducer for wideband vibration energy harvesting: Design, modeling and experiments

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The combination of nonlinear bistable and flextensional mechanisms has the advantages of wide operating frequency and high equivalent piezoelectric constant. In this paper, three magnetically coupled flextensional vibration energy harvesters (MF-VEHs) are designed from three magnetically coupled vibration systems which utilize a magnetic repulsion, two symmetrical magnetic attractions and multi-magnetic repulsions, respectively. The coupled dynamic models are developed to describe the electromechanical transitions. Simulations under harmonic excitation and random excitation are carried out to investigate the performance of the MF-VEHs with different parameters. Experimental validations of the MF-VEHs are performed under different excitation levels. The experimental results verify that the developed mathematical models can be used to accurately characterize the MF-VEHs for various magnetic coupling modes. A comparison of three MF-VEHs is provided and the results illustrate that a reasonable arrangement of multiple magnets can reduce the threshold excitation intensity and increase the harvested energy.

1. Introduction

Energy harvesting from the vibration source in the environment is considered as a promising way to replace or widen the lifespan of the conventional batteries [1,2]. One of the key challenges for vibration energy harvesting is that linear oscillators, which are suited for narrow band excitation near their natural frequencies, are less efficient when the ambient vibration energy is distributed over a wide spectrum and dominant at low frequencies [3]. Therefore researchers designed low frequency energy harvesters which were more useful under low frequencies excitation [4]. The frequency up-converting method was used to efficiently harvest energy from low frequency vibration environment [5,6]. An array of vibration energy harvesters which consists of multimodal oscillators was proposed to harvest energy in a wide frequency band [7]. Self frequency tuning is a feasible approach to extend the operational frequency range [8].

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Compared with linear energy harvesters, nonlinear systems possess a wider frequency bandwidth which can be utilized to improve the performance of vibration energy harvesters in ambient environments [9–11]. One shared approach to design a nonlinear system is to introduce a nonlinear restoring force. The nonlinear magnetic force can be easily obtained and has been used in a multitude of nonlinear energy harvesting systems, involving monostable oscillator [12], bistable oscillator [13–20] and multistable oscillator [21–27].

Bistable energy harvesters transition from one stable state to the other, could give rise to large amplitude motion and dramatically increase power output [3]. Stanton et al. [13,14] presented a bistable energy harvester using a magnetic repulsive force, and then used Melnikov theoretic methods for characterizing the dynamics of the bistable system in complex spectral environments. Zheng et al. [15] investigated that stochastic resonance was deliberately exploited for improving the performance of the bistable energy harvester. Erturk et al. [16,17] presented a bistable energy harvester using two symmetrical magnetic attractions for broadband vibration energy harvesting. Litak et al. [18] considered this bistable energy harvester driven by stationary Gaussian white noise. Zhao and Erturk [19] investigated the performance of this bistable energy harvester under stochastic excitation, and provided a comparison with a monostable piezoelectric cantilever. Harne et al. [20] presented an analytical approach for predicting the energy harvesting of the bistable energy harvester with impulsively-exciting. Furthermore, multistable energy harvesters have been proposed. Zhou et al. [21,22] presented a tristable energy harvester and then theoretically analyzed the dynamic responses using harmonic balance method. Cao et al. [23,24] provided the influence of potential well depth on the performance of the tristable energy harvester. Li et al. [25] presented a tristable energy harvester which realized inter-well oscillation at low-frequency base excitation. Zhou et al. [26,27] presented a novel quad-stable energy harvester which can improve the harvesting efficiency considerably.

However, most studies converted vibration energy into electrical energy via bending single or double piezoelectric layers which were attached to a beam (31 coupling mode). The electromechanical coupling coefficient is lower than the 33 mode and the piezoelectric ceramic layer cracks easily under dynamic bending stress [28]. The flextensional piezoelectric transducers possess a higher coupling coefficient and are more robust [28–32]. But the flextensional transducers were mainly used in the high force environment and could not harvest energy efficiently in weak vibration environment. The vibration can be converted to the periodic force acting on the flextensional transducer via magnetic coupling. The combination of nonlinear bistable and flextensional mechanisms has the advantages of wide operating frequency and high equivalent piezoelectric constant [33]. In this paper, the magnetically coupled flextensional transducer for wideband vibration energy harvesting is investigated via three kinds of magnetically coupled flextensional vibration energy harvesters (MF-VEHs) which utilize a magnetic repulsion, two symmetrical magnetic attractions and multi-magnetic repulsions, respectively. The electromechanical coupling dynamic models of the MF-VEHs are developed by the energy method based on Hamilton's principle. The characteristics of three MF-VEHs with different parameters are investigated numerically under harmonic excitation and random excitation. Experimental validations of the MF-VEHs are performed under different excitation levels. The paper is organized as follows: In Section 2, the designs are described and the electromechanical coupling dynamic models are established. In Section 3, a parametric study is provided. The experimental procedure is presented in Section 4. In Section 5, the results are discussed. The summary is concluded in Section 6.

2. Design and modeling

2.1. Design

The magnetic coupling mechanism of the MF-VEH is shown in Fig. 1. The cantilever has two equilibrium positions due to the vertical component of the magnetic force. Vibration is converted to variable magnetic force, then the horizontal component of the magnetic force is amplified and transmitted to the piezoelectric layer by the flextensional structure, and

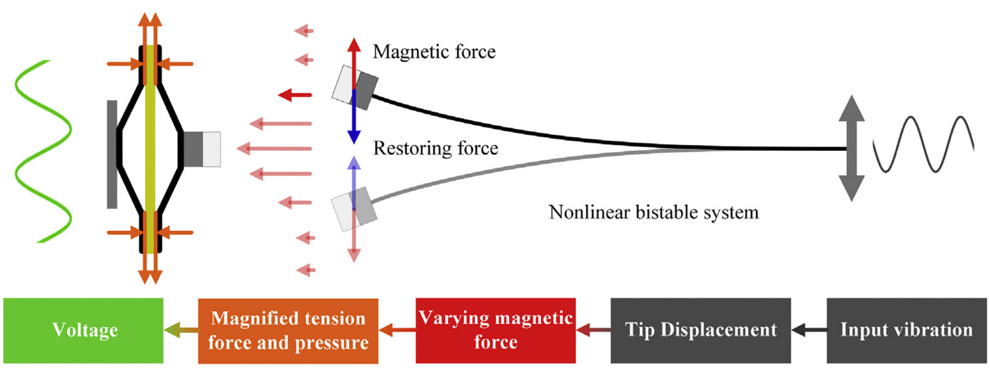

Fig. 1. The mechanism of the magnetically coupled flextensional vibration energy harvester (MF-VEH).