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A broadband quad-stable energy harvester and its advantages over bi-stable harvester: Simulation and experiment verification

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ABSTRACT

This paper presents a novel quad-stable energy harvester (QEH) to harvest vibration energy. The QEH is composed of a piezoelectric bimorph cantilever beam with a tip magnet and three external fixed magnets. The potential energy of the QEH is derived, which has four potential wells and three low barriers. This implies that the QEH needs relatively lower excitation energy to cross the barriers than the bi-stable energy harvester (BEH). Simulations are carried out for the BEH and QEH at different levels of excitations. Results show that the QEH owns a smaller threshold and a wider range of frequencies for occurrence of snap-through than the BEH. Thus the QEH can give out a large output voltage. Corresponding experiments were performed for validation. The experimental results are in agreement with the simulations, which means that the QEH can improve the harvesting efficiency considerably.

1. Introduction

Energy harvesting from ambient vibration power in the environment has been intensively studied during the past few years, mainly because of the need to power wireless sensors or communication node networks. The methods of transduction of vibration to electricity via piezoelectric materials have motivated many researchers because of its high power density, green and high voltage output properties [1–5]. The typically piezoelectric harvester is composed of a cantilever beam with one or more piezoelectric patches which can generate electric charge when subjected to mechanical strain.

The linear devices can only exhibit resonance within a very narrow frequency range. To make them more applicable, researchers began to explore active and semi-active strategies to increase their efficiency [6–8]. Within the past few years, the bi-stable piezoelectric inertial generator has emerged as a popular mechanism for harvesting. The main advantage of nonlinear energy harvesters over their linear counterparts is that the nonlinear harvesters scavenge energy over a broader frequency range of vibrations. It has been demonstrated that nonlinear bi-stable systems, under proper conditions, have better performance in terms of the amount of energy extracted from wide spectrum vibrations [9–14]. A typical BEH is as shown in Fig. 1, which has two stable equilibrium positions and an unstable equilibrium position.

To enhance the conversion ability of the piezoelectric energy harvester, magnets have been frequently adopted to alter the stiffness of the energy harvester and thus tune the resonant frequency of the energy harvester, which is ideally suited to

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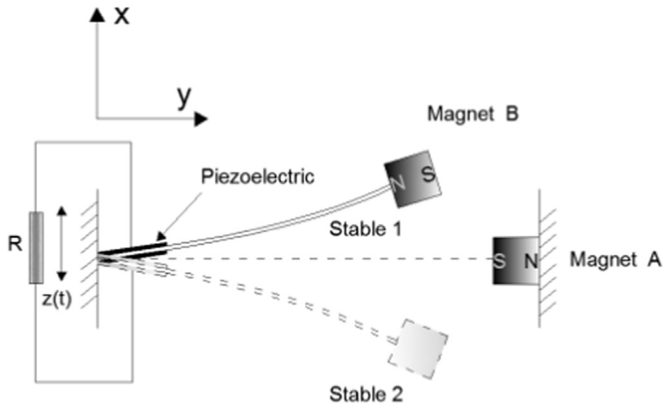

Fig. 1. Bi-stable energy harvester (BEH) with two stable states.

efficiently harvest energy from ambient excitations with slowly varying frequencies [15,16]. Tang [17] exploited a pair of magnets in repulsive and attractive configurations to enhance the vibration amplitude and the bandwidth of frequency. Miso et al. [18] presented a closed form solution to harvesting efficiency that allows device comparison. The optimized electrical loading conditions are studied. The BEH device has the capability of snapping from one stable state to another at a certain intensity of excitation. Such snap-through motion can bring about a large-amplitude vibration and shows a good performance in energy harvesting. But there exists a difficult point for the bi-stable harvester. The increase of the distance between the two potential wells can enlarge the amplitude of snap-through, but the barrier height will increase accordingly. This hinders the BEH from breaking through the constraint of potential barriers [19].

To further enhance the performance of the energy harvester, some studies focused on using adjustable or movable magnets. Lin [20] investigated a magnetically coupled piezoelectric cantilever beam, in which the displacement of the fixed magnet could be altered to achieve off-resonance to enhance the broadband frequency response. Zhou et al. [21] investigated a magnetically coupled nonlinear piezoelectric energy harvester by altering the angular orientation of its external magnets for enhanced broadband frequency response. Tang and Yang [22] introduced a magnetic coupled piezoelectric energy harvester, in which the magnetic interaction is produced by a magnetic oscillator. Gao et al. [23] conceived a structure with an elastic support external magnet and proved that elastic support systems have better power output performance than rigid support systems when excited at low-intensity vibrations. However, when it comes to small excitations, the above improved BEH cannot gain enough energy to break through the constraint of potential wells and generally go to intrawell oscillations. So the performance of the bi-stable energy harvester is not satisfied at all time.

Recently, more complex energy harvesting systems with multi-stable state have been proposed. Jung et al. [24] investigated the piezoelectric energy harvester with two rotatable external magnets. The results show that the angle of the external magnet and separation distance between the tip magnet and the external ones could alter the potential energy of the harvester system. Kim and Seok [25] investigated the numerical analysis of bifurcation of a multi-stable bimorph energy harvester that used the magnetic attraction effect. Zhou et al. [26,27] carried out numerical and experimental investigations on a tri-stable bimorph cantilever energy harvester with two rotatable external magnets at swept sine excitations. The results reveal that the tri-stable energy harvester can improve the broadband performance to generate high energy output. Cao et al. [28] considered the influence of potential well depth on tri-stable energy harvesting performance and the corresponding experiment results show that the shallower potential well depth will enhance the broadband performance and the capability of harvesting energy at low frequency excitations. Tékam et al. [29] analyzed the dynamics of a tri-stable energy harvester which has fractional order viscoelastic flexible material and the results showed that the energy output could be enhanced by choosing a material with a small value of viscoelasticity coefficient and a large fractional order.

This paper proposes a novel quad-stable energy harvester (QEH). The theoretical model of the QEH is established using energy-based methods and Hamiltonian principle. The potential energy of the BEH and QEH are derived. The electromechanical equation is solved and the results show that the QEH owns a wide frequency bandwidth for occurrence of snap-through. Compared with the BEH, the QEH can realize snap-through more easily and generate high output voltages.

2. Quad-stable piezoelectric energy harvester

As Fig. 2 shows, the QEH consists of a bimorph cantilever beam with a tip magnet D and three fixed magnets A, B and C. Two piezoelectric layers are attached to the root of the cantilever beam. The piezoelectric layers are connected to an electrical load.

The dynamic equations of the QEH can be derived by the Euler-Bernoulli beam theory and Hamilton principle. The general form of Hamilton's principle for this electromechanical system can be written as