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Enhancing ability of harvesting energy from random vibration by decreasing the potential barrier of bistable harvester

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ABSTRACT

When a bistable energy harvester (BEH) is driven by weak random excitation, its harvesting efficiency will decrease due to the seldom occurrence of interwell motion. To overcome this defect, we developed an improved bistable energy harvester (IBEH) from BEH by adding a small magnet at the middle of two fixed magnets. It is proved that the attractive force originated from the additional magnet can pull down the potential barrier and shallow the potential well, but still keep the middle position of beam unstable. This can make jumping between potential wells easier. Thus IBEH can realize snap-through even at fairly weak excitation. The magnetic potential energy is given and the electromechanical equations are derived. Then the harvesting performance of IBEH under random excitation is studied. Validation experiments are designed and carried out. Comparisons prove that IBEH is preferable to BEH in harvesting random energy and can give out a high output voltage even at weak excitation. The size of additional magnet can be optimized to reach the best performance of IBEH.

1. Introduction

Over the past decades, with the development of piezoelectric materials, researchers were attracted to investigate the potential of using piezoelectric patches to harvest vibration energy in environment. Nowadays vibration energy harvesting is one of the most promising green technologies and becomes a research frontier. The piezoelectric energy harvester based on the linear structures has been studied in depth. Tang [1] reviewed the technologies of broadband vibration energy harvesting, such as single-degree system, multi-degree system, elastic structures and so on. It was proven that this kind of structures can harvest vibration energy effectively when resonance takes place. Lei [2] showed that the large-scale harvesting technologies had a wide application on energy harvesting from human motion, vehicles, transportation and civil structures.

In recent years many research papers showed that the nonlinear piezoelectric structures were more effective for broadband energy harvesting. If the system parameters and external excitation conditions were suitable, the nonlinear structure could give rise to rich nonlinear dynamical phenomena, such as strange attractors, chaotic motion and snap-through motion. The experimental results of Ferrari [3] and Erturk [4] showed that the bistable system could produce a remarkable improvement in output power over a wider bandwidth. Friswell [5] studied the energy harvesting efficiency of a vertical cantilever beam with a tip mass when excited by horizontal excitation. Both simulations and experiments showed

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that this bistable system was effective over a broad-frequency bandwidth. In practice many structures realize bistability by magnetic attraction, magnetic repulsion or material properties. Syta [6] investigated an energy harvester based on the bistable laminated plates by utilizing material properties to obtain the bistability. Harne [7] reviewed the recent researches on vibration energy harvesting via bistable system and concluded that the snap-through action could cause large amplitude motion and dramatically increase power generation. Stanton [8] applied the method of Harmonic Balance to analyze the existence and stability of bistable system. The influence of parameters on the intrawell and interwell oscillations was studied. Recently some researchers designed 2-DOF nonlinear energy harvesters to realize broadband energy harvesting. Wu [9] developed a nonlinear 2-DOF piezoelectric system with magnetic repulsion. The results showed that the nonlinear coupled energy harvester was effective for broadband energy harvesting. Su [10] made a broadband magnet-induced dual-cantilever piezoelectric energy harvester. The results indicated that the bistable energy could provide a significant improvement in harvesting bandwidth. Zhou [11] investigated another nonlinear doubly magnet-coupled energy harvesting system and demonstrated that the frequency bandwidth and performance could be enhanced by adjusting the magnets. Moreover some researches tried using the internal resonance to increase the harvesting efficiency. Experiments on vertical beam with tip mass showed that when it was excited near the second mode, there appeared strong coupling between modes [12]. Chen [13] employed the internal resonance enhance vibration energy harvesting. The numerical simulations showed that the internal resonance design could produce more power under both Gaussian white noise and exponentially correlated noise.

The performance of bistable energy harvester(BEH) excited by random motions is an important index. Cotton [14] found that for a certain intensity of random excitation, a well designed BEH could tremendously improve the output power. Litak [15] simulated the dynamic response of BEH driven by random excitation. His analysis indicated that the energy harvested from a bistable device was most efficient for a certain range of noise intensity. The equivalent linearization-based analytical approach was developed for the analysis of harvesting power by Ali [16]. Other researchers found the stochastic resonance phenomenon could be used to harvest energy [17,18]. Daqaq [19] provided theoretical investigation into the bistable electromagnetic energy harvester subjected to white and exponentially correlated Gaussian noises. It was pointed out that the bistable harvester was not preferable to the monostable harvester always. Kummar [20] used the finite element method to solve the FP equation and gave the joint probability density functions of response as well as the output voltage. His analyses proved Daqaq's conclusion. Cammarano [21] investigated the bandwidth of optimized nonlinear vibration-based energy harvesters. It was concluded that the nonlinear harvester exhibited a wider bandwidth only if it was operated in the upper branch of multiple solution regions. Zhao [22] compared the performances of monostable and bistable power generators. The results showed that a bistable energy harvester could potentially be preferred only if it is appropriately designed to operate in the neighborhood of a specific random excitation intensity. litak [23] investigated the performance of a magnetiopizoelastic bistable system driven by different kind of random excitation. Results show that the bistable system excited with Gaussian noise tends more clearly to one of the different solutions (i.e. motion in a single well or in both wells) while the uniform noise case leads to intermittency with multiple solutions.

The mechanism of bistable piezoelectric beam under random excitation can be summarized briefly as follows: (1) if the intensity of random excitation (σ_f^2) is quite low, the beam will be trapped in one single potential well, and the output voltage will not be high since there is no interwell motion; (2) if σ_f^2 is large enough to cause the beam to overcome the potential barrier, the beam can realize the interwell motion and give out a high output voltage. Comparing to the monostable system, the main advantage of bistable system lies in the fact that the interwell motion can leads to the large vibration and deformation and thus generate more output power. Generally the deep potential wells can bring about the large vibration amplitude. But the deep wells will make a high barrier. Thus the bistable system with deep potential well needs more energy to overcome its potential barrier. Namely when the intensity of random vibration is not much strong, the bistable system will be trapped in one well and hardly cross the potential barrier. This will lead to the low output voltage.

The intent of this paper is to make improvements on BEH to prompt its harvesting ability for weak base excitation. A small magnet is added at the middle of two existing symmetric magnets of BEH to form an improved bistable energy harvester (IBEH) (Figs. 1 and 2). The additional magnet produces an attractive force on the tip magnet, which can pull down the potential barrier. Thus IBEH can cross the barrier easier and scavenge more excitation energy. This work mainly studies how the additional magnet improves the harvesting efficiency, especially for the low intensity of random excitation. In Section 2 by introducing the magnetic forces we derive the electromechanical equations. Then in Section 3 we explain how

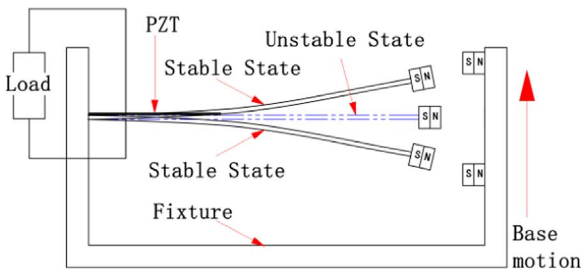

Fig. 1. Bistable energy harvester (BEH) (viewed from above).