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Improved energy harvesting from low-frequency small vibrations through a monostable piezoelectric energy harvester

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ABSTRACT

Scavenging energy from low-frequency and low-level excitations has always been a huge challenge for the piezoelectric energy harvesting since the frequencies of ambient excitations are usually below the device's operating frequency and small excitations may fail to actuate the device to produce usable electricity. To remedy this key issue, a piezoelectric energy harvester with stoppers (PEHS) has been proposed by the authors. The stoppers and the magnetically attractive coupling employed in the PEHS make the device monostable, removing the requirement for overcoming the potential barrier that normally appears in a bistable or tristable system. A theoretical model for the PEHS is established and experimentally validated, with which the PEHS is investigated under both harmonic excitations and random excitations. The results indicate that the operating frequency range of the PEHS can be tuned toward the lower frequency by changing the (mass-magnet) gap between the tip mass and the external magnets, making the efficient energy harvesting from low-frequency excitations possible. For a given harmonic excitation, the PEHS can provide a larger power output and wider operating bandwidth than the linear PEH no matter what way the frequency sweep is conducted. Moreover, compared with the linear PEH, improved power output can also be attained under the Gaussian white noise with a small intensity, enabling the PEHS to deliver useful power even in the presence of small random excitations. Although the optimal PEHS configuration in terms of mass-magnet gap is found to vary slightly with the excitation levels, there exists a certain gap that can guarantee the optimal or near optimal performance of the PEHS under both low-level harmonic excitations and low-intensity random excitations, demonstrating the harvester's superior adaptation to the ambient excitations with variable strengths.

1. Introduction

Harvesting ambient vibration energy to generate electricity has been increasingly considered as a pivotal point for the development of self-sustained micro-powered electronic devices [1–3]. The almost omnipresent vibration energy can be captured to recharge electrochemical batteries, currently the main power source of micro-powered devices, or even to replace batteries to directly power these devices, contributing to the realization of completely self-sufficient microsystems [4,5]. In accordance with human society's call for renewable green energy, vibration energy harvesting technologies

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exploiting the ambient waste energy can provide a sustainable power source and then demonstrate potential applications in a variety of fields, such as embedded sensors/microsystems in buildings and structures, wearable devices, medical implants, and wireless sensor networks [6–11].

Among various vibration energy harvesting mechanisms, the piezoelectric energy harvesting has attracted most attention due to its simple structure and high energy density [9,12,13]. Conventional piezoelectric energy harvesters (PEHs) are generally designed as a linear resonator and then operate effectively only in a limited frequency range around the resonance, leading to poor harvesting efficiency under broadband ambient vibrations [8,14–16]. One straightforward approach for solving this key issue is integrating multiple linear harvesters with different but close resonant frequencies in one device to construct an array harvester [17–19]. It is not surprising that the array harvester can cover a wide frequency range but at the cost of reducing the power density. A retrofitted version of array harvesters is the multi-modal energy harvester [20], which is realized by attaching an additional oscillator or dynamic magnifier to the linear PEH so that two close resonances can be achieved in one structure [4,8,21–24]. Another strategy for broadband energy harvesting is the tuning mechanism, which shifts the natural frequency of a harvester into the spectral region where most of the vibration energy is available [25]. Although the tuning mechanism can be implemented via several different ways, such as applying axial load on a cantilever beam [26] and changing the position of the proof mass [17], the increased complexity in design and extra power consumption for active tuning may overwhelm the performance improvement brought about by this strategy.

In recent years, nonlinearities generated by the magnetic interaction have been widely exploited to improve the harvester performance as the nonlinearity-induced bending of response curves can be employed to cover a wider frequency range [27]. A typical nonlinear PEH is composed of a piezoelectric cantilever beam with one magnet affixed at the free end and the other one at the enclosure of the device [14,28–32]. For small spacing of the two magnets with repulsive arrangement, this nonlinear structure exhibits bistable behavior [33], whereas the large spacing or attractive arrangement makes the PEH monostable. A comprehensive study by Tang et al. [29] indicates that the bistable PEH works very well when the spacing of the two repulsive magnets is set close to the monostable-to-bistable transition region. Another commonly adopted approach for constructing nonlinear PEHs is based on the Duffing oscillator that consists of a ferromagnetic cantilever beam with two magnets positioned symmetrically near the free end [15]. By bonding two piezoelectric patches to the root of the cantilever beam, the Duffing oscillator based piezomagnetoelastic structure is capable of extracting energy from broadband vibrations [34]. This piezomagnetoelastic structure was further ameliorated by Cao et al. [35] via attaching a magnet at the beam's free end and making the two external magnets rotatable. Depending on the angular orientation of the two external magnets, the improved piezomagnetoelastic structure can be monostable, bistable, or even tristable [36,37]. On the other hand, if the magnet at the beam's free end is arranged to be repelled by the two external magnets, both softening and hardening responses can be attained through moving the two external magnets along the beam's longitudinal direction [38]. Moreover, the magnetic interaction has also been explored to tune the PEH's resonance frequency [39], stimulate the internal resonance [8,40], and enable the energy exchange between different vibration modes [4,41]. Furthermore, special structural benefits have been exploited in recent years to expand the working bandwidth of an energy harvesting device. For example, Wei and Jing [42] proposed a novel nonlinear energy harvesting system that consists of a lever system and an X-shape supporting structure to achieve tunable resonant frequency and large energy harvesting bandwidth. In addition, diverse harvesters/nanogenerators have also been developed based on the exploitation of novel materials, such as the porous polymer composite membrane based nanogenerator [43], fish-skin-based nanogenerator [44], prawn shells made nanogenerator [45], fish gelatin nanofibers based harvester [46], and the harvester made of modified polyvinylidene fluoride (PVDF) that can convert both mechanical and thermal energies into electrical power [47].

Although various broadband strategies have enhanced the PEH's robustness to the varying excitation frequencies and then its performance, the enlarged operating bandwidth may still fail to cover the excitation sources of low frequencies, such as vehicle motion, machine vibration, and wind-induced vibration, which usually occur at comparatively low frequencies [29,48–50]. This weakness is usually tackled by what is called the frequency up-conversion technique that generally involves two oscillators: a low-frequency oscillator, which is designed to match the excitation frequency better; a high-frequency oscillator that absorbs energy from the low-frequency oscillator and generates electricity. The transfer of mechanical energy from the low-frequency oscillator to the high-frequency oscillator is mainly performed by mechanical impact and magnetic coupling. Since the energy loss caused by the mechanical impact is normally unavoidable, magnetic coupling has drawn increasing attention in recent years with intent to minimize the energy dissipated in the frequency up-converting PEHs [48,50–52].

For the aforementioned nonlinear PEHs, striking improvement in the operating bandwidth has been demonstrated by several studies provided that the excitation is sufficiently large and/or the appropriate frequency sweep operation (upward or downward sweep) can be guaranteed. Otherwise, the above nonlinear PEHs show no obvious superiority to the conventional PEH. To address this issue, we [53] proposed a new mechanism of utilizing the monostable PEH with stoppers (PEHS) to achieve wide operating bandwidth under low-level excitations. The PEHS consists of a piezoelectric beam with a magnetic tip mass, two external magnets, and two stoppers. The two external magnets are symmetrically placed near the beam's free end so that attractive force is applied on both sides of the beam. The two stoppers are employed to confine the beam's deflection range within which the elastic force dominates the magnetic force, making the device monostable. A preliminary analysis has shown that the PEHS can outperform the linear PEH in terms of operating bandwidth and peak voltage under both upward and downward frequency sweeps [53]. However, this observation is based only on the harmonic excitation with one