

On Broadband Nonlinear Piezoelectric Energy Harvesting Techniques

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Abstract. With the development of portable electronic devices, internet of things, micro-electromechanical system (MEMS) and wireless sensor networks, micro sources and self-powered devices have been attracted great attention. It is an effective way to supply micro power or realize the miniaturization of the device via the piezoelectric energy harvesting effect. Therefore, research on piezoelectric energy harvesting techniques has been highly valued. To enhance adaptability and improve harvesting efficiency, the broadband nonlinear piezoelectric energy harvesting technique turns to be a research hotspot. The current status of broadband nonlinear piezoelectric energy harvesting technique with nonlinear stiffness was reviewed according to methods of realizing nonlinearity. The characteristics and existed problems of each kind of nonlinear harvester were then concluded. The nonlinear piezoelectric energy harvester with nonlinear stiffness has a good prospect if its advantages can be given full use.

1. Introduction

As reported in the published literature, nonlinearities in energy harvesters are mainly manifested in the following two aspects: nonlinear stiffness and nonlinear piezoelectric coupling. Compared to the nonlinear piezoelectric coupling which results from piezoelectric materials, the nonlinear stiffness of a harvester is relatively easier to be achieved and controlled. Until now, three methods have been reported to realize nonlinear stiffness [1-3]: nonlinear magnetic force, piecewise-linear stiffness and nonlinear large strain. Therefore, this paper reviews recent advances in designing broadband piezoelectric energy harvester (PEH) with nonlinear stiffness based on the above methods. The paper will include the following sections: three realization ways of nonlinear stiffness, comments on nonlinear PEH and conclusion.

2. PEHs with Nonlinear Stiffness

A PEH with nonlinear stiffness has a wider frequency band and triggers a larger voltage, so this kind of PEH can more easily adapt to the environment and harvest more energy from vibration. Comprehensive analysis of the existing literatures, there exist three methods to realize nonlinear stiffness: nonlinear magnetic force, piecewise-linear stiffness and nonlinear large strain. The following section will develop the contents according to the three methods.

2.1. PEHs Excited by Nonlinear Magnetic Force

The magnets are initially introduced to tune resonance in PEH. With the further research, these magnets also induce changes in both linear and nonlinear stiffness. The nonlinear behavior becomes



apparent when the harvester experiences oscillation with significant amplitude. Consequently, it takes significantly effect on widening frequency broadband and improving the harvesting efficiency. PEHs with monostable or bistable nonlinear motion are described below.

PEHs with monostable nonlinear motion. The hardening mechanism of nonlinear monostable harvester was investigated by Ramlan et al.[4]. The study revealed that the maximum amount of power harvested by PEH with a hardening stiffness was the same as one by a linear PEH, regardless of the degree of nonlinearity. However, this kind of device had such a larger bandwidth that the significant power can be harvested over a wider resonant frequency. Typical frequency-response curve for a hardening system was shown in **Figure 1**.

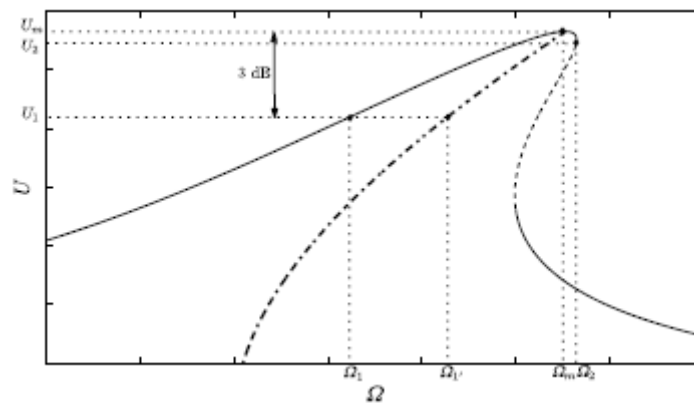


Figure 1. Typical frequency-response curve for a hardening system[4]

Another monostable device in **Figure 2** was proposed by Stanton et al.[5]. Both hardening and softening responses may occur by tuning the nonlinear magnetic interactions around the end mass. The result showed that as compared to the linear PEH, both a wider bandwidth and a better performance could be obtained by a PEH with monostable motion. The reason lied in that the high-energy attractor was captured through a linearly decreasing or increasing frequency sweep. Hence the bandwidth for the softening and hardening cases could be improved. However, it is difficult to guarantee such conditions in practical application, particularly in the low-energy branch and the requisite actuation energy. The problem of offering the required momentary perturbation did not address in many previous reported studies. Fortunately, a fast pulse perturbation system was used to realize the transition from low-energy to high-energy solutions in Ref.[6-7]. The output power of the nonlinear PEH was 16.5 times of that of the linear one and two steady-state harmonic solutions at the maximum output power in the PEH was obtained.

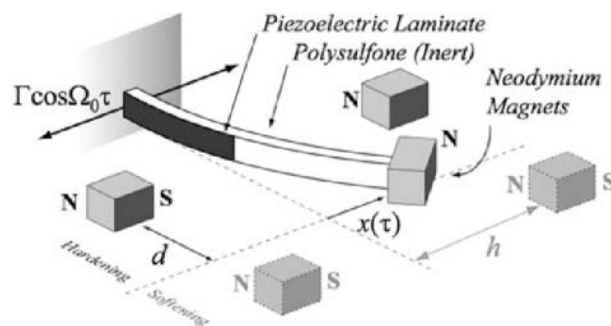


Figure 2. Monostable nonlinear PEH[5]

PEHs with bistable nonlinear motion. A broadband piezo-magneto-elastic generator, as shown in **Figure 3**, was designed by Erturk et al.[8-9]. The voltage response could be chaotic strange attractor

motion or large-amplitude periodic motion when an initial deflection at one of the stable equilibriums was offered under small or large harmonic excitations. While applying a disturbance or equivalently an initial velocity condition, the large-amplitude periodic motion could also be obtained under small excitation level. On the other hand, with a clear advantage over the linear piezo-elastic configuration (with two magnets removed), a large-amplitude response as well as broadband performance may be acquired at off-resonance frequencies.

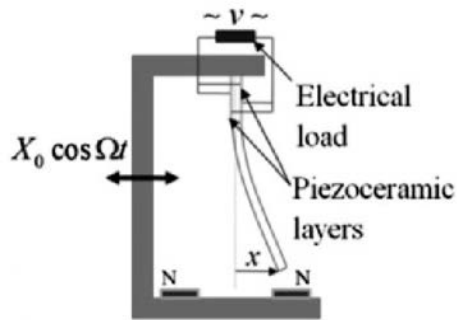


Figure 3. The piezo-magneto-elastic generator [8-9]

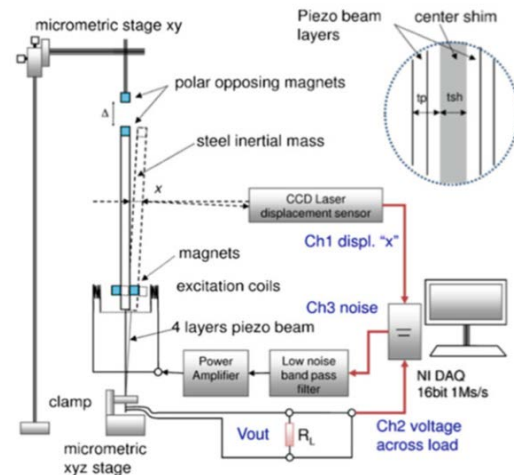


Figure 4. A piezoelectric inverted pendulum [10]

By using the bistable mechanism, a PEH similar to pendulum was realized by Cottone *et al.* [10], as shown in **Figure 4**. The pendulum swung with small oscillations around each equilibrium or with large excursions from one equilibrium position to another excited by the random vibration. In a specific Δ and noise level, the maximum deflection of the pendulum displacement of x_{RMS} could be reached to generate the maximum power which was up to 4-6 times of the linear PEH.

The idea was extended to study energy harvesting performance of bistable cantilevers with repulsive magnets under wide-spectrum vibrations. In these studies[11-13], the critical issue on how to enable the harvester to readily transit between the two stable states was involved. For the broadband energy harvesting, stable transition between two states was dependent on the excitation amplitude, frequency, and the extent of nonlinearity.

2.2. PEHs with Piecewise-Linear Stiffness

Other than the Duffing-type oscillator, a piecewise-linear stiffness is also introduced to realize the nonlinearity of PEH. The common configuration is to use mechanical stoppers, as shown in **Figure 5**.

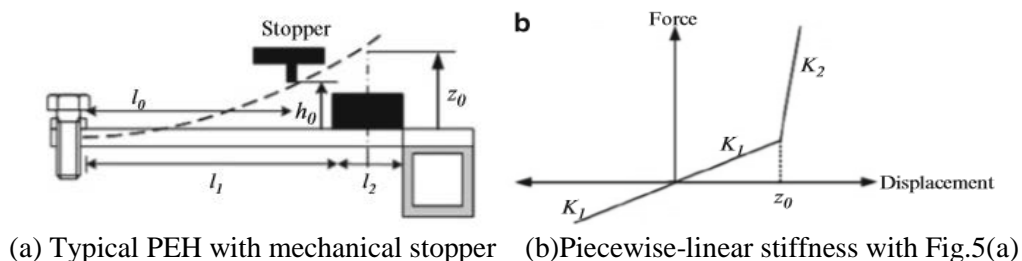


Figure 5. A typical PEH and stiffness with a mechanical stopper

The benefit of a PEH with a stopper was investigated by Soliman *et al.*[14]. The analytical, numerical and experimental results were showed in **Figure 6**. It could be seen that vibration frequency randomly changed in a range of 13.8Hz around the natural frequency. The overall collected energy

was up to 30% due to a larger bandwidth. However, the power output of this kind of PEH was smaller than a PEH without stopper owing to the stop absorbing most of the vibration energy.

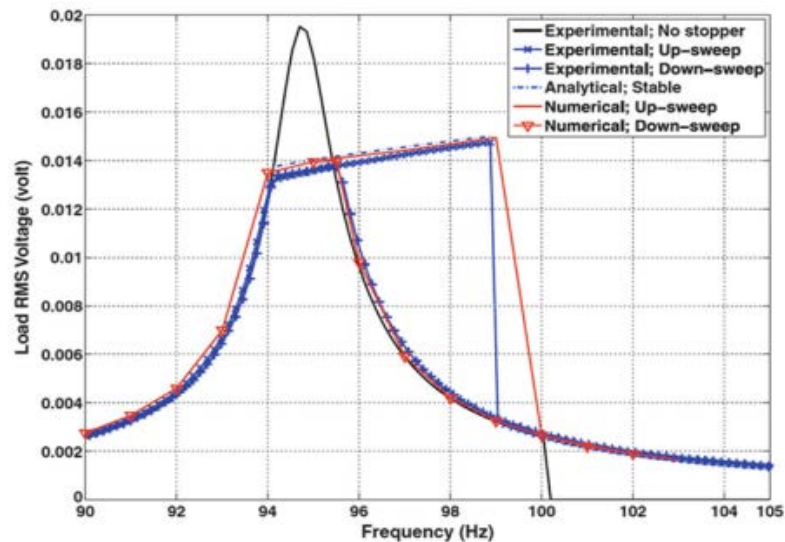


Figure 6. Analysis, numerical and experimental frequency response [14]

To solve the above question, an optimization procedure for a harvester with stopper was presented by researchers [15]. The studied result revealed that two factors dominated the performance of such a device were listed in the following: the stiffness ratio and the velocity of the beam at the impact point. The two factors are controlled by the stopper height and the offset distance of the stopper from the cantilever support. As long as the two factors are reasonably selected, higher capture energy can be obtained in a wider frequency range with this kind of PEH.

Based on the two-degree-of-freedom PEH with elastic base, Halim *et al.* [16] proposed a new configuration of enlarging the base structure and making the end mass to collide with the base during vibration, as shown in **Figure 7**. The bandwidth of the improved PEH is 2.5 times that of one without collision under the same conditions. Meanwhile, the base is similar to the stopper, and the collision behavior effectively broadens the bandwidth.

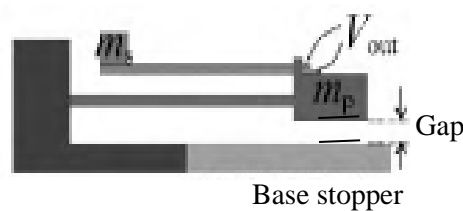


Figure 7. 2DOF piecewise-linear PEH[16]

2.3. PEHs with Nonlinear Large Strain

Hajati *et al.*[17] introduced the non-linear stiffness by using tensile strain of the fixed beam of the MEMS, and proposed an ultra-wideband PEH, as shown in **Figure 8**. The study revealed that frequency bandwidth and energy density of the PEH were one order of magnitude higher than those ones reported previously.

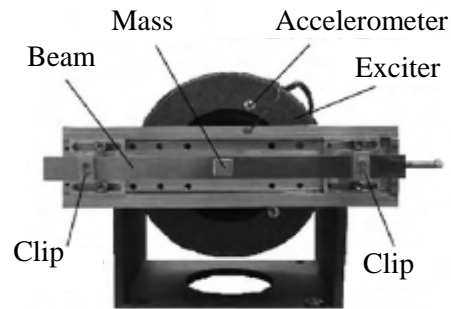
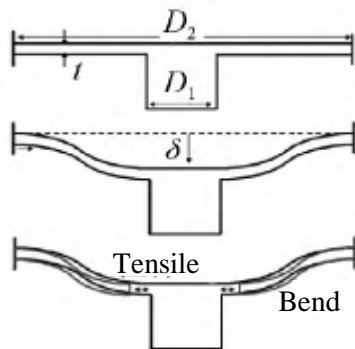


Figure 8. An ultra-wideband PEH[17] **Figure 9.** Post-buckled PEH[18]

Sneller *et al.*[18] proposed one nonlinear post-buckled PEH with buckling beam in **Figure 9**. A mass was put on the middle of the beam. Jumping phenomenon occurred under harmonic excitation. Two equilibrium positions existed in the system. Experimental result showed that the additional mass was helpful to broaden the working frequency of PEH and the jumping motion makes PEH to produce larger amplitude oscillation and power generation. Besides, increasing the mass helps to reduce the threshold of exciting force for induced jump.

Cottone *et al.*[19] studied the generation characteristics of PEH with buckling beams under broadband random excitation. The result shows that output power of PEH is more than 10 times that of the non-buckling state.

3. Conclusions

In practical scenarios, the ambient vibration source is frequency-variant or random. Therefore, the drawback of narrow bandwidth of linear PEHs limits their application. To overcome this drawback, PEHs with nonlinear stiffness were proposed. The typical nonlinear PEHs can be classified into three kinds: a Duffing-type oscillator with cubic nonlinear stiffness typically introduced by using magnets, a piecewise-linear oscillator with nonlinearity caused by a mechanical stopper, a piezoelectric cantilever beam with nonlinear large strain. Each kind of PEH may be preferable in some specific application conditions. For nonlinear PEH with wider broadband and higher efficiency, characteristics of ambient vibration source should be taken into account, which include the type of excitation (periodic or stochastic), the variation of frequency (infrequent or frequent), the excitation level and the targeted frequency range, *etc*[20]. In the small exciting environment, the output frequency response of the nonlinear PEH is similar to that of the linear one, and nonlinear advantages are not obvious.

Although the nonlinear PEHs exhibit broadband characteristics in the sweeping process, most of them require large exciting acceleration. Only when the nonlinearity of PEHs is excited, can a wider frequency band be obtained. There are multiple solutions to causing the nonlinearity of PEHs in a certain frequency range or under excitation conditions, it is worth studying how to keep the harvester's stability in the high energy orbit (especially for PEHs with bistable characteristic).

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