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Improving energy harvesting from random excitation by nonlinear flexible bi-stable energy harvester with a variable potential energy function

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ABSTRACT

In this paper, aim at improving the performance of bi-stable energy harvester (BEH), we proposed a flexible bi-stable energy harvester (FBEH). The FBEH is composed of two elastic beams: one is the piezoelectric cantilever beam with a tip magnet and the other is the clamped-clamped beam with a mid-magnet. The dynamic behavior of FBEH was studied, and the results show that the FBEH owning a variable potential energy function is beneficial for snap-through. The governing equations of FBEH are derived by energy principles. Then its dynamic response under random excitation was studied. The results prove that the FBEH not only has a smaller threshold for snap-through, but also can generate a larger power output for the excitation intensity larger than the critical one. Validation experiments were designed and carried out. The experimental results are in good agreement with the simulation ones.

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1. Introduction

With the development of wireless sensor networks, providing green renewable energy for small scale electronic devices has received a great attention over the last two decades [1]. Harvesting energy from ambient sources such as rain, wind, ocean wave and mechanical vibration has been widely studied [2–5]. Among these sources, mechanical vibration energy has been regarded as one of most attractive power source for micro power generator due to its abundance in ambient environment. The piezoelectric vibration energy harvester is a realization of converting mechanical energy to electrical energy, because its energy density is relatively high and it has the advantage of easy application [6,7].

In the early stage, the vibration-based energy harvesters are generally designed as linear resonators, which only have effective and efficient power outputs near the resonant frequency [8]. If the ambient excitation frequency does not match the resonant frequency of linear energy harvesters, the performance of power output will reduce drastically. As the ambient vibrations are generally in the form of broadband or random, this work mechanism will make these linear resonators not efficient [9]. Therefore, increasing the effective (converting frequency) bandwidth will promote the efficiency of energy conversion. Many researchers began to explore some novel methods to broaden the bandwidth, such as multi-oscillator structures and nonlinear oscillators. Nonlinear energy harvesters with mono-stable, bi-stable, tri-stable, quad-stable and even penta-stable characteristics have been extensively studied such as to improve the harvesting performance in natural envi-

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Nomenclature

b_p	width of piezoelectric layer
h_p	thickness of piezoelectric layer
ρ_p	density of piezoelectric layer
l_p	length of piezoelectric layer
e_{31}	electromechanical coupling coefficient
b_s	width of substrate
h_s	thickness of substrate
ρ_s	density of substrate
L	length of substrate
b_c	width of clamped-clamped beam
h_c	thickness of clamped-clamped beam
ρ_c	density of clamped-clamped beam
L_c	length of clamped-clamped beam
EI	bending stiffness of piezoelectric beam
E_cI_c	bending stiffness of clamped-clamped beam
$\boldsymbol{r}_{AB}$	vector directed from the magnetic moment source of the magnet A to that of the tip magnet B
$M_{A(B)}$	mass of magnet A(B)
$V_{A(B)}$	volume of magnet A(B)
$\boldsymbol{m}_{A(B)}$	magnetic dipole moment vectors
$\boldsymbol{\mu}_0$	magnetic permeability constant
d	distance between the tip magnet and mid-magnet
D	noise intensity
C_p	electric displacement
Δx	displacement of the beam's tip in x-direction
E_z	electric field component
$\phi(x)$	first mode shape function of cantilever beam
$\varphi(x)$	first mode shape function of clamped-clamped beam
$q(t)$	generalized temporal displacement of cantilever beam
$p(t)$	generalized temporal displacement of clamped-clamped beam
$w(x,t)$	the transverse displacement of cantilever beam at distance x and instant t
$s(y,t)$	the transverse displacement of clamped-clamped beam at distance y and instant t
p^{ins}	instantaneous power at an instant of time t
R	resistance load
$v(t)$	voltage of generated by piezoelectric material
ω_A	first natural frequency of clamped-clamped beam
ω_B	first natural frequency of cantilever beam
α	rotation angle of tip magnet

ronments. For example, the effects of softening and hardening stiffness in a mono-stable energy harvester act to bend the resonant response frequency towards the lower and higher value and extend the operating frequency band as compared to the linear scenario [10,11]. Palagummi and Yuan [12] used the semi-analytical technique to investigate the optimal design of mono-stable energy harvesters. Quinn et al. [13] investigated the large-amplitude branch of response of a mono-stable energy harvester, the results showed that the proper design could give a significant improvement in performance. Sebald et al. [14] presented a theoretical study for mono-stable energy harvesters. It was shown that the mono-stable harvester could get maximal harvested power by reaching a high energy solution. However, the performance of the mono-stable harvester more or less is like the linear one when the excitation is relatively weak. Then the bi-stable energy harvester (BEH) was proposed to tackle this defect, which has a twin-well potential energy function with one barrier between two potential wells. Masana and Daqaq [15] investigated the performances of mono-stable energy harvester and BEH under similar harmonic base excitation. The results showed that the BEH with shallow potential wells could activate the super-harmonic resonance even for small base accelerations. Panyam and Daqaq [16] compared the output power of the mono-stable and bi-stable configurations. The results illustrated that the BEH could produce a higher power output than the mono-stable one while subjected to similar excitations. Zou et al. [17] proposed a novel bi-stable and flextensional energy harvester which could increase the operational frequency bandwidth. Su et al. [18] reported a cantilever energy harvester with variable damping, which is similar to those in Refs. [19,20]. Chiacchiari et al. [21] numerically examined the response of a BEH subjected to impulsive excitations. Recently, by introducing additional potential wells to BEH, the bi-stable configuration was modified to become a tri-stable [22–24], quad-stable [25] and even penta-sable one [26], which might lower the potential well barriers and extend the distances between the potential wells. Thus the snap-through could take place more easily. Zou et al. [27] exploited magnetic force intervention to enhance the performance of a broadband compressive-mode BEH. The

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