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Broadband energy harvesting using nonlinear vibrations of a magnetopiezoelastic cantilever beam

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ABSTRACT

This paper investigates the mechanical behavior of a unimorph piezoelectric cantilever beam with a tip magnet and nonlinear boundary conditions imposed by repelling permanent two external magnets, subjected to a harmonic base excitation for broadband energy harvesting. The energy harvester is modeled as an in-extensional beam with Euler-Bernoulli assumptions. The curvature and inertia terms are assumed to be nonlinear due to large amplitude vibrations. The governing equations of motion are derived using the Euler-Lagrange equations. The reduced-order model equations (ROMs) are obtained based on the Galerkin method. A numerical study is performed to reveal the influence of different parameters such as tip magnet, presence and absence of the external magnets, gap distance between magnets, mechanical damping ratio and external resistance load on the scavenged power from the nonlinear energy harvester. It is shown that the addition of two external magnets and a sufficient tip magnet, and proper gap distance between magnets significantly increases the power and the voltage. In addition, it is shown that considering geometric nonlinearity, for both in the absence and presence of the two external magnets, affect and broaden the frequency range. It is observed that gap distance between beams significantly affect the frequency range and hysteresis region of the broadband energy harvester. Energy conservation is examined in the absence of the mechanical damping ratio, and it is shown that energy harvesting annihilates the vibrations. In addition, the effect of the external resistance load on the average power is discussed in the presence and absence of the external magnets for different value of the tip magnet and gap distance and the optimum value of the resistance load is obtained for each system.

1. Introduction

In recent decade, energy harvesting from ambient vibrations of natural environments, such as air flows and human motions, which are available everywhere and all the time, has been the focus of many works. One main purpose of these works, is to power small electrical components such as batteries and capacitors, with no need of replacement, especially at less accessible locations. Researchers are working on alternative energy sources such as solar, thermal, acoustics, and vibration (Paradiso & Starner, 2005; Penella & Gasulla, 2007). Among these alternative sources, environmental vibration energy harvesting has become a prominent research endeavor, owning to its potential and technical challenge, and because of its abundance (Mitcheson, Green, Yeatman, & Holmes, 2004a; Roundy, Wright, & Rabaey, 2003a). The ambient mechanical vi-

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bration energies can be converted to useful electrical energy by using electromagnetic (Arnold, 2007; Elvin & Elvin, 2011; Glynne-Jones, Tudor, Beeby, & White, 2004; Williams & Yates, 1996), electrostatic (Meninger, Mur-Miranda, Amirtharajah, Chandrakasan, & Lang, 2001; Mitcheson et al., 2004b; Roundy, Wright, & Rabaey, 2003b; Tvedt, Nguyen, & Halvorsen, 2010), piezoelectric (Abdelkefi, 2016; Dutoit & Wardle, 2006; Erturk & Inman, 2009; Jeon, Sood, Jeong, & Kim, 2005; Roundy et al., 2003a) and magnetostrictive (Adly, Davino, Giustiniani, & Visone, 2010; Wang & Yuan, 2008) methods. Among these transduction methods, piezoelectric energy harvesting from cantilever beams; owing to its easy application; has been widely focused in the literature (Anton & Sodano, 2007; Beeby, Tudor, & White, 2006; Erturk & Inman, 2011a; Xie & Wang, 2015; Xie, Wang, & Wu, 2014; Xie, Wu, Yuen, & Wang, 2013). This technology is considered to be a promising way to provide the energy supply for small sensors and MEMS devices (Cook-Chennault, Thambi, & Sastry, 2008; Ottman, Hofmann, Bhatt, & Lesieutre, 2002). In many works in last studies, a series of different linear resonance – based piezoelectric harvesters have been designed to generate electric energy by harvesting ambient vibrations. However, a challenging problem associated with this kind of energy harvesting systems, is the frequency ranges in which the average power is scavenged, where, they will not efficiently harvest ambient vibration energy when the excitation frequency deviates from their resonant frequency range. To solve this problem, many researchers have been focusing on widening the effective frequency range of energy harvesters by adjusting the vibration characteristics of an energy harvester by tuning the excitation frequency. These include added masses (Jiang & Hu, 2007; Jiang et al., 2005), mechanical preloads (Hu, Xue, & Hu, 2007) and varying the geometrical parameters of the structure (Hu, Cui, & Cao, 2007). The excitation frequency for all of the above mentioned cases was near the resonance frequency of the system. Also, for widening the effective excitation frequency ranges, an extensive investigation of broadband vibration energy harvesters with nonlinear monostable (Abdelkefi & Barsallo, 2014; Barton, Burrow, & Clare, 2010; Daqaq, 2010, 2012; Mann & Sims, 2009; Stanton, McGehee, & Mann, 2009), bistable (Cao, Zhou, Inman, & Chen, 2015; Daqaq, 2011; Erturk & Inman, 2011b; Litak & Borowiec, 2014; McInnes, Gorman, & Cartmell, 2008; Panyam et al., 2014; Stanton, McGehee, & Mann, 2010; Stanton, Owens, & Mann, 2012), and tristable (Cao, Zhou, Wang, & Lin, 2015; Kim & Seok, 2014; Tékam, Kwuimy, & Woafo, 2015; Zhou et al., 2014) characteristics have been studied. Abdelkefi and Barsallo (2014) designed an energy harvester which consists of a partially covered piezoelectric beam with a fixed magnet mass at the top of the magnet tip mass. They concluded that the derived distributed parameter model accurately predicts the experimental measurements and the accompanying softening behavior. Also, they demonstrated that the approximated distributed parameter and lumped parameter models give erroneous predictions of the resonance range, and the softening behavior. Barton et al. (2010) investigated both theoretically and experimentally a nonlinear electromagnetic energy harvesting device that has a broadly resonant response which the nonlinearity have generated by a particular arrangement of magnets in conjunction with an iron-cored stator. They concluded that a nonlinear energy harvester is able to overcome some of the inherent limitations of a linear energy harvester which the results were in good accuracy with the experimental results. Daqaq (2010) investigated the stiffness type nonlinearities on the transduction of vibration energy harvester under random excitations that approximated by a white Gaussian noise process by considering both mono- and bi-stable piezoelectric Duffing type harvesters. Their research concluded that for bistable harvesters, the shape of the optimal potential function is sensitive to the noise intensity which further complicates the design of efficient bi-stable vibration energy harvester for random excitations with unknown and variable noise intensity. Mann and Sims (2009) designed and analyzed a novel energy harvesting device in which they used magnetic levitation to produce an oscillator with a tunable resonance. They concluded that the nonlinear response of the system can result in relatively large oscillations over a wider range of frequencies and improving the ability to harvest energy under certain circumstances. McInnes et al. (2008) developed a theoretical model of bistable harvesters using stochastic resonance mechanism to enhance the energy harvesting performance. Daqaq (2012) theoretically investigated the response of an inductive bistable energy harvester to white and exponentially correlated Gussian noise. Their research concluded that the potential shape has no influence on the expected mean power. Cao, Zhou and Inman et al. (2015) investigated the nonlinear dynamic characteristics of fractionally damped broadband piezoelectric energy harvester under low frequency excitations. They used frequency analysis, bifurcation diagrams and Poincare maps to analyze the chaotic and periodic dynamic responses of bistable harvesters under harmonic excitations. Litak and Borowiec (2014) modeled a bistable dynamical system with the Duffing potential, fractional damping, and random excitation. They numerically investigated the effect of the mechanical damping for bistable systems under stochastic noise excitations. Panyam, Masana, and Daqaq (2014) theoretically and numerically analyzed the nonlinear dynamic characteristics of bistable energy harvesters. They analyzed the influence of three critical design parameters, namely the time constant ratio, the electromechanically coupling, and the potential shape, on the effective bandwidth. They concluded that the effective frequency bandwidth can be increased by simply increasing the amplitude of excitation also, increasing the electromechanical coupling results in the narrowing of the effective frequency bandwidth of the harvester. Stanton et al. (2010, 2012) theoretically and numerically analyzed the nonlinear dynamic characteristics of bistable energy harvester. Erturk and Inman (2011b) theoretically and experimentally investigated the broadband high-energy orbits in a bistable piezomagnetoelastic energy harvester over a range of excitation frequency. Electromechanical phase trajectories of the piezomagnetoelastic and the piezoelastic configurations are compared theoretically and the substantial advantage of the former is observed at several frequencies. They experimentally verified this observations and it has been shown that the piezomagnetoelastic configuration can generate larger power compared to piezoelastic configuration over a range of frequencies. Also, they compared chaotic response of the piezomagnetoelastic configuration against the periodic response of the piezoelastic configuration for the same base acceleration. They demonstrated that the rms voltage output of the chaotic response in the piezomagnetoelastic configuration and that of the periodic response in the piezoelastic configuration is very similar. In order to enhance the energy harvesting