Chapter 34
Modeling and Performance Enhancement of Low-Frequency Energy Harvesters

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ABSTRACT

There exist numerous low-frequency excitation sources, such as walking, breathing, and ocean waves, capable of providing viable amounts of mechanical energy to power many critical devices, including pacemakers, cell phones, MEMS devices, wireless sensors, and actuators. Harvesting significant energy levels from such sources can only be achieved through the design of devices capable of performing effective energy transfer mechanisms over low frequencies. In this chapter, two concepts of efficient low-frequency piezoelectric energy harvesters are presented, namely, variable-shaped piezoelectric energy harvesters and piezomagnetoelastic energy harvesters. Linear and nonlinear electromechanical models are developed and validated in this chapter. The results show that the quadratic shape can yield up to two times the energy harvested by a rectangular one. It is also demonstrated that depending on the available excitation frequency, an enhanced energy harvester can be tuned and optimized by changing the length of the piezoelectric material or by changing the distance between the two tip magnets.

INTRODUCTION

Harvesting energy from wasted mechanical energy has been the topic of several investigations in the past decade (Sodano, Park, & Inman, 2004; Anton & Sodano, 2007; Erturk, 2009; Karami, 2011; Abdelkefi, 2012). The ultimate goal of designing and fabricating these harvesters is to replace small batteries that have finite life span or would require expensive and difficult replacement. They are also used to operate self-powered devices including wireless and structural health monitoring sensors, cameras, pacemakers, data transmitters, and medical implants (Roundy & Wright, 2005; Clair, Bibo, Sennakesavababu, & Daqaq, 2010; Karami & Inman, 2012; Abdelkefi & Ghommem, 2013). These harvesters can be deployed in different locations including structure's surface, cell phones, pacemakers, buildings, bridges,

DOI: 10.4018/978-1-5225-5643-5.ch034

etc. Different transduction mechanisms have been used, such as electrostatic (Anton & Sodano, 2007), electromagnetic (Arnold, 2007; Karami, 2011), and piezoelectric (Sodano et al., 2004; Erturk, 2009). Because of its ease of application, non-reliance on external input voltage, and its suitability for designing small energy harvesters, the piezoelectric option has flourished in most of the recent investigations.

Tuning and Broadband Mechanisms

Researchers have proposed different structural systems for energy harvesting from base or aeroelastic vibrations (Bryant & Garcia, 2009; Erturk, 2009; Abdelkefi, Nayfeh, & Hajj, 2012a; Abdelkefi & Nuhait, 2013; Zhao, Tang, & Yang, 2013; Dai, Abdelkefi, & Wang, 2014; Yan & Abdelkefi, 2014). Several investigations have been performed to design efficient piezoelectric energy harvesters from harmonic and random excitations. In order to exploit low-frequency excitation sources, such as walking, breathing, ocean waves, and the contraction and expansion of human muscles to power many critical devices inside and outside the human body, many concepts have been proposed to design efficient piezoelectric energy harvesters with a low natural frequency. One of the examples is to power modern pacemakers from heartbeat vibrations. In fact, these modern pacemakers require a one microwatt with a present dominant excitation frequency around 39 Hz (Karami & Inman, 2012). One particular focus was paid to design tunable energy harvesters to operate effectively at the available excitation frequency. To this end, different active and passive tuning mechanisms (Roundy & Wright, 2005; Shahruz, 2006; Challa, Prasad, Shi, & Fisher, 2008; Abdelkefi, Najar, Nayfeh, & Ben Ayed, 2011; Elvin & Elvin, 2011; Masana & Daqaq, 2011a; Lui, Lee, Kobayashi, Tay, J., & Quan, 2012; Daqaq, 2012) have been introduced to tune the natural frequency of the harvester to the available excitation frequency. For active tuning mechanisms, Roundy et al. (2005) showed that some of these mechanisms cannot be efficient in cases of fast-varying frequency or random excitations. In fact, they reported that the needed external power to operate the used actuator could be larger than the harvested power. For passive tuning mechanisms, Shahruz (2006) designed an energy harvester which was consisted of multiple cantilever beams with various lengths and tip masses attached to a common base. They showed that this device is capable of harvesting energy over a wide range of frequencies by properly selecting the length and tip mass of each beam.

Other research findings have proposed the use of monostable configurations for broadband transduction. In these systems, a nonlinear restoring force is introduced which can result in a significant change in the potential energy function of the harvester. This nonlinear restoring force can be obtained when considering the piezoelectric coupling in the harvester (Quinn, Triplett, Vakakis, & Bergman, 2011; Abdelkefi, Nayfeh, & Hajj, 2012b, 2012c) or when including an external magnetic force (Mann & Sims, 2008; Stanton, McGehee, & Mann, 2009; Barton, Burrow, & Clare, 2010; Erturk & Inman, 2011; Karami, 2011), or when applying an external axial loading force (Masana & Daqaq, 2011a). The presence of these stiffness nonlinearities results in the appearance of softening or hardening behaviors which lead to a wider range of resonant frequencies of the harvester. Considering the effects of the piezoelectric coupling, Abdelkefi et al. (2012b, 2012c) showed that broadband regions for the harvester's response can be obtained through hardening or softening responses due to the piezoelectric coupling, as shown, respectively, in Figures 1 and 2. An axially-loaded piezoelectric clamped-clamped beam was proposed by Masana and Daqaq (2011a) to tune the natural frequency of the harvester with the excitation frequency. They showed that, in the monostable region, an increase in the preload results in a decrease in the natural frequency of the harvester and an enhancement in the level of the harvested power. Mann and Sims (2008)