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Broadband vibration-based energy harvesting improvement through frequency up-conversion by magnetic excitation

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Abstract
Traditional vibration-based energy harvesters are designed for a specific base excitation frequency by matching its fundamental natural frequency. This work presents the modeling and analysis of a nonlinear, magnetically excited energy harvester that exhibits efficient broadband, frequency-independent performance utilizing a passive auxiliary structure that remains stationary relative to the base motion. This system is especially effective in the regime of driving frequencies well below its fundamental frequency, thus enabling a more compact design solution over traditional topologies. A model based on Euler–Bernoulli beam theory is coupled to a linear circuit and a model of the nonlinear, magnetic interaction to produce a distributed parameter magneto-electromechanical system. This model is used in both harmonic and stochastic base excitation case studies. The results of these simulations demonstrate multiple-order-of-magnitude power harvesting performance improvement at low driving frequencies and an insensitivity to time-varying base excitation. Furthermore, the proposed system is shown to outperform an optimally designed, standard energy harvester in the presence of broadband, random base excitation.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Vibration-based energy harvesting has received significant attention due to the ubiquity of untapped vibrational energy available in or around most man-made systems (Roundy *et al* 2003). Several methods of electromechanical transduction have been considered for exploiting this energy source, including electromagnetic induction (e.g. Glynne-Jones *et al* 2004), electrostatic varactance (e.g. Mitcheson *et al* 2004), and the piezoelectric effect (e.g. Anton and Sodano 2007), the latter being the means of energy conversion utilized in this study. Although the power harvested from ambient vibrations is generally small compared to the power required to operate sensors and transmit data continuously, several researchers have demonstrated that, through careful energy budgeting, piezoelectric energy harvesting can provide a viable design solution for maintenance-free, wireless electronics. For example, Shenck and Paradiso (2001) have investigated energy harvesting from heel strikes during walking and have designed power management circuitry for intermittent radio-frequency identification (RFID) transmission. Wireless sensors utilizing energy harvesting have also been produced for temperature and humidity measurement (Arms *et al* 2005) and machinery acceleration monitoring (Discenzo *et al* 2006).

In order to maximize harvested power, vibration-based generators are designed to match one of their natural frequencies—typically the fundamental frequency—to the

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