

BROADBAND AND LOW FREQUENCY VIBRATION-BASED ENERGY HARVESTING IMPROVEMENT THROUGH MAGNETICALLY INDUCED FREQUENCY UP- CONVERSION

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ABSTRACT

In order to extract as much energy as possible from ambient vibrations, many vibration-based energy harvesters (VEHs) are designed to resonate at a specific base excitation frequency. Unfortunately, many vibration energy sources are low frequency (0.5 Hz-100 Hz), intermittent, and broadband. Thus, resonant VEHs would not be excited continuously and would require a large mass or size to tune to such a low frequency. This work presents the modeling, analysis, and experimental application of a nonlinear, magnetically excited energy harvester that exhibits efficient broadband, frequency-independent performance. This design utilizes a passive auxiliary structure that remains stationary relative to the base motion of the VEH. This device is especially effective for driving frequencies well below its fundamental frequency, thus enabling a more compact design compared to traditional resonant topologies. A mechanical 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. The results of both harmonic and broadband, stochastic simulations demonstrate multiple-order-of-magnitude power harvesting performance improvement at low driving frequencies and an insensitivity to time-varying base excitation frequency content. Furthermore, the proposed system is shown to enable more practical designs than a resonant energy harvester for the specific example of harvesting energy from walking motion.

INTRODUCTION

In the last decade, vibration-based energy harvesting has received significant attention due to the ubiquity of untapped vibrational energy available in or around most manmade systems [1]. In order to maximize harvested power, vibration-based generators are designed to match one of their natural frequencies – typically the fundamental frequency – to the base

excitation frequency. Additionally, it has been shown that minimizing the mechanical damping in the system enhances the power harvesting performance [2–4]. Unfortunately, lightly damped systems, while exhibiting the greatest peak power, also have the least bandwidth. In many applications for which energy harvesting could be utilized, vibrations are intermittent, time-varying, and stochastic, rendering standard energy harvester designs ineffective. Indeed, Halvorsen [5] has shown large qualitative differences in the behavior of vibration-based energy harvesters under stochastic excitation. Hence, a means of making these devices less constrained to a single operating regime is desirable.

If a single magnet is placed in the vicinity of the magnetized tip mass of the beam, a “hardening spring” effect can occur. This effect can increase the mechanical response of the beam over a wider range of excitation frequencies; however, this setup suffers from hysteresis and can perform worse than the baseline system if it is operating in the non-resonant branch of the response [6]. Lin et al. [7] place a magnet in the vicinity of the tip and note an increase in voltage generated in a wider bandwidth around the resonant peak compared to the baseline system. This phenomenon is magnified when the nearby magnet is attached to the end of another cantilevered beam; however, no energy is harvested from the secondary beam in that study, thereby reducing the power density of the device. Nonlinear stiffness can also be created structurally, as in [8], in which the tip mass of the beam is attached to a pre-buckled plate. This auxiliary structure produces greater damping at high base excitation amplitudes, which may be considered a safety feature to prevent excessive strain in the device.

In this paper, a design consisting of a permanent magnet attached to the tip of a cantilevered, piezoelectric beam structure is presented. As the beam vibrates due to base excitation, the tip passes through the wells of attraction of