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Analysis and experiment of magneto-mechanically coupled harvesters

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ABSTRACT

Current trend in energy harvesting research is to increase the operating bandwidth of energy harvesters. Multiple harvesters, nonlinear harvesters and hybrid harvesters are suggested to address the issue. In this paper, a system consisting of two electromagnetic harvesters with magnetic and mechanical couplings subjected to harmonic support excitations is proposed. Two pendulums with close resonating frequencies are used to generate power over a broad range of frequencies. The pendulums behave nonlinearly under the influence of magnetic interaction. This nonlinear motion harvests power at broader bandwidth. A mathematical model of the proposed harvester is established. Experiments are performed to validate the theoretical results. It has been observed that the nonlinear responses due to both magnet and mechanical couplings improve individual harvester performance. This is advantageous over harvesters that have magnetically coupling only. Additionally, the dynamics of harvesting system is numerically studied where large amplitude chaotic motion, quasi-periodic oscillations and periodic motions are observed and reported.

1. Introduction

Recent developments in automation, wireless technology and smart systems have necessitated the development of self- and low-powered sensors. Energy harvesting based batteryless devices have become more attractive and serve as an alternative to battery powered devices. Energy harvesting involves scavenging ambient energy and transforming them into electrical energy, either for immediate use by the sensors or stored in capacitors for later usage [1,2]. Conventional linear harvesters are efficient only at resonance, which limits their applications for almost all practical vibration sources with broadband or uncertain frequency content [3,4].

To overcome the bandwidth constraint of the linear harvesters, designs with tuning mechanisms to deal with uncertainty in natural frequencies and broadband spectra are studied. Various tuning methods have been proposed (for example, passive [5] and active [6]) to adaptively tune to the source frequency. Tuning is useful when the host frequency is unknown and is within a narrow band of the frequency. The disadvantage of tuning mechanisms is that most of them require an external power sources which reduces the net power obtained from the harvester [6].

Extensive studies exploring nonlinear structural designs to harvest broadband power are also reported [7–9]. Nonlinearity induced by magnetic interaction to provide monostable, bistable and tristable configurations has also been reported. A

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Moon's beam under magnetic field has shown potential for broadband harvesting [7,8,10]. Enhancement in bandwidth is achieved by matching trajectories of cantilever tip magnets with that of the side magnets [11]. Internal resonance of a beam is also explored for broadband harvesting [12,13]. A periodic time-varying damping can also enhance bandwidth [14]. Structural instability due to buckling has been analyzed for broadband harvesting [9].

Another way to increase bandwidth is to use multiple or multi-modal harvesters [15]. Multimodal harvesters can harvest power at multiple modes effectively either with an additional mass on the harvester [16] or with a folded geometry of the harvesters [17]. While a close eigenmode provides a broadband application with lower power output, a large frequency gap between the modes makes these harvesters ineffective for harvesting power over a continuous frequency band [18]. Mechanical coupling of these multiple harvesters enhances both the magnitude and bandwidth of power [19]. Multiple harvesters with magnetic coupling between them also have been reported for broadband harvesting [20,21]. Effect of both magnetic and mechanical coupling together on the power magnitude and bandwidth needs to be explored.

Inspired by recent advances in harvesting with multiple coupled harvesters, this article reports a magneto-mechanically coupled harvesters to increase the bandwidth. The harvesting system consists of two pendulums with magnets attached at the free end for electromagnetic harvesting. The magnetic force on the oscillators due to magnets at the base is calculated based on point magnets and dipole approximation. The method provides considerably accurate results when the physical dimensions of magnets are small compared to the distance between them [22,23]. The magnetic force on the oscillator due to magnets at the base can also be obtained experimentally and via curve fitting [24,25]. Though this method evaluates the magnetic interaction well enough, conducting experiments is time consuming especially when the distance between the magnets needs to be changed frequently.

In this work, pendulums are chosen such that they have close natural frequencies in the magnetic field. The dynamics of the system due to magneto-mechanical coupling is reported and advantages in energy harvesting are drawn. It has been observed that the system of two pendulums shows interesting dynamics ranging from large orbit chaotic oscillation to quasi periodic motion and to low amplitude periodic motions under harmonic support excitation. Experiments are conducted to access the amount of power drawn and its frequency.

The flow of the paper is as follows. A mathematical model for a two pendulum harvesting system with magnetic and mechanical coupling is developed in Section 2. Section 3 presents the numerical study of the harvesting system. A discussion on the numerical study is presented in Section 4. Section 5 presents experimental results to support the numerical study. Based on the study a set of conclusions are drawn in Section 6.

2. Magneto-mechanical model of the harvester

This section reports the mathematical model of the harvesting system with magnetic interactions between mechanically coupled pendulums. As shown in Fig. 1, the mechanical coupling is obtained using spring arrangement between the pendulums and between the support and pendulum. The pendulums are coupled and grounded by mechanical springs k_1, k_2 and k_3. The spring between the pendulums is referred to as a coupling spring and the springs between the support and each pendulum is referred to as a grounding. The system is analyzed and tested under harmonic support excitation (x_g) given at the pivot.

Pendulums considered are of lengths l_1 and l_2. A permanent magnet is attached at the tip of each pendulum. The magnets are oriented such that they face the same polarity and are modeled as dipoles [23]. The repulsive force in the magnets depends upon the relative position between magnetic dipoles (r). Copper coils are placed beside the pendulums to harvest electromagnetic energy.

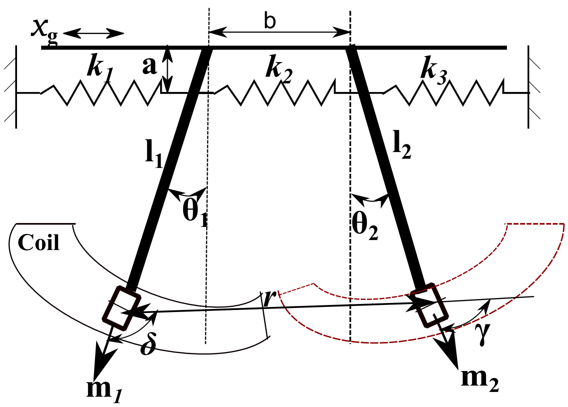

Fig. 1. Schematic representation of magneto-mechanically coupled harvester model.