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Electromechanical behavior of a pendulum-based piezoelectric frequency up-converting energy harvester

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A B S T R A C T

In the present study, the possibility to extract more vibrational energy by utilizing a high number of magnets on the proof mass of a piezoelectric frequency up-converting energy harvester is investigated. Due to magnetic interaction, the beam is actuated whenever the proof mass passes over its tip. It is observed that several peaks occur in the voltage signal of PZT beam when the angular velocity of the proof mass increases linearly. It is shown that the peaks locations which found to be dependent on the natural frequency of the PZT beam as well as the number of rotating magnets can be estimated by a mathematical formulation. Considering the effects of magnetic interactions on the pendulum dynamics, the generated power of the harvester is obtained for harmonic excitations. Although the determination of exact optimum number of magnets that can lead to the best generated power in all excitation characteristics is impossible, it is found that by applying an appropriate number of rotating magnets (e.g. six, seven or eight magnets), the extracted power from high amplitude excitations can be enhanced. It is noteworthy that, at some particular cases, it is possible that the generated power be increased to even more than ten times. At the end, by conducting some experiments, the validity of the mathematical modeling as well as the applied numerical method is examined.

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1. Introduction

Increase in demand for wireless sensing and the decrease in power requirements of many electronic devices made the energy harvesting a realistic alternative for powering wireless sensors and self-powered devices [1,2]. In this regard, many energy harvesters have been designed to extract energy from ambient sources, and transform it into electrical energy which then can be used by micro-electronic devices such as wireless sensors [3–5], health monitoring sensors [6,7] and pace-makers [8]. Commonly, available mechanisms for this transformation can be categorized as electrostatic [3,9,10], electro-magnetic [11–15], piezoelectric [16], magnetostrictive [17] and more recently, triboelectric [18–20] mechanisms.

Conventional linear piezoelectric inertial energy harvesters extract noticeable amount of energy when their natural frequency is matched the natural frequency of ambient vibration. Considering the fact that in reality the majority of ambient excitations have spectral content distributed over a range of frequencies, many methods have been introduced to broaden the usable bandwidth of linear harvesters such as [21–25] in which improving the performance of an energy harvester using intentional nonlinearities has been aimed.

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The possibility of harvesting energy from low frequency excitations has been investigated in some research which are described as follows.

Renaud et al. [26] have shown that the performance of a piezoelectric bender for harvesting energy from shock and impact will be optimized by maximizing the generalized electromechanical coupling coefficient and mechanical quality factor of the structure. An electromagnetic vibration-to-electrical power generator has been presented by Kulah et al. [27] which, by means of a mechanical frequency up-converter, up-converts low-frequency environmental vibration to a higher frequency. A low frequency resonator which is attached to a magnet, in response to external vibration, catches a cantilever beam and the attached coil due to magnetic interaction between the magnet and the metallic tip of the beam.

Galchev et al. [28] presented an inertial power generator, called PFIG, for harvesting non-periodic low frequency vibrations. It has been shown in which ambient conditions it is better to choose the PFIG over a resonant harvester. Moreover, it has been found that the PFIG offers better efficiency than resonant devices when the amplitude of ambient vibration is higher than the internal displacement limit of the device. Gu et al. [29] presented experimental and theoretical investigations on an energy harvesting device in which a low frequency resonator impacts a high frequency one. These impacts resulted in energy harvesting predominantly at the system's coupled vibration frequency. It has been shown that, in comparison to conventional technology, a reduced mechanical damping ratio during coupled vibration enables increased electrical power generation.

To improve the harvesting performance at low frequencies, Zhang et al. [30] proposed a multi-impact harvester. In their device a series of impacts between a hung mass and two piezoelectric cantilever beams trigger high frequency vibrations in the beams. It has been found that under a sinusoidal excitation, the output power of the proposed harvester is more than that of the single-impact conventional harvester.

An impact-driven piezoelectric energy harvester for extracting energy from human motion has been proposed by Wei et al. [31]. In their device, low frequency human motion has been converted into high frequency vibrations. Due to the external excitations, a sliding-free cylinder slides on a shaft and actuates tip of a PZT bimorph cantilever beam. In the harvester presented in [32], a cylindrical proof mass actuates an array of piezoelectric bi-morph beams through attractive magnetic interactions. The beams are excited whenever the proof mass passes over them. After initial excitation, the beams have been left to vibrate at their fundamental frequencies. The same authors, later, presented experimental results for a piezoelectric frequency up-converting harvester which worked based on the beam plucking mechanism [33]. In their device, magnetic coupling between two permanent magnets attached to the tip of a PZT beam and an eccentric proof mass have been utilized.

Halim et al. [34] presented a mechanical impact-driven frequency up-converting piezoelectric vibration energy harvester. In response to external excitations, a tip mass mounted on a low frequency flexible driving beam hits two high frequency piezoelectric cantilevers. Alghisi et al. [35] presented a piezoelectric converter for energy harvesting from low frequency random vibration of human body. Their device was composed of a rigid ball surrounded by six piezoelectric diaphragms. In response to external excitations, the ball repeatedly hits the diaphragms and hence, the impact energy has been converted into the electrical one. Haroun et al. [36] presented a micro-electromagnetic vibration energy harvester which worked based on free/impact motion. In response to external excitations, the relative oscillation between a permanent magnet and the tube-carrying coil has led to power generation in the device

The motivation behind the present study is the research reported in [33], in which the authors experimentally investigated a piezoelectric frequency-up converting energy harvester. In their device, upon external excitations, a rotating proof mass actuates a PZT cantilever beam due to magnetic interaction. In reference [37], the authors have tried to improve the performance of an eccentric frequency up-converting PZT harvester, phenomenologically similar to the harvester presented in [33] in which a large number of piezoelectric transducers have been utilized. To achieve this improvement, full rotational course of the pendulum has been considered. For the harvester studied in the present paper, the use of full rotational course of pendulum is also considered by mounting a higher number of magnets on it. In this regard, present paper investigates the possibility of extracting more vibrational energy from a phenomenologically similar configuration by utilizing a higher number of magnets on the proof mass. In fact, due to this low-cost change, generation of more energy from the same external excitation is aimed. It should be noted that, similar to the harvester presented in [37], the presented design in this paper can decrease the sensitivity of the harvester to its orientation regarding the direction in which the external excitation is applied.

In the present study, by developing an appropriate mathematical model, a series of simulations are accomplished to investigate the electromechanical behavior of the harvester. In this way, considering some assumptions about the motion of rotating proof mass, the problem is divided into several cases. The solution of mathematical formulations is found using Runge–Kutta numerical method. The obtained results are discussed and the accuracy of the mathematical modeling and the applied numerical procedure are examined through some experimental tests.

2. Theoretical description of the model

The piezoelectric energy harvester considered in this study is shown in Fig. 1. Nonlinear magnetic interaction exists between the neodymium magnet located on the free end of a piezoelectric cantilever beam and a number of similar magnets mounted on a circular frame which is attached to a rotating proof mass. Therefore, the angular displacement of the

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