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Explorations of displacement and velocity nonlinearities and their effects to power of a magnetically-excited piezoelectric pendulum

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ABSTRACT

This paper explores the relation of the nonlinearities of displacement and velocity dynamics with the power of a piezoelectric pendulum under a periodic magnetic excitation. Initially, the theoretical formulation including the mechanical, magnetic and electrical terms is realized. Then a simulation study has been done by using the theoretical formulation based on the experimental parameters. Then, a detailed experimental survey has been carried out for some representative system parameters. Results of simulation based on the proposed model are presented and compared with the experimental results. It is observed that the periodic magnetic flux can cause different responses from regular dynamics to chaotic one. Phase space constructions, Poincare sections and FFTs are determined on parameter sets including the excitation frequency f and amplitude U_c of electromagnet. It is proven that the periodic magnetic flux exerts high frequency velocity fluctuations nearby the minimal and maximal values. While the displacement of the tip exhibits a harmonic fluctuation, FFTs prove the high frequency responses in addition to the main frequency. When f differs from the natural frequency of the system f_0, the responses become chaotic. It is proven that lower and higher frequency fluctuations in displacement and velocity, which are different from f_0 decrease the electrical power harvested by the piezoelectric pendulum. However, in the case of rms values of displacement/velocity, the harvested power is perfectly proportional to the rms values. Therefore, useful relations between power and rms values of displacement/velocity have been determined for the estimation of power output in such systems for the first time. The piezoelectric pendulum harvests much energy when f is closed to f_0 and the distance to the magnetic device should be closer in order to decrease the nonlinearities in displacement and velocity.

1. Introduction

Piezoelectric materials get much interest due to their immense applications in engineering and technology. Among them, the most reputable field is energy harvesting due to their high power densities comparable to other regenerative energy technologies, such as lithium-ion batteries and electromagnetic power supplies [1–3]. Another need for piezoelectric harvesters is that the batteries require regular replacement; therefore an effective power saving strategy can be adopted to increase the life span of battery by using the harvesters [3–5]. This situation becomes much important if the devices are in hard environmental conditions in nature. Portable and wireless devices; for instance navigators, wireless sensors, cell phones, can have longer battery life, thereby less recharging time by the adjustment of the harvesters.

The effective power density and the output power should be increased further in such harvesters in order to have much power following the mechanical vibrations. Within that context, for instance, power rates less than 100 μW are sufficient to supply the above-mentioned wireless nodes [6]. In addition, while different harvesting methodologies are explored to enhance the energy harvesting, the explorations on designing materials draw much attention. With efficient techniques, mechanical energy can be converted and stored in electrical form, in order to feed the wireless electronics. Mostly a piezoelectric material can be used in order to transform this mechanical energy into electricity via the ambient vibration to supply wireless sensors [7]. In that context, the wireless sensors become popular because of their increasing applications and they have an ability to operate in inaccessible and hostile

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environments such as the complicated electrical networks, and nature, namely, space, ocean, forest, etc. [8]. Therefore they can also be supplied by such harvesters for longer life spans.

Above-mentioned systems convert the mechanical energy to the electricity, if an appropriate vibration mechanism is implemented in a suitable media. Among of possible alternatives, vibration-based energy harvesters take broader interest via the application environment. Those vibrations can be generated in different ways, for example, by wind, ocean tides, railways, human and vehicle movements, buildings and seismic noises, etc. [9–14]. The effects of vibrations must be analyzed in order to design and implement an efficient energy harvester by a required power rate. For example, a piezoelectric energy harvester including two electromagnets in a homogeneous magnetic field can be stated as an inverted pendulum in a recent paper [10]. The paper states the dynamics of the stochastically nonlinear vibrations and the harvested energy by using an external stable magnetic excitation. Since many permanent magnets are used in the paper [10], the system requires a large space for installation. Besides, the effect of periodic magnetic field is still an open question for such pendulum harvesters, although different works have been done by using permanent magnets or different tuning frequencies in the literature [15–17].

On the other hand, mechanical systems with quadratic or cubic nonlinearities get considerable attention for harvesting studies [18–20]. According to literature, the dynamic responses of beams can be different in terms of external excitations and system parameters and this reality obviously affects the energy harvesting mechanism of the proposed system. In previous papers [21,22], we studied such complicated responses of a magnetoelastic beam in a step-pulsed magnetic field, experimentally and theoretically. A numerous dynamic responses including periodic and chaotic ones were observed. The damping coefficient γ is proven to be important in order to characterize such a harvester system. The effects of excitation frequencies in terms of even and odd values are undeniable in the sense that the system generates much complexity for odd frequencies (see in [21]). In addition, the intermediate regimes of two-well chaos persist for appropriate parameter sets such as the magnetic field magnitude and excitation frequency. These regimes are important in the sense that the transition from one well to two well chaos causes larger displacements in piezoelectric layers, thus the amount of the harvested energy can be increased further by exploring the dynamic responses. In other words, the exploration on dynamic features such as position and velocity is a key subject for harvesters. In an earlier study, Cummings [23] and Eisley [24] obtained a rich dynamics by exploring the mechanical vibrations without any magnetic media. Similarly, Tseng and Dugundji [25,26] worked the nonlinearity of the buckled beam under the fixed ends and they observed periodic and aperiodic responses in the experiments and theoretical analyses. Between two permanent magnets, Moon and Holmes [18] studied the vibrations of a simple beam enforced by a periodic mechanical stress. A chaotic snap-through behavior was observed for some parameter sets in their study. Saymonds and Yu examined the elastic beam [27] and the numerical results were found for the transient responses of the beam with the help of finite element analysis. In addition, they also extended the system to a chaotic vibration problem [28]. Among the recent studies, the subharmonic resonance excitations [29], an analytical approach such as the distributed parameter of buckled beams [30], the analytical modeling of rotating effects on the beams [31], and an exploration on the snap-through behaviors [32] can be mentioned with that regard.

From the electromechanical view, the piezoelectric pendulum systems can have different hysteresis regimes, when the mechanical, electrical or magnetic excitations are considered. For instance, the softening and hardening hysteresis regimes are observed on the plane of excitation frequency (f) and output voltage (V), when the mechanical or magnetic periodic excitation exist [33,34]. In addition, piezoelectric materials can exhibit a hysteresis behavior on the plane of applied voltage and displacement as in Refs. [35,36]. Thus the control of piezoelectric actuators and hysteresis modeling for compensation are important issues [36]. Strictly speaking, the sign of the cubic nonlinearity of tip displacement determines the regime of the hysteresis; thereby the nonlinear dependence to displacement in the excitation force cannot be ignored. The hysteresis nonlinearity can affect the performance of the system. In a very recent paper [33], we have proven that the frequency sweep down yields to higher output voltage in our pendulum system. In this piezoelectric pendulum setup, the authors have explored some electrical features of a piezoelectric harvester under a periodic magnetic excitation. In that study, the pendulum output has been explored, in fact some vibrational responses have been explored in order to construct a good theory under the periodic field. However, the dynamics of the pendulum and the frequency-dependent motion has not been investigated in detail for this setup, yet. The displacement-dependent nonlinearity of the field becomes vital to understand the energy generation mechanism.

In the present paper, we aim to find out the relevance between the nonlinearities of displacement/velocity data of the piezoelectric pendulum and output power. The motivation comes from the requirements of optimized operation conditions, since these kinds of systems can be used as energy harvesters in the ambient periodic magnetic fluxes, when the power–nonlinearity relation is understood clearly. In this manner, the effects of the ambient magnetic flux frequency f and the nonlinearities of velocity and displacement on the power are examined. It will be shown that the piezoelectric pendulum can harvest much energy when f is closed to the natural frequency f_0 of the pendulum and the distance to the magnetic device should be closer in order to decrease the nonlinearities in displacement and velocity. In this manner, the electromechanical model and the simulation of the piezoelectric pendulum operating in a changeable magnetic media are studied experimentally and theoretically. The findings from the proposed model and the experiments are discussed and a comparison is done for the reliability of the model. It is shown that the nonlinear nature of the magnetic field causes different responses at the piezoelectric beam tip. The displacement of the tip, velocity, harvested voltage over the load and output powers are investigated as function of different magnetic stresses for various magnetic distances.

The paper is organized as follows: In Section 2, the experimental details of the pendulum system are presented. The theoretical aspects of the proposed model and the simulation background are presented in Section 3. The main results from the simulations and a comparison with the experimental findings are discussed in Section 4. In addition, a sample experimental setup and the harvested power are given at the end of Section 4. Finally, the concluding remarks are presented in the last section.

2. Experimental

The experimental setup of the proposed piezoelectric pendulum is presented in Fig. 1. The setup includes the following units: The magnetic excitation unit, ferromagnetic beam with piezoelectric layer (lead zirconate titanate), rectifier and storage circuit, signal generator, laser displacement sensor (LDS) and data acquisition and monitoring unit. The moving part of the pendulum is arranged as a pendulum including a ferromagnetic cubic knob (having 10 mm × 10 mm × 10 mm size) at the tip of the pendulum. The piezoelectric layer is positioned at the top of the pendulum connecting the non-ferromagnetic beam to the clamp.

An external non-constant magnetic force is exerted to the pendulum through the electromagnet (Fig. 1). Therefore the