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Snap-through twinkling energy generation through frequency up-conversion

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ABSTRACT

A novel experimental energy harvester is investigated for its energy harvesting capability by frequency up-conversion using snap-through structures. In particular, a single-degree-of-freedom (SDOF) experimental energy harvester model is built using a snap-through nonlinear element. The snap-through dynamics is facilitated by the experimental setup of a twinkling energy generator (TEG) consisting of linear springs and attracting cylindrical bar magnets. A cylindrical coil of enamel-coated magnet wire is used as the energy generator. The governing equations are formulated mathematically and solved numerically for a direct comparison with the experimental results. The experimental TEG and the numerical simulation results show 25-fold frequency up-conversion and the power harvesting capacity of the SDOF TEG.

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1. Introduction

There is an abundance of energy available in the low frequency range, but the conversion of this mechanical energy into usable form for micro-scale devices is a primary concern. For example, consider harvesting energy from a micro-scale beam. A primary concern is the beam natural frequency would typically be in the tens of kHz, but the bulk of the available energy is in the low tens of Hz, i.e. maybe below 25 Hz in many applications. Twinkling phenomenon could potentially be used to up-convert low-frequency excitations into a usable frequency range. Twinkling occurs when a nonlinear spring-mass snap-through chain is loaded slowly and the masses snap-through, converting the low-frequency input to high-frequency oscillations. In this paper, a demonstration of an energy harvester that exploits the up conversion in frequency associated with the twinkling phenomenon is presented.

Vibration-based energy harvesting has recently gained lot of attention. Nonlinear spring-mass systems, such as snap-through structures, have the potential to harvest energy from a variety of low-frequency sources. To be able to harvest such energy, it is critical to understand the underlying dynamics of the coupled snap-through oscillators. Several authors have studied the dynamics of various snap-through negative-stiffness and bistable systems [1–8]. Vibration-based energy harvesting from linear systems [9,10] has been optimized experimentally [11–13] by tuning the forcing frequency to the natural frequency of the oscillator. Piezoelectric materials are used for successful experimental energy harvesting from vibrating

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sources [9,10,14–17] and fluctuating pressure load [18,19].

Nonlinearity has been studied by various authors for energy management. For example, essential nonlinearity has been used as a nonlinear energy sink (NES) for energy harvesting [20–23], nonlinear energy pumping [24–27], and nonlinear targeted energy transfer (TET) [28–33]. Various authors have conducted experimental energy harvesting for low-frequency ambient excitations [34,15,16,35,36], nonlinear oscillations of magnetic levitations [37], and snap-through oscillators [38–42,16,43–46].

The vibration-based energy harvesting in this article is based on the nature-inspired dynamics of the hairs in bull-frog's ears [47,48] that exhibit bistable properties [49,50]. Recently there has been growing interest in designing materials that can exhibit multiple stable equilibrium states and help channel the flow of energy in a desirable direction and/or for a desirable frequency. One way to achieve this is by using bistable elements in a mass-spring chain. There are two stable equilibrium states for every bistable element. Though the stability of a single-degree-of-freedom (SDOF) bistable structure seems simple, when more bistable elements are added, it forms a complex dynamical system and exhibits multiple equilibria [51,52]. These bistable elements, when combined, enable high-frequency oscillations. This property of a bistable chain can be exploited in order to convert low-frequency vibrations into high-frequency oscillations, which in turn can be used for energy harvesting and energy transfer. This paper takes a step toward demonstrating such a capability by exploiting frequency up-conversion of twinkling in a SDOF pulled snap-through mass-spring to harvest energy.

This work explores snap-through twinkling and energy harvesting by using magnets and coils. The main idea of this research is to increase the frequency in order to take advantage of a magnet-coil harvester system that performs best for fast oscillations of the magnet inside the coil. The frequency up-conversion is done using the snap-through phenomenon. In this research frequency up-conversion is done by using attracting magnets and linear springs in a novel fashion to form a snap-through system. It is demonstrated that by using the snap-through phenomenon one can increase the response frequency more than 25-fold for a low frequency vibration excitation input.

The work is organized as follows. In Section 2, the experimental setup and the corresponding physical parameters are presented. Keeping the experimental setup in focus, we describe the system mathematically in Section 3. In this section the forces due to the linear springs, the nonlinear magnetic attraction forces between cylindrical magnets, and the idle equilibrium state force balance are discussed. The numerical simulation results are presented in Section 4. In Section 5, the experimental results for harvested power are presented in comparison with the numerical simulations of the analytical models to confirm the power harvesting capacity, and the frequency up-conversion as well as the broadening of the frequency spectrum. Finally, the results obtained in this paper are summarized in Section 6.

2. Experimental setup of the twinkling energy generator

In this section the details of the experimental setup and the experimental parameter values are described. The experimental parameter values are later used in the mathematical model for obtaining the numerical simulation results. A SDOF experimental snap-through twinkler is built for power harvesting from low-frequency input oscillation. Snap-through is achieved with attracting magnets which are “locked” in contact until the force of a pulled spring overcomes the attraction force, at which point the magnets release and the mass can oscillate about a non-contact equilibrium.

The experimental setup consisted of an air track for low mechanical damping, a horizontal shaker to induce a low-frequency vibration input, a triangular shaped cart as the moving mass with 3D-printed mounts for the magnets, and a combination of linear springs and cylindrical bar magnets to induce snap-through in the system as well as to facilitate power generation in a coil made of enamel-coated magnet wire, as shown in Fig. 1. The mass consisted of the moving cart, a magnet mount, and a magnet. The mass was constructed in such a fashion that the magnets were fixed to the magnet mounts using nuts and bolts. A stationary magnet was attached through a magnet mount to a fixed base (the fixed cart in Fig. 1). Beads were attached to the magnets to provide a spacer of distance d_m that reduces the attractive force between the magnets when they are “locked” in the idle state. The beads also avert direct impact between the magnets and prevent impact damage. The harvester coil was mounted outside the air track such that when the mass-mounted magnet cylindrical bar magnet was passed through the center of the coil, power was generated. Fig. 1 (a) shows the twinkling energy generator (TEG) in its idle equilibrium state, for which the magnets are in contact through the spacer beads, and (b) shows the TEG in its dynamic state when the magnets are detached and the magnet oscillates inside the harvester coil, which was located a distance x_{0coil} from the idle position of the oscillating magnet. Springs with different stiffnesses were used in various setups of the SDOF TEG experiment. Generator models with both unsymmetric springs with different stiffnesses and symmetric springs with almost identical stiffnesses were investigated.

An electrical circuit was set up in order to capture the voltage output generated in the harvester coil when the oscillating magnet passes through the inducing coil. The horizontal shaker initiated through a MATLAB script was used to induce external excitation and the generator coil was connected to the circuit board that fed the output analog signal (voltage) into a data acquisition board (DAB). This DAB converted the analog output into a digital signal. The output digital signal was the voltage output generated in the generator coil. The mechanical, magnetic, and electrical circuit parameter values are tabulated in Table 1.

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