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Fabrication and characterization of non-resonant magneto-mechanical low-frequency vibration energy harvester

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ABSTRACT

This article presents a non-resonant magneto-mechanical vibration energy harvester. When externally excited, the energy harvester converts vibrations into electric charge using a guided levitated magnet oscillating inside a multi-turn coil that is fixed around the exterior of the energy harvester. The levitated magnet is guided using four oblique mechanical springs. A prototype of the energy harvester is fabricated using additive manufacturing. Both experiment and model are used to characterize the static and dynamic behavior of the energy harvester. Measured restoring forces show that the fabricated energy harvester retains a mono-stable potential energy well with desired stiffness nonlinearities. Results show that magnetic spring results in hardening effect which increases the resonant frequency of the energy harvester. Additionally, oblique mechanical springs introduce geometric, negative, nonlinear stiffness which improves the harvester's response towards lower frequency spectrum. The unique design can produce a tunable energy harvester with multi-well potential energy characteristics. A finite element model is developed to estimate the average radial flux density experienced by the multi-turn coil. Also, a lumped parameter model of the energy harvester is developed and validated against measured data. Both upward and downward frequency sweeps are performed to determine the frequency response of the harvester. Results show that at higher excitation levels hardening effects become more apparent, and the system dynamic response turns into non-resonant. Frequency response curves exhibit frequency jump phenomena as a result of coexistence of multiple energy states at the frequency branch. The fabricated energy harvester is hand-held and measures approximately 100.5 [cm^3] total volume. For a base excitation of 1.0 g [m/s^2], the prototype generates a peak voltage and normalized power density of approximately 3.5 [V] and 0.133 [mW/cm^3 g^2], respectively, at 15.5 [Hz].

1. Introduction

Vibration-based energy harvesting has been investigated as a promising route for powering portable electronics such as wireless sensors and smartphones [1,2]. The working principle of a vibration energy harvester is explained using the first law of thermodynamics, i.e. law of conservation of energy. In this way, a vibration energy harvester is a device that is used to convert vibrations from kinetic energy into useful electric energy. Although ambient vibration energy is free and available everywhere, the use of vibration energy harvesters is still limited. This is mainly because most vibration energy sources

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are comprised of a broadband frequency spectrum [3–5]. A typical linear energy harvester is capable of generating significant power when the excitation frequency matches the resonant frequency of the device. Operating the linear harvester off-resonance results in a substantial reduction in harvested power [6,7]. Thus, for applications that are targeting self-powered portable devices there is a need for a broadband energy harvesters [8,9].

Magnetic levitation has been studied as an alternative approach to achieve broadband energy harvesting operation [10–12]. Fig. 1a–c shows a traditional magnetic levitation-based energy harvester. A traditional magnetic levitation-based energy harvester consists of two (or more) magnets placed in a repulsive configuration (like-poles facing each other). The repulsive magnetic force developed between the levitated and stationary magnets counteracts gravity. A magnetic levitation-based energy harvester experiences a nonlinear force-displacement relationship due to the repulsive forces developed between alike poles. This nonlinear stiffness behavior shifts the resonant frequency of the system, producing a broader frequency response in comparison to the frequency response of a linear energy harvester. As a result of the nonlinear force-displacement relationship, the energy harvester's equation of motion can be described by Duffing's equation [10,11]. A displacement rod (Fig. 1a) [12] or rails (Fig. 1c) [13] are used to guide the moving levitated magnet inside the energy harvester. Occasionally, the vertical rod is removed [10,14,15] and tight-fit container (Fig. 1b) is used to prevent magnets from realigning. Upon external excitation, voltage is induced in the coil positioned around the static position of the levitated magnet as a result of levitated magnet movement. Air holes are drilled in the body of the energy harvester to allow air flow in and out of the harvester.

In previous work, we have investigated the limitations and obstacles facing traditional magnetic levitation-based energy harvester designs [16,17]. The presence of a vertical displacement rod dictates the use of a hollow levitated magnet. Results from our previous work [16,17] have shown that a traditional energy harvester with hollow magnets guided by a rod (Fig. 1a) experienced a weaker electromagnetic field compared to a traditional energy harvester with solid magnets tightly-fit inside of a container (Fig. 1b). Also, it has been demonstrated that dry friction was a dominant form of damping and, thus, hindered the performance of traditional magnetic levitation-based harvesters by increasing the overall energy dissipation. In addition, previous work has revealed that magnetic force-displacement curves of traditional magnetic levitation-based energy harvesters showed weak nonlinearity correlation and was approximately linear over moderate displacements [16,17].

In this work, we report an enhanced novel design of a nonlinear magnetic levitation-based energy harvester to overcome several of the challenges faced by traditional designs. This work is focused on fabrication and characterization of the enhanced novel magnetic levitation-based nonlinear energy harvester. The harvester is fabricated using 3D printing. Its static and dynamic behavior are characterized experimentally. A finite element model is developed to estimate the average radial flux density experienced by energy harvester. Also, a lumped parameter model of the energy harvester is developed and validated against measured data.

Fig. 2 shows the design and structure of the enhanced novel energy harvester presented in this work. The energy harvester consists of a combination of mechanical and magnetic springs. This unique arrangement of a levitated magnet and linear, oblique mechanical springs has several advantages over traditional magnetic levitation-based energy harvester designs. As will be shown later in this article, a geometric negative stiffness is introduced using the oblique, mechanical springs. This improves the total nonlinearity of the energy harvester. This is especially important since the magnetic springs show weak nonlinearity over moderate displacements as discussed earlier. When subject to an external vibration, the levitated magnet moves vertically within the harvester casing. The moving magnet experiences nonlinear forces in the direction of motion, i.e. vertical direction, due to the combination of oblique and magnetic springs. As the levitated magnet moves, the oblique springs are stretched vertically along the longitudinal axis. This yields extra nonlinear restoring forces in the direction of motion, i.e. the vertical direction. Moreover, the oblique springs eliminate the need for a displacement rod or rail, typically encountered in traditional designs. Thus, another purpose of oblique springs is to align the levitated magnet along the stationary magnets' common axis, i.e. the vertical axis. Unlike traditional approaches, the presence of oblique springs eliminates any lateral movement of the moving mass. This reduces energy losses that might arise due to contact between

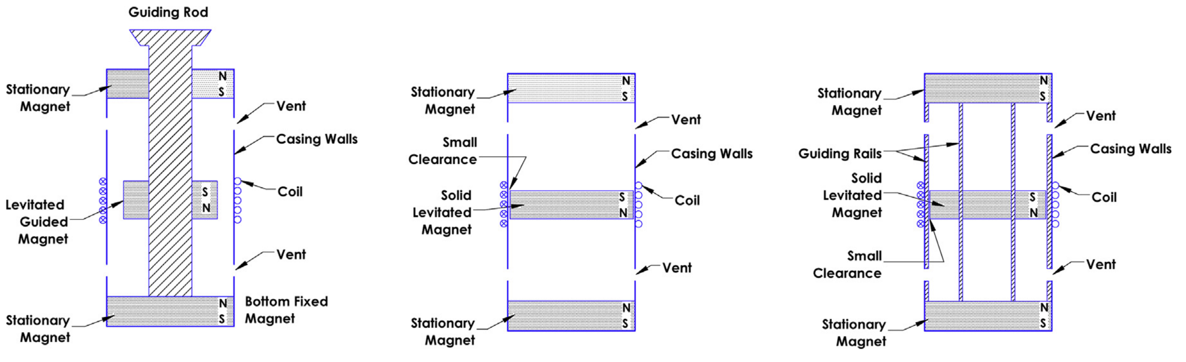

Fig. 1. Traditional magnetic-levitation based energy harvester designs. (a) Displacement rod configuration (LEFT). (b) Tight-fit configuration (MIDDLE). (c) Rail configuration (RIGHT).