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Design and optimization of a magnetically sprung block magnet vibration energy harvester

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ABSTRACT

A magnetically sprung, electromagnetic vibration energy harvester with block magnets is presented. The harvester achieves one of the highest reported measured normalized power densities for a magnetic levitation energy harvester of 7000 μW cm^{-3} g^{-2}. The measured power output at 6.7 Hz was 410 μW and 304 μW at 0.1*g* and 0.075*g* acceleration amplitudes, respectively. The energy harvester was constructed using block magnets, which allow more flexibility in design compared to the typical cylindrical magnet devices. The device has been modeled using analytic equations to calculate the nonlinear magnetic forces and flux, which have been input into a time step model of the harvester to calculate power output. The full design procedure to optimize the device is presented.

1. Introduction

The importance of vibration energy harvesting has increased over the past decade due to decreasing power requirements of electronics and the increasing use of wireless systems. Most vibration energy harvesters consist of a mass attached to a mechanical spring with a transduction mechanism to convert the mechanical energy into electrical energy [1–3]. The transduction mechanism is comprised of one or more of the four transducer types: piezoelectric [4–6], electromagnetic [7,8], electrostatic [9,10], and more recently magnetostrictive [11].

Vibration sources include: machines, such as cars, washing machines, microwaves and many more; infrastructure such as bridges, buildings, and ventilation ducts; or even human movement [12,3]. These sources have peak vibration amplitude ranging from milli gs up to a few gs (where $1g = 9.8\,\mathrm{m/s^2}$) at frequencies from less than 1 Hz up to hundreds of Hertz [12]. Harvesting energy from human motion is of growing interest due to the rising demand for wearable electronics, such as for patient monitoring in healthcare applications and wearable consumer products [13,14]. However, human vibration and motion energy is concentrated below 10 Hz, which causes difficulty because lower frequency sources are more difficult to design for due to the requirement of either a highly compliant spring or large mass.

Recently, magnetically sprung, or levitating, electromagnetic energy harvesters have been studied by researchers [15–23]. One key advantage of magnetic levitation is that the mechanical spring is replaced with a magnetic spring, thus leading to an extended lifetime because the physical spring is the most likely component to fail. Additionally, the removal of a physical spring allows a low spring constant to be designed, leading to a low resonant frequency. These characteristics make the levitating electromagnetic type energy harvester ideal for human motion energy harvesting.

In this paper a magnetically sprung levitating electromagnetic energy harvester that utilizes block magnets rather than cylindrical magnets is presented. In Section 2, the structure of the levitating energy harvester is discussed. In Section 3, the energy harvester modeling is presented with analytic calculations of magnetic force and flux. The design procedure is presented in Section 4. In Sections 5 and 6, the modeling and experimental results are presented, and in Section 7, the results are discussed.

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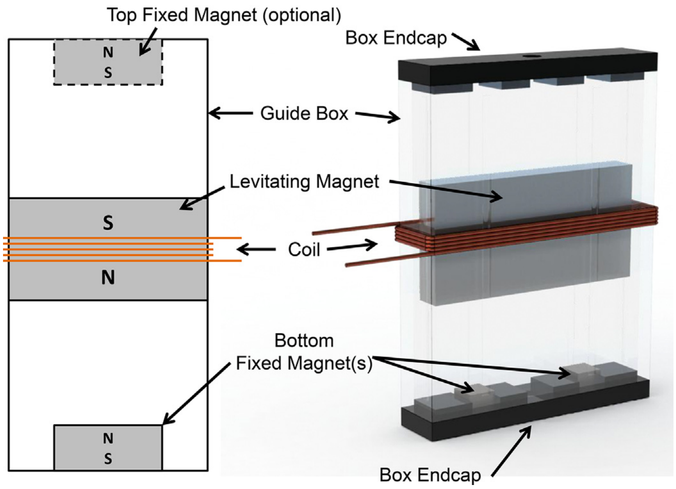

Fig. 1. Levitating block magnet energy harvester 2D (Left) and 3D (Right) views, 3D view shows an energy harvester that is about 40 mm × 30 mm × 10 mm.

2. Structure of the energy harvester

A cross-sectional diagram of the levitating electromagnetic vibration energy harvester is shown in the left of Fig. 1. The device consists of a levitating movable magnet, fixed magnets, a box to contain and guide the levitating magnet, and a coil wrapped around the box to harvest the vibration energy. The fixed magnets are arranged such that they have a repulsive force on the levitating magnet to suspend it in the box. The fixed magnets are placed at the bottom end of the tube and optionally at the top, depending on the orientation of the device with respect to gravity. When an acceleration is applied to the device, the levitating magnet moves relative to the coil causing the magnetic flux through the coil to change. Based on Faraday's law of induction, the changing magnetic flux through the coil induces a voltage on the coil that can be harvested in order to power attached circuitry or to charge a battery.

In previous literature, the magnets have been implemented as cylindrical magnets with a tube as the guide box [15–23]. Implementing the device as a cylinder imposes limits on the form factor of the device. In this paper we propose using block magnets for both the fixed and levitating magnets to allow a thinner device as shown on the right of Fig. 1.

3. Energy harvester model

3.1. Electromechanical model

The magnetic levitation energy harvester is modeled as a mass-spring-damper system as shown in Fig. 2. Based on the free body diagram the sum of the forces acting on the mass can be written as:

$$m\ddot{z}(t)+\left[c_e(z(t))+c_p\right]\dot{z}(t)+F_{Fric}-F_{mag}(z(t))+mg=-m\ddot{y}(t) \tag{1}$$

where m is the mass of the levitating magnet, $c_e(z(t))$ is the electrical damping as a function of mass displacement, c_p is the parasitic viscous damping coefficient, F_{Fric} is the parasitic dry friction (or Coulomb type) damping, $F_{mag}(z(t))$ is the sum of the magnetic forces as a function of displacement, g is gravity, $y(t)$ is the displacement of the device frame due to external forces, and $z(t)$ is the displacement of the mass relative to the device frame. The magnetic force and the electrically induced damping are both nonlinear functions of mass displacement. The parasitic damping is typically modeled as viscous damping in previous literature [15–23], but we have added a term for dry friction damping. It is possible that both forms of parasitic damping occur: viscous due to air movement, and dry friction because the levitating magnet can come into contact and slide along the side walls. Due to the unknown nature of contact of the levitating magnet with the box side wall, the exact form and magnitude of damping is difficult to predict. We show later using the ringdown waveform that dry friction damping is dominant in our device. The dry friction damping opposes the movement of the levitating magnet and has the form:

$$F_{Fric}=\frac{\dot{z}(t)}{|\dot{z}(t)|}F_d \tag{2}$$

where $\dot{z}(t)$ is the velocity of the levitating magnet and F_d is the force of the dry friction damping [24].

3.2. Energy harvester dimensions

The design procedure is presented later in the paper, but Fig. 3 and Table 1 show the dimensions and their values for the final design, since they are referenced throughout the paper. The dimensions include the dimensions of the levitating magnet (L_l, w_l, h_l), fixed magnets (L_f, w_f, h_f), spacing between fixed magnets (L_s), height of the box (h_b), equilibrium position of the levitating magnet (Z_0), height of the coil (h_c), and location of the center of the coil (Z_c).

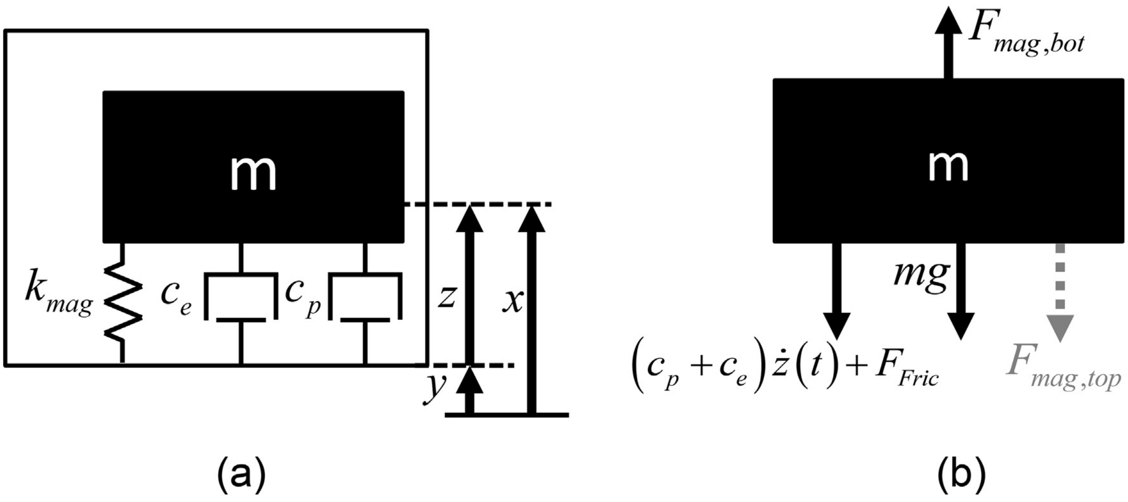

Fig. 2. (a) Physical representation and (b) free body diagram of energy harvester.