VIBRATION ENERGY HARVESTER BASED ON FLOATING MAGNET FOR GENERATING POWER FROM HUMAN MOVEMENT

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ABSTRACT

This paper reports a brand new approach of forming an electromagnetic energy harvester with a pair of pyrolytic graphite substrates to float a magnet in air for generating power from human walking motion. The novel levitation mechanism allows a low resonant frequency (1 - 5 Hz) without a heavy proof mass. A subminiature energy harvester weighing 22 gram has been demonstrated to have a resonant frequency of 3.4 Hz and generate 11.7 µW from the back of a human walking at 2 m/s.

INTRODUCTION

Technical improvement in microelectronics and MEMS, coupled with burgeoning internet of things (IoT), has brought wearable devices closer to our daily lives than ever before. These devices have changed our lifestyle in many ways. For example, a wearable activity tracker monitors and tracks fitness-related metrics (such as distance walked or run, calorie consumption, heartbeat rate, and quality of sleep), and leads us to change our lifestyle for better health. However, users of wearable or handheld devices are often inconvenienced by the need to recharge battery, and would not mind carrying (or paying for) an energy harvester to supplement or even replace battery, as long as it is small, light and affordable. Compared to a solar cell which has been widely used in consumer electronics like calculator, a vibration energy harvester that can generate electrical power from vibration or motion is better for wearable application since it can work day and night independent of availability of light energy.

Vibration-energy harvesters usually convert mechanical energy into electrical energy through capacitive [1], piezoelectric [2] or electromagnetic [3-4] transduction. Capacitive (or electrostatic) energy harvesters can easily be manufactured with a fabrication process that is compatible with CMOS integrated circuit (IC) microfabrication. However, it needs a DC bias voltage or pre-charged membrane which quickly loses its charge when ambient temperature becomes higher than 80 °C. Piezoelectric energy harvester based on PZT [5] or AlN can achieve high open circuit voltage but suffers from low current associated with large resistance of the piezoelectric material itself. Compared to these two mechanisms, electromagnetic energy harvesting based on Faraday's law offers the advantage of high current, even for a low impedance load, and is ideally suited for wearable devices [6-8].

A major obstacle of generating power from human movement such as walking is the inherent low frequency (1 – 5 Hz) associated with such motion [9]. A magnetic spring [10] based on the repelling force between the same pole is one way to suspend the proof mass (usually a magnet or magnet array) to obtain a low resonant frequency, but requires heavy magnets for a resonant frequency as low as 1 - 5 Hz. Thus, we have invented a novel suspension technique based on diamagnetic material that can induce a magnetic field which is directed opposite to an externally applied magnetic field and repels the applied magnetic field.

DESIGN

Electromagnetic vibration energy harvester uses the relative movement between magnet and coil to produce electromotive force (EMV). The magnet also acts as a proof mass in most cases. In order to reduce the friction which is the main source of mechanical damping that reduces the transduction effectiveness, the ideal design would be to completely float the magnet in the air.

A magnetic spring based on the repulsive force between two magnets of same polarity can be used to levitate a magnet. However, according to the Earnshaw's theorem [11], for hard magnets of which the magnetic strength is independent of external fields, a stable stationary equilibrium cannot be maintained solely by the repulsive magnetostatic force. The theory was first proposed for electrostatic fields, but since it applies to any classical force of inverse-square law, it also applies to the magnetic spring. Thus, the Earnshaw's theorem forbids touch-free magnetic levitation by a magnetic spring. Braunbeck further extended Earnshaw's theorem to state that even if the materials are not hard, it is impossible to achieve static magnetic levitation or suspension with magnets of relative permeability greater than one (i.e., paramagnets) [12].

On the other hand, a diamagnetic material creates an induced magnetic field (within the material) in a direction opposite to that of an externally applied magnetic field, and thus is repelled by the applied magnetic field. Superconductors can expel all magnetic field and therefore can be considered as perfect diamagnetic material. But superconductors work below a critical temperature that is far lower than room temperature, and are impractical for energy harvesters. There are plenty of materials that are diamagnetic at room temperature although the effect is usually weak. The most common diamagnetic material is water, and if an external applied magnetic field is large enough, one can levitate a living creature like frog in air.

Pyrolytic graphite is a very strong diamagnetic material, and a thin slice of pyrolytic graphite can be stably levitated above the magnetic field provided by a permanent magnet. However, a magnet cannot be levitated by a pyrolytic graphite sheet alone, no matter how thick the graphite sheet is, due to the heavy weight of a magnet. And a stronger magnetic field (for stronger repelling force) requires a heavier magnet. This means that the gravity of a magnet needs to be reduced partially or completely balanced by other mechanism. We have used another magnet to counteract most of the gravity through an attractive force between the two magnets, while using two graphite sheets (above and below a proof-mass magnet) to stably levitate or float the proof-mass magnet in air.

In the vibration-energy harvester illustrated in Fig. 1, we use a pair of pyrolytic graphite substrates to provide the repelling forces so that a magnet may be floated and confined in air between the two diamagnetic substrates. The floating magnet moves, without contacting the graphite substrates, in response to an applied vibration, and comes back to its static equilibrium position automatically when there is no applied vibration. The relative motion between the floating magnet and the nearby coil, as the magnet moves, induces electromotive force. Since the repelling force from the bottom graphite is not strong enough to overcome the gravity of the floating magnet, an additional magnet (denoted as upper magnet in Fig. 1) has been used.

The upper magnet is chosen to provide enough attractive force to balance the gravity of the floating magnet. Though the attractive force may be large enough to make the floating magnet touch the top graphite, the floating magnet does not come in contact with the top graphite, because of the repelling force provided by the top graphite. As the floating magnet gets closer to the bottom graphite, the attractive force from the upper magnet is reduced, while the repelling force from the bottom graphite is increased, thus the floating magnet does not come in contact with the bottom graphite, either. Instead it stays stably between the top and bottom graphite sheets as a static equilibrium.

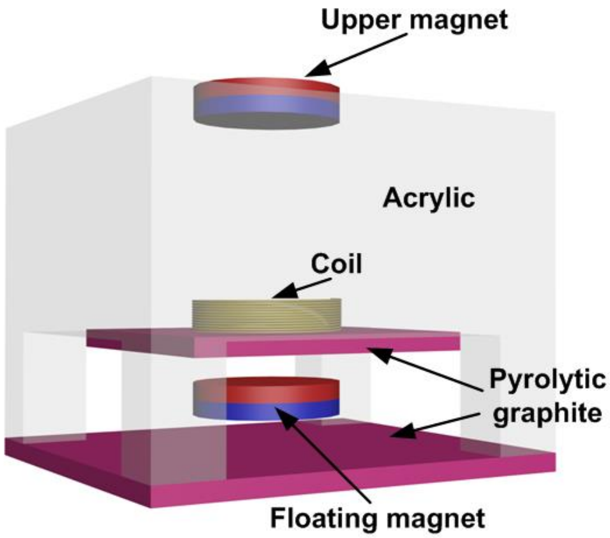

Figure 1: Schematic of the vibration energy harvester based on floating magnet through diamagnetic levitation. Though much of the gravity of the floating magnet is counteracted by an attractive force provided by upper magnet, the floating magnet floats in air, well balanced (without being completely pulled up to the upper magnet), because of the repelling force from the pair of pyrolytic graphite sheets surrounding the floating magnet. Relative movement between the floating magnet and coil due to in-plane vibration induces electromotive force.

With the assumption that the distance between the upper and floating magnets is much larger than the magnet thickness, the two magnets can be simplified as dipoles. When the floating magnet is at the equilibrium position as shown in Fig. 2(a), the attractive force between the upper magnet and the floating magnet should be:

$$\frac{\mu Q_T Q_B}{4\pi h^2} = mg \qquad (1)$$

where μ is air permeability; Q is magnetic field intensity; h is the distance between the upper and floating magnet; m is the mass of the floating magnet; and g is gravitational acceleration.

When the floating magnet deviates from its balanced position as shown in Fig. 2(b), the forces in the vertical direction counter-balance each other, since the repelling forces provided by the graphite sheets self-adjust according to the magnetic field from the floating magnet, and there is a net force in the lateral direction equal to

$$F = \sin\theta \frac{\mu Q_T Q_B}{4\pi (h/\cos\theta)^2} \qquad (2)$$

where θ is the angle between the line connecting the center of two magnets and the vertical direction. In fact, the force in the lateral direction is the horizontal component of attractive force between the upper and floating magnets. If we take equation (1) into equation (2), we can derive the vertical force as a function of the deviated angle θ as follows.

$$F = mg \sin\theta \cos^2\theta \qquad (3)$$

If the deviated distance x is much smaller than the distance between the upper and floating magnets (h), we have the following approximations:

$$\sin\theta \approx \frac{x}{h}, \cos\theta \approx 1, \quad if \ x << h$$

Then the lateral force is linearly proportional to x as expressed in the following equation (4):

$$F \approx -\frac{x}{h} mg \qquad (4)$$

And the equation of motion can be expressed as

$$m\ddot{x} = F$$

$$m\ddot{x} + \frac{x}{h} mg = 0 \qquad (5)$$

Equation (5) is exactly the same as the one for a simple harmonic vibration with an equivalent spring constant of mg/h. Thus, as long as the deviated distance x is much smaller than h, the floating magnet vibrates in simple harmonic motion with the resonant frequency equal to

$$\omega = \sqrt{\frac{g}{h}} \qquad (6)$$

Consequently, the resonant frequency of the energy harvester is inversely proportional to the square root of the distance between the upper and floating magnets (the larger the distance, the lower the resonant frequency). In this way, a very low resonant frequency (e.g., 1 – 5 Hz) can be achieved with relatively small size for scavenging energy from human's walking motion.

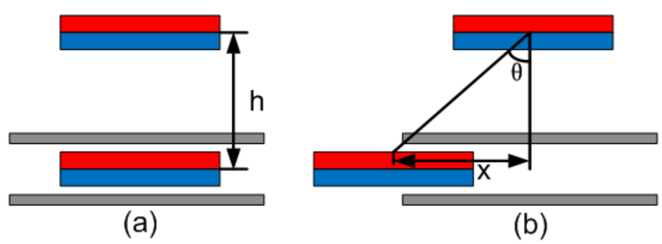

Figure 2: (a) The floating magnet is at balanced position. (b) The floating magnet deviates from its balanced position due to applied vibration. For small deviation, the restoring force in the lateral direction is linearly proportional to the deviation.

FABRICATION

Neodymium (NdFeB) permanent magnets are used since they provide high magnetic flux density. Two disk NdFeB magnets of the same size are used for the upper and floating magnets. Two pyrolytic graphite sheets of 5cm×5cm×3mm and 3.2cm×1.6cm×0.75mm are located below and above the floating magnet, respectively. The upper pyrolytic graphite is chosen to be thinner to minimize the attenuation of the magnet flux, as it is between the coil and the floating magnet. The coil is fabricated by a winding machine, and has 22 Ω resistance and 400 turns. The frame of the energy harvester is made of laser-machined acrylic slab, and the distance between the upper and floating magnets is adjusted to be 2.9 cm to make the attractive force balance out the gravity of floating magnet. The dimensions and parameters of the energy harvester are listed in Table 1. The photos of the fabricated energy shown in Fig. 3 clearly show that the lower magnet is completely floating in air without touching the pyrolytic graphite because of the repelling force provided by the pair of the graphite sheets while the gravity is counteracted by the attractive force from the upper magnet.

Table 1. Dimensions/parameters of the energy harvester.

Magnet diameter	19 mm	Coil turns	400
Magnet thickness	1.58 mm	Coil resistance	22 Ω
Surface field	1,217 Gauss	Effective weight*	21.7 g

**Without the acrylic frame*

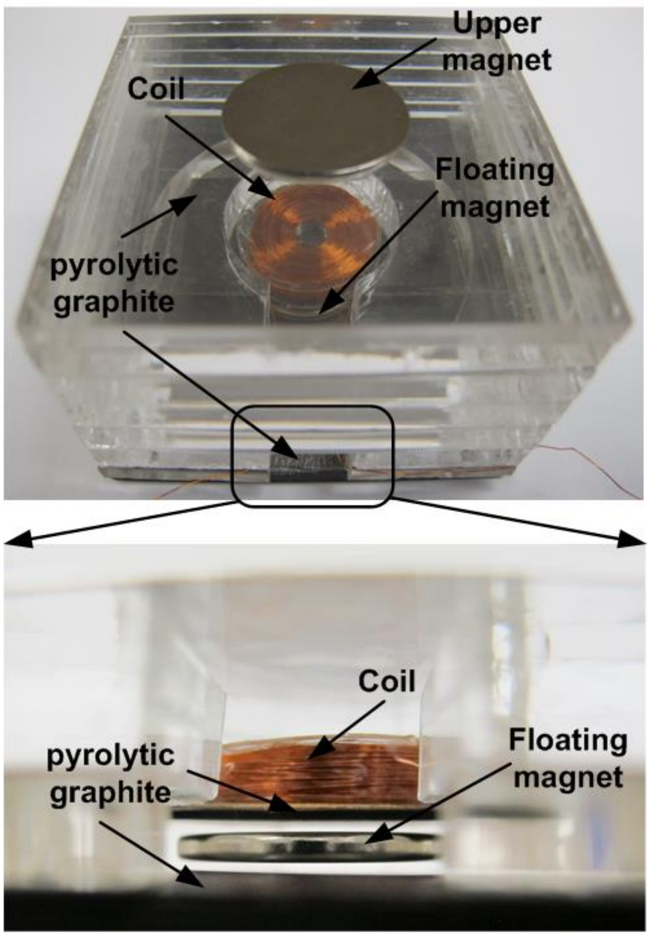

Figure 3: Photos of the fabricated vibration energy harvester. The lower magnet is completely floating in air with the repelling force provided by a pair of pyrolytic graphite substrates. The floating magnet vibrates in the lateral direction without any direct contact with the graphite.

RESULTS AND DISCUSSION

The energy harvester is tested on a linear actuator (Aerotech ACT115DL) with in-plane vibration over 1 - 5 Hz. The schematic of the testing platform is shown in Fig. 4. The linear actuator is driven by a digital controller which receives the control parameters (i.e., the vibration amplitude and frequency) from a computer. The position data of the linear actuator are fed to the computer for accurate control of the vibration. The output signal from the energy harvester is observed by and stored into an oscilloscope.

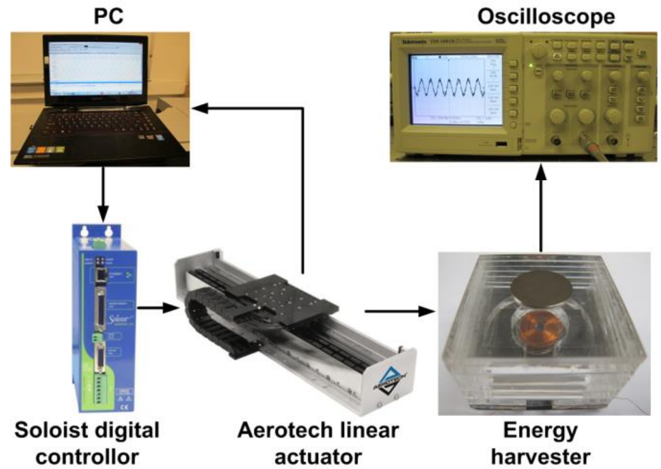

Figure 4: Schematic of the testing platform. The linear actuator is controlled by a computer and calibrated with a feedback signal. The output voltage of the energy harvester is measured with an oscilloscope.

The measured output voltage as a function of frequency under various accelerations is shown in Fig. 5. Under a fixed acceleration, the voltage varies as the vibration frequency is varied, and peaks at a resonant frequency. The measured resonant frequency is around 3.4 Hz, while the theoretical prediction is 2.93 Hz (for 2.9 cm distance between the upper and floating magnets).

The root mean square (rms) output voltage and the corresponding power with a matched load are shown in Fig. 6. The power delivered to a matched load increases as the applied acceleration increases, and 68 µW can be delivered into a load of 22 Ω from 2 g acceleration (corresponding to 43 mm vibrational amplitude) at 3.4 Hz.

The energy harvester is also tested on the back of a human walking on a treadmill as shown in Fig. 7, and 11.7 µW is delivered to a 22 Ω load from 2 m/s walking speed. The power decreases a little beyond 2 m/s, due to (1) more of the vibration energy being at higher frequencies than the harvester's resonant frequency (3.4 Hz) and (2) more energy in the vertical direction instead of the lateral direction, as the walking becomes jogging or running.

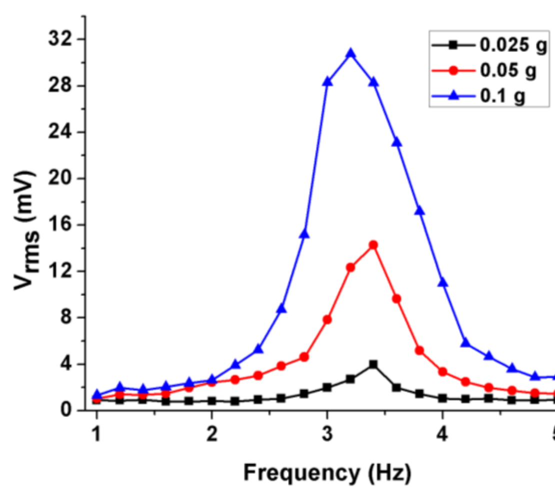

Figure 5: Measured frequency response of the energy harvester under various applied accelerations. The resonant frequency is around 3.4 Hz, while the theoretically calculated one is 2.9 Hz.

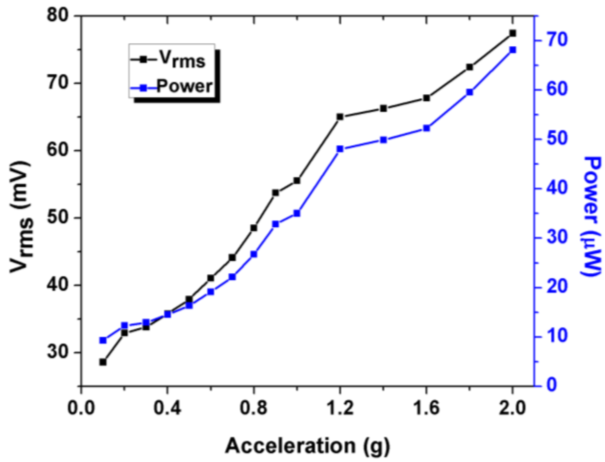

Figure 6: Measured power and rms voltage vs input acceleration at the resonant frequency of 3.4 Hz. A 2 g acceleration produces 68 µW power (into 22 Ω load).

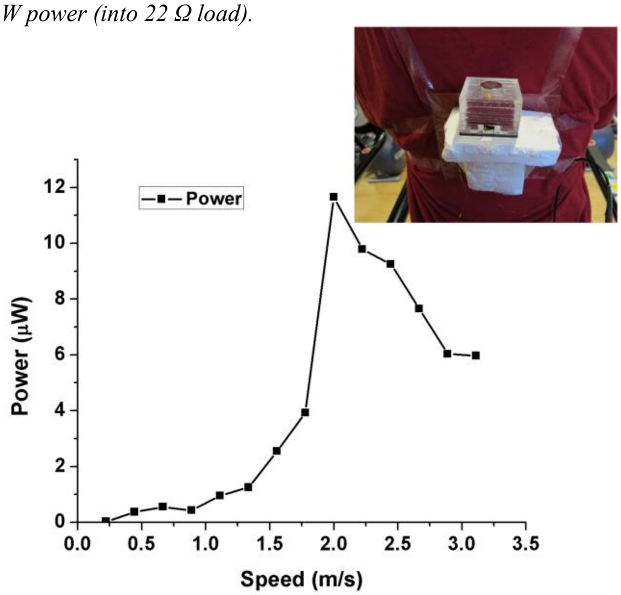

Figure 7: (Top) Photo of the harvester on the back of a human walking on a treadmill. (Bottom) Measured power from the harvester vs the walking speed of the one carrying the harvester on the back: 11.7 µW is delivered to a 22 Ω load from 2 m/s walking speed.

CONCLUSION

The novel idea of a floating magnet based on diamagnetic graphite with an additional magnet to counteract the gravity of the floating magnet has been implemented for electromagnetically generating electrical power from human's walking motion. A prototype energy harvester weighting 21.7 gram produces an rms voltage of 77.4 mV (in open circuit) and 68 µW power output (into 22 Ω load) at the harvester's resonant frequency of 3.4 Hz in response to a vibration amplitude of 43 mm (i.e., 2 g at 3.4 Hz). The low resonant frequency makes the energy harvester suitable for harvesting energy from human walking motion. And 11.7 µW is delivered to a 22 Ω load from 2 m/s walking speed from the harvester mounted on a human's back.

ACKNOWLEDGEMENTS

This article is based on the work supported by Defense Advanced Research Project Agency under grant no. N66001-13-1-4055. Travel support has been generously provided by the Transducer Research Foundation.

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