Low Frequency Vibration Energy Harvester Using Spherical Permanent Magnet with Non-uniform Mass Distribution

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Low Frequency Vibration Energy Harvester Using Spherical Permanent Magnet with Non-uniform Mass Distribution

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Abstract. We present a non-resonant vibration energy harvesting device using springless spherical permanent magnet with non-uniform mass distribution as a proof mass. The magnet has its center-of-mass below the geometrical center, which generates a roly-poly-like motion in response to external vibrations. Two different types of magnet assemblies with different center-of-mass position have been fabricated and tested. Using the roly-poly-like magnets, proof-of-concept electromagnetic energy harvesters have been fabricated and tested. Moreover, effect of ferrofluid as a lubricant has been tested with the fabricated energy harvester. Maximum open-circuit voltage of 154.4mV and output power of 4.53μW have been obtained at 3g vibration at 12Hz with the fabricated device.

1. Introduction

Energy harvester is one of the promising research topics in the area of micro power generation due to the abundance of energy sources in environment. Most widely pursued target applications of energy harvesting include wireless sensor nodes and low power electronics. Among the various sources of energy, environmental vibration is an excellent candidate for a variety of applications due to ease of utilization and abundance in nature. In general, there are three ways to convert vibration into electrical energy which are piezoelectric, electromagnetic and electrostatic transduction mechanisms [1].

Vibration from human motion is three-dimensional and can be characterized with its random nature, relatively high acceleration, and very low frequency range [2]. These factors make it hard to develop a vibration energy harvester for human-body-induced motion using conventional spring-mass-damper-based resonant systems. To overcome these issues, energy harvesters with springless proof mass have been researched as alternatives to the proliferating spring-mass-damper-based harvesting devices. Various approaches including an impact based piezoelectric energy harvester, an electromagnetic harvester using random motion of a spherical magnet in the cavity wrapped with coil, and electrostatic harvester utilizing rolling magnet on variable capacitor array have been demonstrated [3-5].

In this research, we have proposed a non-resonant vibration energy harvesting device using springless spherical permanent magnet which generates a spontaneous wobbling motion to restore the upright position when an external vibration is applied. While utilizing the mass-controlled spherical magnet as a source for time-varying magnetic field, series connected windings have been wrapped on top and bottom of the cavity for power generation. Fabricated device has been characterized at low frequency vibrations. Effect of the center-of-mass position on magnet behavior and effectiveness of ferrofluid as a lubricant have also been investigated.

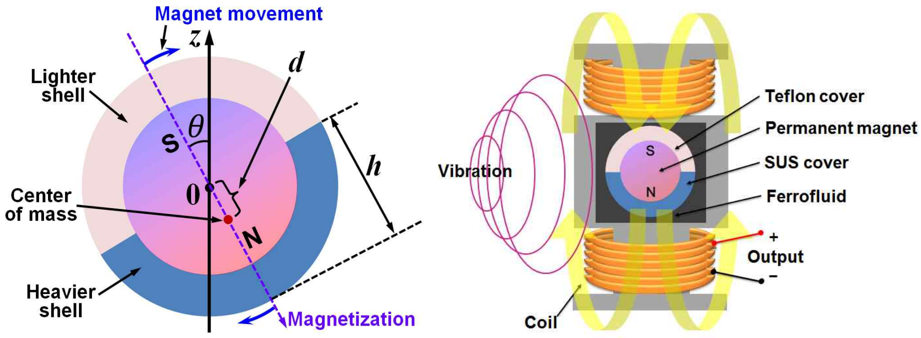
2. Device design

2.1. Magnet design

To analyze the effect of center-of-mass position, magnet assemblies with two different center-of-mass positions have been fabricated and tested. Magnet #1 consists of NdFeB ball magnet covered with two hemispherical shells made of Teflon and SUS as lighter and heavier shells, respectively (figure 1(a)). Magnet #2 has been designed to have its center-of-mass closer to the geometrical center by reducing the height of the SUS shell (h) by half that of magnet #1. Distance between the center-of-mass and geometrical center (d) for magnet #1 and #2 are 0.57mm and 0.39mm, respectively.

2.2. Harvester design

As shown in figure 1(b), designed harvester consists of copper windings on top and bottom of the magnet housing. The magnet assembly has been inserted in a cylindrical cavity formed inside the housing. Diameter of the magnet assembly is 7mm. Outer diameter and height of the housing measure 17mm and 23mm, respectively. Inner cavity measures 9mm in diameter with 8mm-height. Bobbins are formed on top and bottom parts of the housing for copper windings. Effect of ferrofluid as a lubricant for the magnet assembly has been analyzed by comparing the harvester output.

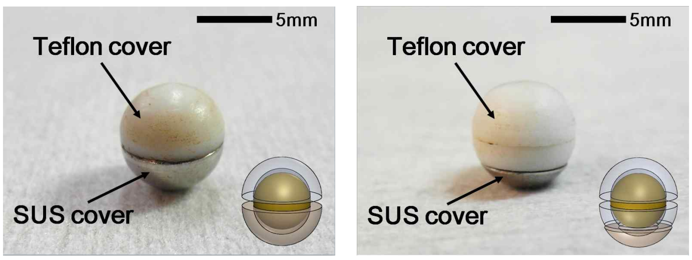


(a) (b)

Figure 1. Schematics of the designed device: (a) magnet assembly with non-uniform mass distribution (θ= tilt angle), (b) electromagnetic energy harvester

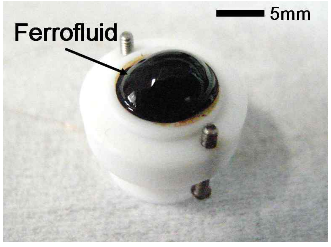
3. Fabrication

A proof-of-concept energy harvester has been fabricated by enclosing a roly-poly-like magnet assembly inside Teflon housing with cylindrical cavity. As shown in figure 2, roly-poly-like magnet has been prepared by attaching 1mm-thick shells made of Teflon and SUS on a 5mm-diameter NdFeB ball magnet with epoxy adhesive. Top and bottom parts of the Teflon housing have been joined using miniature screws and 0.1mm-diameter copper coil has been wound around the 5mm-diameter bobbin formed on top and bottom (figure 3). Number of winding turns measures 700 turns each on top and bottom. Minimum gap between the winding and cavity is 1mm.

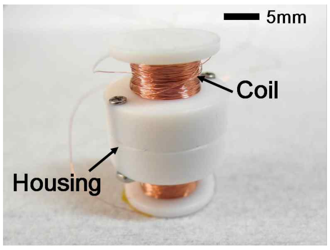


(a) (b)

Figure 2. Magnet assemblies: (a) magnet #1, (b) magnet #2



(a)



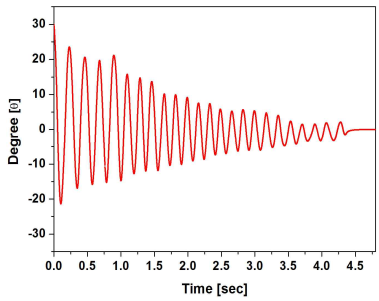
(b)

Figure 3. (a) magnet assembly in Teflon housing covered with ferrofluid, (b) assembled electromagnetic harvesting device

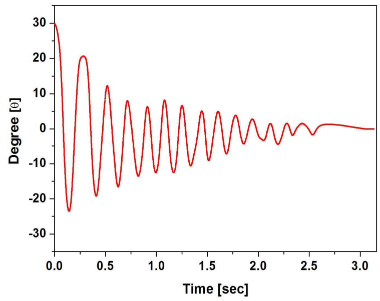
4. Results and discussion

4.1. Characterization of magnet assemblies

For a better understanding of the device architecture, resonant characteristics of two roly-poly-like magnets have been tested. Initial tilt angle was set to 30 degrees and time responses of the roly-poly-like magnets were recorded using 30fps video camera and analyzed. Although pure rotational vibration along specific rotational axis without wobbling motion could not be achieved, relatively clear time responses have been obtained (figure 4). Time constants for exponential decay were 2sec and 0.67sec for magnet #1 and #2, respectively. Estimated resonant frequencies of magnet #1 and #2 were 4.74Hz and 4.52Hz, respectively.



(a)



(b)

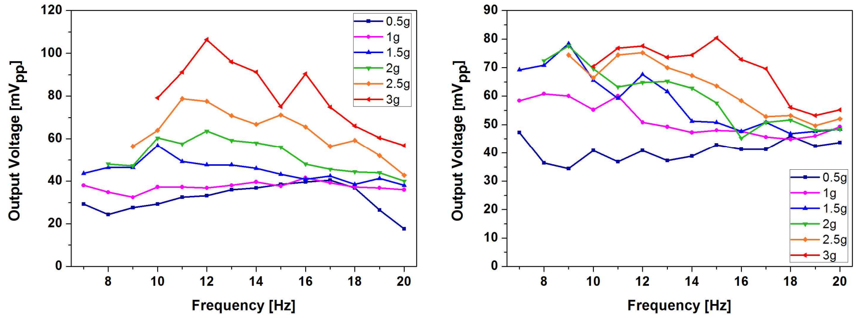
Figure 4. Time response of the roly-poly-like magnet: (a) magnet #1(b) magnet #2

4.2. Vibration exciter test results

Fabricated device has been mounted on a vibration exciter and sinusoidal horizontal vibration has been applied at frequencies ranging from 7 to 20Hz with 1Hz step while increasing the acceleration from 0.5 to 3g with 0.5g step at each frequency. Vibration at frequencies under 6Hz and acceleration over 3g could not be applied due to the limitation of the vibration exciter. Harvesting device #1 and #2 had magnet #1 and #2 integrated inside, respectively.

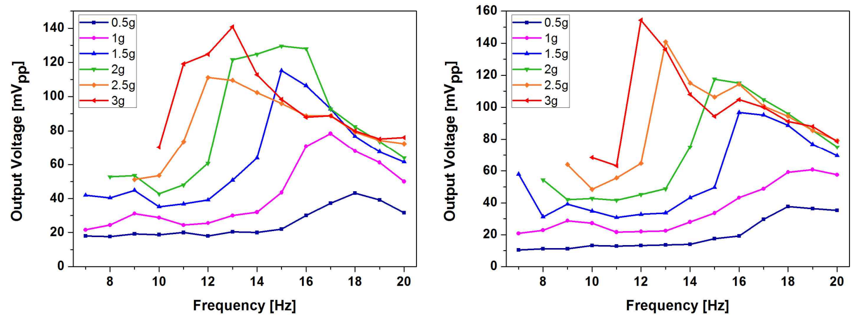
Firstly, open-circuit voltages of the harvesters with magnet assemblies having different center-of-mass have been measured and compared without ferrofluid. As shown in figure 5, both devices showed increasing trend in output voltage as the input acceleration was increased with relatively flat frequency response. Open-circuit voltage was higher for device #2 at accelerations lower than 2g, but the increase in output in response to increased acceleration started to saturate at a faster pace than device #1 at accelerations higher than 2g. Maximum open-circuit voltage of 106.4mV has been obtained with device #1 at 12Hz and 80.4mV has been obtained with device #2 at 15Hz, both at 3g vibrations.

Open-circuit voltages of the harvesters with ferrofluid have also been analyzed. In contrast to relatively flat frequency response shown in figure 5, a non-linear resonant behavior has been observed due to addition of ferrofluid with decreasing resonant frequency at higher accelerations. Open-circuit voltage increase was pronounced near the peak points but saturating trend has been observed afterwards. As shown in figure 6, maximum open-circuit voltage of 140.8mV has been obtained with device #1 at 13Hz and 154.4mV has been obtained with device #2 at 12Hz at 3g vibrations. Despite the initial differences in open-circuit voltage trend at various frequencies and accelerations, both devices showed relatively similar tendency after ferrofluid had been added.



(a) (b)

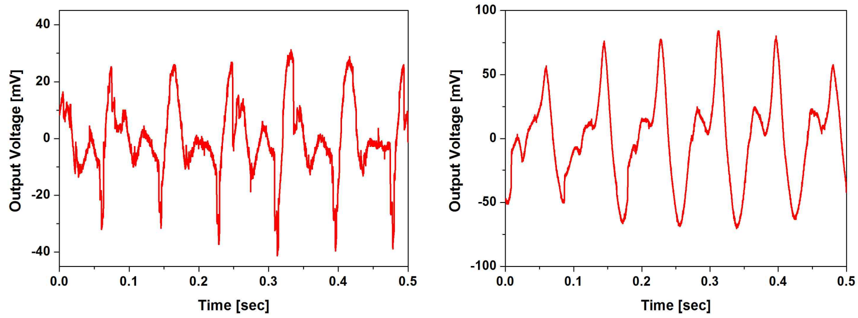
Figure 5. Open circuit voltage at various input frequencies and accelerations without ferrofluid: (a) device #1 (b) device #2



(a) (b)

Figure 6. Open circuit voltage at various input frequencies and accelerations with ferrofluid: (a) device #1 (b) device #2

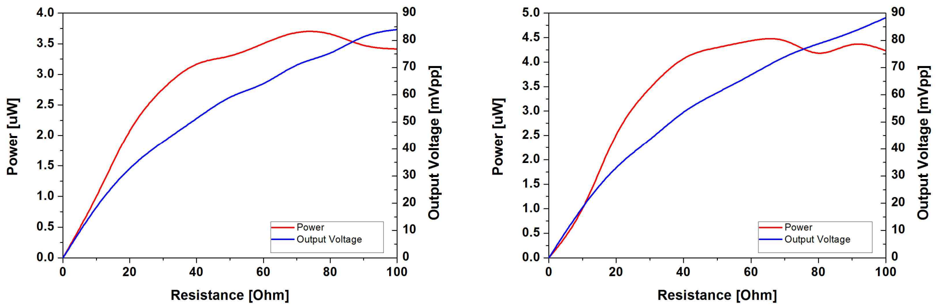
Figure 7 shows the open circuit voltage waveforms of device #2 at 3g vibration at 12Hz, with and without the ferrofluid. In additions to the increase in amplitude, much smoother waveform has been observed which can be ascribed to the lubrication of magnets by ferrofluid.



(a) (b)

Figure 7. Output voltage waveform at 3g acceleration at 12Hz (device #2): (a) without ferrofluid (b) with ferrofluid

Output voltage and power have been analyzed with varying load resistance at conditions where the fabricated harvesters with ferrofluid showed maximum open-circuit voltage. Output from device #1 and #2 has been measured at 13Hz and 12Hz, respectively, at 3g acceleration. Maximum output power reached 3.72μW and 4.53μW across load resistance of 70Ω for device #1 and #2, respectively.



(a) (b)

Figure 8. Output power and output voltage vs. load resistance: (a) 3g vibration at 13Hz (device #1) (b) 3g vibration at 12Hz (device #2)

Without the ferrofluid, device with magnet assembly having smaller time constant (magnet #2) generated relatively higher open-circuit voltage at smaller input accelerations but the trend for accelerations higher than 2g was the opposite. Use of ferrofluid as a lubricant increased the output voltage at the expense of flat frequency response. Although effects of center-of-mass position and ferrofluid as a lubricant require further investigation, the concept of utilizing roly-poly-like magnet in an electromagnetic vibration energy harvester has been tested successfully.

5. Conclusion

We have developed a non-resonant electromagnetic vibration energy harvester using roly-poly-like magnet. A proof-of-concept vibration energy harvester has been designed, fabricated, and tested. Maximum open-circuit voltage of 154.4mV has been obtained at 3g vibration at 12Hz and maximum output power of 4.53μW for a 70Ω load have been achieved at the same condition. Although fabricated device requires further characterization and optimization, we have successfully verified the feasibility of utilizing unique magnet design in electromagnetic harvesting device.

6. Acknowledgement

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