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Design Optimization of a Magnetically Levitated Electromagnetic Vibration Energy Harvester for Body Motion

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Abstract. This paper presents a magnetically levitated electromagnetic vibration energy harvester based on magnet arrays. It has a nonlinear response that extends the operating bandwidth and enhances the power output of the harvesting device. The harvester is designed to be embedded in a hip prosthesis and harvest energy from low frequency movements (< 5 Hz) associated with human motion. The design optimization is performed using Comsol simulation considering the constraints on size of the harvester and low operating frequency. The output voltage across the optimal load 3.5kΩ generated from hip movement is 0.137 Volts during walking and 0.38 Volts during running. The power output harvested from hip movement during walking and running is 5.35 µW and 41.36 µW respectively.

1. Introduction
In-vivo monitoring of joint replacement has been proposed to address the problem of joint replacement failure leading to difficult surgery and rising costs of healthcare [1,2]. To power instrumented hip implants, batteries are not an option because of limited lifetime and replacement requires surgery. Therefore, an electromagnetic vibration energy harvester based on magnetic levitation is presented as an alternative power supply that is compatible with low frequency, high amplitude excitation such as that associated with human motion. The constraints on the size of the harvester due to the volume of the hip prosthesis makes designing an effective energy harvester operating at a frequency below 5 Hz a significant challenge.

The magnetically levitated configuration has been developed previously, with some variations in design and arrangement of the moving-mass components. One of the approaches used to improve the power generated is adding arrays of levitated magnets or coils [3–5]. However, this has to be optimized properly with consideration of the space available for the displacement of the moving magnet in particular applications such as the hip prosthesis. If the moving mass is too large its displacement and velocity will be limited resulting in lower output power [6,7].

In this paper, we present a magnetically levitated electromagnetic vibration energy harvester based on magnet arrays. It has a nonlinear response that extends the operating bandwidth and enhances the power output of the harvesting device. The design investigation using Comsol simulation is described along with experimental results that demonstrate an improvement in performance of the harvester based on the magnet arrays.

2. Structure of the energy harvester

Two harvester configurations were investigated as shown in Figure 1. They both consist of a fixed magnet at the bottom of the glass tube and a moving mass inside the tube, with some variations in the design and arrangement of the moving-mass components as shown.

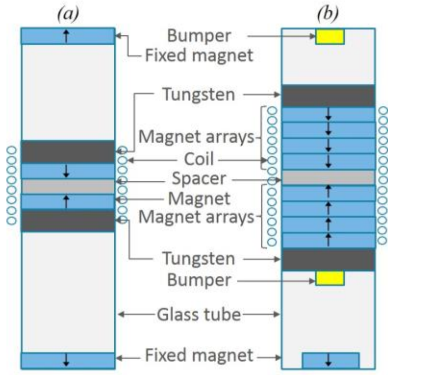

Figure 1. Schematic of electromagnetic vibration energy harvesters: (a) two-magnet and (b) magnet array

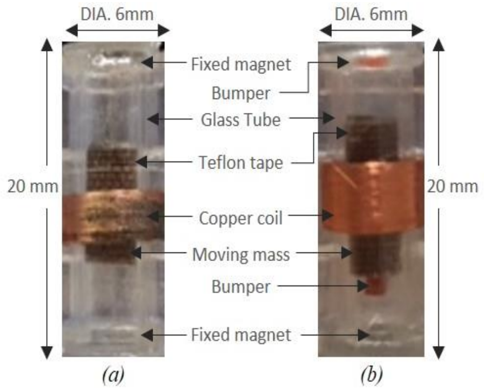

Figure 2. Fabricated harvester (a) two-magnet and (b) magnet array

Both harvester designs were assembled and are shown in Figure 2. The glass tube is 20 mm in length with inner and outer diameters of 5 mm and 6 mm respectively. The 4 mm-diameter NdFeB cylindrical magnets, two cylindrical Tungsten pieces and a ferrite spacer (1.4 mm thickness) have been glued together to form the moving masses. The thickness of each NdFeB magnet and Tungsten piece is 1 mm. The mass of each inertial mass configuration is 1.1 grams and 1.49 grams for the two-magnet harvester and the magnet array harvester respectively. To levitate the moving masses inside the glass tubes, the fixed bottom magnets were attached at bottom of each tube. The coil is wrapped around the outside of the tube and is wound from 30µm-diameter enamelled Copper wire. The inner and outer diameters of the coil are 6 mm and 7 mm respectively with fill factor of 0.54. The coil length was optimized by Comsol (see section 3) for each design and is 3.4 mm for the magnet pair and 5 mm for the array. Teflon tape of 0.1 mm thickness was wrapped around the moving masses to reduce the friction between moving mass and inner surface of the tube. Other variations in the designs include the addition of bumpers made from crepe rubber for the magnet array harvester and the use of a fixed top magnet at top of the tube for the two-magnet harvester.

3. Design investigation

The component dimensions, the number of magnet pairs within the array of levitated magnets and the length of the coil have been investigated given the size constraint of the harvester. This was done using Comsol finite element simulation, which was used to predict the induced voltage given variations in the number of magnet arrays and the coil length.

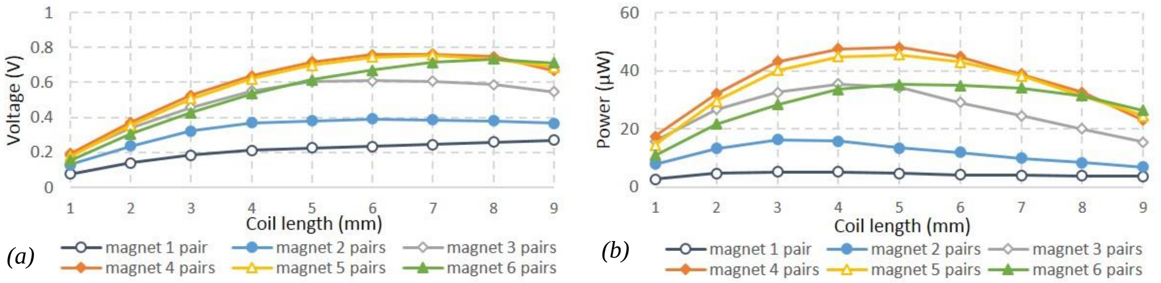

Figure 3. The simulation results of (a) voltage induced and (b) power output with variations in the number of magnets arrays and coil length

The voltage was induced by the varying flux gradients intersecting the coil when the levitated magnet moves from the top to bottom of the tube. The variation in the number of magnets arrays and length of a stationary copper coil lead to the change in the voltage induced as shown in Figure 3. The power output as shown in Figure 3(b) was calculated from the simulation results using a load resistance equal to the coil resistance. It shows that the highest power output can be generated from a 5 mm long coil and a magnet array consisting of 4 pairs of magnets to form the moving mass.

4. Experimental procedures

The experiments have been separated into two sections. In first section, the electromagnetic energy harvesters shown in Figure 2 were tested on an electrodynamic shaker (ET-126B) under sinusoidal acceleration with different levels (0.3g, 0.5g, and 0.8g). The induced voltage was recorded across the frequency range to determine the resonant frequency of the harvester. In the second section, the harvesters were mounted at the hip to record the output voltage during walking and slow running on a treadmill. The walking and running velocities were 2.6 km/h and 7 km/h respectively.

5. Results and discussion

5.1. Experimental results on an electromagnetic shaker

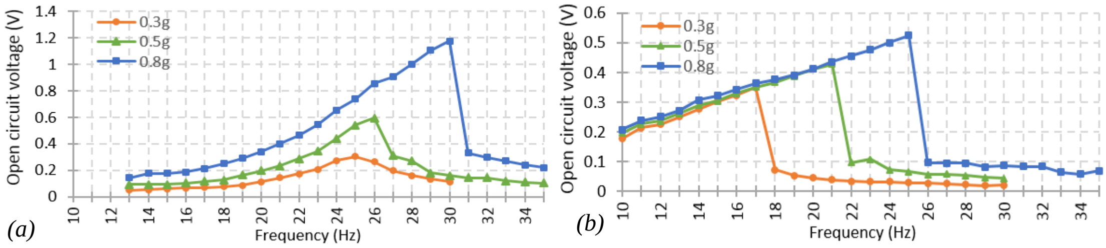

Figure 4. The open-circuit voltage versus exciting frequency at different levels of acceleration of the harvester for (a) two-magnet and (b) magnet arrays.

In Figure 4, the shape of the plot of open circuit voltage versus exciting frequency of the two harvesters at different levels of acceleration tested on the shaker indicates a hard nonlinearity that will influence on the bandwidth and output power of such harvesters. Their resonant frequencies change with increasing acceleration amplitudes going from 25 Hz to 30 Hz and 17 Hz to 25 Hz for the two-magnet magnet array harvesters respectively. The operating frequency of the magnet array harvester is lower than that of the two-magnet harvester. This is due to the removal of the top fixed magnet, the size reduction of the bottom fixed magnet, and the increased mass of moving mass in the tube. The lower resonant frequency implies that the magnet array harvester is more suitable for harvesting energy from human movement, which is characterized by low frequency high amplitude displacements.

5.2. Experimental results on treadmill

The output voltage and the power output of the two-magnet harvester and the magnet array harvester were recorded during walking and running on treadmill. In contrast to the sinusoidal excitation, in this case the output voltage of the two-magnet arrangement is less than that of the magnet array. Results for voltage and power output are given in Table 1 with optimal load resistance of 3.5 kΩ for the magnet array and 3 kΩ for two-magnet harvesters. The experimental results demonstrate that the voltage and power generated by the magnet array harvester is higher than those generated by the two-magnet harvester.

Table 1. Closed circuit voltage and output power harvested during walking and running.

	Closed circuit voltage (V)		Output power (µW)	
	Walking	Running	Walking	Running
Two-magnet harvester	0.012	0.146	0.05	7.08
Magnet array harvester	0.137	0.380	5.35	41.36

The influence of the bumpers on the performance of the magnet array harvester was also investigated and the closed circuit voltage recorded during running on the treadmill with and without bumpers is presented in Figure 5. The voltage signal of the magnet array harvester without bumpers displays higher decay rate compared with that of the magnet array harvester with bumpers. The damping ratio, determined from the decay in the voltage output after stopping the driving vibrations on the shaker is 0.026 and 0.019 with and without bumpers respectively. This implies lower energy loss during the collision between moving mass and top/bottom of the tube when bumpers are present.

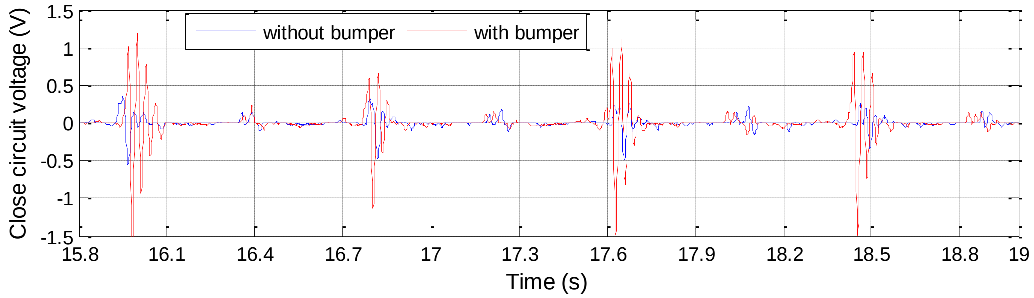

Figure 5. Closed circuit voltage output of the magnet array harvesters with/without bumpers when mounted at the hip and with the user running at 7 km/h.

6. Conclusion

These experimental results have demonstrated a significant improvement in performance of the harvester based on magnet arrays. The operating frequency of the magnet array harvester shifts towards the frequency range of human movements due to increasing mass and weak magnet forces. The integrated bumpers conserve the kinetic energy, covering unavoidable collisions due to the form factor constraints. This optimum design promises sufficient voltage and power output for powering an instrumented hip implant according to experimental results.

Acknowledgement

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