An electromagnetic energy harvester capable of frequency up-conversion and amplitude amplification under pulse excitation

D Zhu and L Evans
College of Mathematics, Engineering and Physical Sciences, University of Exeter, Exeter UK, EX4 4QF
E-mail: d.zhu@exeter.ac.uk

Abstract. This paper reports an electromagnetic energy harvester that is capable of frequency up-conversion and oscillation amplitude amplification to maximize its output power under pulse excitation. The harvester consists of a tube with a shuttle magnet travelling inside. The external force moves a complementary magnet set that reverses the direction of the magnetic force applied to the shuttle magnet. Such alternating magnetic force enables the shuttle magnet to move back and forth inside the tube and electric current can be induced in the coil wound around the tube. A prototype was fabricated and tested. Experimental results showed that when a 1 Hz footstep was applied to the complementary magnet set, the shuttle magnet oscillated at a frequency of 10 Hz and oscillation amplitude was amplified by 6 times. Peak power of over 70 mW was recorded and an average energy of 2.8 mJ can be generated from every footstep.

1. Introduction
Energy harvesting from footsteps has drawn a lot of attention in recent years. It enables electrical energy to be generated while a human is walking or running. Applications of such technology ranges widely from powering wearable electronic devices [1] to powering street lights [2]. One of the major challenges of harvesting energy from footsteps is that input force in this application normally has low frequency, e.g. ~1 Hz for walking and < 5 Hz for running. Fundamental analysis of kinetic energy harvesting suggests that more mechanical power is available to be harvested if the operating frequency is higher and the resonant frequency of the kinetic energy harvester matches it [3]. This makes it difficult to harvest energy harvest from such low frequency movement. However, energy harvesting from footsteps does benefit from large input forces, which makes it still attractive as an alternative power source for various applications.

Two transducers are normally used to harvest energy from footsteps, i.e. piezoelectric and electromagnetic. In the piezoelectric method, piezoelectric materials can be applied where stress and strain are produced by the footsteps, such as shoe insole. The change of strain on the piezoelectric materials result in electric charges being generated. By collecting generated charges using electrodes, electric current can be generated. Traditional piezoelectric materials, e.g. PZT, are rigid and brittle, which makes it not ideal for such applications. Therefore, flexible materials that have piezoelectric properties have been investigated to tackle this problem. Luo et al [1] reported energy harvesting from footsteps by mounting porous polypropylene, a lightweight ferrelectret material on shoe insole. An average energy of over 100 µJ was generated by each footstep and this is sufficient to power a commercial ZigBee transmitter. In the electromagnetic method, the footstep causes a magnet to move with respect to a coil where current is induced. Ylli et al [4] presented two electromagnetic energy...
harvesters for human foot movement. They targeted swing movement and impact during human walking and average power of 0.84 mW and 4.13 mW were achieved by these two harvesters respectively.

This paper investigates a mechanism that can up-convert the operating frequency of an electromagnetic energy harvester and increase the oscillation amplitude of its inertial mass to maximize output power under pulse excitation.

2. Principle

The structure of the proposed energy harvester is illustrated in Figure 1(a). It consists of a cylinder tube with a coil wound around it. A shuttle magnet can travel back and forth inside the tube so that electric current is induced in the coil. One magnet is fixed to one end of the tube to provide repulsive force when the shuttle magnet approaches (the magnet on the left of the tube as in Figure 1(a)). A complementary magnet set (CMS) is suspended by a mechanical spring on the other side of the tube. The CMS consists of two bar magnets with opposite poles facing the end of the tube.

Figure 1(a) shows the original position of the CMS without external force. In this case, the magnet in the CMS that is aligned with the tube has opposite magnetic pole facing the shuttle magnet. Thus, the shuttle magnet moves towards the CMS due to the attractive force between them. When an external force is applied to the CMS as shown in Figure 1(b), the CMS moves downwards and the other magnet in the CMS is aligned with the tube. In this case, there is a repulsive force between the shuttle magnet and the CMS. This causes the shuttle magnet to move away from the CMS. When the shuttle magnet approaches the fixed magnet on the left, the repulsive force pushes it back towards the CMS where it once again encounters the repulsive force from the CMS and thus a higher frequency oscillation is produced. When the external force is released, the CMS returned to its original position thanks to the spring and the shuttle magnet moves back to its original position.

![Figure 1](image_url)

**Figure 1.** Schematic of the electromagnetic frequency up-converting energy harvester. (a) no external force (b) external force is applied.

3. Experimental

A prototype was manufactured for testing as shown in Figure 2. The plastic tube is 80 mm long. All magnets used here are made of NdFeB-38. The shuttle magnet is a 20 mm long cylinder magnet with a diameter of 15 mm. The fixed magnet on the left of the tube is a 15 mm × 15 mm × 5 mm (m) rectangular. The two bar magnets in the CMS have dimensions of 20 mm × 10 mm × 8 mm (m). (m) notates the magnetization of the magnets. The coil is wound using 75 µm thick copper enamel wire. It has around 500 turns and a resistance of 180Ω. All the supporting structures are made of 3D printed PLA.

In all experiment, the prototype was tested under human footsteps at around 1 Hz. The harvester was first connected to resistive loads and output voltage across various resistive loads was measured to find out the maximum output power. It was then connected to a bridge rectifier to charge a 2.2 mF capacitor and the charging rate was recorded.
4. Results and discussion

When the footstep is applied to the CMS, the force moved the CMS downwards by 10mm. As explained in Section 2, the shuttle magnet is pushed to the left of the tube due to the repelling magnetic force by a maximum of 60 mm. This means the oscillation amplitude of the shuttle magnet is amplified by 6 times from the input displacement.

Figure 3 shows a typical waveform of the open circuit voltage of the energy harvester when an external pulse force is applied and released. When the external force was applied, the output voltage demonstrated a 10Hz oscillating waveform. This indicates that the shuttle magnet was oscillating at 10Hz inside the tube although this oscillation attenuated quickly due to friction between the shuttle magnet and the tube. When the force was released, the shuttle magnet was attracted towards the CMS and little oscillation occurred. Thus, only one peak was observed.

Then, peak output voltage of the energy harvester when connected to various resistive loads was recorded and peak output power was calculated using $P = \frac{V^2}{R}$, where $V$ is the output voltage of the harvester when connected to a resistor, $R$. Ten peak voltage readings were taken for each resistive load and the average peak power was calculated. Figure 4 shows average peak output power when the harvester is connected to various load resistances. It is found that the maximum peak power was generated when connected to the optimum load resistance of 180 $\Omega$.

Figure 5 shows instantaneous output power of the energy harvester when it’s connected to the optimum resistive load of 180$\Omega$. Peak power of over 50mW and 20mW can be generated when the force is applied and released, respectively. Figure 6 shows accumulated energy produced by the harvester when connected to the optimum resistive load. An average energy of 2.8mJ can be generated from every step.
The energy harvester was also connected to a bridge rectifier to charge a 2.2 mF capacitor. Figure 7 shows the charging curve when the energy harvester was operated under a series of footsteps. It is found that the 2.2 mF capacitor was charged from 0 to 3.67 V within 20 seconds (19 steps). A total energy of 14.82 mJ was stored in the capacitor. In other words, an average power of 741 µW was delivered to the capacitor during this period.

Figure 5. Instantaneous output power under a series of footsteps.

Figure 6. Accumulated output energy under a series of footsteps.

Figure 7. Voltage of the capacitor that was charged by the energy harvester.

5. Conclusion and future work
It has been demonstrated that the proposed mechanism is capable of up-converting the operation frequency by 10 times and amplifying input amplitude by 6 times when excited under pulse input. Such mechanism is suitable for energy harvesting from footsteps. It can be adapted for either integration with shoes or being embedded into floor. Future work will focus on further increasing the operation frequency by reducing the length of the tube and minimizing friction between the shuttle magnet and the tube.

6. Reference
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