Fabrication and characterization of a low frequency electromagnetic energy harvester

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Abstract: This paper presents the fabrication and characterization of an AA size electromagnetic energy transducer based on vibration. A magnetic spring technique is used to scavenge energy from low frequency external vibration. The output of the harvester is maximized by optimizing the mass of moving and fixed magnets, coil width, coil position and load resistance through a comprehensive experimental analysis. The prototype can generate an open circuit voltage of 3.961 V and 1.18 mW average power at a load resistance of 97 Ω with 9 Hz resonance frequency and 0.5 mm displacement.

Key words: electromagnetic harvester; energy scavenging; vibration; AA size; magnetic spring

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1. Introduction

The prospects of wearable and ubiquitous sensor systems will be enhanced significantly if the energy sources of these systems are maintenance free. A compact, low cost, long operating life and light weight power supply is required in all these applications, which enables the desired portability and energy autonomy. Normally, fixed energy alternatives such as batteries and fuel cells are used as the power source for these applications. However, batteries have the limitations of short life time, chemical hazards, sometimes larger size than MEMS devices and introducing the unwanted burden of replacement or recharging. Energy harvesting techniques that convert light, heat and kinetic energy (e.g., motion, vibration) available in the environment into electrical power offer potential energy sources that can be used as a battery replacement to develop a full sustaining system[1]. Vibration is one of the most ubiquitous sources[2]. A vibration-based harvester captures kinetic energy from the environment and converts it into electrical energy using a piezoelectric[1, 3], electrostatic[4, 5] or electromagnetic[6, 7] transduction mechanism. Electromagnetic energy harvesting is a very popular method for powering wireless sensor and systems because of its ease of fabrication and simple implementation. It can also generate a sufficient amount of power from a lower environmental frequency[8].

An AA size electromagnetic energy harvester is demonstrated in this paper. Some pioneering work related to the AA size harvester has been conducted by several research groups. For example, a group from the Chinese University of Hong Kong, firstly developed an AA size harvester using a mass spring system, which can produce a maximum of 120 μW and 830 μW at 70.5 Hz and 100 Hz resonance frequency, respectively[9, 6]. In Ref. [10], authors inserted piezoelectric elements into two opened slots on the shell of the AA size harvester. They showed that their device could harvest a maximum power of 625 μW at 50 Hz resonance frequency. However, the resonance frequency of the mentioned transducers is too high, but the natural frequency of ambient vibration is very low around 1–10 Hz[11]. Many researchers also proposed various techniques to reduce the operating frequency of the harvester. For example, using a bi-stable mechanical structure, it is possible to generate 288 μW power at 50 Hz resonance frequency, but the system input acceleration is very high (9.8 m/s^2)[8]. Kulah *et al.*[12] presented a mechanical frequency up-converter to scavenge energy from low frequency environmental vibration. The device can produce 3.79 μW output power at a resonance frequency of 25 Hz.

This paper reports the fabrication and characterization of an AA size electromagnetic energy harvester using a magnetic spring. The proposed generator has the advantages of simple construction, easy vibration under off-resonance conditions, lower cost and long operational cost.

2. Model description

The schematic diagram of the proposed magnetic spring generator is shown in Fig. 1. The structure consists of two fixed magnets which are attached at the top and bottom of an inner cylinder. We used a plastic straw for the inner cylinder of the prototype, because of its smooth inner surface. A center magnet is inserted between two fixed magnets. The magnets are placed vertically in such a way that all the magnets facing the surface have the same pole. A wire-wound copper coil is wrapped horizontally around the outside of the inner cylinder. When an external mechanical vibration is applied to the structure, the middle magnet will start to oscillate due to magnetic repulsion of the two fixed magnets and hence an AC voltage will be induced in the coil.

3. Mathematical modeling

The proposed energy harvester can be described as a spring mass system. Assume that a sinusoidal force F is applied to the system. By applying Newton's second law to the moving magnet, we can write:

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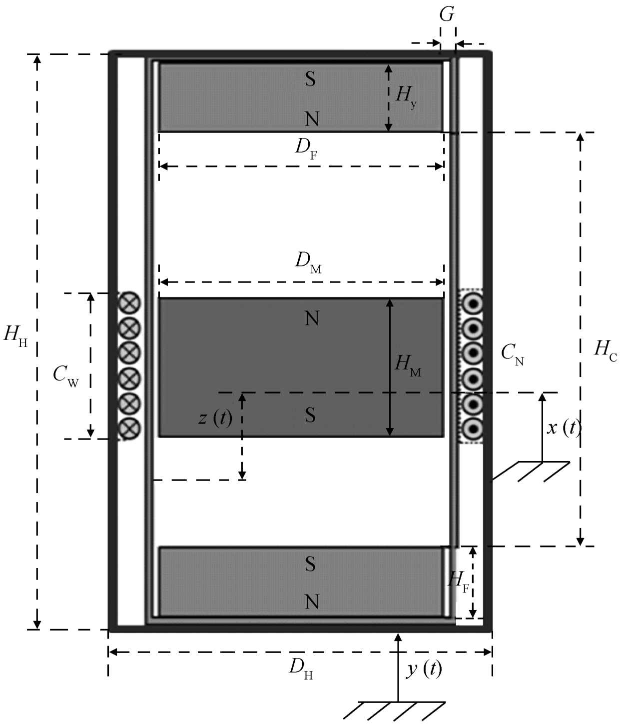

Fig. 1. Schematic of the magnetic spring transducer.

$$m\frac{d^2x}{d^2t} = P + F_{\text{damping}} + F_{\text{spring}} + F, \tag{1}$$

where m is the moving magnet mass, x is the relative displacement between the moving magnet and the generator housing, and P is the gravitational force.

Equation (1) can be written as:

$$m\frac{d^2x}{d^2t} = -mg - (D_p + D_e)\frac{dx}{dt} - kx + F, \tag{2}$$

$$m\frac{d^2x}{d^2t} + (D_p + D_e)\frac{dx}{dt} + kx = F - mg, \tag{3}$$

where D_p and D_e are the parasitic damping coefficient and electromagnetic damping coefficient, respectively. k is the spring constant with the following form:

$$k = \frac{F}{x} = \frac{F_T - F_B}{x}, \tag{4}$$

where F_T is the force between the top and the moving magnet, and F_B is the force between the bottom and moving magnet.

Therefore, the displacement solution of Eq. (3) is written as

$$x(t) = \frac{F_0 - mg}{\sqrt{(k - mw^2) + (D_p + D_e)^2 w^2}}. \tag{5}$$

The average generated power at resonance (i.e., $w = w_n = \sqrt{(k/m)}$) can be written as

$$P_{\text{res}} = \frac{D_e(F - mg)^2}{2(D_p + D_e)}. \tag{6}$$

The maximum power will be transferred to the load if $D_p = D_e$. In the case of $D_p \gg D_e$, the power to the load will be the maximum when the coil and load resistances are equal.

Table 1. Material and dimension of generator parameters.

Parameter	Value/material
Housing material	Titanium
Dimension of housing ($D_H H_H$)	14×48 mm^2
Inner cylinder's material	Plastic straw
Inner cylinder's dimension	7×46 mm^2
Magnet's material	NdFeB (N35)
Coil's material	Copper
Coil thickness	0.1 mm
Number of turns	1500
Coil resistance	96.502 Ω
Coil-magnet gap (G)	1 mm
Distance between fixed magnet (H_c)	42 mm
Displacement	0.5 mm

4. Experimental setup

The materials and dimensions of different parameters of the fabricated harvester are given in Table 1. The experimental setup consists of an electromagnetic shaker (IMV PET-01), a controller module (IMV- PET-0A), and a computer for data acquisition, as shown in Fig. 2. The controller module was used to control the frequency and displacement of excitation supplied to the shaker. The energy harvester was mounted on the shaker using a base, which held the generator and also reduced the electromagnetic effect created by the inner magnets of the shaker. The performance of the energy harvester was measured by using a sine wave input signal and frequency swept process with a displacement of 0.5 mm.

5. Results and discussion

During the experiment, firstly, we measured the output voltage for different combinations of fixed magnets at the top and bottom by keeping all other parameters (e.g., moving magnet size, coil width and coil position) constant. If moving magnet size ($D_M H_M$) is constant the flux density across the coil and moving magnet displacement depends on the fixed magnet size ($D_F D_F$). When the fixed magnet size increases, the flux density also increases. However, the displacement of the middle magnet will decrease. Therefore, a tradeoff is required between the flux linkage and the displacement of the moving magnet to obtain the maximum open circuit voltage. As can be seen from Fig. 3, a maximum voltage of 2.98 V was obtained at 9.5 Hz resonance frequency by using 2×2 mm^2 fixed magnets at the top and bottom of the inner cylinder.

Figure 4 shows the open circuit voltage for different moving magnet sizes with respect to frequency. When the fixed magnets size and number of coil turns is constant, the induced voltage depends on the moving magnet size. If the moving magnet size increases, the flux density across the coil increases, but the mass displacement speed decreases. Thus, to optimize the output voltage, a tradeoff is needed between the flux density and the moving magnet displacement speed. As observed in Fig. 4, an optimum voltage of 3.198 V was obtained with 6×14 mm^2 moving magnet size.

Figure 5 presents the measured open circuit voltage for different coil widths. As seen in the figure, a small coil width (5 mm) provides more output voltage (3.746 V), since it has less possibility of enclosing (i.e., in and out) flux than a large

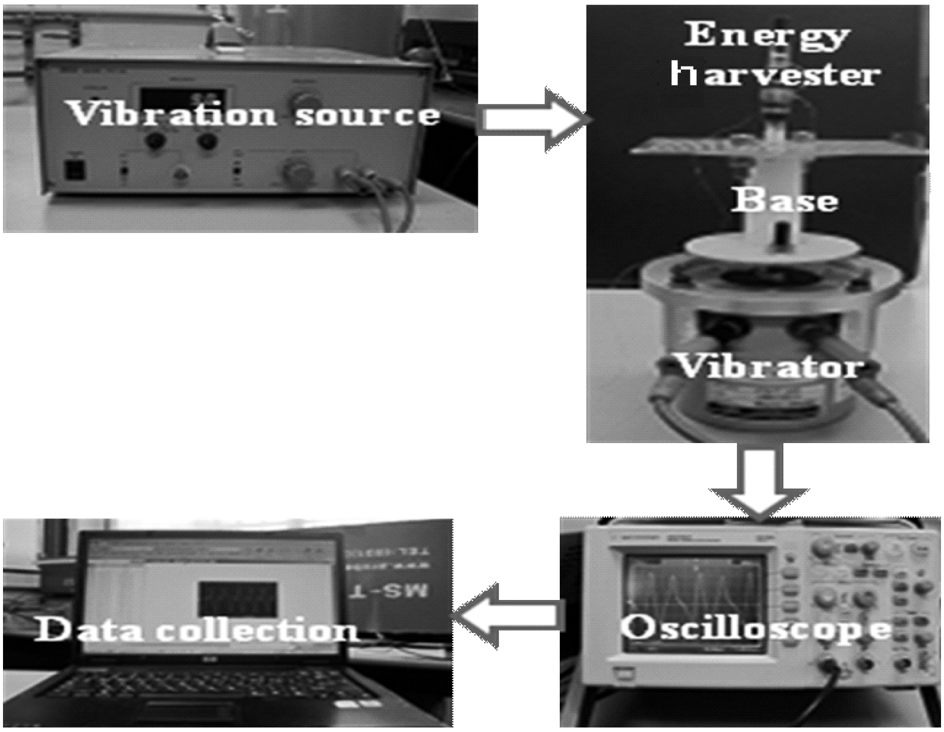

Fig. 2. Photograph of the experimental setup.

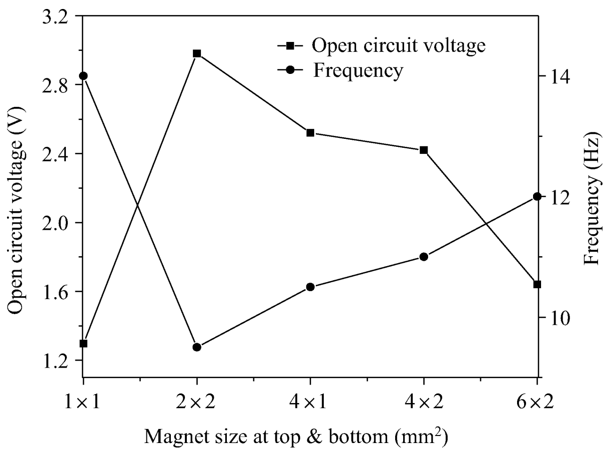

Fig. 3. Open circuit voltage and frequency versus fixed magnets size (same size fixed magnet at top and bottom).

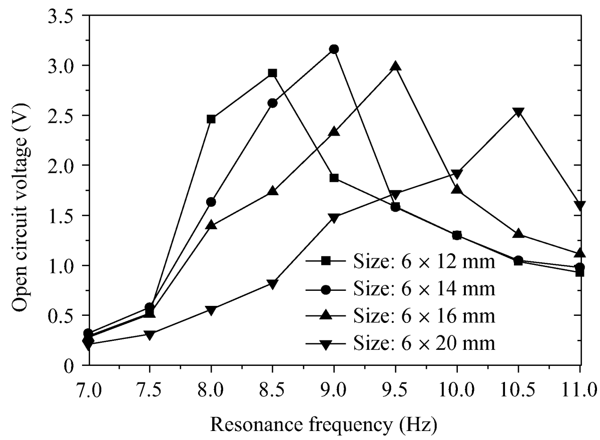

Fig. 4. Open circuit voltage versus frequency for different moving magnet sizes.

coil width. The flux lines totally enclosed by the coil width do not contribute to the resultant output voltage, since the total flux linkage for those flux lines in the coil is constant[13].

For the proposed model, due to gravitational force, the moving magnet resting point is slightly lower than the middle position. Under excitation, the speed of the moving magnet is high around the resting point and gradually decreases towards the end of the cylinder due to the repulsive force of the fixed magnets at the top and bottom. Figure 6 shows the variation of output voltage at different coil center positions from the middle point of the inner cylinder. As can be seen, the output reaches its maximum value of 3.961 V when the position of the coil center is 2 mm below the middle point, since near this position the speed of the moving magnet is at its maximum.

The measured powers for different load conditions are shown in Fig. 7. The optimum load condition was determined by adjusting a variable resistor (0–500 Ω). A maximum average power of 1.18 mW was obtained at 97 Ω, which is close to the coil resistance. This harvester provides the optimum power at the coil resistance because of the high parasitic damping of the device[14, 15]. Large parasitic damping occurs from the collision of the moving magnet with the inner surface of the cylinder. The optimized parameters of the generator are given in Table 2.

To date, several AA size energy harvesters have been investigated. A comparison of a reported AA size transducer with our fabricated generator at resonance frequency is given in Table 3. As can be seen from the comparison, the transducer presented in this study generates more power than previously re-

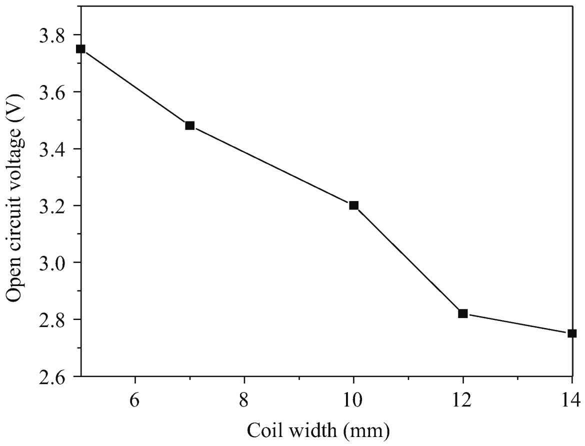

Fig. 5. Open circuit voltage versus coil width.

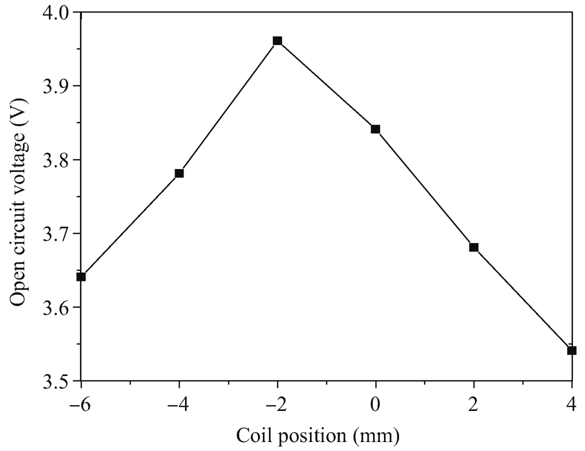

Fig. 6. Open circuit voltage versus centre of coil position from middle point of the cylinder.

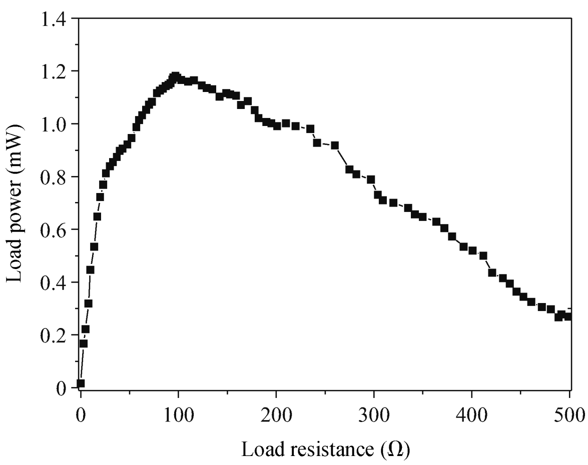

Fig. 7. Measured output power versus load resistance at resonance condition.

ported harvesters, because it is optimized in terms of the size of the moving and fixed magnets, coil width and coil position. The performance of the proposed transducer is affected by the damping loss occurs from the friction of moving magnet with the inner surface of the cylinder. Thus, the power of the harvester can be improved further if it is possible to use a cylinder with smoother inner surface. Moreover, the presented harvester can operate at a lower resonance frequency with respect to previously reported harvesters, because we used a magnetic spring as a cantilever.

Table 2. Optimized generator parameters.

Parameter	Dimension
Moving magnet size ($D_M H_M$)	6×14 mm^2
Fixed magnets size ($D_F H_F$)	2×2 mm^2
Coil width (C_W)	5 mm
Coil position from the middle	–2 mm
Output voltage	3.961 V
Load resistance	97 Ω
Displacement	0.5 mm

Table 3. Comparison of proposed harvester with previously reported AA size energy harvester.

Reference	Generator type	Volume (cm^3)	Resonance frequency (Hz)	Power density (μW/cm^3)
Ref. [12]	Spring mass	7.39	70.5	113.7
Ref. [13]	Spring mass	7.39	100.0	53.1
Ref. [7]	Piezoelectric	10.8	50.0	57.89
Proposed	Magnetic spring	7.39	9.0	159.67

6. Conclusion

An AA size vibration-based electromagnetic transducer which can generate a sufficient amount of power from low frequency environmental vibration is presented. The operating frequency of the harvester has been reduced significantly due to the use of a magnetic spring mechanism. The output of the transducer is optimized in terms of the moving and fixed magnets sizes, coil width, coil position and load resistance. The optimized harvester provides an average power of 1.18 mW at a load resistance of 97 Ω. Moreover, the proposed generator can operate at 9 Hz resonance frequency. Therefore, the presented transducer would be very useful for supplying energy for healthcare and environmental monitoring sensor system applications.

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