DESIGN, FABRICATION AND CHARACTERIZATION OF A VIBRATION DRIVEN MULTI-FREQUENCY ELECTROMAGNETIC ENERGY HARVESTER

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Abstract: This paper presents design, fabrication and characterization of an electromagnetic energy harvester, which can operate at different resonance frequencies. It utilizes magnetic spring technique to scavenge energy from low frequency vibrations. The optimization of generator is done in two stages. First, optimization of a single harvester is done in terms of number of turns, coil width, coil position and spacing between the fixed magnets. Second, a transducer composed of four generators is designed for different combination of moving and fixed magnets and hence, the device can operate at different natural frequencies. The device generates a power of 1.66-2.82 mW for an external vibration of 7-10 Hz frequency range with 0.5g acceleration.

Keywords: energy harvester, electromagnetic, magnetic spring, multi-frequency

INTRODUCTION

In recent years, the size and power consumption of wireless sensor nodes and embedded system is decreasing rapidly. For those systems supplying power through cables or using disposal sources such as batteries, fuel cells are often impractical. A full sustaining system can be implemented by using energy harvesting technique. Energy harvester converts the environmental energy into usable electrical energy. There is several energy scavenging sources, such as solar cell, thermal gradient, wind, vibration etc [1-3]. Among the ambient energy sources vibration is more attractive, because it is inherent in nature [4, 5].

The maximum power of vibration based electromagnetic energy harvester is strongly depends on the frequency of external vibration and drops significantly at low frequencies [6]. On the other hand, natural vibration frequencies are too low (1-10 Hz) and random [7]. When the energy harvester operates at off-resonance condition the output power reduces dramatically. Therefore, if environmental frequency deviates from the resonance frequency, the output of a single frequency harvester will be very low. This problem can be overcome by using frequency tuning or multi-frequency technique. In [8], authors analytically showed that, active frequency tuning technique consumed more power than it can generate. Passive tuning technique requires additional sensors and actuators, which increase the complexity. Another solution is widening the operational bandwidth of the harvester. Several attempts have already reported to operate the energy harvester at different resonance frequencies. For example, by using an array of 40 cantilevers, it is possible to generate a maximum 0.4 µW of power for the frequency range 4.2-5 kHz [9]. In [10], authors used three permanent magnets, at different locations of an Acrylic beam. The device can produce a maximum power of 3.2 µW at 369 Hz, 938 Hz and 1184 Hz resonance frequency. Soliman et al [11], used a mechanical stopper to transfer the harvester from a linear oscillator to a piecewise linear oscillator. They showed that, their device could harvest 13-15 mV for 94.1- 98.89 Hz frequency range.

In this paper, we proposed a multi-frequency energy harvester using magnetic spring. Magnetic spring type generator has the advantages of low frequency, simple construction and easy vibration under off-resonance conditions.

DESIGN

Generator Structure

Fig. 1 presents the schematic view of a magnetic spring generator. When an external force is applied to the generator, then the middle magnet start to oscillate due to magnetic repulsion of two fixed magnets. As a result, an AC voltage induced on the coil for the relative motion between moving mass and coil.

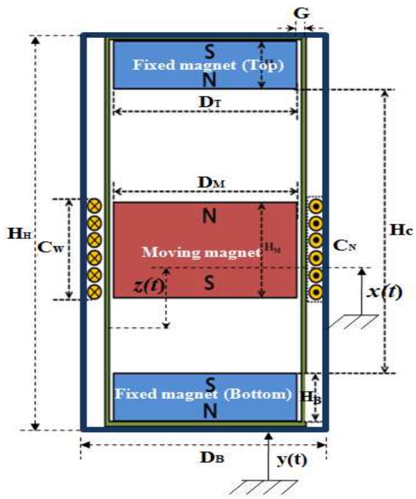

Fig. 1: Schematic diagram of the magnetic spring generator.

The proposed structure of the multi-frequency electromagnetic energy harvester is shown in Fig. 2. It consists of four generators placed on a plastic substrate. Each transducer has the same dimension (14 mm x 46 mm) and different moving and fixed magnets. As a result, each generator operates at different resonance frequency [12, 13].

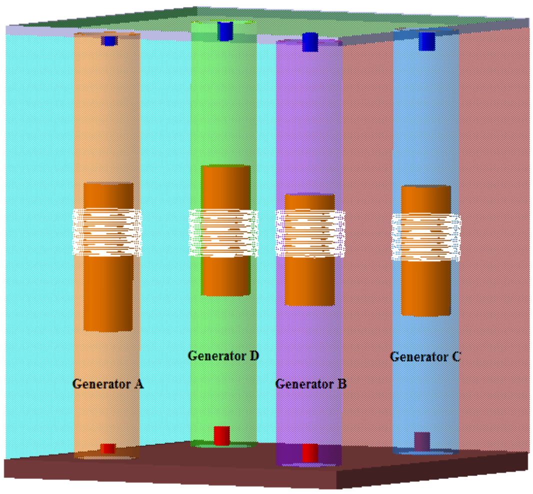

Fig. 2: Structure of the electromagnetic harvester array.

Modeling and Simulation

A vibration based electromagnetic transducer can be represented by a second order spring-mass-damper system. Assume that, the proposed system is based on a seismic mass, *m* and on a linear stiffness coefficient, *k*. By applying Newton's second law, the governing equation of motion of the system can be expressed as:

$$m\ddot{x}+c(\dot{x}-\dot{y})+k(x-y)=0 \quad (1)$$

where, *x(t)* is the displacement of the moving mass, *y(t)* is the input displacement of housing, given by, *y(t)=Ysin(ωt)*, where, *Y* and *ω* are the amplitude and angular frequency of the input vibration, respectively.
For the relative motion between the moving mass and the generator housing, Eq. (1) can be rewritten as:

$$m\ddot{z}+c\dot{z}+kz=-m\ddot{y} \quad (2)$$

where, *z(t)=x(t)-y(t)*.

Assume that, the solution of Eq. (2) is:

$$z(t)=Z_0\sin(\omega t-\phi) \quad (3)$$

Where, Z_0 and ϕ are the amplitude and phase of the system.
By putting the value of *z(t)* in Eq. (2), we can get:

$$Z_0=\frac{m\omega^2 Y}{\sqrt{(k-m\omega^2)^2+(c\omega)^2}} \quad (4)$$

And, $$\phi=\tan^{-1}\frac{c\omega}{k-m\omega^2} \quad (5)$$

So, the study state solution of mass displacement can represented as:

$$z(t)=\frac{m\omega^2 Y\sin(\omega t-\phi)}{\sqrt{(k-m\omega^2)^2+(c\omega)^2}} \quad (6)$$

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

$$P_{res}=\frac{mY^2\omega^3}{4\zeta} \quad (7)$$

Where, ζ is the total damping ratio given by, $\zeta=\frac{c}{2m\omega_n}$.

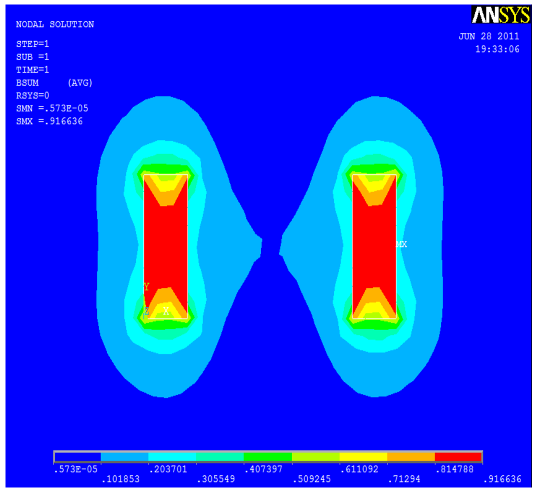

Fig. 3: Flux density distribution to find out the minimum spacing between individual generators.

Table 1: Simulation parameters.

Parameter	Dimension
Magnet material	NdFeB (N35)
Young's modulus	1.517e11 Pa
Magnet density	7.4e3 kgm^{-3}
Poisson's ratio	0.24
Moving magnet size	6x16 mm^2
Fixed magnet size	2x2 mm^2
Spacing between fixed magnets	42 mm
Coil's material	Copper
No. of turns	1500
Coil resistance	96.502 Ω
Spacing between coil & moving magnet	1 mm

ANSYS 2D finite element analysis is used to determine the space distribution between the individual generators as shown Fig. 3. It was found that, when the spacing between the generators is over 2.25 cm, there are few weak fluxes interact with each others. Therefore, we used 2.25 cm spacing between generators in our experiment. Otherwise, performance of each generator will be affected by the adjacent generators. The simulation parameters are given in Table 1.

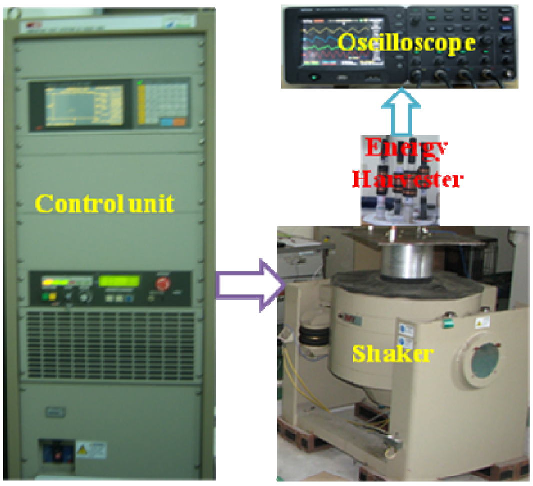

Fig. 4: Experimental setup.

EXPERIMENT RESULT AND DISCUSSION

The measurement setup used to examine the prototype is shown in Fig. 4. This setup is consists of a vibration controller (IMV RC-1120-11), a shaker (IMV CE-3105) and an oscilloscope (WaveAce 214). The vibration controller is used to control the amplitude and frequency of the shaker. The performance of the harvester is measured by using a sine signal and frequency swept process with an acceleration of 0.5g.

The experiment is carried out in two phases. In first phase, a single frequency harvester has been optimized in terms of no. of turns, coil width, coil position and spacing between the fixed magnets. The optimized parameters are given in Table 2.

Table 2: Optimized parameters of the converter.

Parameter	Dimension
Number of turns	1500
Coil width (mm)	5
Coil center position (mm)	-2
Distance between fixed magnets (mm)	42
Magnets size (Generator A) (mm^2)	Top:3x1; Bottom:1x1; Middle:6x16
Magnets size (Generator B) (mm^2)	Top:2x2; Bottom:2x2; Middle:6x12
Magnets size (Generator C) (mm^2)	Top:2x2; Bottom:2x2; Middle:6x14
Magnets size (Generator D) (mm^2)	Top:2x2; Bottom:3x2; Middle:6x16
Frequency range	7-10 Hz
Output power	1.95-3.49 mW
Maximum power density	32.9 μW/cm^3

In second phase, we designed four generators for different combination of moving and fixed magnets. As a consequence, the spring constant and moving mass of the generators are changed. Hence each generator operates at different fundamental resonance frequency. As it is observed from Table 2 and Fig. 5, Generator A, Generator B, Generator C and Generator D is giving maximum output at 7 Hz, 8 Hz, 9 Hz and 10 Hz frequency, respectively. When all coils are connected in series the fabricated transducer produced 5.57-9.45 V for 7-10 Hz frequency range as shown in Fig. 4.

Fig. 6 represents the calculated power for different input frequencies. In magnetic spring type generator, moving magnet directly touches with inner surface of the tube, which will increase the damping loss. So, the proposed harvester will produce maximum power, when the load resistance and the coil resistance are equal [14]. As it is observed from Fig. 6, a maximum power of 2.82 mW is obtained at 95 Ω load resistance, when all coils are in series connection.

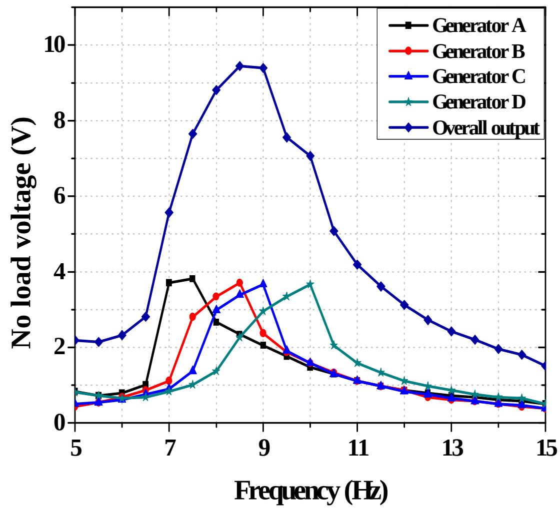

Fig. 5: Measured open circuit voltage for different input frequency.

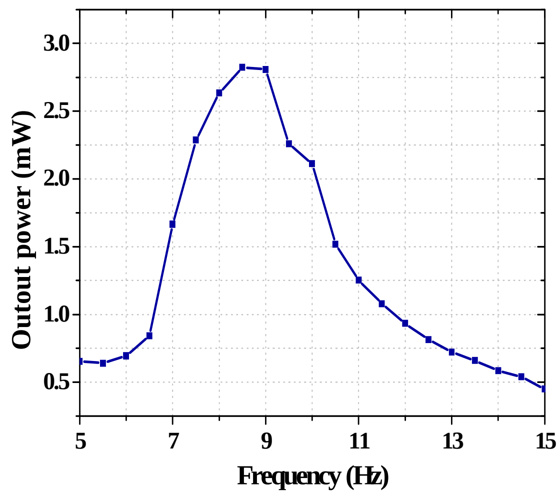

Fig. 6: Calculated output power of the fabricated harvester.

CONCLUSION

A vibration based electromagnetic transducer is presented which capable of producing sufficient amount of power from low environmental frequencies. The output voltage of the converter was optimized in terms of number of turns, coil width, coil position and spacing between fixed magnets. The experimental result shows that, the converter which composed of four generators can generate sufficient amount of power at different frequencies. The prototype can produce 1.66-2.82 mW of power for 7-10 Hz frequency range at an acceleration level of 0.5g. The main advantages of the proposed magnetic spring transducer are simple construction, lower cost, long operating life and capability of producing power from vibration of multi-frequency.

ACKNOWLEDGEMENTS

This work was supported by the Next Generation Military Battery Research Center Program of Defense Acquisition Program Administration and Agency for Defense Development and the Korea Research Foundation Grant through the Basic Research 2011 the Korean Government which was conducted by the Ministry of Education, Science and Technology (No. 2011-0013831).

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