DESIGN, FABRICATION AND CHARACTERIZATION OF A LOW FREQUENCY DRIVEN ELECTROMAGNETIC ENERGY HARVESTER

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Abstract: This paper develops a low frequency driven electromagnetic energy harvester which is composed of a thin flame resistant (FR-4) spring, aNdFeB magnet structure and a copper coil. The active spring mass systems have been simulated using ANSYS in order to determine the resonance frequencies and stress distribution. The FR-4 spring was fabricated by Desk Computer Numerical Control (CNC) 3D modeling machine. The device produces the maximum power of 490 μW at a frequency of 12 Hz across the load resistance of 1.8 kΩ while the acceleration is 0.2 g.

Keywords: Energy harvester, Electromagnetic, Vibration, FR-4 spring

INTRODUCTION

The energy harvesting from ambient vibration is a more attractive method for the replacement of battery compare with solar, wind and heat because of their unlimited operating time and location. Thus, various researchers have studied the energy harvesting from vibration in the past few decades [1]. The reported energy scavenging techniques using vibration source are piezoelectric [2], electrostatic [3], and electromagnetic transduction [4]. Especially, electromagnetic technique is very convenient to convert the energy at low frequency. For example, D.P. Arnold et al. [5] showed multi-pole magnetic generator that can generate output power of 550 μW for 0.8 g external acceleration at its resonance frequency of 9.2 Hz. C.R. Saha et al. [6] showed magnetic spring generator for human motion that could generate 300 μW to 2.5 mW for 0.38 g external acceleration at its resonance frequency of 8 Hz. G. Hatipoglu and H. Ürey [7, 8] proposed the FR-4 spring based energy harvester for wireless sensor nodes. The harvester could generate 144 μW with 0.2 g sinusoidal peak-to-peak acceleration at the 24.4 Hz.

In the electromagnetic transducer, the resonance frequency of spring mass system depends on the spring material, shape and magnet grade, mass, and hence, the choice of spring material will affect the performance of power generator [9]. FR-4 was chosen to be the spring material for the low frequency driven structure because of its specific mechanical properties (Young's modulus, Poisson's ratio and Density) as shown in Table 1. FR-4 is also low cost, highly integrable with electronics, and lends itself naturally to electromagnetic sensing as coils can be routed easily on the copper laminates [7].

The commonly used single-pole magnet structure has a general pole magnetization which shows high flux density at the each end of N and S pole, but very weak flux density in the middle. However, multi-pole magnet structure concentrates the flux lines because of different directions of the magnetic pole, and exhibits a great flux density in the middle.

In this paper, we proposed FR-4 spring based energy harvester using multi-pole magnet structure in order to reduce the resonance frequency and improve the magnetic flux density. Mechanical and magnetic characteristics of FR-4 spring and multi-pole magnet structure were simulated using ANSYS. The proposed energy harvester using multi-pole magnet structure showed a higher flux density than that of the single-pole magnet structure according to the simulation results. The experimental results were in good agreement with the simulation result showing about 50 % higher output power than single-pole magnet structure.

DESIGN

The schematic diagram of energy harvester is shown in Fig. 1. The generator is composed of an active spring mass system, cylindrical titanium housing, acrylic holder and copper coil. The active spring mass system was made in FR-4 planar spring and vertically polarized NdFeB multi-pole magnet. The aluminum bolt and nuts are used to fix the multi-pole magnet which has a repulsive force each other. The FR-4 spring was designed in the light of low system frequency, small spring constant and big amplitude of spring mass.

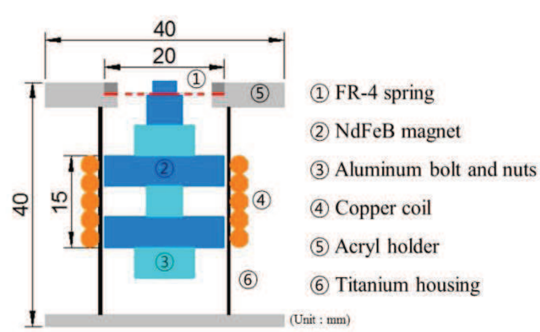


Fig. 1: Schematic diagrams of vibration-driven electromagnetic energy harvester.

The proposed spring has two branches which make lower resonance frequency comparisons with three or four branches and higher stability of movement compare with one branch (cantilever). The spring was 1 mm in width, 250 µm in thickness, 1 mm in the gap between the beam, 17 mm and 20 mm inner and outer diameter, respectively.

The appropriate design of the harvester was achieved through ANSYS simulation. Modal, static, and magnetic flux analysis were observed. The modal analysis was performed to determine the resonance frequencies of spring mass. The static analysis was also performed to evaluate the stress in the spring and finally the magnetic flux analysis was conducted to identify the flux distribution.

Fig. 2 shows the variation of the three lowest resonance modes of the spring mass system with materials; Silicon (yellow), Aluminum (blue), Copper (pink) and FR-4 (green). In the decision of spring material, we should think about the resonance frequency range of the device. The energy harvester with FR-4 spring has the lowest resonant frequencies at each resonance mode due to the its specific mechanical properties. In addition, when we use the longer and thinner beam of spring or heavier mass of magnet, we will be able to drop the resonance frequency consistently.

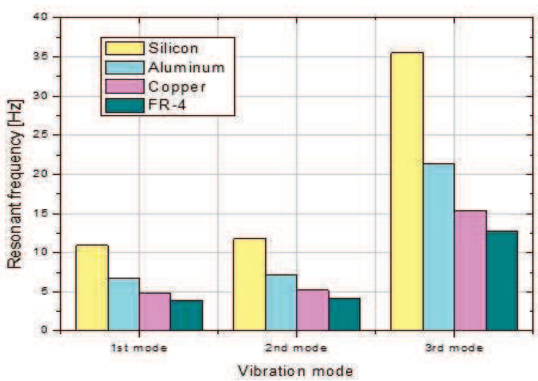
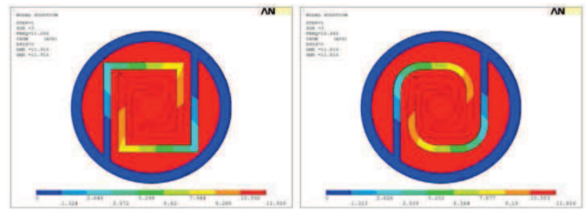


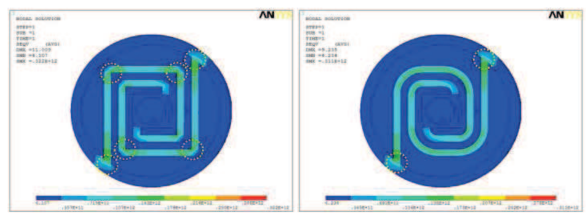
Fig. 2: Variation of the three lowest resonance frequencies of the energy harvester with the materials.

Fig. 3 and 4 show the effect of the spring shape on the dynamic behavior and stress distribution respectively. In designing the mechanical resonating spring, few factors should be considered: the structure should resonate with large amplitude with small input vibration. So the spring geometry should have a long distance as a 'spiral' structure and longer fatigue life [16]. Fig. 3 (a) and (b) depict the resonance frequencies of two types of spiral structures which are right angle and curve type. The right angle type has a lower resonance frequency (11.28 Hz) than that of curve type (12.26 Hz). The resonance frequency is calculated with a spring constant and mass. Although the right angle type confronted the huge problem of the stress distribution, it has a lower spring constant than curve type. Fig. 4 (a) and (b) illustrates the stress distribution of right angle and curve types spring beams at the resonance frequency. The maximum stress (311 MPa) is induced at the connection with a beam and side of the curve type spring. On the other hand, the maximum stress (322 MPa) is seen in the connection area and additional stress areas are seen at the beam corner in case of right angle type spring. The right angle type spring has higher value of maximum stress about 11 MPa and additional stress areas. It will create an effect on the fatigue life of spring mass system.



(a)(b)

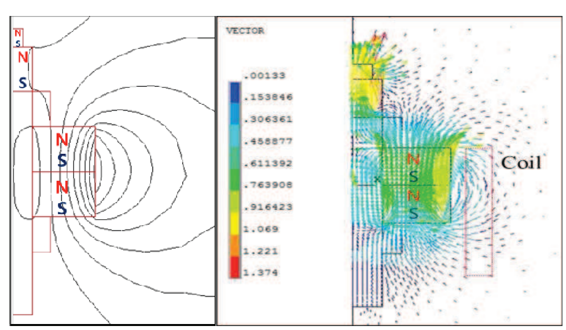
Fig. 3: The effects of the spring shape on the dynamic behavior; (a) right angle type and (b) curve type.



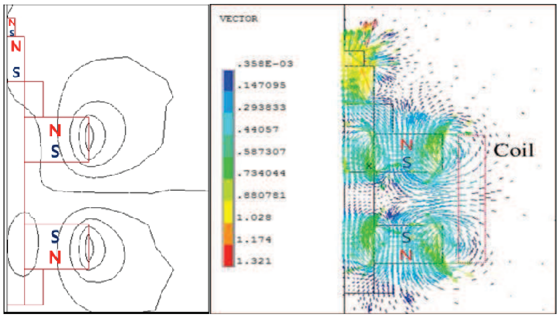
(a)(b)

Fig. 4: The effects of the spring shape on the stress distribution; (a) right angle type and (b) curve type.

Fig. 5 shows the results of axi-symmetric finite element simulation of the corresponding spring mass structure. It shows the magnetic flux lines and the density of the single-pole (a) and multi-pole magnet structure (b). The used magnets are cylinder and ring type NdFeB permanent magnets (grade N52; Br = 1.4 ~ 1.46 T; 4 mm x 2 mm, 6 mm x 5 mm, 20 mm x 5 mm) arranged with N ans S pole magnetizations (magnetization along the 2 mm and 5 mm axis). In addition, the coil is wound around of bottom magnets using 0.1 T copper wire and the dimension of the coil is 3 mm x 15 mm (width x height). Comparing between the single-pole and multi-pole magnet structure, the multi-pole magnet structure concentrates the flux lines because of different directions of the magnetic pole, and exhibits a great flux density in the middle.



(a)

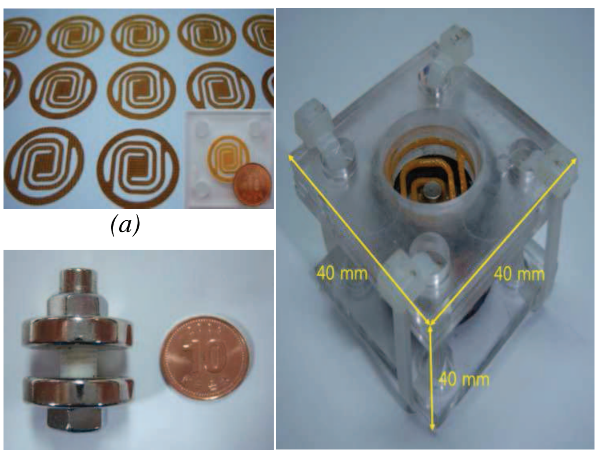


(b)

Fig. 5: The magnetic flux density distributions of the energy harvester: (a) single-pole magnets and (b) multi-pole magnets.

FABRICATION

The fabricated FR-4 spring, multi-pole magnet mass system, and assembled energy harvester are shown in Fig. 6.



(a) *(b)* *(c)*

Fig. 6: Fabricated (a) FR-4 spring, (b) multi-pole magnets, and (c) energy harvester.

The overall design of the spring mass system is composed of NdFeB permanent magnets and a FR-4 spring which is commonly used for PCB material and an electrical insulator. FR-4 spring was fabricated by Desk Computer Numerical Control (CNC) 3D modeling machine that can be used continuously 24 hours a day and are programmed with a design which can then be manufactured hundreds or even thousands of times. Each manufactured product is exactly the same, so it saves time and cost compare with semiconductor and laser processing. In the active mass system, the multi-pole magnets are designed with different pole direction between two fixed aluminum nuts in order to concentrate the magnetic flux density. The magnets are attached to the center of spring that is 1 mm in width and gaps, 250 µm in thickness and 30.5 g of mass. The coil part was designed middle of titanium housing which is a strong metal with low density, quite ductile, fairly hard, non-magnetic and a poor conductor of heat and electricity. The diameter of the coil was 0.1 mm and 2000 turns of induction coil were wound around the titanium housing. Finally, the harvester was assembled by Acryl polymer which is transparent and strong enough to be broken.

EXPERIMENTAL RESULTS

Fig. 7 shows the frequency response of the harvester. The induced output voltage strongly depends on external vibration frequency and dramatically drops above the resonance frequencies. The fabricated multi-pole magnets based energy harvester generates a maximum voltage of 2.32 Vrms at 12 Hz while the acceleration was 0.2 g. The proposed harvester generates approximately 440 mV higher output voltage than that of single-pole magnets.

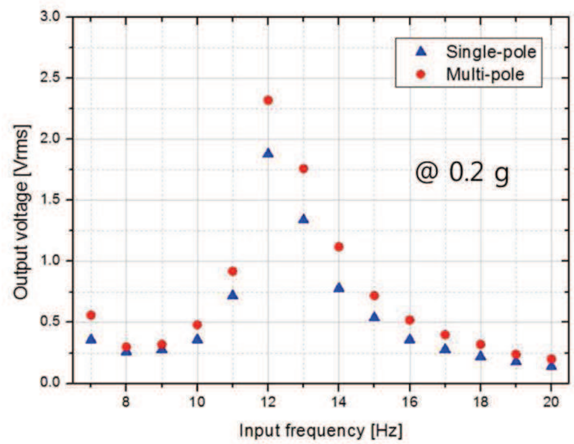


Fig. 7: The resonance frequency of spring mass system with input frequency.

Fig. 8 shows the induced output voltages of single-pole and multi-pole magnets with different acceleration. The induced output voltages increase with the increment of acceleration because of the input displacement from vibrator depends on the input frequency and acceleration. So, when the acceleration of vibrator increases, the displacement of spring mass system will also be increased. But the increment of output voltage reduces for higher accelerating value comparing with lower acceleration.

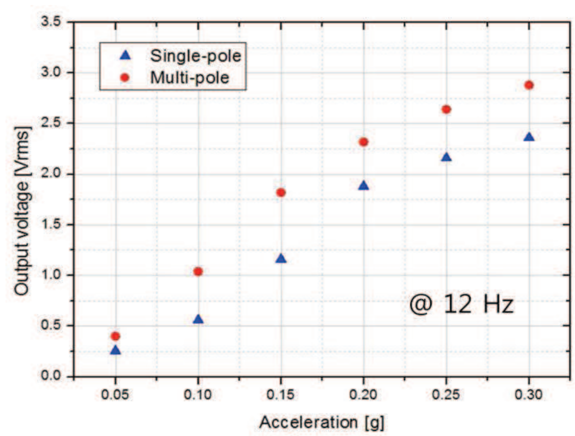
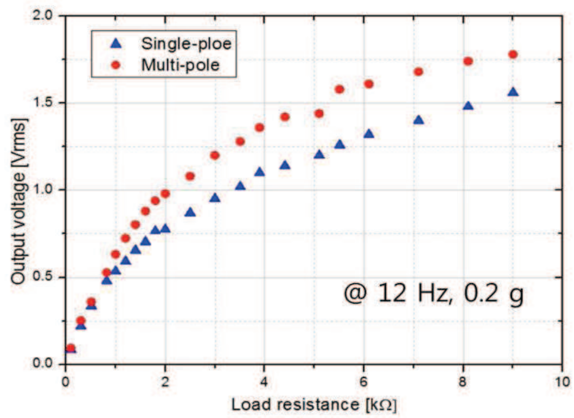
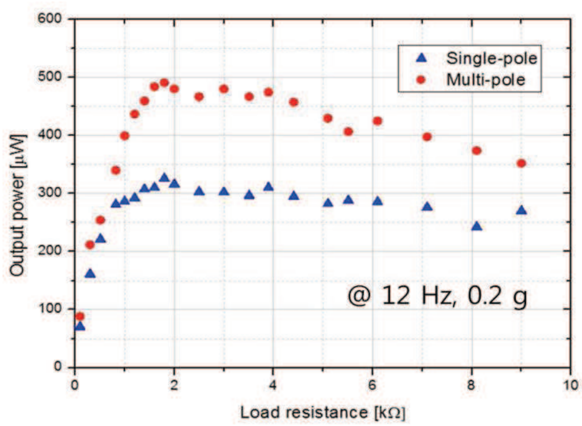


Fig. 8: The results of output voltage with acceleration.

Fig. 9 shows the comparison of output voltage and power of single-pole and multi-pole magnets. The induced voltage increases with the load resistance. The maximum output power of multi-pole magnets based energy harvester reaches its maximum value of 490 μW when the load resistance is 1.8 kΩ. It is elucidated from the Fig.9 that the multi-pole magnet based energy harvester generates approximately 50 % higher output than that of the single-pole magnet.



(a)



(b)

Fig. 9: The results of output (a) voltage and (b) power with load resistance.

CONCLUSIONS

In this work, we present the low frequency driven electromagnetic energy harvester using multi-pole magnet. The proposed energy harvester consists of multi-pole permanent magnets, FR-4 planar spring and cylindrical type copper coil. The final design of the harvester was found through ANSYS simulation. The curve type beam spring is chosen because of its lower maximum stress value and stress distributed area than that of right angle type spring. The FR-4 spring and multi-pole magnets are used to achieve lower resonance frequency and higher output power. FR-4 spring did not show any fatigue failure during operation for 1 ~ 2 hours. The maximum fatigue stress of curve type FR-4 beam spring is around 311 MPa which is in the range of permissible tensile strength (216 MPa ~ 344 MPa). The prototype energy harvester generates the maximum power of 490 μW across a load resistance of 1.8 kΩ while the acceleration is 0.2 g and the resonance frequency is 12 Hz. The proposed device produces approximately 50 % higher output than that of single-pole energy harvester.

ACKNOWLEDGEMENTS

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