DESIGN, FABRICATION AND CHARACTERISTICS OF LOW FREQUENCY VIBRATION DRIVEN AN ELECTROMAGNETIC ENERGY HARVESTER BASED ON FR-4

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Abstract: This paper describes a low frequency vibration driven electromagnetic energy harvester that uses a thin fire resistant (FR-4) spring and converts mechanical energy into electrical power. The proposed energy harvester is composed of a vertically polarized NdFeB permanent magnets attached to the center of a FR-4 spring and a planar type copper coil. In this work, the resonance frequency and the flux density were characterized by using ANSYS software. The experimental results have shown that the fabricated generator is capable of producing 1.5 V_{pp} at 9.625 Hz resonance frequency and a maximum power of 639 μW at a load resistance of 3.25 kΩ.

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

INTRODUCTION

With the rapid development of low-power wireless sensor networks and micro electromechanical system (MEMS), efficiently supplying power for such technologies has become an important engineering problem. Batteries have historically been used but have many disadvantages, such as short lifetime, finite amounts of chemical energy, difficult replacement and recharging, and environmental pollution. Therefore, renewable power supplies must be discovered to substitute for batteries.

Harvesting energy from ambient vibrations became possible during the last few decades [1, 2], and an attractive alternative to batteries due to the almost unlimited lifetime. Power can be generated from various environmental sources, such as ambient heat, light, acoustic noise, radio waves, and vibration. Environmental vibrations are attractive energy sources due to their abundance, and several scavenging techniques based on piezoelectric [3, 4], electrostatic [5, 6] and electromagnetic (EM) transduction [7-9] have been reported. The energy levels obtained using these techniques are sufficient to powering various types of microsystems like data transmission and sensor nodes. However, the maximum voltage and electrical power generated by a vibrating mass are strongly dependent on external vibration frequency, and drop dramatically at low frequencies.

In the literature, a majority of the power scavengers are moving magnet type electromagnetic generators, and moving coil type generators have also been investigated. An energy harvester generates maximum power when the environmental frequency matches with the resonant frequency of the mechanical structure, but environmental vibrations are typically below 100 Hz and have broadband characteristics. Therefore, there is a need for energy scavengers that operate at low and broadband frequencies. Even though all of the reported electromagnetic generators operate at high-level frequencies, generators fabricated using thin fire resistant (FR-4) operate at low frequencies because of the low Young's modulus of FR-4 material, and it is possible to fabricate such generators more easily and cheaply than generators that use silicon and copper materials.

In this paper, a new electromagnetic energy harvester design is introduced and the output voltage and power are analyzed. Mechanical and electromagnetic simulations were conducted to optimize the structure of this generator. The proposed harvester was optimized through an ANSYS simulation. The prototype fabrication and testing are presented.

DESIGN

Fig. 1 is a schematic of the electromagnetic energy transducer for this study. A FR-4 spring and planar type coil are used to generate electric power by electromagnetic induction when the magnet movies.
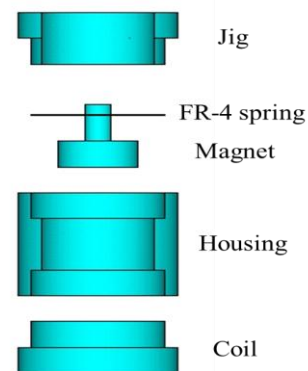

Fig. 1: Schematic structure of electromagnetic energy transducer based on a FR-4 spring.

The generator is composed of a cylindrical titanium housing, a planar type copper coil [7, 10], and an active mass spring [8, 9]. Titanium is a strong metal with low density that is quite ductile, fairly hard, non-magnetic, and a poor conductor of heat and electricity. The most noted chemical property of titanium is its

excellent resistance to corrosion. The induction coil is planar type to increase the coil length. Increasing the length of the coil usually results in higher output voltage, but not always effective. As the length of coil increases, the internal resistance of the coil also increases. Therefore, it is important to compromise between the length of the coil and the internal resistance of the coil to obtain an optimum number of coil turns. The induction coil is planar type to increase the coil length. The active mass spring consists of a vertically polarized NdFeB permanent magnet attached to the center of a FR-4 planar spring, which has two spring beams and a platform. When the magnet vibrates, it moves toward the coil and changes the magnetic flux in the coil. As a result, current and voltage are generated in the coil according to the Faraday's law of induction. The spring has longer beam length, which can produce small spring constant and bigger amplitude of vibration and the corner of the spring beam is circular which can decrease the stress intensity of the spring [7, 11].

ANALYSIS

The mechanical characteristics of magnet-spring system were simulated using ANSYS simulation software. Modal analysis was performed in ANSYS to predict the natural frequencies and mode shapes of every resonant vibration mode [11]. The results of modal analysis are shown in Figs. 2 and 3. Fig. 2 shows the resonant frequencies of different spring materials. As shown, FR-4 has the lowest resonant frequency compared with other spring materials, such as silicon and copper.
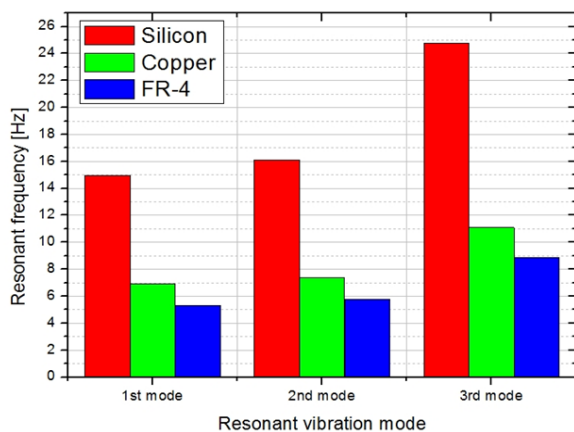

Fig. 2: Resonance frequency according to spring materials with modes.

Fig. 3 shows the three different modes of vibration. The resonant frequencies of the second and the third modes are very close because the magnet moves parallel to the direction of the spring, (a) 6.190 Hz and (b) 6.678 Hz, respectively. The maximum deflection of the spring and the maximum output voltage is generated at the third mode, and has 9.625 Hz of resonant frequency.
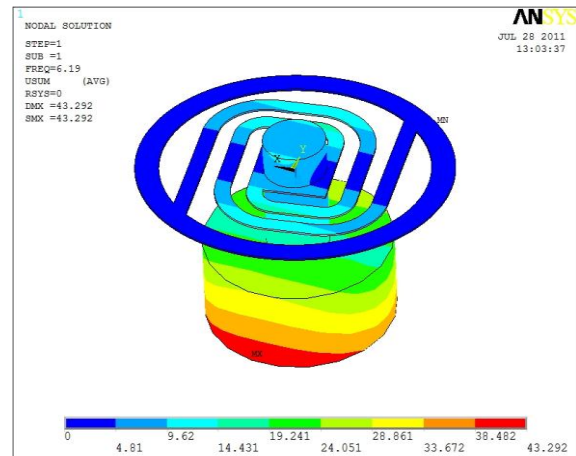
(a)
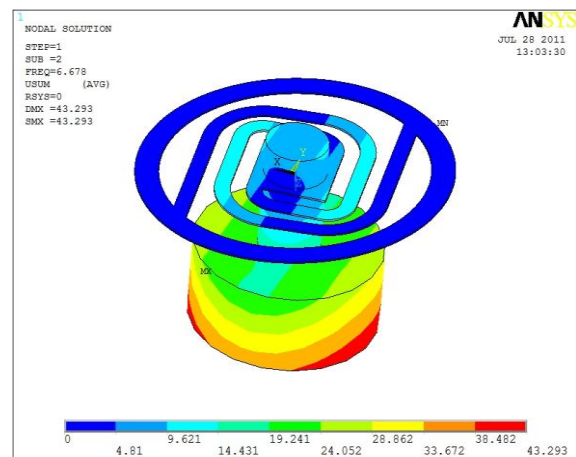
(b)
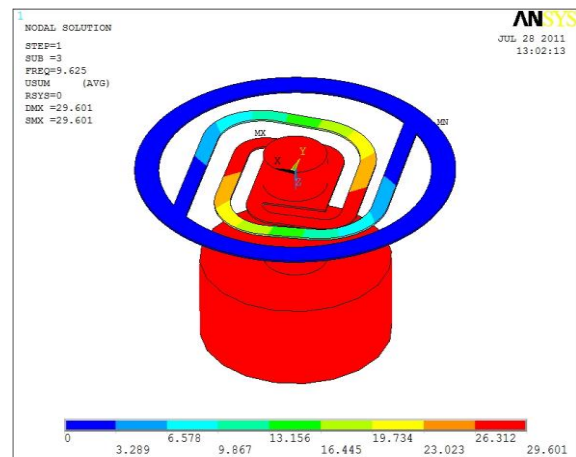
(c)

Fig. 3: Results of mechanical simulations of spring-mass systems; (a) first mode (6.190 Hz), (b) second mode (6.678 Hz), and (c) third mode (9.625 Hz).

A harmonic analysis shown in Fig. 4 and has been done to determine the amplitude of the spring-mass system at resonance frequency by ANSYS simulation. The maximum value will be used in following simulation Figs. 5. Fig. 4 shows that the spring-mass system moves resonance when the frequency is 9.625 Hz and the maximum of the amplitude in Z-direction is 18.1 mm.

The results of structure deflection and stress

distributions at resonance are shown in Fig. 5. The deflection and stress distributions of spring-mass system are quite important when we design the energy harvester. Magnet has the biggest deflection than other part of the spring and the maximum deflection is 18.6 mm in Z-direction.
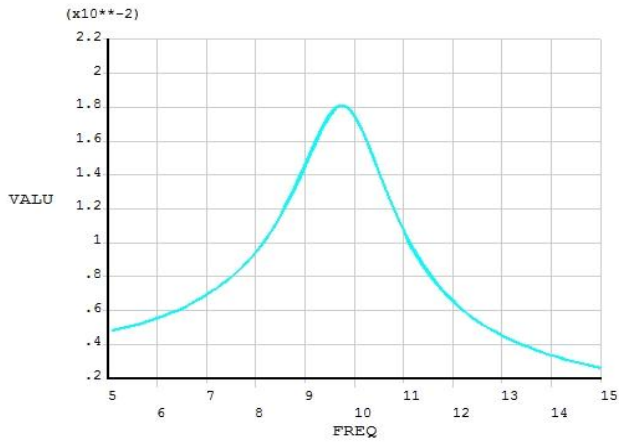

Fig. 4: Harmonic simulation results of spring-mass system.
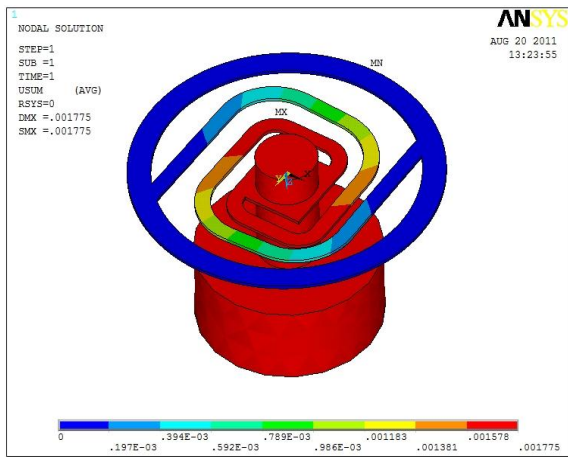

Fig. 5: The results of structure deflection for the spring-mass system at the maximum displacement.

FABRICATION PROCESS

The FR-4 spring and copper coil fabricated for this study are shown in Fig. 6. FR-4 is most commonly used as an electrical insulator due to its considerable mechanical strength [12, 13], and copper material has the highest electrical conductivity of the commercial metals. The overall design of the spring-mass system is composed of permanent magnets (NdFeB) and a FR-4 spring, which is fabricated by Desk Computer Numerical Control (CNC) 3D modeling machine. CNC machines 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 will be exactly the same, so it saves time and cost easily compare with semiconductor [11, 14] and laser processing [7]. The permanent magnets are attached to the center of spring that is 1 mm in width, 200 µm in thickness, and have 1 mm gaps. In order to fabricate an optimized coil, the coil lengths are 10 m, 20 m and 30 m respectively, with a diameter of 0.1 mm.
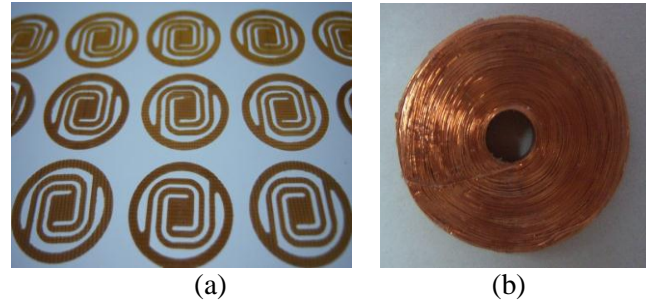

| (a) | (b) |

Fig. 6: Fabricated (a) spring-mass system and (b) copper coil.

EXPERIMENTAL RESULTS

Fig. 7 shows the block diagram of the experimental setup. A power amplifier that has a signal generator is used to vibrate the energy harvester and to regulate vibration strength. The generator is glued on the jig of the vibrator. An oscilloscope is connected to the coil of generator to measure the open-circuit voltage of the generator. When the frequency of the input vibration is equal to the natural frequency of the resonant structure, the spring-mass system operates at resonance; at that point, the permanent magnet has the maximum of the amplitude, and the coil produces the maximum voltage.
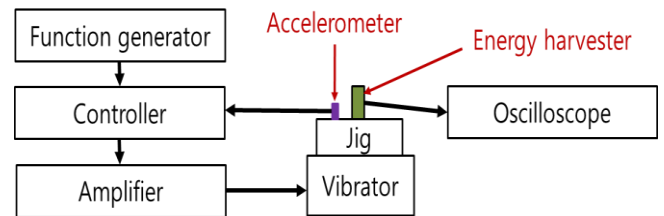

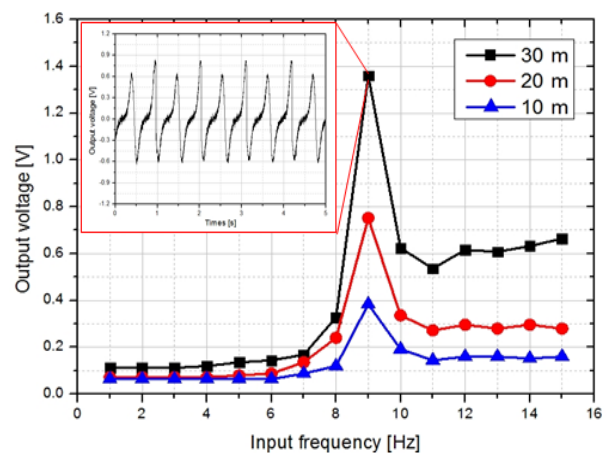*Fig. 7: Fabricated (a) spring-mass system and (b) copper coil.*

Fig. 8: Voltages versus input frequencies with coil lengths and waveforms.

Fig. 8 shows the output voltages calculated for different coil lengths with respect to input frequency.

The output voltage is proportional to the coil lengths, and therefore the turns should be as long as possible within the magnetic field. However, increasing the coil length is not always effective to obtain high voltage. As the length of coil increases, the internal resistance of the coil also increases [15]. The obtained maximum voltage is 1.5 V peak to peak, when the coil length is 30 m. When coil lengths were 10 m and 20 m, the output voltages are 0.4 V and 0.75 V.

The calculated output power with respect to the load resistance is shown in Fig. 9. The output power reaches its maximum value of 639 μW at a load resistance of 3.25 kΩ. In reality, the load will not be as simple as a resistor. However, the load will remove kinetic energy from the vibrating spring-mass system, and so act as electrically induced damping. Some circuit parameters can such that the power transfer to the load is maximized even with more complicated load circuitry [15].
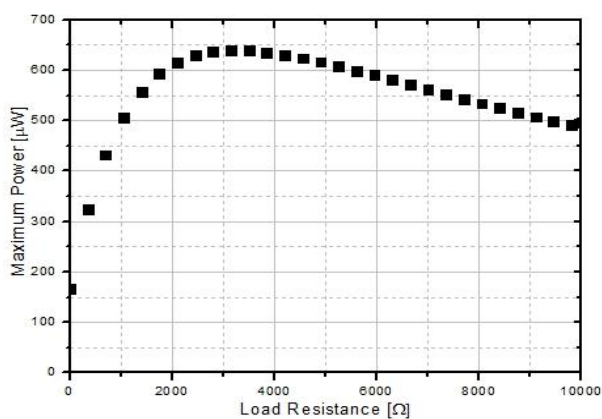

Fig. 9: Power calculated according to different load resistance.

CONCLUSIONS

In this work, we present the design, fabrication, and characterization of a vibration-driven electro-agnetic micro generator based on FR-4. The proposed generator consists of a vertically polarized NdFeB permanent magnet attached to the center of a planar spring and a planar type copper coil. ANSYS software has been used to simulate the mechanical performance. The resonance frequency of the spring-mass system is 9.625 Hz. The maximum obtained voltage is 1.5 V peak to peak when the coil length is 30 m, and the output power reaches maximum value of 635 μW at a load resistance of 3.25 kΩ.

ACKNOWLEDGEMENTS

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