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A Wideband Electromagnetic Energy Harvester for Random Vibration Sources

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Abstract. A novel non-resonant energy harveser with wide band frequency is proposed for collecting energy from ambient vibration at low frequency. A free-standing magnet is packaged inside a sealed hole which is created by stacking 5 pieces of printed circuit board (PCB) substrates with multi-layer copper coils made on double-sides. When the energy harvester is shook from 10 to 300 Hz at 1.9g acceleration along longitudinal direction of hole, a 65 Hz flat-band-like output voltage of 4.5 mV at the case of only one side with drilled air holes on acrylic plate is generated within 35 to 100 Hz. The output power from the coils is measured as 0.1μW under matched loading resistance of 50 Ω within this flat band range under 1.9 g ambient vibration.

Introduction

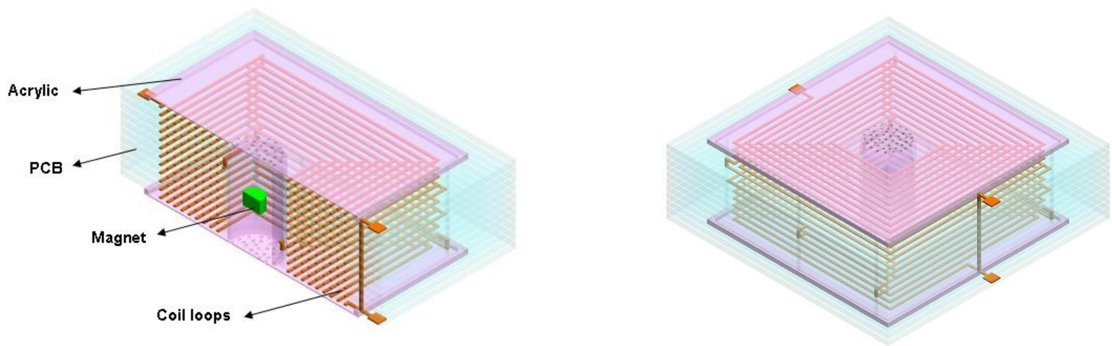
With the growing in the market of low power wireless sensor nodes and wireless electronics devices, miniaturized micro power source system are rapidly developed. Most of these devices use batteries as their energy supplying. Due to the finite lifetime and replacement issues of the batteries, especially in hazardous and low accessibility environments, development of devices harvesting energy from ambient vibration is an attractive R&D subject now [1-2]. The vibration energy harvester will passively absorb this motional energy and convert it into useful electrical energy. The resonant based energy transduction mechanisms working on electrostatic [3-4], piezoelectric [5-7], and electromagnetic [8-10] schemes are reported. Generally speaking, to obtain the maximum output power, vibration-based energy harvesters should be at their resonant frequency, i.e., matched with the mechanical vibration frequency of ambient sources. However, the ambient vibration frequency of various sources in most cases is random and varied. Thus, the vibration-to-electric energy conversion will be limited to the applications with known and fixed vibration frequency. Therefore, it is necessary to develop wideband energy harvesters. Sari [10] et al have reported a wideband frequency electromagnetic energy harvester based on an array of cantilevers with different lengths and resonant frequencies. 10 mV output voltage and 0.4μW power can be obtained within the band width of 800 Hz. By using a non-linear stretched fixed-fixed beam, energy harvester of operation frequency band of 160-400 Hz is reported [11]. However, the ambient available vibration sources exhibit vibration lower than 120 Hz in most of cases [12]. In this paper, we report the preliminary experimental results of low cost wideband electromagnetic harvester based on non-resonant mode for the application of low frequency random vibration sources.

Working principle and simulation

Electromagnetic energy harvesting utilizes electromagnetic induction arising from relative motion between a conductor and magnetic flux gradient. For a coil of N turns each having the same area, the induced electromotive force (emf) $\varepsilon = -N\left(\frac{d\emptyset_B}{dt}\right)$, where ε is in volts, and $\emptyset_B$ is the magnetic flux intercepted by the coil.

Electromagnetic induction can be produced by means of permanent magnets, a coil and in some cases; a resonating cantilever beam can be added. In principle, it is either the magnets or the coil can be chosen to be fixed while another one can move relatively. The electrical energy can be generated by either the relative movement of the magnet and coil, or because of changes in the magnetic field due to vibrations. The amount of electrical energy generated is dependent on the strength of magnetic field, the velocity of relative motion and the number of turns of the coils. For electromagnetic energy harvesters, coils and permanent magnets can be assembled to generate relatively large amount of electrical power [8, 13]. The main advantage of electromagnetic energy harvesters is its relatively high output current. However, its output voltage can be low, which renders the voltage regulation difficult. There are several alternatives such as an increase in the magnetic field strength, increase in the number of coil turns and increase in the coil area, which could be improved to increase the output voltage at vibration frequencies according to preference.

Figure 1(a) and (b) shows the cross-sectional and whole structure drawing of an energy harvester based on electromagnetic mechanism, including up-down movable Neodymium (Nd) disc magnet inside a 4 mm wide middle hole, multi-layer coils and covered Acrylic plates. The disc magnet of 3 mm in diameter and 2 mm in height is packaged inside the middle hole, and this hole is sealed by gluing two pieces of acrylic plates with air holes on both sides.



(a) (b)

Figure 1: Schematic drawing of electromagnetic energy harvester: (a) Schematic cross-sectional drawing of electromagnetic wide band energy harvester; (b) The whole device schematic drawing.

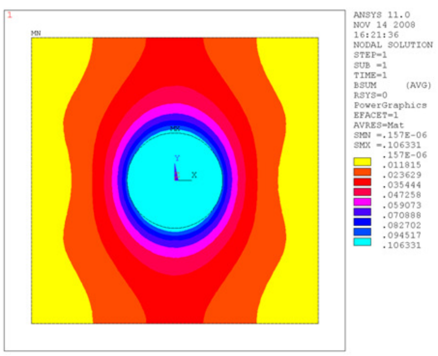


Figure 2: Magnetic flux density simulated using ANSYS

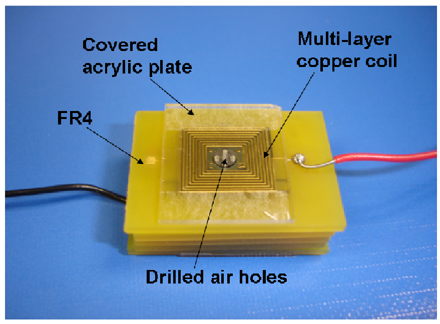
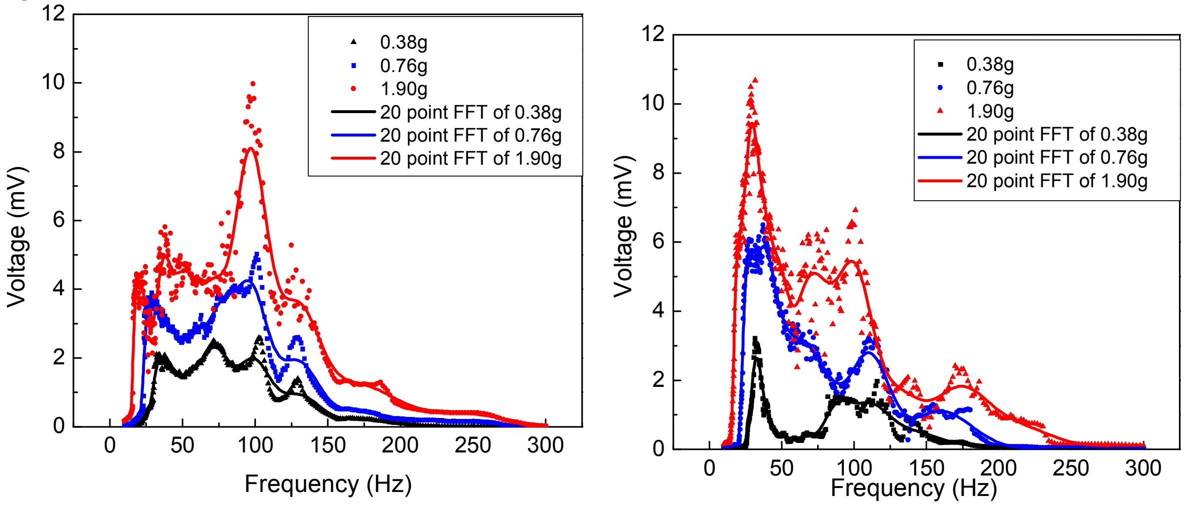


Figure 3: Prototype image of wideband distribution electromagnetic harvester

To understand how the magnetic flux affects on surrounding coils with respect to the free-standing Nd magnet, we deployed the ANSYS software to simulate and analyze it. Figure 2 shows the magnetic flux density distribution, and the effective area is about 1 cm x 1 cm. It points out that the magnetic flux line distribution starts to decay drastically beyond this area. Thus the copper coils are designed and made within this effective area.

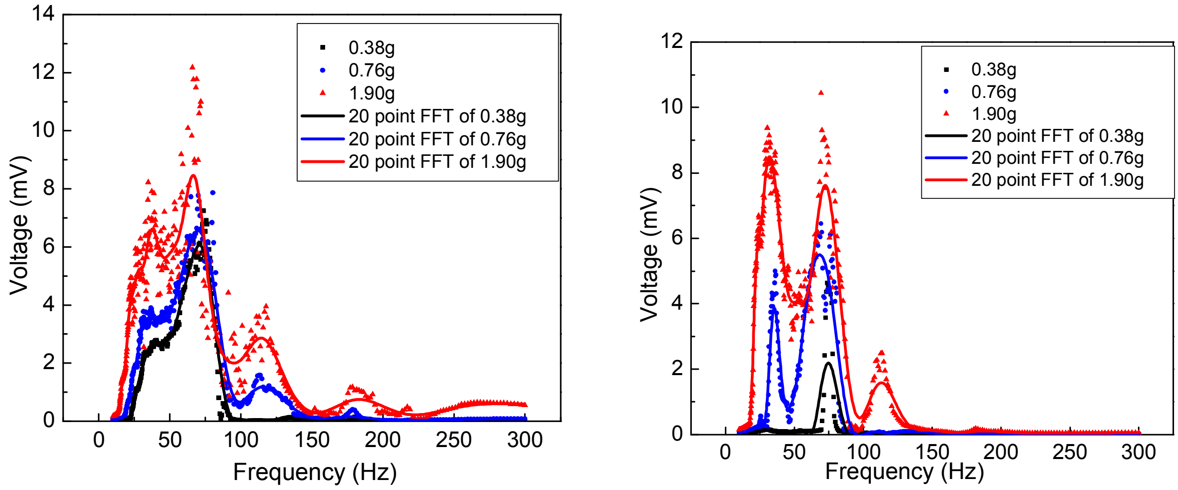
Experimental results and discussion

Figure 3 shows the prototype of wideband electromagnetic energy harvester, which is stacked by five pieces of FR4 (Fire Resistant 4) PCB substrates with multi-layer copper coils. Each one substrate with 2mm thickness was integrated with 12 layers of copper coils. The copper coil width, thickness and spacing are 254, 35 and 254 µm, respectively. There are ten-turn coil lines for sixty-layer coils in total in the stacked substrates. The holes drilled on this acrylic cover plate are used to reduce air damping. Due to this acrylic cover plate, we could not observe the Nd disc magnet in Figure 3.



(a) Single magnet (b) Two magnets

Figure 4: Output voltage versus response frequency at the case of only one side with drilled air holes on acrylic plates: (a) Single magnet up-down moving in middle hole surrounded by coils; (b) Two magnets up-down moving in middle hole surrounded by coils.



(a) Single magnet (b) Two magnets

Figure 5: Output voltage versus response frequency at the case of two sides with drilled air holes on acrylic plates: (a) Single magnet up-down moving in middle hole surrounded by coils; (b) Two magnets up-down moving in middle hole surrounded by coils.

In our experiments, we placed the packaged device horizontally on a holder of a shaker. Figure 4 shows the output voltage versus response frequency at the case of only one side with drilled air holes on acrylic plate. Figure 4(a) and (b) plot the output voltage from multi-layer coils at three different acceleration of 0.38g, 0.76g and 1.90g with single magnet and two magnets up-down

moving in the packaged middle hole. For one magnet, the measured open-circuit voltage is 2 mV, 3.5 mV and 4.5 mV at 35 – 100 Hz for 0.38g, 0.76g and 1.90g, respectively. Compared to one magnet testing result, there is a little difference for output voltage curve profiles of two moving magnets (Fig.4(b)). At 30 Hz, there is a peak value of voltage. The internal resistance of copper coils is measured as 50Ω. When the loading resistance matched with the internal resistance of coils, the maximum output power is 0.1 μW for 1.9g vibration.
In order to investigate the air damping effect on the output voltage and frequency bandwidth, we use the two sides with drilled air holes on acrylic plate to package the moving magnets, which is shown in Figure 5 (a) and (b). We have observed the frequency band width decreases down to 30 Hz (35Hz to 65Hz) and the output voltage can be improved. For two moving magnets, there is two peak values at the different acceleration at 35 Hz and 65 Hz, respectively.

Conclusion

In summary, a novel electromagnetic energy harvester based on non-resonant mechanism is demonstrated by a proof-of-concept device. Five pieces of FR4 substrates are stacked together with a sealed hole at center. A free-standing magnet oscillates within this hole in response to ambient vibrations. It is first demonstrated experimental data that a miniature device can provide flat-band-like output voltage of 4.5 mV in an operation frequency range of 65 Hz for harvesting energy from ambient vibrations of less than 100 Hz. The average output power of 0.1μW can be harvested within this wide 65 Hz range under ambient vibration and shock with 1.9g acceleration.

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