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TECHNICAL PAPER

Non-resonant electromagnetic wideband energy harvesting mechanism for low frequency vibrations

Bin Yang · Chengkuo Lee

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Abstract A novel non-resonant energy harvesting mechanism with wide operation frequency band is investigated for collecting energy from low frequency ambient vibration. A free-standing magnet is packaged inside a sealed hole which is created by stacking five pieces of printed circuit board substrates embedded with multi-layer copper coils. This device was tested under various acceleration conditions. Considering the air damping effect, two types of device structures with different covered plates are investigated. For type I, one covered acrylic plate with drilled air holes and another plate with no holes are used to package the moving magnet. For type II, the middle hole is sealed by two acrylic plates with drilled air holes. The output voltage of type II is better than the one of type I at the same acceleration. When the energy harvester of type II is shook at 1.9 g acceleration along longitudinal direction of the hole, the 9 mV output voltage with 40 Hz bandwidth, i.e., from 40 to 80 Hz, is generated. The maximum output power within the ranges of 40–80 Hz, i.e., operation bandwidth, is measured as 0.4 μW under matched loading resistance of 50 Ω. Experimental results show that type I device has wider frequency bandwidth, higher center frequency and smaller output voltage than type II device because type I device experiences severe damping influence.

B. Yang · C. Lee (✉)
Department of Electrical and Computer Engineering,
National University of Singapore,
E2 #03-29, 4 Engineering Drive 3,
Singapore 117576, Singapore
e-mail: elelc@nus.edu.sg

1 Introduction

With the growing demands in the market of low power wireless sensor nodes and electronics devices, various energy harvesters utilizing ambient mechanical vibrations to generate electricity have been investigated (Dong et al. 2008; Bowers and Arnold 2008; Beeby et al. 2006, 2007; Lo and Tai 2008; Neil et al. 2002; Roundy and Wright 2004; Finkel et al. 2009; Marinkovic and Koser 2009; Hatipoglu and Urey 2010). Several scavenging techniques based on electrostatic, piezoelectric and electromagnetic transduction mechanism have been reviewed (Beeby et al. 2006; Arnold 2007; Zhu et al. 2010). It has been shown that the energy level obtained by these techniques is sufficient to power-up various types of microsystems (Kulah and Najafi 2008). In order to obtain the maximum energy and power output, the mainstream energy harvesting mechanisms work on resonant mode approach (Dong et al. 2008; Beeby et al. 2007; Neil et al. 2002; Roundy and Wright 2004; Finkel et al. 2009), because the excited amplitude reaches its maximum when the mechanical resonant frequency of movable part of energy harvester matches with the ambient vibration frequency. In fact, the vibration frequency of ambient available vibration sources is random and varies from one case to the others (Roundy et al. 2003; Mitcheson et al. 2004). For example, the vibration frequency of human motion varies from 1 to 10 Hz normally, and a spherical magnetic generator intended for human-motion energy scavenging has been reported (Bowers and Arnold 2008). Only mechanisms which can either provide tunable operation frequency (Leland and Wright 2006; Challa et al. 2008) or operate in wide frequency range (Finkel et al. 2009; Liu et al. 2008; Sari et al. 2008) are realistic from the aspect of practical applications. An array of piezoelectric cantilevers integrated with different masses is proposed as an energy harvester operated at multi-frequency (Liu et al. 2008). Electromagnetic energy harvester of an array of cantilevers with various dimensions is reported to generate 0.4 μW corresponding to ambient vibration in frequency range of 4.2–5 kHz (Sari et al. 2008). By using a non-linear stretched fixed–fixed beam, an energy harvester of operation frequency band of 160–400 Hz is reported (Finkel et al. 2009). However, the ambient available vibration sources exhibit vibration lower than 120 Hz in most of cases (Roundy et al. 2003). A piezoelectric energy harvester is reported to have resonant frequency tuning range of 22–32 Hz by incorporating magnetic force based actuation mechanism (Challa et al. 2008). Although it achieves 10 Hz tuning range, the manually adjusted mechanism can only provide bandwidth of 2–3 Hz in one experimental try due to its nature of resonant beam characteristics.

Printed Circuit Board (PCB) technology is a low cost approach for making microelectromechanical systems (MEMS) devices (Urey et al. 2008), in which it requires short design and fabrication cycles, and produces rather robust devices. Fire resistant 4 (FR4) is a well-known engineering material used in PCB technology. It has been demonstrated that PCB devices are made as scanner (Yalcinkaya et al. 2007), spectrometer (Ataman et al. 2006) and multi-frequency energy harvester (Yang et al. 2009). Based on an approach used in commercial "shaking flashlight" products, an electromagnetic power generator (Saha et al. 2008) is reported with a movable magnet packaged inside a sealed tube, which has two magnets fixed on both ends of the tube in centimeters. The interaction of movable magnet and fixed magnets at both ends forms a virtual spring which results in resonant frequency of 8 Hz. In most of reported designs, operation bandwidth of resonant frequency is limited in a range of a few Hz, because most of the reported vibration based energy harvesters work on resonant mechanism (Challa et al. 2008; Liu et al. 2008; Saha et al. 2008). In this paper, we proposed a novel non-resonant wideband energy harvester based on PCB technology for low frequency vibration source of 40–80 Hz. The design and simulation based on finite element analysis (FEA) will be reported and the experimental results will be discussed in detail.

2 Experimental design and simulation

Unlike the conventional resonant vibration-based energy harvesters which have a movable mass with springs linked to a stationary frame packaged in a house, there is no mechanical structure to physically connect Nd magnet with FR4 substrates. In other words, these resonant based energy harvesters only operate within small bandwidth at mechanical resonant frequency of devices. To overcome the limitation of operation bandwidth in the resonant mode, a new non-resonant based energy harvester is proposed in this study. It is a free moving magnet assembled in the middle hole surrounded by multi-layer coils. Figure 1 shows the cross-sectional drawing of this electromagnetic energy harvester including up-down movable Neodymium (Nd) cylinder magnets inside a 4 mm wide middle hole, multi-layer coils and covered Acrylic plates. The dimension of cylinder magnet is 3 mm in diameter and 4 mm in length. The poling NS-direction of magnet is along the central axis direction of cylinder magnet. The material properties and structural parameters of the magnet are shown in Table 1.

Owing to relative motion between a conductor and magnetic flux gradient, electromagnetic induction generated current in metal coils is an intriguing energy harvesting mechanism. For a coil of N turns each having the same area, the induced electromotive force (emf) voltage V_{em} is given by

$$V_{em} = -N\left(\frac{d\phi}{dt}\right) \quad (1)$$

where ϕ is the magnetic flux density intercepted by the coil. In principle, either the magnets or the coil can be chosen to be stationary while the other moves relatively. The generated electrical energy per vibration cycle is a function of the relative vibration amplitude of the movable part, which refers to changes in the magnetic flux within a vibration cycle. It is also dependent on the strength of magnetic field. Another parameter is the number of turns of the coils. To understand how the magnetic flux affects on the number of turns of the coils with respect to the free-standing Nd magnet, we deployed the ANSYS FEM (finite element method) tool to analyze it. Figure 2a and b show

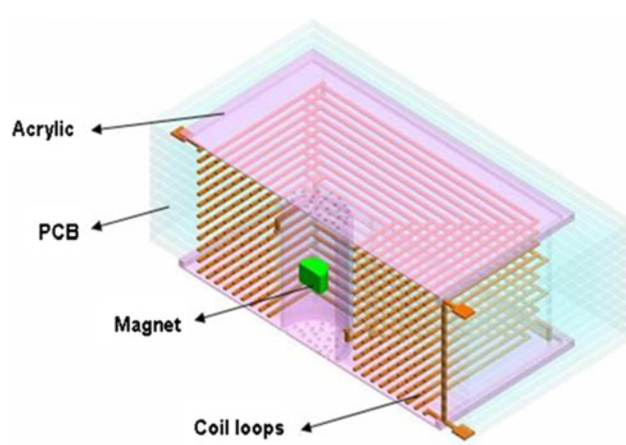

Fig. 1 Schematic cross-sectional drawing of electromagnetic wide band energy harvester, a disc magnet of 3 mm in diameter and 4 mm in height is packaged inside the middle hole, and this hole is sealed by gluing two pieces of acrylic plates with air holes

Table 1 Material properties of magnet and covered acrylic plate and structural parameters

Parameter	Description	Value
Material properties		
E_1	Nd magnet Young's module	41.4e9 Pa
ρ_1	Nd magnet density	7.4e3 kg/m^3
v_1	Nd magnet Poisson	0.28
B_r	Remnant flux density	0.8 T
E_2	Acrylic plate Young's module	3.2e9 Pa
ρ_2	Acrylic plate density	1.4e3 kg/m^3
v_2	Acrylic plate Poisson	0.40
Structural parameters		
D	Diameter of Nd magnet	3e-3 m
L	Length of Nd magnet	4e-3 m
l_1	Length of single layer coil area	1e-2 m
W_1	Width of single layer coil area	1e-2 m
N	Turns of single layer coil	10
T	Thickness of each piece FR4 substrate	2e-3 m
n	Number of coil layers on each piece FR4 substrate	12
l_2	Length of the whole device	1.5e-2 m
W_2	Width of the whole device	1.5e-2 m
H_2	Height of the whole device	1.2e-2 m
d	Diameter of middle hole	4e-3 m

the two dimensional (2-D) magnetic flux lines and flux density distribution along the magnet cross section plane (x–z plane), respectively. The simulation results show that the flux lines and density are mostly distributed in this area (x–y plane) of about 1 cm × 1 cm for the whole cylinder magnet. It points out that the magnetic flux line distribution starts to decay drastically beyond this area. When the magnet moves, the coils with effective area can cut the magnetic flux and introduce an induced electromotive force voltage at both ends of the coil based on Eq. (1). Thus the copper coils are designed and made within this effective area as we observed in Fig. 2.

The vibration of excited magnet inside the middle hole (Fig. 1) is categorized as two cases. The free-standing magnet oscillates in the middle hole and the oscillation amplitude is a function of acceleration of ambient vibration. In the first case, the magnet can not contact the upper covered acrylic plate when the acceleration is lower than a certain value. When the oscillation amplitude becomes larger as the acceleration increases, the magnet may approach the acrylic cover plate at both ends during an oscillation swing. At the upmost position of an oscillation swing, the air damping influence may affect the magnet movement and compensate the kinetic energy carried by the magnet, because air in between the magnet and the acrylic cover plate is squeezed such that the air damping effect is amplified. For the second case, the magnet may even impact on the acrylic cover plate at both ends during an oscillation swing when the acceleration of ambient vibration increases above a certain value. In the second case, the movement of magnet is constrained by two acrylic cover plates as the mechanical limit stop, and such impact is defined as a partially elastic collision (Spreemann et al. 2008). With a decreasing displacement (displacement between two acrylic plates is decreased which causes the mass to hit the limit stop) and an increasing phase shift with respect to the unrestricted motion occurs (Spreemann et al. 2008). In the first case, the free-standing magnet oscillates stochastically in a range of different amplitude due to random excited acceleration is the main fact which responses to the observed wide operation bandwidth. As a result, the proposed electromagnetic energy harvester prefers to have long movable distance for the free-standing magnet, then the maximum output voltage with the flat operation bandwidth is enlarged.

3 Measurement and discussion

Five pieces of FR4 (Fire Resistant 4) PCB substrates with multi-layer copper coils were stacked together to form the non-resonant based energy harvester as shown in the Fig. 3. Each piece of 2 mm thick substrate contains 12 layers of copper coils. There are ten turns for each layer coil in the stacked substrates. The copper coil width, thickness and spacing are 254, 35 and 254 µm, respectively. The dimension of whole device is 1.5 × 1.5 × 1.2 cm^3. The holes drilled on this acrylic cover plate are

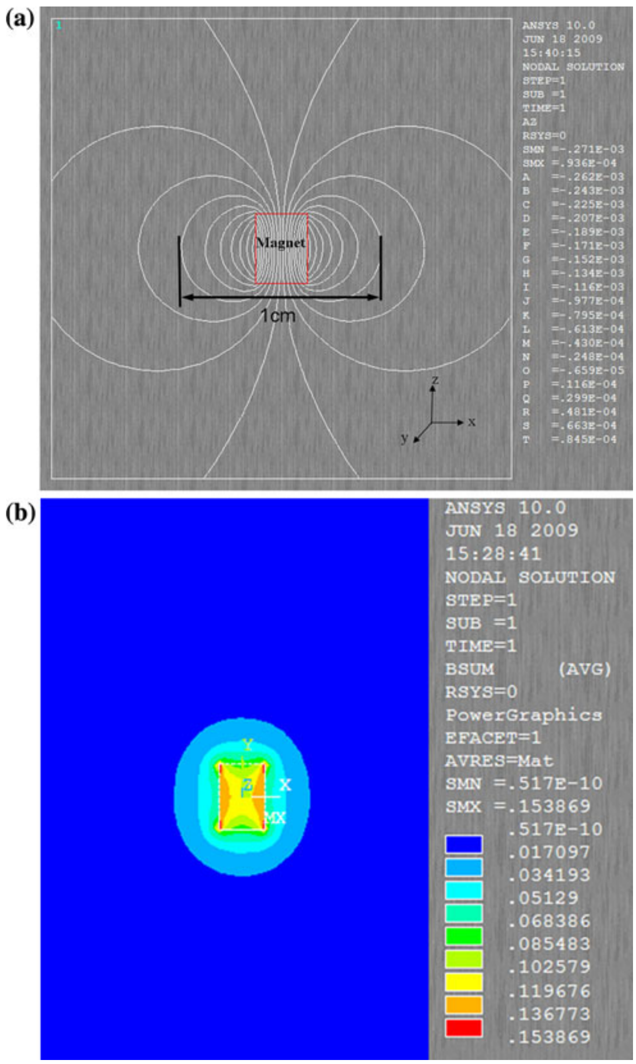

Fig. 2 **a** Simulated magnetic flux lines distribution and **b** magnetic flux density distribution by ANSYS

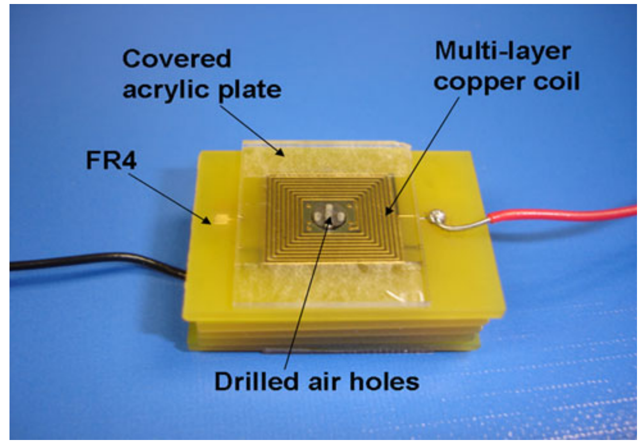

Fig. 3 Prototype of developed electromagnetic wide band energy harvester

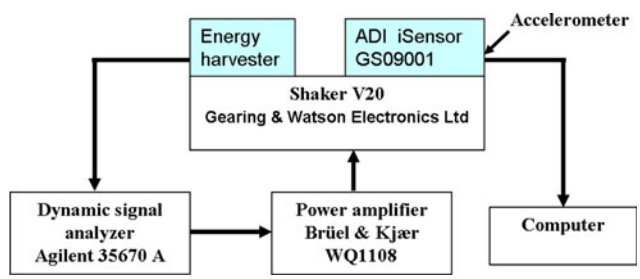

Fig. 4 System diagram of the testing setup

used to reduce air damping. Due to this acrylic cover plate, we could not observe the Nd disc magnet in Fig. 3. In order to investigate the air damping effect, two types of structures with different covered plates are constructed. For type I, one covered acrylic plate with drilled air holes and another plate with no holes are used to package the moving magnet. For type II, the middle hole is sealed by two acrylic plates with drilled air holes.

In the measurement set-up, we placed the packaged device vertically on a holder of a shaker. Figure 4 shows the experimental platform diagram. We controlled the vibration amplitude and frequency of shaker (Gearing & Watson Electronics Ltd V20, UK) by a dynamic signal analyzer (Agilent 35670A) via a power amplifier (Brüel & Kjær WQ1108, Demark), while acceleration of shaker is detected by a MEMS accelerometer (ADI iSensor GS09001, USA) placed on the holder. The random excitation is applied on the shaker. The measured output voltage from coils of type I device versus ambient vibration from 10 to 300 Hz at three different accelerations (peak-to-peak values), i.e., 0.76, 1.14 and 1.90 g, is shown in Fig. 5. Twenty-point fast fourier transform (FFT) curve is used to fit the measured data for rapid averaging of output voltage. The average measured open-circuit based output voltage (rms) in the frequency of 35–100 Hz (i.e., operation bandwidth) is 3, 4 and 5 mV for vibrations of 0.76, 1.14 and 1.90 g, respectively. Its center frequency of wide operation bandwidth is about 67 Hz. The peak value of output voltage at around 100 Hz is measured as 10, 7 and 5 mV for vibrations of 0.76, 1.14 and 1.90 g, respectively. In contrast, the smallest output voltage is measured as 4, 3 and 2.5 mV for vibrations at around 50–70 Hz of 0.76, 1.14 and 1.90 g, respectively.

Figure 6 shows the output voltage of type II device from 10 to 300 Hz versus different accelerations. The measured open-circuit based output voltage is 3.5 ± 0.5 mV (3.5 is the mean and 0.5 is the deviation) at 30–75 Hz, 7.2 ± 0.7 mV at 35–75 Hz, and 9 ± 0.8 mV at 40–80 Hz for 0.76, 1.14 and 1.90 g vibrations, respectively. Its center frequency is about 10 Hz lower than the one of type I. Compared to measured results of type I, the output voltage of type II at 1.9 g in the range of 30–75 Hz increases from

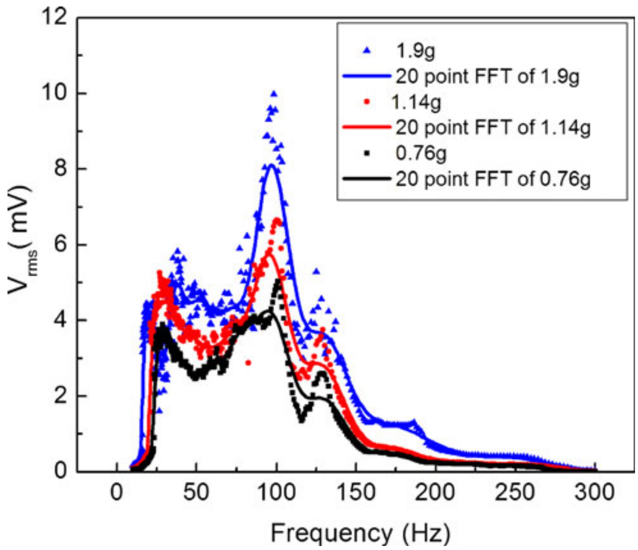

Fig. 5 Measured output voltage versus frequency under various accelerations of 0.76, 1.14 and 1.90 g for type I

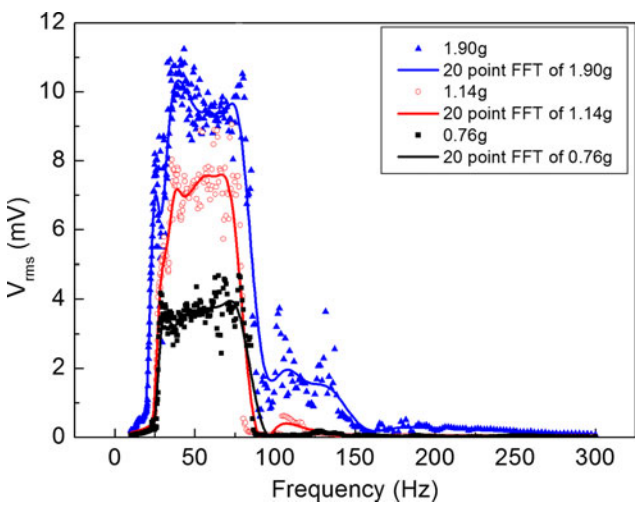

Fig. 6 Measured output voltage versus frequency under various accelerations of 0.76, 1.14 and 1.90 g for type II

5 to 10 mV because air damping force has been reduced, while output voltage does not change a lot for data measured at 0.76 g. It implies that the damping force for type I becomes stronger at 1.9 g acceleration and suppresses the vibration amplitude of moving magnet within this operation bandwidth. But the operation bandwidth in the case of 1.9 g vibration is reduced from 65 Hz of type I to 40 Hz of type II. The damping coefficient is proportional to the natural frequency. Smaller damping coefficient leads to narrower frequency bandwidth. Thus we observed a narrower frequency bandwidth and lower center frequency of type II in Fig. 6 than the data of type I in Fig. 5.

The internal resistance of copper coils is measured as 50 Ω. Figure 7 shows the relationship between output

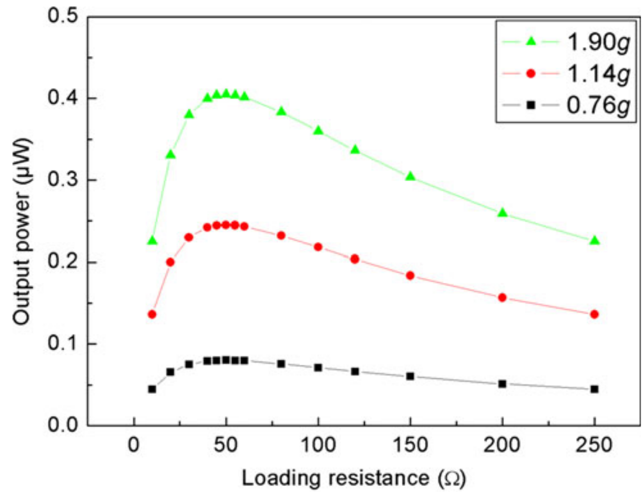

Fig. 7 Output power of type II versus loading resistance under various accelerations

power of type II and loading resistance with respect to vibrations of different acceleration in the operation frequency bandwidth of 35–75 Hz. As the shaker acceleration level increases from 0.76 to 1.9 g, the output power increases about five times, as shown in Fig. 7. When the loading resistance matched with the internal resistance of coils, the maximum output power is 0.4 μW for 1.9 g vibration. The power density is derived as 0.148 $\mu W/cm^3$. Referring to the state-of-the-art resonant based MEMS based electromagnetic energy harvesters, the reported typical power density is in the range of 0.2–2 nW/cm^3 (Kulah and Najafi 2004; Mizuno and Chetwynd 2003; Huang et al. 2003). With the derived proof-of-concept results reported in this study, we may improve the power generation performance of this sort of non-resonant energy harvester by two approaches: (1) to develop a micrometer scale device with much higher coil density by MEMS technology, as a result, the induced electromotive force voltage is improved significantly, since it is proportional to the turns of coils and the output voltage according to Eq. (1); (2) we may use the Nd–Fe–B magnet to replace Nd magnet such that smaller Nd–Fe–B magnet of smaller mass can achieve the same flux density, while its smaller mass only require shock of less acceleration. Eventually we may possibly have MEMS energy harvester using non-resonant mechanism operated at acceleration less than 1 g.

4 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. By using cover with air holes, the type II energy harvester generates higher output voltage and narrower operation bandwidth than type I energy harvester. The experimental data demonstrated that the type II energy harvester can provide flat-band-like output voltage of 9 mV in a wide operation bandwidth of 40 Hz for harvesting energy from ambient vibration of frequency within 40–80 Hz at 1.9 g acceleration. The maximum output power of 0.4 μW can be harvested within this wide 40 Hz range regarding to vibration and shock of 1.9 g acceleration. It shows a promising potential of using a generic energy harvester to collect ambient low frequency vibration energy of random frequency from various sources within a wide operation bandwidth as high as 40 Hz.

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