A low frequency vibration energy harvester using dual Halbach array suspended in magnetic springs

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Abstract. An electromagnetic (EM) low frequency vibration energy harvester is newly developed based on dual Halbach array which is suspended in two magnetic springs. Each Halbach array concentrates the magnetic flux lines on one side of the array while suppressing the flux lines on the other side. Dual Halbach array allows the concentrated magnetic flux lines to interact with the same coil in a way where maximum flux linkage occurs. With the goal of higher power generation in low amplitude and low frequency vibrations, the magnetic structures (both the dual Halbach array and the magnetic springs) were optimized in terms of operating frequency and power density. A prototype was fabricated and tested. It is capable of delivering maximum 1.09mW average power to 44Ω optimum load at 11Hz resonant frequency and 0.5g acceleration. The prototype device offers 33.4µWcm⁻³ average power density which is much higher than recently reported electromagnetic energy harvesters.

1. Introduction

With current development in microelectronic technology, the dimension and the power expenditure of electronic components and integrated electronic systems have been meaningfully decreased. These formations qualify applications requiring high mobility and long term freedom. Generally permanent energy alternatives such as batteries have the limitations of limited lifespan, chemical hazards and sometimes larger size compare with micro-electromechanical system (MEMS) devices. Energy harvester is a possible substitute of batteries that converts the existing environmental energy into usable electric energy. The ambient energy scavenging, as known as energy harvesting or power harvesting, is the process of obtaining usable energy from natural and human-made sources that surround us in the everyday environment. General ambient sources are solar, acoustic noise, thermal, biochemical, radio waves, and vibration etc. Commonly used vibration based energy harvesting techniques are electromagnetic [1], electrostatic [2], and piezoelectric [3]. The electromagnetic energy harvesting technique offers high energy conversion efficiency and very low frequency operation due to the easy mechanical resonator composition of the device [4-5].

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A suitable electromagnetic vibration energy harvester can be used to power various consumer electronics such as mobile phones, wrist watches, audio devices, hearing aids and implanted biomedical devices. Energy harvesting from low frequency vibration is attractive due to its availability around the ambient environment. But significant power generation at low frequency vibration is challenging because power flow decreases with the decrease in frequency. Moreover, designing a spring-mass system suitable for low frequency vibration energy harvesting is difficult. In an electromagnetic vibration energy harvester, the resonance frequency depends on the spring characteristics and magnet characteristics such as grade, structure, and mass. The selection of spring (material, structure and shape) plays an essential role in the performance of the harvester [6]. In order to address low frequency harvester design challenge, EM energy harvesters using magnetic spring was proposed in [7]. This paper is mainly focused on Halbach array based electromagnetic energy harvester. A Halbach array is an arrangement of magnets which increases the magnetic field in one side of the array, minimizing the magnetic field to nearly zero on the other side of the array [8]. Generally Halbach array can enhance the magnetic field intensity and reduce the overall volume of the electromagnetic energy harvester [9]. Halbach array in an EM energy harvester increases the magnetic flux density as well as the power generation at low frequencies which was addressed in [10,11] instead of a single magnet.

2. Harvester design and fabrication

Figure 1 shows the schematic structure of the proposed magnetic spring based low frequency vibration energy harvester using dual Halbach array. The electromagnetic low frequency energy harvester is made of dual Halbach array, magnetic springs and three copper coils. The dual Halbach array structure is suspended between two magnetic springs. Each Halbach array is formed using seven block (10×5×2mm³) magnets. Dual array structure is made by attaching the Halbach array to a hollow rectangular shape polycarbonate structure. The air gap between two Halbach arrays is 14 mm and the volume of single Halbach array is (35×10×2mm³). Each magnetic spring is formed by a magnet (5×5×2mm³) fixed at the end cover of the prototype and a magnet (5×5×2mm³) fixed at the side of the array structure in a repulsive manner. A bobbin containing 3 series connected coils (each 400 turns) is placed in the middle of the hollow Halbach array structure. Two polycarbonate spacers (10×5×2mm³) is placed at both sides of Halbach array so that the flux lines of the magnets attached to the Halbach array frame do not interact with those of the spring magnets fixed to the Halbach array frame. In order to determine the position of each Halbach array and two other magnets with the hollow rectangular Halbach array structure, finite element simulation was done so that no significant magnetic interaction occurs among the magnets as shown in figure 2. All the components were assembled to make the prototype energy harvester and tested to observe its output performance as shown in figure 3. Each magnetic spring is formed by two spring magnets facing similar poles. During experiment, vibration was applied in horizontal direction in order to

Figure 1. Schematic structure of the proposed dual Halbach array based electromagnetic energy harvester.

Figure 2. Finite element simulation by FEMM: (a) Schematic of simulation parameters and (b) magnetic flux lines.
reduce the gravity effect on the Halbach array structure. The dual Halbach array based generator structure has been modelled using finite element simulation by FEMM in order to realize the forces created by spring magnets and to determine the Halbach array position and flux linkage with the coil. Figure 2(b) shows the results of FEMM simulation of the corresponding Halbach array generator structure of figure 2(a), showing magnetic flux density at 2mm distance is 0.31T. According to Faraday's Law of electromagnetic induction, the induced open circuit e.m.f voltage (time varying) \( V_{ac}(t) \) is given by

\[
V_{ac}(t) = -N \frac{d}{dt} \left( \int B \cdot dA \right) \dot{z}(t) = NBL\dot{z}(t)
\]  

(1)

where \( \int B \cdot dA \) is the net magnetic flux through the differential component area \( dA \) of the magnet coil assembly. \( N \) is the number of coil turns, \( B \) is the magnetic flux density, \( l \) is the coil length across the magnetic flux lines, and \( \dot{z}(t) \) is the relative velocity between magnet and coil. The output power delivered to the load connected to the coil terminals at the resonance condition is [12]

\[
P = \frac{\omega_0^2 Y_0^2 (NBL)^2}{8\xi^2 (R_L + R_C)}
\]

(2)

where, \( \xi \) is the damping ratio, \( R_L \) is the load resistance and \( R_C \) is the coil resistance. According to maximum power transfer theorem, maximum power is delivered when the load resistance \( R_L \) is equal to the coil resistance \( R_C \).

### 3. Experimental results and discussion

The fabricated dual Halbach array energy harvester prototype was mounted on an electrodynamic vibration excitier (TMS 2004E) connected to a function generator (Agilent 33250A) in conjunction with a power amplifier (TMS 2004E21) which provide sinusoidal excitation of various frequencies and accelerations to the harvester prototype. The amplitude of the input vibration was monitored by a reference accelerometer (Type 8305; Brüel &Kjær) attached to the base of the vibration excitier, connected to a measuring amplifier (Type 2525; Brüel & Kjær). A digital storage oscilloscope (Tektronix TDS5052B) was connected to the harvester outputs in order to measure and record its output response.
Figure 4 shows the frequency response of the energy harvester prototype under various input accelerations. Results show that the device has a resonant frequency of 11Hz at which the output voltage is maximum. At resonance, 378.3mV, 441.7mV and 545mV RMS voltages are obtained while vibrated at 0.3g, 0.4g, and 0.5g accelerations, respectively. Figure 5 plots the measured RMS output voltage across the load resistances and the average power delivered to the loads at a resonant frequency of 11Hz under various acceleration of vibration. The voltage across the load increases with the increase in the load resistance values. However, a maximum average power of 447µW, 726µW, and 1093µW were delivered to the optimum load resistance of 44Ω at 0.3g, 0.4g, and 0.5g accelerations, respectively. As the acceleration increases, the output load voltages and power increases linearly. The generated average power is experimentally equal to $V_{RMS}^2/R_L$; where $V_{RMS}$ is the RMS load voltage across the load $R_L$.

Figure 5. RMS load voltage (dotted lines) and average output power (solid lines) against load resistances at 11Hz resonance frequency.

Figure 6. Instantaneous voltage waveform across the optimum load resistance at 11Hz resonant frequency and 0.5g acceleration.

Figure 6 shows the instantaneous voltage (619mV peak-peak voltage) waveform generated by the harvester prototype across the optimum load resistance 44Ω at 11Hz resonance condition and 0.5g acceleration. The device shows much better output performance than a number of recently reported electromagnetic energy harvesters in terms of both output power and average power density as shown in Table 1. This device is not properly optimized so that this device resonance frequency is 11Hz and other reported electromagnetic energy harvesters have the resonant frequency below 10Hz which were intended to be used in human-body-induced motion applications. In the next stage of the work, proper optimization will be done by improved design to reduce the resonant frequency so it can be used in human-body-induced motion applications. Moreover, reducing the volume and friction of the Halbach array structure with the housing of the harvester is in our consideration. The dual Halbach array generator presented here has been shown to generate meaningful power from low frequency fitful behaviour. The magnetic springs in this dual Halbach array structure has several benefits such as reliability, simple structure and easy to use at resonance frequency conditions.

| Reference number | Operating condition | Acceleration(g) | Average Power (µW) | Average Power Density (µWcm$^{-3}$) |
|------------------|---------------------|-----------------|-------------------|-----------------------------------|
| [7]              | 8Hz                 | 0.04g           | 14.55             | 2.85                              |
| [13]             | 4.6Hz               | 2g              | 110               | 15.4                              |
| [14]             | 5.8Hz               | 2g              | 103.55            | 5.4                               |
| [15]             | 10Hz                | 1g              | 13.6              | 2.85                              |
| This work        | 11Hz                | 0.5g            | 1093              | 33.4                              |
4. Conclusions
The proposed dual Halbach arrays energy harvester device has been designed, fabricated, and tested. Arranging magnets in Halbach array configuration is impressive because the flux density increases on one side of the array and reduces to nearly zero on the other side which in turn, reduces overall volume of the harvester. The goal of this work is to increase the power at low amplitude and low frequency vibrations by optimizing the magnetic spring structures. Our fabricated prototype offers maximum of 1.09mW average power to 44Ω optimum load at a resonant frequency of 11Hz and input acceleration of 0.5g. The prototype shows much better output performance than other recently reported electromagnetic energy harvesters in terms output power and average power density. The next stage of this work will include further optimization of the prototype to be used in energy harvesting from different human-body-induced motions such as hand-shaking, walking, running, cycling etc.

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