ELECTROMAGNETIC VIBRATION ENERGY HARVESTING USING AN IMPROVED HALBACH ARRAY

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Abstract: This paper reports an electromagnetic vibration energy harvester using an improved Halbach array. A Halbach array is a specific arrangement of permanent magnets that concentrates the magnetic field on one side of the array while cancelling the field on the other side to almost zero. Previous research showed that although the Halbach array has higher magnetic field density compared to normal magnet layouts, its magnetic flux gradient is not as high. Thus, output powers of energy harvesters with Halbach arrays were found to be less than those with normal magnet layouts. This paper proposes an improved Halbach array that achieves both high magnetic field strength and magnetic flux gradient. Test results showed that the improved Halbach array can increase the output power of energy harvesters by a factor of seven compared to the previous Halbach design and by a factor of 1.5 compared to the normal configuration.

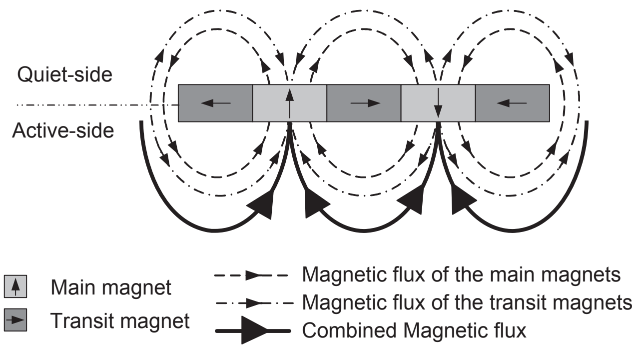
Keywords: Electromagnetic energy harvester, Halbach array

INTRODUCTION

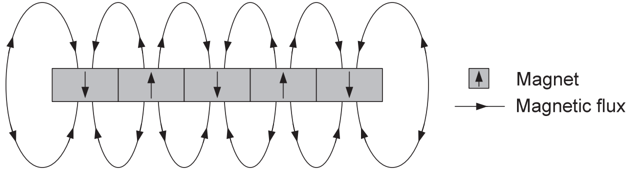
Vibration energy harvesting, as a promising solution to powering wireless sensor nodes, has been studied comprehensively over the recent years. Piezoelectric, electromagnetic, electrostatic and magnetostrictive transduction mechanisms are commonly used to convert mechanical energy into electrical energy [1]. Among these transducers, the electromagnetic transducer has received special attention due to its high power density, especially in macro-scale. Methods have been developed to increase the output power of electromagnetic energy harvesters, such as optimizing the power conditioning circuitry [2], using adaptive energy harvesters [3] and using special magnets layouts, such as Halbach arrays [4].

The Halbach array consists of two sets of magnets (main magnets and transit magnets) as shown in Fig. 1 alongside the normal configuration. The superimposition of the magnetic flux caused by the main magnets and the transit magnets concentrates the magnetic field to one side of the Halbach array (the active side). Assuming the magnetic field strength generated by the main magnets is identical to that generated by the transit magnets, the active-side of the Halbach array will have double the magnetic field strength compared with the normal configuration. The other side of the Halbach array (the quiet-side) will have a negligible magnetic field.

The application of Halbach arrays in vibration energy harvesting was recently reported by the authors of this paper [4]. It was found that the energy harvested with a Halbach array was actually less than the normal configuration despite the increased magnetic field strength.



(a) Halbach array



(b) Normal configuration

Fig. 1: Halbach array and normal configuration.

This paper presents an improved Halbach array used in vibration energy harvesting that is able to increase output power compared to the previously reported design [4].

DESIGN

Analysis of the Problem

According to Faraday's law of induction, the induced voltage within the coil is:

$$V = -N \cdot \frac{d\varphi}{dt} \tag{1}$$

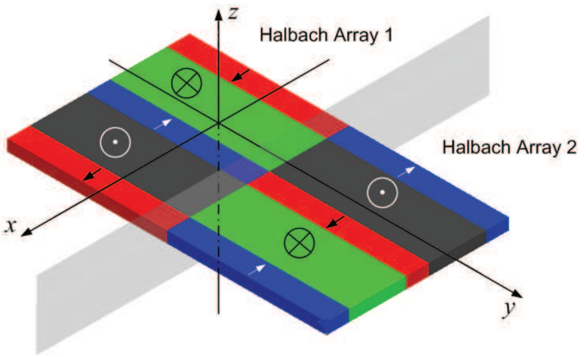
where N is the number of turns of the coil and $\frac{d\varphi}{dt}$ is the magnetic flux gradient. The output voltage is therefore proportional to the magnetic flux gradient. Consequently, it is important to increase the magnetic flux gradient as well as the magnetic flux density in order to increase the output power of an electromagnetic energy harvester. Previous experimental results [4] showed that although the Halbach array has a higher magnetic field density compared to normal configuration, its magnetic flux gradient is not as high. Thus, the output power of an energy harvester with a standard Halbach array will be less than those with normal magnet layouts. The reason for this is that the existence of transit magnets increases the flux path length and reduces the flux gradient though the coil.

Therefore, the solution is to minimise the effect of the transit magnets and achieve high magnetic flux gradient in the improved Halbach arrays.

Solution

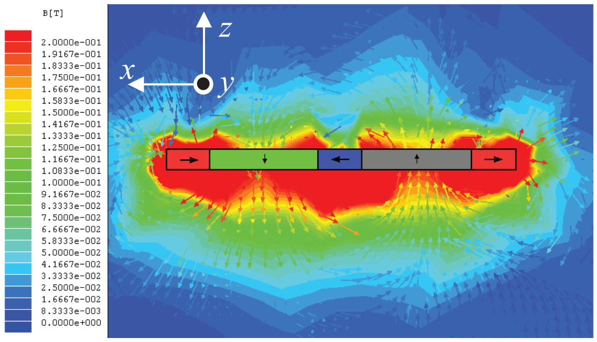
Based on the analysis above, a double Halbach array shown in Fig. 2a was investigated. The two Halbach arrays are placed side by side with the polarity of the magnets flipped. Both arrays have their active sides in the negative z direction.

The simulation results of magnetic field are shown in Fig. 2b and 2c. For each Halbach array, the magnetic flux distribution is the same as a single Halbach array as shown in Fig. 1. By observing the magnetic flux distribution along the y axis, it was found that the magnetic flux direction reverses immediately across the transition line. If coils are placed beneath the transition line and the Halbach array moves in the y direction, a higher magnetic flux gradient and thus increased output power can be achieved.

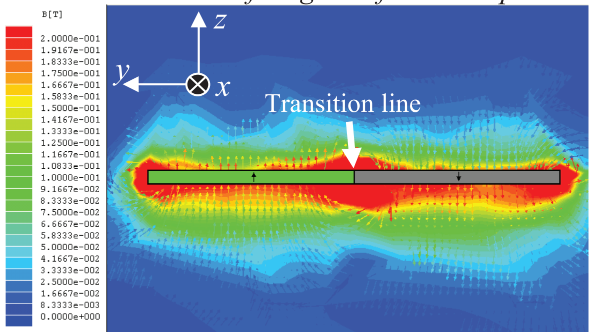


(a) Structure

Fig. 2: A double Halbach array (to be continued).



(b) Simulation results of magnetic field in xz plane



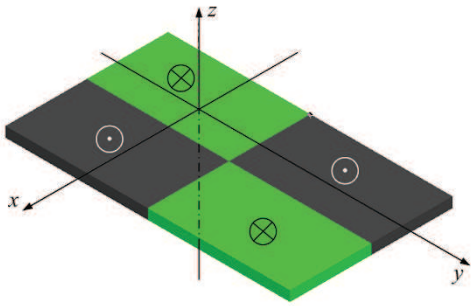
(c) Simulation results of magnetic field in yz plane

Fig. 2: A double Halbach array (continued).

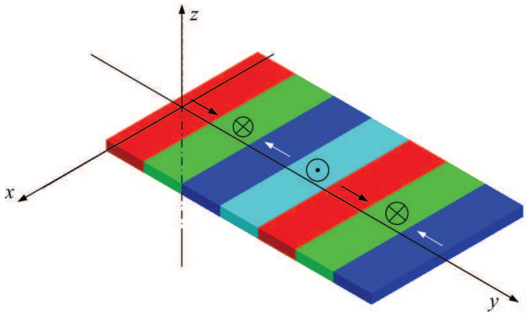
EXPERIMENTAL

Magnet Layouts

The double Halbach array was compared with three other magnet layouts that occupy the same total area ($28\times16\times1$ mm^3): normal 4 magnets (Fig. 3a), single Halbach array (Fig. 3b) and normal 7 magnets (Fig. 3c).

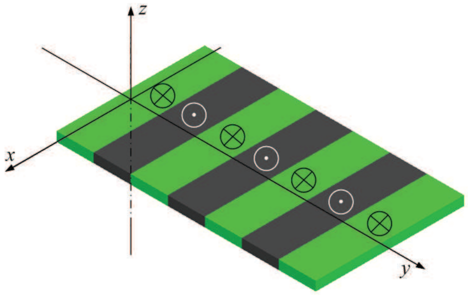


(a) Normal magnet layout (4 magnets)



(b) Single Halbach array

Fig. 3: Other magnet sets used in the test (to be continued).



(c) Normal magnet layout (7 magnets)

Fig. 3: Other magnet sets used in the test (continued).

The normal 4 magnets layout was chosen because it has a similar magnetic flux distribution to that of the double Halbach array in the negative z direction. Normal 7 magnets layout was chosen as it was found to have the maximum magnetic flux gradient in the previously reported test [4].

Table 1 compares the measured magnetic field density (B) in different locations in the four layouts. The measurement was taken in planes parallel to the xy plane and Z mm beneath the bottom of the magnets. The maximum measured value in each case was recorded. It is found that the double Halbach array has the highest magnetic field strength 1mm from the magnets where the centre plane of the coil is.

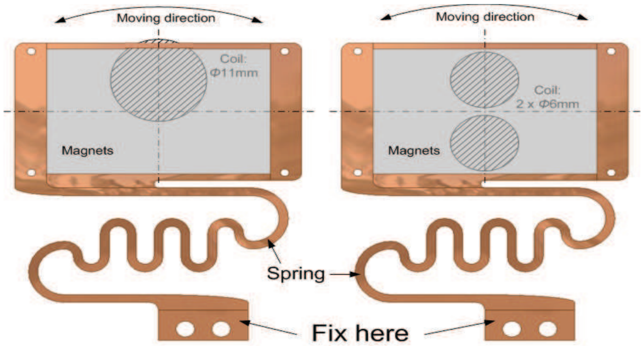
Table 1: Comparisons of measured magnetic field density in different layouts of magnets.

Layout of magnets	**B (T) measured Z mm from the magnets**		
	Z = 0	**Z = 0.5**	**Z = 1**
Single Halbach array	0.26	0.21	0.14 (∇ = 1)
Normal layout (7 magnets)	0.21	0.158	0.136 (∇ = 2.2)
Double Halbach array	0.185	0.17	**0.153** **(∇ = 2.74)**
Normal layout (4 magnets)	0.135	0.122	0.11 (∇ = 2.13)

The magnetic flux gradient (∇) was estimated in the plane 1mm from the magnets and normalised to the magnetic flux gradient of the single Halbach array as shown in brackets in Table 1. It was assumed that displacements (10mm) and operational frequencies (49Hz) are same in all cases. It was found that the double Halbach array has the highest magnetic flux gradient and an increment by a factor of 2.74 was achieved compared to the single Halbach array.

Spring and Coils

Each of the magnet sets was attached to a meander spring made of BeCu as shown in Fig. 4. The meander spring allows the resonator to move in-plane (y-direction) with a low resonant frequency (discussed later). The spring was designed to be stiffer in the x and z directions increasing the resonant frequencies of modes in these directions beyond the range of interest. The frame connected to the spring holds the Halbach array and additional mass. The resonant frequency of the resonator can be tuned by varying the mass before installation.



(a) one big coil (Φ11mm) (b) two small coils (Φ6mm)

Fig. 4: Two sets of coils and their positions.

Two coil arrangements were investigated for comparison. The first has one coil with a diameter of 11 mm and a thickness of 1 mm. The coil resistance was 1620 Ω. The second arrangement has two small coils; each 6 mm in diameter and 1 mm thick. The two coils were connected in series and the total resistance was 1370 Ω. All coils were placed beneath the magnets with a 0.5mm gap in-between.

Experimental Setup

The energy harvester was tested on a shaker as shown in Fig. 5. The electromagnetic energy harvester has in-plane displacement, which allows more space for the resonator to move within a planar structure. A total mass of 2.5 grams was attached to the energy harvester giving a resonant frequency of 49Hz.

Results

All energy harvesters were excited with a sinusoidal vibration of 49Hz and accelerations between 0.1 and 0.6 G_{rms} and connected to their respective optimum resistive loads.

Fig. 6 shows the experimental comparisons of output power of energy harvesters with different magnet layouts and coils. For the one-coil scenario, it was found that the output power of the double Halbach array energy harvester is 50% greater than those of the two normal layouts. Compared with the single Halbach array, the double Halbach array energy harvester has achieved a 700 % increase in average output power. In this case, the width of each magnet in the normal 7 magnet layout is much smaller than

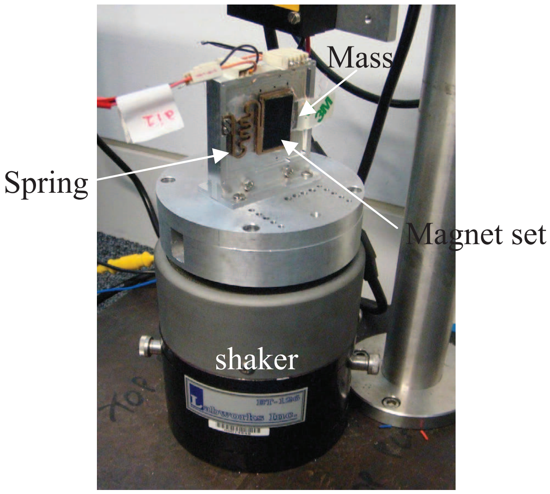


Fig. 5: Experimental setup.

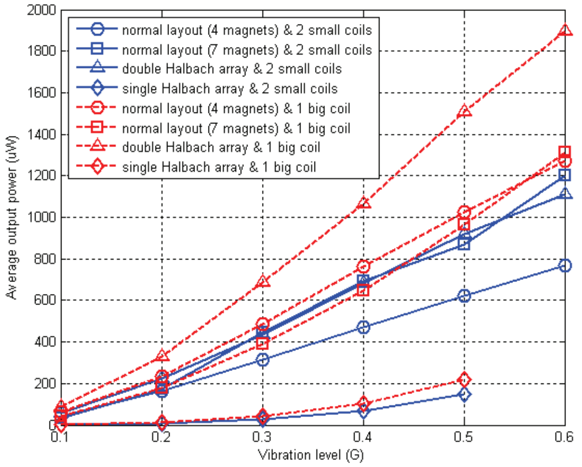


Fig. 6: Comparisons of output power of energy harvesters with different magnet layouts and coils.

the diameter of the big coil. Thus, the magnetic coupling between magnets and the coil is relatively low. In contrast, the double Halbach array has the highest magnetic flux gradient and thus the highest output power.

For the two-coil scenario, it was found that the energy harvester with the double Halbach array has similar output power to that with the normal 7 magnet layout and both are 50% better than the energy harvester with normal 4 magnet layout. This is because the width of each magnet in the normal 7 magnet layout is similar to the diameter of each small coil and greater magnetic coupling is achieved. This gives it a similar magnetic flux gradient, thus similar output power to that of the double Halbach array.

When comparing the same layout in different coil arrangements, it was found that energy harvesters with one big coil, in most cases, have higher output than those with two small coils because the one big coil has greater total volume than the two small coils combined. The only exception is the normal 7 magnet layout where output power is similar in the two coil sets. The reason is that although the big coil has more volume, it does not couple with the magnet as efficiently as the two small coils since its diameter is greater than the length of the magnet in the moving coupling direction.

CONCLUSION

Based on analysis of the energy harvester with a single Halbach array, it was found that although the Halbach array has higher magnetic field density compared to normal magnet layouts, its magnetic flux gradient is not necessarily high due to the existence of transit magnets. Thus, output powers of energy harvesters with the single Halbach array are not always greater than those with normal magnet layouts.

A double Halbach array proposed in this paper successfully minimises the effect of the transit magnets in the Halbach array and thus increases the magnetic flux gradient. Experimentally, it is found that the energy harvester with the proposed double Halbach array increased the output power by a factor of seven compared to the previous design of single Halbach array. The work also highlights the importance of selecting the correct coil dimensions and arrangement.

ACKNOWLEDGEMENT

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