

CYLINDRICAL HALBACH MAGNET ARRAY FOR ELECTROMAGNETIC VIBRATION ENERGY HARVESTERS

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ABSTRACT

This paper reports the design, optimization, and test results of a new magnetic structure for kinetic energy harvesters allowing seven-fold increase in power density compared to single-magnet configuration. Electromagnetic energy harvesters with “single cylindrical Halbach array” and “double-concentric Halbach array” magnetic structures composed of NdFeB magnets with 1.4 T residual flux density were fabricated and tested: respectively 5 mW and 15 mW power was measured and generated at low-amplitude (1 mm) low-frequency (<10 Hz) vibrations. These structures yield respectively a maximum power density of 14 mW/cm³/g² and 26 mW/cm³/g².

INTRODUCTION

With recent progress in microelectronic technology, the size and the power consumption of electronic components and integrated electronic systems have been significantly reduced. These features enable applications requiring high mobility and long-term autonomy. To power such systems, a reliable power source is required. Whilst batteries are usually selected to accomplish this role, their need for regular maintenance and frequent replacement, especially in extreme operating temperatures, motivates the search for other alternatives. To procure a cost-effective solution and a reliable power source, energy harvesters turn out as an attractive replacement.

Kinetic energy harvesting has been widely studied in the past few decades to generate power from ambient vibrations found excessively in most civil infrastructures, marine/air-ground transportation, and human motions. The challenge of generating useful amounts of power becomes more acute when the harvester has to operate under low-amplitude low-frequency vibrations. Numerous design approaches have been proposed to improve the output power of kinetic energy harvesters by: using a resonant oscillating mechanism [1], deploying mechanical frequency up-conversion [2], or using rotational movement of an eccentric mass [3]. In electromagnetic energy harvesters, however, few reports concentrate on power improvements via configuring the magnetic structure instead of the abovementioned approaches [4-8].

With a focus on electromagnetic harvesters, this paper studies two new magnetic structures with the goal of achieving a higher power density, a feature which becomes attractive for industrial applications requiring compact harvester units. This paper first compares different magnetic structures in terms of the change rate of magnetic flux using finite element method (FEM). Second, with the goal of improving power density, the most attractive magnetic structure is geometrically

optimized. Then, dynamic measurements are carried out on built harvester prototypes, and finally the tests results are discussed.

MAGNETIC STRUCTURE

The energy transduction of electromagnetic harvesters is based on Faraday’s law of induction which relates the generated electromotive force ε to the changing rate of the magnetic flux $\delta\Phi_B/dt$ passing through an N-turn coil:

$$|\varepsilon| = N d\Phi_B/dt \quad (1)$$

When assuming an energy harvester with R_{Coil} and R_{load} as the source and the load resistance respectively, the harvester output power P_{out} becomes proportional to:

$$P_{out} \propto (N^2 R_{Coil}/(R_{Coil}+R_{Load})^2) (dz/dt)^2 (d\Phi_B/dz)^2 \quad (2)$$

where $d\Phi_B/dz$ is the variation of the magnetic flux with coil-magnet linear displacement and dz/dt is the vibration velocity.

As (2) shows, the output power of electromagnetic energy harvesters is governed by three main factors: 1) the coil parameters (number of turns, electrical resistance, relative positioning to magnets, etc.), 2) the vibration velocity (coil-magnet relative motion), and 3) the flux linkage created by magnet(s). Our previous works [9-10] showed that the first and second factors could be improved respectively through design optimization, and by coupling the harvester to a mechanical amplifier, respectively. Since the output power varies with square of magnetic flux, the last factor is also essential to maximize the output power.

Instead of using a single magnet (Fig. 1-a), other magnetic structures have been studied for micro/macro-scale energy harvesters: axial magnets with like-poles facing each other (Fig. 1-b), and with a ferromagnetic spacer between permanent magnets (Fig. 1-c), an array of flat magnets with poles alternated up/down [6], planar Halbach arrays [7], and circular Halbach arrays for rotary energy harvesters [8]. Arranging magnets in Halbach configuration is attractive because the flux density intensifies on one side of the array, the coil side, and attenuates to near zero on the other side where electronics may be placed to reduce device size, or eliminate the need for magnetic shielding.

To design more efficient electromagnetic harvesters, a cylindrical stack of axial and radial magnets configured in Halbach order can be used instead. Fig. 1-d illustrates a proper rotating pattern of four magnetizations (toward center, up, out-of-center, and down stacked up on top of each other) to intensify the magnetic field near the coils. Compared with structures of Figs. 1-a to 1-c, this structure improves channeling of the flux linkage through coil

windings which are aligned with radial magnets.

For better channeling of flux linkage through all coil layers, a ferromagnetic tube can be installed around the outer edge of coils. However, depending on its permeability and saturation magnetic flux density, a minimum tube thickness is necessary to modify the spatial distribution of magnetic flux created by permanent magnets. When the tube is replaced with a second array of magnets properly oriented, not only better magnetic channeling is achieved, but also the magnetic flux density is increased due to the added magnets. This is the reason for which a second cylindrical Halbach array with inward intensified field and in 180° phase difference with the first array is added on the outer coil edge (Fig. 1-e). This architecture enhances the channeling of magnetic flux through coil windings while superimposing the Halbach effects of 1st and 2nd arrays to enhance the output.

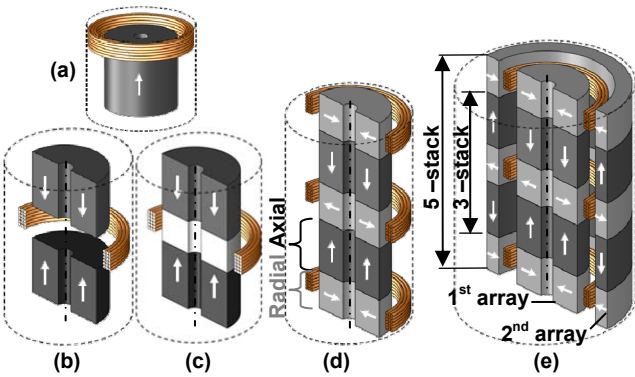


Figure 1: Schematic presentation of analyzed magnetic structures: (a) single magnet, (b) axial magnets with like-poles facing each other, (c) same structure incorporating soft magnet spacers, (d) single cylindrical Halbach array, (e) double-concentric Halbach array

To compare these structures, FEM simulations were performed using ANSYS. Dimensions of axial magnets were set at 19 mm in diameter and 10 mm in height. The spacer (or the radial magnet in case of Halbach arrays) was sized 19 mm in diameter and 6 mm in height. With respect to NdFeB permanent magnets of grade N50M, a residual magnetic flux density of 1.4 T was defined for both axial and radial magnets. Fig. 2 compares the change rate of the magnetic flux for each of Fig. 1

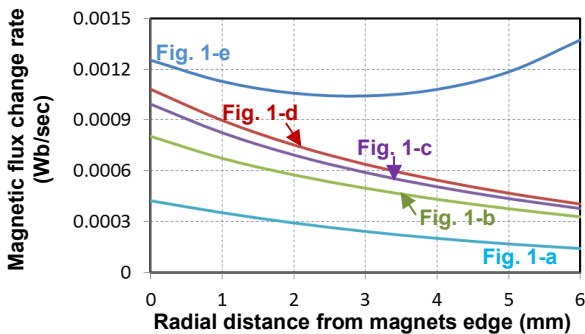


Figure 2: FEM analysis of magnetic flux rate as a function of radial distance from magnets edge for Fig. 1 structures at 5 Hz and 1 mm amplitude

structures as a function of radial distance from the magnets edge. To introduce the term of velocity, sinusoidal vibrations with 1 mm peak amplitude and 5 Hz frequency were considered. As Fig. 2 shows, the magnetic structure with like-poles facing each other is better by almost a factor of 2x than the magnetic flux rate of single-magnet structure (curves 1-b vs 1-a). By introducing a soft magnet as spacer, e.g. low carbon steel, between hard magnets (Fig. 1-c) further 20% increase is obtained in the flux change rate. The increase relative to the magnetic structure with like-poles facing each other is 30% when using single cylindrical Halbach magnet array (curves 1-d vs 1-b). However, when using the structure of double-concentric Halbach array, the flux change rate increases not only in the vicinity of inner magnets edge (first 3 mm in radial distance), but also near the outer magnets edge (3-6 mm following radial distance in Fig. 2) causing 3-10x increase relative to a single-magnet structure.

When comparing the performance of described magnetic structures at low-frequency low-vibration amplitudes (Fig. 3), it is noticed that relative to a single magnet, the single-cylindrical and double-concentric Halbach magnet arrays can improve the power density by as much as 3.5 and 7 respectively. The inset of Fig. 3 illustrates the spatial distribution of magnetic flux density created by the double-concentric Halbach array structure with the coil sandwiched between magnet arrays and initially aligned with radial magnets.

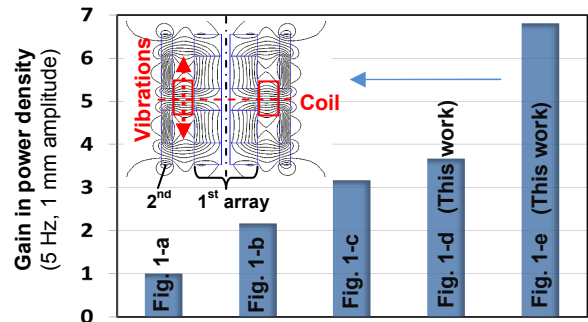


Figure 3: Calculated gain in power density for structures of Fig. 1, inset: distribution of magnetic flux density for double-concentric Halbach array

DESIGN OPTIMIZATION

In this section, the dimensions of coils and magnets composing the double-concentric Halbach array structure are calculated to maximize power density. For this purpose, first FEM simulations are performed to provide the cartography of magnetic flux density for different geometries of magnets. Then, with the help of analytical calculations, for each configuration the coil length is adjusted in a way to obtain the maximum output power. For all analyzed configurations the inner diameter of the 1st magnet array was set at 3 mm (equal to the diameter of the rod which is used later to assemble inner magnets). In the same way the outer diameter of the 2nd magnet array was set at 38 mm. The available space between the 1st and 2nd arrays is used to integrate the coil which is spaced as much as 1 mm from each magnet edge to prevent

mechanical contacts with magnets.

Fig. 4 shows the variation of the power density with height of axial magnets at 5 Hz and 1 mm vibration amplitude. The curves represent different height ratios of radial to axial magnets (from 1/3 to 2/1). For all these configurations, the 1st array outer diameter is 19 mm, the 2nd array inner diameter is 32 mm, and the coil thickness remains constant at 4.5 mm. It is worth noting that on this graph there is more than one specific configuration which yields the maximum power density around 0.11 mW/cm³ (i.e. the peaks on 1/2 and 2/1 curves). To find the maximum power density, FEM simulations and analytical calculations were also performed for magnet arrays with other diameters. Among all we selected one of the most attractive configurations to build prototypes: 1st array with 19 mm outer diameter, 2nd array with 32 mm inner diameter, axial magnets with 10 mm height, radial magnets with 5 mm height (height ratio: 1/2), and a coil section of 4.5 mm x 8 mm.

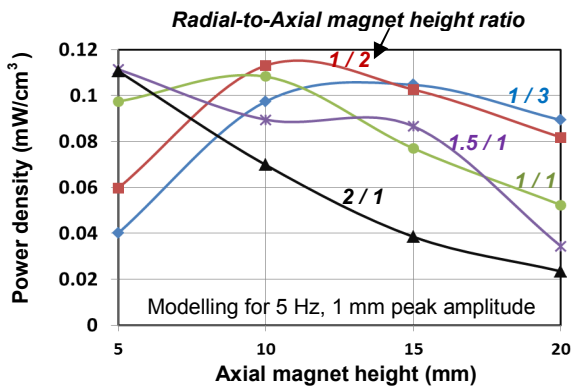


Figure 4: Optimization of double-concentric Halbach array, 1st array 19 mm in diameter, 2nd array 32 mm and 38 mm in inner and outer diameter respectively

FABRICATION AND TEST RESULTS

Based on optimized dimensions of magnets in the previous step, custom-made NdFeB magnets with grade N50M were used to fabricate energy harvester prototypes. Due to the high aspect ratio of axial magnets of the 2nd array, an assembly of four 90° arc segments was used instead. Owing to unavailability of radially magnetized NdFeB magnets, magnet arc segments were also assembled for the 1st and 2nd magnet arrays. Knowing that the radial segments are magnetized along a straight axis, but not along the radial axis, the assembly of smaller arc segments was preferred, i.e. twelve juxtaposed 30° segments, to approximate as much as possible perfect radial magnets. To mount the magnets, metallic jigs and fixtures were designed and machined. Loctite instant adhesive was used for chemical bonding. Fig. 5 shows the assembled axial and radial magnets under green magnetic field viewing film with indicated magnetization direction.

After assembling axial and radial magnets one-by-one, they were stacked up on top of each other in Halbach rotating pattern. Figs. 5-a and 5-b show 3-stack magnets for the 1st and 2nd arrays, respectively. Inserting the 1st array inside the 2nd array completes the double-concentric

Halbach array structure. For the coil, a 39 AWG copper wire was wound around a 70- μ m thick Teflon tube over a length of 8 mm resulting in 0.9 k Ω resistance. A thin brass rod connects the coil to the external vibrating source (Fig. 5-c). Fig. 5-d shows the complete electromagnetic energy harvester next to a D-cell battery with inserted coil which vibrates inside and between two cylindrical magnet arrays.

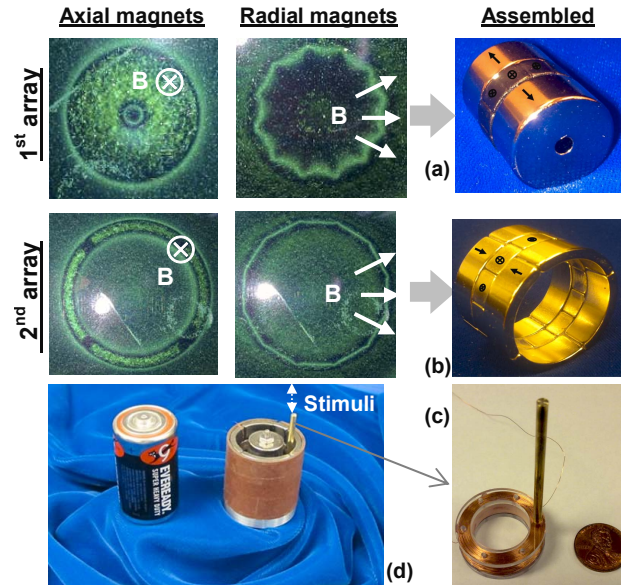


Figure 5: Harvester fabrication in double-concentric Halbach array configuration: (a) assembly of 1st magnet array, (b) assembly of 2nd magnet array, (c) copper coil, (d) harvester beside a D-cell battery

For dynamic tests, other prototypes based on Figs. 1-a, 1-b, and 1-d were also prepared. Then the magnet part was fixed to a stationary ring stand, and the coil was connected via the rod to APS 113 Electro-Seis shaker. The output power was measured at 1 mm peak vibration amplitude for each of magnetic structures across a load with a resistance identical to the coil. The results are presented in Fig. 6.

At 10 Hz, 5 mW and 15 mW were respectively generated with “single cylindrical Halbach array” and “double-concentric Halbach array”. The latter in average increases the output power by as much as 15x over the

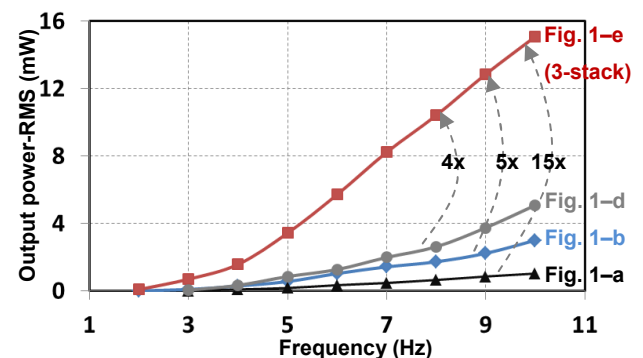


Figure 6: Measured output power for prototypes based on Fig. 1 magnetic structures at low-frequency low-vibration amplitude (1 mm peak), indicated gain factor by switching to double-concentric Halbach array

single-magnet structure. It, furthermore, improves the generated power by a factor of 5 over the magnetic structure with like-poles facing each other, and by 4 in average relative to single cylindrical Halbach array.

Fig. 7 compares the performance of double-concentric Halbach array with state of the art in terms of normalized power density. Despite being a non-resonant harvester, the developed magnetic structure provides power densities higher than most of other resonant electromagnetic generators. In good correlation with Fig. 3, by replacing single-magnet structure with double-concentric Halbach array, a gain ranging from 5 to 7 is achieved in power density. This new magnetic architecture can also be implemented in resonant harvesters to improve the power density of $26 \text{ mW/cm}^3/\text{g}^2$, or be employed in electromechanical actuators requiring high force densities.

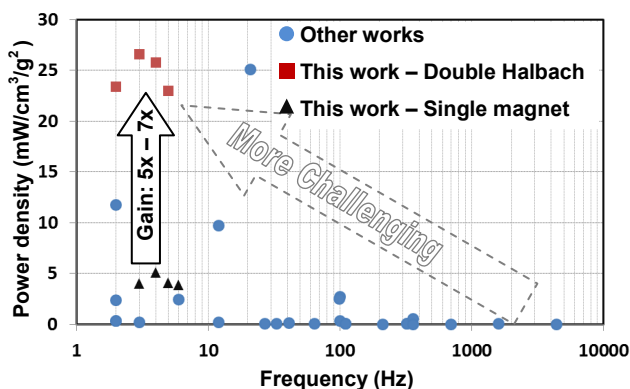


Figure 7: Comparison of normalized power density for electromagnetic energy harvesters

CONCLUSION

This paper presented two cylindrical magnetic structures based on Halbach array to be used in electromagnetic energy harvesters. With goal of higher power generation especially in low-amplitude low-frequency vibrations, the proposed magnetic structures were optimized in terms of power density and their prototypes were fabricated using custom-made NdFeB magnets.

The dynamic tests measured 5 mW and 15 mW output power, respectively for “single cylindrical Halbach array” and “double-concentric Halbach array” structures at 10 Hz and 1 mm peak vibration amplitude. These built energy harvesters present respectively maximum of $14 \text{ mW/cm}^3/\text{g}^2$ and $26 \text{ mW/cm}^3/\text{g}^2$ power densities at low frequencies.

In good correlation with simulations, the measurements showed the double-concentric Halbach magnet array yields seven-fold increase in power density compared to a single-magnet structure. The gain in generated power reaches 15 as a result of improved channeling of magnetic flux density and higher flux change rate for coil windings.

Although this work uses cylindrical Halbach arrays in direct-force energy harvesters, the proposed magnetic structure can be exploited in other types of energy harvesters like resonant-based systems, or even in

electromechanical actuators to provide high driving power densities. With the goal of miniaturization, further investigations should also be conducted to study the influence of downscaling on the harvester performance.

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