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Analysis of different cylindrical magnet and coil configurations for electromagnetic vibration energy harvesters

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ABSTRACT

Electromagnetic vibration energy harvesting is a relatively new technology that transforms kinetic energy from mechanical vibrations into electrical energy, allowing the substitution of batteries or cables for powering ultra-low-power devices like wireless sensor networks for structural health monitoring. For this aim, different magnet and coil configurations have been proposed for the design of these harvesters by several researchers. In this paper, four cylindrical "Magnet in-line coil" configurations with back steel, which include a typical single-magnet, a double-magnet array, and two proposed cylindrical Halbach magnet arrays of three and five magnets, are analyzed using the finite element method and compared in terms of their magnetic flux linkage and transduction factor. The numerical simulations are conducted in all cases with the same materials properties, coil parameters, and geometrical boundaries, the latter consisting of the total cross-sectional area of the magnets and the coil, the air gaps, and the total volume of the transducer mechanism. Furthermore, the design that provides the best performance is analyzed with two different coil configurations. It is finally found that the proposed cylindrical Halbach magnet array with three magnets and one-center coil presents the best results, reaching an average transduction factor of 95.83 Vs/m and a normalized power density of 19.72 mW/cm^{3}g^2.

Keywords: Electromagnetic vibration energy harvesting, Halbach magnet array, Cylindrical magnet, Vibration-based generator

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1. Introduction

The recent progress made in ultra-low-power devices like wireless sensor networks (WSNs) for structural health monitoring (SHM), which are primarily battery-powered, has increased the interest of industries for substituting batteries with other power systems with non-hazardous disposal, non-periodical replacement, and low-maintenance as offered by the electromagnetic vibration energy harvesting (EMVEH) systems. This technology transforms kinetic energy from vibrations, which are ubiquitous in natural and built environments [1], into electrical energy with an electromagnetic transduction mechanism. For this aim, different magnet and coil configurations in the design process of these harvesters have been proposed in the last decade by several researchers [2]-[4] with the main focus on efficiency and power improvement. Spreemann and Manoli [5] classified different EMVEH configurations into two general groups: "Magnet in-line coil", whenever the center axis of the magnet and coil are congruent with the oscillation direction, and "Magnet across coil", whenever the center axis of both elements is orthogonal to the oscillation direction. Some of the most typical and widely applied magnet configurations for the “Magnet in-line coil” type include one and two cylindrical magnet arrays [6]-[9], but only very few research has been conducted with cylindrical Halbach magnet arrays, which theoretically present some outstanding features that can be exploited for EMVEH. For instance, Qiu *et al*. [10] presented a multi-directional electromagnetic vibration energy harvester using a circular Halbach magnet array. The experimental results show that the device could generate a considerable amount of electrical output power in all vibrating directions, with a maximum value of 9.32 mW obtained in the vertical axis with an acceleration of 0.5 g. Shahosseini and Najafi [11] compared different electromagnetic transducers against a single-cylindrical and a double-concentric Halbach magnet array. The best performance was obtained by the optimized double-concentric configuration with a corresponding normalized power density (NPD) of 26 mW/cm^{3}g^2.

This paper analyzes four cylindrical “Magnet in-line coil” configurations with back steel, which include a typical single-magnet, a double-magnet array, and two proposed cylindrical Halbach arrays of three and five magnets, and compares them in terms of their magnetic flux linkage and transduction factor. The design that provides the best performance is also analyzed with two different coil configurations to find out which of them presents the best results. Finally, the electrical output power of the selected configuration is estimated and compared in terms of their NPD with devices from the state-of-the-art.

2. Materials and methods

2.1. Halbach magnet array

A Halbach magnet array is an arrangement of permanent magnets that concentrates the magnetic field on one side of the array while attenuating the field near to zero on the other side, as shown in Fig. 1. This is achieved by applying a rotating pattern of magnetization with two sets of magnets identified as main and transit magnets. Some of the most relevant advantages of this type of arrangements, beside concentrating the magnetic field in the working side (coil location), is to improve the transduction factor in small spaces and to reduce the overall dimensions of the harvester by eliminating the use of magnetic shields [11], [12].

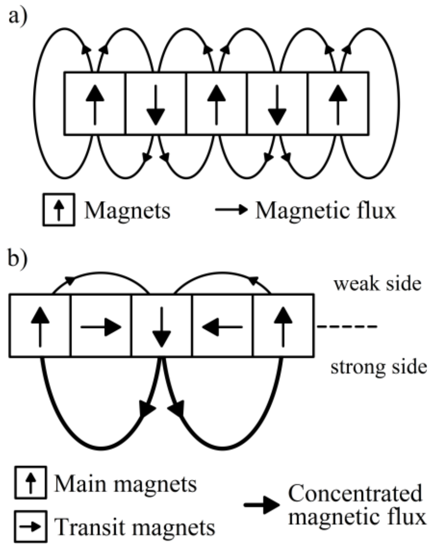

Figure 1. a) Normal magnet array and b) Halbach magnet array

2.2. Electromagnetic vibration energy harvesting

An EMVEH device can be represented in the simplest configuration as a linear single-degree-of-freedom (SDOF) system with external base excitation, from which the relative vertical motion of the mass m with respect to the transducer’s housing is represented by $z(t) = x(t) - y(t)$, where $x(t)$ and $y(t)$ represent the vertical motion of the mass and housing, respectively [13]. By solving the system’s equation of motion, the amplitude of the relative displacement of the moving mass can be expressed as

$$Z = \frac{m\omega^2 Y}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}}, \tag{1}$$

where Y is the excitation amplitude, k is the spring stiffness, ω is the angular frequency, and $c = (c_m + c_e)$ is the viscous damping coefficient, from which c_m is the mechanical damping and c_e is the electrical damping.
The electromagnetic transduction mechanism is based on Faraday's law of electromagnetic induction. The resulting electromotive force ε through the conductive coil can be written as

$$\varepsilon = -\frac{d\Phi}{dz}\frac{dz}{dt} = k_t \dot{z}\,, \tag{2}$$

in which Φ is the total magnetic flux linkage and it is a function of the number of turns N of the coil and the magnetic flux density B, k_t is the transduction factor (also known as electromagnetic coupling factor), representing the change in coupled flux per unit of displacement, and $\dot{z}$ is the relative velocity between the magnets and the coil [5], [14]. Then, the electrical output power P_{out} of an EMVEH can be expressed as

$$P_{out} = \frac{R_l}{(R_l + R_c)^2} k_t^{\,2} \dot{z}^2\,, \tag{3}$$

where R_l and R_c are the load resistance and coil resistance, respectively [6], [7]. In order to compare the performance of different vibration energy harvesters, Beeby et al. [15] has derived an equation for NPD, which consists of the stated electrical output power of the device normalized to the excitation amplitude and divided by the total volume V. The estimated NPD can be written as

$$\text{NPD} = \frac{P_{out}}{Y^2 V}\,. \tag{4}$$

2.3. Analysis of different cylindrical magnet configurations

To make sure that a fair comparison is done between the four cylindrical "Magnet in-line coil" configurations proposed and analyzed in this paper, several parameters are fixed for all configurations as presented in Table 1. These overall fixed parameters include the general dimensions of the magnets (which are the moving mass of each system), the air gaps (which are the distances between the magnet and the coil and the coil with the back steel), the material of each element, the coil characteristics, and the volume of the harvester, which does not include the volume of the resonant element and the housing because they can be designed and executed in different ways. The first two configurations are a typical single-magnet (Fig. 2a) and a double-magnet array with repelling forces (Fig. 2b), which provide higher magnetic flux gradients than attracting forces [6], [11]. The other two configurations correspond to the proposed cylindrical Halbach magnet arrays with three (Fig. 2c) and five magnets (Fig. 2d), which include main and transit magnets with the same dimensions. The direction of each arrow specifies the polarity of the magnets from south to north. Finally, one coil located in the most efficient position (defined by numerical simulations), is used for the analysis of each configuration.

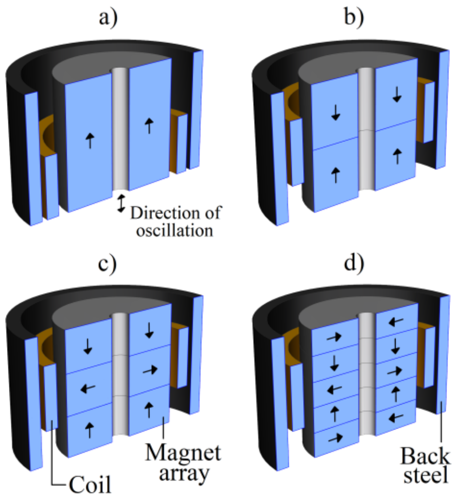

Figure 2. Cross-sectional view of the cylindrical magnet configurations: a) single magnet, b) double-magnet array with repelling forces, c) Halbach array with three magnets, and d) Halbach array with five magnets

Finite Element Method Magnetics (FEMM) is a software for solving electromagnetic problems on 2D planar and axisymmetric domains [16]. It has been used to simulate the magnetic flux density of all configurations, as illustrated in Fig. 3, and to estimate the flux linkage as a function of the mass displacement of vibration. Consequently, the transduction factor was calculated and presented with the corresponding flux linkage in Fig. 4. In this paper, to pursue all FEMM simulations, one model for each configuration is created within the software. The meshes of these models, with a minimum angle constraint of 30°, were automatically created by the software. Also, an open boundary condition is considered and it has been automatically modeled by the software using seven circular shells that emulate the impedance of the surrounding air.

Table 1. Fixed Parameters for the Overall Study

Parameters	
Coil material	Copper
Magnet material	NdFeB N52
Back shield material	1010 steel
Back shield thickness (mm)	1.5
Magnets inner radius (mm)	2
Magnets outer radius (mm)	12
Magnets total height (mm)	24
Moving mass (m) (g)	79.2
Maximum mass displacement (x_{max}) (mm)	4
Transducer volume (V) (cm^3)	30.15
Air gap (mm)	2
Coil inner radius (mm)	14
Coil outer radius (mm)	16.5
Coil height (mm)	12
Coil wire diameter (mm)	0.1
Coil number of turns (N)	2483
Coil resistance (R_c) (Ω)	510
Coil fill factor	0.65

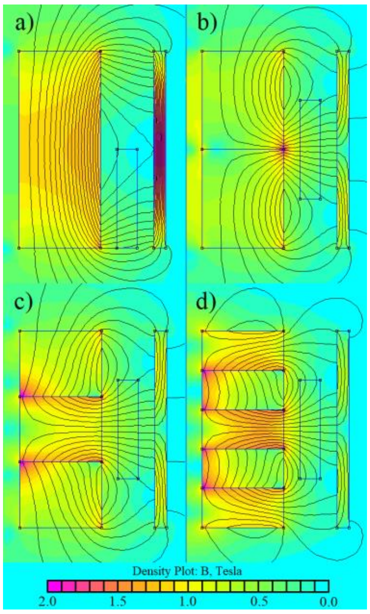

Figure 3. 2D view of the axisymmetric FEMM simulation of the magnetic flux density for:
a) single magnet, b) double-magnet array with repelling forces, c) Halbach array with three magnets, and d) Halbach array with five magnets

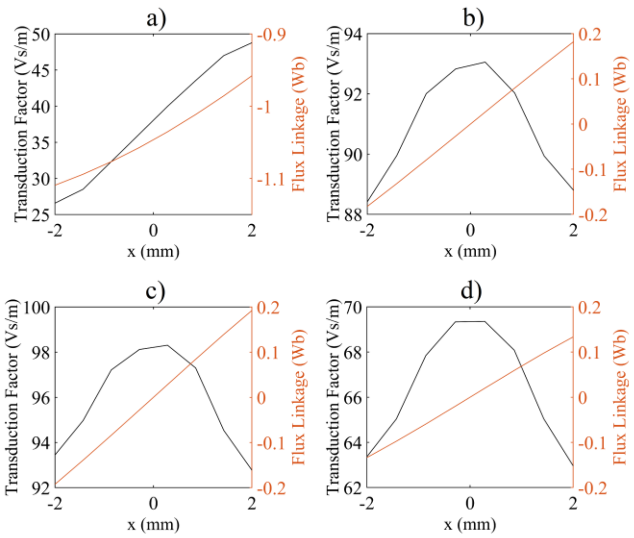

Figure 4. Transduction factor and flux linkage as a function of the mass displacement of vibration for: a) single magnet, b) double-magnet array with repelling forces, c) Halbach array with three magnets, and d) Halbach array with five magnets

2.4. Analysis of different coil configurations

From the results presented in the previous section, we can determine that the proposed cylindrical Halbach magnet array with three magnets and one-center coil provides the highest average transduction factor in comparison to the single-magnet, double-magnet array with repelling forces, and the proposed cylindrical Halbach magnet array with five magnets. In the present section, this configuration is analyzed with two different coil configurations, which are two-end coils and three-distributed coils, as illustrated in Fig. 5. It is important to notice that the polarity of the magnets has been rotated in the two-end coils configuration to redirect the magnetic flux according to the location of the coils without modifying the Halbach magnet array effect. The results of the FEMM simulations of the magnetic flux density obtained for these two configurations are shown in Fig. 6.

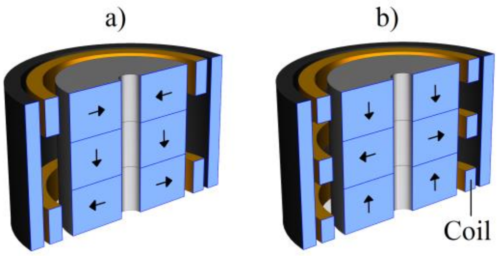

Figure 5. Cross-sectional view of the coil configurations applied to the Halbach array with three magnets: a) two-end coils and b) three-distributed coils

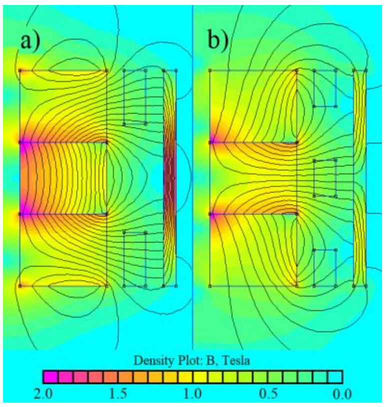

Figure 6. 2D view of the axisymmetric FEMM simulation of the magnetic flux density for: a) two-end coils and b) three-distributed coils

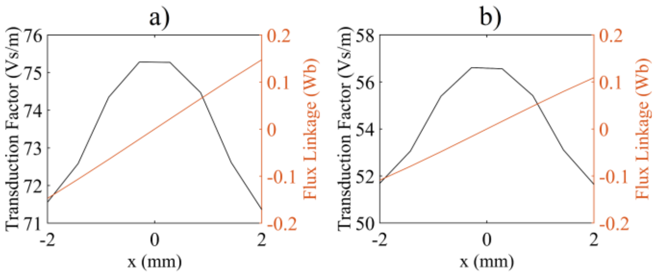

Figure 7. Transduction factor and flux linkage as a function of the mass displacement of vibration for: a) two-end coils and b) three-distributed coils

They were achieved using the same parameters previously established in Table 1. The main difference with the previous configurations lies in the fact that the total cross-sectional area of the coil, and consequently the total number of turns and coil resistance, is equally distributed in two and three coils. Fig. 7 shows the estimation of the flux linkage and transduction factor for both configurations as a function of the mass displacement, which is established in the mechanical design process.

3. Results and discussion

3.1. Comparison of magnet and coil configurations

The proposed cylindrical Halbach array with three magnets and one-center coil provides 2.53, 1.05, 1.30, 1.77, and 1.44 times higher average transduction factor than the single magnet, the double-magnet array with repelling forces, the Halbach array with three magnets and two-end coils, the Halbach array with three magnets and three-distributed coils, and the Halbach array with five magnets, respectively, as exposed in Table 2. The double-magnet array with repelling forces provides the second highest results with only 5.5% less average transduction factor. The main reason for this can be that the repelling magnets and the back steel generate a magnetic flux with very similar direction than the cylindrical Halbach array with three magnets and one-center coil, providing almost the same flux density in the coil location. The configurations with two-end coils and three-distributed coils decreased the average transduction factor of the cylindrical Halbach array with three magnets even if the magnetic flux was redirected to their coil's location as maximum as possible. The reason for these phenomena are that the magnetic flux density through the middle area of each coil has decreased from 0.49 T in the one-center coil to 0.35 T and 0.24 T in the two-end coil and the three-distributed coil configurations, respectively.

Table 2. Comparison of Results Obtained from the Proposed Cylindrical "Magnet in-line Coil" Configurations

Configuration	Maximum flux linkage (Wb)	Average transduction factor (Vs/m)
Single magnet	-0.95	37.86
Double-magnet array with repelling forces	0.18	90.85
Halbach array with three magnets and one-center coil	0.20	95.83
Halbach array with three magnets and two-end coils	0.15	73.44
Halbach array with three magnets and three-distributed coils	0.11	54.18
Halbach array with five magnets	0.13	66.38

3.2. Normalized power density

According to (2) and (3), a higher transduction factor will result in a greater electromotive force (induced voltage) and electrical output power, which are part of the main objectives of the proposed vibration-based generator. Fig. 8a illustrates the maximum electrical output power of the selected cylindrical Halbach array with three magnets and one-center coil as a function of the excitation frequency in a range of 50 to 60 Hz and different sinusoidal excitation amplitudes, at optimal load resistance of 37.55 kΩ. These simulations were obtained assuming a mechanical damping coefficient of 0.25 kg/s, which was experimentally estimated by ReVibe Energy Company for their harvesters mechanical systems. Finally, an NPD of 19.72 mW/cm^{3}g^2 is calculated and compared with the experimental results of different EMVEH devices from the state-of-the-art as observed in Table 3 and Fig. 8b. A precise comparison between these results is difficult to achieve due to the lack of standard characterization test procedures, allowing them to take place under different parameters and conditions. Therefore, some relevant information can be omitted in the device description, for example, to specify if the presented volume corresponds to the transducer mechanism or the complete device (which could include a power management system and an internal energy storage), the weight of the moving mass, or the vibration frequency and acceleration. In any case, the aim of the comparison in Table 3 is not to judge which is the best generator but only to give an overall indication of the performance of different exposed devices.

Table 3. Comparison of Different Electromagnetic Vibration Energy Harvesters from the State-of-the-Art

Reference	**Model**	**Frequency (Hz)**	**Acceleration RMS (g)**	**Mass (g)**	**Volume (cm^3)**	P_{out} **(mW)**	**NPD (mW/cm^{3}g^2)**
This work	-	55	0.2	79^a	30.15^c	23.8	19.72^d
Yaşar *et al.* [6]	-	7	0.35	1.9^a	7^b	0.24	0.28^e
Qiu *et al.* [10]	-	15.4	0.5	895^b	806^b	9.32	0.05^d
Shahosseini *et al.* [11]	-	10	0.28	-	-	15	26^e
Nico *et al.* [17]	-	10.5	0.6	-	13.22^b	5	1.05^e
ReVibe Energy [18]	Model D	62.5	0.4	120^b	49^b	21	2.67^e
	Model Q	80	0.4	60^b	15.6^b	7.5	3^e
Kinergizer [19]	HiPER-D	35	5	90^b	68.5^b	90	0.05^e
Perpetuum [20]	PMG	50	0.5	1030^b	253^b	27.5	0.43^e

[a] Value considering only the moving mass.
[b] Value considering the complete device.
[c] Value considering only the transducer mechanism.
[d] Value corresponding to a non-optimized device.
[e] Value corresponding to an optimized device.

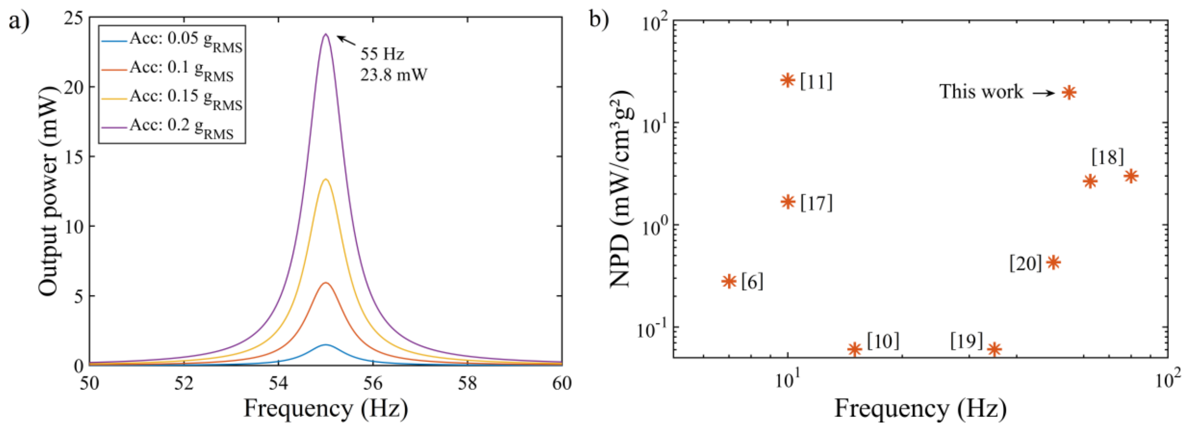

Figure 8. a) Output power of the selected cylindrical Halbach array with three magnets and one-center coil for different sinusoidal excitation amplitudes and b) NPD for different electromagnetic harvesters from the state-of-the-art

4. Conclusions

The proposed cylindrical Halbach array with three magnets and one-center coil presents the highest value of magnetic flux linkage and transduction factor in comparison to the other proposed and analyzed configurations. A maximum electrical output power of 23.8 mW at 0.2 g acceleration and 55 Hz is estimated for the selected device. Finally, a corresponding normalized power density of 19.72 mW/cm^{3}g^2 is calculated and compared with different EMVEH devices from the state-of-the-art, demonstrating that the proposed cylindrical Halbach array with three magnets and one-center coil can efficiently harvest the kinetic energy from low amplitude vibrations and is a good candidate for powering WSNs. Further work will focus in the improvement of the performance by optimizing different components of the proposed configuration without varying the initial volume of the transducer mechanism and the total cross-sectional area of the magnets, for example, the wire diameter, the height of the main and transit magnets, and the air gaps. A prototype of the optimized device will be developed and experimental tests will be carried out under controlled laboratory conditions to validate the numerical models and simulations.

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