ELECTROMAGNETIC HARVESTER DEVICE FOR SCAVENGING AMBIENT MECHANICAL ENERGY WITH SLOW, VARIABLE, AND RANDOMNESS NATURE

N. Fondevilla[1], C. Serre[1], A. Peréz-Rodríguez[1,2], M.C. Acero[3], J. Esteve[3] and J.R. Morante[1,2]
[1]Department Electronics, University of Barcelona, Spain
[2]IREC: Catalonia Institute for Energy Research, Barcelona, Spain
[3]IMB (CNM-CSIC), Barcelona, Spain

Abstract: This work describes the design and optimization of an electromagnetic energy harvester to generate electrical power from slow oscillating movements present in the ambient (produced by the sea waves, the wind,…). A spherical magnet with a spindle moves inside a cylindrical coil along large distances owing to the little inclination produced by the oscillations. Such inertial generator has many advantages for powering remote systems and autonomous applications. It is clean, robust, and can be manufactured as hermetic systems without maintenance costs. Simulations of the generated average power densities are compared to experimental results from a first set of prototypes.

Keywords: electromagnetic energy harvesting, scavenging energy, renewable power source.

INTRODUCTION

Mechanical energy harvesting devices have many advantages over other "renewable" power sources, such as solar or temperature gradient, related to their simpler design and the fact that they are not conditioned to a temperature difference or illumination level.

Mechanical energy is usually converted into electricity by using electrostatic, electromagnetic or piezoelectric transduction mechanisms [1]. The electromagnetic devices are the most compatible with the Si technologies, simple and easy to integrate at low cost.

Several micro-fabricated electromagnetic energy scavengers based on resonant devices, which are well suited for harvesting of vibration energy induced by the operation of machines and engines, have been recently presented [2-4]. These vibrations are characterized by a well defined frequency and low displacement amplitudes [5]. Adjusting the resonant frequency of the system to that of the vibrations allows amplification of these low amplitude displacements. On the other hand, there are a lot of energy sources (human body motion, sea waves, wind…) that present an inherent variable nature and randomness. In these cases, where this energy has a wide range of low frequencies and high displacement amplitudes, non resonant devices become a better option.

The device presented in this work includes a spherical magnet with a spindle, which turns little inclinations (such as those produced by the sea waves or the wind) into large displacements of a magnet inside of a cylindrical coil. Such kind of inertial generator, capable of harvesting energy from the environment, has many advantages for powering remote systems and autonomous applications. It is clean, robust, and can be manufactured as a hermetic system without maintenance costs. The spherical magnet with spindle design maximizes the generated power even for small inclination angles, by allowing a higher average magnetic flux rate during the whole displacement of the magnet within the coils as compared to the conventional sliding configuration. The spindle also insures an optimum orientation of the magnet with respect to the coils plane. The spindle radius should be as small as possible, whilst maintaining enough robustness, in order to maximize the rotation speed, and consequently the magnetic flux rate. However, the spherical magnet can slide or rotate depending on the inclination and the material of the tube, around which the coil is wound. In this sense, the device design can be improved by taking advantage of the microsystems technology and nanotechnology for the spindle micro-mechanization, in order to force the magnet to rotate instead of sliding.

Simulations of the optimum design configuration show the possibility to generate total average power densities up to about 80 mW/cm^3, depending on of the excitation conditions. These data are compared to experimental results from a first set of prototypes.

MODELING

The design of the device shown in Fig. 1 has a structure formed by a magnet that moves inside of a cylindrical coil. This generator turns little inclinations produced by oscillating movements into a large displacement of a spherical magnet with a diametrical magnetization along the cylindrical coil. This movement along the tube produces a variation of magnetic flux. This change induces intensity in the coil according to Lenz's law of induction. From Faraday's law the voltage generated as the magnet moves through the coil is given by

$$V = \frac{\partial \Phi}{\partial t} = \frac{\partial \Phi}{\partial x} v \tag{1}$$

where v is the velocity of the magnet, x is the longitudinal displacement, $\frac{\partial \Phi}{\partial x}$ is the flux rate and V is the generated voltage.

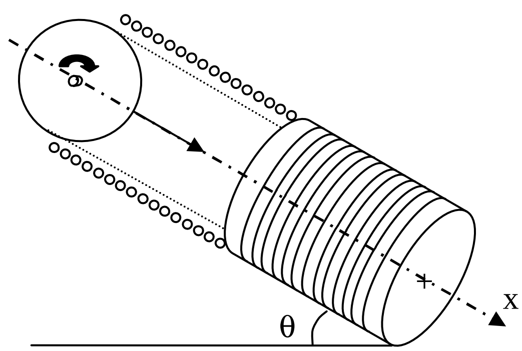

Fig. 1: Cross section of the proposed device.

The designed device is especially suitable for harvesting of energy from slow oscillating movements that has a wide range of low frequencies and high displacement amplitudes, such as the sea waves or the wind.

SIMULATIONS

The design of the prototype has been based on the calculation of the magnetic flux rate distribution simulated by Finite Elements Analysis (ANSYS). These simulations have allowed developing a systematic analysis of the design and loading conditions required for the optimization of flux rate.

Sliding

Fig. 2 shows the flux rate obtained by a spherical magnet that slides without rotating along the tube with two optimized coils. Each coil has 125 turns with 100 µm Cu wire diameter and is wounded in the opposite direction with respect to the previous one (phase opposition). The spherical magnet has a 2.5 mm radius. When the magnet slides along the tube at a certain angle θ of inclination, the velocity equation can be expressed as follows (2):

$$v = \sqrt{2gx \sin\theta} \tag{2}$$

According to this, the simulations indicate that a total average power density of 1.5 mW/cm^3 could be achieved with this design (assuming an optimum magnet orientation along the whole displacement).
In this configuration, magnetic flux variations (hence output generated voltage) occur only when the magnet enters or leaves each coil. Therefore, the optimum coil length is the same as the magnet diameter, and the magnetization of the magnet must be parallel to the axis of the coils.

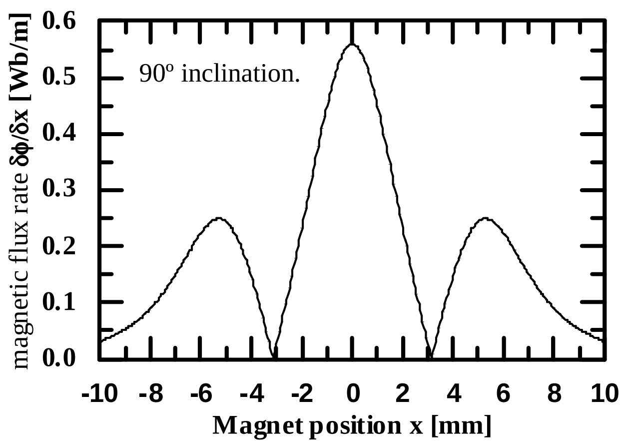

Fig. 2: Flux rate distribution created by a sliding spherical magnet along a tube with two optimized coils (assuming optimum magnet orientation along whole displacement).

Rotating

Fig. 3 illustrates the flux rate distribution given by a spherical magnet with a spindle which rotates along a tube with two optimized coils, connected in series and in phase. Each coil has 125 turns and is made of 100 µm diameter Cu wire. The rotating spherical magnet has a radius of 2.5 mm and a magnet/spindle size ratio of 10 has been used. In these conditions the simulations indicate that a total average power density of up to 80 mW/cm^3 could be achieved, using the following velocity equation (3):

$$v = \sqrt{xg \sin\theta \Big/ \left(1/2 + R_{magnet}^2 \big/ 5r_{spindle}^2 \right)} \tag{3}$$

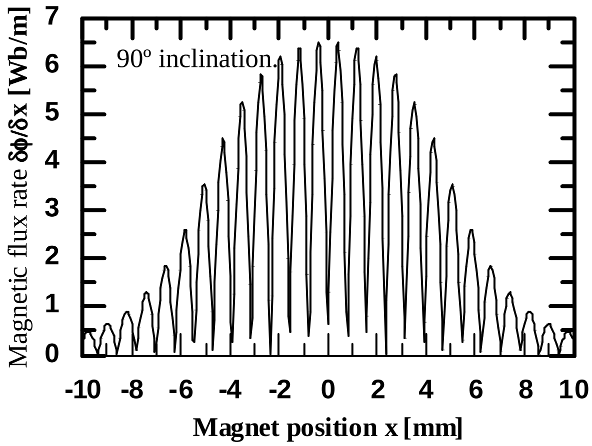

Fig. 3: Flux rate distribution along a tube with two optimized coils from a rotating spherical magnet with a magnet/spindle size ratio of 10.

According to this analysis, the device made up of a spherical magnet with a spindle has several advantages:

- A high value of the magnet to spindle size ratio allows an increment of the number of revolutions, thus increasing the frequency of the generated signal.
- A higher and more continuous flux rate is generated during the magnet displacement along the whole coils length.
- The spindle avoids lateral rotation of the magnet, thus maintaining an optimum orientation of the magnetic field with respect to the coils plane.

As a consequence, the proposed spindle design should be able to harvest a higher output power from the targeted slow oscillating movements.

CHARACTERIZATION AND RESULTS

A first prototype has been implemented using a spherical Nd magnet with 1 cm radius and magnet/spindle size ratio of 10, in a tube with 8 coils. Each coil has 3000 turns of 100 µm diameter Cu wire. Fig. 4 shows the maximum open circuit output voltage, generated through a single coil as a function of the inclination angle for both types of device. As can be seen, experimental results are in good agreement with the simulations. Fig. 5a plots the open circuit output voltage generated when the magnet rotates along the tube through the 8 series in phase coils at an inclination of 12º. This can be compared to the output of a sliding spherical magnet of the same size through the same 8 coils connected in phase opposition (Fig. 5b). In this case, the magnet was mounted on a special ring to avoid lateral rotation (otherwise, the spherical magnet would spontaneously orient itself towards a zero flux rate position!). In both cases, the results are recorded

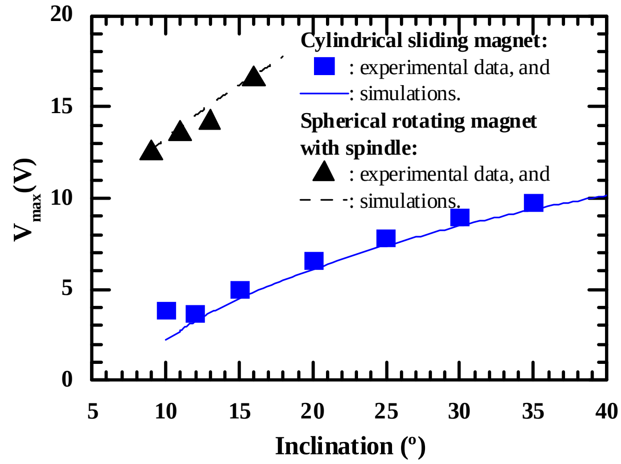

Fig. 4: maximum open circuit output voltage, generated through a single coil as a function of the inclination angle for both types of device.

when the magnet travels once through all 8 coils.
As expected, many more peaks and at higher output voltage are generated with the spindle design. At the 12º inclination angle of Fig. 5, an average output power of 1.2 mW/cm^3 is obtained, against 0.3 mW/cm^3 for the sliding magnet design.

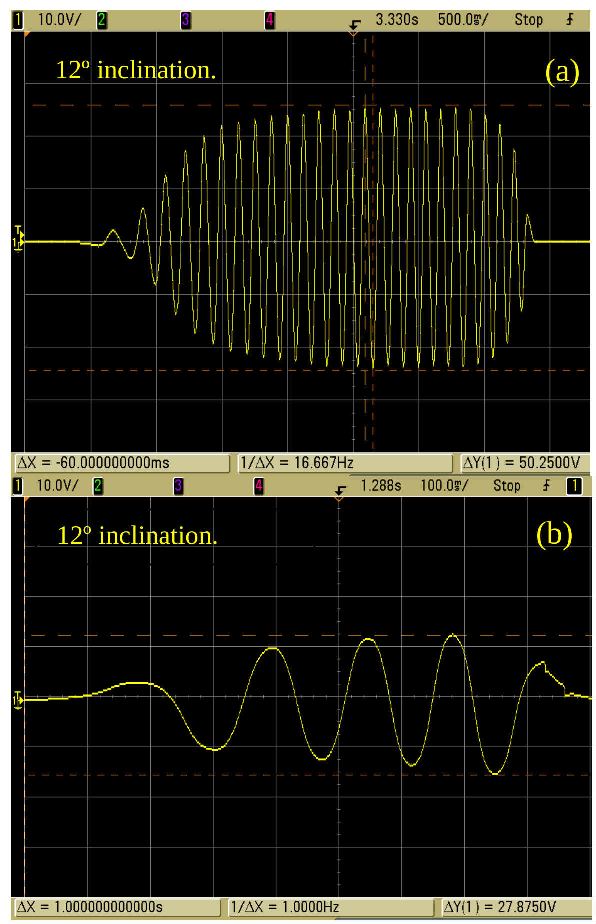

Fig. 5: Open circuit output voltage for a) spindle design, and b) sliding magnet design.

DEVICE OPTIMIZATION.

Since the optimum coil length corresponds to the magnet diameter, further improvements of the magnetic flux rate are related to the density of tracks in the coils, i.e. by decreasing the Cu wire diameter, while increasing the number of turns. However, the flux rate decreases with the distance from the magnet. On the other hand, increasing the number of turns also increases the coil series resistance, which counteracts the optimization of the magnetic flux rate. Our analysis shows the existence of a critical distance z_c to fill with coil tracks (Fig. 6). In these conditions, for a diameter of wire d_1, there are $n_1 = n_{x1}.n_{z1}$ turns (n_{x1}, n_{z1}: number of turns in x, z axes resp.). For a wire diameter $d_2 = k.d_1$, it follows:

$$n_{x2} = \frac{n_{x1}}{k} \; ; n_{z2} = \frac{n_{z1}}{k}; \Rightarrow n_2 = \frac{n_1}{k^2};$$

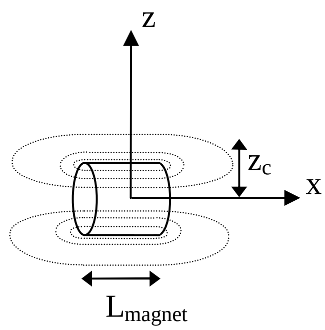

Fig. 6: Schematics of the filling critical distance z_c.

Therefore, the total length of wire will reduce by a factor of k^{-2}, while its section will be k^2 times bigger. As a result, the coils series resistance corresponding to wire diameter d_1 and d_2 will be:

$$R_{2series} = \frac{R_{1series}}{k^4}$$

The output voltage V_o is proportional to the flux rate, which is proportional to the number of turns:

$$V_{o2} \propto \varphi \propto n_2 = \frac{n_1}{k^2} \Rightarrow V_{o2} = \frac{V_{o1}}{k^2}$$

Then the output power is:

$$P_{o2} = \frac{{V_{o2}}^2}{R_{2series}} = \frac{{V_{o1}}^2}{k^4} \times \frac{k^4}{R_{1series}} = P_{o1}$$

Therefore, the output power is independent of the distribution of turns. The dimensions of the magnet determine a critical volume around it that can be filled with any winding distribution. The wire diameter and number of turns will depend on the desired output voltage of each application.

Finally, significant mechanical optimizations are being carried out for the manufacturing of the spindle using micro-fabrication techniques.

CONCLUSIONS

A non resonant electromagnetic generator based on a spherical magnet with spindle design is proposed for scavenging energy from slow oscillating movements that present an inherent variable nature and randomness (such as those produced by the sea waves or the wind). As compared to conventional sliding configurations, this design maximizes the generated power even for small inclination angles, allowing a higher and more continuous average magnetic flux rate during the whole displacement of the magnet within the coils. It also insures an optimum magnet orientation with respect to the coils plane. The preliminary characterization of a first prototype has led to an average output power in the mW/cm^3 range at an inclination angle as small as 12º. The analysis also revealed that for fixed magnet dimensions, there is an optimum volume of wires, which gives an output power independent of the wire distribution. Future work aims at mechanical optimizations for the manufacturing of the spindle using micro-fabrication techniques.

REFERENCES

[1] Sterken T, Baert K, Van Hoof C, Puers R, Borghs G, Fiorini P 2004 Comparative Modelling for Vibration Scavengers *Proc. IEEE Sensors* **3** 1249–1252

[2] Arnold D P 2007 Review of microscale magnetic power generation *IEEE Trans. Magn.* **43** 3940–3951

[3] Huang WS, Tzeng K-E, Cheng MC, Huang RS 2003 Design and fabrication of a vibrational micro-generator for wearable MEMS *Proc. 17th Eur. Conf. Solid State Sensors* **Eurosensors XVII** 695–697

[4] Serre C, Pérez-Rodríguez A, Fondevilla N, Martincic E, Martínez S, Morante J R, Montserrat J, Esteve J 2008 Design and implementation of mechanical resonators for optimized inertial electromagnetic microgenerators *Microsyst. Technol.* **14** 653-658

[5] Roundy S, Wright P K, Rabaey J 2003 A study of low level vibrations as a power source for wireless sensor nodes *Comput. Commun.* **26** 1131–1144