A multi degree of freedom vibration magnetic energy harvester for transport application

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Abstract. This paper reports a parametric study of a multi degree of freedom vibrations magnetic energy harvester for transport application. Two aspects were studied. First we focused on downsizing capability of our harvester. We showed that the output power is proportional to the scavenger volume. Typical output power of 100 $\mu W/cm^3$ was demonstrated with 0.5g harmonic excitation and 5 $\mu W/cm^3$ when harvesters were excited by the movement of a trolley. Then we studied the effect of the coil winding to optimize both output power and output voltage. Raising the number of turns and the wire radius can increase output power. Output voltage is only related to the number of turns.

1. Introduction

While resonant energy scavenger like piezoelectric [1], [2] or magnetic magnet-coils [3] cantilevers are able to harvest a large amount of energy on a specific resonant frequency and a specific direction of excitation identified in the environment, resonant harvesters are not suitable with broadband frequency signals and a chaotic displacement. Few studies deal with non-resonant harvesting method [4], [5], [6] and [7]. The most interesting study for non-resonant and multiple direction of excitation energy of vibration harvesting was presented by Bowers and Arnold [8]. In this paper, we report the design, fabrication and test of such prototypes with harmonic and real-time excitation to determine the downsizing capability of this kind of electromagnetic transducers. We finally focus on output voltage, which is a well-known drawback of magnetic scavengers.

2. Device design and fabrication

A drawing of the device is presented on Figure 1. A 1.4T neodymium (NdFeB) magnetic ball from Supermagnete company is inserted in a composite spherical cavity fabricated with a 3D printer ZBuilder. Two 600-turns coils are positioned around each piece of the support as presented on Figure 2. Both parts of the cage where then fixed with plastic screws. This geometry allows the magnet to move in the six degrees of freedom.

The coil is separated in two parts to maximize the amount of energy scavenged as proposed by Bowers [8]. 4 prototypes were fabricated with different cavity size. The ratio magnet diameter / cavity diameter was fixed to 85% as proposed by Bowers and Arnolds. Magnets and cavities diameters were summarized in table 1.

Table 1. Dimensions of the 4 prototypes

Prototype	#1	#2	#3	#4
Magnet diameter (mm)	26	19	13	10
Cavity diameter (mm)	30	22	15	11.5

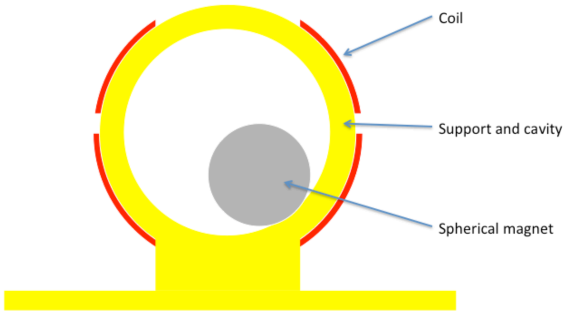

Figure 1. Schematic view of the multi-degree of freedom electromagnetic energy harvester.

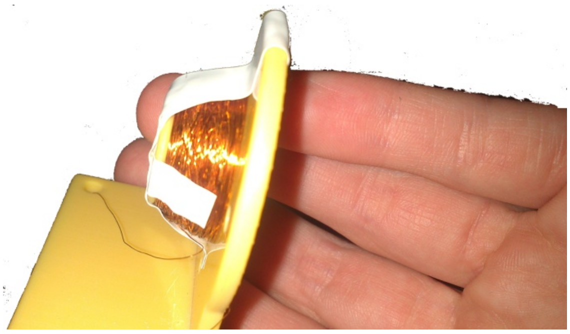

Figure 2. View of one part of the harvester #2 with the coil.

3. Harmonic analysis

Prototypes were tested at with harmonic acceleration at 15 Hz and 0.5g to determine output power on a shaker as shown on Figure 3. Below 0.5g, magnet movement is too small to harvest energy. Below 15 Hz, shaker movement is noised due to its large displacement. Output powers versus load are presented on Figure 4. Optimum load were 200 ohm for both 30 mm and 22 mm diameter prototypes and 150 ohm for both 15 et 11.5 mm diameter prototypes. They fit with coils resistances. Results are summed up on Table 2. We obtained power of 1.2 mW, 500 μW, 350 μW and 80 μW with the 30, 22, 15 and 11.5 mm cavities prototypes respectively. Power densities are closed to 100 μW/cm^3 for all the prototypes excited by an harmonic signal.

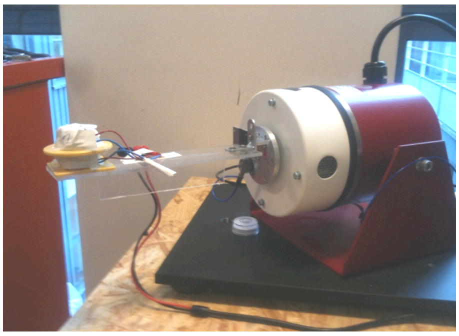

Figure 3. Prototype #1 mounted on the skaker.

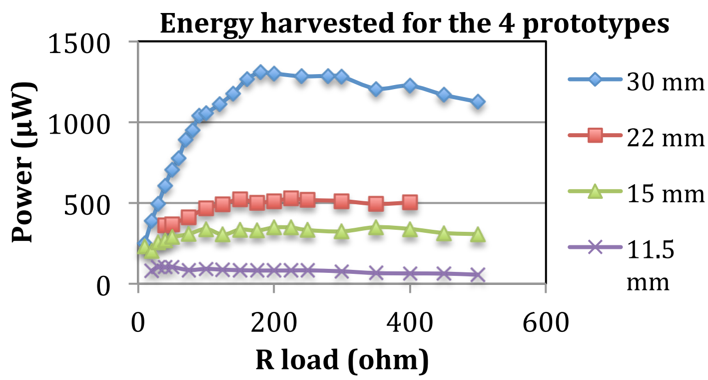

Figure 4. Output power in function of resistance load with an harmonic excitation signal of 0.5g at 15 Hz. Blue diamonds : 30 mm cavity. Red squares : 22 mm cavity. Green triangles : 15 mm cavity. Violet crosses : 11.5 mm cavity.

Table 2. Optimal load and output power measured on each prototype.

Cavity diameter (mm)	30	22	15	11.5
Optimal load (ohm)	200	200	150	150
Output power (μW)	1200	500	350	80

4. Real-time excitation

Prototypes were then mounted on a trolley, which was displaced on a metallic footbridge during 140s to simulate a non-resonant application. Harvesters were plugged to their optimum load and output voltages were measured with a DAQ interface. Acceleration was sensed with an inertial measurement unit. A specific bunch set-up has been developed on Labview to sense both harvesters output and IMU signal.

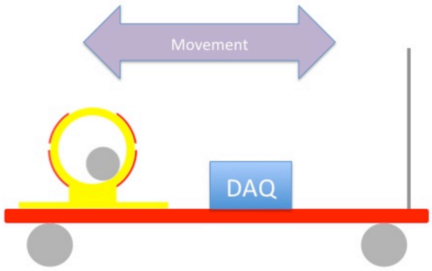

Figure 5. Schematic view of one harvester mounted on the trolley.

Acceleration along z-axis time signal and FFT are presented on Figure 6 and 7 respectively. Prototype 1 output voltage time signal and FFT are presented on Figure 8 and 9 respectively. FFT analysis of acceleration signal shows that a frequency band is excited between 10 and 20 Hz. The variation is probably due to trolley speed change. FFT analysis of both acceleration and output voltage doesn't show a matching between the two spectra.

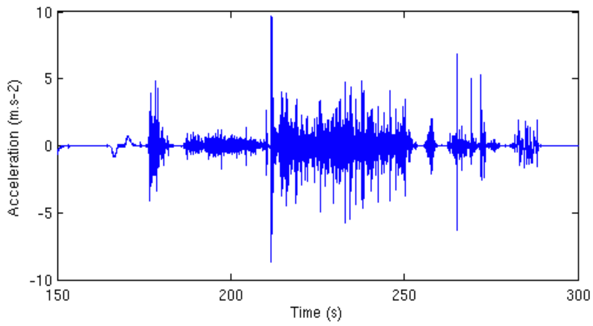

Figure 6. Acceleration signal along vertical axis during the move on the trolley.

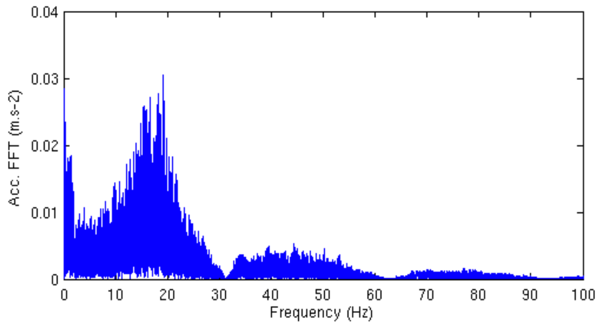

Figure 7. FFT analysis of acceleration signal along z-axis.

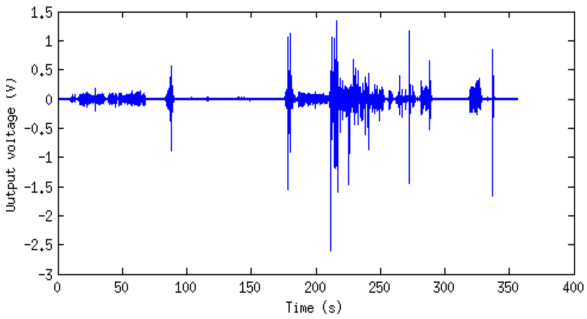

Figure 8. Prototype 1 output voltage.

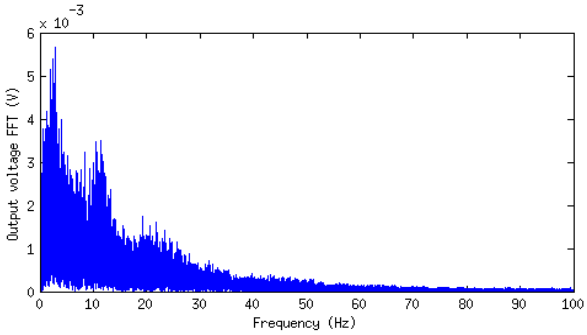

Figure 9. FFT analysis of prototype 1 output voltage.

Results were summed up on Figure 10. There is a strong decrease of the amount of energy when the cavity diameter decreases. For each cavity size, the power per unit of volume is quite constant and around 5 μW/cm^3. We showed that output power of this kind of electromagnetic transducers is proportional to cavity volume. Therefore, downsizing will not give benefits in terms of power density. Size of the prototype will only be determined by the output power required by application.

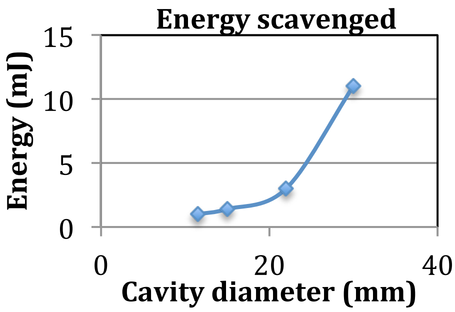

Figure 10. Energy scavenged during 140s on the trolley in function of the diameter of the cavity.

5. Modeling

In order to provide ways of improvement, we made a rough simulation of the classical damped resonant energy harvester because flux linkage gradient is hard to estimate for non-resonant and 3D displacement of our magnet. At low level of excitation, harmonic output voltage could be expected. For higher amplitude of excitation, chaotic behavior is expected. We used the Williams & Yates model [9] adapted by Saha to magnetic energy harvesters [10]. We focus on the voltage output power and how we can improve it by changing the coil winding. Output voltage is a critical issue for magnetic energy harvester because large amount of energy can be extracted at the optimal load but output voltage levels are too weak to be extracted by an electronic circuit.

To be close to the non-resonant harvester, we simulate harvester resonating at 15 Hz with a Q of 2. Electromagnetic damping is negligible compared to structural damping. Furthermore, due to the large air gap between the magnet and coils, we assume that the electromagnetic damping is weak. With these damping conditions and due to the low resonance frequency, optimal load is then equal to the coil resistance.

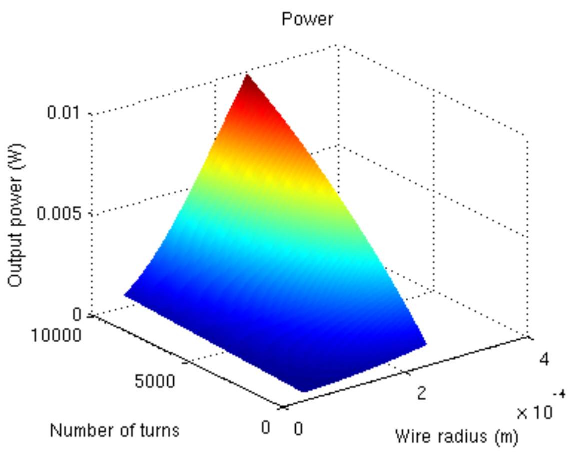

Figure 11. Output power in function of the number of turns and wire radius.

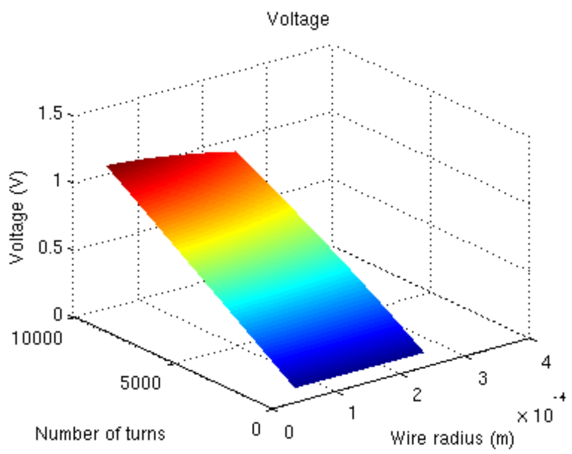

Figure 12. Output voltage in function of the number of turns and wire radius.

We changed the number of turns and the diameter of the coil wire. Output power results are presented in Figure 11. Output power increases when number of coil turns increases and wire radius increase, due to the raise of the electromagnetic damping. At the same time, as shown in **Figure 12**, the output voltage only depends on the number of turns. This result is interesting to increase output power and output voltage to power conversion electronics. As shown on Figure 13, the decrease of harvester impedance is compensated by the increase of the electromagnetic coupling.

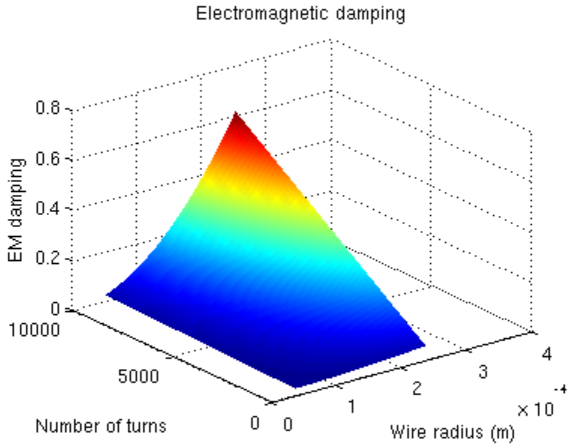

Figure 13. Electromagnetic damping in function of the number of turns and wire radius.

6. Conclusion

We showed that output power of this kind of electromagnetic transducers is proportional to cavity volume. Typical output power of 100 $\mu W/cm^3$ was demonstrated with 0.5g harmonic excitation and 5 $\mu W/cm^3$ when harvesters were excited by the movement of a trolley. Therefore, downsizing will not give benefits in terms of power density. However, the total amount of energy we can obtained with a 30 mm cavity diameter is important and can be useful to power Zigbee applications for instance [11].

We also demonstrated that the output power can be increased by increasing the number of turns and the wire radius with a rough harmonic model. The most interesting thing is the fact that the output voltage only depends on the number of turns, even if coil resistance and optimal resistance become very small when we increase the wire radius.

Acknowledgment

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