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Optimized Electromagnetic Harvester with a Non-Magnetic Inertial Mass

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Abstract

This paper presents an optimization study to decrease the operation frequency and increase the output power of a miniature electromagnetic (EM) energy harvester, by incorporating a non-magnetic inertial mass together with the moving magnet. The harvester coil position has been optimized through FEM, and validated through tests. Experimental studies on the inertial mass showed that increasing the magnet size further increases the resonance frequency due to the increased magnetic forces. Conversely, using a non-magnetic mass over the magnet effectively decreases the resonance frequency (27 Hz to 15 Hz), and increases the generated output power. The power output during operation at even lower frequencies is also improved by adding the non-magnetic mass. The optimized 6 cm^3 harvester generates 0.45 V_{rms} and 110 μW_{rms} output power at 15 Hz and 0.7g peak acceleration.

Keywords: Energy Harvesting, Vibration-Based Energy Harvesting, Electromagnetic Energy Harvester, Optimized Energy Harvester, Energy Harvester Modeling

1. Introduction

Small, lightweight and low-cost network elements enable the self-powered wireless sensor networks by powering them up with energy extracted from environment. The environmental sources mainly appear as solar, thermal and vibration in nature. Vibration is a promising solution to harvest energy for low power wireless network applications

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[1]. Vibration can be harvested from the environment with electromagnetic, electrostatic and piezoelectric technologies. The low resonance frequency due to high inertial mass and the low input impedance that helps to take nearly all of the harvested voltage at the output makes electromagnetic harvesters especially attractive among these structures.

Portable autonomous systems demand miniaturized harvesters, functional at low-frequency ambient vibrations (<20 Hz). However, they should be well optimized to operate efficiently with these size and frequency limitations [2], [3]. Several attempts have been reported in the literature for electromagnetic energy harvester optimization [4–6], but these studies are not focused on decreasing the operation frequency. On the other hand, most of the vibrations occur at low frequencies in nature which makes optimizing the resonance frequency of the harvester a keystone for maximizing the output power.

In this study, the resonance frequency of an in-house EM energy harvester is effectively reduced while maximizing the output power. The EM harvester is modeled with an FEM simulator and the optimum coil position is identified. The EM harvester is further optimized adding a non-magnetic inertial mass on a moving magnet and increasing its performance for low frequency vibrations. Both optimum coil position and improvement at the low frequency performance of the harvester have been verified by the test results.

2. Design and Modeling

Fig.1 (a) shows the structure of the EM energy harvester module where the harvester is composed of a fixed magnet attached to the bottom cap, and a moving magnet in a cylindrical tube. A pick-up coil is wound around the designated cavity on the tube. When an external vibration comes in the direction of motion an alternating voltage induced on the coil due to the variation of the magnetic field. The aim is to harvest larger voltage at low excitation frequencies which can be handled by reducing the resonance frequency of the system. Natural frequency of such systems is defined as $f_n = (1/2\pi)\sqrt{k/m}$ where k is the magnetic stiffness of the system and m is the mass of moving .part. Therefore an additional mass has been attached on the moving magnet to increase the mass of the moving part and decrease the natural frequency. Fig. 1 (b) presents the fabricated prototype where the inertial mass is composed of Ø:10 mm, h:3 mm, 1.7 gram NdFeB magnet and Ø:10 mm, h:5 mm, 6.8 gram tungsten-copper mass. The harvester is modeled by using COMSOL Multiphysics as shown in Fig. 2. In the simulations the inertial mass oscillates sinusoidally at the determined frequency and amplitude levels to model the vibration condition. The moving magnet induces voltage on a 1500 turn coil with 60 μm of wire diameter. Therefore the harvested open load voltage of the system can be obtained for different coil positions.

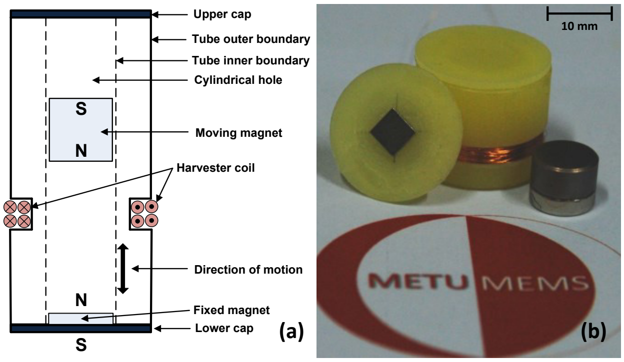

Fig. 1. (a) Structure of the EM energy harvester and (b) the fabricated prototype where the inertial mass is composed of Ø:10 mm, h:3 mm, 1.7 gram NdFeB magnet and Ø:10 mm, h:5 mm, 6.8 gram tungsten-copper mass.

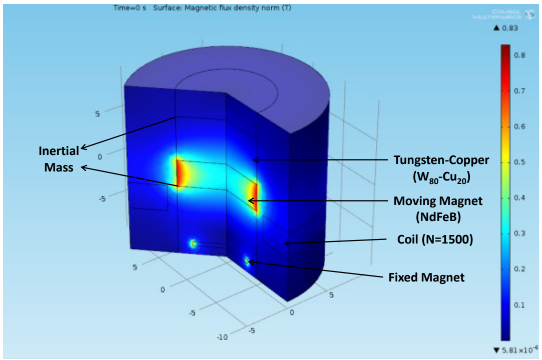

Fig. 2. EM harvester model used to optimize the coil position at COMSOL with 1500 coil turns, fixed magnet and free moving magnet system.

3. Experimental Results and Discussions

EM harvester prototypes with same size and different coil positions are fabricated and tested on a shaker table to validate the optimum coil position and low frequency performance of the harvester. Fig.3 presents the fabricated EM harvester prototypes where prototypes from P1 to P6 have coils located 3 mm to 8 mm from the bottom of the harvester with 1500 coil turns. All of the harvesters have 19 mm of height and 20 mm of diameter which corresponds to 6 cm^3 of volume.

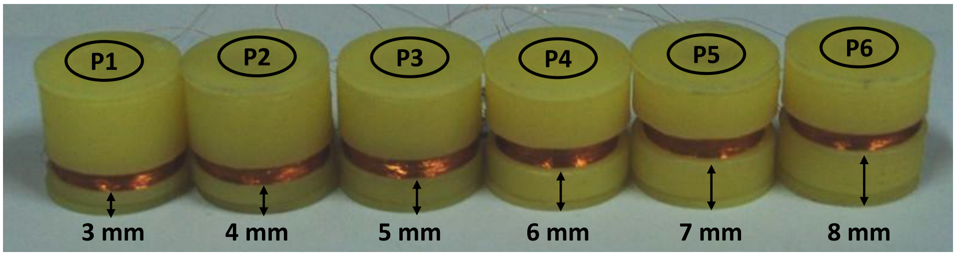

Fig. 3. Fabricated EM harvester prototypes (h:19 mm, Ø:20 mm, 6 cm^3, N:1500).

Fig. 4 presents the peak-to-peak output voltages (V_{pp}) of 6 prototypes at 8 Hz and 0.4g vibration which corresponds to non-resonant operation. Both simulation and test results yield an optimum coil position at 5 mm above the bottom of the harvester. This result is further proved by for resonance condition of the harvesters. Fig. 5 presents the frequency response of the prototypes where P3 yields the maximum output.

The decrease at the resonance frequency and improvement of the low frequency performance of the harvester when the tungsten-copper mass is attached to the moving magnet is illustrated in Fig. 6. Increasing the moving magnet size itself (3.4 to 4.5 gram) results in an increase of the resonance frequency (23 Hz to 27 Hz). This is due to the fact that the magnetic forces and hence the system stiffness increases more than the increment of the inertial mass. Conversely, attaching 4.1 and 6.8 gram tungsten-copper masses on a 1.7 gram NdFeB magnet, pulls the resonance frequencies down to 12 and 15 Hz, and increase the generated voltage. Fig. 7 presents the harvested AC voltage at 15 Hz and 0.7g acceleration where 1.61 $V_{peak\text{-}to\text{-}peak}$ and 110 μW_{rms} output power is generated. Table 1 presents the optimized system specifications. The results show that the presented approach is effective in increasing the harvester performance for low frequency operation within a fixed device volume.

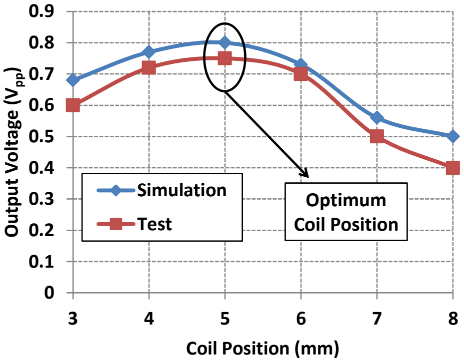

Fig. 4. Simulation and test results of the harvester output for different coil position. (8 Hz, 3 mm peak-to-peak vibration with 0.4g peak acceleration).

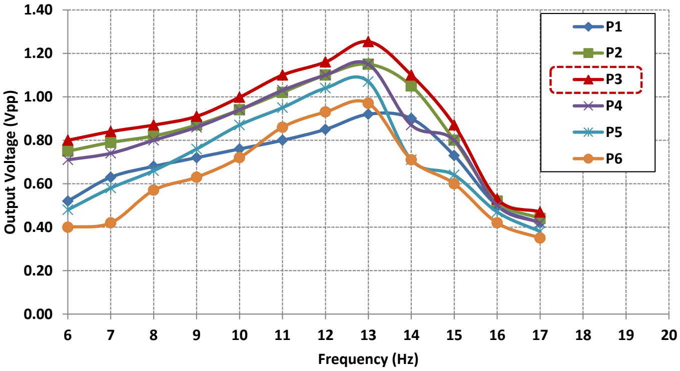

Fig. 5. Frequency response of EM harvester prototypes (P1-P6) at 0.5g peak vibration acceleration. P3, where the coil is placed 5 mm above the bottom of the harvester, yields the maximum output.

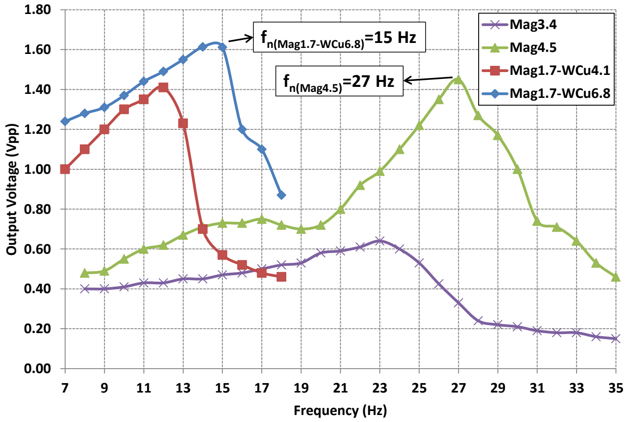

Fig. 6. Frequency response of P3 at 0.7g peak vibration acceleration for different inertial masses, where the maximum output voltage is obtained with 1.7 gram magnet and 6.8 gram tungsten-copper mass (Mag1.7-WCu6.8).

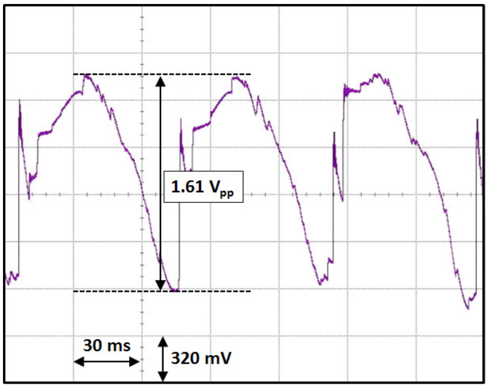

Fig. 7. Harvested AC voltage from P3 with 1.7 gram magnet and 6.8 gram tungsten-copper inertial mass at 15 Hz and 0.7g peak acceleration (Oscilloscope screen).

Table 1. The system specifications.

Harvester Dimensions		Ø:20 mm, h:19 mm, 6 cm^3	Saturation Magnetization	1.2 T
Inertial Mass	NdFeB	Ø:10 mm, h:3 mm, 1.7 gram	Coil Turns	1500
	W_{80}-Cu_{20}	Ø:10 mm, h:5 mm, 6.8 gram	Coil Resistance	450 Ω
Input Vibration		15 Hz and 0.7g peak acceleration	Output Voltage	1.61 $V_{peak-to-peak}$, 0.45 V_{RMS}
			Harvested power	110 μW_{rms}
Fixed Magnet		5.3x5.3x0.5 mm^3	Power Density	18 $\mu W_{rms}/cm^3$

4. Conclusion

This paper presents modeling, optimization and tests of an electromagnetic energy harvester with a non-magnetic mass which helps to reduce the resonance frequency of the harvester (reduced from 27 Hz to 15 Hz) and increase its performance at low frequency vibrations. The optimum coil position of the harvester is found by COMSOL and validated by the test results. The harvester generates 1.61 V_{pp} output voltage with maximum of 110 μW_{rms} output power. The optimized harvester is a good candidate for powering up wireless sensor networks while scavenging low frequency ambient vibrations.

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