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Electromagnetic Generators Employing Planar Inductors for Autonomous Sensor Applications

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Abstract

Autonomous sensors are receiving increasing interest, mostly because they offer flexibility for measurements into inaccessible location. Moreover, measurement application requiring long-lived capability does not commonly match the performance of the batteries. An autonomous sensor consisting of completely embedded structures with no physical links to the outside world, exploiting power from the ambient sources is an alternative solution. An electromechanical power generator is proposed for converting mechanical energy in the form of vibrations available in the measurement environment into electrical energy. The operating principle is based on the relative movement of a planar inductor with respect to permanent magnets. A specific configuration of magnets is proposed and analyzed with the aim to improve the conversion efficiency, increasing the spatial variation of magnetic flux. Furthermore, the proposed configuration can be adopted for its low profile and modularity.

Keywords: energy scavenging, power *generators, energy harvesters and scavengers, electromagnetic power generation.*

1. Introduction

Autonomous sensors are increasingly used in many applications, mostly in measuring physical phenomena. They can be applied for measurement purpose of quantities both in mobile devices, or in protected environments, or in environment where the electrical energy is absent. Their use widens also to applications where the wires connecting the acquisition unit and the sensitive element cannot be used. Considering the small size and wireless nature of such a systems, one major challenge is the energy source. For long-lived systems, energy scavenging from ambient source is an attractive alternative to batteries, which require periodical maintenances. Environmental vibration is a particularly attractive energy source and several examples are reported in literature [1-3]. In this paper an electromechanical power generator is proposed for its low profile, low resonant frequency and a specific configuration of magnets which improves the conversion efficiency, increasing the spatial variation of magnetic flux. Three different resonators have been fabricated. This paper describes the design and analysis of the electromagnetic generator: the formulation of the system's governing equations, the experimental system and several experimental results are reported.

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2. Operating Principle

The most important parameters influencing the design of the proposed generator are conversion efficiency, physical size and external vibration frequency range [4, 5]. The size must be compatible with the application requirements. However, reducing the size of the generator, mechanical resonances tend to increase in frequency.

The moving mass is fabricated by printed circuit board (PCB) technology, a low cost technology. Three PCB shapes with multiple Cu windings were easily fabricated exploiting micro-cutting techniques. The output from each individual coil depends on the magnetic flux change designed by the permanent magnets into the space occupied by the moving masses. The position of the permanent magnets increases the density of the magnetic flux change. The schematic design of vibration-based on the two sets of magnets and the resonator is shown in Fig. 1. The resonator can be schematized as a moveable planar inductor realized over a FR4 substrate (thickness: 300 µm). Three different resonant shapes were fabricated directly using the FR4 substrate. As shown in Fig. 1, the resonator is fixed by its external edge at the cylindrical case and it is placed symmetrically between two sets of magnets. The adopted Neodymium (NdFeB - N35) magnets are shown in Fig. 1. The dimensions of the cylinder and ring magnets were chosen considering the dimensions of the resonators. The thickness of the magnets is 2.5 mm.

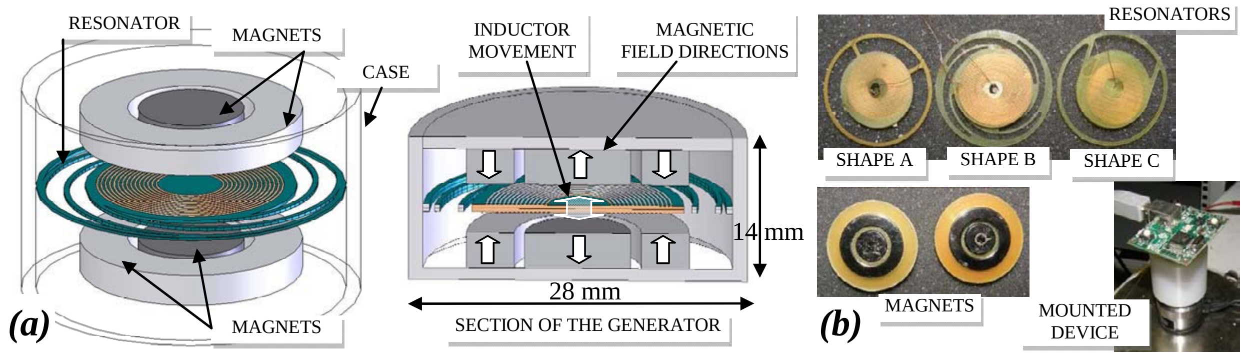

Fig. 1: Electromagnetic generator and cross section through the device (a). Generator components (b).

A mathematical model has been formulated assuming the electromechanical generator as a spring-mass-damper system with a base excitation. The damping coefficient consists of mechanical (c_m) and electrical (c_e) contributions. For a harmonic excitation of the base $y=Y \sin\omega t$ and considering z the relative position of the resonator with respect to the base, the model can be described by the following equations:

$$m\ddot{z} + (c_e + c_m)\dot{z} + kz = m\omega^2 Y \sin \omega t \quad (1)$$

$$c_e \cong (d\phi / dz)^2 / (R_{Load} + Z(\omega)) \quad (2)$$

Where ω is the external vibration angular frequency, m the mass of the resonator, k the stiffness, R_{Load} the resistance connected to the generator, $Z(\omega)$ the impedance of the generator and ϕ the magnetic flux. The electrical damping coefficient depends on the magnetic flux density variation and the impedance of the coil. Furthermore the magnetic flux density distribution has been analyzed as an important parameter to improve the power transfer: Analytical considerations have been formulated and verified by Finite Element Methods (FEM) simulations. Furthermore, in order to determine and predict the practical performance of the device, electromechanical and magnetic simulations have been undertaken (Fig. 2). Comsol Finite Element Methods (FEM) has been used to determine the mechanical behaviors of the generators including the mechanical resonant frequencies. FEM for the magnetic field distribution solution have been employed using Ansoft's Maxwell3D software. In Fig. 2 the B-field plot and the flux line plot show the adopted Mixed Vectors solution. In this condition the resonator is modeled as a planar copper conductor, the two central magnets have opposite magnetization vectors, while the two external magnets have opposite magnetization vectors, but inverted than the other two. This configuration permits to improve the distribution of the magnetic field density in the area between the magnets, as reported in Fig. 2. Simulations reported in Fig. 3 shown that the adopted magnet configuration (Mixed Vectors) improves considerably the electromotive force (e.m.f.).

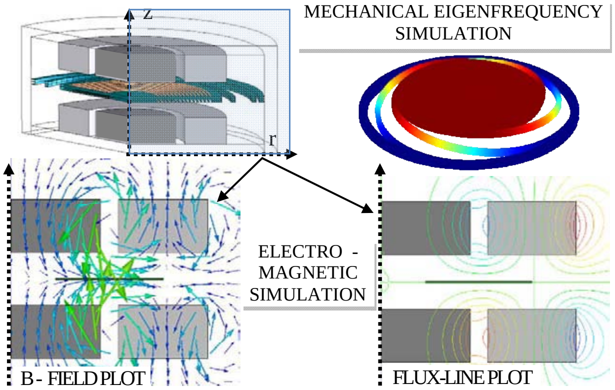

Fig. 2: Simulation plots in mechanical eigenfrequency and electromagnetic domains.

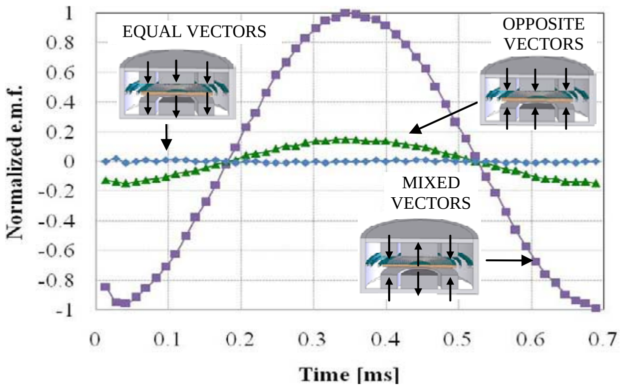

Fig. 3: Simulations results of electromotive force using different configurations of the magnets.

3. Experimental System

In Fig. 4 the block diagram of the experimental set-up for testing of the three fabricated prototypes is reported. An electrodynamic shaker (Bruel & Kjaer 4290) is used to supply mechanical vibrations to the generator under test. Each resonant shape was tested inside the generator case and fixed on the shaker using a particular designed clamp. A 3-axis accelerometer (LIS3LV02DL) with the conditioning electronics (STEVAL-MKI005V1) is mounted axially above the set-up to provide data on the amplitude of the vibrations applied to the generator. The frequency response from each prototype is recorded by a gain/phase analyzer. The resonant frequencies of the three generators were measured by HP4194A. The generators output were applied across a resistive matched load and the voltage were observed on a digital oscilloscope.

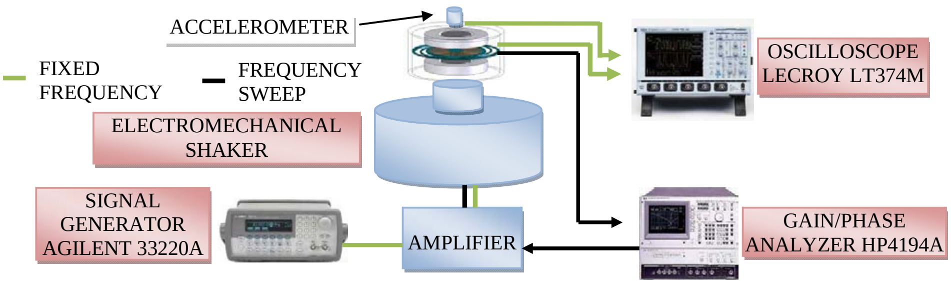

Fig. 4: Block diagram of the experimental set-up for controlled vibration system.

4. Experimental Results

The electrical characteristics of the three resonators measured by an impedance analyzer HP4194A are reported in Table 1. The fabricated inductors can be modeled with a series of an inductance and a resistance, both in parallel with a capacitance. Due to the manual process of windings, the inductors have not the same characteristics. The mechanical resonances were measured using the frequency-sweep setup, as reported previously. While the quality factor for the devices was calculated considering that the ratio of the resonant frequency and the difference between the 3-dB frequencies at each side of the resonance.

Several experimental results are reported in Fig. 5 and Fig. 6; all the data are obtained setting the maximum acceleration of the system at about ±9.81 m/s^2. The variation of power with frequency of prototypes is presented in Fig. 5. In Fig. 6 the output power of the generators versus load resistance measured at its resonant frequency is reported. The maximum of the power is in correspondence with a load resistance that is higher than the resistance of the resonator.

Table 1: Experimental results for the three different resonators.

Resonator	*Resistance [Ω]*	*Electrical Resonance [kHz]*	*Load Resistance [Ω]*	*Mechanical resonance [Hz]*	*Quality Factor Q*	*Power at resonance [µW]*	*Voltage at resonance [mV]*
Shape A	14.1	4910	65	127	31.7	265	185.7
Shape B	27.1	2420	76	102	20.4	290	183.2
Shape C	9.8	13950	47	98.2	27.2	229	148.5

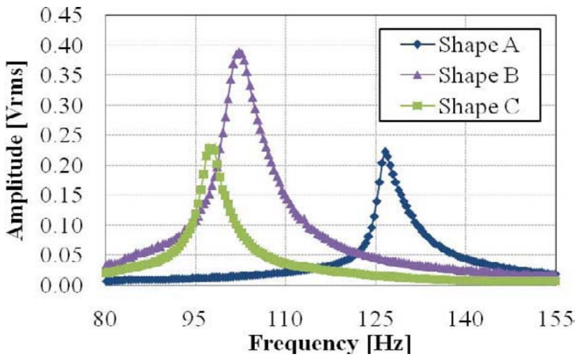

Fig. 5: Output voltages for the resonators for different frequencies at 1-MΩ load resistance.

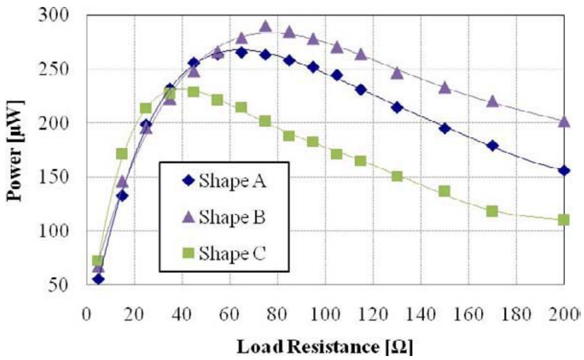

Fig. 6: Output power of the resonators for different load resistances at mechanical resonance.

5. Conclusions

An electromagnetic generator employing planar inductors for autonomous sensor applications was presented. Efficiency of energy conversion was improved by a specific configuration of magnets. Proposed system has been tested using FEM simulations and experimental measurements. Data show that it is possible to generate maximum power and voltage of about 290 µW and 183 mV at about ±9.81 m/s^2.

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