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Nonlinear Electromagnetic Generators with Polymeric Materials for Power Harvesting from Vibrations

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Abstract

The power consumption reduction of electronic devices has allowed supplying them through the harvesting and subsequent conversion of electrical energy that is present in different forms in the measurement environment. Mechanical energy from vibrations is the most common energy source. In the proposed nonlinear electromagnetic generators, the vibrations generate an oscillatory movement of a planar inductor placed in a constant magnetic field, thereby generating a voltage on the coil due to the change in magnetic flux. In the case of low-frequency vibrations, it is necessary to consider two conflicting demands: firstly, in the hypothesis of linearity, the resonant frequency reduction requires an increase in mass and softness of the spring, against the size reduction requires structural stiffening and an obvious reduction in mass. The generator considers a proposed nonlinear elastic behavior of the suspension on which the inductor is placed, improving the system efficiency than the linear case, and especially by introducing behaviors that are not intuitively predictable and potentially exploitable for the proposed purpose. A mathematical model is used to study the nonlinear behaviors; the model is referred to a mass-spring-damper system with harmonic force support. The retraction force is nonlinear by adding a cubic term, and damping is proportional to the speed with an electrical and mechanical component. The generators are built and tested using a specially designed experimental setup. The working frequencies of the generators are between 25 – 40 Hz. The experimental results are compared with results obtained by the mathematical model, getting a good match.

Keywords: energy scavenging; power generators; energy harvesters and scavengers; electromagnetic power generation; nonlinear resonator.

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1. Introduction

Power harvesting modules are a viable solution to the problem of supplying autonomous systems. They also avoid wired connection and contribute to the problem of battery disposal and replacement. The reduction of power consumption of electronic devices has made possible to supply them through the harvesting and subsequent conversion of electrical energy that is present in different forms in the environment. Mechanical energy from

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vibrations is the most common energy source. There are numerous issues that must be taken into consideration for a proper design of a power harvesting module that harvests energy form vibrations. One of the most significant issues concerns the frequency of mechanical vibrations: in many application fields, from industrial [1, 2] to the medical [3], the frequencies are often low. Therefore, the geometric dimensions of the traditional resonating element of a power harvesting module should be a problem, lowering the frequency increases the dimensions, making the systems too big for the required application. A solution can be the use of specific material that has also a nonlinear behavior [4]. In this paper, a nonlinear resonator is proposed, modeled and implemented. The use of polymeric materials for the fabrication of the resonator has allowed on one hand the lowering of the damping constant, thus lowering the resonant frequency, and secondly has allowed higher amplitude of the oscillation given by nonlinear behaviors of the system. A mathematical model has been developed for the analysis of mechanical and electrical behavior. The model allows to understand the resonant behavior of the generator and to assess the linear component. Different plastic materials were tested and different resonators were built. The generators were then studied using a system developed for experimental tests. In the following paragraphs some considerations and experimental results are reported.

2. Operating Principle

The proposed generator is based on the electromagnetic-conversion principle; an inductor is attached to a polymeric structure of circular shape as shown in Fig. 1 and Fig. 2. The resonator is placed between two pairs of magnets having the opposite direction of the magnetic field [5]. The developed resonators are made by polymeric materials and have two shapes A and B (Fig. 2). A planar inductor has been glued on the central surface of the resonator.

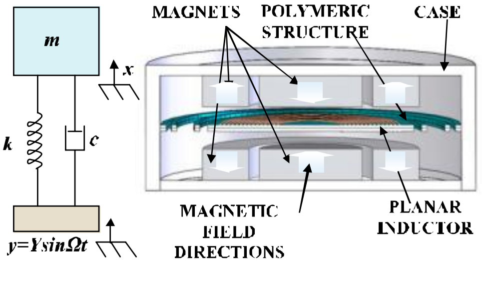

Fig. 1. Electromagnetic generator structure and mechanical model.

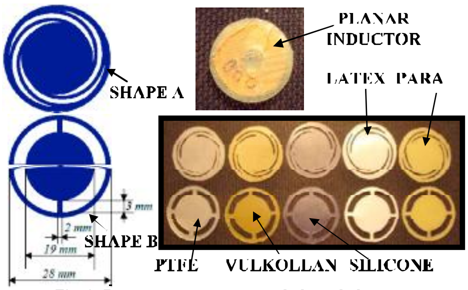

Fig. 2. Resonator components and planar inductor.

A mathematical model has been studied; the generator has been modeled as a spring-mass-damper system in which there are two dampers, one mechanical (c_m) and one electric (c_e), and a nonlinear spring, with a nonlinear coefficient (k_3). Thus,

$$m\ddot{z}+(c_m+c_e)\dot{z}+kz+k_3z^3=mg+m\Omega^2Y\sin\Omega t \qquad (1)$$

With z=x-y (Fig. 1).

After several mathematical procedures an expression that relates the frequency (Ω) with the amplitude (a) can be obtained.

$$\Omega=\left(8a\omega_n^6+3a\beta\left(a^2\omega_n^4+4g^2\right)\pm8\omega_n^4\sqrt{\left(\Omega^2Y/2\right)^2-\left(a\xi\omega_n^2\right)^2}\right)/\left(8a\omega_n^5\right) \qquad (2)$$

With ω_n the natural frequency, $\beta=k_3/m$ and ξ the damping ratio.

The mathematical model was simulated using Matlab, which allows understanding the influence of various parameters on the behavior of the generator in frequency and amplitude. Five different types of polymeric materials have been chosen to manufacture the resonators (Fig. 2): PTFE, Vulkollan, Silicone, Latex and Para. A planar inductor has been realized using a wire with a diameter of 0.1 µm. The planar inductor has 280 windings, the equivalent circuit parameters have been measured by an impedance analyzer (HP4194A). The resistance is 22.51 Ω, the inductance is 242 µH, and the resonant frequency is 3405 kHz. 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.

3. Experimental System

In Fig. 3 the experimental system used for the generator characterization is shown. An electrodynamic shaker (Bruel & Kjaer 4290) is used to supply mechanical vibrations to the generator under test. The sinusoidal excitation is supplied by a function generator (Agilent 33220a) programmed by PC using the GPIB cable. Each resonant shape was tested inside the generator case and fixed on the shaker using a particular designed clamp. Two different analysis have been undertaken, a frequency analysis to study the mechanical resonant frequency and a power analysis to study the behavior with different resistive loads. The frequency response from each prototype has been recorded by an optical sensor (OptoNCDT 2200) and the output was measured by a multimeter (Agilent 34401 A). The voltage signal of the generators with no load condition was measured by a second multimeter. A power analysis has been conducted as well; a 3-axis accelerometer (LIS3LV02DL) and the conditioning electronics (STEVAL-MKI005V1) were mounted axially above the setup to provide data on the amplitude of the vibrations applied to the generator. The generators output were applied across a resistive matched load and the voltages were measured by a multimeter.

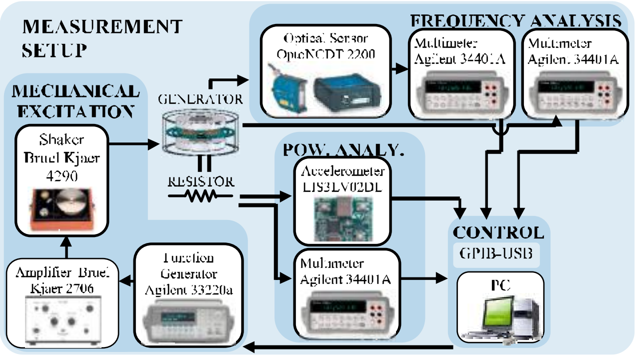

Fig. 3. Block diagram of the experimental setup for the controlled vibration system.

4. Experimental Results

The frequency characterization was performed to evaluate the generator resonant frequencies and the output voltage for each resonator, reported in Table. 1; all the data are obtained with a fixed excitation of about 9.81 m/s^2.

Table 1. Generator results with frequency analysis.

Materials	Resonant Freq. [Hz]	Vout max [mVrms]
Para	36.8	104
Silicone	27.3	81
Vulkollan	28.6	66
PTFE	30.2	90
Latex	41.0	378

Table 2. Generator results with power analysis.

Materials	Resistance [Ω]	Power [mW]
Para	39	0.011
Silicone	22	0.027
Vulkollan	22	0.020
PTFE	22	0.041
Latex	33	0.153

In the graphs and tables, the experimental data of resonators are labeled as the polymeric material and "Para" and "Latex" have shape B, while the others have shape A. Due to nonlinear behaviors, "Para" and "Latex" show the highest output voltages (Table 1). All the generators have lower resonant frequencies than in linear case [5].

The resonators made with "Latex" and "Para" have a strongly nonlinear behavior permitting high amplitudes (Table 1). In Fig. 4, the experimental results are compared with the simulation results; the trend obtained using the experimental data and the trend obtained from simulated tests show a good agreement. In Fig. 5, diagrams of the generated power with different applied loads are shown. "Latex" generates about 0.16 mW at 30 Hz, the data are reported in Table 2 as well. The use of polymeric materials for the resonant generator realization has allowed the lowering of the resonant frequency and the increase in power output compared to linear generators.

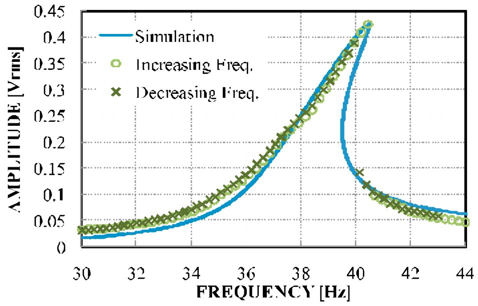

Fig. 4. Comparison between simulation results and experimental data (Latex).

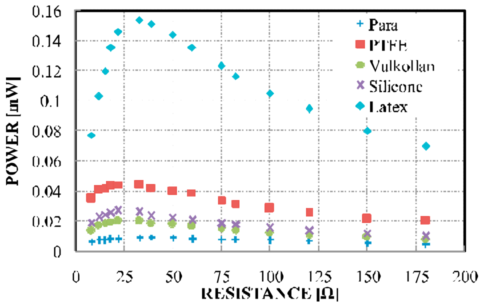

Fig. 5. Output power of the generators for different load resistances at mechanical resonances.

5. Conclusions

Nonlinear electromagnetic generators with polymeric materials for power harvesting from vibrations were presented. A mathematical model was developed for the analysis of mechanical and electrical behavior. An experimental system was developed and several tests were performed. The use of polymeric materials for the construction of the resonator made possible to lower the resonant frequencies of the generators, than in the linear case. Furthermore, nonlinear elastic behavior of the suspension on which is placed the inductor has improved the harvested energy than the linear case. The proposed generators represent an interesting solution for powering low-power systems by using low-frequency vibrations.

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