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Coupled multiphysics finite element model and experimental testing of a thermo-magnetically triggered piezoelectric generator

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Abstract. This paper deals with the coupled multiphysics finite element modeling and the experimental testing of a thermo-magnetically triggered piezoelectric generator. The model presented here, which has been developed in ANSYS software and experimentally validated, promotes a better understanding of the dynamic behavior of proposed generator. Special attention was put into the coupled multiphysics interactions, for instance, the thermal-dependent demagnetization of soft magnetic material, the piezoelectric transduction and the output power. In order to characterize the power generator, many finite element simulations were conducted, included modal and transient analysis. To verify the effectiveness of the model, a prototype was built and tested. The findings thus obtained were compared with simulation results. Obtained results describe for the first time a fully coupled model of an innovative approach for thermomagnetic energy harvesting. Moreover, the total volume of our harvester (length x width x height: 20 x 4 x 2 mm) is 85 times lower than that of previous experimental harvester.

1. Introduction

Thermomagnetic generation of electricity is based on a change in magnetic properties of soft magnetic materials such as nickel-iron or iron-silicon alloys, which occurs when those materials, that are easily magnetised and demagnetised, are under temperature variations [1]. These temperature-dependent properties can be deployed for different purposes, for instance, power supply transformers, electromagnets, and quite recently, for energy harvesting applications [2]. Carlioz *et al.* [3] reported a thermomagnetic energy harvester able to harness the ambient thermal energy from a variation in environmental temperature and convert it into electrical energy to power wireless sensors. However, a key limitation of their power generator is that it is too bulky to be integrated into a wireless sensor node and studies on predictive modeling of such device are still lacking. With this goal, the present work seeks to offer a finite element model able not only to miniaturize the power generator but to predict its dynamic behavior, while maximizing its output energy. Furthermore, a test prototype is characterized to verify the validity of developed model. The remainder of the paper is organized as follows: the proposed power generator will be discussed in Section 2. The finite element model is presented in Section 3. Section 4 shows the experimental measurements of test prototype. Finally, Section 5 concludes with a summary.

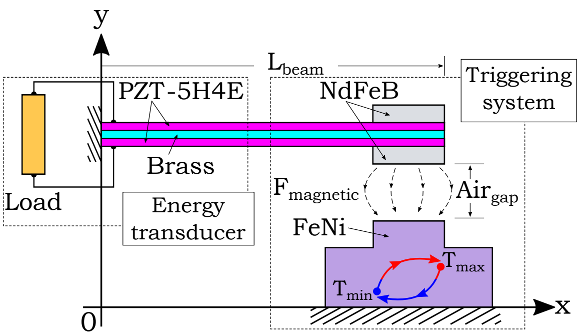

Figure 1. Side view of power generator. The variations in temperature on soft magnetic material triggers the piezoelectric transduction. Output power is dissipated on a load resistor, R_L.

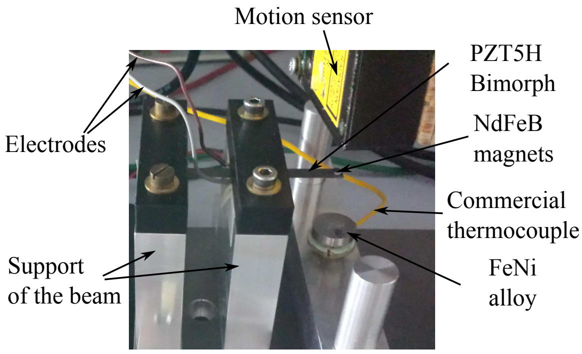

Figure 2. Test prototype. The in-house developed test bench is able to produce necessary conditions for the operation of the generator.

2. Design

As shown in Figure 1, the power generator has two main sections according to their respective functions: the energy transducer and the triggering system. The energy transducer is composed of a piezoelectric bimorph-type cantilever beam, namely PSI-5H4E from Piezo Systems, Inc with a series-type polarization. Concerning the triggering system, it consists of two permanent magnets (NdFeB), that are attached to the free end of the beam, and a soft magnetic material (FeNi), fixed under the free end of the beam, forming an air gap.

2.1. Working principle

Our power generator is based on a piezoelectric transduction, that is triggered by the interaction between a constant magnetic field and cycled variations in temperature acting along a permanent magnet and a soft magnetic material. The generator has two operation states: the closed position and the open one. In the initial state (open position), at a cold environmental temperature, the soft magnetic material is magnetized so the cantilever beam is pulled-down due to magnetic force. After, at closed position, when the environmental temperature increases, the magnetic properties of soft magnetic material change from ferromagnetic to paramagnetic, causing the magnetic force to dissapear. The beam is pulled back to its initial state because of the spring-back force of the beam. This process of pulling-down and pulling-back of the beam is periodically repeated as long as the energy harvester is placed in an environment with cycled variations in temperature. The basic generator parameters used in both simulation and test prototype have been listed in Table 1.

3. Modeling

Many finite element models have been reported to analyse the operation of energy harvesters. However, most of them do not take into account the prediction of the power output. We developed, in ANSYS software, a model able to predict the dynamic behavior and output power of proposed generator.

3.1. Configuration of finite element model

Our 2D model considers a sandwich cantilever beam with piezoelectric layers of opposite polarization, on top and bottom of a reinforcement brass layer, a pair of permanent magnets attached to its free end, a direct connection of a load resistor to piezoelectric layers, and a ferromagnetic block fixed under the free end of the beam. The adhesive thicknesses of the

Table 1. Basic parameters of proposed thermo-magnetically triggered piezoelectric generator.

Parameter	Symbol	Value	Units
Beam length	L_{beam}	20	mm
Beam width	W_{beam}	4	mm
Beam thickness	Th_{beam}	380	μm
PZT thickness	Th_{PZT}	130	μm
Brass thickness	Th_{brass}	120	μm
Magnet thickness	Th_{magnet}	1	mm
Air gap	Th_{air}	2	mm

beam are neglected because they are very thin compared to rest of the layers thicknesses. The element PLANE223 is used for modeling piezoelectric layers. Reinforcement layer is modeled by element PLANE183. For simulating permanent magnets, soft magnetic material and air gap, element PLANE13 is applied. Load resistor is simulated with CIRCU94 electric element. The pair magnetic contact, which occurs during the open-to-closed position switching, is modeled using CONTA172 and TARGE169 elements. Firstly, a modal analysis is carried out aiming at exploring the natural resonance frequency of the system. Special focus was given to modal damping by using QRDAMPED method. Secondly, a full transient analysis is realized to study the dynamic operation of the generator. The considered input, the variation in temperature as function of time, is as follows: the temperature of ferromagnetic alloy, is 45°C and kept constant for a short time. It is then decreased to 25°C and maintained there for a larger period of time before being increased to 45°C. The finite element model couples these time-dependent variations in temperature to temperature-dependent magnetic properties of the triggering system to compute the magnetic force and the mechanical displacement. Furthermore, the mechanical strain piezoelectric effect are coupled to calculate the electrical charge. Finally, the electrical charge is converted into voltage across the load resistor resulting in the dissipated power output of the model.

4. Experimental testing

Our test prototype consists in a platform for fixing both the cantilever beam and the ferromagnetic material. A DC current of 3A, flowing across the support base of the FeNi material, is periodically applied and cut to obtain cycled variations in temperature. To measure the temperature on the ferromagnetic material, a thermocouple type K is introduced, by a drilled hole, to the FeNi alloy and the output signal is then displayed in a multimeter in Celsius degrees. The electrodes of the energy transducer are connected to the terminals of a resistance decade box *CENTRAD DR07*. Through an oscilloscope *Tektronix DPO3014*, the differential voltage across the load resistor is measured. A laser-based motion sensor *ELITEC LAS-2010* is used to monitor the tip displacement of the beam. Figure 2 presents the developed test bench.

4.1. Results analysis

The dynamic operation of the power generator has been studied through many cycles of temperature variations. The values of temperature, cold and hot, were 25°C and 45°C, respectively. At cold temperatures, the generator is in closed position until a raise in temperature produces the closed-to-open position switching. The electrical power harvested was determined as a function of the load resistor. To determine the optimal load resistor value, the average of the dissipated power during a cycle of operation is calculated. Simulation and experimental results are illustrated in Figures 3, 4, and 5.

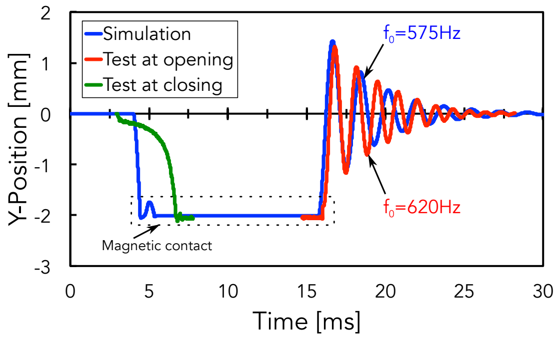

Figure 3. Tip displacement when $R_L = 10k\Omega$ is connected. Clearly, on simulation model, the rate of decreasing temperature is smaller than the experimental one. Magnetic contact is present at closed state.

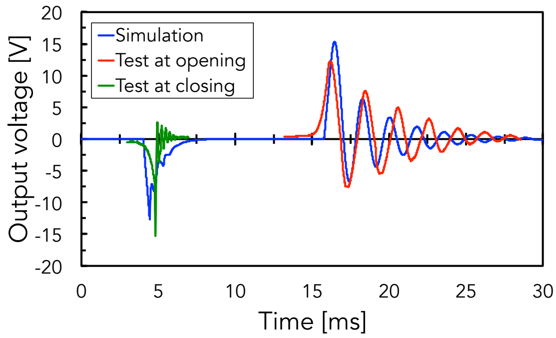

Figure 4. Output voltage when $R_L = 10k\Omega$ is connected. During the open-to-closed position switching, the output is a peak of voltage, whereas a sine wave output is exhibited during closed-to-open switching.

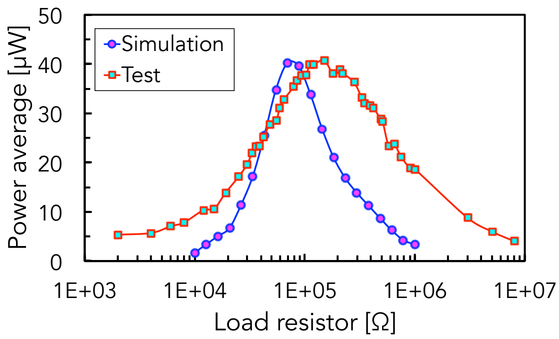

Figure 5. Harvested electrical power average as a function of load resistance. The power average during a complete cycle of operation is considered to find the optimal value of load resistor, $R_{Loptimal}$.

5. Conclusion

This paper has proposed a solution for thermomagnetic energy harvesters design. The maximum average power and average power density is 40μW and 250μW/cm^3, respectively. The data obtained show that smaller generators than that previously reported in [3] are feasible. Current research involves finding appropriate materials that favor the generator optimization.

Acknowledgments

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