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## EXPERIMENTAL INVESTIGATION OF PIEZOELECTRIC VIBRATION-BASED ENERGY HARVESTING WITH SHAPE MEMORY ALLOY ELEMENTS

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**Abstract.** Piezoelectric vibration-based energy harvesting systems have an inherent disadvantage when operating in linear conditions. The maximum power output for these systems is obtained by matching their resonance frequencies with the ambient source frequencies, but significant reduction of the output power occurs for small source frequency deviations, resulting in a narrowband harvester system. Nowadays, many researches have included different kinds of nonlinearities to increase the bandwidth of the energy harvesters producing a broadband energy harvesting system. This paper presents an experimental analysis of a system based on a new concept with the synergistic use of smart materials considering a piezoelectric energy harvester combined with shape memory alloy (SMA) helical spring proposed to improve system performance through the temperature control. The main idea is to use temperature variations to change the power amplitude and also to shift the peak of the power curve as a function of frequency. The piezoelectric-SMA system is temperature dependent and two major mechanisms are used to modify the system dynamics: change in stiffness and dissipation due to hysteresis promoted by temperature variations of the SMA element. It is shown an analysis about output power and efficiency considering thermo-electro-mechanical aspects. Experimental results shows that the proposed methodology can be used to increase the operational bandwidth of the energy harvesters systems.

**Keywords:** Energy harvesting, smart materials, piezoelectric materials, shape memory alloys, experimental analysis

### 1. INTRODUCTION

Vibration-based energy harvesting is a nowadays interesting topic due to the possibility of using alternative sources of vibration to power portable devices eliminating the need for frequent battery replacements or power cables. The majority of literature addresses linear electric-mechanical conversion approaches (Erturk et al., 2010; Kim et al., 2010). Once the excitation frequency is tuned to the natural frequency of the system, a maximum output power is captured. This strategy results in a narrowband harvester system since the ambient vibrations are usually frequency-varying or random with energy distributed over a wide frequency range (Tang et al., 2010).

Several researchers have been working to enhance the frequency response of energy harvesters introducing different nonlinearities into the system. The possibility to transform an energy harvester in a broadband system can be achieved by different methods: using bistable structures (Erturk and Inman, 2011), using mechanical preload (Leland and Wright, 2006), including symmetric tip mass (Bai et al., 2014), varying the geometry of the structural energy harvester (Friswell et al., 2012), including mechanical end-stops (Basset et al., 2014).

An interesting nonlinear approach to enhance energy harvesting system capacity is the synergistic use of smart materials. The inclusion of shape memory alloy (SMA) elements can enhance system performance. SMAs unique properties related to solid phase transformations can be exploited either to change stiffness or to dissipate energy. Avirovik et al. (2013) developed a hybrid device coupling piezoelectric element with SMA for dual functionality, both

as an actuator and an energy harvester. Silva et al. (2015) employed a numerical analysis of an SMA-piezoelectric energy harvesting system where the thermomechanical behavior of SMA is described using a constitutive model with internal variables. Results indicated that the inclusion of the SMA element can be used to extend the operational range of the system.

This work develops an experimental investigation of a piezoelectric vibration-based energy harvesting system combined with shape memory alloy spring in order to improve system performance through the temperature control. Details of the system dynamics can be seen through frequency responses, force versus displacement and phase diagrams. Spring temperature is estimated through a contactless infrared sensor. Also, output power and efficiency are calculated during the testes. Results suggest that the incorporation of the SMA element can be used to extend the operational range of the system, adjusting the system performance in terms of energy harvesting. Even with small levels of efficiency, output power achieved by the device presents enough amount of power to supply small scale devices.

## 2. EXPERIMENTAL PROCEDURE AND METHODOLOGY

This section describes experimental tests which analyzes the vibration-based energy harvesting system combining piezoelectric and shape memory alloy elements. A piezoelectric sample (Midé Technology) is bonded to a cantilevered beam made of aluminum material (275 mm x 30 mm x 2 mm). The cantilever beam is clamped to an electromagnetic shaker (V350-DataPhisics Signal Force). A laser displacement transducer (Micro-Epsilon  $\mu\epsilon$  model optonNCDT2200) is used to measure the free end displacement and the base beam acceleration is measured by PCB333B40 accelerometer to check the performance of base beam acceleration in transverse direction. A shape memory helical spring with a mean diameter of 5.6 mm, wire diameter of 0.8 mm and length of 25 mm (Dynalloy 3-642 NiTi spring tension model) is attached to the free of the beam, with the other spring end fixed to a rigid support. A load cell *Leader CS-5* is used to measure the restitution force provided by the SMA spring. At the beginning of each test, the SMA helical spring in martensite phase at room temperature (24°C). Temperature variations on SMA spring are induced through Joule effect by the application of electric current using a stabilized current source (TOE 8950). Harmonic excitation is used for the frequency response measurement through a data acquisition system (CDAQ-9174 National Instruments). Also, steady state anlysis are carried out.

With the objective to make an energetical analysis, an electrical resistance (150k Ohms) is used and output power calculated by the square of electrical voltage measured in piezoelectric element divided by the resistance. Also, to obtain information about the energy used to heat the SMA spring and consequently the input power added to the system, a commercial 10A-750mV shunt resistance is employed. So, electrical tension can be measured trough the shunt resistance and electrical current estimated. Electrical voltage trough the SMA spring terminals are measured provide information of the input energy used to heat SMA spring. Efficiency analysis is then obtained dividing output power by input power. A schematic of the experimental setup is shown by Fig. 1.

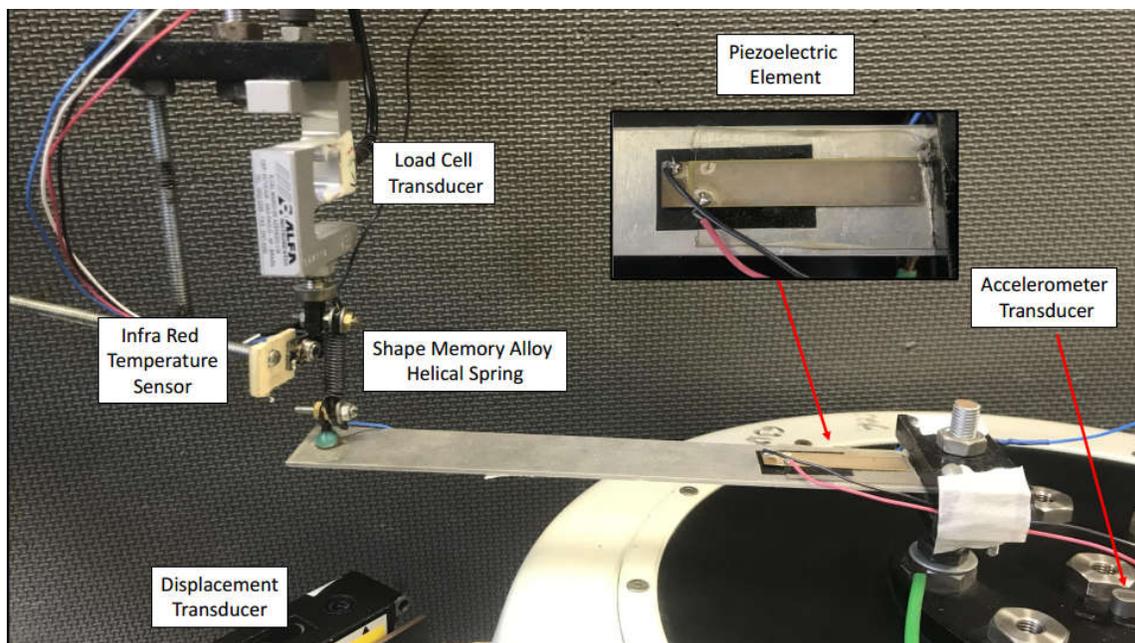


Figure 1 – Experimental dynamical setup.

First, a quasi-static mechanical characterization of the SMA spring are performed at different constant electric currents (0 A, 1.5 A and 2.5 A) using an Instron machine (5966 model) by assuming a controlled displacement rate of 5 mm/min for mechanical loading–unloading procedure. Figure 2 presents results of force–displacement curves for each electric current value where a change between shape memory (0 A) and pseudoelastic effects (1.5 and 2.5 A) can be observed as the electrical current values increase. Force x displacement diagram for null electrical current condition shows a shape memory effect behavior, indicating an element stiffness of near 150 N/m associated to the presence of martensite. The pseudoelastic effect is present when the electric current is equal to 1.5 A. Note that, the increase of electric current causes the increase of the critical stress level where phase transformation begins to occur. Therefore, the temperature increase is related to higher positions of the hysteresis loop in the stress-strain space, associated to higher values of critical transformation stress. For 2.5 A it is not possible to observe the hysteresis loop for the same load levels showed for 1.5 A. For these conditions the presence of austenite is expected, and an element stiffness of near 300 N/m is observed.

The temperature measurement of the SMA helical spring is a difficult task in dynamic tests due to reduced diameter of the SMA wire and its geometry. Temperature changes in SMA spring can be monitored using a contactless infrared sensor (MLX90614 GY-906) right positioned in front of the up spire and data acquired by an Arduino Uno board. The different SMA behaviors, shape memory and pseudoelastic effects, are associated with electrical current values and temperature in Celsius degree. Before dynamical tests run, attention to spring temperature were carefully conducted. It was considered thermal equilibrium between heated SMA spring and room air respectively: 0.0 A to 24 °C, 0.5 to 29.6 °C, 1.5 to 59.4 °C and 2.5 to 114.6 °C. Figure 2 (d) show a diagram relating measured temperature with applied current. Those tests were conducted for spring free of stress and pre extended spring to obtain a correlation between SMA temperature and applied electrical current. Due to spiral wire different geometric configuration that can affect the convection phenomenon and electrical resistivity phase dependence it's possible to see a difference between the two conditions. These results were obtained under static conditions and should be considered as a temperature estimation. In dynamic tests the SMA helical spring can be subjected to different convection conditions.

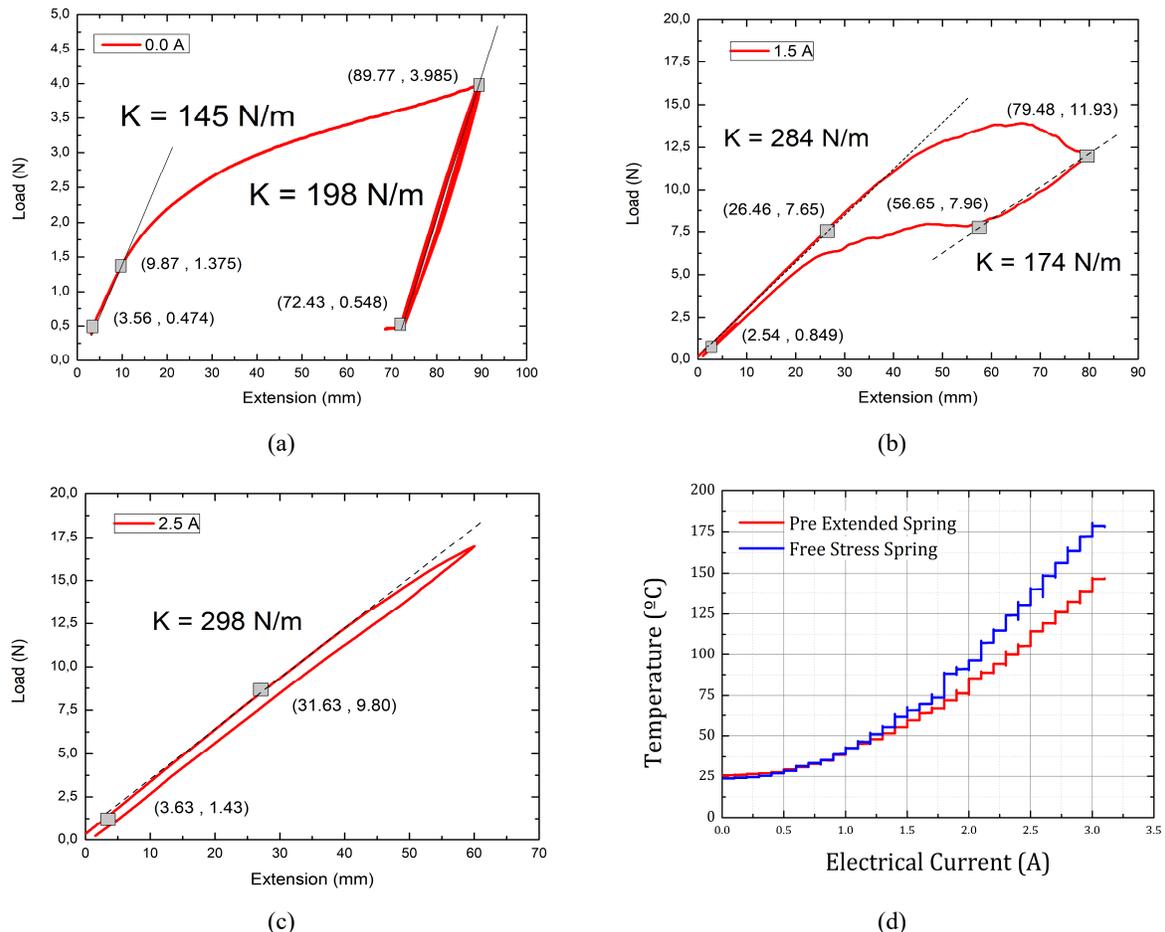


Figure 2 – Quasi-static tensile tests: (a) 0.0 A. (b) 1.5 A. (c) 2.5 A. (d) Temperature x Electrical current diagram.

### 3. RESULTS AND DISCUSSION

A dynamical approach is on focus now considering dynamical tests with acceleration base excitation. First, a pre-extension of 40 mm was applied on the SMA spring to avoid the contact between spires. Tests with a base acceleration excitation amplitude of 1g were developed for 4 different electrical current values applied to the SMA spring: 0.0, 0.5, 1.5 and 2.5 A. Frequency excitation from 30 to 37 Hz with a sweeping rate of 0.1 Hz/s were applied to the system. The following resonance frequencies were identified for each of the 4 electrical current conditions: 33.0 Hz (0.0 A); 33.1 (0.5 A); 33.7 Hz (1.5 A) and 35.6 Hz (2.5 A). Tests with fixed frequency excitation with 1000 cycles performed at the 4 resonance frequencies were developed to characterize the system behavior operation under these conditions.

Figures 3 (a), (b), (c) and (d) shows the tip displacement, output power obtained from the piezoelectric element, the input power and calculated efficiency versus frequency curves considering the 4 electric current values applied to the helical SMA spring. A comparison between the curves for 0.0 A and 2.5 A shows that a peak shift of near 2.6 Hz occurs for both electrical tension and displacement curves, which represents a variation of near 7.8% in relation to the resonance frequency associated to 0.0 A, indicating that temperature can be used to adjust the dynamic response of the system and increase the bandwidth of the energy harvester system.

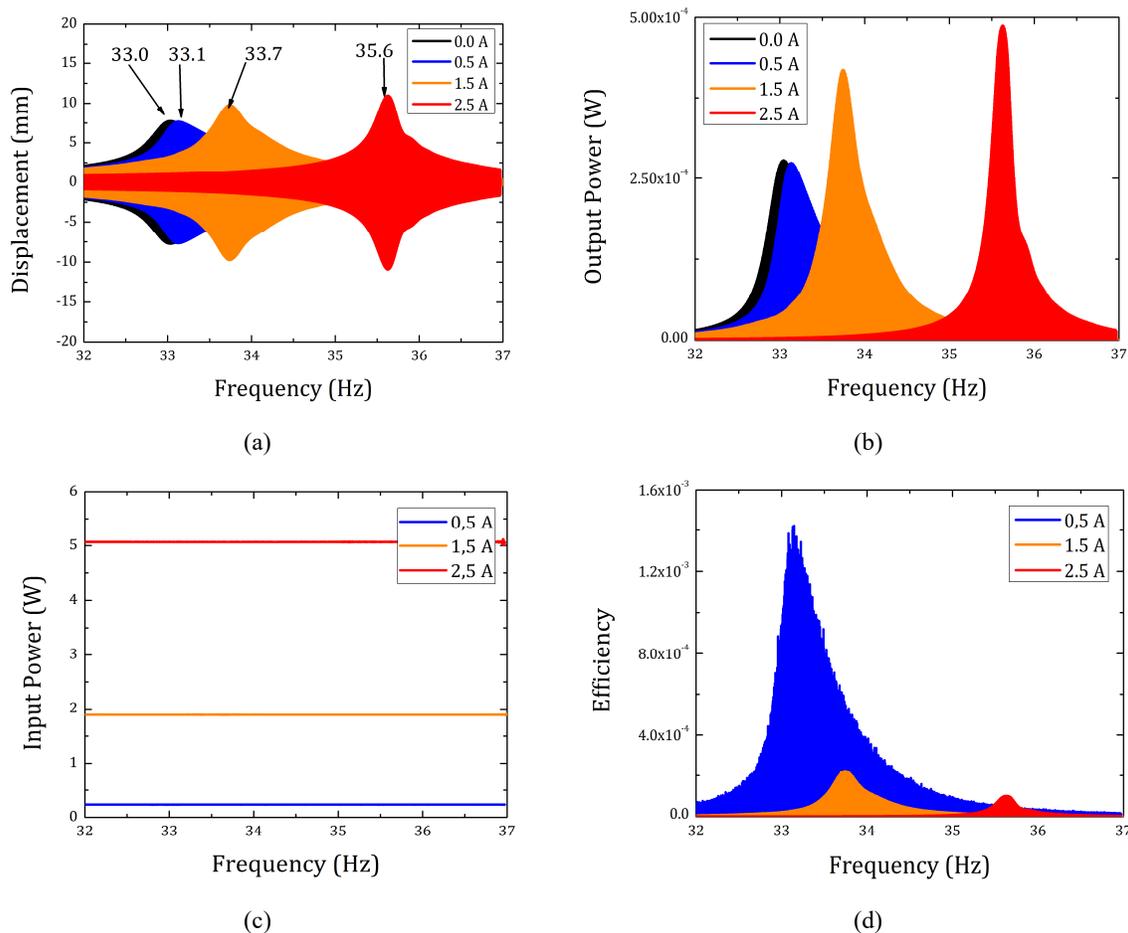


Figure 3 – (a) Electrical tension-frequency curve. (b) Tip displacement-frequency curve. (c) Device Output Power. (d) Device Efficiency

Figure 4 (a) shows experimental data obtained from tests developed at fixed resonance conditions for the 4 applied current conditions. The load x displacement curve presented shows that the current increase promotes a rise in the average stiffness and a variation in the dissipation associated to the hysteretic behavior of the SMA element. Fig. 4 (b)

shows the steady state of electrical tension from a starting frequency of 30 Hz to the resonance frequency for each of the 4 conditions. The same base excitation amplitude used in the previous cases are considered (1.0 g).

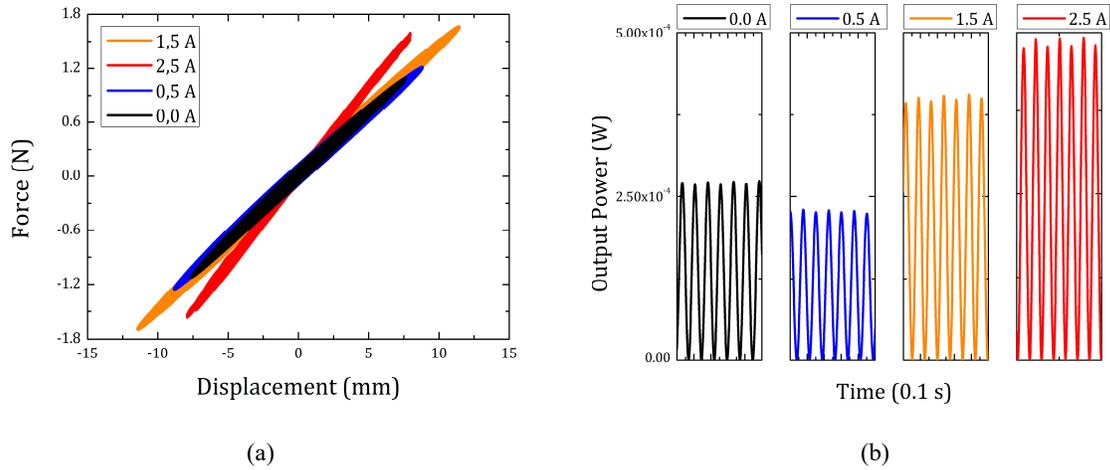


Figure 4 – (a) Force-displacement diagram (b) Piezoelectric output voltage. Base acceleration amplitude of 1 g at steady state for 4 associated conditions on resonance frequency.

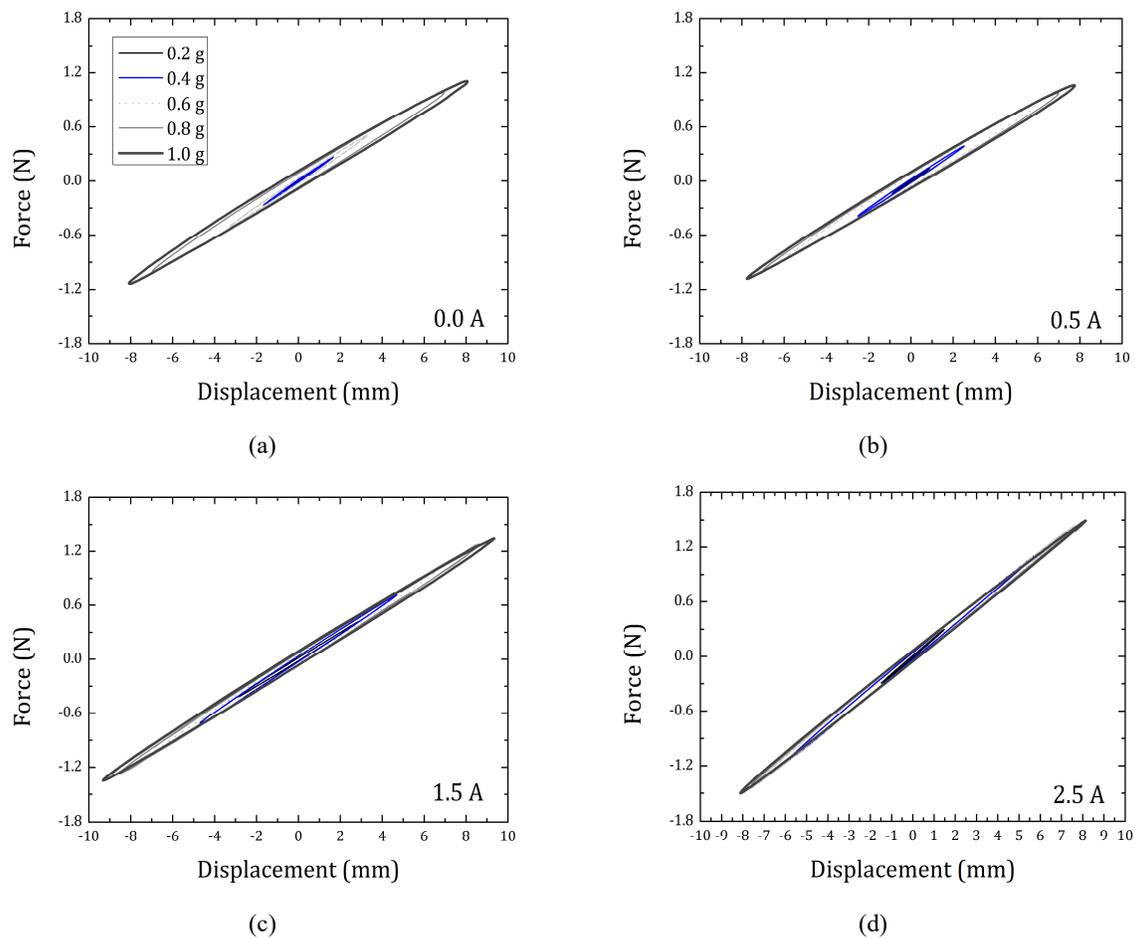


Figure 5 – Stiffness and damping evolution through force x displacement diagram. (a) 0,0 A (b) 0,5 A (c) 1,5 A (d) 2,5 A.

Figure 5 illustrates stiffness and damping evolution during an increase of acceleration base amplitude by consequently changes in hysteresis loop. At fixed frequency loops, amplitude of base acceleration increases from 0.2 to 0.4g, 0.6g, 0.8g until 1g. It's possible to observe martensite transformation by mechanical load occurring more evident with 0.0 A and 0.5 A. As expected, dynamical load at forcing frequency presented in experimental analysis produces a short increase in spring temperature, promoting martensite transformation and hysteresis. It's possible to see a softening in spring stiffness and hysteresis loop when dynamical load is running.

For higher temperatures (1.5 A and 2.5 A) transformations stresses increase and mechanical load is not able to promote transformation no longer. Hysteresis loops tends to get thinner with spring large temperatures. For 2.5 A, almost no difference can be observed from low levels of base acceleration to high levels.

Figure 6 shows the output power and efficiency envelope curves as a function of exciting frequency for the four temperatures presented. One can see a trend by connecting the picks of output power and efficiency and that booth curves cross itself. Output power tends to increase for larger displacement. As expected, piezoelectric effect tends to achieve saturation at a level where deformations are not able to promote the increase of electrical voltage and output power reach to a maximum level. On the other hand, efficiency tends to decrease for conditions presented. Heating shape memory alloy spring for larger temperatures by the increase the furnished electrical current results in high levels of input power compared to output power. However, it contributes to extend the devices operational range and this kind of devices has a better use near available heat fonts to make heating control instead to use an electrical current.

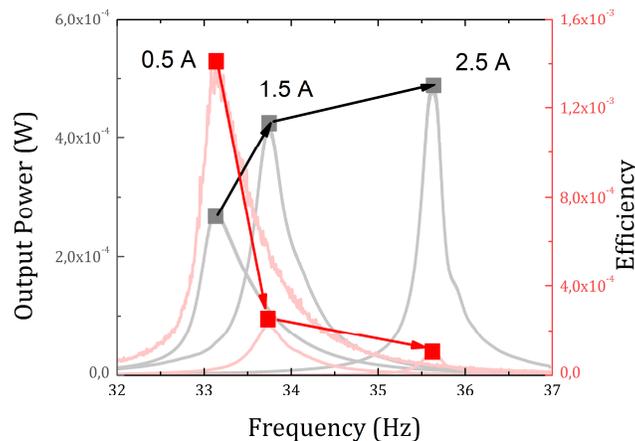


Figure 6 – Output power and efficiency tendencies.

#### 4. CONCLUSIONS

Mechanical oscillations frequencies available in nature normally can be random or unpredictable. Optimal conditions for piezoelectric energy harvesters require the operation over a wide frequency range which motivates the development of adaptative devices. In this paper, an experimental investigation of a system based in the synergistic use of smart materials considering a piezoelectric energy harvester combined with shape memory alloy (SMA) helical spring used to improve system performance through the temperature control is developed. For the system studied the application of an electric current between 0.0 and 2.5 A promotes the shift of the system resonance frequency of near 7.8 % in relation to the frequency associated to ambient temperature (0.0 A). The current increase promotes a rise in the SMA element temperature which affects its stiffness and dissipation associated to the hysteretic behavior, both effects related to phase transformation phenomena.

Experimental results show that the shape memory alloy SMA helical spring can be used to change the nonlinear dynamical behavior of the system and, therefore, increase operational range of piezoelectric energy harvesters making then adaptative devices according to ambient conditions. Output power obtained with the energy harvester studied can be used to supply a low consumption electrical device this work shows experimentally the performance of the energy harvesting with shape memory alloy. Device can operate in regions with elevated output power but low efficiency levels and vice e versa. Efficiency levels achieved with the device still low for the conditions presented and must be improved. Heat sources available in nature can be used to furnish the input power to control for SMA element.

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