

Experimental Investigation of Piezoelectric Vibration-Based Energy Harvesting with Shape Memory Alloy Elements

Arthur Adeodato¹, Daniel Macedo Barreto¹, Brenno Tavares Duarte¹, Ricardo Alexandre Amar de Aguiar¹, Sergio de Almeida Oliveira¹, Luciana Loureiro da Silva Monteiro¹, Pedro Manuel Calas Lopes Pacheco¹, Marcelo Amorim Savi²

¹ CEFET/RJ, Department of Mechanical Engineering - Programa de Pós-Graduação em Engenharia Mecânica e Tecnologia de Materiais (PPEMM), Av. Maracanã, 229, 20271-110, Rio de Janeiro, RJ - Brazil.

² UFRJ - Universidade Federal do Rio de Janeiro, Center for Nonlinear Mechanics, COPPE – Department of Mechanical Engineering, P.O. Box 68.503, 21941-972, Rio de Janeiro, Brazil.

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 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: stiffness change and dissipation due to hysteresis.

Keywords: Energy Harvesting, Smart Materials, Piezoelectric Materials, Shape Memory Alloys, Experimental Analysis

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 (Anton & Sodano, 2007, 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. But, this strategy results in a narrowband harvester system since the ambient vibrations are usually frequency-varying or totally random with energy distributed over a wide frequency range (Tang et al., 2010).

Several researchers have been working to enhance the frequency response of the energy harvester introducing different nonlinearities into the system. The possibility to transform the 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 (Hu et al., 2007; 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. 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.

EXPERIMENTAL PROCEDURES AND RESULTS

This section describes experimental tests which analyzes the vibration-based energy harvesting system combining piezoelectric and shape memory alloy elements. A commercial piezoelectric film (*MEAS-SPEC ESA*) is bonded to a cantilevered beam made of aluminum material (275 mm x 30 mm x 2 mm), see Figure 1. The cantilever is clamped to an electromagnetic shaker (*V350-DataPhisics Signal Force*). Two lasers transducers (*Micro-Epsilon $\mu\epsilon$ model optonNCDT2200*) are used to measure the free end and the base beam displacements 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 (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 dynamical force transducer (*PCB 208*) was used to measure the restitution force provided by the SMA spring. At the beginning of each test, the SMA helical spring is stable in martensite phase at room temperature (25°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 (*Spider 6.0* from *HBM*). A schematic of the experimental setup is shown by Fig. 2.

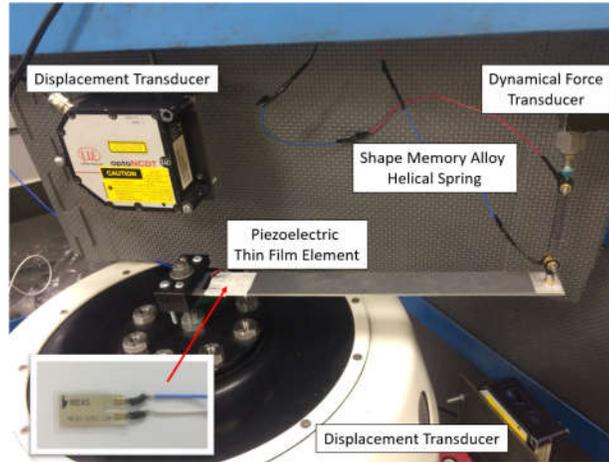


Figure 1 – Experimental dynamic setup

The temperature cannot be measured directly in dynamic tests, since during passage of electrical current in a reduced diameter of the SMA wire subject to dynamic vibrations is very difficult using thermocouples directly on its surface or infrared sensor. Therefore, in the absence of an accurate and reliable technique for direct measurement of the SMA spring temperature, the different SMA behaviors, shape memory and pseudoelastic effects, are associated with electrical current values. For this, the quasi-static mechanical characterizations 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 and establishes an evolution between shape memory (0 A) and pseudoelastic effects (1.5 and 2.5 A) 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 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. Therefore, 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.

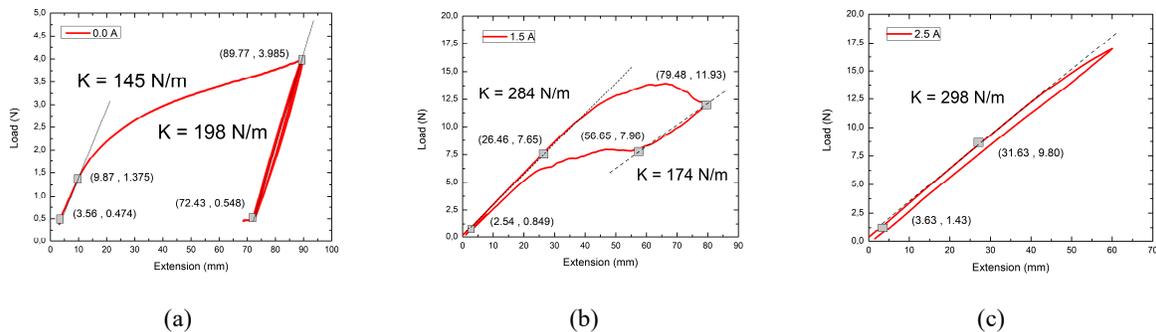


Figure 2 – Quasi-static tensile tests: (a) 0.0 A. (b) 1.5 A. (c) 2.5 A

A dynamical approach is on focus now considering dynamical tests with displacement base excitation. First, a pre-extension of 60 mm was applied on the SMA spring in order to avoid spires to touch each other. Tests with a base excitation amplitude of 2 mm 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 20 to 30 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: 22.3 Hz (0.0 A); 22.4 (0.5 A); 23.1 Hz (1.5 A) and 25.1 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) and (b) shows electrical tension obtained from the piezoelectric element and the tip displacement of the beam 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 2.7 Hz occurs for both electrical tension and displacement curves, which represents a variation of near 12% 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 (c) and (d) shows experimental data obtained from tests developed at fixed resonance conditions for the 4 applied current conditions. The load x displacement curve presented in Fig. 3 (c) 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. 3 (d) shows a *phase space* diagram.

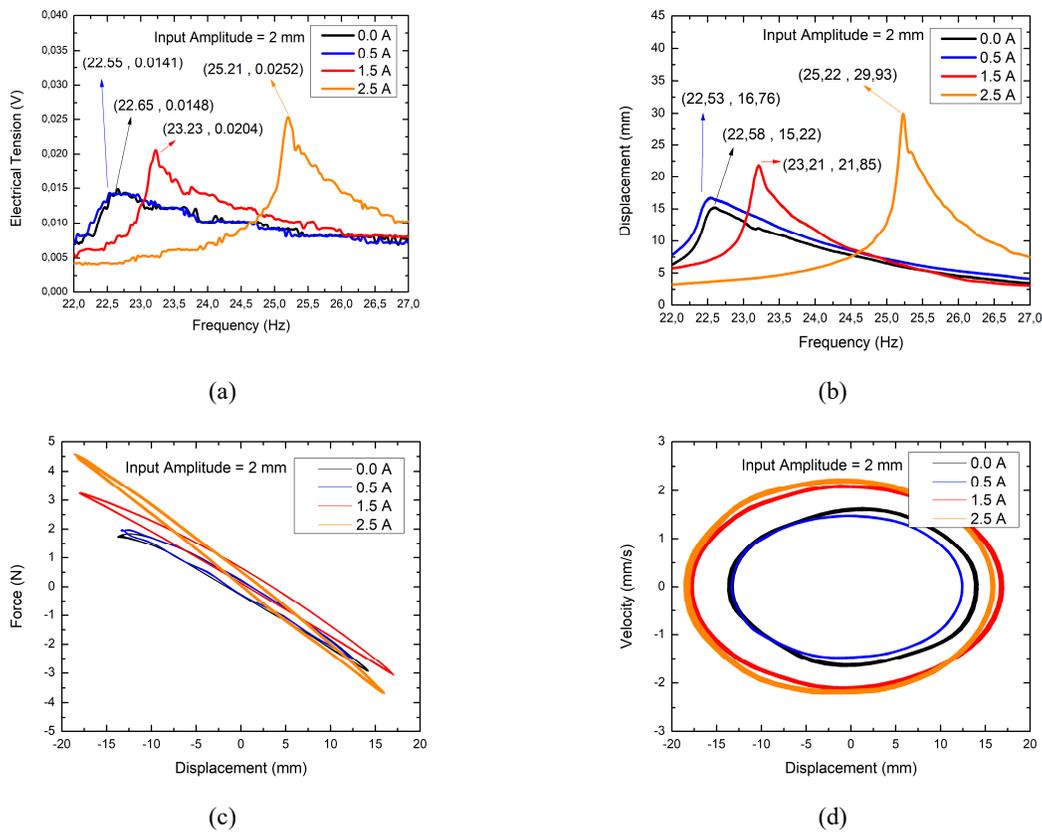


Figure 3 – (a) Electrical Tension x Frequency. (b) Tip Displacement x Frequency. (c) Force x Displacement. (d) Phase Space.

Figure 4 shows the time evolution of electrical tension from a starting frequency of 20 Hz to the resonance frequency for each of the 4 conditions. The same base excitation amplitude used in the previous cases are considered (2 mm). After the resonance frequency is reached, 1000 cycles were performed. Results shows that device is able to perform at a steady state condition.

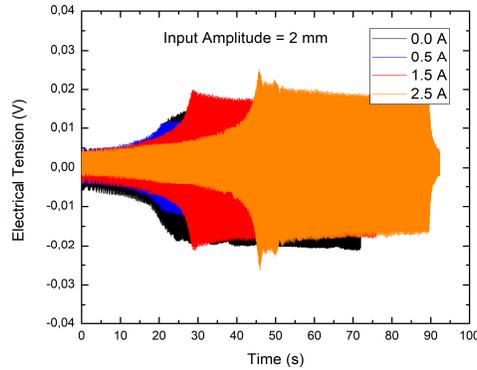


Figure 4 – Electrical tension time evolution from a starting frequency of 20 Hz to the resonance frequency. Base excitation amplitude of 2 mm.

CONCLUSIONS

Mechanical oscillations frequencies available in nature normally can be completely random or unpredictable. Optimal conditions for piezoelectric energy harvesters require the operation over a wide frequency range what motivate 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 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 12% 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. Results show that the shape memory alloy 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.

REFERENCES

- Anton, Steven R., and Henry A. Sodano. "A review of power harvesting using piezoelectric materials (2003–2006)." *Smart materials and Structures* 16.3 (2007): R1.
- Basset, Philippe, et al. "Electrostatic vibration energy harvester with combined effect of electrical nonlinearities and mechanical impact." *Journal of Micromechanics and Microengineering* 24.3 (2014): 035001.
- Arrieta, A. F., et al. "A piezoelectric bistable plate for nonlinear broadband energy harvesting." *Applied Physics Letters* 97.10 (2010): 104102.
- Avirovik, Dragan, et al. "Remote light energy harvesting and actuation using shape memory alloy—piezoelectric hybrid transducer." *Smart Materials and Structures* 22.5 (2013): 052001.
- Basset, Philippe, et al. "Electrostatic vibration energy harvester with combined effect of electrical nonlinearities and mechanical impact." *Journal of Micromechanics and Microengineering* 24.3 (2014): 035001.
- Chu, C. L., et al. "Surface structure and properties of biomedical NiTi shape memory alloy after Fenton's oxidation." *Acta biomaterialia* 3.5 (2007): 795-806.
- Erturk, A., and D. J. Inman. "Broadband piezoelectric power generation on high-energy orbits of the bistable Duffing oscillator with electromechanical coupling." *Journal of Sound and Vibration* 330.10 (2011): 2339-2353.
- Friswell, Michael I., et al. "Non-linear piezoelectric vibration energy harvesting from a vertical cantilever beam with tip mass." *Journal of Intelligent Material Systems and Structures* 23.13 (2012): 1505-1521.
- Kim, Miso, et al. "Modeling and experimental verification of proof mass effects on vibration energy harvester performance." *Smart Materials and Structures* 19.4 (2010): 045023.
- Leland, Eli S., and Paul K. Wright. "Resonance tuning of piezoelectric vibration energy scavenging generators using compressive axial preload." *Smart Materials and Structures* 15.5 (2006): 1413.
- Tang, Lihua, Yaowen Yang, and Chee Kiong Soh. "Toward broadband vibration-based energy harvesting." *Journal of intelligent material systems and structures* 21.18 (2010): 1867-1897.
- Silva, L.L.M., Oliveira, S.A., Pacheco, P.M.C.L., Savi, M.A., 2015. "Synergistic use of smart materials for vibration-based energy harvesting". *The European physical journal special topics*. 2015.