25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

# NONLINEAR EFFECTS ON EXPERIMENTAL PIEZOMAGNETOELASTIC ENERGY HARVESTING

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***Abstract.*** *Recently, the study of the conversion of vibrational energy into electrical power has become an important field of research for clean and renewable energy resources. That concept has been improved on smart material field, due the last decade technological achievements on piezoelectric materials. Further, several low power devices as sensor and actuators were developed, so the energy harvesting through piezoelectric materials excited by environmental vibrations become a potential energy source on engineering. However, researchers still face challenges for the low energy efficiency of those conventional devices. The bistable energy harvesting devices have drawn significant attention due to some of their unique features, that method may enchance those devices efficiencies. This paper investigates a piezomagnetoelastic systems that consists of a permanent magnet fixed to the end of a piezoelectric cantilever which interacts with another magnet placed close to the free end of the cantilever, when the system is subjected to a harmonic base excitation. The magnets generate nonlinear repulsive force and make the structure bistable. The nonlinear energy harvester responds to vibration with large tip deflections and high energy orbit oscillations. Thus, the system can exhibit a broadened frequency response and sometimes chaotic motion, enhancing its energy harvesting potential.*

***Keywords:*** *Nonlinear systems, Energy Harvesting, Piezomagnetoelastic, Smart Materials.*

## 1. INTRODUCTION

In the last decades electro-mechanical conversion through piezoelectric materials has shown to be quite promising. Those materials function as a generator by converting ambient mechanical energy to electrical energy through direct piezoelectric effect. Thus, different applications can be considered, one of those is the possibility to develop self-powered sensors where its power source come from ambient mechanical vibrations. (Erturk et al., 2009; du Toit & Wardle, 2006).

Despite this, piezoelectric energy harvesting devices are still limited, and the literature have shown that the introduction of nonlinear effects has brought positive results, increasing the energy efficiency and its operation range.

Stability analysis of the system results in a bistable working configuration which shows the most desired behavior for energy harvesting purposes (Silva et. al., 2015; De Paula et al., 2014). Experimental and theoretical studies on nonlinear energy harvesters manifested that the piezoelectric energy harvesters (PEHs) must work around the resonance states to generate high-power output (Yang, et. al., 2017).

Figure 1 illustrates bistable proposed configuration. The system can oscillate around one stable equilibrium point (blue arrow), around two stable equilibrium points (red arrow), or even present the two response situations, depending on the vibration conditions. This behavior can be achieved adjusting the distance of the magnets and the intensity of the magnetic forces.

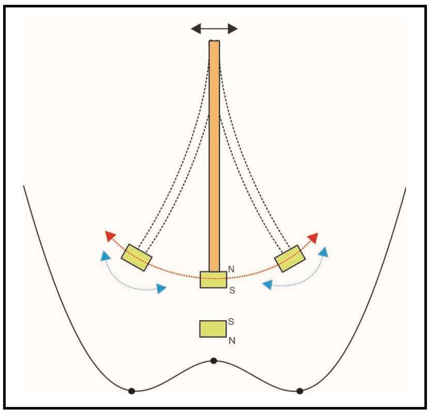



Figure 1. Schematic bistable piezomagnetoelastic system.

In this work, an experimental apparatus is developed for the study of the bistable piezomagnetoelastic system. A piezoelectric cantilever with a permanent magnet bonded on the free-end, and another permanent magnet fixed placed close to the free end of the cantilever. The two magnets are placed with same magnetic poles facing each other to produce repulsive force. The system is then subjected to a harmonic base excitation. According to the literature, it's expected by other authors results that the nonlinear magnetic forces exert great influence on energy generation, showing different kinds of responses, including periodic and chaotic regimes. This contribution deals with the effects of the nonlinearities in PEH systems, investigating the influence of the magnets and showing the system responses at different forcing frequencies.

## 2. FUNDAMENTAL THEORY

A usual approach is to explore bistable structures with double-well potential and, depending on vibration conditions, it is possible to achieve high-orbit motion visiting the two potentials. This is essentially a Duffing-type oscillator that can be experimentally built using magnetic forces to modify the effective stiffness of the harvester. The governing equations for electromechanical piezomagnetoelastic system can be expressed as a single-degree-of-freedom (SDOF) system (De Paula et al., 2014, Cellular, 2018) as:

$$x'' + 2\zeta x' + \beta x + \alpha x^3 - \theta v = w'' \tag{1}$$

$$\phi x' + v' + \delta v = 0 \tag{2}$$

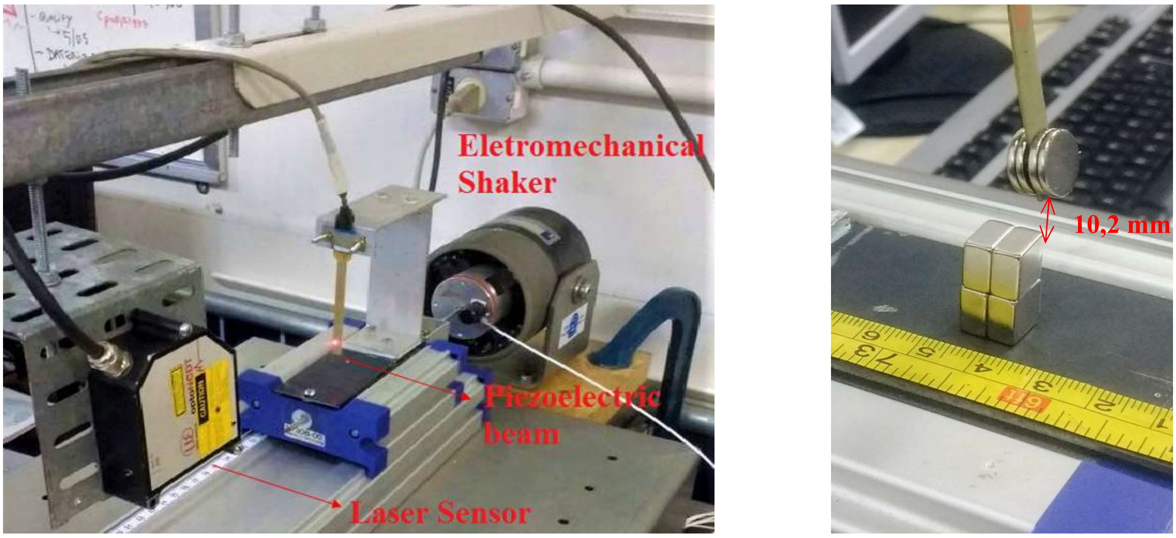
where $x$ is the dimensionless tip displacement of the beam in transverse direction, $v$ is the dimensionless voltage, $\zeta$ is the mechanical damping ratio, $\theta$ is the dimensionless piezoelectric coupling term, $\phi$ is the reciprocal of the dimensionless time constant, $\delta$ is the dimensionless piezoelectric coupling term in the electrical circuit equation, $\beta$ and $\alpha$ are respectively, the linear and the nonlinear stiffness coefficients and $w$ is the dimensionless displacement of the base. The $(\,)'$ represents differentiation with respect to dimensionless time.

Different values of $\beta$ and $\alpha$ characterize different behaviors. When $\beta < 0$, the system has a double-well potential with bistable aspects. On the other hand, when $\beta > 0$ the system is nonlinear monostable. Linear system is characterized by $\beta > 0$ and $\alpha = 0$.

Nonlinear effects generate complex responses often being highly sensitive to initial conditions and external inputs. Therefore, methods such as bifurcation diagram, Poincaré sections and phase spaces were used in order to investigate those nonlinearities of the system.

## 3. EXPERIMENTAL METHODOLOGY

The experimental setup is shown in Fig. 3.a. The energy harvester is assembled on a shaker (Labworks, Inc. ET-126). The shaker provides the external harmonic excitations on the system and is coupled to a car moving on horizontal axes with an aluminum structure that fix the piezoelectric beam (V22BL from Midé Volture Piezoelectric Energy Harvesters) on the vertical position. A permanent magnet fixed to the end of a piezoelectric cantilever and another magnet placed close to the free end of the cantilever. The spacing between the magnets is 10.2 mm and this distance was selected to achieve the bistable configuration, after some preliminary tests. A laser displacement transducer with 100 μm range from Opton NCDT 2200 Micro-Epsilon (με) was employed to measure the displacement at the free end of a cantilever beam. For data acquisition, Spider model 600 Hz Spider8 from HBM was used. The piezoelastic configuration without the magnets is shown Fig. 3.a and piezomagnetoelastic configuration with the magnets is shown in Fig. 3.b. The output power is evaluated from the measured voltage and applied electrical resistance of 150 KΩ.



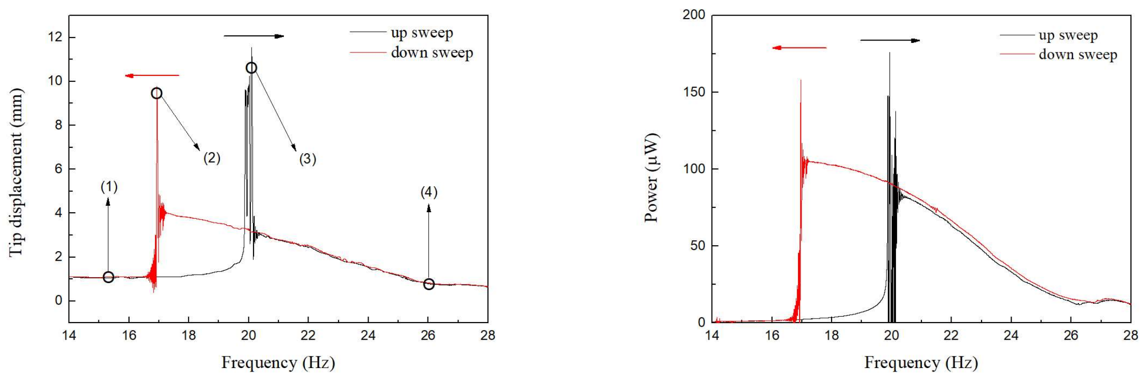

(a) (b)

Figure 3. Experimental Apparatus. Sensors setup (a) and nonlinear configurations (b).

Experimental tests were carried out on piezoelastic and piezomagnetoelastic configurations. The harmonic vibration excitation was held constant at an acceleration amplitude of 1.4g under a variation of excitation frequency from 14 Hz to 28 Hz. The frequency sweeping rate was set to 0,2 Hz/s. Measured frequency responses of the output power and displacement in up and down frequency sweep were recorded using a fit-for-purpose data acquisition system with sampling rates of up to 1200 samples/sec/channel. Results are summarized in frequency responses of maximum values of output power and displacement, bifurcation diagram obtained from the Poincaré sections, phase spaces e responses on time for some specific frequencies.

## 4. EXPERIMETAL RESULTS

Figure 4.a and 4.b shows displacement and electrical power versus frequency for piezomagnetoelastic configuration, respectively. Each Figure present up and down sweep. Dynamical jumps between equilibrium points on large displacement regions are observed. These jumps are associated with dramatic changes that can reduce the response amplitude and the harvested energy. Note that, those jumps occur on different frequencies comparing up and down sweep, which is a characteristic behavior of nonlinear systems, due to high sensitivity to initial conditions. It's also observed that near those large displacement regions the system shows larger amplitudes of displacements and power compared to frequencies far from the regions with dynamical jumps. Details of the system dynamics for some set of frequencies, 15 Hz (1), 17 Hz (2), 20 Hz (3) and 26 Hz (4) near and far from large displacements regions for both up and down sweep are depicted in Fig. 5.




(a) (b)

Figure 4. Experimental results. (a) Displacement vs. Frequency. (b) Electrical Power vs. Frequency.

Figure 5 illustrates displacements in function of time for frequencies mentioned in Fig. 4. Different kinds of response can be noticed in the detailed pictures. The Fig. 5.a and 5.b display a periodic steady-state response far from dynamic jumps while the Fig. 5.c and 5.d exhibit chaotic-like response close to dynamic jumps.

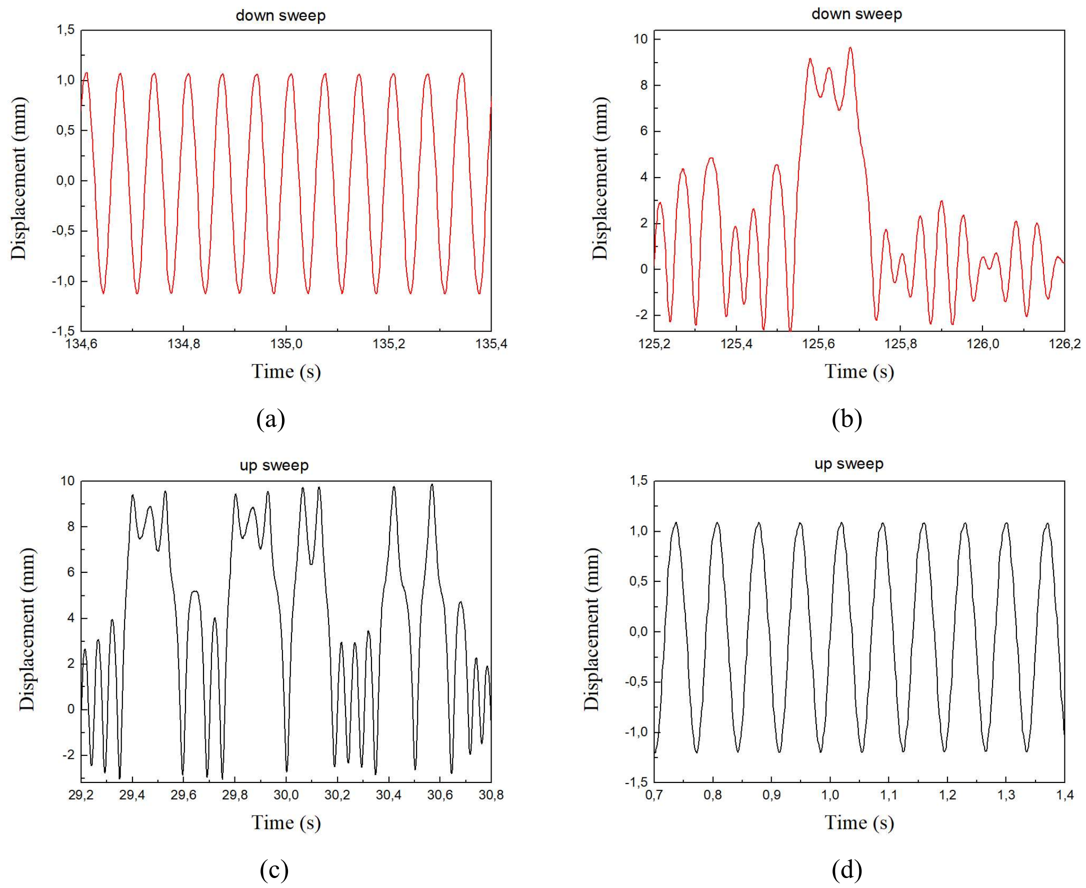



Figure 5. Experimental result of signal behavior. (a) 15 Hz (b) 17 Hz (c) 20 Hz (d) 26 Hz

Figure 6 presents bifurcation diagram using Poincaré sections considering displacement for different values of the excitation forcing frequency. Periodic and Chaotic responses are observed, while the second is associated with regions that present a cloud of points. Figure 7 shows phase spaces and Poincaré sections for frequencies of 18.9 Hz (1), 19.2 Hz (2), 19.3 Hz (3) and 19.7 Hz (4). The Poincaré section reduces continuous dynamics system into a discrete system. This technique achieves a better understanding of the global system dynamics, due to eliminate at least one variable of the problem (Savi, 2006).

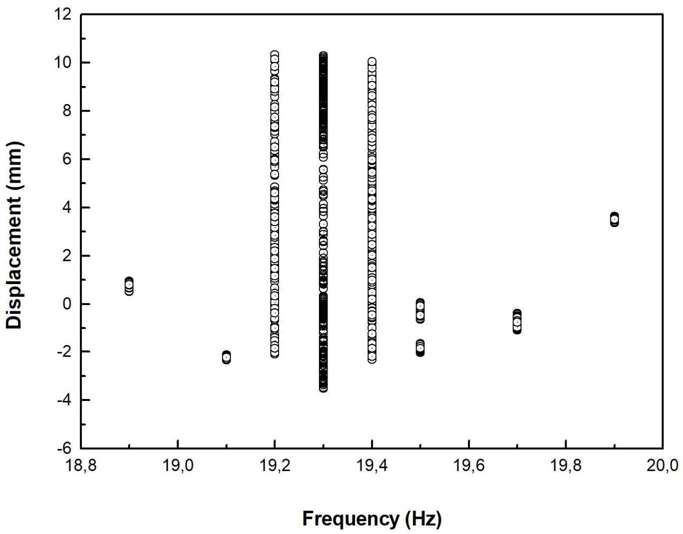
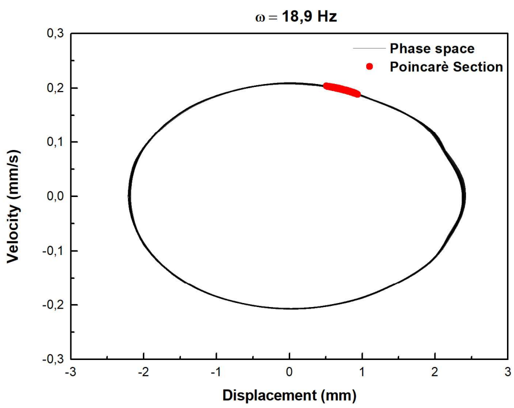
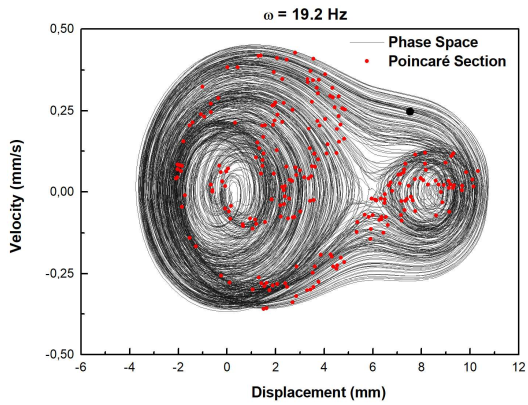


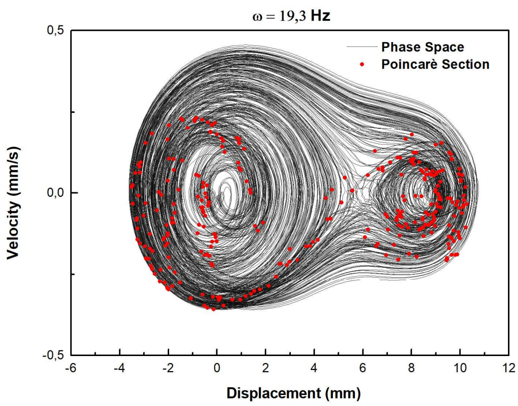

Figure 6. Bifurcation Diagram. Displacement (mm) vs. Frequency (Hz).



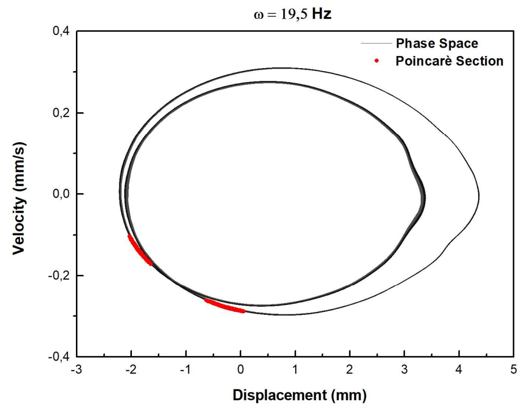

(a)




(b)




(c)




(d)

Figure 7. Phases space and Poincaré Section for: (a) 18.8 Hz – Period-1 response, (b) 19.0 Hz – Chaotic-like response, (c) 19.4 Hz – Chaotic-like response, and (d) 19.7 Hz – Period-2 response.

## 5. CONCLUSION

This article has brought a study of clean and renewable energy harvester through piezoelectric materials. Experimental analyses of nonlinear effects on piezomagnetoelastic energy harvester behaviors were investigated. It was observed that those systems are very sensitive to the intensity of the input excitations. Furthermore, parameters variation or different initial conditions generate abrupt influences in the system responses that can generate high power output at a wide bandwidth. The system behavior has riches responses that include chaotic-like and periodic motions. Chaotic-like motion is shown under different frequencies and proven to enhance the vibration amplitude. It is possible to assume that piezomagnetoelastic systems are promising for clean energy generation, due to generate high power output at a wide bandwidth. However, it was also observed that parameters variation or initial conditions generate abrupt influences in the system responses, due this sensitivity and complexity further studies and development are needed to achieve its full potential.

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