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CHARACTERIZATION OF MECHANICAL AND ELETRICAL PARAMETERS OF A LEAD ZIRCONATE TITANATE PIEZOELETRIC GENERATOR

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Abstract. *The need to provide electricity for low power circuits, often installed in remote locations, has stimulated research in the development of electric power generators based on the concept of energy harvesting. In general, these are small generators that generate low power but of sufficient capacity to power some circuits. Among the elements that are intended to generate electricity, piezoelectric materials has gained prominence, especially because they are easy to install and generate relatively high voltages depending on the setting made. With interest to contribute a little more to the understanding of the experimental behavior of these elements, this paper presents a study of characterization of a piezoelectric power generator. The main objective was to determine the most relevant mechanical and electrical parameters of the generator and their relationships. In the study, a single-cantilever beam excited by a piezoelectric actuator which allowed variation of the mechanical vibration frequency in a wider frequency range. Other ceramic piezoelectric element (Lead Zirconate Titanate - PZT) was used for the electricity production. Results of mechanical deformation and generated electrical voltage are presented in addition to the relationship between these parameters. The study also shows the electronic instrumentation that made possible the collecting of experimental results.*

Keywords: *Piezoelectric Materials, Power Harvesting, Alternative Energy*

1. INTRODUCTION

Energy harvesting has gained great importance, because the demand for portable electronic devices and the need to be self-powered has been growing constantly. In this way, small systems has been developed that can acquire energy from environment to supply some these low power devices. Some scientific studies have been performed in an attempt to explore the efficient of these systems, contributing with the preservation of another limited energy sources.

Piezoelectricity is characterized by the capacity of some materials induce an electric field to be mechanically deformed (direct mode) or suffer deformations when they are submitted to a potential difference (inverse mode). This property can be explained by the low degree of symmetry of its crystalline structure (Callister, 2000). The effect occurs due the existents of dipoles deformation in the molecular structure, causing a higher concentration of charges on the material surface and, thus, be used to power supply other devices (Anton and Sodano, 2007).

Using of piezoelectric materials is linked directly to their large facility of application in dynamics systems and great conversion of vibrational energy, that's normally unwelcome in some mechanisms and/or wasted to environment in electric energy among the other existing methods (Anton and Sodano, 2007). According to Rangel *et al* (2014) these transducers have great efficient in the conversion of mechanical stress in electric voltage; support large mechanical loadings; they have better capacity of miniaturization and mass production when compared to other materials cited in other studies.

Farias and Sallum (2013) got the necessary energy to illuminate the UNICAMP university restaurant using piezoelectric generator, due the imposed pressure by the users walking. Reilly *et al* (2011) used a trapezoidal piezoelectric plate in a workplace with 0.25 g and 100 Hz to power supply a wireless sensor and the associated electronics. Keawboonchuay e Engel (2003) held a work seeking the maximization of the generated electric power for three different types of piezoelectric materials applying a compression force of 7 kN and varying the relation thickness cross area (TAR). This way has been reached an output power between 7 and 28 kW. Filho (2014) obtained a generated power of 1.87mW using a Lead Zirconate Titanate piezoelectric ceramic coupled in an aluminum beam single-cantilever, having a shaker as exciter element.

In this work, utilization of an aluminum beam is related to piezoelectric ceramic fragility, since it will be used mechanical forces that produce deformation; so, it is necessary to couple this support structure. Filho (2014) claims in his study that the single-cantilever beam setup presents a high value of deformation to a given force input and these parameters are associated to the conversion of mechanical energy into electric energy. According to Andrade (2004) the Lead Zirconate Titanate (PZT) ceramics offer some advantages: high value of rigidity, low cost of manufacturing, volume small and they are lightweight. From of the advantages that have been shown previously is justified the employment of a single-cantilever beam and PZT in our research.

This study had like objective to relate the suffered mechanical deformation and generated electric voltage of a Lead Zirconate Titanate (PZT) piezoelectric ceramic of rectangular geometry, being coupled to an aluminum beam single-cantilever and other piezoelectric element of the same type as exciter for this structure. Have been also compared experimentally results obtained to a numerical model created in the finites elements software: ANSYS®, in addition to demonstrate the electronic instrumentation used to data capture. The development this research aims at contributing to the improvement of electric energy generation techniques of way alternative and renewable.

2. NUMERICAL MODEL

The ANSYS® *Mechanical* is a tool of comprehensive study of FEA (finite element analysis) for structural analysis, including linear studies, no linear and dynamics. The product of engineering simulation provides a full set of the elements behavior, materials models and equations solver for a broad range of mechanical project problems. Furthermore, the software offers thermal analysis and couple physics capacity involving piezoelectric (ANSYS, 2015).

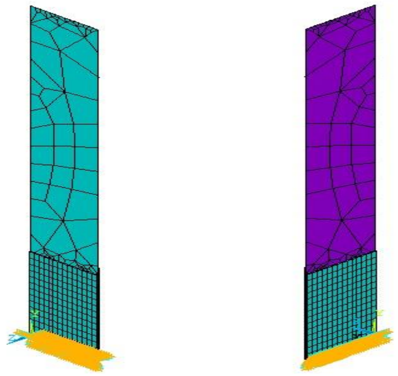
Tzou and Tseng (1990) and Ha *et al* (1992) performed dynamic and static analysis of thin plates with coupled piezoelectric actuators and sensors using the Element Finites Method (FEM), where the host structure of the adaptive materials and the own set actuator and sensor are shaped for solid elements with the same parameters of 8 nodes. Koyama and Nakamura (2008) presented a study in which it was analyzed the output electric power of a piezoelectric ceramic. In another study, Zhu *et al* (2009) presented a model based in finites elements to analyze, in the capture process of electric energy, the electric power density of a piezoelectric material when the same has been connected to a load and submitted to mechanical vibration.

The numerical simulation using the finites elements software ANSYS® has been developed to the objective of create a model approaching the maximum of the experimental prototype. This method is relevant in any research, because is possible to know the characteristics of a structure before confection of the prototype. In this study this model has shown the system electrodynamics behavior, allowing previously to verify the amount of generated electric voltage and the suffered mechanical deformation for a given parameter selected.

The choice of the finite element that has been used was based in the application, dimensions and properties or special forms. To shape the aluminum beam has been implemented a shell element (characterized by having ones of dimensions smaller than others) available in ANSYS® library, the SHELL93. It has capacity of plasticity, stress stiffening, deflection large and deformation, defined for 8 nodes and 6 degrees of freedom on each. The two piezoelectric transducers (exciter and the energy generator) have been shaped for element SOLID226 that has 20 nodes with up to 5 degrees of freedom on each and has piezoelectric capacity (ANSYS 11.0, 2007).

Seeking to know some important parameters of the structure as the natural frequencies and vibration modes associated, was made initially a modal analysis, that's always important in the project of a structure submitted the loadings. It is known that when a system reaches resonance it oscillates to maximum amplitude, it's only possible when the excitation frequency is equal the natural frequency. Taking as reference piezoelectric plates with constants dimensions established next to cantilever area that's the place where the large deformation occurs, have been done simulation varying the length of the aluminum beam trying to find an interest frequency band. For these values has been taken into consideration the equipment operation frequencies where this generator could be installed.

In the Figure 1 is shown the beam scheme used in this analysis, with the boundary conditions, the finites elements and the mesh represented. Each one of the piezoelectric has been fixed next to the cantilever area on the beam surface. Being one the PZT generator and other the actuator element.



(a) (b)

Figure 1. Modal analysis: (a) front view and (b) rear view.

In the Table 1 are presented the dimensional, mechanical and electric parameters of the piezoelectric and of the aluminum beam used in the simulations. These values have been used after adjustment made from experimental results. The values range of the adopted parameters respected the limits of provided values by the literature and PZT manufacturer.

Table 1. Properties and dimensions of the piezoelectric ceramic (PZT-C64) and aluminum beam (PIEZO SYSTEM, INC, 2008; ALUMICOPPER, 2011).

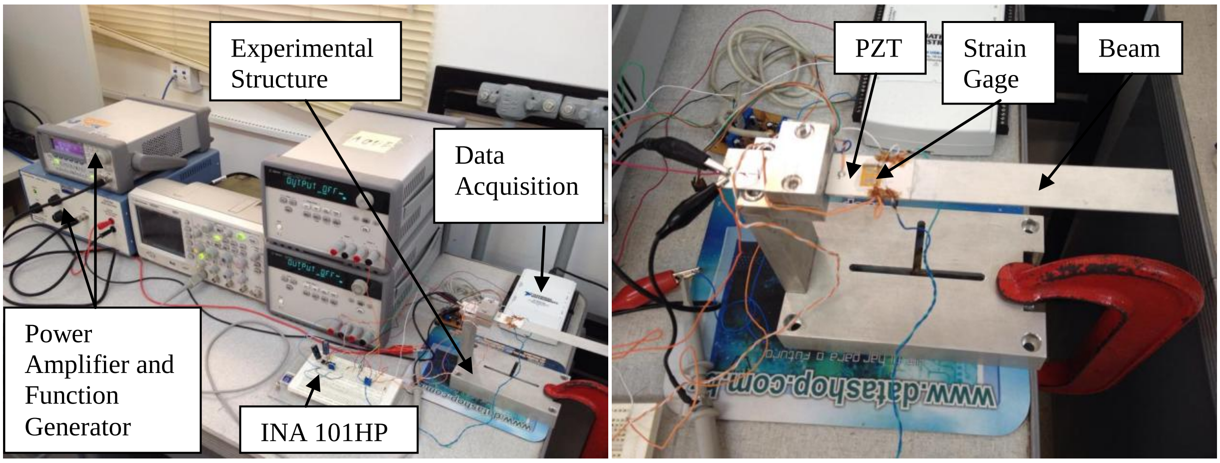
Material		PZT-C64	Aluminum
Piezoelectric coefficient (m/V)	d_{31}	190e-12	
	d_{32}	190e-12	
	d_{33}	-390e-12	
Relative permittivity	$\varepsilon/\varepsilon_0$	1.2	
Elastic coefficient (N/mˆ2)	Y^E_1	6.6e10	
	Y^E_3	5.2e10	
Poisson`s ratio	υ	0.35	0.33
Width (m)		21.89e-3	22e-3
Thickness (m)		0.2e-3	1e-3
Length (m)		38.66e-3	150e-3
Elasticity Modulus (N/mˆ2)	E		74.5e9
Density (Kg/mˆ3)	ρ		2630

Once defined the structure parameters, as well as the natural frequencies associated, has been performed an harmonic analysis for to determine the structure mechanical behavior. With this method is possible to get the values of mechanical deformation and generated electric voltage for a given force input. This analysis determines the system response in the frequency domain for cyclic loading. To simulate in the model the vibration imposed by the exciter PZT of the experimental, has been used a force applied in the beam next to the cantilever area.

3. EXPERIMENTAL SETUP

The experimental prototype was designed after the modal simulation, whereas the beam dimension were previously defined, approximating to ideal model as possible, in other words, no clearance in the cantilever area, the piezoelectric and extensometers too coupled on the aluminum beam, the collage process followed for manufacture's instruction manual of each these ones and the metal base too firm on the experimental workbench so that the errors could be minimize.

Piezoelectric exciter was powered for a power amplifier with a sinusoidal excitation signal. For data collecting of generated electric voltage and the suffered mechanical deformation, it was used an acquisition board and data control connected via USB cable on a managed computer by *LabVIEW* software. It's shown in the Fig. 2(a) the experimental setup used, and the Fig. 2(b) is highlighting the extensometers and the beam with PZT.



(a) (b)

Figure 2. Experimental workbench: (a) disposition of the equipment e (b) prototype.

3.1 Eletronic Instrumentation

A system has been developed to obtain the values of deformation suffered by PZT, formed four extensometers of electric resistance connected in a *Wheatstone* bridge setup. An INA101HP instrumentation amplifier with gain 830 and a low pass filter have been implement. In the Figure 3 it's shown the developed steps to collect the system data.

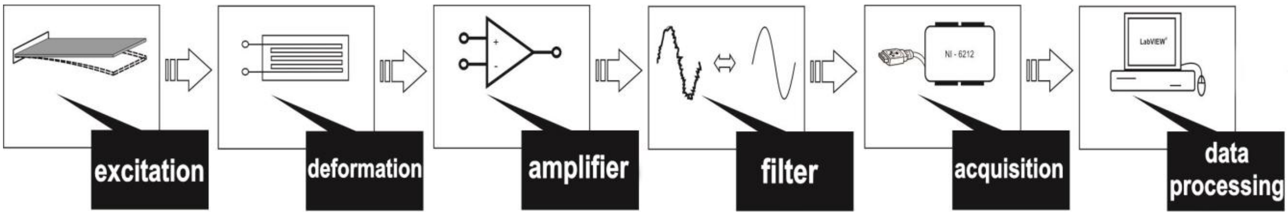


Figure 3. Data flow chart.

When it's desired to measure mechanical deformation on bodies subjected to mechanical loadings it's normally used extensometry method by allow detect small variation on low frequency. Among the existing principles, the extensometers of electric resistance are quite employed to these applications, where these are based in the length variation of a conductor. For these extensometers disposition like shown in the Fig. 4(a) the force applied on a x distance it related with the output electric voltage E_o according to the Eq. 1 and relation between deformation ε and the force F on this situation can be described according to the Eq. 2 (Balbinot and Brussamarello, 2011).

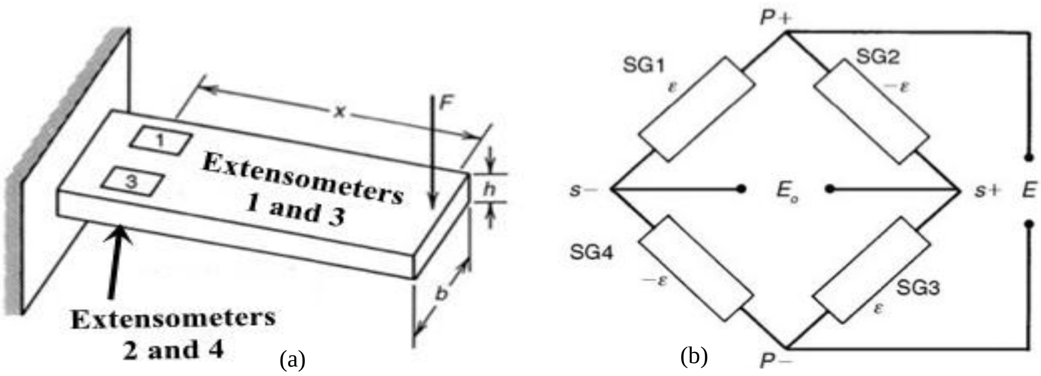


Figure 4. (a) Disposition of the extensometers on the beam and (b) type of connection between them (Adapted from Balbinot and Brusamarello, 2011).

$$Eo = \frac{6.F.K.x.Efonte}{E.b.h\hat{}2} \tag{1}$$

$$\varepsilon 1 = \varepsilon 2 = \varepsilon 3 = \varepsilon 4 = \frac{6.F.x}{E.b.h\hat{}2} \tag{2}$$

Where F is the force, K the gage constant, E the beam's elasticity modulus, b the width, h the thickness and E_{fonte} the *Wheatstone* bridge power voltage.

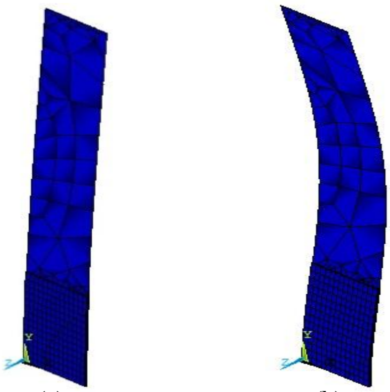
Doing a simple algebraic manipulation it`s possible to relate directly the electric output voltage to the suffered deformation. In this paper has been used exactly this equation for calculate the deformation, so the imposed force by exciter piezoelectric doesn`t need to be calculated but just the deformation it has caused. The extensometers have been positioned on the beam like in the Fig. 4(a) forming the connection of the Fig. 4(b) having 120 Ω of electric resistance and the K equal to 2.11, these values are established for their manufacturers.

The use of the instrumentation amplifier has been necessary because the bridge output signal amplitude was of the magnitude order of 1 mV. In the amplifier output has been used a first order low pass filter made by a resistor and a capacitor to cutoff frequency equal to 800 Hz, with the objective of mitigate noise above this frequency.

For read electric voltage generated by PZT has been used a high impedance resistive divisor, because this signal amplitude is higher than the supported by acquisition device.

4. RESULTS

The obtained frequencies in the modal simulation have been: 41.79 e 250.37 Hz, to the first and second vibration mode respectively. The Figure 5 shows the associate mode the each natural frequency.



(a) (b)

Figure 5.Vibration modes: (a) first mode and (b) second mode.

To determination of structure natural frequencies has been made an impact test with a hammer. The piezoelectric electric output voltage has been connected to data acquisition device conjunction with to the *LabVIEW* software where applied in this signal a FFT (Fast Fourier Transformer) and so obtained the signal spectrum. Can be checked in the Fig. 6 the higher amplitudes associated to values: 47.114 and 247.1 Hz, to the first and the second natural frequency, respectively. It was also observed these values were the same for the two piezoelectric of the structure.

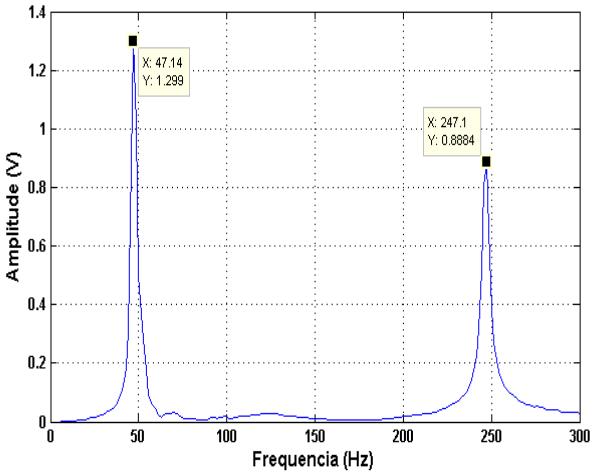
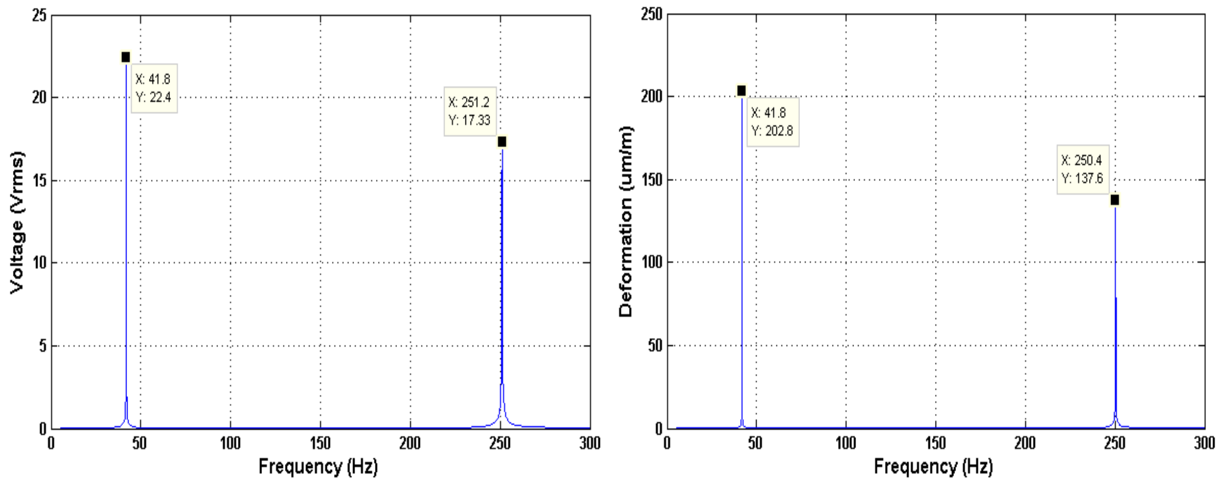


Figure 6. Output voltage of the PZT in the impact test.

From obtained results it verify the value experimental error relation to the numerical model is 12.79 % for the first natural frequency and 1.30 % for second. These calculated errors can be explained the fact that the piezoelectric ceramic implies a rigidity increase in the physic system than computational, and also occur the wire influence that the extensometers are connected.

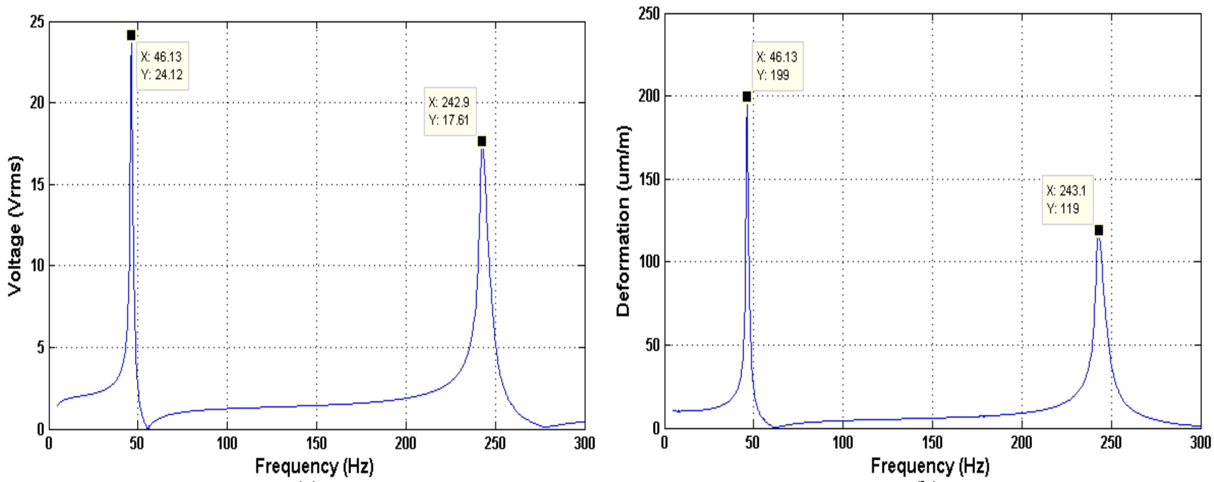
In the harmonic analysis the data have been read on three nodes: of deformation positioned to 11 mm of X axis and 19.33 mm of Y axis, both of electric voltage and force located to 11 mm of X axis and 7 mm of Y axis, the axis X and Y the width and length references of the beam. The amplitude of force $F=F_0.\sin(\omega.t)$ applied it was of $F_0=0.055$ N in a frequency band between 5 and 300 Hz. So that the piezoelectric shows an electric voltage on their surfaces it was required to take some place as reference to a null value of voltage (0 Volts).The full area has been selected to be ground, because the nodes of bottom surfaces of each PZT are connected in this same region. These are the same places selected in the experimental apparatus. The value of electric open voltage RMS are: 22.4 and 17.33 V_{RMS} and deformation obtained are: 202.8 and 137.4 μm/m, for the first and second natural frequency respectively. In the Figure 7 can be observed the graph obtained in this simulation.



(a) (b)

Figure 7. Harmonic analysis: (a) generated electric open voltage RMS by the PZT and (b) deformation.

To find the values of mechanical deformation and generated electric voltage has been done a sweep between 5 and 300 Hz frequencies, well as in the harmonic analysis. With the functions generator has been possible to do this test, since the exciter piezoelectric can to strain in a frequency band too wide. Have been found the following values of generated electric open voltage RMS by PZT: 24.12 and 17.46 V_{RMS} and to deformation: 199 and 119 μm/m, for the frequencies 46.12 and 243.1 Hz, respectively in this experiment, like it's also shown in the Fig. 8. The natural frequencies in this experimental test differ a little of the impact test because the mode as the PZT excites the structure is different than impact about structure. The PZT excites the beam of localized way and the impact the full structure.



(a) (b)

Figure 8. (a) Generated electric voltage RMS by the PZT and (b) deformation in the frequency domain.

5. CONCLUSION

This paper demonstrates the direct relation there is between electromechanical parameters in a piezoelectric ceramic, the suffered deformation and generated electric voltage. Has been also shown the possibility to create a numerical model this system using the elements finites method, the results presented a good precision in the practical. In the present study has been used a force in the computation simulation for this was similar the forced vibration imposed by PZT. In what way the magnitude was adjusted according to the experimentally data obtained. It was also used as experimental exciter a PZT it causes less influence on the beam unlike other electromechanical exciters.

The results showed both in the simulated model ANSYS as in the experimental, the higher amplitude of deformation and electric voltage occurs when the excitation source reaches the system natural frequency. With maximum experimental values of: 199 and 119 μm/m for deformation, and generated electric voltage RMS by PZT of: 24.12 and 17.46 V_{RMS}, for the frequencies 46.13 and 243.1 Hz, respectively. Deformations of: 202.8 and 137.4 μm/m, and electric open voltage RMS: 22.4 and 17.33 V_{RMS}, in the frequencies 41.8 and 250.4 Hz, respectively in the numerical model.

In this way this paper contributes to better the understanding in what refer the project of piezoelectric generators excited in the resonance region.

6. ACKNOWLEDGEMENTS

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