



20 A 24 DE MAIO DE 2018 SALVADOR – BA – BRASIL

## Piezoelectric Scroll Floor Harvesting System Subject to Different Loads and Induced Vibrations

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**Abstract:** *This paper is a numerical and experimental analysis of the behavior of piezoelectric disks inserted between two plates subjected to different loads and induced vibrations. There are many studies of harvesting energy systems, that are considered one of the most promising researches for cleanable and renewable energy. Among sources such as solar energy, wind, temperature gradients, antenna and microwave, the vibration stands out for the transformation of mechanical energy into electric energy with piezoelectric materials. Piezoelectric systems are already being installed around world to take advantage of this kind of energy and with the improvement of your efficiency, it can be used in large scale for energy transduction. The objective of this work is to verify the behavior of the piezoelectric plates in different circumstances to make easier the development of new energy pickups using this type of technology. To achieve this goal, was developed a mathematical model for a numerical analysis of the behavior of the disks observing the stability of the system, and then an experimental analysis was produced where measurements were made of the energy released by the piezoelectric when they were under the influence of an initial vibration and when they were submitted to different loads. As a result a great influence was found between the compression loads and initial vibrations with the voltage output by the system.*

**Keywords:** *Efficiency, Control, Energy Harvesting, Piezoelectric road.*

### 1. INTRODUCTION

Considering the growing need for energy and the fact that currently 90% of the fuels used include polluting carbon dioxide and greenhouse-related problems, it is clear the need for new, clean and renewable energy sources. (Abbasi, 2013). Also observing that roadways are major infrastructure for connecting people and providing access and mobility and the traffic induced strains and stresses generating a great amount of mechanical energy that is wasteful and can be potentially used for energy harvesting purposes the piezoelectric devices show yourselves are ideal candidates for harvesting energy in asphalt pavement roadways as they convert mechanical strain energy into electric voltage. (Roshani et al. 2016)

Piezoelectricity was discovered by French physicists Jacques and Pierre Curie (Gupta et al. 2014) and consists of the capability of some materials like quartz, Rochelle salt, tourmaline, topaz, cane sugar (Abbasi, 2013) certain ceramics, and biological matter such as bone, DNA and various proteins to accumulate electric charge in response to applied mechanical stress (Gupta et al. 2014). The piezoelectric effect is based on the fundamental structure of a crystal lattice. Certain crystalline structures have a negatively and positively polarized charge balance, which neutralize along the imaginary polar axis. When this charge equilibrium is disturbed with external stress in the crystal lattice, the energy is transferred by electric charge transporters creating current in the crystal. On the other hand, with the piezoelectric effect, an external load will create an imbalance in the neutral load state causing mechanical stress (Calio et al. 2014).

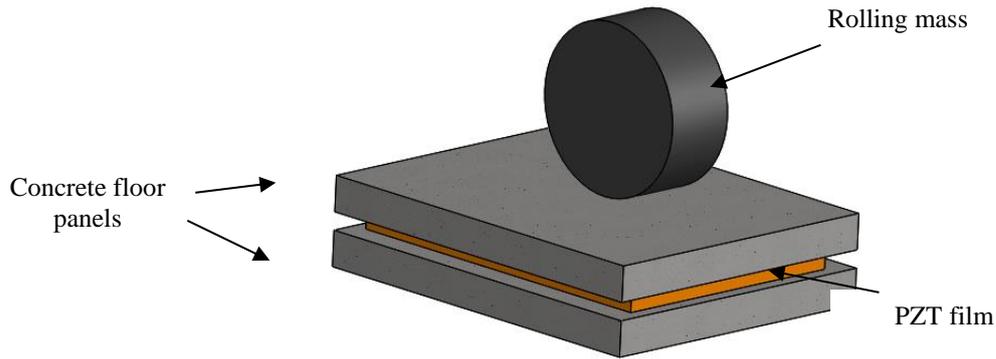
Nowadays, this ability has already been used on roads to capture the mechanical energy wasted by cars and transduce it into electric energy, POWERleap, a licensed technology manufacturer, has provided a data proving the reliability of power asphalts. The experiment involves 1 Km stretch power asphalt with vehicle passing rate of 200-400 in 16 h. Based on this experiment, the total electrical energy generated range between 400 KWh - 600 KWh (Gupta et al., 2014). In

other hand, it is estimated that close to  $2.218 \times 10^{16}$  KJ of energy are wasted annually by motor vehicles in the USA (Xiong et al., 2016). If 1/1000 of this energy can be captured, it will be enough to supply about 6 million houses in United States. It can be achieved by widely deployed piezoelectric energy harvesters on roadways (Xiong et al., 2016). This reveals a promising source of energy to replace fossil fuels in future.

The most usual study is related to tuning the vibration mode to resonance (Challa et al., 2018; Erturk and Inman, 2011; Secord et al., 2010) using control that can be mechanical, electrostatic or piezoelectric. Among several works to increase the efficiency of piezoelectric plates, the use of piezoelectric controllers stands out, in this way the harvest system proposed in this work will be compressed with different loads and external vibrations to observe their behavior when converting mechanical energy into electric energy.

## 2. MATHEMATICAL MODEL

The scroll floor energy harvesting system is designed with a double concrete floor panels and an insert of PZT film as shown in Fig 1.



**Figure 1: Draft of scroll floor energy harvesting system**

The mathematical model of the designed system is given in Equation 1 (Roshani et al., 2016), where  $W$  is the output energy power from the stressed system,  $d$  is the piezoelectric charge constant (Coulombs/N),  $g$  is the piezoelectric constant of the material (Volts/m/Pa),  $Y$  is the Young's modulus and  $\epsilon$  is the normal strain in the related direction (in this case, direction 33) and  $abc$  is the volume of the finite element from the energy harvesting system.

$$W = \frac{1}{2} dgY^2 abc \int \epsilon^2 d\xi \quad (1)$$

Considering a harmonic excitation  $f \cos \Omega t$ , the spring-mass system coupled to a piezoelectric output load can be described as:

$$\ddot{x} + 2\zeta\dot{x} + \frac{1}{2}x - \chi v = f \cos \Omega t \quad (2)$$

$$\dot{v} + \kappa\dot{x} + \Lambda v = 0 \quad (3)$$

For simulation, it is necessary to determine the space state for the equation and naming  $x = y_1$ ,  $\dot{x} = y_2$  e  $v = y_3$ , then the space state for the equation (2) and (3) is given by equations (4), (5) and (6).

$$\dot{y}_1 = y_2 \quad (4)$$

$$\dot{y}_2 = -\frac{1}{2}y_1 - \zeta 2y_2 + \chi y_3 + f \cos \Omega t \quad (5)$$

$$\dot{y}_3 = -\kappa y_2 - \Lambda y_3 \quad (6)$$

### 2.1. Numerical Analysis

A numerical study from the energy harvesting system was conducted for the presented mathematical model to evaluate the stability system behavior. It was determined the eigenvalues from the system as shown in Table 1. The piezoelectric material utilized in the simulation was PZT (Pb-lead, Zr-zirconium, Ti-titanium) because it exhibits higher rigidity and brittleness, low permittivity and dielectric losses and are harder to depolarize which make them ideal for high power application and for hard conditions such as pavements. The PZT parameters are density of  $7.6 \text{ gm/cm}^3$  and Young's modulus of  $6.8E10 \text{ N/m}^2$  and piezoelectric charge constants of  $290E-12 \text{ m/v}$ . The simulation considered an excitation frequency 10 Hz which is the frequency of loading caused by vehicles in roadways (Kour and Chariff, 2016).

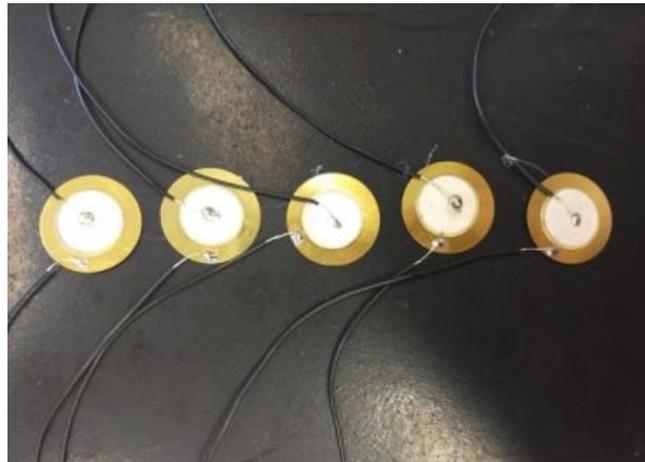
Table 1 – Eigenvalues for the dynamical system

Variables	Eigenvalues
$y_1$	$-0.0112 + 0.7244i$
$y_1$	$-0.0112 - 0.7244i$
$y_1$	$-0.0476 + 0.0000i$

The energy harvesting presented all negative eigenvalues, which determine the stability of the system as stable.

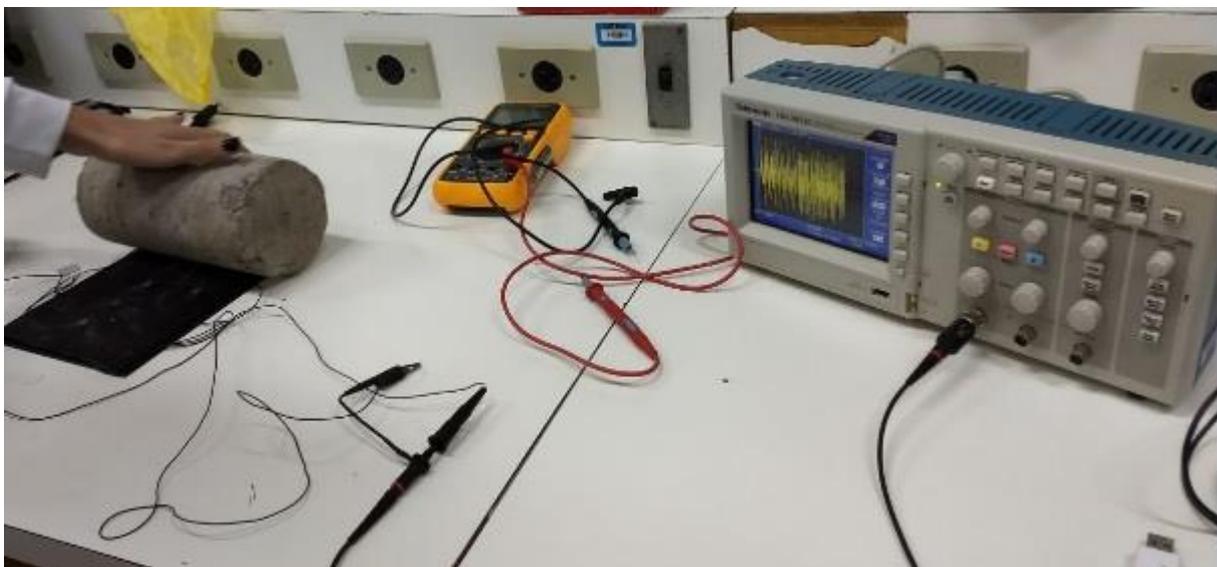
## 2.2 Experimental Analysis

For the experimental analysis, was used two plates of a natural rubber mat NR 1087, of hardness 70 Shore A (Fonseca et. Al., 2008) with 20,4 cm length, 15 cm wide and 3,5 thick to simulate the asphalt pavement, where was inserted 5 PZT discs that were connect in parallel as shows the fig. 2.



**Figure 2: Piezoelectric harvest system**

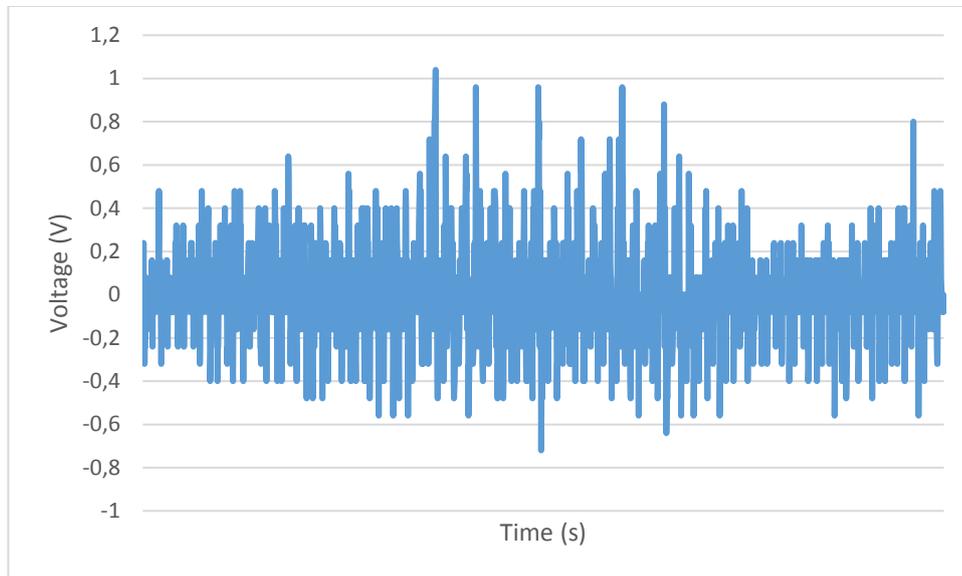
The harvest system was plugged on a Tectronix TDS 2012C oscilloscope, which has been set to 2 Volts/Div on the vertical axis, and the time was set to 10 sec/div on the horizontal axis. To make the experiment cylinders of different weights were scrolled with a tangential velocity about 0,15 m/s above the surface plates. The oscilloscope captured and recorded the data of the voltage output released by the disks. After that, a cell phone vibrating at certain frequencies by a linear vibrational app using a coin type - linear vibration motor that generate a rotational vibration due to a rotating unbalanced mass (Nam et al., 2014), was placed under the plates to induce the disks an initial vibration and new measurements were made. To determine which frequency the cell phone was vibrating was used another cell phone with an app “Vib Sensor” that uses the tri-axial accelerometer contained in the apparatus to measure the vibration input at the system. In fig. 3 it is possible to see the configuration in operation.



**Figure 3: Photo of the tests performed on the harvest system**

### 3. RESULTS AND DISCUSSIONS

At first, a cylinder of 0,2850 kg was rolled on top of the plates in a repetitive movement of back and forth, the data registered by the oscilloscope is showed in Fig. 4



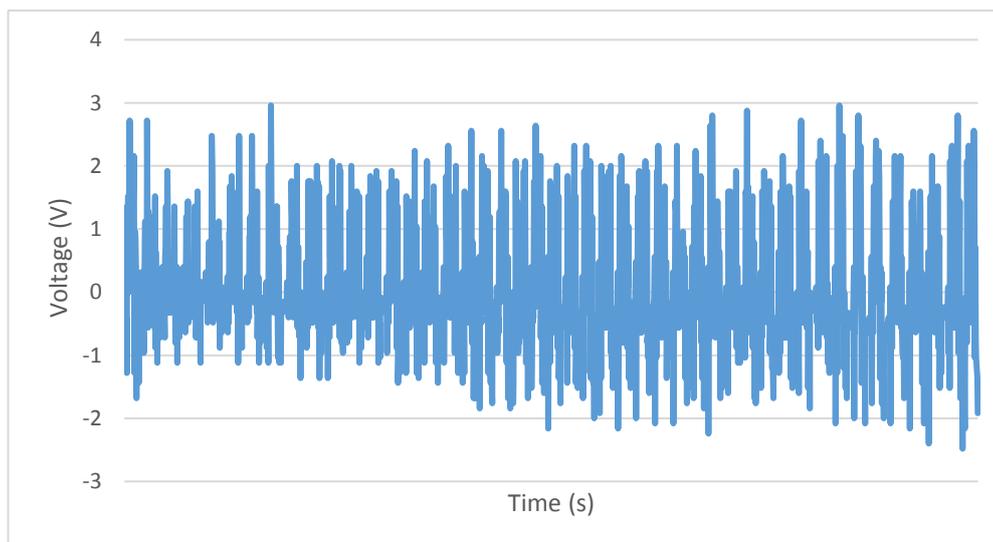
**Figure 4: Energy output by the harvest system submitted a pressure of a cylinder of mass 0,2850 kg**

Using the data collected by the oscilloscope was possible to determinate a root mean square of the instantaneous positive values of voltage output transmitted by the system by the formula:

$$rms(x) = \sqrt{\frac{1}{N} * \sum_{i=1}^N xi^2}$$

As a result, was obtained a rms = 0,250084.

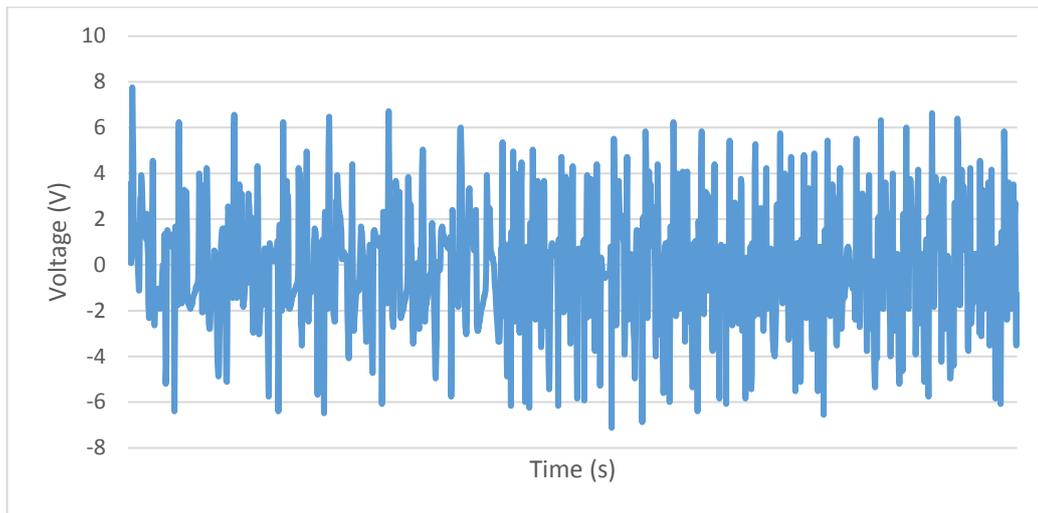
Then, the cylinder mass was changed for 1,3050 kg, which represents a raise of 457,89% on the mass under the plates. The experiment was performed again following the above standards. The result is shown in Fig. 5



**Figure 5: Energy output by the harvest system submitted a pressure of a cylinder of mass 1,3050 kg**

Using the same calculation method as above was found a value of rms: 1,19753, which represents an increase of 478,85% of the energy output with the increase of the mass exerting pressure under the plates.

A cylinder of mass 4,1635 kg, 1460,88% of the original mass, was placed on the top of the plates, and following the parameters already mentioned, the graph shown in Fig. 6 was found.



**Figure 6: Energy output by the harvest system submitted a pressure of a cylinder of mass 4,1635 kg**

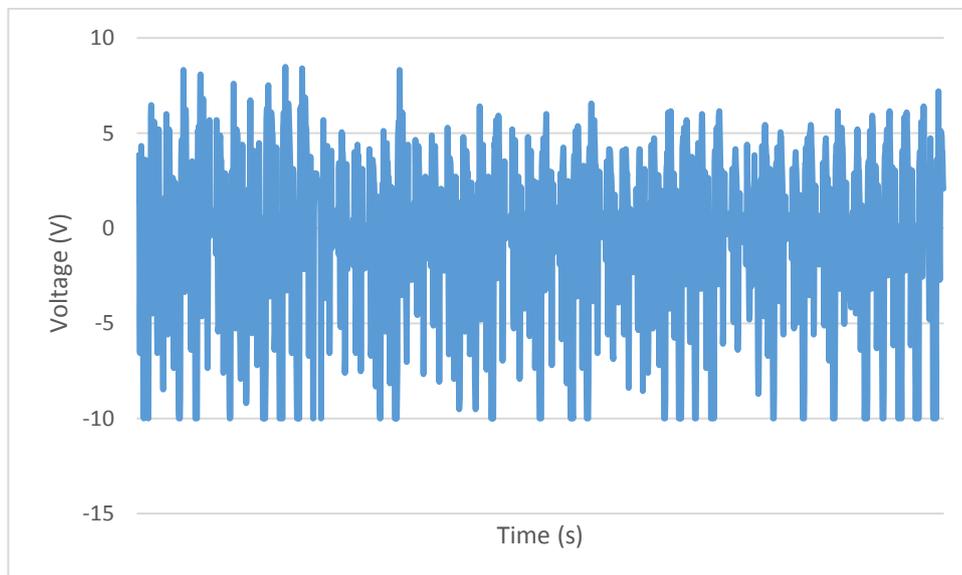
Calculating the root mean square value for the instantaneous positive values, is obtained rms: 2,199415, which shows an increase of 879,47%. Which represents a large influence of the compressive force that the system was submitted and your voltage output.

Continuing the experiment, the harvest system was coupled a cell phone commanded by a coin type - linear vibration motor that generate a rotational vibration, the app Vib sensor was used to collecting, analyzing, and exporting data. The power spectrum captured by the app was showed the fig. 8 and is calculated from 0 Hz to the Nyquist frequency. The units are acceleration squared divided by the frequency.

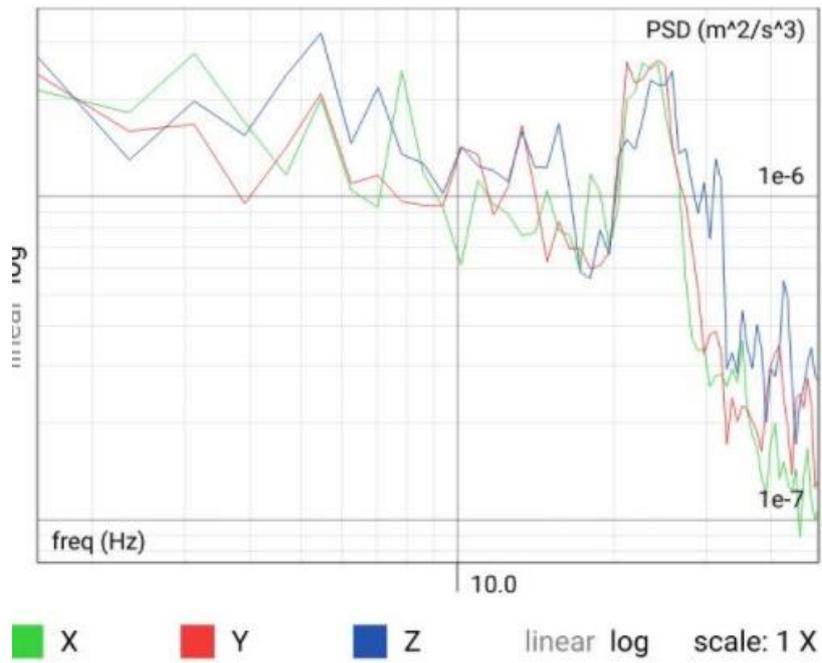
The resonances and rms of each axis are presented below, calculated by the application itself, from the power spectral density.

X: 3,1 Hz; 23 Hz; rms 0,0059; Y: 24 Hz rms 0,0061; Z: 5,5 Hz rms 0,0067 (a)

The cylinder of 4,1635 kg was rolled above the surface of the plate again with the initial vibration, the result can be observed at the fig. 7.



**Fig. 7 Voltage output with initial vibration (a)**

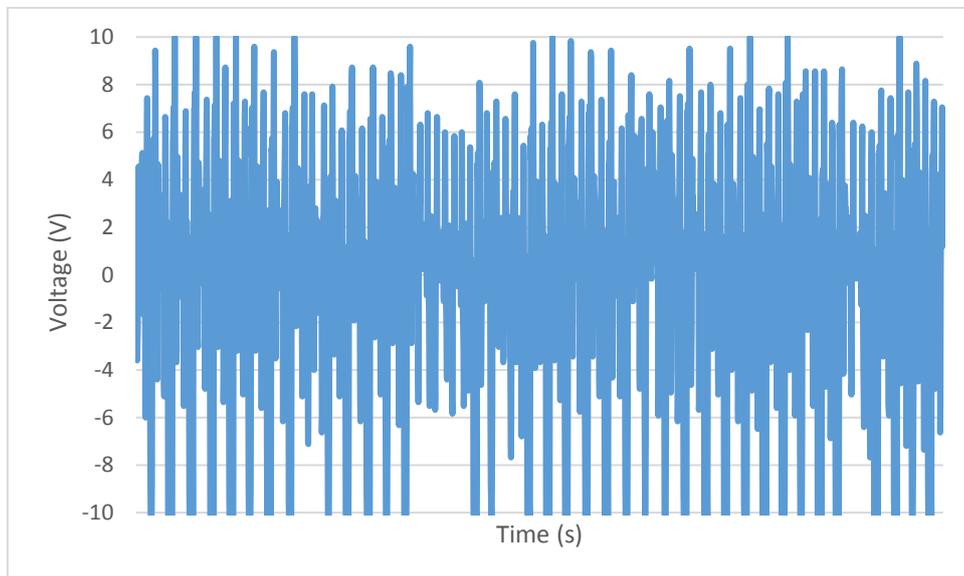


**Fig. 8 Power spectrum representation of the induced vibration (a)**

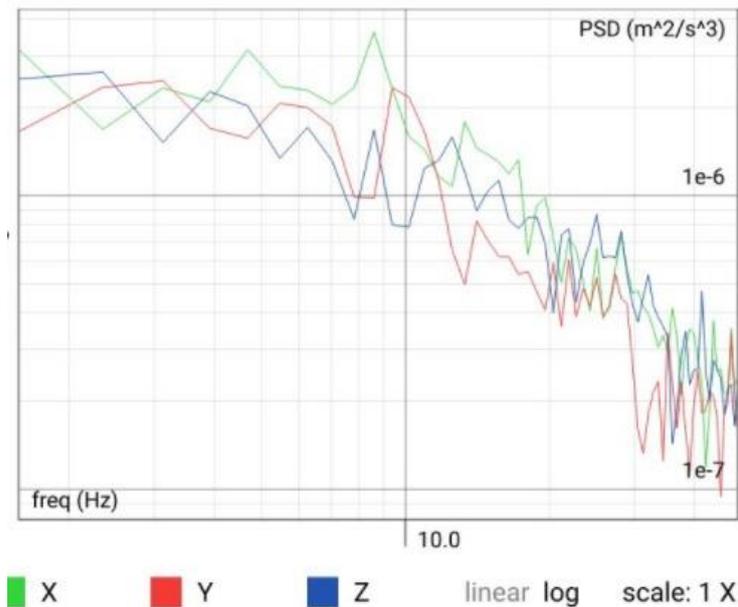
Calculating the rms value for the data collect from the oscilloscope is obtained rms: 3,11419, a gain of 136,92% in relation to the value found when the system was submitted to the same weight, but without the initial vibration. After that, the initial vibration was changed for the follow resonances and rms:

X: 8,6 Hz; 1,6 Hz; rms 0,0062; Y: 3,1 Hz; 9,4 Hz; rms 0,0051; Z: 2,3 Hz; rms 0,0055 (b)

And the experiment was realized once more. The voltage output result and power spectrum can be observed on Fig. 9 and Fig. 10 respectively.



**Fig. 9 Voltage output with initial vibration (b)**



**Fig. 10 Power Spectrum representation of the induced vibration (b)**

Calculating, rms of the output voltage: 3,504391. Which shows a increase of 159,33% of the same experiment without the initial vibration.

As it can be seen, the initial vibration pre-placed in the system caused a high increase of the energy transformed by the PZT, but, due the degree of error of the data collect by the vibrational measuring instrument it is believed that in a more controlled system of vibration a more consolidated result can be obtained.

#### 4. CONCLUSION

With the increase in energy used by mankind over the years, and with the large use of fossil fuels, it is evident the need to seek new sources of energy that are clean and renewable. In this article, a piezoelectric harvest system of energy was approached to verify its behavior when subjected to several initial vibrations and different loads. As a result, a of increase of 478,85% when the mass was altered in 457,89% and 879,47% was shown when the mass was altered in 1460,88%, which shows a nonlinear but extremely expressive influence between the load and the voltage transmitted by the system. When an initial vibration was introduced in the system, the results showed gains of 136,92% and 159,33% in relation to the results without vibration. It is hoped that this article may contribute to further studies of piezoelectric energy capture so that in the future this type of clean and renewable energy can be used by the population on a large scale.

#### 5. ACKNOWLEDGMENTS

The authors would like to thanks to Institutional Program of Volunteering in Scientific and Technological Initiation of the Federal Technological University of Paraná (UTFPR), UNESP - Univ. Estadual Paulista and Pato Chaos Science Group for support. To Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP Process No. 2014/16807-3) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq Process No. 301769/2012-5) for funding. To Fundação Araucária and CAPES for scholarship.

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