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Experimental investigation of charging batteries with piezoelectric beams

Daniel Silvério Campetti Nieto, danielcampetti@gmail.com[1]
Aline Souza de Paula, alinedepaula@unb.br[1]

[1]Universidade de Brasília, Department of Mechanical Engineering - 70.910.900 – Brasília – DF, Brazil.

Abstract: *Energy harvesting technology using piezoelectric materials has gained a lot of attraction in the last decades. In this context, a potential application consists in the power supply for low power device, such as some sensors. At first, this paper addresses an analysis of energy harvesting by a PZT piezoelectric beam harmonically excited and coupled to a purely resistive circuit. At this point both mechanical and electrical behaviors are discussed. After that, the piezoelectric beam is coupled to a battery charging circuit and its charging capacity is evaluated. At last, two piezoelectric beams are associated and used to charge the same battery charging circuit. A comparison of charging performances with one and two piezoelectric beams is presented.*

Keywords: *Piezoelectric materials, Energy harvesting, Charging batteries.*

1. INTRODUCTION

Smart materials are those that exhibit coupling between at least two physical domains and is able to convert energy between these domains Leo *et al.* (2007) . In the case of piezoelectric material, the coupling is between the mechanic and electric domains, thus, the material allows conversion between mechanical and electrical energy. Due to the direct effect, the piezoelectric materials are able to provide electrical output voltage when mechanically deformed. According to Hehn *et. al.* (2009) and Jeon *et al.* (2005) these voltage can be used to power electric circuits that require low power supply, such as sensors, electronic circuits and micro-electromechanical systems (MEMS).

In this context, the application of piezoelectric materials for environmental energy harvest used in MEMS supply has received great attention from researchers in recent years. According to Shu (2006) these applications are critical for wireless data transmission sensor networks, including monitoring of machines and equipment used in smart homes and tracking devices for wildlife, as even with the technological development of electronic components, the power supply is still a problem. The conventional solution for powering wireless sensors is the use of traditional batteries, however, the size, weight limitations due to short payload time and the need for constant replacement of the batteries of these various applications unfeasible.

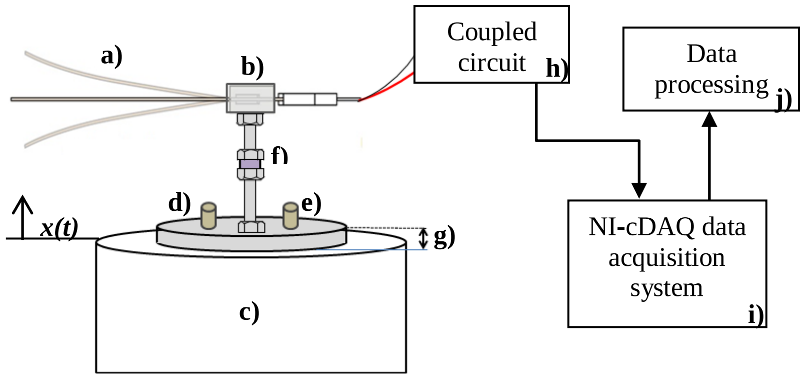
This work evaluates the voltage, current, electric power of the piezoelectric beam Volture PZT25w. At first, the electromechanical coupling is analyzed for different forcing frequencies when the beam is coupled to a resistive circuit. After that, the capability of the piezoelectric beams in charging rechargeable batteries is evaluates. In this analysis, the performance of a single beam is compared to the case where two beams are associated in parallel.

2. EXPERIMENTAL ANALYSIS

The experiment consists to evaluate the energy harvesting performance of piezoelectric beams mechanically excited. In all experiments the beams is coupled to an electrical circuit. A shaker provides the mechanical forcing, that imposes a harmonic base excitation to the beam as follow:

$$x(t) = Asen(\omega t) \tag{1}$$

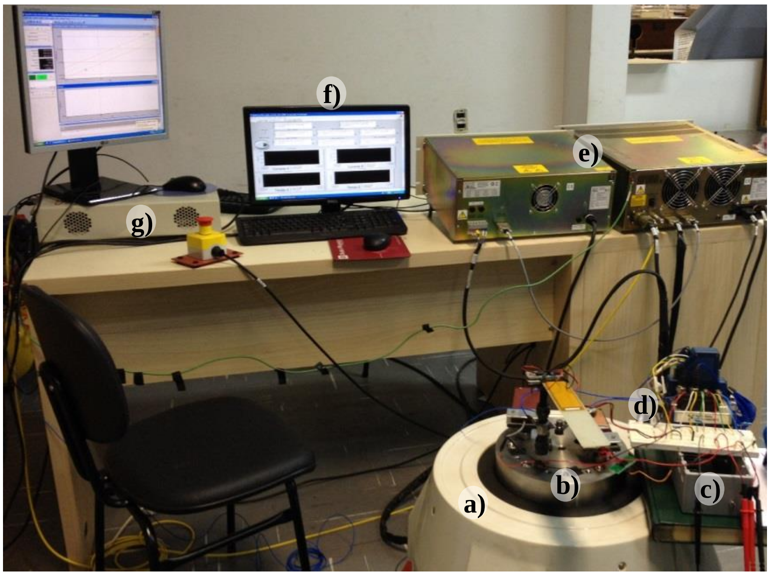
where A is the peak to peak oscillation amplitude, ω is the base excitation frequency and t is time. Figure 1 shows the schematic representation of the experiment.



a) Cantilever beam
b) Clamp
c) Shaker
d) Control Accelerometer
e) Acquisition Accelerometer
f) Force transducer
g) Base oscillation amplitude
h) Coupled electronic circuit
i) NI-cDAQ data acquisition system
j) Data processing

Figure 1. Schematic representation of the experiment.

The electrical circuit is mounted on a protoboard that is coupled to the piezoelectric beam as shown in Figure 2. The performance of the piezoelectric material depends on the imposed mechanical excitation as well as on the coupled electrical circuit, i.e., the amplitude and forcing frequency and the electrical circuit consist on parameters that influence the dynamic behavior of the system and, thus, the harvested energy. Figure 2 also shows the data acquisition set up.



a) Shaker
b) Cantilever beams
c) NI-cDAQ data acquisition system
d) Coupled circuit (protoboard)
e) FPS and Amplificator
f) Data processing
g) Shaker Controller

Figure 2. Experimental setup.

Table 1. Material parameters - Volture Midé V25W

Parameters	Values
Typical Thickness (mm)	0.61
Active area (mm)	33.2 x 46
Operating Temperature Range (°C)	-40 to 90
Piezo max strain	800 micro-strain
Max. Tip-to-Tip Displacement (mm)	3.81
Single Wafer Series Capacitance (nF), measured at 100 Hz	130
Single Wafer Series Resistance (Ω), measured at 100 Hz	210
Tip Mass (g)	15.6 and 17.3
Mode Generator	d_{31}
Type	bimorph
Full bridge rectifier and filter	EH20W Rev2 (midé corp)

The first piezo beam, called Piezo A, shown in Figure 3 is from Midé Inc. Note that the V25W beam is protected by an aluminum structure and has three components. The first is the cantilever beam itself, the aluminum tip mass and finally the rectifier circuit, a BAT199 diodes and a filter capacitor of 100uF. The parameters of the Volture™ - V25w material are presented in Table 1.

The second beam, called Piezo B, shown in Figure 4, and is similar to Piezo A, with a tip mass attached to the V25W beam that is coupled to a rectifier circuit. A tip mass of 17.3g is used in Piezo B so that it is tuned to Piezo beam A.

Rectification is the AC to DC conversion and can obtained from the use of diodes or electronic valves. The DC supply is essential for the majority of electronic devices as well as for charging batteries. Full bridge rectifier uses four diodes and is a way to perform the rectification. Piezo A and B uses a Midé EH20W rectifier circuit with BAV199 diodes and 100μF capacitor.

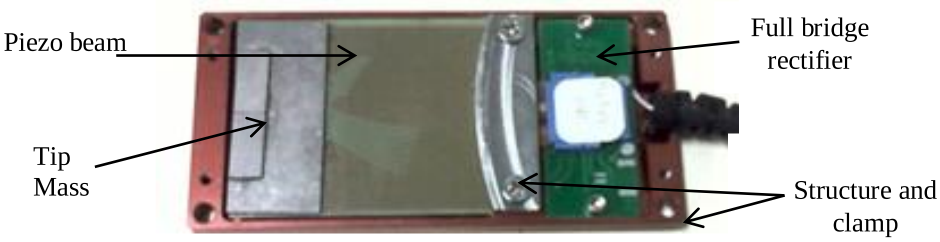


Figure 3. Piezo A beam with a tip mass attached.

Figure 4. Piezo B beam with a tip mass attached.

3. ELECTROMECHANICAL FREQUENCY RESPONSE FUNCTION (FRF)

According to Feucht *et. al*. (1990), fundamentally a frequency response function (FRF) is a representation of the relationship between the input and the output of a system. Frequency response is the quantitative measure of the output spectrum of a system or device in response to an excitation, and is used to characterize the system dynamics. It is a measure of magnitude and phase of the output as a function of frequency, in comparison to the input.

The FRF is constructed from a sweep up experiment with forcing frequency varying from 38 to 50 Hz and forcing amplitude of 1mm. The experiment is evaluated for 10 different values of load resistance: 5.6, 7.8, 11.2, 16.4, 24.0, 30.0, 40.0, 54.0, 66.0 and 78.0 kΩ. Each resistive load leads to different results in voltage, current and power FRF as shown in Figures 5, 6 and 7, respectively.

As it can be observed in Figure 5, there is an increase of voltage with resistance increase. Note that a maximum voltage of 1.75V occurs at 44.98Hz when a resistance of 5.5 kΩ is used, while a maximum voltage of 8.91V occurs at 45.33Hz when the resistance is 78.0 kΩ. Thus, the resonance frequency increases with the increase of the electrical resistance. A similar behavior was observed Erturk *et. al.* (2009).

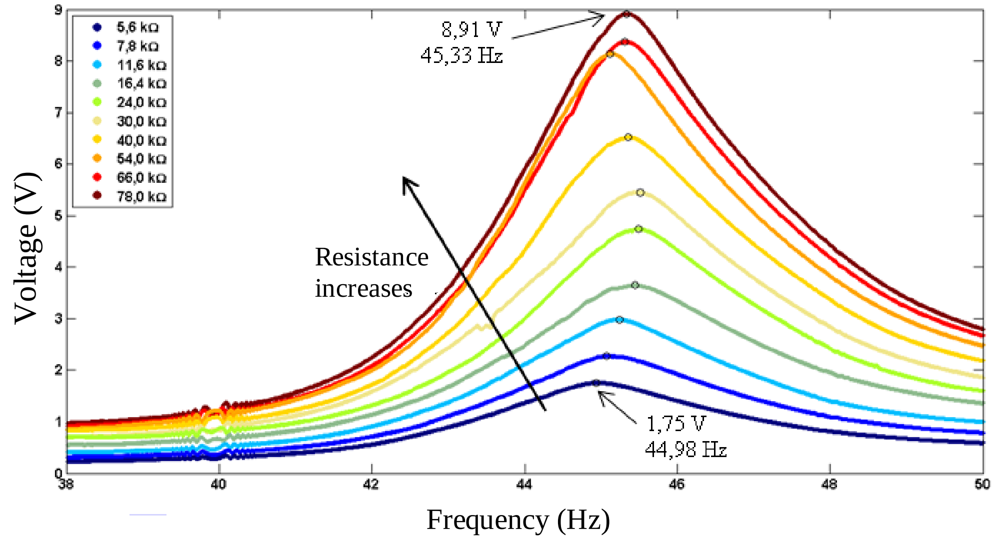


Figure 5. Voltage FRF for different electrical resistances.

As it can be observed in Figure 6, there is a reduction in the electric current with the increase of resistance, an opposite behavior when compared to the voltage (Figure 5). A maximum electric current of 0.65mA occurs at 44.98Hz when a resistance of 5.5 kΩ is used, while a maximum electric current of 0.22Hz occurs at 45.33Hz when the resistance is 78.0 kΩ. This result is also coherent with the one obtained by Erturk *et. al.* (2009), which addresses that the electric current FRF exhibits the opposite behavior of the voltage FRF.

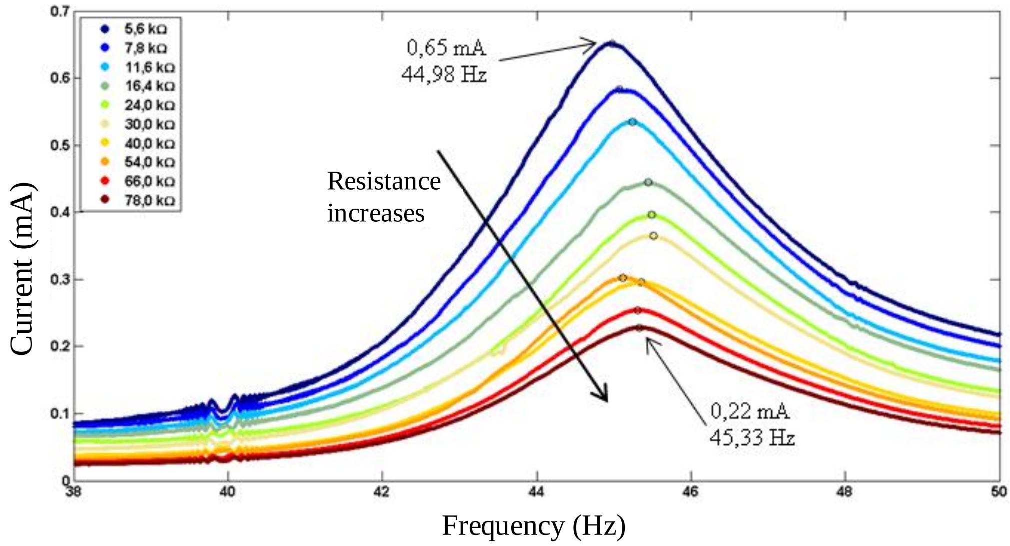


Figure 6. Current FRF for different electrical resistances.

Figure 7 shows the electrical power FRF for different resistive loads. As the power depends on voltage and current, there is not a monotonic behavior of electrical power with respect to the resistance, thus, it is difficult to identify the behavior of the maximum power from Figure 7. Figure 8 shows maximum power obtained for different electrical resistances. The optimum resistive load, which yield the maximum electrical power of 2,34mW, is 54 kΩ.

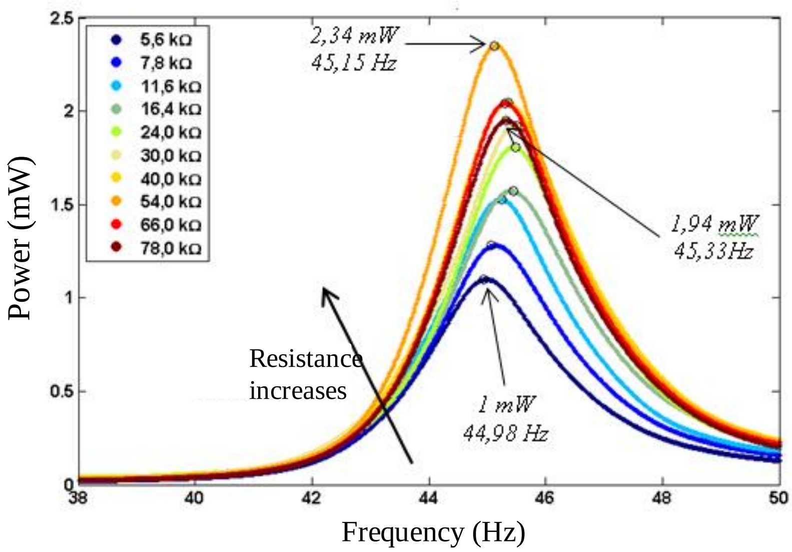


Figure 7. The experimental electromechanical frequency response function (FRF) for Power

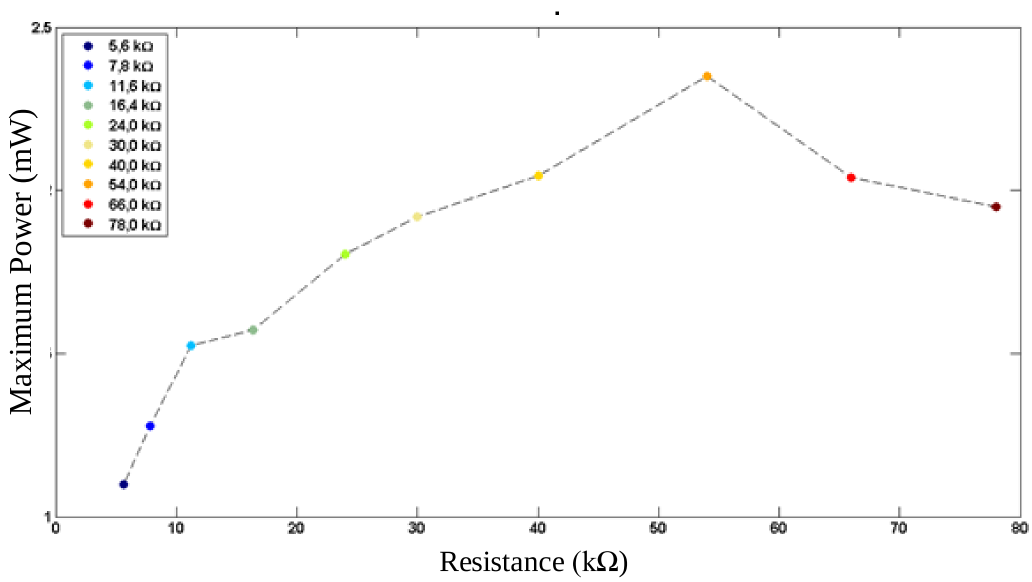


Figure 8. Maximum Power response as a function of electrical resistance

4. BATTERY CHARGING

In this section Piezo A and B are used to charge a low capacity battery of 20mAh (V20HR from Varta Inc.). The beams are used alone and coupled in parallel.

The current measured during charging and/or discharging batteries can be used to quantify the amount of energy flowing through the battery. The capacities of the batteries are given by milliampere hours (mAh) and describe the average load over time. According to Pereira *et. al.* (2006) and Pereira *et. al.* (2008) the capacity obtained during the loading and unloading can be calculated by performing numerical integration of the measurement of the electric current over time, as presented in Eq. (2).

$$C = \int i \, dt \tag{2}$$

where C is the battery capacity, i is the electric current measured, and t is time.

Figure 9 shows the electrical current obtained when charging the battery for different forcing frequencies when using Piezo A alone, Piezo B alone and both beams coupled in parallel. In this experiment the forcing frequency was increased from 39 to 45 Hz with constant base amplitude oscillation of 0.8mm and connected to a 20kΩ resistor.

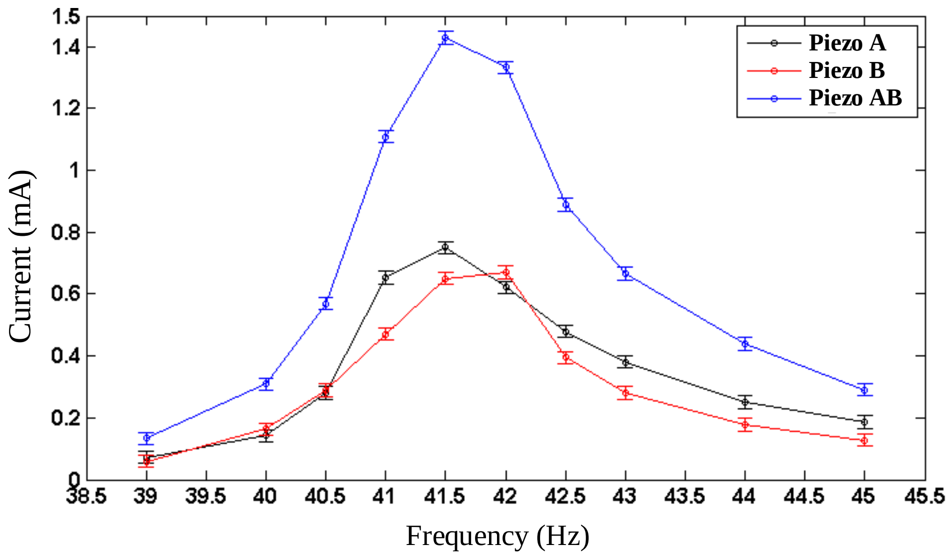


Figure 9. Electrical current when charging V20HR battery.

A concentrated mass was used in the beams in order to tune them in about 41.5 Hz, that is the frequency used in this work to charge batteries. At this forcing frequency, it is obtained 0.75 ± 0.02 mA for the Piezo A and 0.65 ± 0.02 mA for the Piezo B, as shown in Figure 9. When both beams are associated electrically in parallel, the electric current increases to 1.43 ± 0,02 mA. This value is close to the usual current used to charge 20mAh batteries capacity of 2mA.

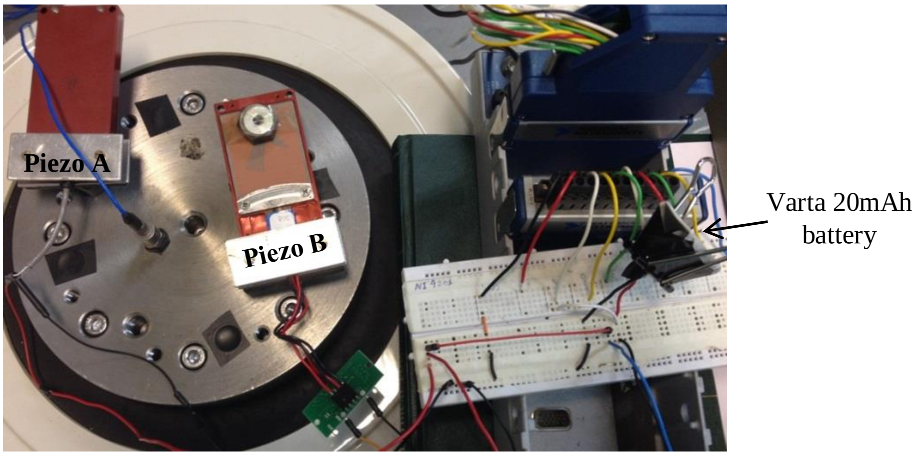


Figure 10. Experimental setup used to charge the 20mAh battery.

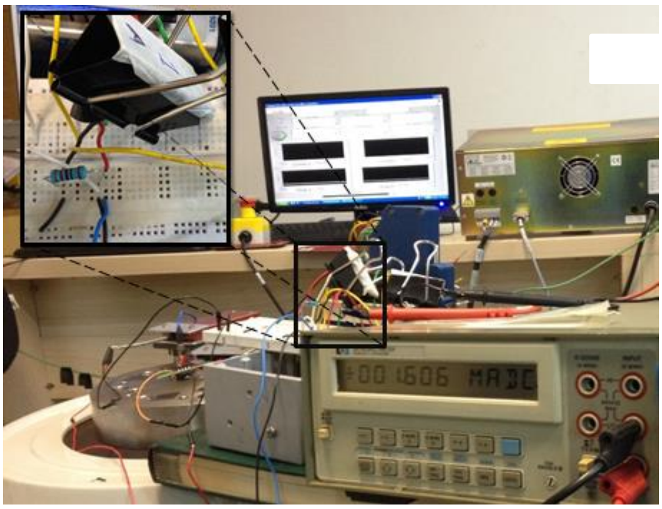


Figure 11. Experimental setup used to charge the 20mAh battery for 2 hours.

The battery charge was preceded with a 0.8mm forcing amplitude at 41,5Hz and duration of two hours. At first Piezo A is used, and then Piezo A and B coupled in parallel are used. By using Piezo A, and considering the charging electrical current obtained in Figure 9, the charge capacity is approximately 1.52mAh. When Piezo A and B are associated in parallel, the charge capacity increases to 2.86mAh.

To confirm the effective charge, the discharge of the battery is evaluated. In this context, a resistor of 890Ω is connected to the battery after the charge procedure is completed and the electrical current is monitored. The discharge battery experimental set up is shown in Figure 11. Figures 12 and 13 show the results of discharging the battery. By applying Eq. (2), when using Piezo A it is obtained 1.42mAh and when both Piezos are associated in parallel a discharge capacity of 2,47mAh is obtained. The obtained capacities when discharging the battery is close to the capacity estimated by the current obtained when charging the battery.

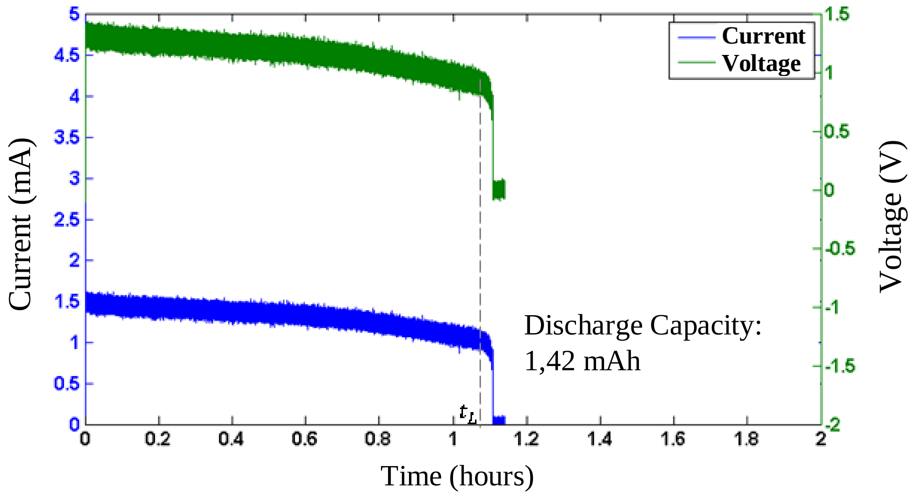


Figure 12. Discharge of the 20mAh battery charged with Piezo A during 2 hours.

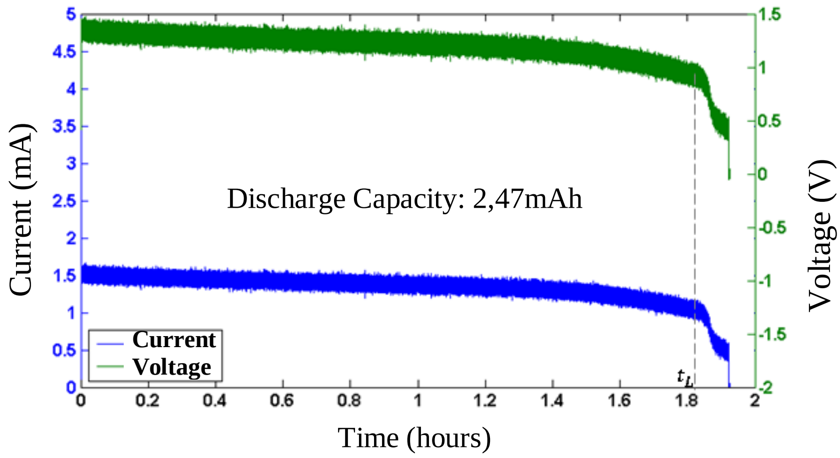


Figure 13. Discharge of the 20mAh battery charged with Piezo A and B associated in parallel during 2 hours.

5. CONCLUSIONS

At first this paper presents an analysis of the energy harvested by a piezoelectric beam harmonically excited when coupled to a purely resistive circuit. Different resistances are considered in the resistive circuit and electrical voltage, current and power are evaluated. From the results, we conclude that voltage increases with resistance increase. In the other hand, current decreases with resistance increase. As the power depends on voltage and current, there is not a monotonic behavior of electrical power with respect to the resistance. The best resistance, associated with the highest electrical power, is obtained.

After that, two piezoelectrical beams (Piezo A and Piezo B) are used to charge a low capacity battery of 20mAh for 2hours. The electrical current is evaluated during the charge procedure considering Piezo A alone, Piezo B alone and both beams associated in parallel. This current is used to estimate the charge capacity when 2 hours of charging is considered. The battery effective charge is evaluated by its discharge. Results show that when using Piezo A alone the battery presents a capacity of 1.42mAh and when Piezo A and Piezo B are associated in parallel a capacity of 2,47mAh is observed. Thus, the association of the beams in parallel results in an increase of 74% in the effective charge when compared to the piezoelectric beam alone.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Erturk A. and Inman, D.J., "An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations", Smart Materials and Structures 18 (2009) 25009 (18pp).

Feucht, D.L. (1990). "Handbook of Analog Circuit Design". Elsevier Science. p.192. ISBN 978-1-4832-5938-3.

Hehn, T.; Hagedorn, F.; Manoli Y; "Highly Efficient Energy Extraction from Piezoelectric Generators". Procedia Chemistry, v.01, n.01, p.1451-1454, September 2009.

Jeon, Y.B., Sood, R, Jeong, J.H., Kim, S.G., "MEMS power generator with transverse mode thin film PZT". Sensors and Actuators A: Physical, v.122, n.1, p. 16-22, july 2005.

Leo, D. J.; "Engineering Analysis of Smart Material Systems". Hobokeb, New Jersey: John wiley & Sons, 2007.

Shu Y.C. and Lien, I.C. "Analysis of power output for piezoelectricenergy harvesting systems", Smart Mater. Struct. Vol.15 pg1499–1512, 2006

Pereira, T., Scaffaro, R., Nieh, S., Arias, J., Guo, Z., and Thomas Hahn, H., 2006, "The performance of thin-film li-ion batteries under flexural deflection," Journal of Micromechanics and Microengineering, 16(12), pp. 2714–2721.

Pereira, T., Scaffaro, R., Guo, Z., Nieh, S., Arias, J., and Hahn, H. T., 2008, "Performance of thin-film lithium energy cells under uniaxial pressure," Advanced Engineering Materials, 10(4), pp. 393–399.