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A MULTIFREQUENCY PIEZOELECTRIC STRUCTURE FOR VIBRATION ENERGY HARVESTING

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Abstract. *The piezoelectric structures when under the resonance condition generate the maximum amount of energy possible. However, when the excitation frequency drives away from resonance energy level generated is reduced presenting a low efficiency. This work proposes the use of a multifrequency piezoelectric structure to scavenge energy from vibrations for powering sensor systems turning into autonomous systems. The multifrequency piezoelectric structure was modeled using finite element method through ANSYS software looking for a reliable model to the physical system. As a way of mitigating the low efficiency when the excitation frequency varies, a multifrequency piezoelectric structure composed of different simple structures (beams) with close natural frequency was developed, so that small variations are compensated by resonance excitation from one of the beams in the array. The numerical results of the model were compared with experimental data showing the potential of implementing the proposal.*

Keywords: *multifrequency piezoelectric converter, autonomous sensor system, power harvesting, narrowband vibrations*

1. INTRODUCTION

The current technological advancement provides the development of powerful unmanned aircraft vehicles (UAV) and structural condition monitoring systems (SHM). However, some systems of these UAV's and SHM systems located in unreachable places require a constant power supply and extended life span. This is impossible to achieve using a battery to power these systems, once the batteries have a limited life span, besides the impossibility, in most cases, of their replacement and environmental problems related to their disposal.

In this context, the use of energy harvesting techniques for the conversion of energy from the environment (vibration, electromagnetic, etc.) into electrical energy, has stimulated the scientific community and arose as an attractive alternative in replacing batteries and common power systems. Thus, various methods to extract energy from the environment have been used, whose sources being highly diverse, such as solar, wind, etc. (Morais et al, 2008). Among these, highlights the conversion of energy from mechanical vibration into electrical energy. This conversion can be achieved through three methods: electromagnetic (Sari et al. 2008), electrostatic (Roundy et al, 2002) and piezoelectric (DuToit, 2005).

Among various papers broaching this issue, the use of piezoelectric materials has been highlighted by both the ease of applying in industrial environment (Zhu et al., 2010) and great ability converting a mechanical strain into electric voltage and vice versa (Anton and Sodano, 2007). Thus, a piezoelectric converter can be designed in a simple way and easily developed as a simple cantilevered beam associated with a piezoelectric material (PZT, PVDF). A piezoelectric converter correctly positioned on a vibrating structure, with its natural frequency tuned to optimize energy generation, generates up to hundreds of microwatts (DuToit, 2005).

Most works in the literature, presents the development of linear converters generating maximum power when the excitation frequency matches the natural frequency of the piezoelectric oscillator. In this case, if the excitation frequency varies, as in most practical cases, the generated power decreases drastically (Tang et al. 2010). Thus, simple piezoelectric beams (piezoelectric converters) operating out of resonance have low efficiency. According to Zhu et al. (2010), there are basically two ways to mitigate this limitation, the first one would be by tuning the resonance frequency of the piezoelectric converter according to the frequency of the vibration condition (actively or passively) at all times (Roundy and Zhang, 2005) and the second way would be by widening the operation frequency band of the generating piezoelectric structure (beam + PZT). The second mode can be achieved using a simple array of multiple converters, each with a different resonant frequency (Ferrari et al., 2007) or using non-linear converters, for example, among others.

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As a general aim, this paper presents an alternative structure, in relation to the piezoelectric converter system as a simple beam type, in order to assure a reasonable level of energy generated by the piezoelectric converter in environments whose excitation frequencies vary around a narrowband frequency. This procedure is performed by developing a structure consisting of piezoelectric beams with different and close natural frequencies so that small variations in excitation are compensated by resonance of one of the beams in the multifrequency piezoelectric structure array. At first the piezoelectric structure is simulated in a finite element software, and later, the structure will be subjected to laboratory tests.

2. MODELING AND SIMULATION

The piezoelectric ceramics have a high mechanical quality factor, which is related to the mechanical damping, representing a high voltage level when the piezoelectric structure is operated under resonance condition and a narrowband operation frequency (Kok et al, 2011). Due to this narrow range operation frequency, the use of such devices becomes limited, especially in cases where the conditions of operation and power generation can oscillate. According to Zhu et al (2010), it is possible to mitigate this limitation using a system that tunes the natural frequency with the excitation frequency or by increasing the operating bandwidth. One way to increase the frequency band of operation of the piezostructure is by using an array of simple converters. In the case of this work, an array with three piezo-generators has been proposed and the first step was the development of a numerical model of a simple structure, a single beam, in order to study the physical phenomena correctly. Initially, the entire development was conducted for only one of the piezoelectric converter and then extended to other piezo-generators of the multifrequency piezostructure.

2.1 Finite Element Model

Several researchers have been developed their works based on the idea of a simple converter and therefore their electromechanical models were developed from a one degree of freedom mass-spring system initially described by Williams and Yates (1996). Many other models were developed (Ajitsaria et al., 2007; Adachi et al., 2009) using the concept of a one degree of freedom mass-spring system. Despite these models being able to predict the voltage generated by the piezo-generator, some problems have been observed in these models, such as oversimplification of models, low correlation between the numerical model and the physical phenomenon, using static expressions in fundamentally dynamic problems among others (Erturk and Inman, 2008b). These problems can be better analyzed by using a more accurate numerical model and the modeling of physical system through finite element method (Hagood et al, 1990; From Marqui et al, 2009) that, besides predicting the voltage and power generated by the piezostructure with exactitude, also has been shown to accurately represent the physical phenomenon in question.

The structural behavior of the proposed multifrequency piezostructure was modeled using the finite element software ANSYS©. The governing equations of the coupled electromechanical system used by the software have been discussed in Allik (1970). The global coupled finite elements equation derived for the model is given in matrix form by:

$$\begin{bmatrix}[\boldsymbol{M_{uu}}] & [\boldsymbol{0}]\\ [\boldsymbol{0}] & [\boldsymbol{0}]\end{bmatrix}\begin{Bmatrix}\{\ddot{\boldsymbol{u}}\}\\ \{\ddot{\boldsymbol{\varphi}}\}\end{Bmatrix}+\begin{bmatrix}[\boldsymbol{C_{uu}}] & [\boldsymbol{0}]\\ [\boldsymbol{0}] & -[\boldsymbol{C_{\varphi\varphi}}]\end{bmatrix}\begin{Bmatrix}\{\dot{\boldsymbol{u}}\}\\ \{\dot{\boldsymbol{\varphi}}\}\end{Bmatrix}+\begin{bmatrix}[\boldsymbol{K_{uu}}] & [\boldsymbol{K_{u\varphi}}]\\ [\boldsymbol{K_{u\varphi}}]^t & -[\boldsymbol{K_{\varphi\varphi}}]\end{bmatrix}\begin{Bmatrix}\{\boldsymbol{u}\}\\ \{\boldsymbol{\varphi}\}\end{Bmatrix}=\begin{Bmatrix}\{\boldsymbol{F}\}\\ \{\boldsymbol{Q}\}\end{Bmatrix} \quad (1)$$

Where *{u}* is the mechanical displacement vector describing the motion in each structural element and *{φ}* the electrical degrees of freedom describing the electrical potential at structural nodes. With $[M_{uu}]$ being the elemental mass matrix, $[K_{uu}]$ elementary stiffness matrix. $[K_{\varphi\varphi}]$ is the elementary matrix of coefficients of dielectric permittivity, $[C_{\varphi\varphi}]$ is the elementary dielectric damping matrix (capacitance), *{Q}* is the vector of nodal, surface and body loads, $[K_{u\varphi}]$ is the piezoelectric coupling matrix, *{F}* is the vector of nodal and surface forces applied in the system. The damping was introduced in this case by the Rayleigh equation as being proportional to the mass and rigidity matrices $[C_{uu}]$:

$$[\boldsymbol{C_{uu}}]=\alpha[\boldsymbol{M_{uu}}]+\beta[\boldsymbol{K_{uu}}] \quad (2)$$

where α is a coefficient proportional to the mass and β is the coefficient of proportional to stiffness, where the values of α and β indicate the type of damping. In this case the piezoelectric element considered is the damping of Rayleigh where $\alpha > 0$ and $\beta > 0$ (Lerch, 1990).

2.2 Piezoelectric Structure

The piezoelectric converters, developed in this work, consist of a cantilevered beam as the host structure with a piezoelectric element (PZT-5H) attached near the clamped end. For the host beam, the material chosen was the acrylic due to its low value of Young's modulus, which enables a very flexible beam transmitting the high deformation to the

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piezoelectric element generating a high energy level and allows the structure to have a reduced size. The physical properties of the host beam and the piezoelectric element characteristics are given in Table 1.

Table 1 - Dimensions and properties of one of the piezostructure beams.

Beam Properties	**Value**	**PZT Properties**	**Value**
Length (mm)	107.50	Length (mm)	20.00
Thickness (mm)	1.10	Thickness (mm)	0.19
Width (mm)	20.00	Width (mm)	20.00
Young's Modulus (GPa)	2.90	Young's Modulus $Y^E{}_1$ (GPa)	62.00
Density (kg/mm³)	1150.00	Young's Modulus $Y^E{}_3$ (GPa)	50.00
		Piezoelectric constant d_{33} (m/V)	6.50e-10
		Piezoelectric constant d_{31} (m/V)	-3.20e-10
		Dielectric relative constant $K^T{}_3$	3800.00
		Coupling coefficient k_{31}	0.44
		Density (kg/mm³)	7800.00

The analysis of the piezostructure dynamic behavior was performed using ANSYS© and, therefore, two element types was used, one for the host beam and one for piezoelectric element. The host beam was modeled using the element SOLID45 with 8 nodes, displacement degrees of freedom in the x, y and z directions, and the beam was divided into 105 elements. For the piezoelectric element the element SOLID5 with 8 nodes, and displacement degrees of freedom of in the x, y and z directions and the electric potential, the PZT was discretized in 100 elements. The proposed model, Fig. 1, was evaluated based on theoretical modal analysis and the natural frequencies of piezostructure were identified for clamped-free condition. For the first four modes of vibration, the natural frequencies obtained are presented in Table 2.

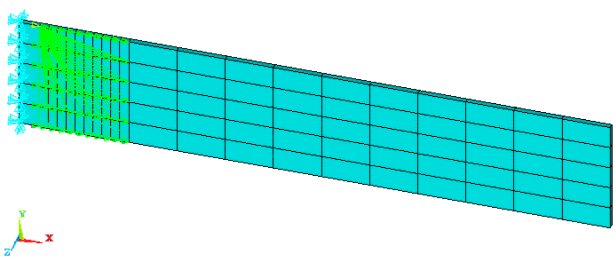

Figure 1. Piezostructure modeled by finite element

Table 2 – Model natural frequencies.

Modes	Frequency f_n (Hz)
1	30.70
2	174.30
3	301.50
4	457.00

Once natural frequencies of the piezoelectric converter were identified, simulations were made for evaluation and prediction of the electrical potential generated by a single piezoelectric converter of the piezostructure. The converter was evaluated for a vibrating condition equivalent to a sinusoidal acceleration amplitude 9.81 m/s² and frequency of 30.70 Hz which corresponds to the first mode natural frequency of the model, applied at the clamped end, in the z direction. The damping was considered as proportional damping (α = 0.70 and β = 6.00x10^{-4}). The electric potential measured in the simulated model under above conditions was 11.90 V peak to peak. Figure 2 shows a graph of the electrical potential estimated in the simulation process.

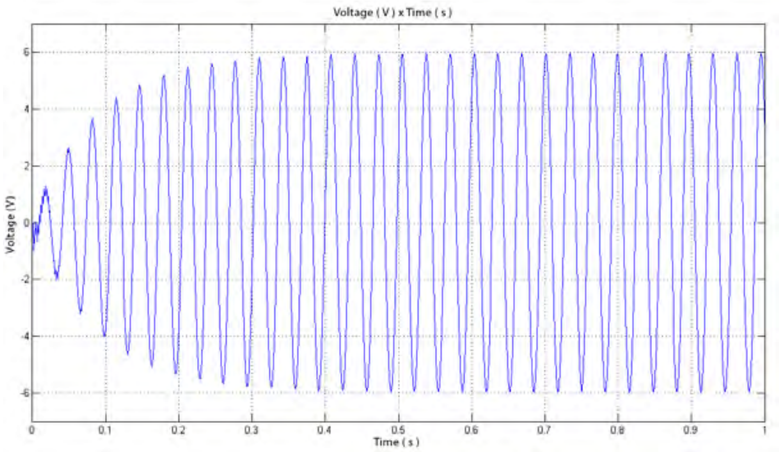

Figure 2. Electrical voltage obtained by simulating the piezostructure

To evaluate the representativeness of the proposed model an experimental test was performed with the same conditions applied in the numerical model, then the numerical and experimental model were confronted.

3. NUMERICAL MODEL VALIDATION

To evaluate the representativeness of the model an experimental test was conducted where the piezoelectric converter was excited with a frequency of 30.00 Hz and a sinusoidal acceleration equivalent to that used in the simulation, applied at the same point of the simulated model. For this, a signal generator (MINIPA MFG-4220 20MHz) was used connected to an amplifier (VEB METRA MESS - MMF LV103), which sends the signal to an electrodynamic shaker, and the voltage generated by the piezo-generator was measured using an oscilloscope (TEKTRONIX TDS 1012B).

The amplitude of the applied acceleration was measured using an accelerometer (PCB Piezotronics Model: 352C22 - 10.30 mV/g), with the current of the amplifier controlled so that the amplitude was 9.81 m/s². In Figure 3 is shown the schematic diagram of the experimental setup used.

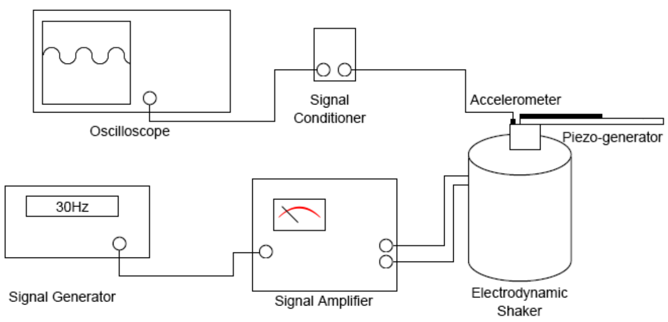

Figure 3. Schematic diagram for experimental validation of numerical model

The electric potential generated by the piezostructure and measured using the oscilloscope was 11.50 V peak to peak. Table 3 shows a comparison of experimentally measured electric potential with the potential obtained in the numerical model.

Table 3 – Results obtained by the two methods and the difference between them.

Method	Numerical	Experimental	Difference (%)
Frequency f_n (Hz)	30.70	30.00	2.18
Voltage (V)	11.90	11.50	3.47

*Difference = (Experimental – Numerical / Experimental)*100*

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The results indicate that the numerical model and the experimental model are sufficiently correlated to provide a basis for the development of the multifrequency piezostructure, composed by an array of three single piezoelectric converters.

4. MULTIFREQUENCY PIEZOSTRUCTURE

A multifrequency piezostructure was developed using a system composed by three single piezoelectric converters whose host beams have different lengths. The proposed multifrequency system is able to store an amount of energy suitable even if the vibration frequency of the structure is oscillating in a given range. In this case, the oscillations in the excitation frequency around a given frequency of piezostructure vibration are compensated by the different piezo-generators in the structure and in terms of the amount of power generated, power generation somehow responds independently of the varying in the excitation frequency. Figure 4 schematically shows the structure used, the second beam (beam 2) has the same characteristics as the structure investigated in the previous section, wherein the first mode natural frequency is 30.70 Hz.

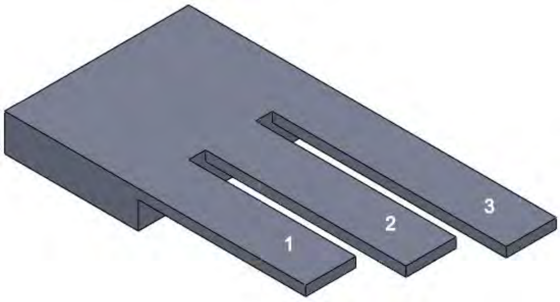

Figure 4. Piezostructure with different length

To extract maximum power from the multifrequency piezostructure the other beams were adjusted so that the reduction of power generated by the beam number 2 due to reduction/increase of the vibration frequency could be offset by the other beams. The concept of half-power bandwidth was used to estimate the first natural frequency of the other two beams, in this case, it is considered that the reduction of power generated by the beam 2 due to the oscillation in the excitation frequency was not less than 3.00dB ensuring a reasonable level of power generated. Therefore, the graph of the voltage generated by beam 2 was used as the reference, Fig. 5, and the frequencies were estimated where the reduction of the energy generated fell to values below 3.00dB, Equation 3.

$$3dB = 20 * log_{10}(\frac{V}{V_{ref}}) \tag{3}$$

Where V_{ref} is the reference voltage obtained experimentally and V is the reduced voltage when the structure operates off the ideal condition (resonance) due to the oscillation in the vibration frequency. In this case, the corresponding frequencies obtained were 27.00 Hz and 33.00 Hz.

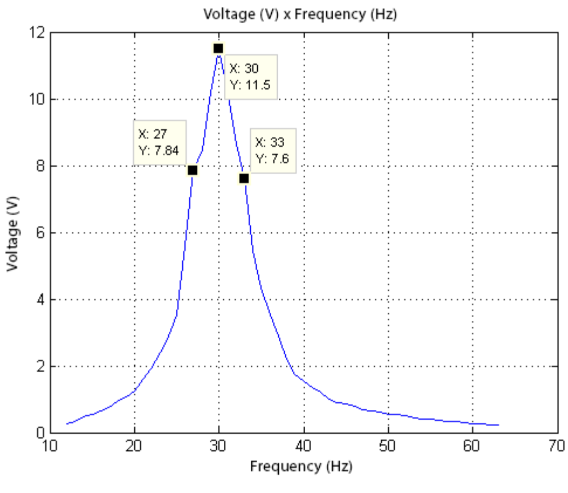

Figure 5. Voltage generated through frequency sweep

A reevaluation of the model was made trying to obtain the highest electric potential generated by each piezo-generator. In this case, new simulations were conducted where the lengths of the piezoelectric element was varied. The peak voltages generated in each piezoelectric element lengths were recalculated and can be seen in Fig. 6.

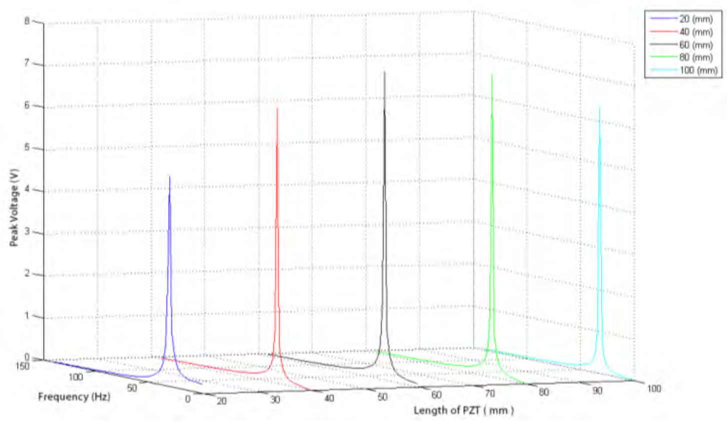

Figure 6. Peak voltages generated with different piezoelectric element length

In this case it was observed that the largest generation was achieved using a piezoelectric element of length equal to 60.00 mm which was taken as the base and the multifrequency piezostructure was reevaluated. The other beams were modeled similarly, and their natural frequencies were adjusted across the length of the beam so that the beams 1 and 3 present the natural frequencies of 28.60 Hz and 32.50 Hz, respectively Table 4.

Table 4 – Natural frequencies of each beam according to the length.

Beam	Length (mm)	Natural Frequency (Hz)
1	110.50	32.50
2	114.00	30.60
3	118.00	28.60

4.1 Energy extraction

The energy extraction and storage was taken from experimental tests in the laboratory, considering the piezoelectric elements as voltage sources connected in series with a parallel circuit formed by a capacitance and internal resistance as shown in the diagram of Fig. 7.

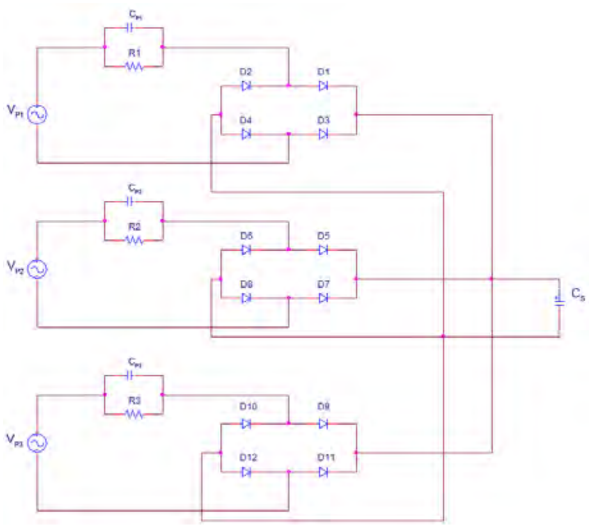

Figure 7. Schematic diagram simulating the full-bridge rectifier

The values of the internal resistance of the piezoelectric elements were R1 = R2 = R3 = 27.50 KΩ, and the values of the internal capacitances CP1 = CP2 = CP3 = 211.00 nF. The 1N5817 diodes were used, considering its voltage drops as VD = 0.75 V and the storage supercapacitor, CS, was 1.50 F/5.00V.

The multifrequency piezostructure behavior was analyzed in order to evaluate its power generation under the influence of oscillations in the excitation frequency. The piezostructure was excited at each of the piezo-generator natural frequencies (28.00 Hz, 30.00 Hz and 32.00 Hz), and the voltage produced by them is stored in a supercapacitor 1.50 F/5.00V for a period of 5 minutes. Thus it was possible to verify the contribution of each piezo-generator in energy storage.

At first, the multifrequency piezostructure was excited with an acceleration of 1g (9.81 m/s²) and frequency of 32.00 Hz during the five-minute interval, where it was possible to store 35.00 mV in supercapacitor. In a second step, all the features were kept unchanged except the excitation frequency, set to 30.00 Hz, and at the end of the five minutes it was found a voltage of 38.50 mV stored in the supercapacitor. Likewise, the piezostructure was excited at a frequency of 28.00 Hz and at the end of five minutes a voltage of 42.00 mV was stored in the supercapacitor. Based on these results it is observed that, when excited at a frequency of 28.00 Hz, the natural frequency corresponding to the higher piezo-generator, the piezostructure were able to store more energy in a given time interval. This is due to the fact that the lowest natural frequency of piezostructure among the three has higher vibration amplitude since it has greater length. The length has a direct influence on the value of the stiffness of the system, and this in turn directly affects the amplitude of vibration, since the greater the length, the lower the stiffness of piezostructure, and the lower the stiffness, the higher the vibration amplitude, thereby the greater the generated voltage. Table 5 presents the results obtained.

Table 5 – Voltage generated by each piezo-generator according to frequency.

	f_1 = 28Hz	**f_2 = 30Hz**	**f_3 = 32 Hz**	***f_4 = 28-32Hz***
Supercapacitor Voltage	42.00mV	38.50mV	35.00mV	33.00mV

And finally, a test was performed where all conditions from the previous tests were kept the same with the exception of that excitation frequency was varied randomly between 28.00 Hz and 32.00 Hz during the same time interval. In this case the energy stored in the supercapacitor was 33.00 mV a value smaller than the one stored when the piezostructure was excited at a frequency tuned to the resonance of each of the piezo-generators. However, this value represents 85.00% of the energy generated in ideal condition (resonance) demonstrating the effectiveness of the proposed configuration for power generation even in a condition that differs from the ideal condition.

5. CONCLUSIONS

This paper discusses a proposal of a multifrequency piezostructure able to generate a reasonable level of energy in environments whose excitation frequencies vary in a given frequency band. Initially, the structure was modeled numerically by finite elements and the energy generation was evaluated for different conditions and, subsequently, experimental tests were performed showing the feasibility of the proposal.

6. ACKNOWLEDGEMENTS

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