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AN ALTERNATIVE WAY OF SENSING IN SMART STRUCTURES USING PIEZOELECTRIC ELEMENTS

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Abstract. *For a long time the use of sensors has helped the man in the study and process control. Due to the increasing complexity of industrial plants, the evolution of measurement methods was necessary, and therefore the sensors. With the discovery of materials denominated smart or functional, came the possibility of utilization for a range of new applications. Among these materials, piezoelectric stand out for their versatility as sensor and actuator in structures and systems. This paper proposes the use of piezoelectric materials such as vibration sensor embedded in a structure, to evaluate their dynamic behavior. One beam model in ABS polymer by 3D printing was built with the piezoelectric inside. To evaluate the dynamic behavior of the system was applied a base excitation in the structure, monitoring its behavior through the voltage generated in the piezoelectric, compared with an accelerometer.*

Keywords: *piezoelectric, embedded sensor, ABS beam.*

1. INTRODUCTION

Over the years, man has searched in technological improvements a solution for the difficulties in monitoring systems, processes and structures. In the past they were used mechanical, hydraulic, pneumatic and different complex mechanisms. The advance in the electronic area enabled the development of remote sensing systems and autonomous, which facilitates the work of control and inspection of industrial plants.

Over time, such systems have become increasingly complex and difficult to monitor both the size of the plants such as the number of variables to be measured. In most cases, these systems are in remote locations and difficult to access, which required the evolution of sensors.

The use of piezoelectric transducers for sensing systems is not new. The piezoelectric effect was discovered in 1880 by the brothers Curie, but one of its first practical applications was given by the French physicist Paul Langevin during the First World War, in the development of sonars for the French Navy (Venet and Pereira, 2004).

After that, the piezoelectric began to popularize and gained ground in different areas. As sensor, has basically two ways to use: when the piezoelectric are the sensors themselves (e.g. structural health monitoring) and when they are used as energy generating sources, feeding the electrical circuits and sensors/actuators associated with them. Figure 1 shows two examples of piezoelectric application, such as sensor and as a source of electricity (energy harvesting).

Figure 1. (a) A wind turbine rotor blade under test with piezoelectric sensor mounted (Taylor, *et al.*, 2016). (b) A small scale energy harvesting using piezoelectric elements for wireless sensor networks (Myers, *et al.*, 2007).

In Figure 1 (a) the authors coupled piezoelectric elements in a wind blade to monitor the structural integrity of the system when subjected to loads, and they concluded that prototype system developed by them is able to predict the behavior of the structure (Taylor, *et al.*, 2016). And the authors of the system shown in Fig. 1 (b) presented results of a low-power generator for powering wireless sensors. And they showed that with this system it was possible to generate a maximum power of up to 5 mW (Myers, *et al.*, 2007).

Recently, Borges (2012) performed different experimental and numerical tests on hybrid (metal-composite) joints in the form of beams, bonded together, with the objective of comparing the results obtained for the detection of damage in this type of joint using piezoelectric transducers and accelerometers, through of Structural Health Monitoring (SHM) techniques.

In this same direction, we have the work published by Flor (2016), which uses vibration methods for SHM in sandwich structures and in bonded metal-composite joints. Computational and experimental tests are carried out to measure displacement and debonding damages of beam structures made of titanium. Aided by impact tests (free-free) and traction (biclamped) through the use of accelerometers and a piezoelectric sensor.

In this work, the piezoelectric sensor will be used directly in a structure of beam type, made of Acrylonitrile Butadiene Styrene (ABS). Usually the piezoelectric sensors are bonded to the surface of the structure to which you want to monitor, in this configuration the sensor is exposed to external interference, which could damage it and cause measurement errors.

In the proposed configuration the sensor is integrated into the structure, inserted inside and suffering only influence of the dynamic behavior imposed on the system. Figure 2 shows the configuration used of the structure with piezoelectric element inside.

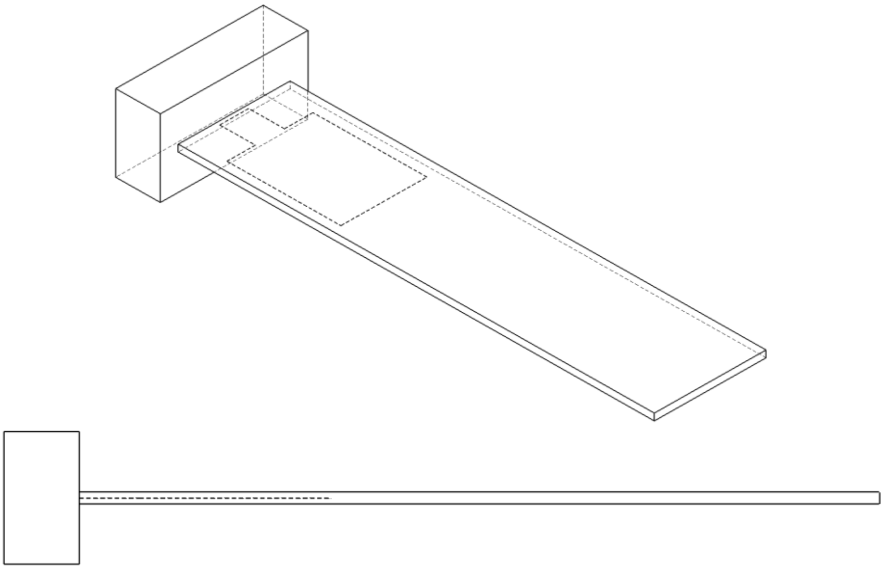


Figure 2. Structure used with the sensor inside.

The main advantage of this configuration is that the influence of the piezoelectric on the structure is minimized due to the distribution of mechanical stresses in its interior, so that the structure can be subjected to larger displacements. Thus, the identification of the dynamic parameters of the structure subjected to base excitation was made and its response was compared with the results obtained by an accelerometer positioned on the free end of the beam.

2. THEORETICAL APPROACH

2.1 Piezoelectric sensor

The use of piezoelectric transducers as sensor has grown significantly in recent years, in part due to the fast development of electronics and manufacturing capacity of such materials. According to a survey published by the company Transparency Market Research (TMR), the global market for smart materials is driven by the increasing popularity of piezoelectric devices and their diversified market applications (TMR, 2015).

Piezoelectric materials have two properties that define and are known as direct and converse piezoelectric effect. The direct effect occurs when the piezoelectric is subjected to a mechanical deformation and generates a potential difference on its surface. Already the reverse effect produces a mechanical deformation when subjected to an electric field (Moheimani and Fleming, 2006). The equations that describe the electromechanical behavior of a linear piezoelectric material for applications involving sensing, can be written as follows (Moheimani and Fleming, 2006):

$$\begin{aligned} \varepsilon_i &= S_{ij}^{D} . \sigma_j + g_{mi} . D_m \\ E_i &= g_{mi} . \sigma_i + \beta_{ik}^{\sigma} . D_k \end{aligned} \tag{1}$$

Where the indexes *i*, *j* = 1, 2, …, 6 and *m*, *k* = 1 , 2, 3 refer to different directions within the material coordinate system. The symbols in the equation can be defined like:

σ – Stress vector (*N/m²*)
ε – Strain vector (*m/m*)
E – Vector of applied electric field (*V/m*)
S – Matrix of compliance coefficients (*m²/N*)
D – Vector of electric displacement (*C/m²*)
g – Matrix of piezoelectric constants (*m²/C*)
β – Impermitivity component (*m/F*)

Furthermore, the superscripts *D* and σ represent measurements taken at constant electric displacement and constant stress.

2.2 3D prototyping

The form chosen for building the model with the piezoelectric introduced into the structure is the prototyping by deposition of fused material (FDM), commonly known as 3D printing.

This prototyping technique allows the execution of projects in a shorter time and cost when compared with most conventional machining processes. The limitations associated with the complexity of the geometric form structures and their interactions do not represent an obstacle to this technique.

3. METODOLOGY

3.1 Physical model

The methodology consisted of the construction of a structure of the beam type that could incorporate a piezoelectric element inside without compromising the functionality of the form, made of ABS by 3D printing. The beam was built in three stages: the first stage was the construction of layers until the layer where the piezoelectric has been installed; the second was to install piezoelectric; and the third stage was given continuity printing, finishing the process.

This procedure ensured adhesion between the ABS layers to the sensor surface. Figure 3 shows the dimensions used in the beam construction, with space reserved for the piezoelectric sensor.

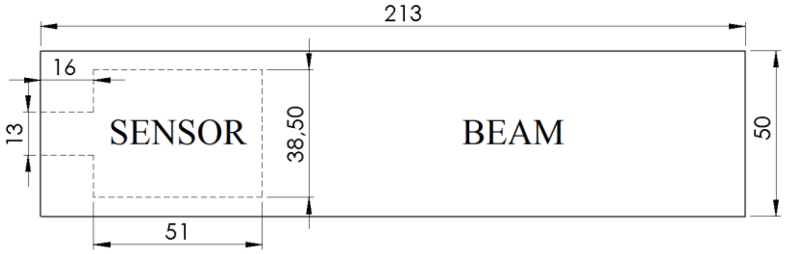
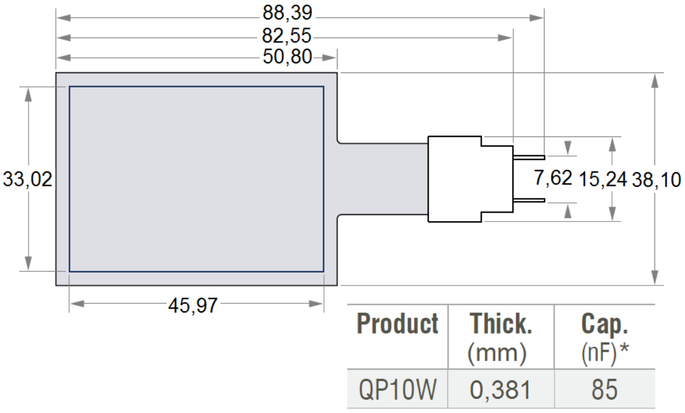


Figure 3. Dimensions of the beam in *mm*.

The piezoelectric element used in the structure, it was the QP10W of *Midé®* manufacturer. It is composed of the piezoelectric which has a flexible adhesive membrane on each side covering the electrodes called *Espanex®*, bonded with epoxy (Midé, 2014a). In addition to protecting the piezo against mechanical impact, the adhesive also protects from excessive temperatures, corrosion of the electrodes and makes it more resistant when used in bending.

Figure 4 shows the piezoelectric element to its capacitance value and their dimensions according to the information provided by the manufacturer (Midé, 2014b).



Product	Thick. (mm)	Cap. (nF)*
QP10W	0,381	85

Figure 4. Piezoelectric dimensions in *mm*.

The main electromechanical properties of piezoelectric are shown in Tab. 1. All data were taken from the material properties tables published by the manufacturer (Midé, 2014a).

Table 1. Main properties of piezoelectric used – *QP10W*.

Property	Symbol	Value	Unit
Relative Permittivity	ε^{S}_{33}	830	-
	ε^{S}_{11}	916	-
Coupling Factors	k_{15}	0.59	-
	k_{31}	0.36	-
	k_{33}	0.72	-
	k_{13}	0.715	-
Piezoelectric Constants	d_{33}	390e-12	*C/N*
	d_{31}	-190e-12	*C/N*
	d_{15}	584.5e-12	*C/N*
Voltage Constants	g_{33}	24e-3	*V.m/N*
	g_{31}	-11.3e-3	*V.m/N*
	g_{15}	38.2e-3	*V.m/N*
Quality Factor	Q_m	80	
Compliances	Y^{E}_{11}	6.7e10	*N/m2*
	Y^{E}_{33}	5.3e10	*N/m2*
Density	ρ	7800	*Kg/m3*
Curie Temperature	*Tc*	350	*°C*

3.2 Experimental setup and testing

Vibration tests were performed based on forced excitation in a known condition. This test was configured with a sinusoidal signal with variable frequency applied by a signal generator, which were amplified and used to feed the shaker with an AC voltage of 2.5 V. This signal had a frequency varied progressively from 0.1 to 150 Hz for a period of time of 5000 s.

In the system output, were measured voltage signals generated in the sensor (V) and acceleration (g) of the tip beam as a function of frequency (Hz), both measured through a portable device for data acquisition and then processed on the computer. The flow information of the experiment for obtaining the experimental results is schematized in Fig. 5.

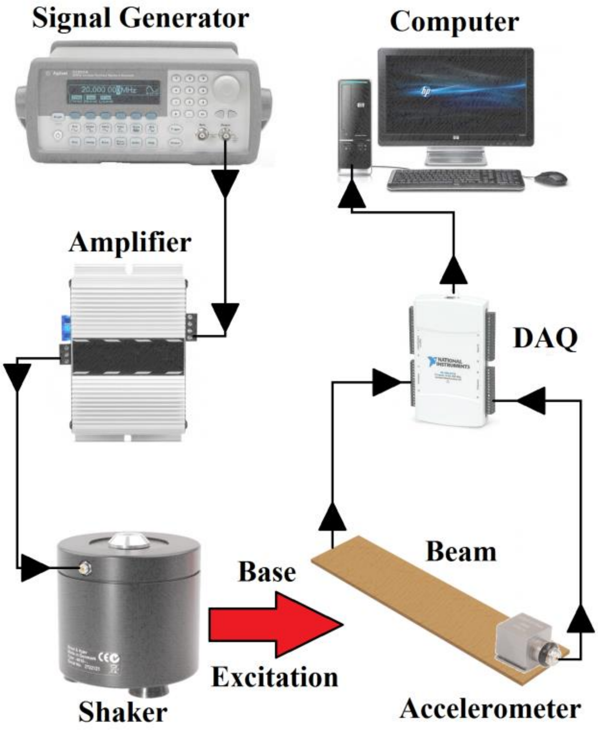


Figure 5. Utilized equipment and realization of the experimental procedure.

The aim of these experiments was to determine the ability of the sensor to capture the natural frequencies of the system and compare them with results obtained from an accelerometer (conventional sensor for this kind assay). All tests were made with the sensor without electrical load, or open circuit.

4. RESULTS AND DISCUSSIONS

For the accomplishment of the experiments the data obtained from the accelerometer were taken as reference values and compared with the values obtained by the piezoelectric sensor. The sampling rate used for data acquisition was 20 kHz with 20,000 points for each variation of frequency.

The frequency spectra determined through signals acquired by the accelerometer (g) and by the piezoelectric sensor (V) as FFT are shown in Fig. 6 and 7.

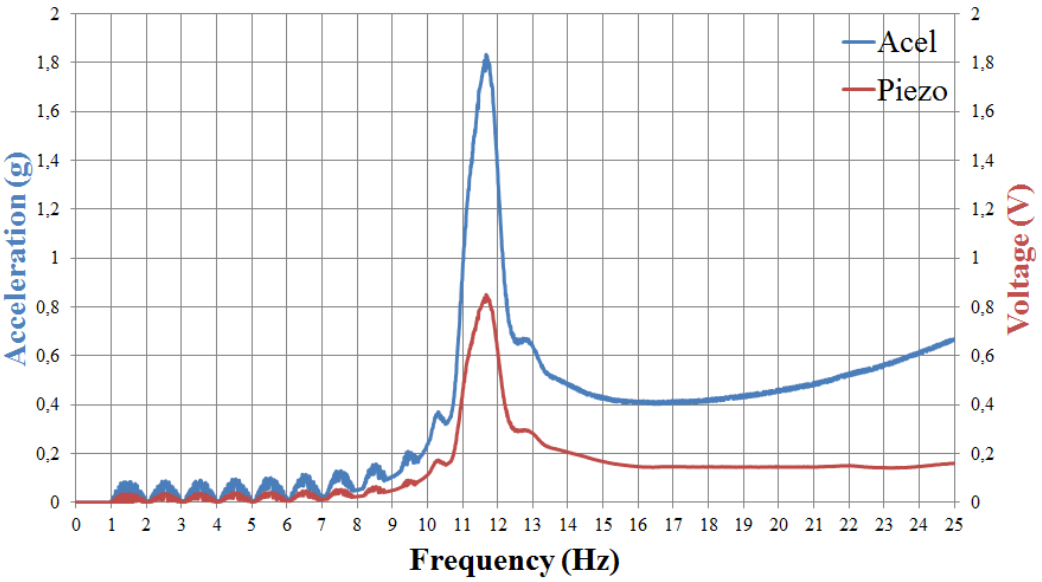


Figure 6. FFT for the first mode (11.67 Hz).

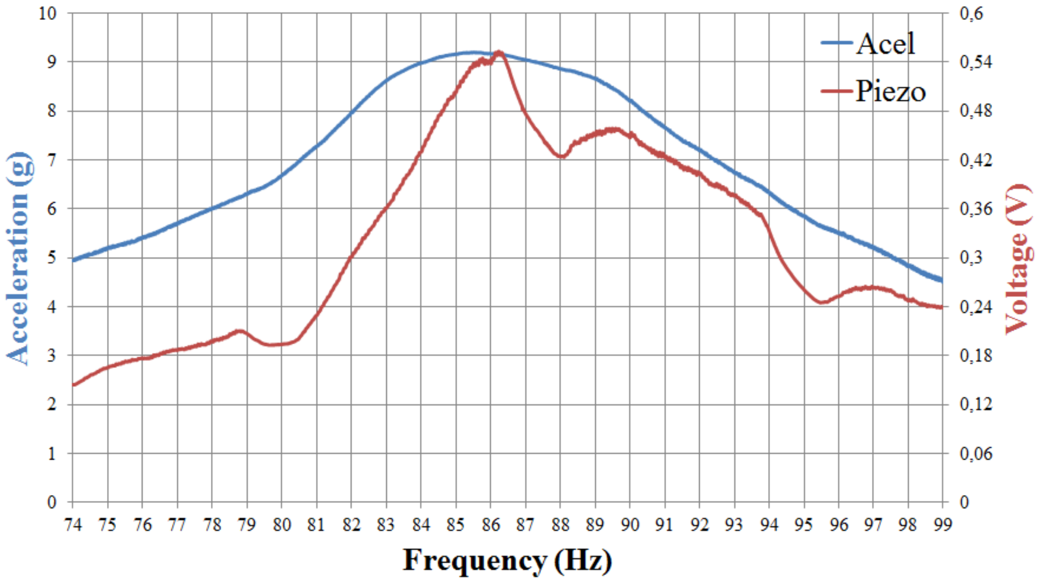


Figure 7. FFT for the second mode (85.53 Hz).

We have that, for the accelerometer the first two modes of vibration of the structure corresponds to the natural frequency of 11.67 Hz for the first mode with a maximum amplitude of 1.83 g, and 85.53 Hz for the second mode with an amplitude of 9.19 g measured on the free end of the beam.

For the piezoelectric sensor, the values were found 11.67 Hz and 86.23 Hz for the first and second mode, respectively. The maximum amplitude of the peak voltage generated for the first natural frequency was 0.85 V and 0.55 V for the second frequency.

We can see that for the first natural frequency the values found by the accelerometer and by the sensor was the same. For the second natural frequency, there was a difference of 0.82%, which can be considered an acceptable error.

The variation of the signals encountered in the first graph it is due to DAQ system does not have a good precision for too small frequencies. And the difference between the peaks obtained from the accelerometer and the PZT sensor can be explained due to the measurement location chosen to place them. Because the piezo is more subject to interferences, per be closer to the base then the accelerometer, generating lower amplitudes of displacement.

5. CONCLUSIONS

The results were satisfactory and capable of representing the system behavior, by using a piezoelectric type sensor inside a beam structure made of ABS. With maximum error of approximately 0.8% in the determination of natural frequencies of the system.

As noted earlier, this configuration makes way for a new kind of sensing in structures, facilitating its use and covering a series of possible applications that previously would be considered complex.

However, it is necessary to do a deeper study on some aspects of the configuration of the structure. As the study of adhesion of the piezoelectric ABS with layers deposited on its surface, which has a direct impact on the system and can further improve the efficiency and accuracy of the results.

Preliminary results for the selected geometry are the basis for extrapolation with more complex geometries, which will be tested in the future. It is intended to apply the same methodology described in this work, and thus obtain new and different sensors, which are closer to the practical applications found currently.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Borges, E. N., 2012. “Manufacturing, computational modeling and experimenting evaluation of hybrid bonded joints monitored through smart composites”. São Paulo - São Carlos, Brazil. DOI: 10.11606/D.18.2012.tde-11052013-111650.

Flor, F. R., 2016. “Damage monitoring in composite structures via vibration based method: metal-composite bonded joints and sandwich structures”. São Paulo - São Carlos, Brazil.

Moheimani, S. O. R. and Fleming, A. J., 2006. “Piezoelectric transducers for vibration control and damping. Newcastle - Callaghan, England, pp. 26-31.

Myers, R., Vickers, M. and Kim, H., 2007. “Small scale windmill”. *Applied Physics Letters*, Vol. 90, pp. 1-3. DOI: 10.1063/1.2435346.

QuickPack®, 2014a. “Packaged Piezoelectric Actuators and Sensors Datasheet”. Midé® Engineering Smart Solutions, Massachusetts - Medford, USA, pp. 1-13.

QuickPack®, 2014b. “Products – Material Properties & Spec Sheets”. Midé® Engineering Smart Solutions, Massachusetts - Medford, USA, pp. 1-3.

Taylor, S. G., Raby, E. Y., Farinholt, K. M., Park, G. and Todd, M. D., 2016. “Active-sensing platform for structural health monitoring: Development and deployment”. *Structural Health Monitoring*, pp. 1-10. DOI: 10.1177/1475921716642171.

Transparency Market Research (TMR). “Smart Materials Market for Actuators & Motors, Sensors, Transducers, Structural Materials, and Other Applications: Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2014 – 2020”. 1 Feb. 2015. <http://www.transparencymarketresearch.com/pressrelease/smart-materials-market.htm>.

Venet, M. and Pereira, A. H. A., 2004. “A course - Piezoelectric materials and devices: fundamentals and development”. São Paulo - São Carlos, Brazil.

8. RESPONSIBILITY NOTICE

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