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PIEZOELETRIC TRANSDUCERS FOR MEASUREMENT OF DYNAMIC STRAINS

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Abstract. *The piezoelectric materials have a well known relationship between electrical and mechanical energy which give them great applicability as sensors and actuators. The high sensitivity of these materials to strain makes them appropriate to design high precision transducers for measurement of dynamic displacements in the order or micrometers or even sub-micrometer scales. In this sense, the objective of this work is the study of new configurations of strain transducers based on piezoelectric sensors operating under different mechanical loads (traction, compression and shear). Using the software based on the finite element method, ANSYS, some simulation were performed and compared with analytical ones. From this work, some conclusions related to the transducer geometry and modes of operation of piezoelectric sensor are presented. Additionally, from some experimental results, testing transducer prototypes using piezoelectric ceramics of lead zirconate titanate (PZT), the high sensitivity to strain was proved. Finally, some circuits to amplify the electric signals from the transducers are presented. As a consequence, all these results may be helpful in the optimization of strain transducers.*

Keywords: *Piezoelectric sensors 1, Strain transducer 2, Measurement of dynamic strain 3*

1. INTRODUCTION

The piezoelectricity phenomenon has been recognized as a useful propriety of some materials which allow the measurements of very small displacements, even in the sub-micrometer scales. These materials become electrically charged when subjected to mechanical strain. Such materials also exhibit an inverse effect, that is, the occurrence of mechanical deformation when subjected to an electric field (Waanders, 1991). Although much research has been done on the use of surface-bonded piezoelectric elements for measurement of dynamic strains (Sirohi and Chopra,, 2000, Belova et al. 1988, Jenq and Chang,1995, Luo, and Hanagud, 1999), little attention has been paid to the use of piezoelectric materials as sensing elements of displacement and strain transducers.

The design of piezoelectric transducers involves mathematical modeling and experimental verifications, which are necessary to validate them. Due to the complexity of mathematical formulations for non-simplified geometries and faithful reproduction of the boundary conditions, it was decided to work with finite element models. To be able to represent a transducer with acceptable reliability, the electrical properties, piezoelectric and mechanical properties of materials must be accurately known.

Using classical analytical methods, from the solution of differential equations, it is possible to calculate the exact response of the displacements, strains and deformation, in all the points of a known structure. However, these solutions are only valid for very simple geometries, load and support conditions (ALVES, 2005).

In this work, numerical analysis was carried out with the finite element software ANSYS and then compared with the analytically obtained. The principal contribution is the study and development of piezoelectric transducers for measurement of dynamic strains. Applications can range from the usual cyclic test of materials to the measurement of strain in machines and structures. As material of the piezoelectric sensor, it was considered the APC-851 with parallelepiped format, with hexagonal symmetry and family of 6 mm. Slices of piezoelectric ceramics, polarized in the thickness direction, with electrodes deposited on its upper and bottom surfaces were used. Different transducer formats were simulated and their behavior was compared with some experimental results. Finally, as the research intends to continue, some amplifiers appropriate for these transducers are described.

2. MATERIALS AND METHODS

2.1 Materials

Equations (1) and (2) are the constitutive equations of a linear piezoelectric material (ANSI/IEEE std, 1987). In linear piezoelectricity the equations of elasticity are coupled to the charge equation of electrostatics by means of piezoelectric constants.

The polarization axis or axis 3 is that parallel to the polarization direction of the material. The polarization vector (P) is established during the manufacture of piezoelectric, is also represented in Fig.1.

$$\{T\}=\left[c^{E}\right]\{S\}-[e]^{T}\{E\} \tag{1}$$

$$\{D\}=[e]^{T}\{S\}+\left[\varepsilon^{S}\right]\{E\} \tag{2}$$

where: $\{T\}$, is the stress vector; $\{D\}$, the electric flux density vector; $\{S\}$, elastic strain vector; $\{E\}$, electric field intensity vector; $\{E\}$, electric field intensity vector; $[c^E]$, elasticity matrix (evaluated at constant electric field); $[e]$, piezoelectric stress matrix and $[\varepsilon^S]$, dielectric matrix (evaluated at constant mechanical strain).

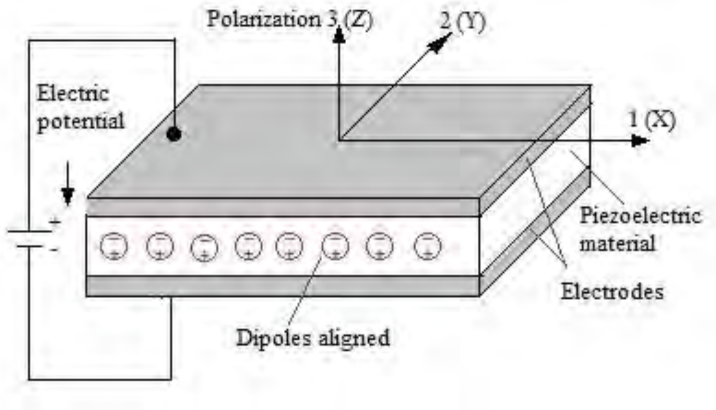

Figure 1. PZT Configuration Direction and orientation axis of piezoelectric material

The sensor is made of a commercial piezoelectric ceramic APC 851 (hexagonal symmetry class 6mm with anisotropy in the direction Z). The aluminum alloy 7075-T6 was used for the body of the transducer.

Table 1. Properties of the piezoelectric ceramic APC 851.

E (Gpa)	**ν**	**ρ** (Kg/m^3)	Piezoelectric Constants (10^{-12}m/V)			**Ɛ$_{33}$**	**g** (10^{-3}Vm/N)	
			d_{31}	d_{33}	d_{51}		**g_{31}**	**g_{33}**
63	0,3	7600	-175	400	590	1950	-10,2	24,8

d: piezoelectric strain coefficient
g_{31}: piezoelectric voltage coefficient
ε_3: relative dielectric constant between poling coefficient
ρ: density
E: Young’s modulus
ν: poisson’ s ratio

As the PZT is isotropic in the plane 1-2, the properties in direction 1 and direction 2 have the same values, see Fig 1. Thus, the elastic compliance constant matrix [C], the dielectric permittivity matrix [ε] and the piezoelectric constant matrix [e] are:

Anisotropic elastic compliance matrix:

$$[C] = \begin{bmatrix} C11 & C12 & C13 & 0 & 0 & 0 \\ C12 & C11 & C13 & 0 & 0 & 0 \\ C13 & C13 & C33 & 0 & 0 & 0 \\ 0 & 0 & 0 & C44 & 0 & 0 \\ 0 & 0 & 0 & 0 & C44 & 0 \\ 0 & 0 & 0 & 0 & 0 & C66 \end{bmatrix} \tag{3}$$

Dielectric permittivity matrix:

$$[\varepsilon] = \begin{bmatrix} \varepsilon 11 & 0 & 0 \\ 0 & \varepsilon 11 & 0 \\ 0 & 0 & \varepsilon 33 \end{bmatrix} \tag{4}$$

And Piezoelectric constant matrix:

$$[e] = \begin{bmatrix} 0 & 0 & 0 & 0 & e15 & 0 \\ 0 & 0 & 0 & e15 & 0 & 0 \\ e31 & e31 & e33 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

2.2 Methodology

The piezoelectric sensor can operate in different ways as shown in Fig 2(a.3), 2(b.3) and 2(c.3). The objective of this study was to develop transducers where the piezoelectric sensor is submitted to different types of mechanical stresses. Initially, simulations of the piezoelectric sensor operating in the extensional mode were performed. Then, the results were compared with the analytical ones to validate the model, obtaining a reliable finite element model. The sensor dimensions were: 20 x 5 x 0,5 mm. After validation of the sensor model, three structural configurations of transducers were analyzed. With the configuration 01, the sensor is submitted to compressive mechanical stresses, applied in the parallel direction to the polarization. In this way, a deformation in thickness generates an electrical potential difference as output (Fig. 2(a)). With the configuration 02, a shear deformation is applied in the direction of the polarization and an electrical potential difference is generated (Fig. 2(b)). Finally, with the configuration 03, the sensor is submitted to an extensional displacement. The mechanical strain is applied in the direction perpendicular to the polarization, which arises in a deformation length and an electrical potential difference is generated (Fig. 2(c)).

With respect to the experimental analysis, two prototypes were built. One related to the configuration 01 and the other one to the configuration 03, as shown in Fig 2(a.2) and 2(c.2). The attachment of the transducers to the surface of the specimen or structure for measurement of strain is performed using the knifes shown in the bottom of the transducers.

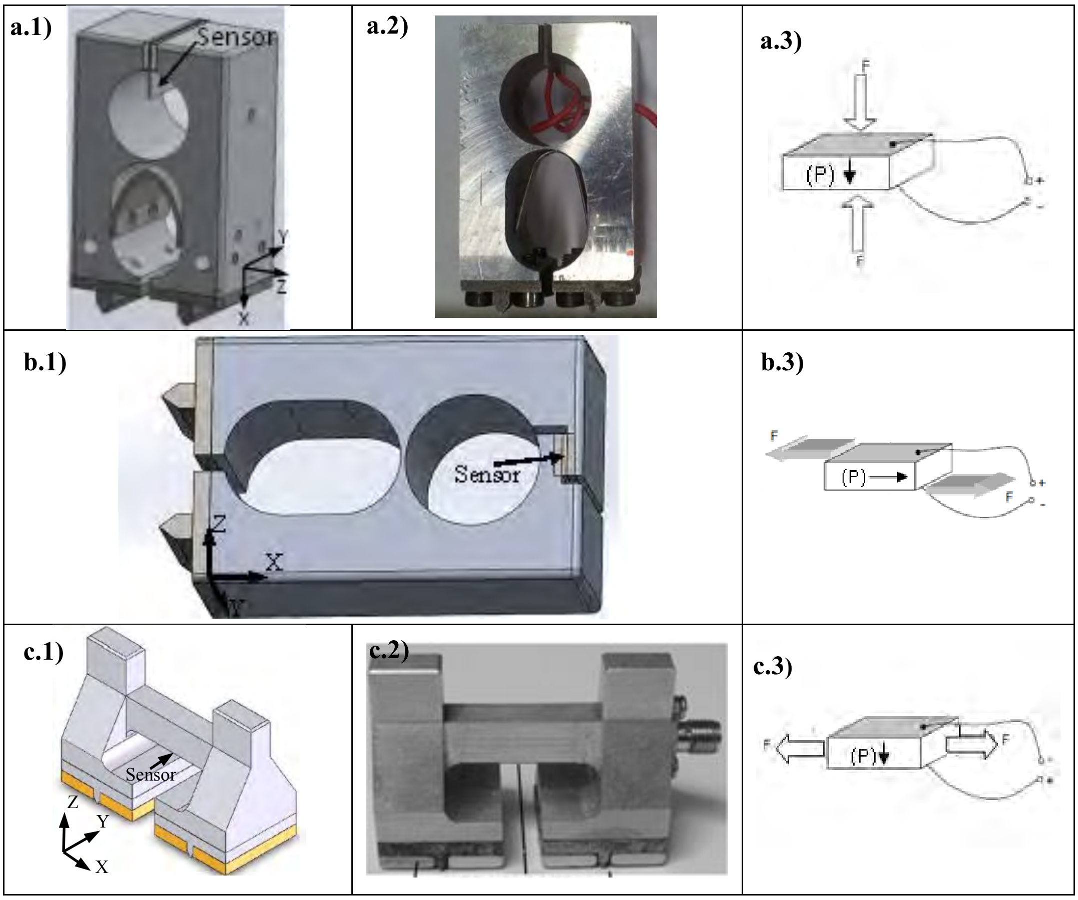

Figure 2. Piezoelectric transducers. (a.1), (b.1) e (c.1): configuration 01, 02 e 03, respectively; (a.2) and (c.2): photograph of the prototype; (a.3), (b.3) e (c.3): Piezoelectric sensor operation modes Longitudinal (d_{33}),Shear (d_{15}) and extensional (d_{31}), respectively.

2.2.1 Finite Elements Method

Numerical analysis of the piezoelectric transducers were performed using the finite element method (FEM) through the commercial software ANSYS.

ANSYS solves the equilibrium equations of these materials, but it is necessary to insert the values of the constants of the constitutive equations (Eq. (1) and Eq. (2)) presented before. As mentioned above, when three-dimensional analysis are performed, the polarization direction is around the axis Z. The constants inserted in ANSYS, for non-piezoelectric solids, are related to Hooke's law.

To perform the piezoelectric analysis, the element SOLID5 of ANSYS, was used. Three degrees of freedom of displacement along x, y and z and a degree of freedom of voltage, were considered. For the element SOLID5, the relative electrical permittivity PERX, PERY and PERZ must be specified. These values are the components of the matrix diagonal permittivity [*ε*], Eq. (4). It is important to note that the values of permittivity specified using the MP command will always be interpreted as the permittivity constant strain. Furthermore, if the permittivity values are lower than one, the program interprets these values as absolute permittivity.

There are two ways of modeling piezoelectric devices in ANSYS. One is to define the array of piezoelectric stress matrix [*e*] (Eq. (5)) and the anisotropic elasticity matrix (stiffness matrix [*C*] (Eq. (3)). The other way is to set the array of piezoelectric strain matrix [*d*] along with the flexibility matrix [*S*]). In this case, ANSYS transforms the matrix [*d*] in the matrix [*e*] using the elasticity matrix [*C*] which is the inverse of matrix [*S*], as shown in Equation (6).

$$[e]=[C][d] \text{ ou } [e]=[S]^{-1}[d] \qquad (6)$$

Another important factor in the modeling of piezoelectric devices is the application of the boundary conditions of the problem. First, you should check if the device is free or fixed by some end. By instance, in this work, the transducer has two knifes at the bases (Fig. 3). As a boundary condition, one of these knifes is fixed and the other can move. The free base is subjected to a displacement of 15 μm in the direction parallel to the contact surface. This condition was applied to the three transducer configurations.

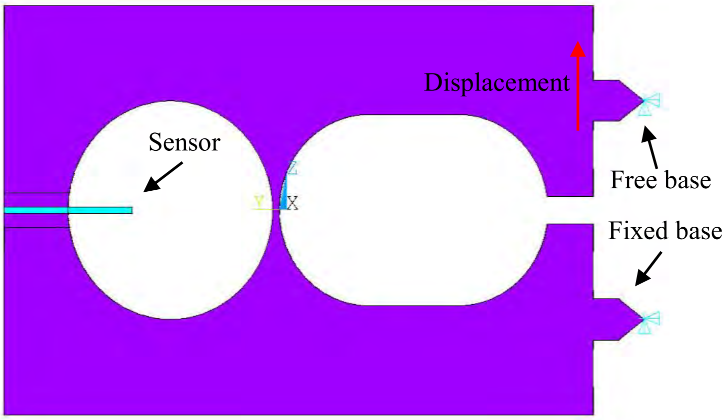

Figure 3. Specimen of transducer in the ANSYS

Another indispensable information is related to the definition of the upper and lower electrodes. In the sensor, the boundary condition to be imposed is to define the electrode and ensure that all selected nodes have the same voltage. The same procedure is performed on the other electrode but, while in the inferior electrode the voltage applied must be null, in the superior one, an initial condition of null current is established.

For the ANSYS piezoelectric analysis, three kinds of solutions are possible. These include static analysis, used to find displacements or electrical potential difference; dynamic analysis, used for determining the system response to the transient or harmonic excitations; modal analysis, used to find the natural frequencies and vibration modes. In this study, only the static and modal analysis was used.

3. RESULTS AND DISCUSSION

3.1 Validation of the finite element model of the piezoelectric sensor

In this section, a comparison between analytical and simulation results is shown.

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Firstly, the electric potential difference generated by the sensor was investigated considering only the effect of an extensional displacement of 2.5 μm of the transducer legs along the 1-direction (Fig. 1). This displacement corresponds to a strain of 500 μm/m (micro strain), which resulted in an electrical potential of 111.10 V.

Figure 4 shows the curves of the electric potential sensor PZT comparing the response obtained in the ANSYS with two analytical equations (Eq. (7) and Eq. (8)).

The Equation (7), developed by Sirohi and Chopra (2000), shows the relationship between the deformation (ε) and electric potential (V_c) generated across the electrodes of the sensor. The electric potential generated is related to the capacitance (C_p) and the sensitivity parameter (S_q) of the sensor. C_p and S_q are determined from geometric properties and constants of the piezoelectric sensor.

$$\varepsilon = \frac{V_c C_p}{S_q} \Rightarrow V_c = \frac{S_q \varepsilon}{C_p} \tag{7}$$

According to Sirohi and Chopra (2000), even applying a unidirectional shift the sensor is exposed to in reality both longitudinal and transverse strains. For the transverse stress, there will be a longitudinal strain due to Poisson's effect at the sensor. Hence, Equation (7) can be rewritten as:

$$V_c = \frac{S_q K_p \varepsilon}{C_p} \tag{8}$$

Where:

V_c= voltage generated across the sensor electrodes
C_p = capacitance of the sensor
S_q = sensitivity parameter
ε = strain along the displacement direction
K_p = correction factor due to poisson's effect

The same authors also affirm that this effect is a key distinction between piezoelectric sensors and conventional foil gages. The transverse sensitivity of the piezoelectric sensor is of the order the same-its longitudinal sensitivity. However, for a conventional strain gage, the transverse sensitivity is close to zero and is commonly neglected.

A relationship between the voltage signal V measured from the surface electrode of a piezoelectric sensor and the strain on the sensor can also be calculated by Eq. (9) (Gama and Morikawa, 2008). When the electrodes are open-circuited, the electric displacement in the thickness direction is zero (D3=0). Taking this into account and assuming the one dimensional stress state, Eq. (9) is obtained from equations 1 to 7 as:

$$V = \frac{t S_1}{\varepsilon_{33} + \frac{e_{33}^{\;2}}{c_{33}}} \left[e_{31} - \nu e_{31} + \frac{e_{33}}{c_{33}} \left(\nu c_{31} - c_{31} \right) \right] \tag{9}$$

Where: S, is strain; t, the piezoelectric thickness; ν, the Poisson's ratio; c, the elastic stiffness constants; e, the piezoelectric stress and ε, the permittivity.

Therefore, by measuring the strain generated in the piezoelectric material, from ANSYS, it is possible to calculate the voltage in the material from the Eqs. (8) and (9).

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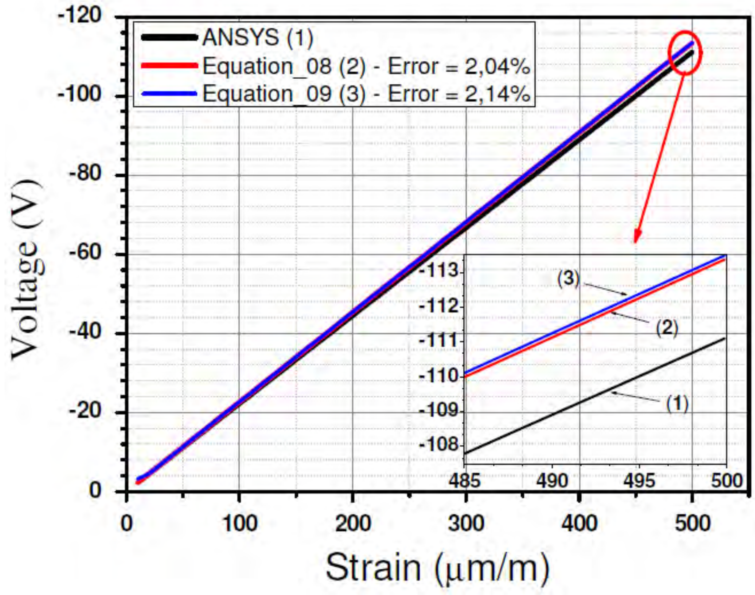

Figure 4. Voltage *versus* strain is extensional displacement of the sensor

In Figure 4, one can see that the results with ANSYS are very close with those obtained by the equations (8) and (9), being observed a difference of 2.04% compared to Eq (8) and 2.14% with respect to equation (9). It is noteworthy that for determining the voltage using the analytic equations, rounded figures are used, which affect the accuracy of the results. The sensitivity of the sensor, was 222 mV/(μm/m).

The higher the sensitivity, the better is the transducer ability for measurement lower strain amplitudes.

3.2 Analysis of the transducers configurations

In Figure 5, the characteristic responses of the sensor, obtained by FEM for each configuration of transducer, are shown. Figure 5(a) shows the average voltage and Figure 5(b) the average deformation of the sensor, both as a function of displacement between the knife edges of the transducer.

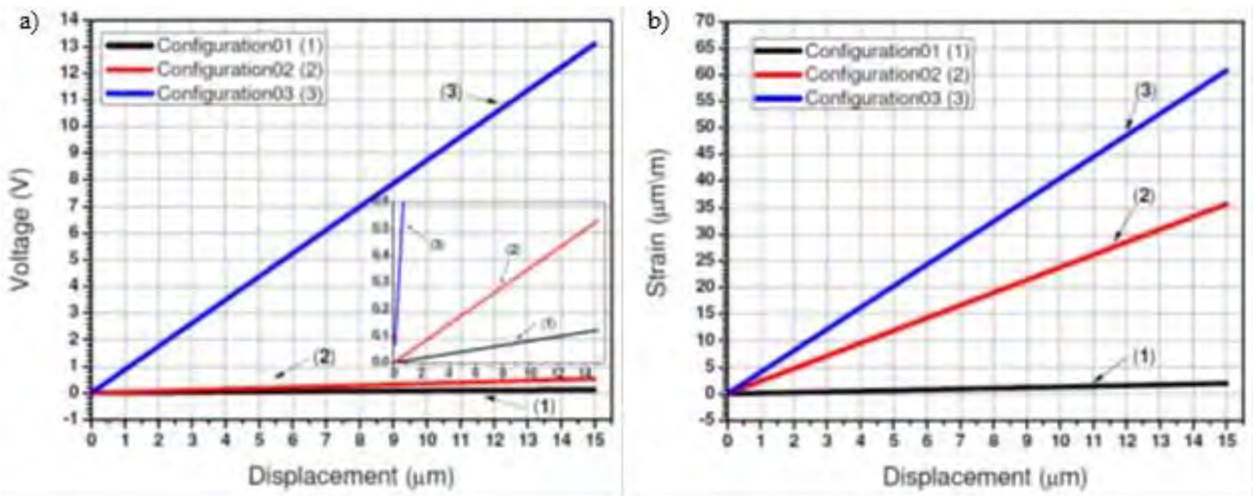

Figure 5. Transducer's sensibility as a function of displacement for each configuration: (a) Voltage; (b) Strain

From Fig. 5(a), the configuration 03 shows a higher electric potential difference, reaching 13.1 V, which can be explained by the greater deformation of the sensor, as can be seen in Fig. 5(b). On the other hand, the configuration 01 provides the smaller deformation of the sensor, resulting in an electric potential difference of 0.121 V. The configuration 02 showed an electrical potential of 0.15 V.

Additionally, from Fig. 5(a) it is observed that the voltage increases linearly as a function of the displacement. The linear adjust of the curves provides the following equations:

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$$V_{01} = 1.84 * 10^{-9} + 0.0081 * \delta_{01} \tag{10}$$

$$V_{02} = -9.99 * 10^{-16} + 0.0353 * \delta_{02} \tag{11}$$

$$V_{03} = -1.69 * 10^{-14} + 0.8733 * \delta_{03} \tag{12}$$

Where V_{01}, V_{02} *and* V_{03} is the average voltage (V) generated by the sensor and δ_{01}, δ_{02} and δ_{03} is the displacement (µm) suffered in each transducer configuration 01, 02, and 03, respectively.

Each mode is associated with a piezoelectric constant load (d_{ij}) representing the ratio of the dimensional change of piezoelectric material and the applied potential difference in volts and vice versa. The extensional mode is related to d_{31}, the shear mode to d_{51} and the compression to d_{33}. . It must be pointed out that any of the transducer configuration showed here can present a high sensitivity to strain. The results shown in Fig. 5 are only illustrative, and do not mean that one configuration is better than the others.

4. PROTOTYPES DEVELOPMENT

The simulation results have encouraged the construction of prototypes with the configurations presented here. These are strong candidates to substitute the conventional method of extensometry, which use bonded strain gages in structures submitted to vibrations. As in certain industrial environments this method is difficult to be implemented, the possibility of constructing portable transducers using piezoelectric sensors, has wake up a strong interest in the development of new transducers (Gama *et al.*, 2012). Thus, until the moment, prototypes for configurations 01 and 03 (Fig 6(a) and 6(b)) have been developed. A prototype for configuration 02 is under construction.

On the other hand, as the voltage signals from the transducers are in general saved to subsequent analysis, the complexity of measurement instrumentation and analysis techniques can vary substantially. Thus, without a clean and amplified signal, the analysis results would not be reliable. In this sense, as a final topic, some basic electric circuits are suggested in order to have a competitive final product.

4.1 Prototypes

The transducers developed for the measurement of dynamic strains are composed basically of a small elastic element made of aluminum containing a piezoelectric strain sensor.

The prototype in Fig. 6(a) has 30 mm length, 20 mm width and 35 mm height. The transducer body is made of aluminum, as mentioned before, and the bases are made of steel 1045 which are attached to the body of the transducer with screw. As the ceramic is 0.5 mm thick, 2 mm to fixate the insulation between it and the faces in contact with the transducer body were left. In addition of the holes to mounting the bases, the transducer body has two holes with 3mm of diameter supporting and fixing the transducer to the surface where it is installed. Four holes on each of its sides, two for adjusting the rod supporting and fixing the transducer and two to hold a central spring. It was needed to insert a stainless steel plate spring, so that the sensor is subject to a pre tension of compression. This spring also contribute to the safety of the part.

The prototype in Fig. 6(b) has 50 mm length, 22 mm width and 44 mm height. Two magnetic bases specially designed for the attachment of the transducer with the structure are fixed to the aluminum elastic element. The magnetic bases were constructed using rare earth magnets of neodymium mounted on small steel cases. The steel knifes were designed to provide specific contact points with pipe's curved surface and to provide transducer axis alignment stability (Gama *et al.*, 2012).

The Figure 6(c) shows the transducer 03 (Fig. 6(b)) under testing. In this case, the measurement was performed in a pipe. A strain measurement was performed simultaneously by a strain gage glued under the transducer, as showed in the same figure.

4.2 Experimental results

In Figure 7, the strain measured with the piezoelectric transducers and with a strain gage is compared. The Figure 7(a) shows the response of transducer 01 and Fig. 7(b) the response of transducer 03. In Fig. 7(b), the dynamic strains were obtained from the experiment shown in figure 6(c). These results show the excellent agreement between the measurements performed with the piezoelectric transducer. Nevertheless, the sensitivity of ceramic depends on the specimen material tested. The sensor is less sensitive to materials with low stiffness. Even more, it should be considered the effect of reinforcement produced by the sensor, especially components of small thickness (LANNES, 2009).

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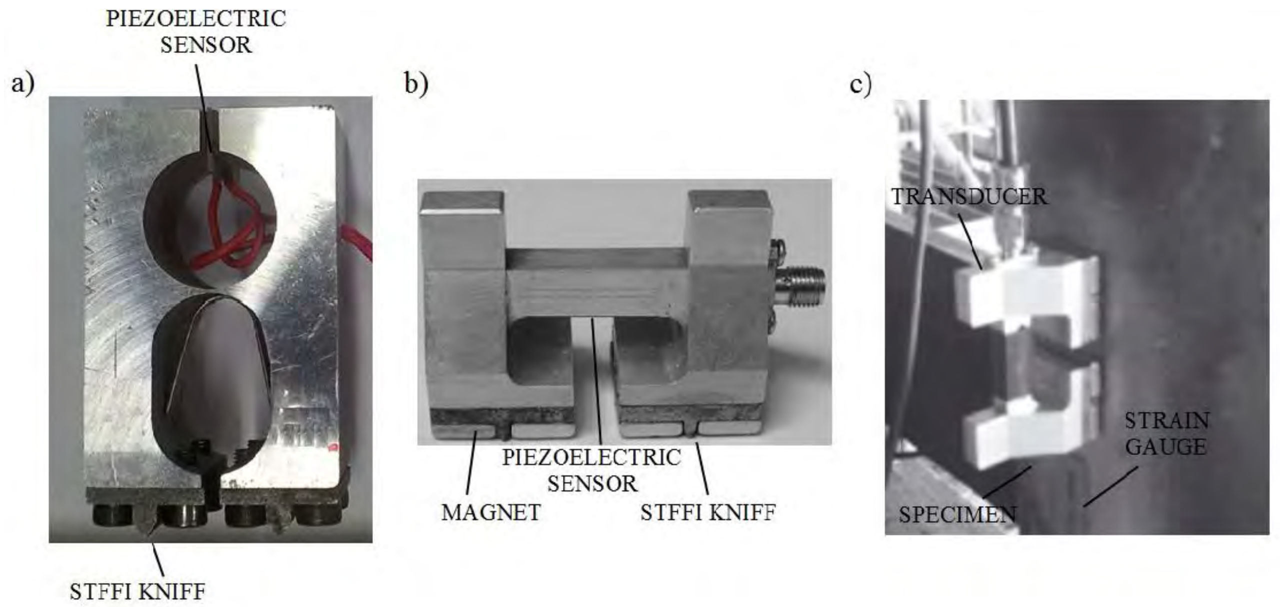

Figure 6. Strain transducer photographs: (a) Transducer with configuration 01, (b) Transducer with configuration 03 and (c) Transducer under testing.

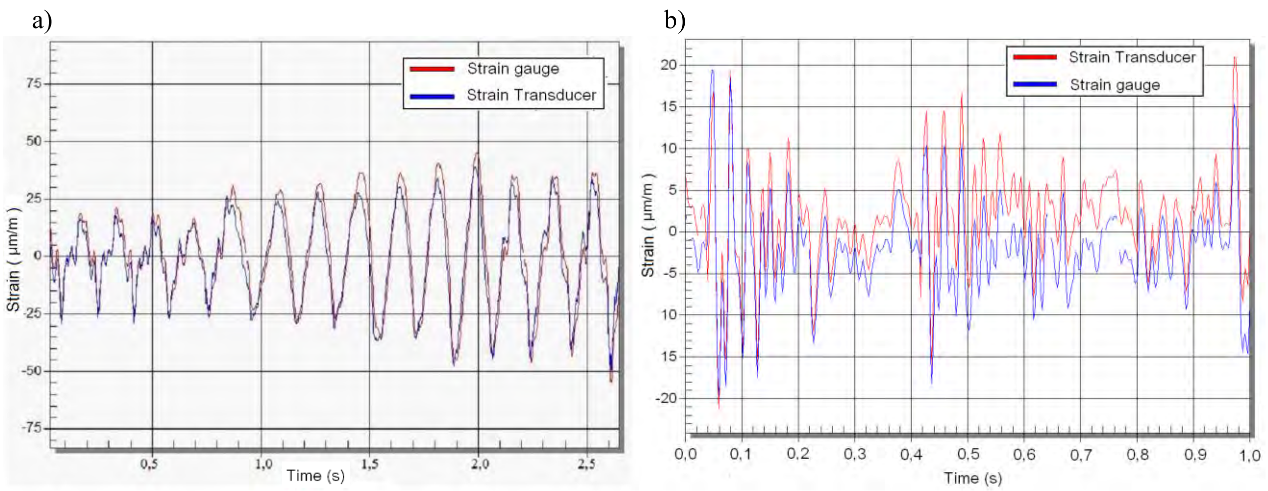

Figure 7 - Comparison between the strain measured by the transducer and a strain gage: (a) Prototype 01 and (b) prototype 03

4.3 Electric circuits

In order to amplify the induced voltage in the piezoelectric sensor, after mechanical deformations, in an appropriated level to further analysis, two approaches have been studied. In both cases, the equivalent electrical model of these sensors is taken into account. It consists of a voltage source controlled by the displacement and a series capacitive impedance (C1), as depicted in Fig. 8. In this way, to do not attenuate the generated voltage of the sensor, any circuit connected to their terminals should have high input impedance

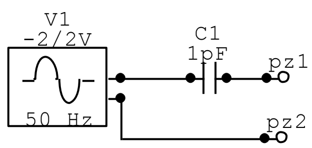

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Figure 8. Simplified electrical model of a piezoelectric sensor.

4.3.1 Direct amplification

In the first approach, the use of an operational amplifier (opamp) with FET, or MOSFET, inputs is required. This is due to its higher input impedance when compared with an opamp with bipolar transistors in their inputs (Franco, 2002).

In Figure 9, a typical inverter configuration has been tested (Lannes, 2009). In this case, when the sensor is without deformation, the natural drift to saturation is avoided by using the resistor R1 in parallel with the capacitor C2. Even more, this configuration gets a first order high pass filter with a low cut frequency calculated as 1/(C2.R1). The high cut frequency is limited by the open loop gain of the operational amplifier. In Figure 10, a photo with this approach is shown.

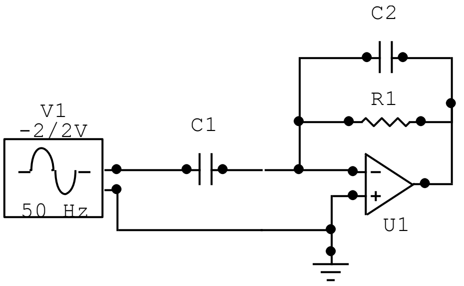


Figure 9. First order low pass amplifier.

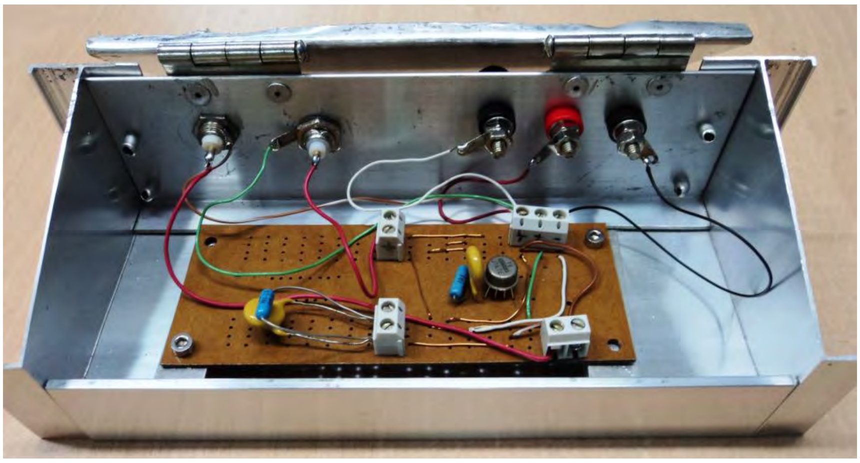
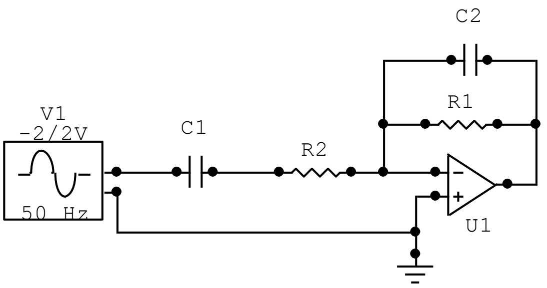


Figure 10. Experimental amplifier with low cut frequency (Farias, 2013).

On the other hand, if the high cut frequency needs to be lower than the obtained in Fig. 9, getting a pass band filter, a series resistor R2 with the sensor can be used (George Clayton and Steve Winder, 2003). This frequency is calculated as 1/(C1.R2). The modified circuit and a particular frequency response are depicted in Fig. 10. Although simple, when the sensors are far from the amplifier, these arrangements require a high degree of shielding, as the electric noise can be easily amplified.



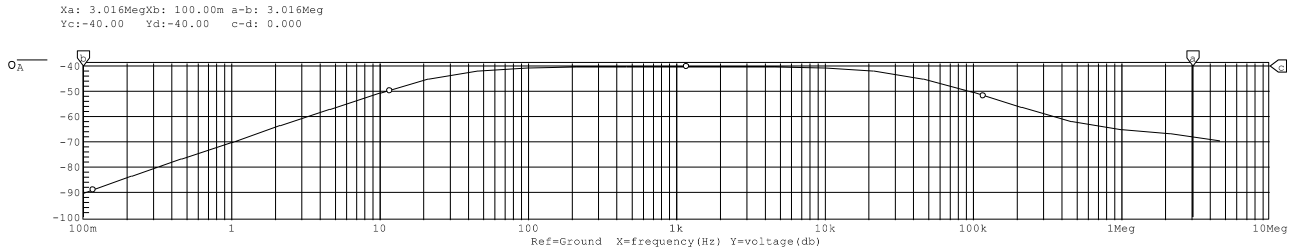


Figure 11. Amplifier with low and cut frequencies and its frequency response

4.3.2 Indirect amplification

In the second approach, a depletion type FET, or MOSFET, is utilized. In this case, the resistance of the semiconductor channel, formed between the terminals drain and source, Rds, changes as a nonlinear function of the applied voltage between the terminals gate and source, Vgs. As the impedance gate-source is very high, a direct connection with the piezoelectric terminals is possible, as depicted in Fig. 12.

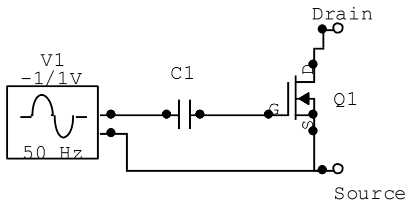


Figure 12. Piezoelectric sensor connected to a depletion MOSFET.

In order to detect the displacement changes, the controlled resistance Rds can be part of some auxiliary circuit like the suggested in Fig.13. The voltage variations (Va-Vb) may be subsequently amplified by an instrumentation amplifier.

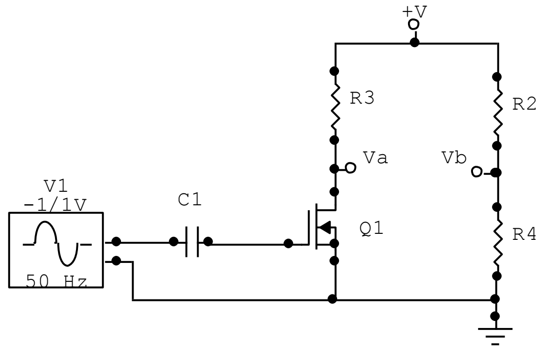


Figure 13. Displacement detection using Rds as part of a wheatstone bridge circuit.

On the other hand, if the amplifier should be far of the sensor, a better alternative is the use of a constant current power supply, as depicted in Fig. 14. Knowing the resistance of the shield cable, Rwire, in the terminals of the current source, a voltage Vt dependent of the displacement variations is obtained. Again, this signal can be subsequently amplified. The photo in Fig.15 shows this approach just in development.

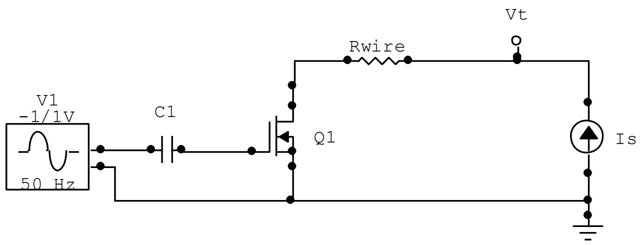


Figure 14. Displacement detection using Rds with a constant current source.

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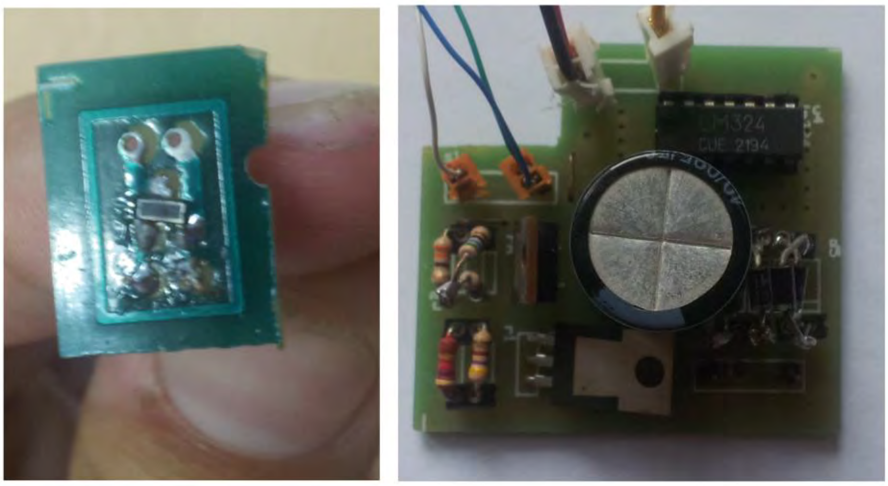

Figure 15. Mosfet (left) and constant current source (right).

5. CONCLUSIONS

This paper has presented satisfactory results regarding the performance of dynamic strain transducers based on piezoelectric sensors. The APC 851 piezoelectric ceramic was used as sensor in the transducers, but using the same procedures, the piezoelectric effect can be modeled for other materials, being enough to know the three characteristic matrices of the material.

Three of the possible configurations of the piezoelectric strain transducer has been described and successfully demonstrated. Through comparisons between the strains measured with the piezoelectric transducer and those measured with a strain gage, glued on the test structure, it was found that the piezoelectric transducer can accurately measure dynamic strains. This transducer can be constructed with different sensitivities to strain by varying its geometry, piezoelectric sensor, and signal conditioner.

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