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DAMAGE LOCATION IN SMART STRUCTURES USING LOW COST IMPEDANCE MEASUREMENTS

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Abstract. *There are many papers available in the literature about fault detection. Each technique has advantages and disadvantages. In this work we present a non-model technique to detect and locate structural damage using vibration data measured in high frequency ranges. This technique uses signals of electrical impedance obtained from a low cost equipment constructed in the laboratory. Due the high frequency range and low voltage applied in the piezoelectric patches (usually 1 V), these measurements are very sensitive to minor structural changes in the near field of the piezoelectric sensor. So, the PZT actuator/sensor is arranged in order to define an influence area for each sensor. This technique is able to detect the damage in its early stage and to estimate the nature of damage without prior knowledge of the mathematical model of the structure. The paper shows the circuit used to construct the low cost impedance analyzer. It is an alternative equipment that was validated through a commercial equipment. The paper concludes with an experimental test in a truss structure made of aluminum beam, which has three bonded PZTs for damage characterization.*

Keywords*: Electrical Impedance, Piezoelectric Element, Fault Detection, Smart Structures.*

1. Introduction

There is great interest in the engineering community, in the development of real-time, in-service health monitoring techniques to reduce cost and improve safety, based on preventive inspection schedule. Maintenance by using vibration signals inspection is classified as one of nondestructive technique for condition monitoring. The weakest point of maintenance inspection today is that there is no general function for warning when incipient damage occurs in service (Egawa, 1997). The crucial factors that are of concern when any Non-Destructive Evaluation (NDE) technique is considered are (Raju, 1998):

- The principle behind these techniques is “preventive inspection”, i.e., inspect the structure in question at frequent intervals in an attempt to detect damage in the early or incipient stages;
- The capability of the technique to perform on-line health monitoring, i.e., monitor the integrity of the structure while it is in service;
- Ideally, an NDE technique should rely on use of small, non-intrusive sensors and actuators.

To deal with these problems, the present paper applies the concept of smart structure. The terms “smart structure”, or “intelligent material”, are fast becoming common phrases among the engineering community. These terms are used to describe a variety of modern advances in the engineering world. There is no agreement for the definition of these systems, however, the terms used in this work refer to structures with material components that are able to transform mechanical motion or force in electrical or magnetic fields, and vice versa. A list of materials employed in smart material system includes piezoelectric, electrostrictive and magnetostrictive elements, fiber optics, etc.

The impedance-based health monitoring technique relies on small patches of piezoelectric (PZT) materials, surface bonded or embedded in the structure, which utilizes the electromechanical coupling property of theirs materials (Park et al., 2000). The basic principle behind this technique is the use of high frequency (typically > 10kHz) to detect changes in structural point impedance due internal cracks, surface cracks, or loose connections (Lopes et al., 2001).

The electrical impedance data obtained from a piezoelectric actuator/sensor can be used to train the artificial neural network to quantify the fault severity. This technique is very sensitive to minor structural changes in the near field of the piezoelectric sensor. So, the PZT actuator/sensor is arranged in order to define an influence area for each sensor. The measuring can be made by using commercial analyzer, as for instance, HP 4192A, or any other similar equipment. These equipments are very expensive, cost approximately of US$30.000,00. Inconveniences of these equipments are the large size and heavy weight. The impedance technique uses a small subset of the capabilities of the instrument. Therefore, one other cheaper and lighter option should represent a great improvement in this proposal. The Low Cost Impedance Analyzer proposed in this paper is small and the cost is approximately US$50,00. It intends to popularize this technique.

2. Principle of Electric Impedance-Based Method

This technique uses actuator and sensor that are combined into a single piezoelectric element, called self-sensing actuator. Self-sensing actuator has a number of desirable features, related to collocated control, not easily achieved with a separated piezoelectric sensor and actuator (Inman 1990). The actuator is typically part of the structure and the stress, strain, electric field, and electric displacement within a piezoelectric material can be fully described by a pair of electromechanical equations. There are many equivalent statements for the electromechanical equations, and the best choice depends on the problem.

A piezoceramic (PZT) exhibits a bi-directional effect. Piezoelectricity describes the phenomenon of the generation of an electric field in a material when submitted to a mechanical stress. Using the notation of IEEE Standard 176-1987, the stress, strain, electric displacement within a piezoelectric material can be described by Eq. (1) and (2). The letters in brackets indicate the units of the variables (SI system) with N, m, V, C denoting Newton, meter, Volt and Coulomb, respectively.

$$\{S\} = [s^E]\{T\} + [d]\{E\} \quad \text{(actuator equation)} \tag{1}$$

$$\{D\} = [d]^t\{T\} + [e^T]\{E\} \quad \text{(sensor equation)} \tag{2}$$

where {S} is the strain tensor [m/m], $[s^E]$ is the compliance tensor [m^2/N], {T} is the stress tensor [N/m^2], [d] is the piezoelectric constant [C/N], {E} is the electric field [V/m; N/C], {D} is the electric displacement or induction [C/m^2], and $[e^T]$ is the dielectric permittivity. The superscripts E and T indicate that these quantities are obtained at constant electric field and constant stress, respectively. The impedance-based technique utilizes the PZT as a collocated actuator and sensor. A PZT bonded on the structure and driven by a fixed alternating electric field excites and induces vibrations in the structure (actuator effect). The vibration resultant modulates the current flowing through the PZT (sensor effect), which is function of the degree of mechanical interaction between the PZT and the base structure over the frequency range considered.

Electromechanical transducer material, as a piezoelectric patch, provides a means of coupling the mechanical and electrical impedance. Since it is easier to measure electrical impedance than mechanical impedance, this feature can be utilized with advantages, for many applications, where the FRF could be difficulty obtained. The electrical impedance can be measured with impedance analyzers, and it allows extraction of mechanical impedance information from a purely electrical impedance measurement. More information about this technique can be found in Park et al (2000) and Lopes Jr. et al (2000).

3. Methodology

The process to be used with the impedance-based monitoring method utilizes both the direct and converse effect of the piezoelectric simultaneously to obtain an impedance signature for the structure. The PZT is driven by a sinusoidal voltage sweep. Since the patch is bonded to the structure, the structure is deformed along with it and produces a local dynamic response to the vibration. The structural healthy is monitored through the variation of the electric impedance signal.

This method is based on high frequency ranges, low voltage, and local vibrations modes; therefore, the area of influence of each PZT is small. This technique can define with good accuracy the region of the fault. It is important to note that this method is not capable to supply the fault severity. To overcome this difficulty, Neural Networks, or any other optimization algorithm, can be used to quantify the damage through the solution of the inverse problem.

The electric impedance is measured in high frequency, which guarantees great sensitivity for local structural variations. The impedance signals must be processed and normalized in order to represent all conditions of faults that one wants to monitor. One of the largest advantages of this method is that the variation of the signal is local and it doesn't affect the others sensors (PZT). Therefore, simultaneous faults, that are difficulty identified for conventional methods, can be treated as if they happened independently. Solution of the wave-equation for the PZT bar connected to the external mechanical point impedance of the structure lead to the frequency-dependent equation of electrical admittance, (Sun, 1996).

$$Y = i\omega a[\in_{33}^{T}(1 - i\delta) - \frac{Z_S(\omega)}{Z_S(\omega) + Z_a(\omega)} d_{3x}^2 Y_{xx}^E] \tag{3}$$

where Z_a and Z_S are the actuator and structure mechanical impedance respectively, Y_{xx}^E is the complex Young's modulus of the PZT at zero electric field, d_{3x} is the constant of piezoelectric coupling in the x direction at zero stress,

ϵ_{33}^T is the constant at zero stress, δ is the dielectric loss tangent of the PZT, ω is the frequency, and a is the geometric constant of the PZT. The electrical impedance method has advantages compared to conventional vibration methods based on low frequency excitation, as for instance, lower excitation forces, usually the voltage applied is 1V, better capacity of detect incipient faults. The small wavelengths at high frequencies allow the impedance method to detect minor changes in the structural integrity.

4. Circuit of the Low Cost Impedance Measurements

The most common method of making impedance measurements uses commercial Impedance Analyzer. Usually, these equipments simultaneously measure 2 independent, complimentary impedance parameters. The combination of these parameters represents both resistive and reactive characteristics of the electrical impedance. The *R* - *X* function is, generally, used for health monitoring. *R* represents the real component of impedance in ohms and *X*, the imaginary component in ohms. In an equivalent series circuit this impedance is equal to $R + jX$. The absolute impedance, *Z*, and phase angle, θ, can be calculated as follows:

$$Z = \sqrt{R^2 + X^2} \tag{4}$$

$$\theta = tag^{-1}\left(\frac{X}{R}\right) \tag{5}$$

Instead of using magnitude (Z) and phase (θ), the component *R* is generally employed for structural health monitoring. This is due to the fact that *R* is more reactive to damage or changes in structural integrity, while *X* is more sensitive to variation of temperature, loading or wire length (Raju 1998). Other devices have been suggested for making impedance measurements for health monitoring, but are not commonly used. The impedance method represents just one technique for developing a self-sensing technology.

To overcome the prohibitive cost and portability for practical application, a new method of generating impedance measurements utilizing an FFT analyzer, or any other data acquisition system, has been developed. The equipment uses a small current measuring circuit and it is based on work proposed by Peairs (2002). The electric impedance from the PZT bonded in the structure can be found by the applied voltage in the PZT divided by the current. One approximation can be obtained using the circuit showed in Fig. 1.

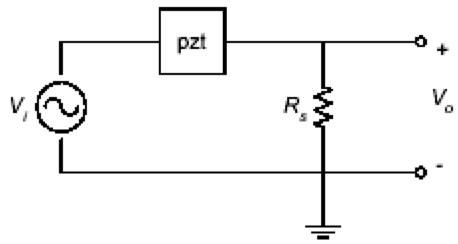


Figure 1. Circuit for approximate impedance measure from PZT.

The input voltage is V_i. Considering the resistance R_S in series with the PZT, one can measure the output voltage V_0. The output voltage is proportional to the current across the PZT. The current across the PZT is the same in the resistor, so, using the Kirchoff´s law one can find

$$V_i - Z(PZT) * I - R_s * I = 0 \tag{6}$$

$$V_0 = R_s * I \quad \Rightarrow \quad I = \frac{V_0}{R_s} \tag{7}$$

where *I* is the current in the PZT. Using equations (6) and (7) one can find the electric impedance *Z* from the PZT.

$$Z = \frac{V_i - V_0}{I} = \left(\frac{V_i - V_0}{V_0}\right) * R_s = \frac{V_i}{V_0} * R_s - R_s \tag{8}$$

For a small resistance R_S , it is possible to consider:

$$Z \cong \frac{V_i * R_s}{V_0} \tag{9}$$

The PZT is a capacitive element; therefore, the current in the PZT changes in function of the frequency. An elevation of frequency increases the current. On the other hand, at low frequency the circuit has high value of impedance, Eq. (10).

$$|Z| = \left| \frac{1}{\omega * c} \right| \tag{10}$$

where:

ω = excitation frequency
c = capacitive constant

In this case one inverse amplifier for the circuit can improve the range of output. One amplifier circuit for approximate measure of electric impedance from PZT, is presented by Peairs (Peairs, 2002), Fig. 2.

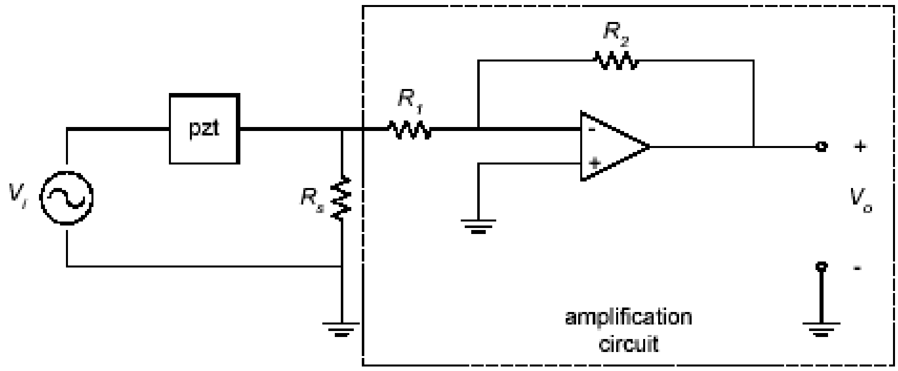


Figure 2. Impedance approximating circuit with amplification.

Using this amplifier, the output voltage V_0 is given by Eq. (11), where G is the gain of the amplifier circuit. However, since it is an inverse amplifier, the gain is negative.

$$V_0 = G * V_i$$
$$G = -\frac{R_2}{R_1} \tag{11}$$

The components used to construct the alternative equipment can be observed in the Fig. 3. Where R represents the resistance and C represents the capacitive constant. All units are in the SI system.

Figure 4 shows the equipment constructed using this circuit. It is a light and cheap equipment, and the final cost was approximately US$50,00. There is a key selector in order to choose the gain factor, like 1000, 5000 and 10.000. This equipment has three terminals, one to PZT, one to input voltage and one to output voltage, and one button to turn on and to turn off, since it is alimented from two batteries.

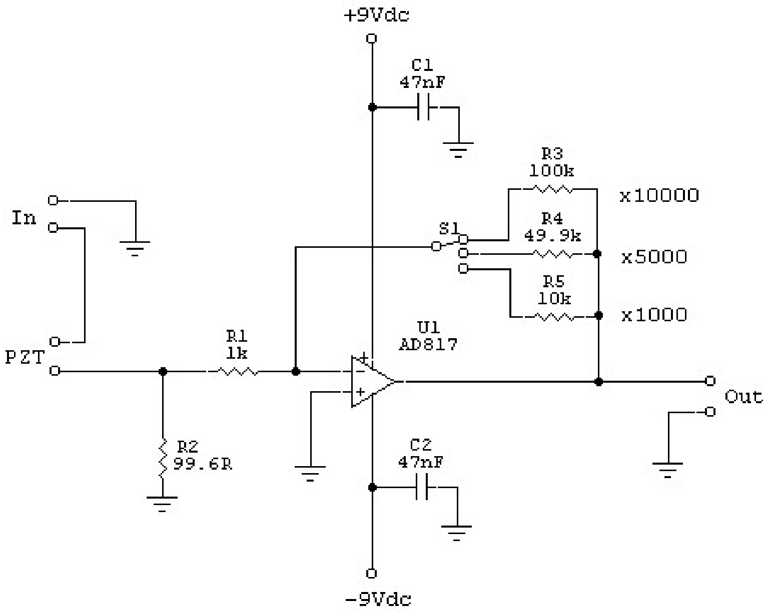


Figure 3. Low Cost Impedance Measure circuit.

Figure 4. Picture of the Low Cost Impedance Measurements (LCIM) equipment.

To realize measurements with the proposed LCIM is necessary to couple other equipments, as for instance, computer, a system for signal generation, a system for signal acquisition, filters and conditioners. Figure 5 shows the schematic setup used in the experimental tests.

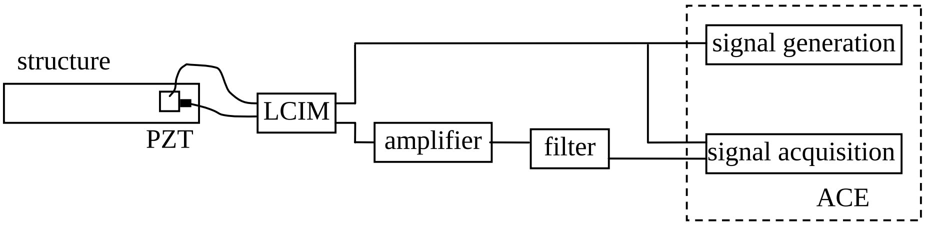
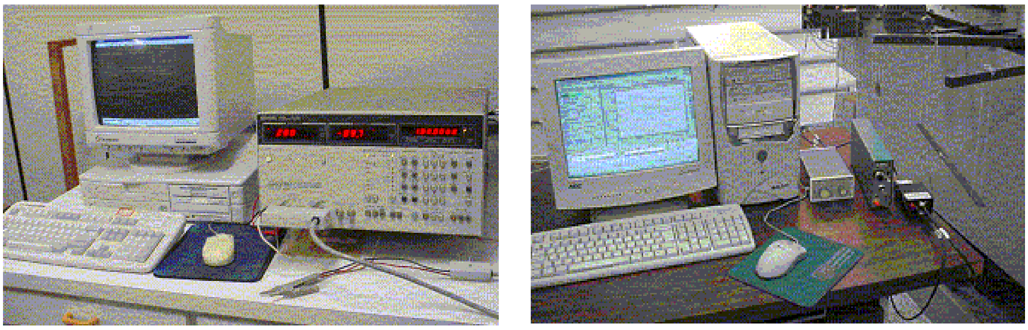


Figure 5. Scheme of measurements.

5. Experimental Application

In order to validate the alternative system, it was used a commercial analyzer to compare electrical impedance measurements. The commercial equipment is the HP Analyzer 4192A controlled by PC, Fig. 6a. The alternative setup uses the Low Cost Impedance Measuring (LCIM), defined in the previous section, a voltage amplifier PCB model 494A, a robotron filter model 01017, and an acquisition data software ACE®, Fig. 6b (Furtado, 2004).



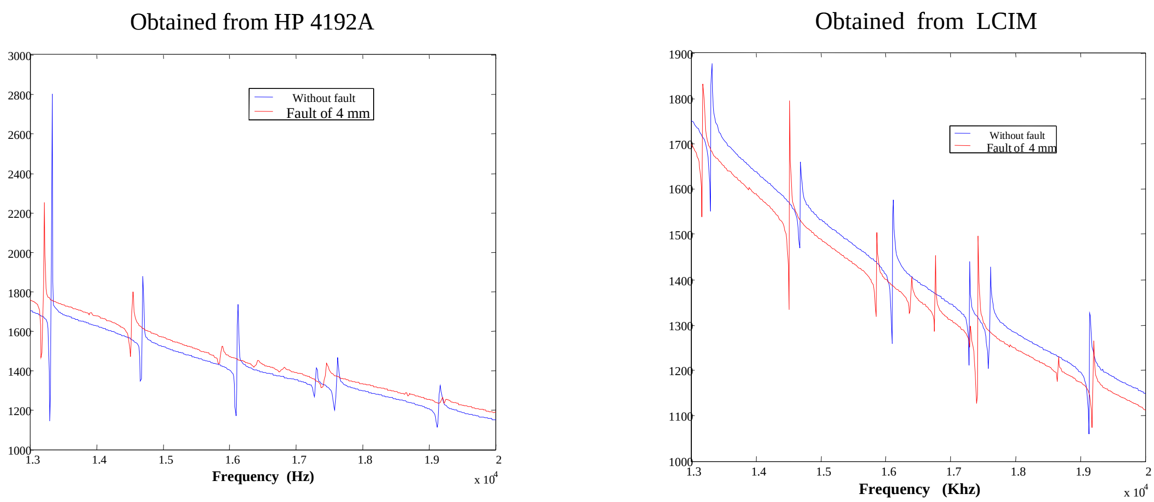
(a) (b)

Figure 6. Set of instruments used for electrical impedance acquisition.

Several tests were done with these two sets of equipments. Figures 7 show the signals obtained using the HP Analyzer and the LCIM system for the aluminum truss structure, showed in Fig. 8, for two damage situations. There are different ways to assess the damage through electrical impedance signals. One can use damage metrics, which is defined by,

$$M = \sum_{i=1}^{n} \left[\mathrm{Re}\left(Y_{i,1}\right) - \mathrm{Re}\left(Y_{i,2}\right) \right]^2 \qquad (12)$$

where $Y_{i,1}$, is the reference electrical impedance signal and $Y_{i,2}$ is the on-line signal of the monitored structure.



(a) (b)

Figure 7. Comparison between HP (7a) and LCIM (7b) systems analyzer.

Since both systems gave the same results for damage metrics, the experimental application will be demonstrated on the elasto-mechanical structure, Fig. 8, utilizing only the LCIM system. The damages consist of cuts in different positions. The impedance signals were monitored in the frequency range varying from 10 to 20 kHz. There are three PZT sensors/actuators bonded in the structure. Each PZT is monitored independently, and this characteristic permits to identify the damage in its sensing area.

The aluminum truss structure has 300mm of height, 200mm of width and 500mm of length. In practical situations the PZTs must be fixed in locations that are vulnerable to occur faults. Each PZT is responsible for monitoring a small region. The PZTs bonded on the truss structure is from Piezo System, PSI-5A-S4 with Young modulus E = 63 GPa, dielectric constant d_{31} = -190e-12 m.V^{-1}, and 0,267 mm of thickness.

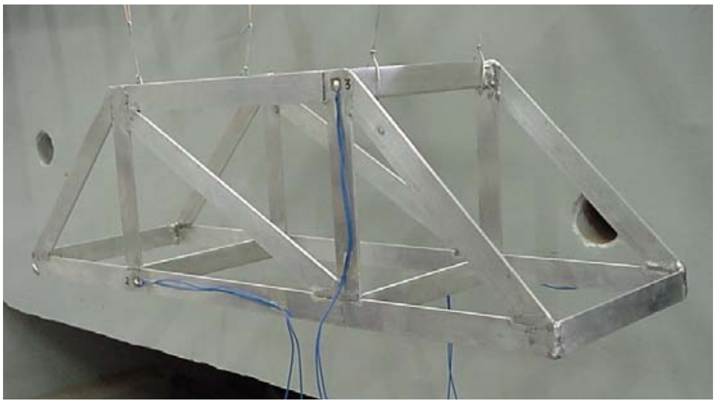
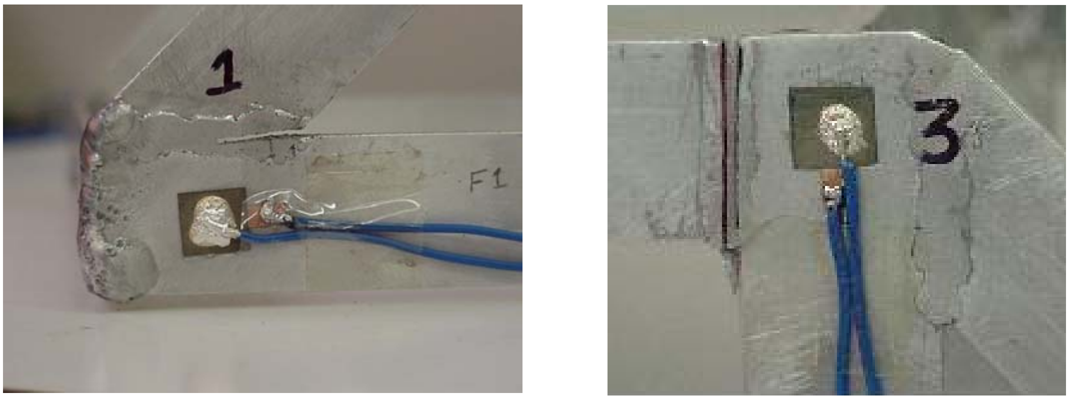


Figure 8. Aluminum truss structure with bonded PZTs.

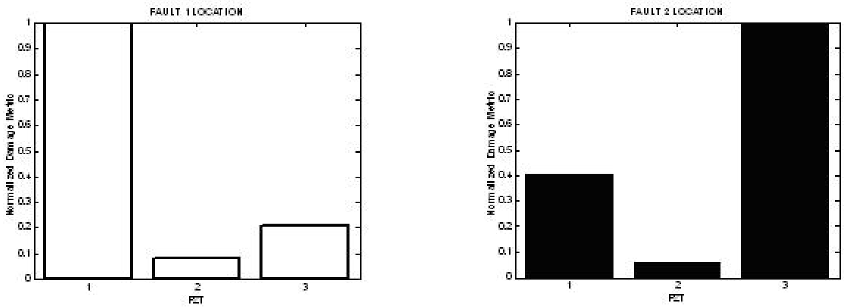
The reference signals were obtained for the intact structure for each PZT sensor/actuator. For this experimental application, it was introduced different levels of faults in two positions. The first damage was inserted in the cross section of the aluminum beam around the PZT1, Fig. 9a. This damage has approximately 1,5mm of width and 7mm of length. After the damage insertion, a new set of measurements was done for this situation. The second damage was inserted around the PZT3 in the beam surface with approximately 1,5mm of width and 1,5mm of depth, Fig. 9b. In the following, another set of measurements for this situation of simultaneous damages was taken.



(a) (b)

Figure 9. Damages inserted in the aluminum structure.

Figure 10 shows the normalized damage metric chart for all three PZTs in a single graphic, with the maximum value set to unity. The value of the damage metric is function of the severity and the distance between the damage and the PZT. As can be seen in the Fig. 10a, the value in the PZT1 is an indication of damage in its influence area. The damage metric of PZT2 and PZT3 are indications of variation in some boundary conditions or damage far away of theirs influence area. Fig. 10b shows the results after the second damage was introduced. It can be seen an indication of damages near of PZT1 and damage near of PZT3. These results show the independence of each sensor/actuator and the possibility of identification of simultaneous damages.



(a) (b)

Figure 10. Damage metric for each PZT after the introduction of the first damage (a) and after the simultaneous damages (b).

Figure 11 shows the behavior of the damage metric for both damage situations in a single graphic. The white bars represent the measuring for the first damage situation, and the black bars represent measuring for the second damage situation. The maximum value was set to unity.

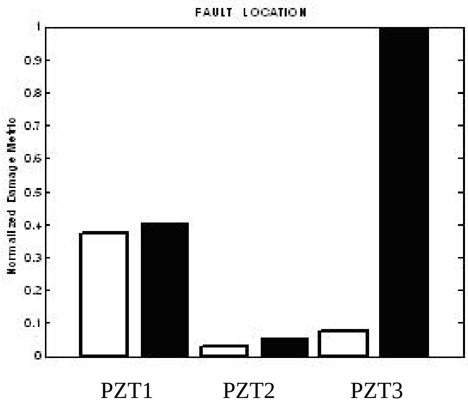


Figure 11. Damage metric chart for each PZT, after first (white) and second (black) damage situation.

In both cases PZT2 presented small value of damage metric, in other words, there is no damage indication in this region. With this procedure is possible to identify, with accuracy, the damaged regions. So, with this information is possible to propose an optimization algorithm to quantify the fault severity with a small subset of parameters.

6. Summary

In order to make possible the application of the electrical impedance technique in practical situations, a low cost and portable equipment was presented. Impedance technique gives clear information about the damage location, and therefore, it can be used to select a small subset of parameters. The damage severity can be described by an optimization algorithm, since the number of variable to be considered in the procedure is small, when compared with the full model. High frequency structural excitations through surface-bonded piezoelectric sensors/actuators were utilized to monitor the structure.

The alternative low cost impedance measuring (LCIM) instrument was validated through a commercial impedance analyzer. The experimental investigation successfully located and identified simultaneous damages in a welded aluminum truss structure. The authors believe that the simple manner for identifying simultaneous damage locations is the bigger advantage of this technique.

7. Acknowledgements

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