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## **SHM BASED ON THE ELECTROMECHANICAL IMPEDANCE FOR DAMAGE DETECTION IN A COMPOSITE SHAFT**

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**Abstract.** *The use of composite material in mechanical and aeronautical structures has increased, because of the characteristics of this material, such as low weight/strength ratio and long fatigue life. Despite the advantages of this kind of material, it presents distinct damages from structures manufactured with traditional materials, e.g., delamination and fiber rupture. Therefore, it is essential to develop methods to detect damages in early stages in order to avoid economic loss and equipment breakdown. In this context, the objective of this paper is to evaluate and improve the robustness of the SHM method based on electromechanical impedance (ISHM) to detect damages on a composite rotor hollow shaft. The temperature variation effect in the impedance signatures was evaluated since this SHM methodology is influenced by this factor. This non-destructive technique uses the property of the piezoelectric transducers, acting as sensors and, actuators. For the experiment, a composite shaft (532mm length, 17mm diameter, and 1.35mm thickness) was used. Three piezoelectric transducers (each one with four piezoelectric patches electric connected in parallel) were bonded on the shaft surface. To simulate the damage, a mass (steel nut) was attached on the shaft. Measurements were performed before and after the damage at room temperature and inside a thermal chamber with controlled temperature (5°C, 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35°C, 40 °C and 45°C). To quantify the damage, a damage index was used. Furthermore, an optimization method based on hybrid optimization was developed to minimize the temperature effect on these signatures, preventing false positives.*

**Keywords:** *Composite shaft, ISHM, electromechanical impedance, damage metrics.*

### **1. INTRODUCTION**

Composite materials have been applied in civil, aerospace, and mechanical structures. These are formed by a combination of two or more types of materials at the macroscopic level, in order to obtain physical and mechanical properties that are not presented when analyzed individually. With the manipulation of the components, it is possible to improve these material properties: stiffness, mechanical strength, weight reduction, corrosion resistance, thermal properties, fatigue and wear resistance, among others (Reddy, 2004).

However, the mechanisms of failure of this material are more complex than traditional materials depend not only on its properties but also on its geometric characteristics. Additionally, damage detection methods for composite materials are time-consuming and expensive (Miguel et al., 2018). There are many research about SHM techniques to detect damage in composite structures, like based on Lamb Waves (Rocha, 2017), Acoustic Emission (Pearson et al., 2011), Vibration Analysis (Mei et al., 2019), Fibre Optic (Güemes et al., 2014) and Electromechanical Impedance (Tsuruta, 2008; Rocha, 2017).

So, the objective of this work is to investigate and improve the robustness of the ISHM method based on electromechanical impedance. This technique monitors the variations in the electrical impedance of a piezoelectric sensor bonded to (or embedded into) the monitored structure. This is possible since the sensor electrical impedance is directly related to the mechanical impedance of the structure, so any changes in the mass, stiffness and damping of the structure change these signals. This method generally uses the real part of the impedance since the imaginary part, which corresponds to the capacitive part of the response, is more sensitive to temperature variation. It is worth mentioning that the imaginary part can be used in several applications in order to evaluate the integrity of the sensor.

This methodology is a well-studied topic in the industrial and academic environments (Palomino, 2008; Finzi Neto et al., 2011; Tsuruta et al., 2017; Ai et al., 2018), although for composite shafts there are no publications.

In this context, this work aims to evaluate and improve the robustness of the ISHM approach to detect damage in a composite hollow shaft at different temperatures. For this, a test rig was mounted inside a thermal chamber, an optimization procedure based on hybrid optimization was used to minimize the effect of the temperature in the impedance signatures, avoid false-positives.

## 2. IMPEDANCE ELECTROMECHANICAL METHOD

The ISHM technique uses the electromechanical coupling property of the piezoelectric transducers. This sensor is coupled on/into the host structure, using their sensor and actuator properties to detect damage, monitoring changes in the stiffness, damping, and mass of the structure.

For this aim, an electrical impedance measurement is acquired from the piezoelectric transducer, as due to the difficulty of obtaining the mechanical impedance of the structure. Considering that the properties of the PZT patch (Lead Zirconate Titanate) do not vary over time, changes in the electrical impedance will be directly related to changes in the mechanical impedance, which is affected by the presence of damage (Park *et al.*, 2006).

Figure 1 shows a *single-degree-of-freedom* (DOF) electromechanical model proposed by Park *et al.* (2006) that describes the measurement process. The piezoelectric transducer is bonded directly with a high-strength adhesive on the surface of the structure to ensure better electromechanical coupling (Peairs, 2006).

The dynamic properties of the monitored structure are represented by a mass (M), a stiffness (K) and a damping factor (C). So, the piezoelectric transducer is excited by a sinusoidal voltage source  $V_i(\omega)$  with amplitude  $V$  and angular frequency  $\omega$ . Using the actuator effect, the piezoelectric transducer applies a force on the host structure; in response, it returns an induced strain. Through the sensor effect, this induced strain generates an output current  $I_o(\omega)$  with amplitude  $i$  and phase  $\phi$ . The mechanical impedance  $Z_m(\omega)$  of the monitored structure is given by the relation between the force applied  $F(\omega)$  to the structure and the speed  $\dot{X}(\omega)$  developed. Making an analogy with an electric circuit, the force and speed correspond to a voltage and output current, respectively, resulting the electrical impedance  $Z_e(\omega)$ . This function is measured using an appropriate measurement device (normally, the inverse of the impedance is analyzed, the admittance).

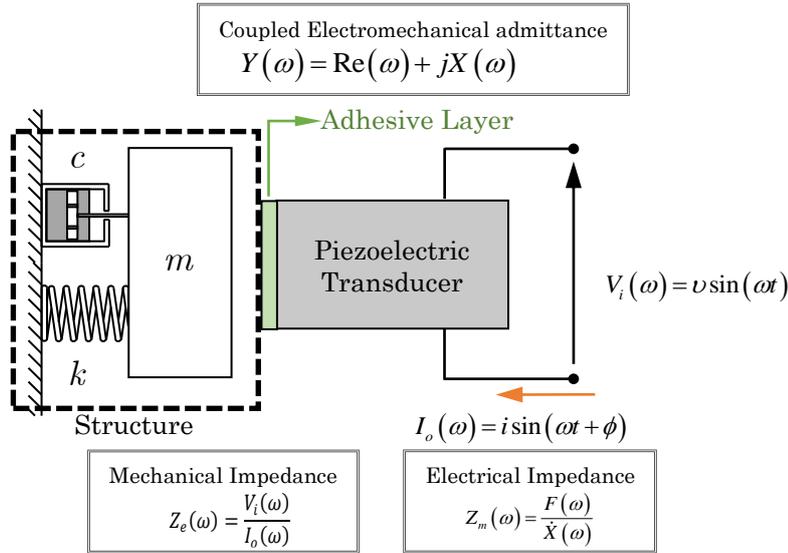


Figure 1. A single DOF Electromechanical Model of the impedance-based structural health monitoring method (Park *et al.*, 2006).

Equation 1 shows the frequency-dependent electrical admittance. This is the solution of the wave equation for the piezoelectric transducer connected to the structure (Park *et al.*, 2006). Based on the system shown in Fig. 1, the *admittance*  $Y(\omega)$  (inverse of impedance) of the piezoelectric transducer is a combined function involving the mechanical impedance of the PZT actuator  $Z_a(\omega)$  and the structure  $Z_s(\omega)$ , according to:

$$Y(\omega) = R(\omega) + jX(\omega) = \frac{I_o(\omega)}{V_i(\omega)} = j\omega \frac{b_a l_a}{h_a} \left( \bar{\epsilon}_{33}^T (1 - j\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{31}^2 \hat{Y}_{11}^E \right) \quad (1)$$

where  $R(\omega)$  and  $X(\omega)$  are the real part and imaginary part of the electromechanical admittance, respectively;  $j$  is the imaginary unit,  $\omega$  is the angular frequency;  $b_a$ ,  $l_a$ ,  $h_a$  is the width, length and thickness of the piezoelectric transducer;

$\varepsilon_{33}^T$  is the dielectric constant at zero stress,  $\delta$  is the dielectric loss tangent to the piezoelectric transducer;  $d_{31}^2$  is the piezoelectric coupling constant at zero electric field;  $\hat{Y}_{11}^E$  is the complex Young's modulus of the PZT patch with zero electric field. The impedance is a frequency dependent complex function. To obtain the electrical impedance, both the direct and inverse effects of the piezoelectric transducer are used. The direct effect (or sensor effect) is characterized by producing a voltage when the piezoelectric transducer is mechanically deformed in the elastic phase, and the inverse effect (or actuator effect) appears as a piezoelectric ceramic patch is subjected to a voltage, resulting a mechanical deformation (Peairs, 2006).

Frequency band for the ISHM method is normally chosen by a trial and error method considering the structure characteristics, according to the work developed by (Peairs, 2006). It has been found that a frequency range with a high mode density exhibits a higher sensitivity since it generally covers more structural dynamic information (Peairs, 2006).

The detection and evaluation of the structure integrity is based on the comparison between the real part of the impedance signatures acquired from both the healthy and damaged (or unknown condition) structure. A visual examination of the signals is not enough for evaluation, since it gives only a qualitative comparison. Consequently, it is necessary to use an adequate metrics for defining quantitative criteria. Thus, damage metrics (DM) are employed, i.e., scalar parameters are properly defined so that they can numerically represent the difference between the two signals (without and with damage). According to Palomino (2008) the most used metric in this case is the root mean square deviation (RMSD), defined by Eq. (2), where  $Z_{1,i}$  and  $Z_{2,i}$  are the impedance functions measured for the healthy and damaged structure, respectively, and  $n$  is the number of frequencies in the observation band. This metric will be used to analyze the results of this work.

$$RMSD = \sqrt{\sum_{i=1}^n \left\{ \frac{[\text{Re}(Z_{1,i}) - \text{Re}(Z_{2,i})]^2}{n} \right\}} \quad (2)$$

### 3. OPTIMIZATION PROCEDURE

Temperature variation effects are known to cause horizontal (frequency) and vertical (amplitude) shifts in impedance signatures. A review of temperature variation effects and temperature methods can be found in Rabelo *et al.* (2016).

Figure 2 shows a flowchart to illustrate the proposed temperature compensation methodology. The method starts by obtaining the impedance signatures of the healthy analyzed system ( $\text{Imp}_{\text{baseline}}$ ; temperature  $T_{\text{baseline}}$ ). The impedance signatures of the system for an unknown condition ( $\text{Imp}_{\text{unknown}}$ ; temperature  $T_{\text{unknown}} \neq T_{\text{baseline}}$ ) are also required, so that the optimizer is responsible for shifting their effective frequency and amplitude. The  $\text{Imp}_{\text{unknown}}$  signatures are compared with the  $\text{Imp}_{\text{baseline}}$  ones by means of a given objective function, i.e., a damage metric, as presented by Eq. (2) ( $\text{Imp}_{\text{baseline}} = Z_1$  and  $\text{Imp}_{\text{unknown}} = Z_2$ ).

In Fig. 2, if the procedure converges to a minimum value of the objective function, the effects of temperature variation are compensated through the frequency shift and vertical shift design variables. If this is not the case, the optimization procedure continues the search with new frequency and amplitude shifts. The optimization process continues iteratively until convergence is assured, which can lead to temperature compensation (if the objective function is close to zero) or a damage indication associated with temperature compensation.

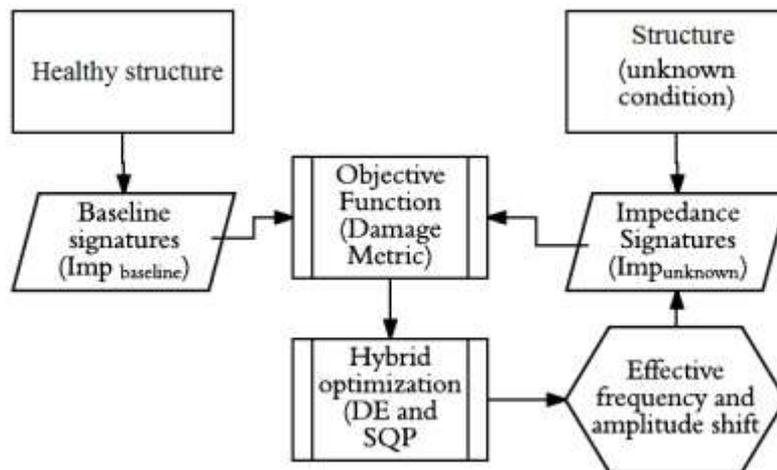


Figure 2. Proposed noise compensation flowchart.

The present contribution, a hybrid optimization technique is primarily devoted to minimizing temperature during the impedance measurement process. Also, this optimization process was used to test its effectiveness in minimizing the influence of the external excitation on the impedance signatures. The following section describes the hybrid optimization algorithm.

The proposed temperature compensation technique is based on the solution of a typical inverse problem, in which the optimal effective frequency and amplitude shifts are determined by minimizing the damage metric associated with two impedance signatures (i.e., one of the signatures corresponds to the baseline). Thus, the evolutionary technique known as Differential Evolution (DE) (Price, Storn, Lapinen, 2005) is devoted to the global search for the optimum (i.e., the effective frequency and amplitude shifts). It is worth mentioning that the DE algorithm must be performed  $n$  times to avoid local minima. The best result obtained by DE is then used as a starting point for the classical direct method Sequential Quadratic Programming (SQP) to obtain the local and refined optimal solution.

The DE algorithm is an optimization technique that belongs to the family of evolutionary computation, which differs from other evolutionary algorithms in the mutation and recombination schemes. DE executes its mutation operation by adding a weighted difference vector between two individuals to a third one. Then, the mutated individuals will perform discrete crossover and greedy selection with the corresponding individuals from the last generation to produce the offspring. The key control parameters for DE are the population size (NP), the crossover constant (CR), and the associated weight (F).

#### 4. STATISTICAL THRESHOLD DETERMINATION

The concepts of statistical process control were used to establish limits in a control chart so that a threshold can be established using the upper control limit. These limits can be defined so that 95.4% or 99.7% of the data from a normally distributed population remain if those control limits are established as expressed in Equations 3 and 4 (Barros Neto, Scarminio and Bruns, 2001). A Shapiro-Wilk normality test was used to determine the probability distribution of the obtained RMSD values.

$$\bar{x} + 2s \text{ to } 95.4\% \text{ confidence} \quad (3)$$

$$\bar{x} + 3s \text{ to } 99.7\% \text{ confidence} \quad (4)$$

#### 5. EXPERIMENTAL PROCEDURE

Figure 3 presents the composite roller shaft (17mm diameter, 1.35mm thickness, and 532mm length) used in this work. Three PZT transducers were attached to the specimen surface. Each one is composed with four piezoelectric transducers with 10mm length, 3mm width, and 1mm thickness. The distance between this sensor was 100 mm to each other. In the first test case, a steel nut was coupled to the shaft 25mm from PZT#2 to simulate the damage condition. Impedance signatures were measured considering a room temperature condition before and after the introduction of the damage. In the second test, a thermal chamber was used to evaluate the temperature variation. Impedance measurements were made at 5 °C, 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C, and 45 °C. Also, to simulate damage, a nut was attached at 25mm from PZT#1. The frequency range was determined experimentally based on the density of peaks: 50 kHz to 80 kHz for all PZT patches. Figure 4 shows the thermal chamber and the impedance meter used to obtain the signatures. The Shapiro-Wilk normality test was used to determine the probability distribution of the obtained RMSD values and, consequently, to determine the threshold of damage detection for a statistical limit with 95.4% confidence.

Table 1 shows the experimental configurations adopted to obtain the rotor impedance signatures. For each condition of the experiment, 30 measurements were acquired, with 3000 points and 256 averages each.



Figure 3. Composite material shaft with damage.

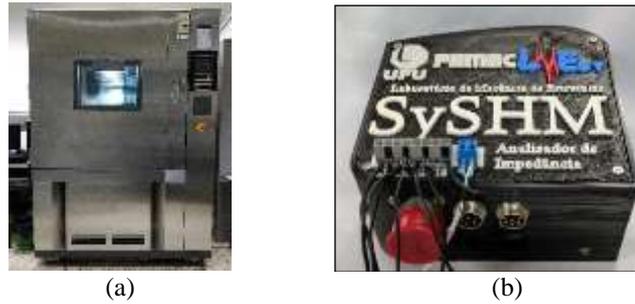


Figure 4. (a) Thermal chamber; (b) Impedance meter.

Table 1. Test set-up

Run	Temperature	Damage (25mm from PZT#1)	Indication/ Graphic
1	5°C	-	B1
2	10°C	-	B2
3	15°C	-	B3
4	20°C	-	B4
5	25°C	-	B5
6	30°C	-	B6
7	35°C	-	B7
8	40°C	-	B8
9	45°C	-	B9
10	5°C	x	D1
11	10°C	x	D2
12	15°C	x	D3
13	20°C	x	D4
14	25°C	x	D5
15	30°C	x	D6
16	35°C	x	D7
17	40°C	x	D8
18	45°C	x	D9

## 6. RESULTS

Figures 5 (a), 6 (a) and 7 (a) show the real part of impedance signatures of the PZT#1, PZT#2, and PZT#3, respectively. These signals were measured before and after simulated the damage on the composite shaft. In the impedance signatures graphics, for the three sensors, it is possible to observe peaks, it is important, considering that the composite materials present high associated damping values, which can attenuate the amplitude of the impedance signatures and, consequently, affect the damage detection capability of the ISHM approach. Damage metrics are shown in Fig. 5 (b), 6 (b) and 7 (b) of the PZT#1, PZT#2, and PZT#3, respectively.

By analyzing the damage metrics graphics, it is possible to visualize that the value of the metric after the addition of the damage is greater than the value of the metric before the damage in all graphics, showing that this method is able to detect the presence of the damage in the monitored structure. Also, as expected, the damage metric value of the PZT#2 is higher than the others, due to the proximity of the piezoelectric transducer from the damage.

Equation (3) was used to determine the statistical threshold. Before this, a Shapiro-Wilk normality test was performed to determine the probability distribution of the obtained RMSD values.

In the second experiment, to evaluate the temperature influence in the impedance signatures, the same procedure of measurement was repeated, but in this experiment, the test rig was placed inside the thermal temperature. Regarding the hybrid minimization algorithm used to compensate for the environmental condition (variation of the temperature), the evolutionary optimizer DE was performed 5 times considering 10 individuals in the initial population (this is one of the advantages of DE). The *RMSD* damage metric was used as an objective function. The impedance signatures were digitally filtered with a 3<sup>rd</sup> order Savitsky-Golay Finite Impulse Response (FIR) smoothing filter with a frame size of 200.

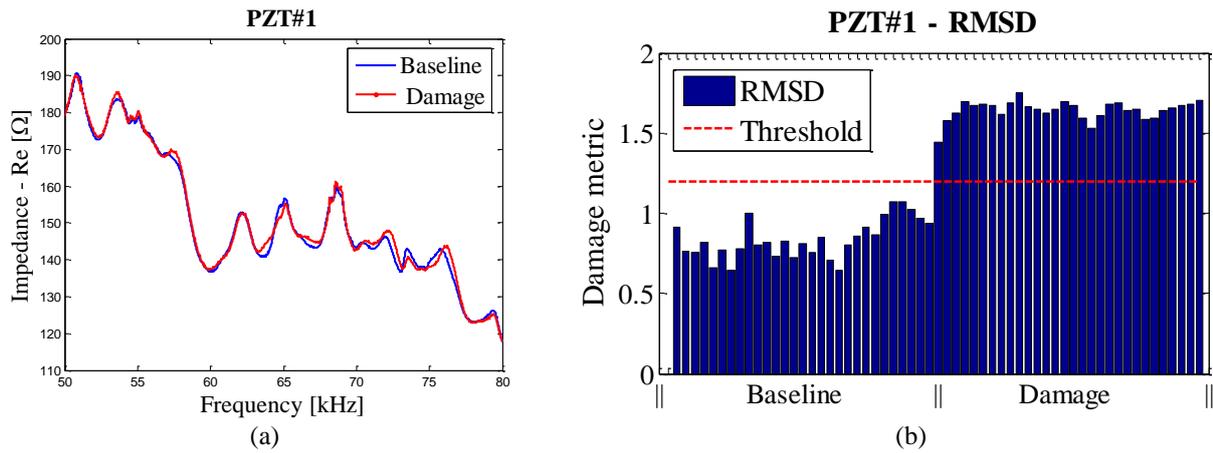


Figure 5. PZT #1: (a) Real part of impedance signatures; (b) RMSD damage metric.

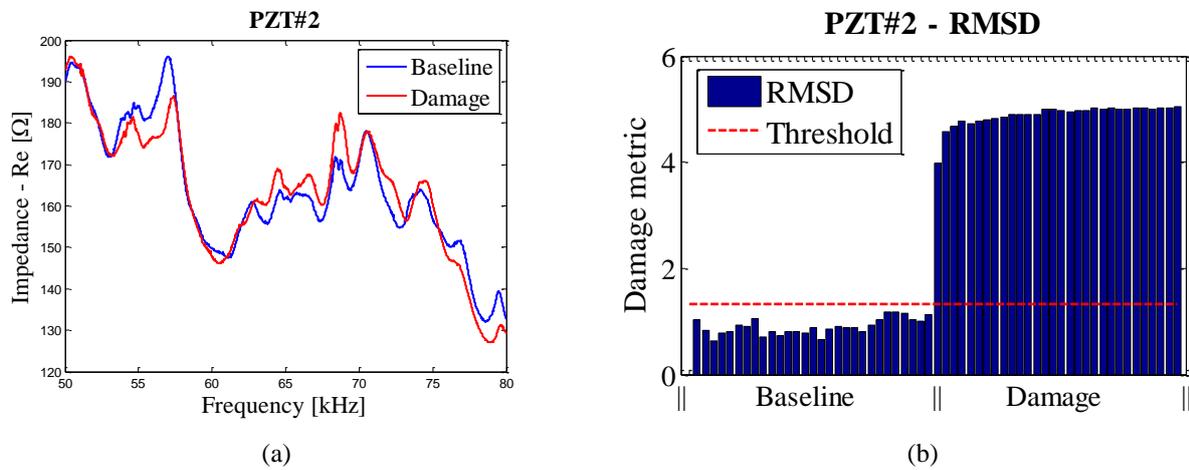


Figure 6. PZT #2: (a) Real part of impedance signatures; (b) RMSD damage metric.

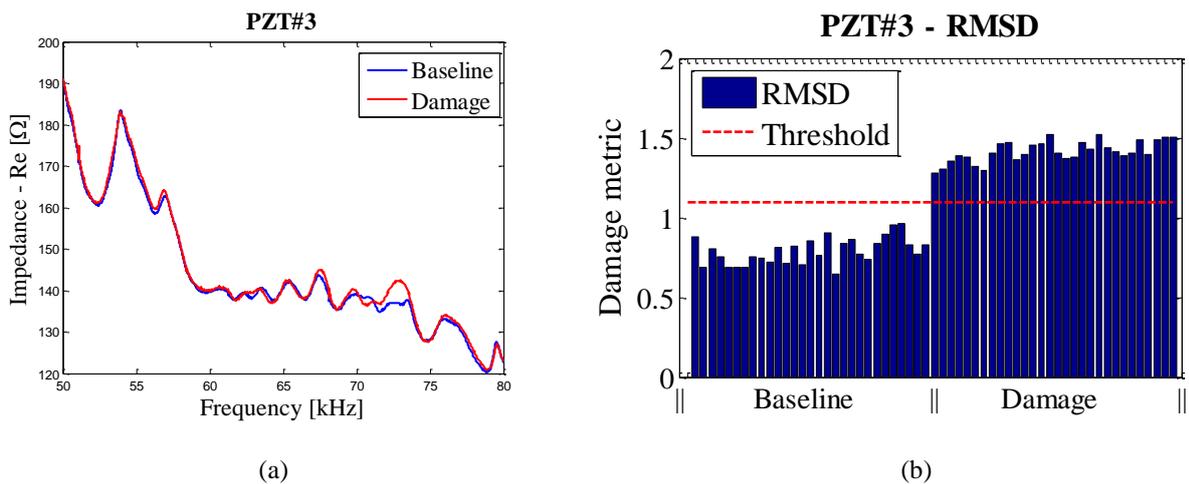


Figure 7. PZT #3: (a) Real part of impedance signatures; (b) RMSD damage metric.

Figures 8 (a), 9 (a) and 10 (a) shows the real part of the impedance signatures for the PZT#1, PZT#2 and PZT#3, respectively. With these graphics, it is possible to notice the impedance signals changes in function of the temperature. With the optimization procedure it is possible to minimize this influence, as shown in the Fig. 8 (b). With the impedance signatures of the structure without damage and with the damage it was possible to calculate the damage metrics, considering the baseline of 5°C for all the cases and using hybrid optimization. The results of damage metrics are shown in Figs. 8 (c), 9 (b) and 10 (b), for damage at 25mm from PZT#1. Each condition was described in Table 1.

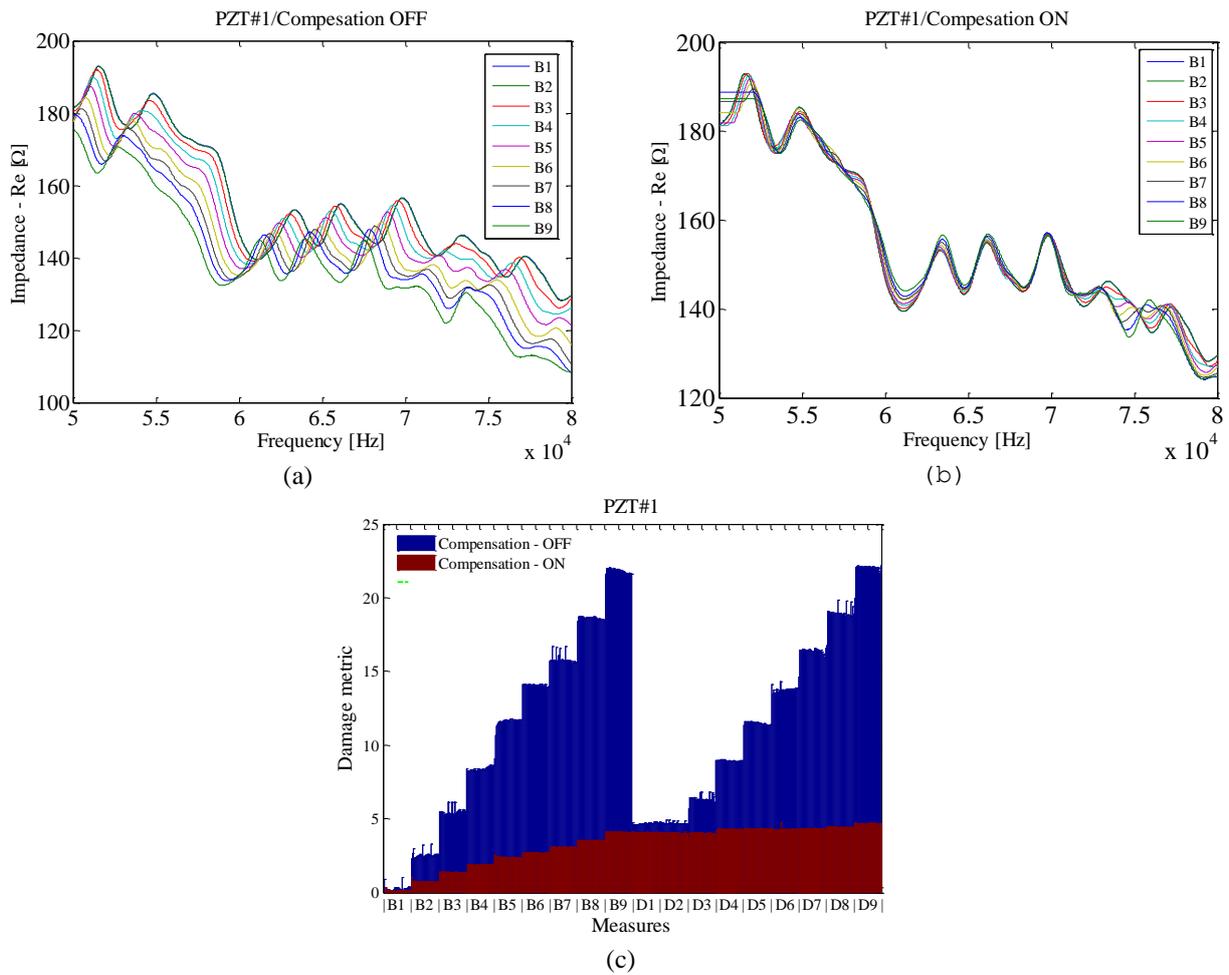


Figure 8. PZT#1: (a) Real part of impedance signatures for different temperatures (Compensation OFF); (b) Real part of impedance signatures for different temperatures (Compensation ON); (c) RMSD damage metric.

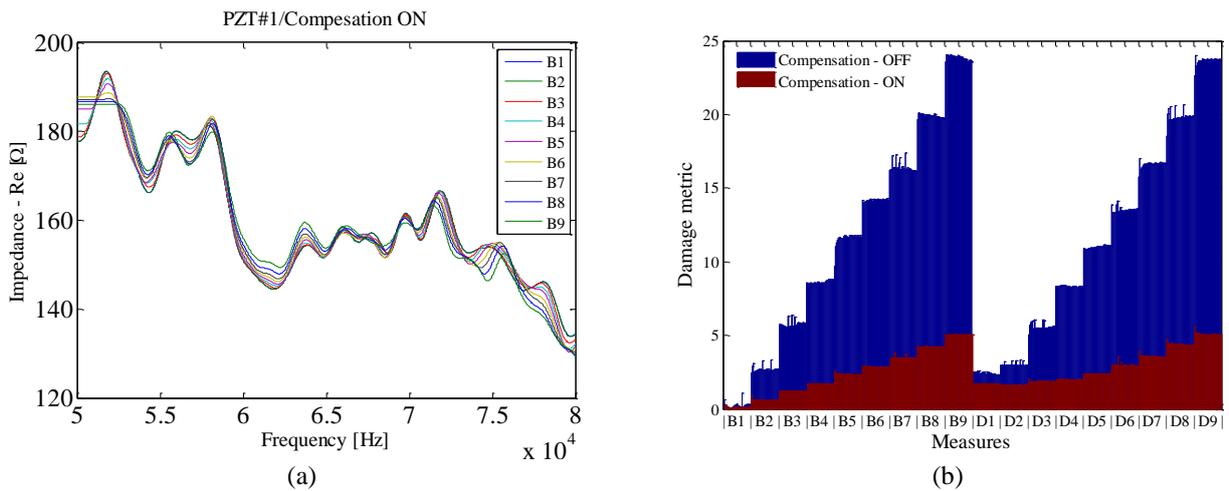


Figure 9. PZT#2: (a) Real part of impedance signatures for different temperatures (Compensation ON); (b) RMSD damage metric.

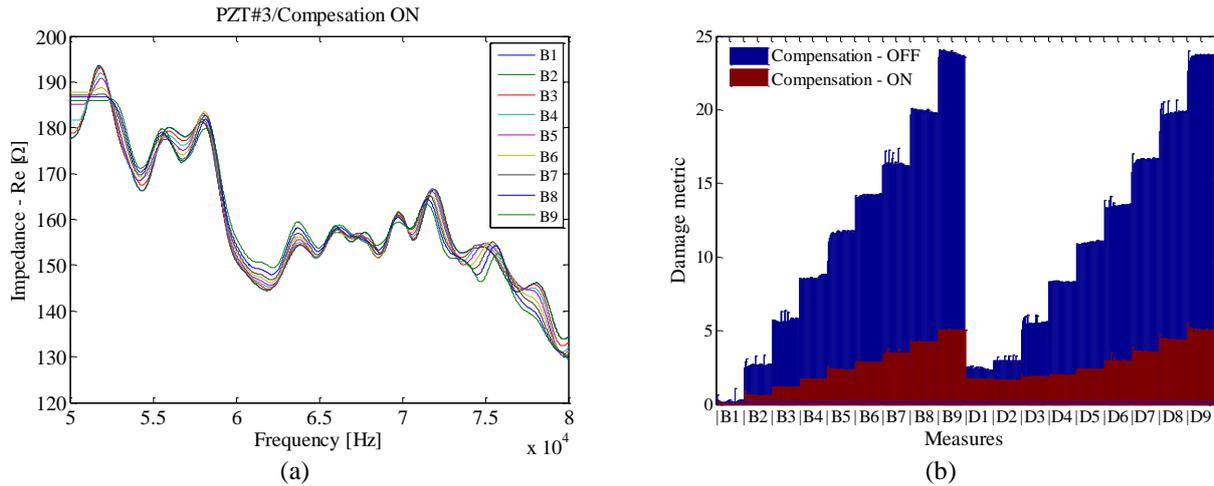


Figure 10. PZT#3: (a) Real part of impedance signatures for different temperatures (Compensation ON); (b) RMSD damage metric.

## 7. CONCLUSION

The objective of this work is to improve the robustness of the structural health monitoring method based on electromechanical impedance (ISHM) to detect damages on a composite rotor shaft considering the temperature variation, since this methodology is influenced by such factor. Three piezoelectric transducers (each one with four piezoelectric patches electric connected in parallel) were bonded on the shaft surface. To simulate the damage, a steel nut was attached to the shaft. Measurements were performed before and after the damage at room temperature and inside a thermal chamber with controlled temperature (5 °C, 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C and 45 °C).

The results shown in the present contribution demonstrate the efficiency of the electromechanical impedance method for the detection of incipient faults in a composite hollow shaft with low-temperature change. For higher temperature variation, it was possible to notice that impedance signals changes in the function of the temperature. With the hybrid optimization procedure, it was possible to minimize this influence, as shown in the Fig.8 (b). Evaluating the results of damage metric shown in Figs. 8 (c), 9 (b) and 10 (b), considering 5 °C the pristine condition, it was possible to notice that the ISHM method can detect the damage simulated, also the temperature variation. So more detailed studies should be done.

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