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INCREASING ROBUSTNESS TO THE ISHM APPROACH FOR FAULT DETECTION IN A COMPOSITE HOLLOW SHAFT

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Abstract. Composite materials has been applied to manufacture rotating shafts for the automotive, marine, and aerospace industries. This kind of material can reduce structural weight, wear, acoustic noise, and vibration amplitude. Additionally, it can increase the performance of the system when replacing the components made with traditional materials. However, the composite material suffers different damage modes hard to be detected. Thus, many methods were proposed in the last years for damage detection purposes in composite materials, such as the so-called electromechanical impedance approach (ISHM method). In this context, the objective of this work was to improve the robustness of the ISHM technique for damage detection in a composite hollow shaft considering large temperature variations (0°C to 50°C). To minimize the effects of temperature variation in the impedance signatures, a hybrid optimization strategy (Differential evolution and Nelder-Mead methods) was used. However, this technique reveals to be not efficient to minimize the influence of temperature over the entire frequency range investigated. Therefore, a new compensation methodology using compromise programming was proposed looking for optimal frequency regions in the measured impedance signatures. The obtained results demonstrated the effectiveness of the proposed temperature compensation approach for increasing the robustness of the ISHM technique.

Keywords: Rotating machines, ISHM, composite shaft, temperature compensation, optimization.

1. INTRODUCTION

Composite material has been applied in the manufacture of rotating shafts used in the automotive, maritime, and aerospace industries, as it reduces structural weight, wear, vibration amplitude. Increases the performance of the system when compared to the same component made of traditional materials. However, due to their manufacturing issues, these materials have different damages, such as delamination, fiber breakage, internal voids, and the debonding between the matrix-fiber interface (Askaripour and Zak, 2019). Therefore, sophisticated SHM techniques are required to detect damage in this type of material.

One of these techniques is the SHM method based on the electromechanical impedance (ISHM method), which can provide real-time information about the structure integrity. In this methodology, piezoelectric transducers (PZT - Lead Zirconate Titanate) are attached on/or inside the structure to obtain impedance signatures based on the PZT's direct and inverse effects (Chaudhry *et al.*, 1995).

Despite the advantages of the ISHM technique, this methodology has some disadvantages, such as the influence of the temperature on the measured impedance signals. As the temperature variations cause horizontal and vertical shifts (frequency and amplitude, respectively) in the impedance signatures, which may lead to false-positive or false-negative interpretations in the damage detection process. To minimize this problem, temperature compensation techniques have been proposed to obtain more reliable results (Park *et al.*, 1999).

The objective of the present work is to evaluate the ISHM technique applied in a composite material hollow shaft under different temperatures. Additionally, an optimization procedure considering the Differential Evolution (DE) and Nelder-Mead (NM) methods associated with compromise programming is proposed to minimize the effect of the temperature on impedance signatures and avoid false positives. In this case, a search for optimal compensation regions according to the frequency range is performed. The obtained results are compared with the ones obtained by using a hybrid optimization procedure investigated by Tsuruta *et al.* (2017).

2. IMPEDANCE ELECTROMECHANICAL METHOD

One of the first works describing the process of measuring impedance signatures was presented by Liang *et al.* (1993), who proposed a one-dimensional theoretical model. The electromechanical model, which represents the process of measuring the electromechanical impedance in a single-degree-of-freedom (DOF) system, is presented in Fig. 1. In this case, the dynamic properties of the monitored structure are represented by a mass (m), a stiffness (k), and a damping factor (c). The piezoelectric transducer is excited by a sinusoidal voltage source $V_i(w)$ with amplitude v and frequency w . 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 $I_o(w)$ with amplitude i and phase ϕ . The mechanical impedance $Z_m(w)$ of the monitored structure is given by the relation between the force applied $F(w)$ to the structure and the speed $X(w)$ developed. Making an analogy with an electric circuit, the force and speed correspond to a voltage and output current, respectively, resulting the electrical impedance $Z_e(w)$. This function is measured using an appropriate measurement device. Generally, the inverse of the impedance is analyzed, the admittance.

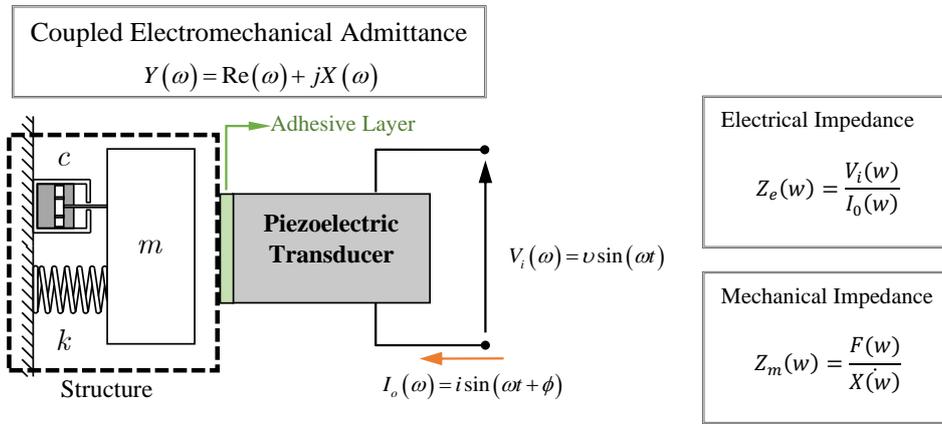


Figure 1: A single DOF electromechanical model of the impedance-based SHM method (Adapted Liang *et al.* (1993)).

From the proposed system and considering that the mechanical properties of the PZT patch do not vary with time, Liang *et al.* (1993) demonstrated that the admittance $Y(w)$ of the PZT actuator can be written as a combined function of the mechanical impedance of the actuator itself Z_a and the structure Z_S , as shown in Eq. (1).

$$Y(w) = \frac{I_o(w)}{V_i(w)} = iw \frac{b_a l_a}{h_a} \left(\bar{\epsilon}_{33}^T (1 - i\delta) - \frac{Z_S(w)}{Z_S(w) + Z_a(w)} d_{3x}^2 \bar{Y}_{xx}^E \right) \quad (1)$$

where $I_o(w)$ is the output current, $V_i(w)$ is the input voltage on the PZT actuator; b_a , l_a , and h_a are the width, length, and thickness of the PZT respectively; $\bar{\epsilon}_{33}^T$ is the complex dielectric constant of the PZT; δ is the dielectric loss factor; d_{3x}^2 is the piezoelectric coupling constant with zero deformation; and \bar{Y}_{xx}^E is the PZT complex Young's modulus with null electric field.

Impedance signatures can be obtained experimentally using an impedance analyzer and then the damage present in the structure is quantified with damage metrics, such as root means square deviation (RMSD) (Peairs, 2006):

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

where $Re(Z_{1,i})$ is the actual part of the measurement impedance signature without damage (reference value, called baseline) at a frequency i , $Re(Z_{2,i})$ is the actual part of the impedance signature at a frequency i for a new structure configuration, n is the number of frequencies points in the observation band, and i ranges from 1 to n .

Then, the results obtained with the damage metric are analyzed using a reliable statistical threshold (see Eq. (3)) with 99.73 % confidence, which is used to estimate the point from which there is a change in the structure, that is, from this value it is possible to separate the healthy from the damaged conditions.

$$PZT_{threshold} = \mu + 3\sigma \quad (3)$$

where μ is the population mean and σ is the standard deviation.

3. TEMPERATURE EFFECT

The environmental conditions of monitored structures are constantly changing, due to temperature variation, humidity, and so on. Regarding the electromechanical method, the temperature variation results in frequency and amplitude modifications on the impedance signatures, which can lead to incorrect conclusions about the state of the analyzed structure (Park *et al.*, 1999). The incorrect conclusion about the structural integrity is because the damage index referring to the electromechanical impedance signatures with temperature variation may have a value corresponding to moderate damage in the structure (Sun *et al.*, 1995).

The study developed by Sun *et al.* (1995) found that there was a difference between the effect caused by temperature variation and the effect caused by structural damage in impedance measurements. The temperature change can cause almost uniform vertical and horizontal deviations of the impedance signatures, whereas, in the presence of structural damages, there are significant changes in the pattern of the signatures. This difference allows the effect of temperature to be isolated and reduced through numerical manipulations.

This behavior has also been observed in composite material shafts. For this aim, a temperature compensation technique based on a hybrid optimization with compromise programming was proposed in this work. It is worth mentioning that the results obtained by using a hybrid optimization temperature compensation process described by Tsuruta *et al.* (2017) is also presented for comparison purposes.

3.1 Hybrid optimization procedure

In this methodology, initially impedance signatures are measured in the healthy structure (baseline measurements). Then, impedance signatures are obtained for an unknown condition of the structure. In this case, the optimizer is responsible for determining the optimal horizontal and vertical displacements in the measured impedance signatures capable of ensuring temperature compensation.

The impedance signatures of the unknown condition are compared with the baseline impedance signatures using an objective function, which in this case is the damage metric given by Eq. (2). If the procedure converges to a minimum value of the objective function, the effects of temperature variation are compensated. If this does not happen, the optimization procedure continues updating the frequency and amplitude values until convergence is achieved, which may lead to temperature compensation.

A better description of this algorithm can be found in Tsuruta *et al.* (2017) and Rabelo *et al.* (2017).

3.2 Proposed optimization procedure

Initially, the impedance signatures of the monitored structure in its healthy condition (baseline) and also for an unknown condition are obtained. The latter are compared with the baseline impedance signatures using two objective functions: RMSD value (see Eq. (2)) and frequency range in which the damage metric is evaluated. The objective functions are combined using the compromise programming technique (CP - Eq. (4)). The optimization methods Differential Evolution and Nelder-Mead are responsible for determining the optimal offsets capable of ensuring compensation in the horizontal and vertical directions of the impedance curve determined for an unknown condition of the shaft in comparison with the baseline. Additionally, a statistical threshold with 99.73 % is used to estimate the value from which there is a change in the structural condition of the shaft.

$$CP(x) = \left\{ \sum_{k=1}^K \left[\frac{W_k \{FO_k(x) - FO_k^*(x)\}}{FO_k^{worst}(x) - FO_k^*(x)} \right]^2 \right\}^{\frac{1}{2}} \quad (4)$$

where W_k is the weighting factor in the k-th objective function; FO_k is the k-th objective function; FO_k^* is the best value of the k-th objective function; and FO_k^{worst} is the worst known value of the k-th objective function (Vanderplaats, 1999).

If the procedure converges to a minimum value of the objective function, the best frequency range is obtained. If this does not happen, the optimization procedure continues updating the values of the design variables until convergence is achieved, which can lead to temperature compensation if the final value of the objective function is close to zero.

Then, the best frequency range found is used as bounds for conventional hybrid optimization, which performs temperature compensation on impedance signatures, with frequency and amplitude offset as design variables. Thus, the original objective function (RMSD) is reapplied to the optimal region, where a better result is expected to be obtained with respect to the entire previously used frequency range.

4. EXPERIMENTAL TESTS

The specimen used in this work was a hollow circular shaft made of composite material, with 532 mm length, 16.7 mm outer diameter, and 14 mm inner diameter, as shown in Fig. 2. The shaft was instrumented using three PZT patches attached to its surface, each one composed of four piezoelectric transducers (10 mm x 3 mm x 1 mm), electrically

connected in parallel, called PZT#1, PZT#2, and PZT#3. To simulate the damage condition, a steel nut was attached to the shaft at 10 mm from PZT#2. Figure 3 shows a schematic representation of the shaft with its main dimensions (in mm), as well as the positions of the piezoelectric transducers and the damage.



Figure 2: Composite material shaft.

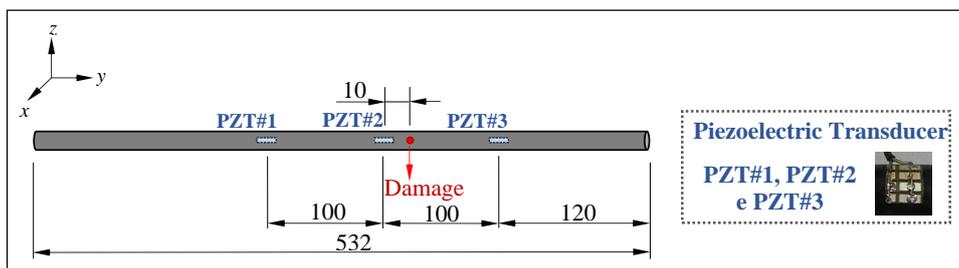


Figure 3: Positioning of piezoelectric transducers and shaft damage.

A climatic chamber (Fig. 4a) was used for temperature control to evaluate the temperature effect. The specimen was positioned inside the climatic chamber (Fig. 4b) and the temperature was varied from 0°C to 50°C with increments of 5°C for the two conditions analyzed (without damage and with damage). The impedance measurements were performed before and after adding the damage in the shaft using the impedance analyzer agilent model 4294A (Fig. 5). The impedance signatures were measured in the frequency range between 25 and 65 kHz for all PZTs and considering 801 points.

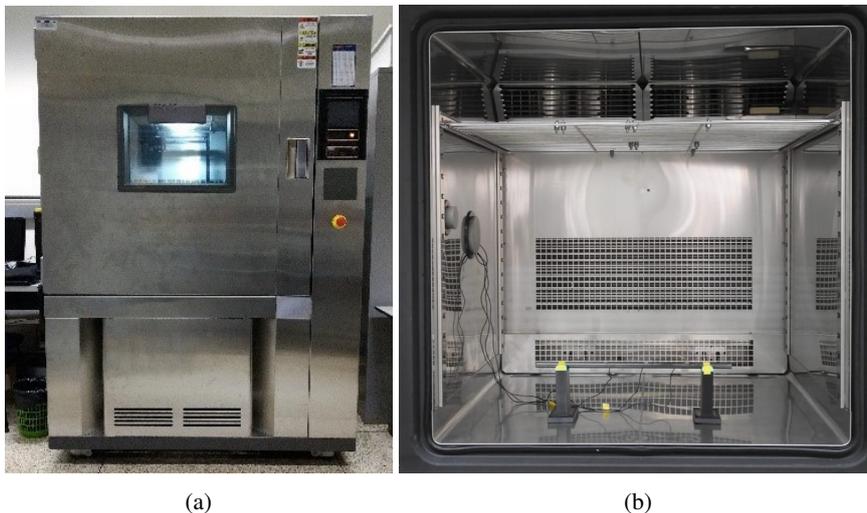


Figure 4: (a) Climatic chamber, (b) Experimental test rig mounted inside the climatic chamber.

The experimental nomenclature adopted for the impedance signatures was B for the baseline condition and D for the condition with damage. The numbers represent the temperature at which the experiment was performed, while LI and LS indicate the lower and upper limits in frequency, respectively. For each condition of the experiment, 8 measurements were obtained.

5. RESULTS

Figure 6 shows the impedance signatures measured using the PZT#1 before and after the application of the temperature compensation approaches. It can be seen in Fig. 6a that the signatures present vertical and horizontal displacements due to

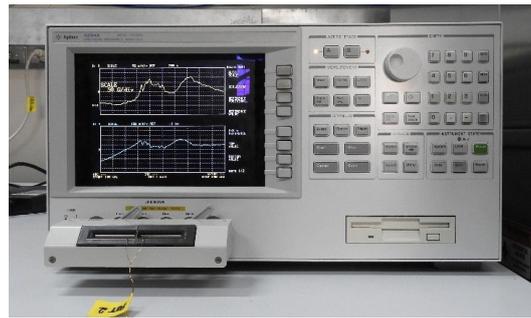


Figure 5: Impedance analyzer agilent 4294A.

the temperature variations. Figures 6b and 6c show the measured impedance signatures compensated by using the hybrid and the proposed temperature compensation approaches, Fig. 6d shows the RMSD values obtained for all the described shaft conditions. It is possible to observe that the proposed optimization approach was able to reduce more the influence of the temperature on the impedance signatures than the hybrid optimization.

The optimal frequency range determined at the end of the optimization process using the proposed optimization procedure was 34.6 to 45.4 kHz. In this case, weighting factors of 0.3 and 0.7 were used in the CP objective functions (RMSD value and frequency range, respectively).

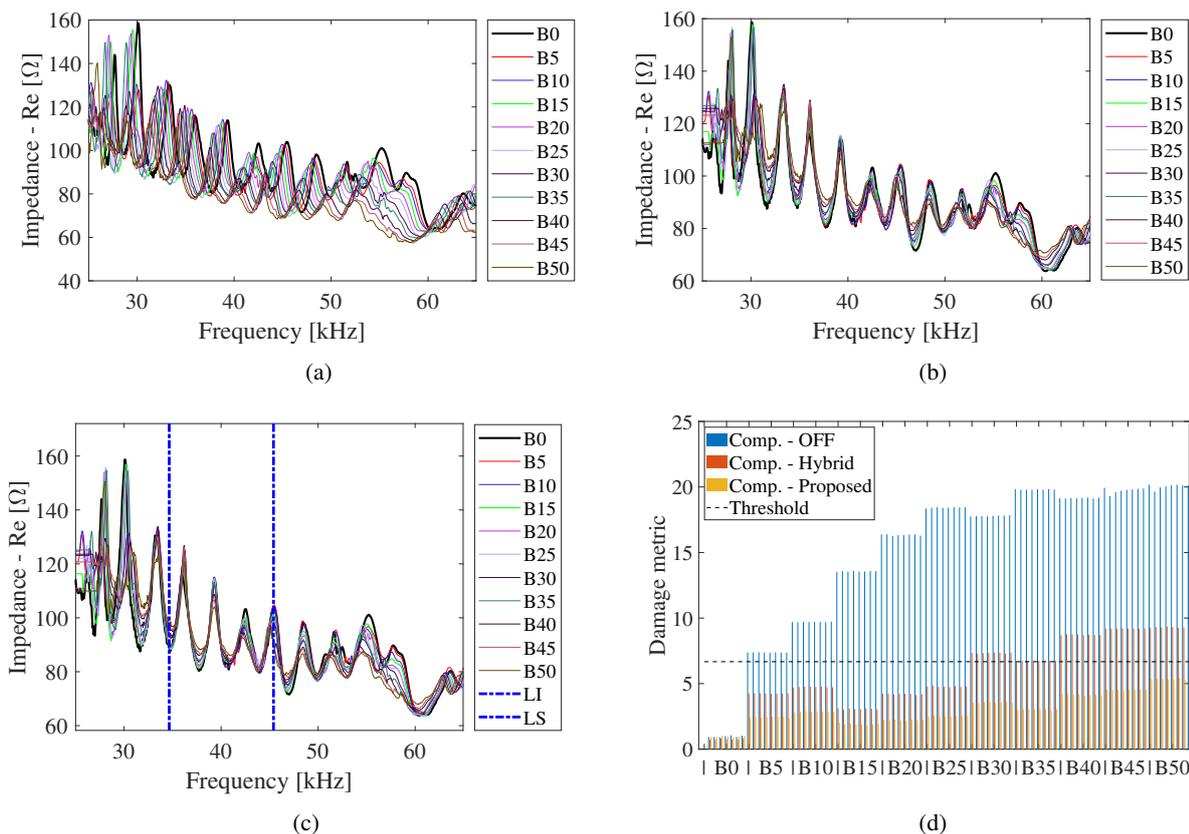


Figure 6: Impedance signatures measured by PZT#1: (a) Without compensation, (b) Hybrid compensation, (c) Proposed compensation, (d) RMSD values.

Figure 7 presents the impedance signatures obtained after the compensation performed using the proposed approach for weighting factors of 0.2 and 0.8 used in the CP objective functions (RMSD value and frequency range, respectively). In this case, a frequency range of 32.5 to 42.4 kHz was achieved in the optimization process.

Figure 8 shows the damage metric obtained from the impedance signatures presented in Fig.7 and the damage threshold (calculated using the damage metric values of the baseline condition for all temperatures). Note that the damage indexes were reduced using the proposed temperature compensation approach when compared with the RMSD valued determined in the signatures compensated applying the hybrid optimization technique. However, it was possible to observe that the ISHM approach could not detect the faults. It is worth mentioning that more severe damages could be detected

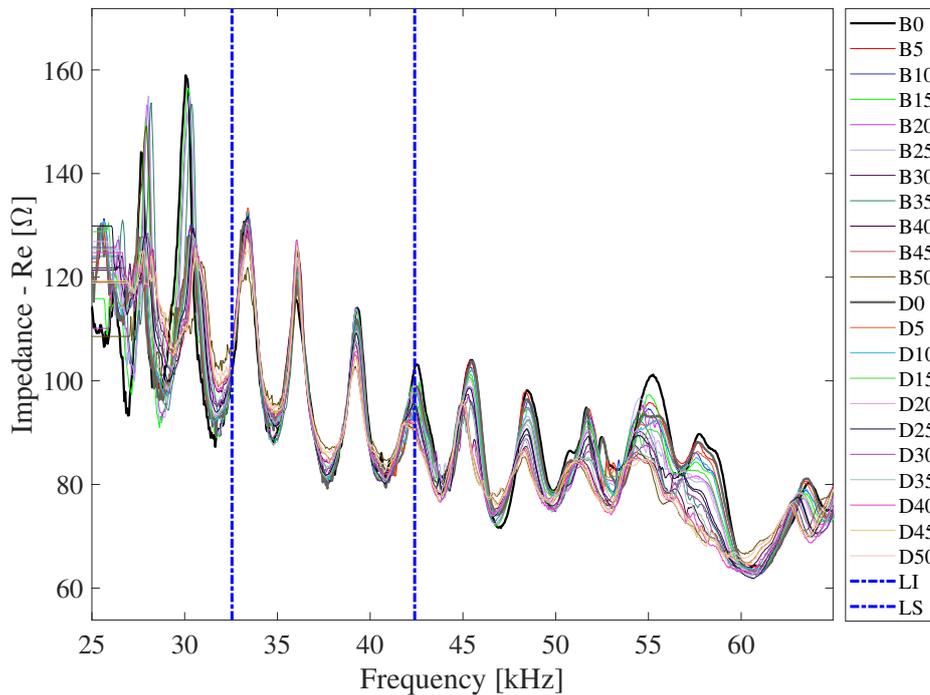


Figure 7: Impedance signatures measured by PZT#1 with proposed compensation and damage.

using the conveyed approach. As mentioned, the objective of the present contribution was to minimize the effects of the temperature on the measured impedance signatures. Similar results were obtained for the impedance curves measured with the PZT#2 and PZT#3.

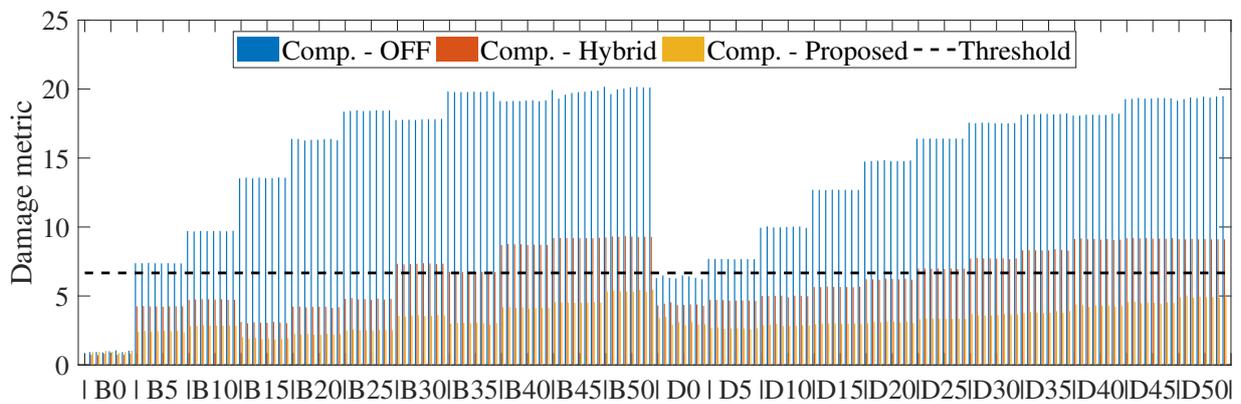


Figure 8: RMSD damage metrics obtained for the condition without and with damage.

6. CONCLUSIONS

This work evaluated the temperature influence in the ISHM method applied in a composite hollow shaft. The obtained results demonstrated that the impedance signatures are influenced by temperature variation. For this reason, an optimization methodology devoted to minimize these influences was proposed. The results shown that the effect obtained by temperature variations in a frequency range of interest was minimized using the proposed optimization approach. Lower RMSD damage metric values were determined for the three conditions, using the temperature compensation technique based on CP. Additionally, it was possible to observe that ISHM approach was not able to detect satisfactorily the fault conditions. It is worth mentioning that more severe damages could be detected using the conveyed approach. As mentioned, the objective of the present contribution was to minimize the effects of the temperature on the measured impedance signatures. Further research work will be dedicated and necessary to better evaluate the experimental tests with the composite shaft mounted in a rotating machine.

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