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FAULT DETECTION IN A THICK STRUCTURE BY USING THE ISHM TECHNIQUE

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Abstract. *The electromechanical impedance-based structural health monitoring technique has been developed as a promising tool for the real-time assessment of structural damages. It has been successfully applied in various engineering projects. This approach uses piezoelectric patches bonded to the structure (or incorporated into it) to measure impedance signatures and to detect mass, stiffness, or damping changes. While the technique has been efficiently applied in detecting damages in thin structures, its application in thick structures still needs to be explored. Therefore, this article contributes to using the technique in this type of structure. Two experimental setups were employed: a steel beam subjected to destructive damages and a steel bar subjected to non-destructive damages. In the evaluation of destructive damages, damages resulting from successive cuts in the beam were detected, while in non-destructive damages, adding mass to the bar was employed. The obtained results demonstrated the technique's effectiveness in detecting and quantifying structural damages in the analyzed setups, showcasing its potential as a promising method for continuously monitoring structural integrity in structures with these characteristics.*

Keywords: ISHM, damage detection, thick structures.

1. INTRODUCTION

Failure detection and monitoring is a subject of considerable interest in industrial sectors, which constantly look for techniques capable of detecting early-stage failures. This detection is important so that corrective measures can occur in advance in order to increase the useful life of engineering systems, thus reducing costs and maintenance time.

In this context, Structural Health Monitoring (SHM) techniques, which involves the detection of damages through non-destructive evaluation techniques, play a fundamental role in engineering. Among these techniques, the Electromechanical Impedance-based approach (ISHM) stands out, that is based on the principle that changes in the mechanical properties of a structure that are associated with the existence of damages affect its electrical response (Chaudhry *et al.*, 1995; Park *et al.*, 2003). A PZT patch is excited at high frequency, resulting in minimal deformation in the monitored structure. The response of the structure is then captured by the PZT patch, generating a corresponding electrical response. Thus, damage in the structure causes changes in the electrical response of the PZT patch due to the electromechanical coupling between the PZT and the monitored structure (Venson *et al.*, 2022).

This technique has proven to be a valuable and non-destructive approach for detecting structural failures, offering a high potential for identifying defects in the early stages. Therefore, it becomes a versatile tool in a wide range of applications, encompassing various structures, such as beams (Askari *et al.*, 2022; Venson *et al.*, 2022), rotating machines (de Rezende *et al.*, 2023), composite structures (Na and Kim, 2023), bolted connections (Wu *et al.*, 2023), among others. However, it is essential to note that the application of the ISHM technique in thick structures has been underexplored, with the majority of existing studies being related to specific applications, such as concrete structures (Naoum *et al.*, 2023; Bansal *et al.*, 2022; Kaur and Singla, 2022, 2023). For this reason, analyses of applying the ISHM technique in various categories of thick structures are still necessary to provide an overview of its potential and limitations.

Therefore, this study aims to partially fill this gap and investigate the application of the ISHM technique in thick steel structures. For this purpose, experimental analyses will be carried out on two structures: a steel beam and a steel bar. The steel beam was subjected to destructive damage by successive cuts in its structure, while the steel billet underwent evaluation by adding mass. The impedance signatures in both structures were measured before and after the damage suffered. The CCD damage metric was used to quantify the variations in impedance signatures resulting. The satisfactory results obtained in these experiments serve as a basis for advancing the application of the ISHM technique in thick

structures, as the method was capable of identifying and continuously monitoring damages.

2. IMPEDANCE ELECTROMECHANICAL METHOD

The ISHM technique uses piezoelectric transducers to identify variations in structural properties, including mass, stiffness, and damping. These variations are detectable due to piezoelectric materials' direct and inverse piezoelectric effects. The direct piezoelectric effect, known as the sensing effect, occurs when the material undergoes mechanical deformation, generating a corresponding electrical charge. Conversely, the inverse piezoelectric effect, called the actuation effect, occurs when the material is subjected to an external electrical potential, resulting in mechanical deformation. (Chaudhry *et al.*, 1995; Park *et al.*, 2003). A single-degree-of-freedom system shown in Fig. 1 illustrates the measurement process, where the mass, stiffness, and damping properties are represented by the letters m , k e c , respectively. The piezoelectric transducer is excited by a voltage source V_i , and the output current I_o is generated by the deformation of the sensor Liang *et al.* (1993).

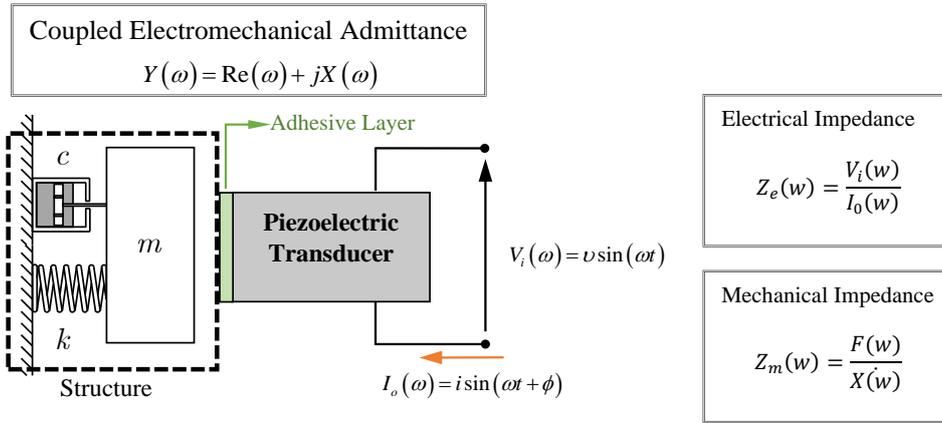


Figure 1. Classical single-degree-of-freedom system for the ISHM technique (Adapted Liang *et al.* (1993)).

From the proposed system and considering that the mechanical properties of the PZT patch do not vary with time, these authors demonstrated that the admittance $Y(w)$ of the PZT actuator could be written as a combined function of the mechanical impedance of the actuator itself Z_a and the structure Z_S (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 e h_a is the width, length and thickness of the PZT, $\bar{\epsilon}_{33}^T$ 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 signature measurements are performed using an impedance analyzer and are obtained at two distinct moments: in the initial condition of the structure (baseline) and the damaged condition. The impedance signature obtained in the initial condition is then used as a reference and compared to the subsequent measurements, enabling the identification of differences between them.

However, this analysis provides only a qualitative assessment, indicating the presence or absence of damage in the structure but not quantifying it. For this reason, statistical treatments, known as damage metrics, are applied to quantify the differences between the impedance curves measured before and after possible damage. One of these metrics is the Correlation Coefficient Deviation (CCD), expressed by Eq. 2.

$$CCD = 1 - \frac{1}{n} \sum_{i=1}^n \frac{[Re(Z_{1,i}) - Re(\bar{Z}_1)] [Re(Z_{2,i}) - Re(\bar{Z}_2)]}{S_{Z_1} S_{Z_2}} \quad (2)$$

where $Re(Z_{1,i})$ is the impedance of the PZT patch measured at healthy conditions and $Re(Z_{2,i})$ is the impedance for the comparison with the baseline measurement at frequency interval i , n is the number of points in frequency ($i = 1, \dots, n$) used in the signature. The symbols $Re(\bar{Z}_1)$ and $Re(\bar{Z}_2)$ represent mean values, while S_{Z_1} and S_{Z_2} represent standard deviations. When the CCD index equals 0, the signals correlate completely, indicating no damage has been identified. The closer the CCD index is to 1 (or 100 %), the more severe the damage and the better its identification (Naidu and Soh, 2004).

3. EXPERIMENTAL TESTS

3.1 Evaluation of cut propagation

For the first impedance technique evaluation, a 1020 steel beam (44.45 mm thick, 850 mm long, and 50.8 mm wide) was used as the experimental setup, clamped at one of its ends as shown in Fig. 2. The beam was subjected to nine successive cuts using an angle grinder, starting from a V-notch present in the beam near the clamped end, as shown in Fig. 3(a). The first and last cuts performed are presented in Fig. 3(b) and 3(c). The cuts were named D1 (first cut) to D9 (last cut).

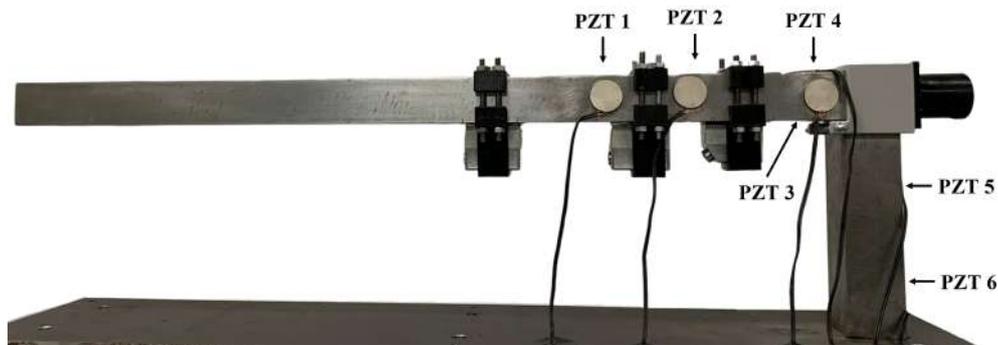
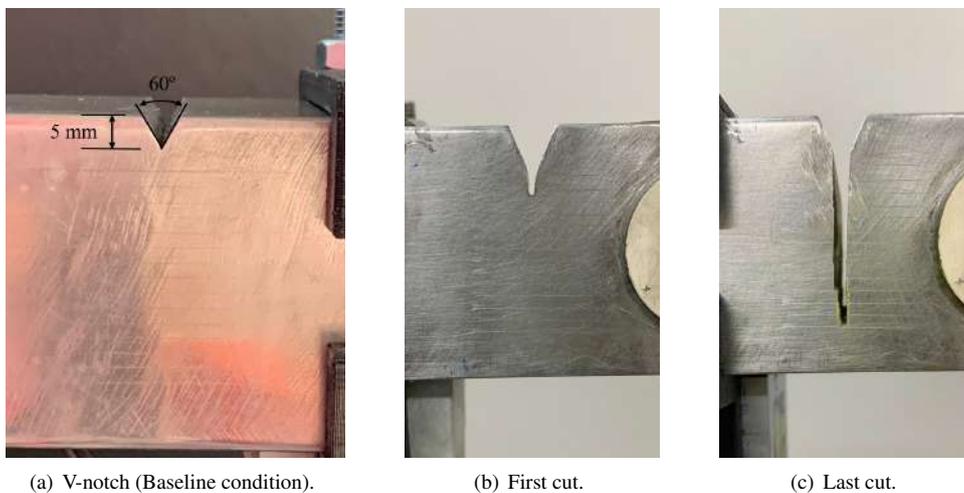


Figure 2. Structure analyzed for cut propagation.

Six piezoelectric transducers, measuring 30 mm in diameter and 2 mm in thickness, were attached along the structure of the beam. They numbered 1 to 6, as shown in Fig. 2. These PZTs were employed to assess the damage through impedance signature measurements. The signatures were acquired before each cut (baseline) and after each cut using the Agilent 4294A impedance analyzer, within the frequency range of 90 to 120 kHz, as depicted in Fig. 4.



(a) V-notch (Baseline condition).

(b) First cut.

(c) Last cut.

Figure 3. Initial condition and damaged.



Figure 4. Agilent 4294A impedance analyzer.

3.2 Evaluation of mass addition

The second experimental setup consisted of a steel cylindrical bar measuring 300 mm long and 200 mm in diameter. It was supported by two square steel bases and four corner brackets, as shown in Fig. 5. The bar was instrumented with three piezoelectric transducers at one of its ends, PZT 1, PZT 2, and PZT 3, as illustrated in Fig. 5(b). However, only PZT 1 and PZT 2, with a diameter of 50 mm and thickness of 2.6 mm, were analyzed in this study. For the proposed analysis, PZT 1 was directly bonded to the bar, while PZT 2 was attached to the structure using a 3 mm thick stainless steel base. This configuration aimed to evaluate the influence of the base on the fault detection sensitivity in the experimental setup. In this study, adding mass on the opposite side of the PZTs' positioning was considered a fault.

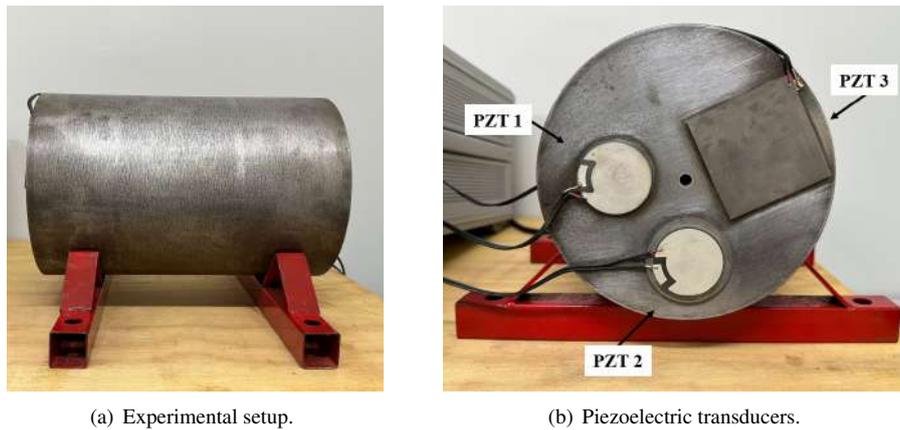


Figure 5. Analyzed steel bar.

The first added mass (D1) corresponds to four threaded bars mounted on the bar using nuts and washers weighing 369.5 g, as shown in Fig. 6(a). As the second damage (D2), the nuts were tightened, and a steel disk was added to the bar, resulting in a total mass of 4163.5 g, as depicted in Fig. 6(b).

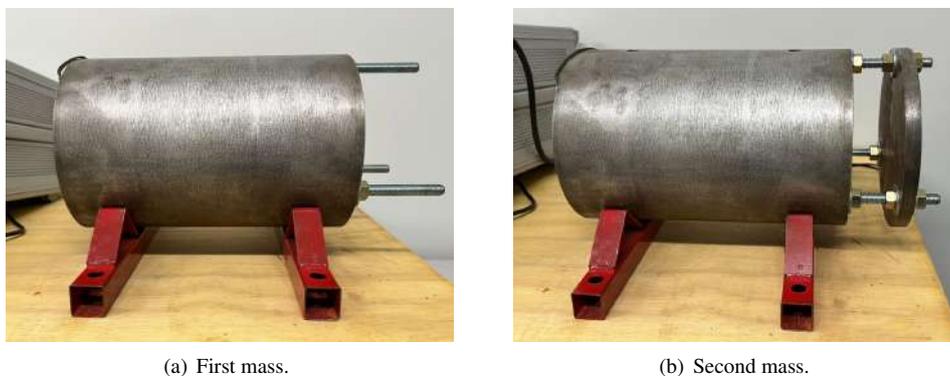


Figure 6. Masses added for failure simulation.

In this case, the impedance signatures were obtained using the SySHM impedance analyzer (Fig. 7), developed by researchers from LMEst. It is an innovative, low-cost, versatile technology with fast processing capabilities, operating in frequencies ranging from 0 to 400 kHz (Finzi *et al.*, 2010).



Figure 7. SySHM impedance analyzer.

4. RESULTS

4.1 Evaluation of cut propagation

For all the cuts made on the beam, impedance signatures were obtained and compared with baseline measurements. The CCD damage metric was used to quantify the variations in these signatures. The interpretation of the damage metric results indicates that the closer the value is to 100 %, the greater the deviation from the reference measurement. This suggests that the piezoelectric transducer located in that region exhibits higher sensitivity in detecting faults, demonstrating its capability to identify and respond to changes in structural integrity.

The impedance signatures and corresponding CCD metric values for all the analyzed piezoelectric transducers are shown in Figs. 8 to 13. It is evident from the impedance signatures presented in Figs. 8(a) to 13(a) that there were changes with increasing cut. The CCD damage metric highlights this change as its value increases with the growth of the cut.

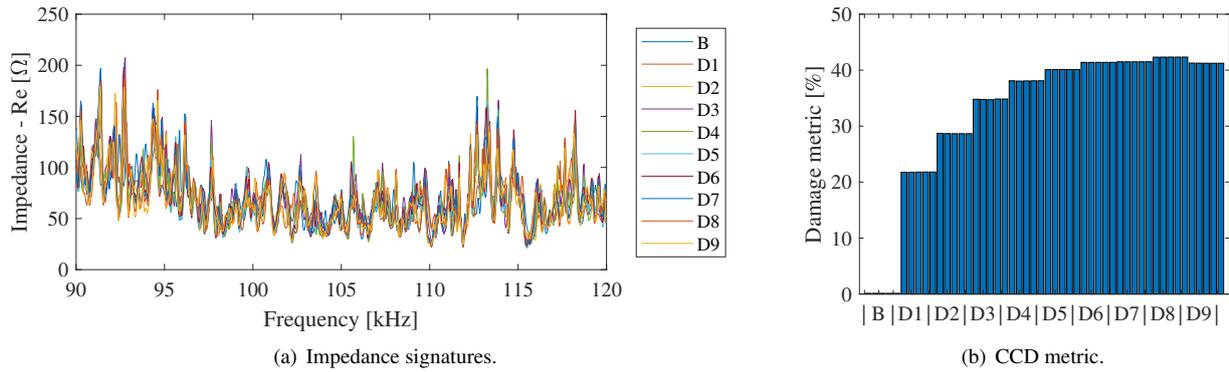


Figure 8. Piezoelectric transducer 1.

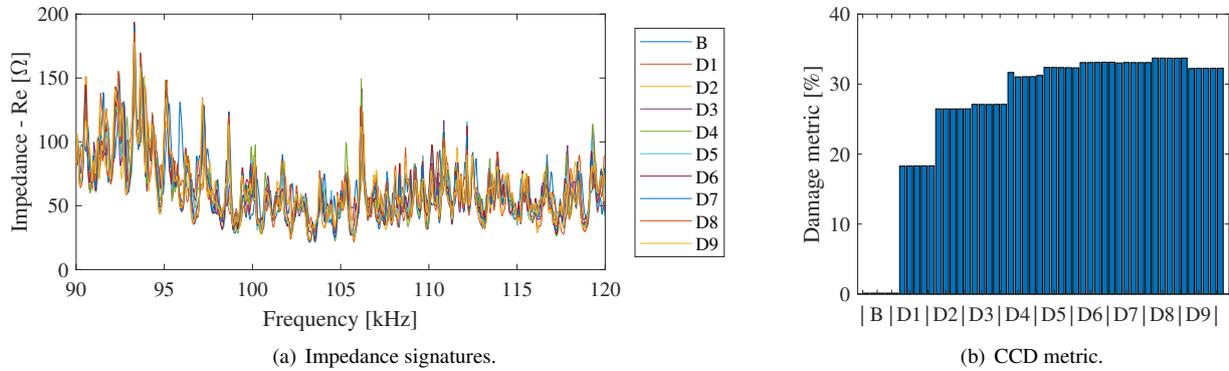


Figure 9. Piezoelectric transducer 2.

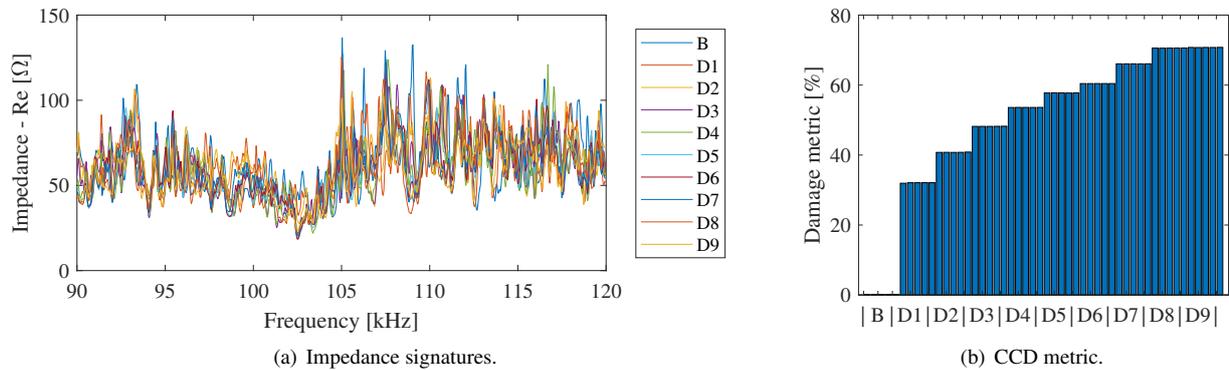


Figure 10. Piezoelectric transducer 3.

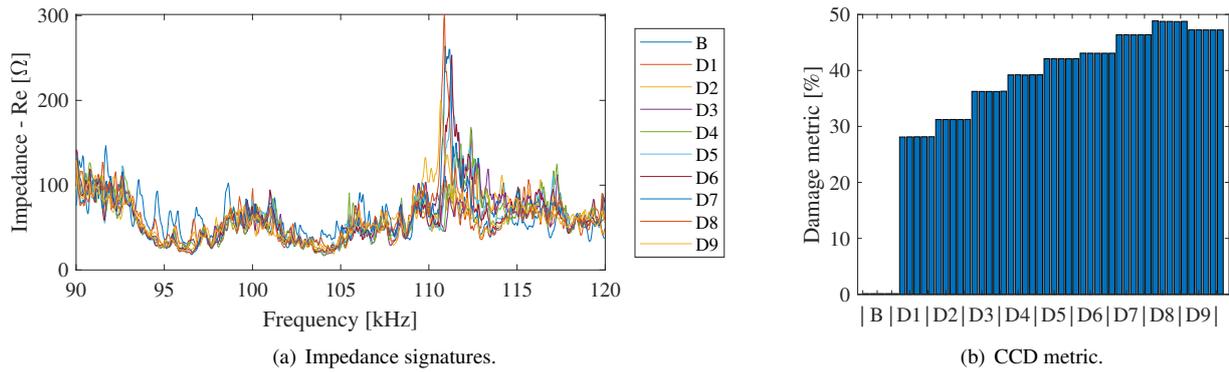


Figure 11. Piezoelectric transducer 4.

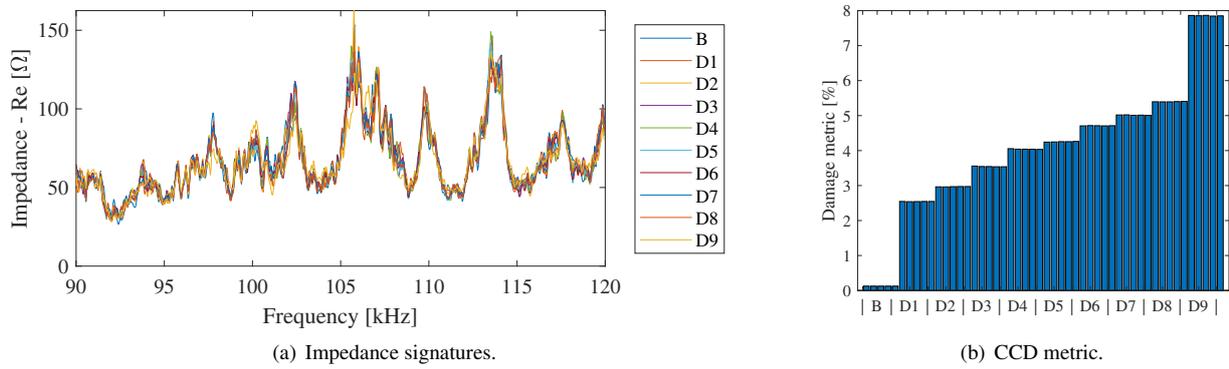


Figure 12. Piezoelectric transducer 5.

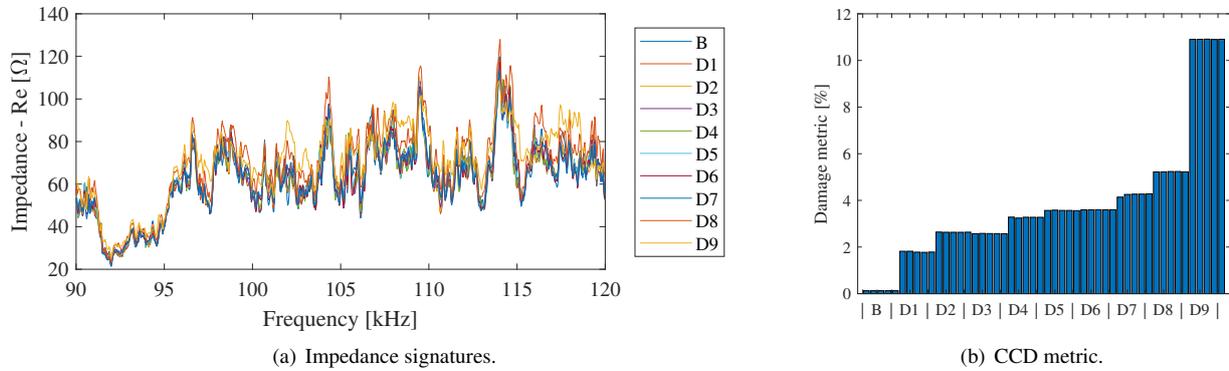


Figure 13. Piezoelectric transducer 6.

Upon examining all the obtained results, it can be noted that minor changes were observed in the piezoelectric transducers labeled as PZT 5 and PZT 6, with CCD values below 15 %. These transducers were positioned farther from where the cut was made. On the other hand, the transducer set closest to the cut (PZT 3) exhibited a more significant variation in the damage metric, with a variation of around 70 %. This demonstrates that the ISHM technique could detect the cut’s propagation in the structure and that the PZT positioned closest to the flaw had higher sensitivity in this detection.

4.2 Evaluation of mass addition

Similarly to the previous analyses, impedance signatures were also obtained for the bar. They were compared with baseline measurements, and the CCD damage metric was used to quantify the variation in the signatures. The impedance signatures obtained through PZT 1 and PZT 2, along with their respective CCD values, are shown in Figs. 14 and 15.

In this analysis, masses were added to the structure, and it can be observed that the impedance signatures also changed due to the non-destructive damage analyzed. Furthermore, it is observed that as the flaw increases, the CCD value also increases, indicating more significant differences compared to the reference measurement.

When evaluating the influence of the base on the sensitivity of flaw detection, it was found that PZT 2 exhibits more

minor alterations compared to the results obtained by PZT 1. However, even with the presence of the base, it was still possible to identify modifications in the impedance signatures.

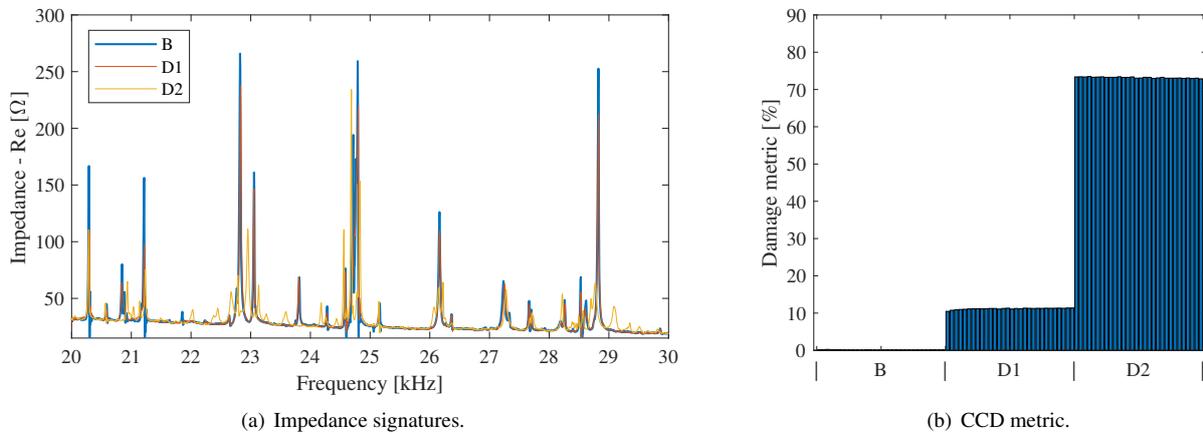


Figure 14. Piezoelectric transducer 1.

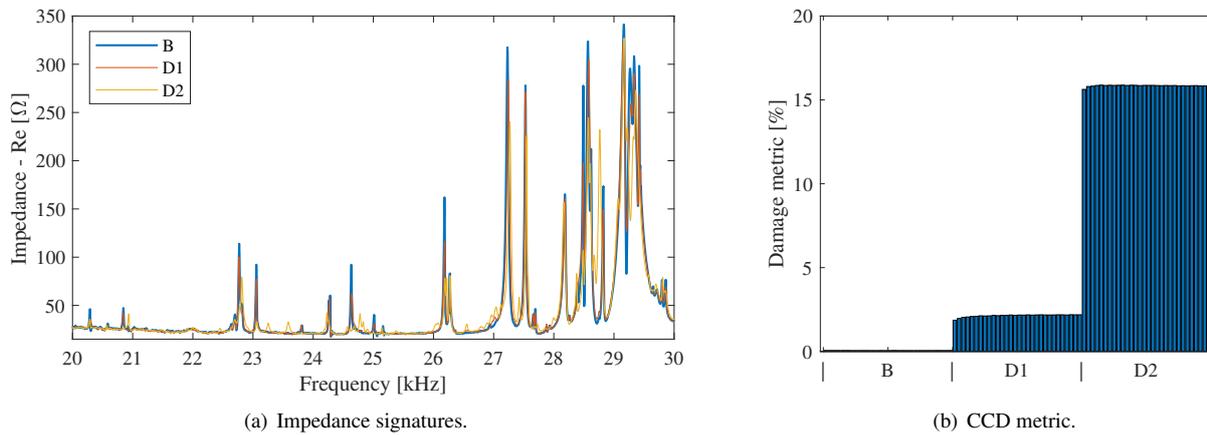


Figure 15. Piezoelectric transducer 2.

5. CONCLUSION

This study aimed to evaluate the effectiveness of the ISHM technique in monitoring thick structures, obtaining results that demonstrated the capability of this technique in detecting damage in the analyzed systems.

By using the steel beam, it was possible to identify the variation of impedance signatures for all the analyzed PZTs according to the cut increase. The CCD damage metric highlighted this variation, as its value increased with each analyzed damage. Additionally, it was found that the piezoelectric transducer closest to the flaw exhibited higher CCD values (approximately 70 %), demonstrating greater sensitivity in detecting the damage.

In the analyses conducted with the bar, it was also possible to observe the variation of impedance signatures in the two evaluated mass additions and an increase in the CCD damage metric value. Regarding the evaluation of PZTs with and without the steel base, it was noted that even with the base, it was possible to detect the variation in signatures, although with slightly lower sensitivity compared to the PZT directly attached to the bar.

These results indicate that the electromechanical impedance technique is a promising approach for structural integrity monitoring in thick structures, allowing for detecting and quantifying damage. However, it is essential to note that this is only an initial study, and further evaluation of other metrics and failure conditions is necessary to achieve advancements and increasingly reliable results in this research field.

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