Calibration of a low-cost electromechanical impedance-based structural health monitoring device

Calibração de um dispositivo de baixo custo para monitoramento da integridade estrutural baseada em impedância eletromecânica

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ABSTRACT
Steel structures undergo loads and stresses during service life, subject to structural damages such as fatigue, corrosion, cracks, and plastic deformations. Therefore, to detect damage, the dynamic responses of the structures are used, comparing two states: with and without damage. These dynamic responses are obtained from a signal representing the structure's electromechanical impedance. Thus, these impedance signatures must accurately represent the analyzed structure. By comparing the impedance signatures of the low-cost device used at UFG/UFCAT with the SySHM system developed by LMEst/UFU, it can be observed that the low-cost equipment requires calibration in its impedance measurements. This work proposes a method based on the Least-Squares approach to determine a mathematical model to convert the signals acquired by the low-cost device into signals suitable for analysis. In conclusion, it was feasible to demonstrate the utilization potential of the cost-effective device under impedance-based monitoring conditions.

Keywords: structural health monitoring, damage detection, low-cost device.

RESUMO
As estruturas de aço sofrem ação de cargas e tensões ao longo de sua vida útil, sujeitas a danos estruturais como fadiga, corrosão, trincas e deformações plásticas. Assim, para detectar danos, são utilizadas as respostas dinâmicas das estruturas, comparando dois estados: com e sem danos. Essas respostas dinâmicas são obtidas a partir de um sinal que representa a impedância eletromecânica da estrutura. Por esta razão, essas assinaturas de impedância devem representar com precisão a estrutura analisada. Ao comparar as assinaturas de impedância do dispositivo de baixo custo usado na UFG/UFCAT com o sistema SySHM desenvolvido pela LMEst/UFU, pode-se observar que o equipamento de baixo custo requer calibração em suas medições de impedância. Este trabalho propõe um método baseado na abordagem dos Mínimos Quadrados para determinar um modelo matemático para converter os sinais adquiridos pelo dispositivo de baixo custo em sinais adequados para análise. Em conclusão, foi viável demonstrar o potencial de utilização do dispositivo econômico em condições de monitoramento com base em impedância.

Palavras-chave: monitoramento de integridade estrutural, detecção de danos, dispositivos de baixo custo.

1 INTRODUCTION
To achieve maximum utilization of a particular structure and ensure its effective operation security, structural monitoring techniques are employed to prevent disruptions in its operations and enable continuous monitoring.
The main objective of structural analysis is to detect incipient damages to predict the system's lifespan. Thus, the damage is defined as an adverse alteration in the structure that affects its present or future performance (FINZI NETO and MOURA JR, 2022). These structural damages correspond to changes in system properties such as stiffness, mass, or damping.

These characteristics directly affect the dynamic response of the structure, and it is possible to identify the presence of such damages through continuous inspection of these properties.

The electromechanical impedance-based structural health monitoring (SHM) method compares the structure's frequency responses in two states: with and without damage. The property directly related to changes in mass, stiffness, and damping is mechanical impedance, which can be obtained through the electromechanical impedance of piezoelectric elements coupled to mechanical systems (FREITAS et al., 2021; GONÇALVES et al., 2021; PALOMINO, 2008; PALOMINO et al., 2011; PALOMINO et al., 2012; PARK et al., 2003; PARK and INMAN, 2005; REZENDE et al., 2023).

This non-destructive evaluation (NDT) technique based on obtaining and comparing variations in frequency response functions uses piezoelectric patches, and the signals related to electromechanical impedance are used to represent the characteristics relevant to the structural health state (SUN et al., 1995). These elements act as sensors, capturing the structure's frequency and actuators, exciting the structure.

The most commonly used materials are lead zirconate titanate (PZT), a piezoceramic, and polyvinylidene fluoride (PVDF), a piezopolymer (FINZI NETO and MOURA JR, 2022). Therefore, metrics for damage quantification are necessary based on two states of the structure: with damage and without damage. Using such techniques for damage quantification is necessary because the signals related to the structure with and without damage are subject to variations associated with the environment and not necessarily the damage itself.

The most commonly used damage metric in this process is the Root Mean Square Deviation (RMSD). Equation (1) represents this model,
\[ \text{RMSD} = \sum_{i=1}^{n} \sqrt{\left( \frac{\text{Re}(z_{1,i}) - \text{Re}(z_{2,i})}{\text{Re}(z_{1,i})} \right)^2} \]  

Where

\( \text{Re}(Z_{1,i}) \) is the real part of the electromechanical impedance signal of the structure under initial conditions for frequency \( i \), \( \text{Re}(Z_{2,i}) \) is the real part of the electromechanical impedance signal of the structure under a new condition (with damage), and \( n \) is the number of sampled points for a given frequency range \( i \) (FINZI NETO and MOURA JR, 2022).

The present contribution compares the impedance signatures of two systems and proposes a method for correcting the electromechanical impedance signal obtained by the low-cost acquisition board. An electromechanical impedance signal was collected from the SYSHM acquisition board developed by LMEst UFU to carry out this work (FINZI NETO and MOURA JR, 2022).

2 METHODOLOGY

The electromechanical impedance method consists of associating the electrical impedance obtained through the PZT patch with the mechanical impedance of the structure, which is affected by the damage. The PZT patch monitors changes in the structure's mass, stiffness, and damping, measuring local dynamic responses (FINZI NETO and MOURA JR, 2022; REZENDE et al., 2020).

When a voltage is applied to the terminals of the PZT patch, it behaves as an actuator, causing mechanical deformation. If there is mechanical deformation, it behaves as a sensor, capturing oscillations from the structure through electrical signals. Thus, if there is any damage (changes in the structure’s dynamic behavior), it will manifest in the electrical response of the PZT patch. The imaginary part is assumed to have capacitive characteristics of the PZT sensor, while the real part demonstrates aspects of the mechanical impedance of the structure (FINZI NETO and MOURA JR, 2022).
These signals are qualitatively analyzed from the samples collected by a signal acquisition board. By plotting the two sets of data corresponding to the signals with and without damage, deviations in the signal curves are analyzed, allowing the identification of the presence of damage. The previously presented damage metric (Equation 1) will be used to quantify this damage.

For the first signal collection, the EVAL AD5933EBZ board from Analog Devices was used (DEVICES, 2013). The board was calibrated with a mixed circuit containing a 1200 Ohm resistor, a 1 M Ohm resistor, and a lead zirconate titanate PZT patch, as shown in Figure 1.

![Figure 1: Low-cost board calibration circuit.](image)

Later, the second impedance signature was collected from the SySHM acquisition board developed by LMEst/UFU. They were plotted with both impedance signatures in hand, and it was observed that the signal obtained from the low-cost board exhibits the main characteristics of the signal obtained from the SySHM board. However, some regions have a certain delay and an increase in amplitude. Therefore, a model is needed to correct the impedance signature of the low-cost board.

The Least-Squares Method (LSM) was used to construct the signal correction model to obtain an equation for correcting the signal from the low-cost board. The LSM was implemented using MATLAB R software. Since the signal has many peaks due to the structure’s resonance at a given frequency, it was necessary to adjust the first-degree equation obtained from the LSM. This proposed adjustment involved increasing the degree of the equation through trial and error.
The residuals between the new signal obtained from the new equation and the impedance signature obtained by the SySHM board were plotted to better analyze the signals, and the coefficient of determination ($R^2$) was obtained. This coefficient varies between 0 and 1, indicating, as a percentage, how much the model can explain the observed values. The higher the $R^2$, the more explanatory the model is, and the better it fits the sample.

3 RESULTS AND DISCUSSIONS

Plotting the two impedance signatures obtained through the acquisition boards made it possible to confirm the need for utilizing the model to correct the signal of the low-cost board. Figure (2) presents the two signals corresponding to the test specimen used.

Figure 2 - Comparison between the signals of the two boards.

The figure (3) displays the SySHM device developed by LMEst/UFU for the acquisition of electromechanical impedance signals. It was employed in this study due to its prior validation for usage.
Figure 3 - Acquisition system developed by LMEst UFU.

Source: authors.

Figure (4) depicts the affordable board employed in the experiment, featuring an AD5933 integrated circuit, a highly precise impedance converter, and a frequency generator capable of reaching 16MHz. The analog-to-digital converter sampled the signal acquisition with a maximum acquisition limit of 511 points. The integrated circuit performs discrete Fourier transformation. The board operates within a voltage range of 2.7V to 5.5V (DEVICES, 2013; DIGILENT, 2016; WANDOWSKI et al., 2014).

Figure 4 – Low-cost acquisition system.

Source: authors.
The specimen used in the experiment was an aluminum beam measuring 400 x 25 x 3 mm, along with a piezoelectric patch with a diameter of 20 mm and a thickness of 2 mm, as shown in Figure (5). Two padded supports supported the specimen to simulate a bi-supported boundary condition and eliminate potential environmental disturbances on the structure’s dynamic characteristics, specifically changes in its impedance signature.

![Figure 5 – Aluminum beam employed as a test specimen.](source: authors)

After recognizing the requirement to utilize the model for correcting the impedance signature of the low-cost board, a program was developed to perform the Least Squares Method (LSM), resulting in equation (2). The polynomial’s degree (17/10) was selected based on empirical considerations.

\[
f(x) = 0.00061882804278x^{17/10} + 111.951248659822483
\]

Where

\[x\] will be the vector of the real part of the electromechanical impedance (low-cost card) to be transformed.

After this transformation, the signals were plotted for comparison. Figure (6) shows the new signal obtained using the model.
According to Figure (6), it is possible to notice a small residue generated by adjusting the low-cost device signals. This was expected but demonstrated the potential use of this device as an alternative to the SySHM device developed by LMEst/UFU, which is much more expensive.

Subsequently, the determination coefficient $R^2$ was obtained to assess the degree of quality of the fitting obtained through the proposed model. It yielded a value of 0.8490, thus indicating a good quality of fit.

4 CONCLUSIONS

The use of affordable systems can enable the application of electromechanical impedance techniques in the maintenance of critical everyday systems (warehouses, structural profiles, overhead cranes, bridges, etc.), where, due to cost constraints, a complex and expensive system would make monitoring unfeasible.

This study demonstrates the capability of a low-cost acquisition system, where, based on a model, the electromechanical impedance signal can be corrected, thus making it suitable for applying the structural integrity analysis method.

Through the proposed adjustment procedure, the intention is to conduct a series of additional evaluations on various types of structures to draw better conclusions.
regarding the actual capability of using the low-cost acquisition board under more adverse conditions.
REFERENCES


