



An enhanced approach for damage detection using the electromechanical impedance with temperature effects compensation

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Abstract

Damage detection is one of the great challenges of the maintenance tasks and it has involved numerous researches to develop techniques in the field of structural health monitoring (SHM). Among different techniques, electromechanical impedance (EMI) technique has attracted attention due to its important and promising results. However, the sensitivity of this technique to variations in environmental conditions can lead to false diagnoses, and the temperature is one of the most critical factors for EMI technique. In view of this point, different researchers have developed compensation techniques to minimize the effects caused by temperature variation in electromechanical impedance measurements. Another important issue related to electromechanical Impedance curves is about the frequency range chosen to be analyzed. Then, the present article introduces an improved approach for damage detection by adding a new step for the temperature compensation technique proposed in a well-established approach in the literature. The proposal comprises a strategy to select the frequency range to compute damage detection indexes, and the technique is demonstrated for an aluminum beam in three different structural conditions: corresponding to the healthy and two types of damaged structure. The results are investigated for four different frequency ranges. The findings demonstrate the effectiveness of the proposed approach to reduce false alarms in damage detection using the EMI technique.

Keywords Structural health monitoring · Electromechanical impedance · Temperature effects · Temperature compensation technique · Experimental data

1 Introduction

Structural Health Monitoring (SHM) is an engineering area focused on investigating the structural conditions to detect damage mainly in early stages. The idea is that part of those accidents caused by structural failure can be avoided [12, 37].

Electromechanical Impedance (EMI) is the basis of a technique used in SHM. It was first suggested by Liang et al. [20] and currently there are promising results known in the literature. The technique is typically characterized by the use of piezoelectric transducers, especially ceramics PZT (Leads Zirconate Titanate). They employ the piezoelectric effect, associated to the electromechanical coupling between structure and PZTs installed on it [9]. The transducer works as an actuator and sensor simultaneously, i.e., it excites the monitored structure and measures its response [36]. This approach basically consists of measuring EMI for the non-damage condition known as baseline signal. The data is

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compared with other EMI signals obtained for unknown structural conditions [27, 34, 39]. The damage is detected when differences are found in those comparisons.

Despite several studies demonstrating the feasibility of applying EMI technique, practical problems have prevented its efficient and reliable use in real structures, with temperature effects on the EMI cited as one of the most critical and challenging [4]. Electromechanical impedance signals are directly affected by changes in properties of structure and piezoelectric transducers [1]. Consequently, temperature acts as a key factor for the performance of an EMI-based SHM system, mainly because it can change both structure and PZTs materials properties. Therefore, several researchers have investigated different approaches to reduce the effects of temperature on electromechanical impedance curves through strategies known as compensation techniques. Sun et al. [33] use the cross-correlation between baseline and unknown electromechanical impedance signals to compensate the changes caused by temperature variations. Lim et al. [22] develop a data normalization technique using Kernel Principal Component Analysis (KPCA) to improve damage detectability under temperature variations. They performed experimental tests on a full-scale aircraft wing to validate their proposed technique. Park et al. [26] compensate the frequency and magnitude shifts in the EMI using a modified metric named as Root-Mean-Square Deviation (RMSD). In this sense, there are many other researchers who investigate different strategies to address this issue, such as Krishnamurthy et al. [19] who define a coefficient to characterize temperature effects in piezoelectric materials from an experimental approach. They successfully implement a temperature compensation technique, eliminating the temperature effects on the PZT sensors, without eliminating the temperature effects on the structure. Koo et al. [18] determine an effective frequency shift (EFS) to compensate the temperature effects by maximizing the cross-correlation coefficient between the baseline electromechanical impedance signal and the signals corresponding to the unknown structural condition. Grisso and Inman [15] generate a model predicting piezoelectric susceptance slope for different temperature, from which they can identify if the differences correspond to the temperature effects on piezoelectric transducers or damage in sensors (e.g., failure device or partially delaminated PZTs). Sepehry et al. [31] introduce a new method using artificial neural networks based on radial basis function (RBF) to compensate for the effect of temperature on the damage index of EMI curves. Baptista et al. [4] present an experimental study of the effect of temperature on the electrical impedance of piezoelectric sensors used in the EMI technique, as well as implement the EFS method to compensate for these effects.

Different approaches are focused on identifying patterns in the measured data, and thus, evaluate the baseline signal from

those influenced by external conditions, such as temperature variations [10, 29]. Huynh et al. [16] develop a radial basis function network (RBFN)-based algorithm to filter out temperature-induced variation in impedance signatures for damage monitoring. Huynh et al. [17] propose a principal component analysis (PCA)-based algorithm to filter out temperature effects on EMI monitoring. Du et al. [11] propose a multitask convolutional neural network (CNN) to accurately detect damage over a wide range of temperature variations with limited training data. The network consists of a temperature compensation subnetwork to compensate for the temperature effect, and a lightweight damage identification subnetwork to detect bolt loosening states. Perera et al. [29] develop an innovative approach that integrates the EMI methodology with multilevel hierarchical machine learning techniques and the use of fiber Bragg grating (FBG) temperature and strain sensors to monitor a problem in which effects due to mechanical damage and temperature variations are coupled to each other.

However, the use of a temperature compensation technique can negatively influence the damage detection because typically the techniques modify the EMI curves [18, 31]. This characteristic introduces an additional challenge for damage detection if the EMI is obtained for an unknown structural condition in a different temperature in comparison with the baseline curve.

In structural monitoring via EMI, the frequency range analyzed can directly affect the sensitivity of damage detection, since selecting an inappropriate frequency range can culminate in erroneous damage detection results [24, 30]. In view of this, different researchers are focused on identifying the optimal frequency range for detecting and assessing damage. This selection is usually achieved by trial and error methods or through analysis by engineers familiar with the technique [2]. However, some authors have created alternative approaches for selecting the optimal frequency range. Peairs et al. [28] propose a method to select the preferred frequency ranges based on the sensor characteristics, even before installing it on the structure. The results indicate that characteristics of the structure, not the sensor alone, determine the optimal monitoring frequency ranges. Annamdas and Rizzo [3] adopt a statistical index to measure and compare the sensitivities for various narrower ranges within the wide frequency range, in order to find the appropriate frequency range for damage detection. Baptista and Filho [6] use a modified equivalent electromechanical circuit to analyze the sensitivity of the PZT transducer in terms of the frequency and mechanical impedance of the host structure. It is stated that there are frequencies where the sensitivity of the transducer is optimal and other frequencies where the sensitivity is minimal. Min et al. [23] propose an innovative technique for autonomous selection of damage-sensitive frequency ranges for the EMI technique using artificial neural networks (ANNs). The approach determines the frequency range that can be used for effective evaluation of damage severity. Singh

and Malinowski [32] propose an innovative standard deviation approach for the selection of effective frequency ranges. The novice nature of frequency range selection is based on the difference between healthy and damaged state data.

In this context, the present article introduces a new strategy to select the frequency range used to compute damage detection index after employing the temperature compensation technique previously developed by Park et al. [26]. The idea is to reduce the temperature effects on the electromechanical impedance curves in more convenient frequency ranges to reduce false negatives, in terms of damage detection. Experimental data measured for an aluminum beam are considered for a temperature range from -10 to 80 °C to demonstrate the approach. Two types of damage were considered in the tests, i.e., a local mass addition and a local mechanical cut. The results show the effectiveness of the method to select the frequency ranges from undamaged and damaged signals previously measured in different frequency ranges. The main idea is a strategy to clip EMI measured in an environmental temperature assumed as a reference, and then, improve the damage detectability when applying the Park et al. [26] technique. The findings demonstrate that the use of this proposed approach allows one to detect the damage more accurately.

2 Methodology

2.1 Electromechanical impedance

Electromechanical Impedance technique commonly involves the use of one or more piezoelectric transducers (PZT) acting as sensor(s) and actuator(s), simultaneously. These devices provide the dynamic coupling between mechanical impedance of the structure and electrical impedance of the PZT, which allows one to monitor the structure [24]. This general idea is illustrated in Fig. 1.

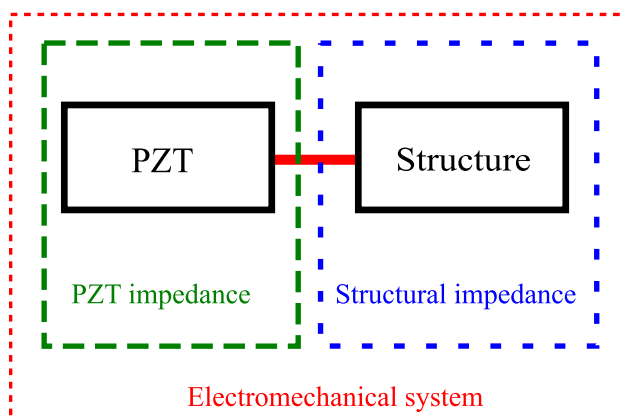


Fig. 1 Schematic representation of a generic system with electromechanical impedance due to a PZT coupled to a mechanical structure

Liang et al. [20] introduces the admittance $Y_{em}(\omega)$ shown in Eq. (1), and its inverse corresponds to the electromechanical impedance $Z_{em}(\omega)$. This equation shows how the structure impedance $Z(\omega)$ and the impedance of a piezoelectric transducer, $Z_A(\omega)$, relate to each other to define the electromechanical impedance.

$$Y_{em}(\omega) = j\omega \frac{b_a L_a}{h_a} \left[\bar{\epsilon}_{33}^T - \frac{Z(\omega)}{Z_A(\omega) + Z(\omega)} d_{31} \bar{Y}_{11}^E \right] \quad (1)$$

where L_a , b_a and h_a are the length, width and thickness of the PZT, respectively. $\bar{\epsilon}_{33}^T$ is the dielectric constant of the PZT in the 3-3 direction (z) under a constant voltage, d_{31} is the piezoelectric constant, $\bar{Y}_{11}^E$ is the complex elastic modulus of the PZT in the 1-1 direction (x) under a constant electric field; and $j = \sqrt{-1}$ is the pure imaginary number [21].

2.2 Temperature compensation techniques: an overview

Based on the literature, environmental temperature changes the EMI curves by introducing cause shifts in frequency (horizontal) and magnitude (vertical), as well as peak smoothing, which can lead to false positives or negatives in terms of damage detection [1, 22, 38]. Then, several researchers have investigated different ways to neutralize the temperature effects on EMI curves through strategies known in the literature as temperature compensation techniques. Among the techniques, stands out those developed by Park et al. [26], Koo et al. [18], Baptista et al. [4] and Grisso and Inman [15] due to their promising result. Although Park et al. [26] technique is a promising approach to compensate the influence of the temperature on the EMI, it is sensitive to the frequency range used to compute damage detection indexes. Then, it can fail depending on the range considered, and generate false alarms in terms of damage, as shown in the following section of this article.

2.2.1 Park et al. [26] compensation technique

Park et al. [26] present a technique based on an empirical approach to minimize the temperature effects on electromechanical impedance-based SHM method. The procedure to apply the compensation is based on V_a minimization. V_a represents the sum of the real electromechanical impedance changes squared and it is defined by Eq. (2). In this technique, k varies, taking advantage that the variation in electromechanical impedance is dominated by horizontal shift of impedance peak.

$$V_a = \sum_{i,k=1}^N [Re(Z_R(\omega_i)) - Re(Z_D(\omega_k))]^2 \quad (2)$$

where N is the number of frequency points, $Re(Z_R(\omega_i))$ is the real part of the reference electromechanical impedance (Z_R) at i -th frequency and $Re(Z_D(\omega_k))$ is the real part of the unknown electromechanical impedance (Z_D) at k -th frequency (lagged with respect to i), which is computed according to Eq. (3). The unknown electromechanical impedance $Z_D(\omega_k)$ can be generated from the unknown measured electromechanical impedance using the following relation:

$$Re(Z_D(\omega_k)) = Re(Z_D(\omega_k)_{measured}) + \delta^S \quad (3)$$

where δ^S is defined as the average difference between reference impedance curve and measured impedance. The $Re(Z_D(\omega_k))$ impedance is vertically compensated (shifted close to the reference curve) compared to the $Re(Z_D(\omega_k)_{measured})$ impedance due to the δ^S sum. The values of (k, i) and δ^S can be found by numerical iteration by shifting the electromechanical impedance curves to the right-hand side when considering temperatures above the reference temperature, or to the left side, for temperatures below the reference temperature, until the minimum value of V_a is achieved. For a better understanding of this procedure, the behavior of the electromechanical impedance curves during the application of the Park et al. [26] technique is presented in Appendix 1. However, if the frequency range increases, this technique becomes less effective to compensate the temperature effects and it can fail to detect the damage depending on the temperature for the unknown structural condition when it is different from the reference temperature. This characteristic is demonstrated herein. Then, this article introduces a new approach to overcome this practical limitation.

In their article, Park et al. [26] analyze the real part of the electromechanical impedance and because it is more sensitive to the changes in physical and/or geometric characteristics in the mechanical systems [5, 7, 18].

2.2.2 The proposed approach

This article aims to improve the Park et al. [26] technique by introducing a strategy to remove parts of the EMI curves obtained in a temperature T_d which present important discrepancies in the EMI real part when comparing with the reference signal measured in a temperature T_r . These differences of shape are illustrated in the schematic drawing shown in Fig. 2, in which two rectangles are used to highlight the frequency ranges with higher differences.

The approach considers parts of the clipped EMI curve measured in a different temperature T_d from the reference temperature T_r , in which the EMI baseline signal is previously measured, and employs the undamaged signal for its execution. Then, the following procedure is computationally implemented and performed:

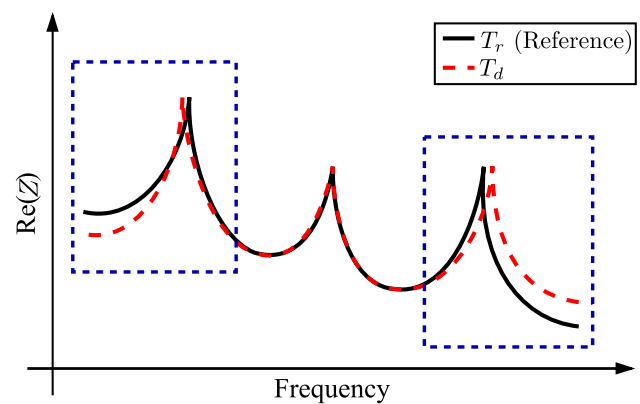


Fig. 2 Representation of typical discrepancies between the compensated (Z_d) and reference (Z_r) EMI curves

- **Step 1** Consider the frequency ranges and temperatures to be used for the application of this new approach. It is recommended to consider the entire measured frequency range in which the EMI is measured instead of a smaller frequency range.
- **Step 2** Identify the curve peaks in the reference signal to remove the influence due to environmental temperature when performing the measurements. The procedure is done by applying the *prominence* parameter. The function takes the signal and finds all local maxima by simple comparison of neighboring values. The prominence of a peak measures how much a peak stands out from the surrounding signal and is defined as the vertical distance between the peak and its lowest contour line. In practice, the analyst needs to observe the original curve and defines a minimum value to establish this contour line. This procedure is employed to avoid detecting small peaks associated to the noise influence on the measured signal. A greater prominence corresponds to a higher EMI peak.
- **Step 3** Remove the corresponding frequency ranges which contain the peaks to eliminate their influence on the EMI curves. Figure 3(a) illustrates the real part of a generic EMI signal and Fig. 3(b) shows it after removing the frequency ranges associated with the peaks. Note that there are limiting frequencies f_{lim_i} , $i = 1, 2, \dots, 2N_{pk} + 2$ for a given number of peaks N_{pk} . The new clipped frequency range f_{cp} considered to evaluate the EMI curve in the proposed damage detection process is defined by:

$$f_{cp} = [f_{lim_a}, f_{lim_b}], \begin{cases} a = 1, 3, \dots, N_{pk} + 1 \\ b = 2, 4, \dots, N_{pk} + 2 \end{cases} \quad (4)$$

N_r points to the right and left-hand sides of each peak are taken from the original frequency f_{or} , obtaining the clipped frequency f_{cp} , and the corresponding number of points are given by:

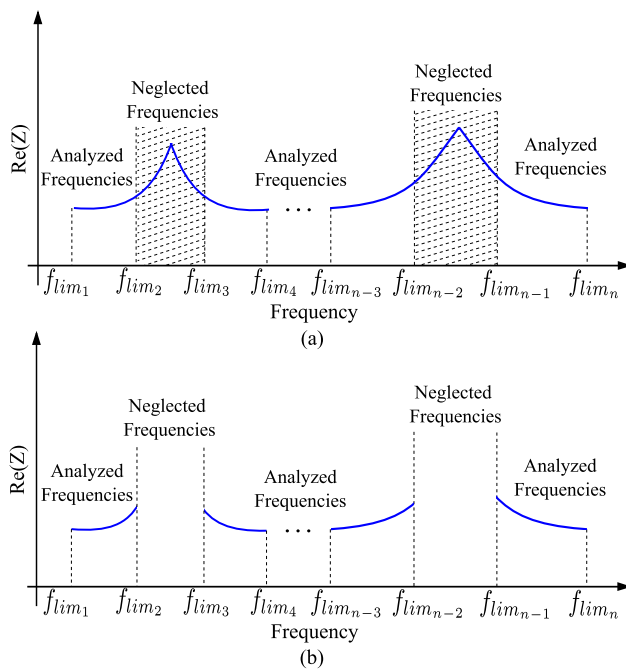


Fig. 3 Signal (a) before and (b) after removing the frequencies associated with the peaks, where $n = 2N_{pk} + 2$

$$N_{cp} = N_{or} - 2N_r \times N_{pk} \quad (5)$$

N_r is obtained by selecting the smallest number of points for which the introduced parameter S assumes its approximately stable value, which usually corresponds to a numerical variation small than 0.001. S is defined by the division between the amplitude of the real part of the clipped signal $\Delta_{Z_{cp}}$ and the amplitude of the real part of the original signal $\Delta_{Z_{or}}$, as shown in Eq. (6). The values of S are computed for different N_r until it assumes its stable value. Figure 4 shows the behavior of S when varying the number of points removed from the curve and highlights the chosen N_r number of points by the biggest red circle.

$$S = \frac{\Delta_{Re(Z_{cp})}}{\Delta_{Re(Z_{or})}} \quad (6)$$

where

$$\Delta_{Z_{()}} = \max(Z_{()}) - \min(Z_{()}) \quad (7)$$

- **Step 4** find the differences in the means (absolute value) of the signals compared to the reference curve. The frequency f_{cp} is divided into n_f frequency intervals or sub-bands, which are employed to analyze the absolute difference between the mean value of the reference signal and the mean value of the unknown signal in that sub-band. These frequency intervals, f_{sub} , is defined as:

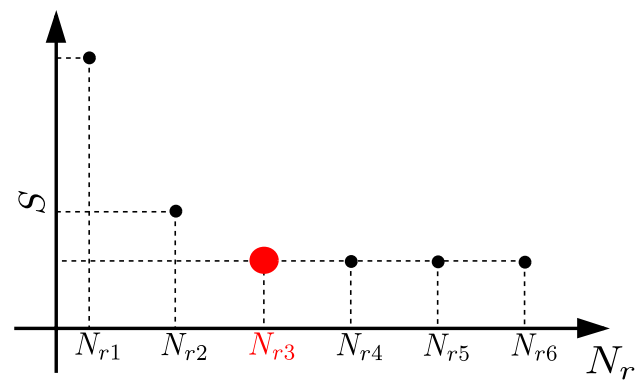


Fig. 4 S -parameter curve as a function of N_r and the number of points chosen in red (N_{r3})

$$f_{sub} = [f_{cp1+a \cdot N_{dif}}, f_{cpN_{dif}+a \cdot N_{dif}}], \quad (8)$$

$$a = 0, 1, 2, \dots, n_f$$

In the present article are used $n_f = 21$ intervals. Note that the standard deviation (Eq. 9) can be computed by considering N_{dif} . However, if $n_f \leq 20$, the common statistical approach suggests using $(N_{dif} - 1)$ instead. In practice, several computational tests indicate that $n_f > 20$ provides accurate results for this proposed approach. Then, Eq. (9) is employed to calculate the standard deviation of the mean differences vector, **Dif**, where $\overline{Dif}$ is its average value.

$$\sigma_{Dif} = \sqrt{\frac{\sum_{i=1}^{21} (\mathbf{Dif}_i - \overline{Dif})^2}{N_{dif}}} \quad (9)$$

where

$$N_{dif} = \text{int}\left(\frac{N_{cp}}{n_f - 1}\right) \quad (10)$$

The width of the sub-bands is determined and a temperature of the electromechanical impedance signal is selected to perform the difference analysis. Then, the vector **Dif** of the mean differences (absolute value) is computed for each sub-band as shown in Eq. (11), where $\bar{Z}_R$ and $\bar{Z}_D$ are the average values of the two electromechanical impedance signatures $Z_R(\omega)$ and $Z_D(\omega)$, respectively.

$$\mathbf{Dif} = \left\{ \begin{array}{l} |\bar{Z}_{R_1} - \bar{Z}_{D_1}| \quad |\bar{Z}_{R_2} - \bar{Z}_{D_2}| \quad \dots \\ |\bar{Z}_{R_{n_f}} - \bar{Z}_{D_{n_f}}| \end{array} \right\} \quad (11)$$

where

$$\bar{Z}_{(y)} = \frac{\sum_{i=f_{subx}} Z_{(y)}(\omega_i)}{N_{dif}}, x, y = 1, 2, \dots, n_f - 1 \quad (12)$$

$$\bar{Z}_{(n_f)} = \frac{\sum_{i=f_{subn_f}} Z_{(n_f)}(\omega_i)}{N_{cp} - (n_f - 1)N_{dif}} \quad (13)$$

in which Eq. (13) uses the remaining points of the clipped signal to determine the average electromechanical impedance, which are calculated as: $N_{cp} - (n_f - 1)N_{dif}$.

The proposed procedure requires to define whether the chosen temperature is higher or lower than the reference temperature, since the curves of the vector of differences presented relatively different behaviors as a function of this condition. In the case of temperatures below the reference temperature, the selected frequency range is determined by selecting the largest frequency interval whose **Dif** is less than σ_{Dif} . On the other hand, for temperatures above the reference temperature, the selected frequency range is determined by selecting the largest frequency interval whose **Dif** is less than its average, $\overline{Dif}$. This process is repeated for all temperatures chosen in Step 1. Lastly, the intersection of all the selected ranges obtained for each temperature is determined, thus obtaining the final selected frequency range. The step-by-step of this stage is introduced in the flowchart shown in Fig. 5.

Figure 6 contains the curves of the mean differences obtained for an arbitrary signal at a different temperature

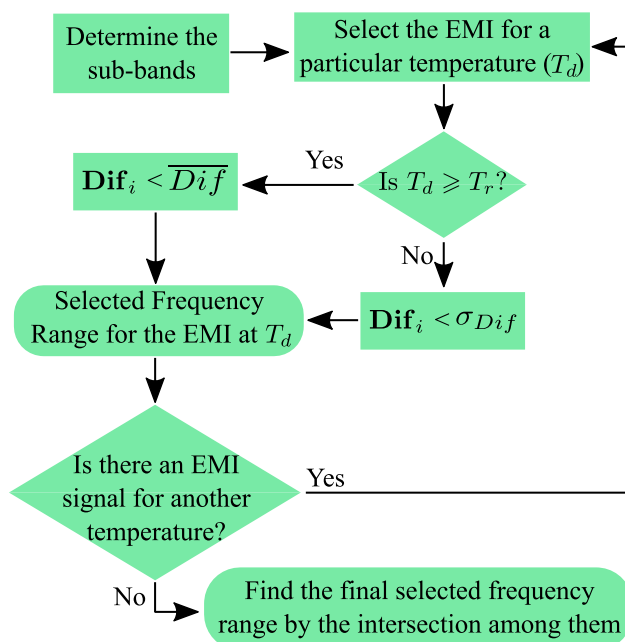


Fig. 5 Flowchart showing the step-by-step of stage 4

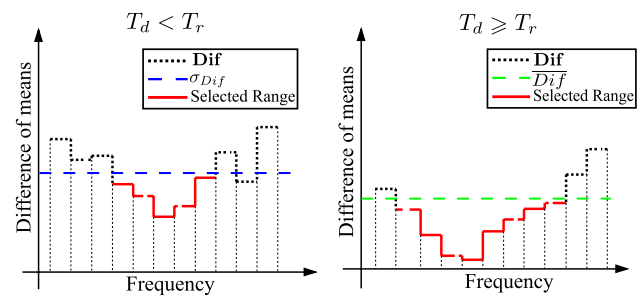


Fig. 6 Mean differences curves of an illustrative and arbitrary signal. Blue-dashed line corresponds to the standard deviation of this vector and red solid line represents the selected range limits

T_d above and below the reference temperature. The red thick line indicates the selected frequency range, since it corresponds to the largest part whose **Dif** is less than σ_{Dif} , for $T_d < T_r$, or $\overline{Dif}$, for $T_d \geq T_r$. Note that there are some blank spaces, which correspond to the location of the removed peaks.

2.3 Quantitative analysis

Quantitative damage characterization is commonly performed using metric indexes [13, 35]. The Mean Square Deviation (RMSD) and Correlation Coefficient Deviation Metric (CCDM) are considered in this present article due to their simplicity and good results [8, 14]. These damage metrics compare two electromechanical impedance signals. One of them is obtained for the undamaged structure (reference value) and the other one corresponds to the unknown structural condition. The RMSD index is more sensitive to changes in the magnitude of EMI curves, whereas the CCDM index is more affected by frequency shifts [4].

The RMSD index is computed as presented in Eq. (14). The higher RMSD value, the more likely the structure is damaged [4, 18, 26].

$$RMSD = \sum_{i=1}^N \sqrt{\frac{[Z_D(\omega_i) - Z_R(\omega_i)]^2}{[Z_R(\omega_i)]^2}} \quad (14)$$

The CCDM index is presented in Eq. (15). This index is defined as the subtraction between 1 and the cross-correlation coefficient C_C , given by [4, 18]

$$CCDM = 1 - C_C \quad (15)$$

$$C_C = \frac{\sum_{i=1}^N [Z_R(\omega_i) - \bar{Z}_R][Z_D(\omega_i) - \bar{Z}_D]}{\sqrt{\sum_{i=1}^N [Z_R(\omega_i) - \bar{Z}_R]^2} \sqrt{\sum_{i=1}^N [Z_D(\omega_i) - \bar{Z}_D]^2}} \quad (16)$$

The lower C_C value, the greater the difference between the EMI curves, implying a higher severity of damage.

3 Results and discussion

This section presents a description of the experimental tests performed to collect the electromechanical impedance signals, the selected data and the results obtained after applying the Park et al. [26] technique and this proposed new approach.

The experimental tests consisted of collecting electromechanical impedance signals from an aluminum beam with a PSI-5H4E piezoelectric transducer from Piezo Systems®. Figure 7 shows a schematic illustration of the experimental setup. A National Instruments® board model NI-USB 6211 (16 bits) has been used. In addition, the impedance analyzer software developed by Baptista and Filho [5], in a LabVIEW® environment and a protoboard with a small resistor with electrical resistance of 10 k Ω have been considered to establish the auxiliary electric circuit and, then, the data acquisition system.

The aluminum beam was considered in free-free boundary condition and it was inserted into a Thermotron® thermal chamber S-Series to simulate different environmental temperatures. Geometric characteristics for both beam and piezoelectric transducer are presented in Table 1.

The EMI signals were measured for different temperatures in a range from -10 to 80 °C, which corresponds to a representative range of operation for different types of structures. An incremental step of 2 and 5 °C was considered for the non-damaged and damaged condition, respectively. A sinusoidal frequency sweep with an amplitude of ± 5 V in a frequency range of 0–125 kHz was used to excite the structure through the PZT. Two types of damage were considered (both

20 cm from the PZT). The first one is the addition of a 4.89 g durepoxy mass (damage 1) and the second one is a 4 mm introduced mechanical cut (damage 2), as shown in Fig. 8.

The seven selected temperatures for the undamaged and damaged signals are shown in Table 2, and the reference signature (at 24 °C) is highlighted by a red rectangle. Note that different temperatures are considered to demonstrate the proposed approach, and four different frequency ranges are evaluated, as shown in Table 3, where f_{min} and f_{max} are the minimum and maximum frequencies for each frequency range.

Figures 9, 10 and 11 show the curves of the real part of the electromechanical impedance of the signals with and without damage (i.e., damaged and undamaged structure) at those selected temperatures on the frequency range number 4, i.e., with 45 kHz of bandwidth. The real part of the EMI is considered to employ this approach because it is more sensitive to the temperature effect, in comparison with the total electromechanical impedance signal [25]. The reference EMI curve is also shown to allow one the comparison among the curves, which is due to the temperature, and the differences can be easily identified by a visual inspection.

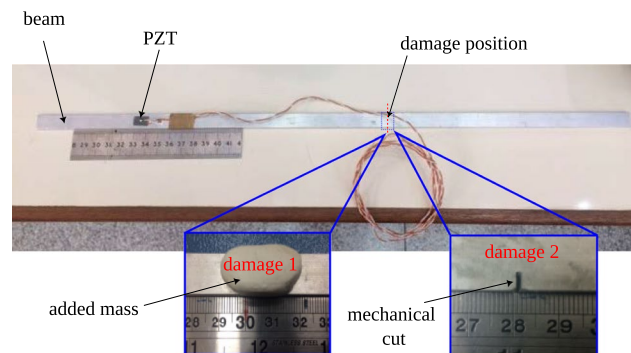


Fig. 8 Beam-like structure with a PZT transducer and both types of damages (damage 1 and damage 2) considered in this work

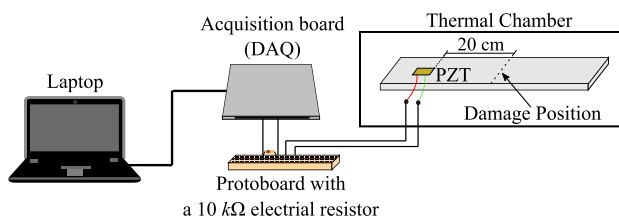


Fig. 7 Experimental setup employed to measure the EMI signals

Table 1 Geometric characteristics of the beam and the PZT

Properties	Beam	PZT
Length (mm)	500	10
Width (mm)	13	5
Thickness (mm)	3	0.7

Table 2 Selected temperatures for the undamaged and damaged signals, with the reference signature (24 °C) highlighted by a red rectangle

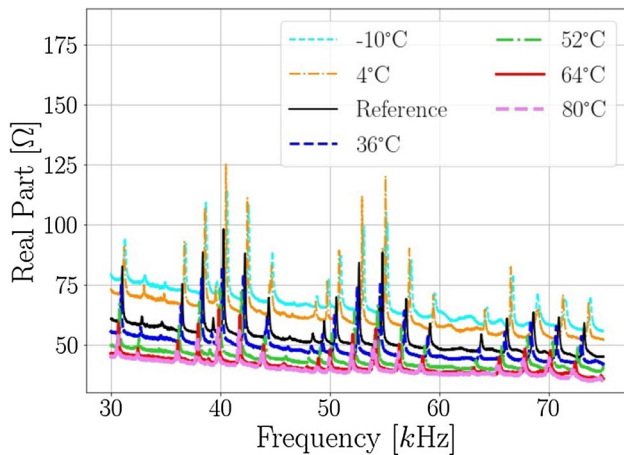
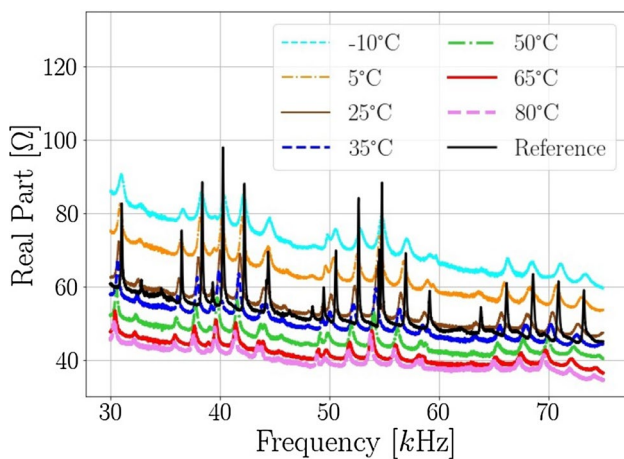
Temperature	Undamaged	Damage 1	Damage 2
1	-10 °C	-10 °C	-10 °C
2	4 °C	5 °C	5 °C
3	24 °C	25 °C	25 °C
4	36 °C	35 °C	35 °C
5	52 °C	50 °C	50 °C
6	64 °C	65 °C	65 °C
7	80 °C	80 °C	80 °C

Data presented as number (%)

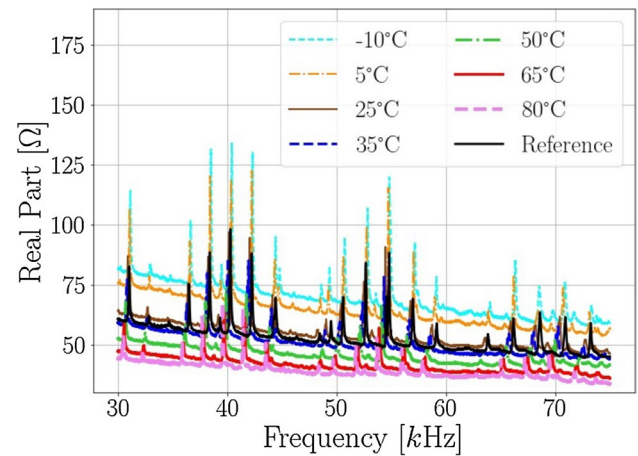
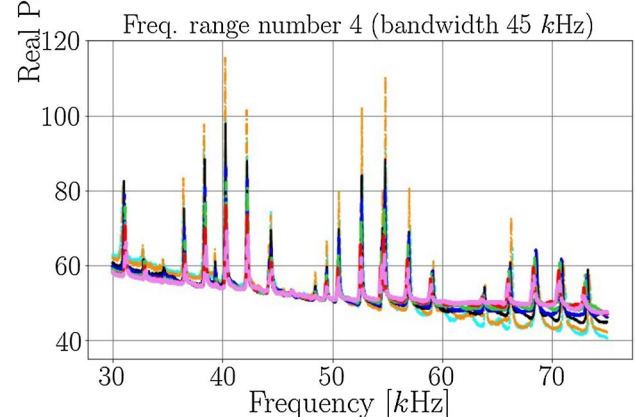
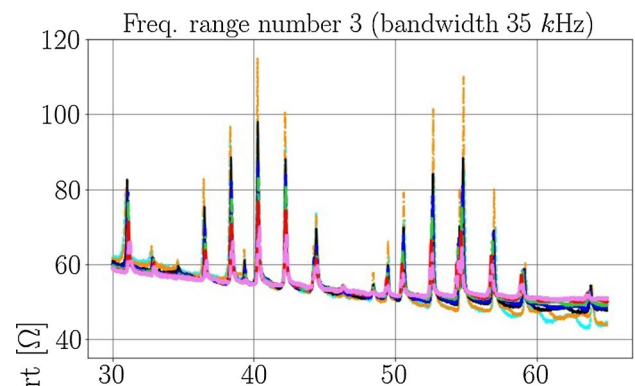
n Number, (*f*) Fisher's exact test

Table 3 Different frequency ranges (FR) investigated in this article

Number	f_{min} (kHz)	f_{max} (kHz)	Bandwidth (kHz)
1	30	45	15
2	30	60	30
3	30	65	35
4	30	75	45

**Fig. 9** Real part of the electromechanical impedance (undamaged condition) at different temperatures**Fig. 10** Real part of the electromechanical impedance (damage 1) at different temperatures

Figures 12, 13 and 14 show the EMI signal after applying the approach proposed by Park et al. [26]. These results respectively present the signals for the undamaged condition, with damage 1 (added mass) and damage 2 (mechanical cut) for two different frequency ranges, corresponding

**Fig. 11** Real part of the electromechanical impedance (damage 2) at different temperatures**Fig. 12** Real part of the electromechanical impedance (undamaged condition) using Park et al. [26] compensation technique for two frequency bandwidths: 35 and 45 kHz. Curves for the temperatures -10°C , 4°C , 24°C (reference), 36°C , 52°C , 64°C and 80°C

to the bandwidths 3 and 4, i.e., 35 and 45 kHz bandwidths (see Table 3). The results for those other bandwidths are presented in Appendix 2. The results shown in Figs. 12, 13 and 14 reveal differences among the curves, mainly when

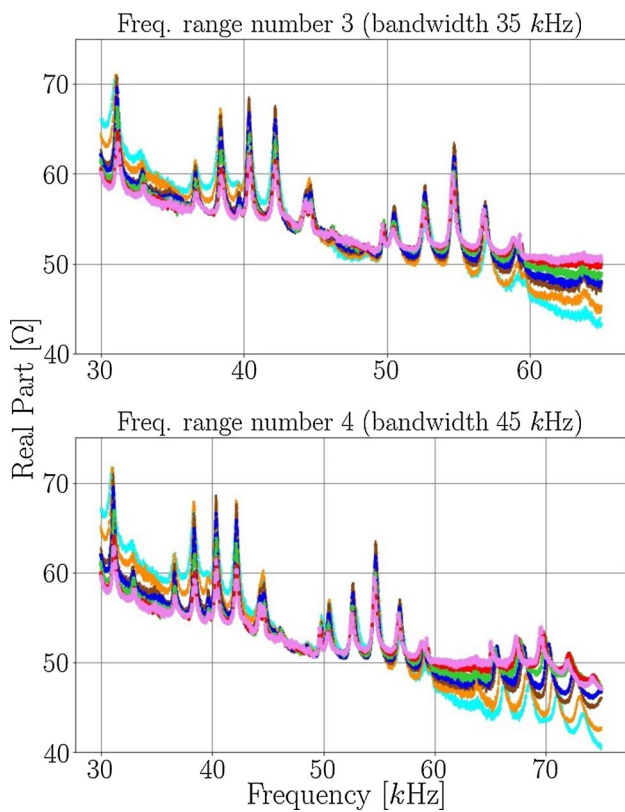


Fig. 13 Real part of the electromechanical impedance (damage 1) using Park et al. [26] compensation technique for two frequency bandwidths: 35 and 45 kHz. Curves for the temperatures -10°C , 5°C , 25°C , 35°C , 50°C , 65°C and 80°C

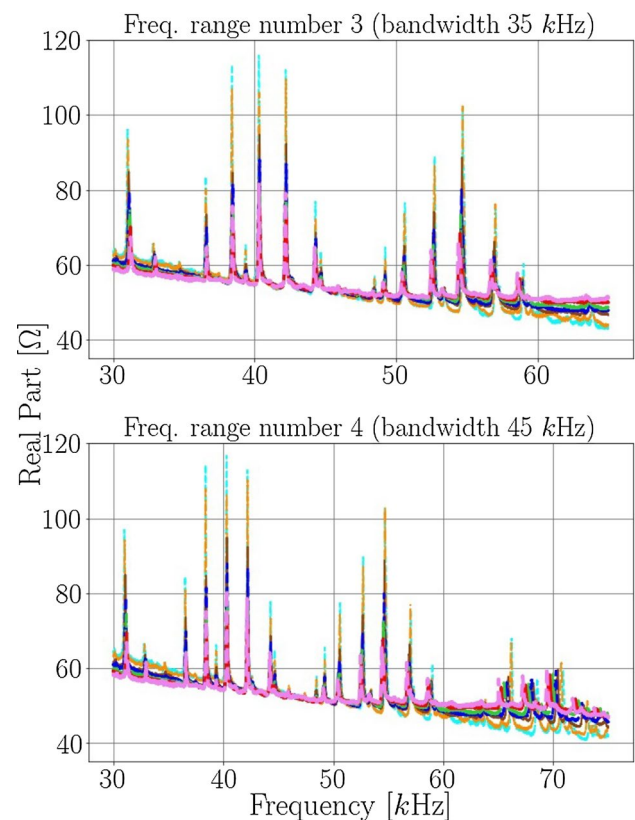


Fig. 14 Real part of the electromechanical impedance (damage 2) using Park et al. [26] compensation technique for two frequency bandwidths: 35 and 45 kHz. Curves for the temperatures -10°C , 5°C , 25°C , 35°C , 50°C , 65°C and 80°C

comparing their peaks and the values in higher frequencies for the three different signal types (undamaged, damage 1 and 2) as the frequency bandwidth increases and details are shown in Fig. 15.

The behavior described above is verified because the offset of the peak values at high frequencies are greater than those ones verified at low frequencies. Consequently, a better result in the horizontal axis of the curves (i.e., in the frequency) occurs for peaks whose frequency shifts have values close to each other. On the other hand, the effectiveness of the approach to compensate the temperature effect in the vertical axis (i.e., in the magnitude) also decreases when increasing the frequency range investigated (i.e., the bandwidth), mainly due to add a constant value δ^S for the entire analyzed frequency range. This characteristic is confirmed by investigating the curves for the three structural conditions: undamaged (healthy) and damage 1 and 2.

The results of a quantitative analysis of this proposed technique are presented in Figs. 16 and 17. They show the differences between the RMSD (in Fig. 16) and CCDDM (in Fig. 17) values computed for both damaged and undamaged conditions when applying the Park et al. [26] technique and using the EMI curve measured at two different temperatures.

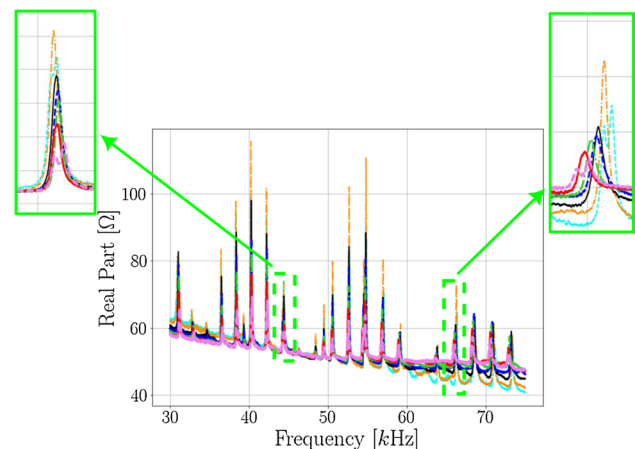


Fig. 15 A zoomed view for two frequency ranges of the undamaged EMI curve shown in Fig. 12 (lower)

The results are computed for both types of damage and considering the frequency ranges numbers 3 and 4 (see Table 3). Note that the damage is detected for each particular temperature if these indexes of differences are positive values.

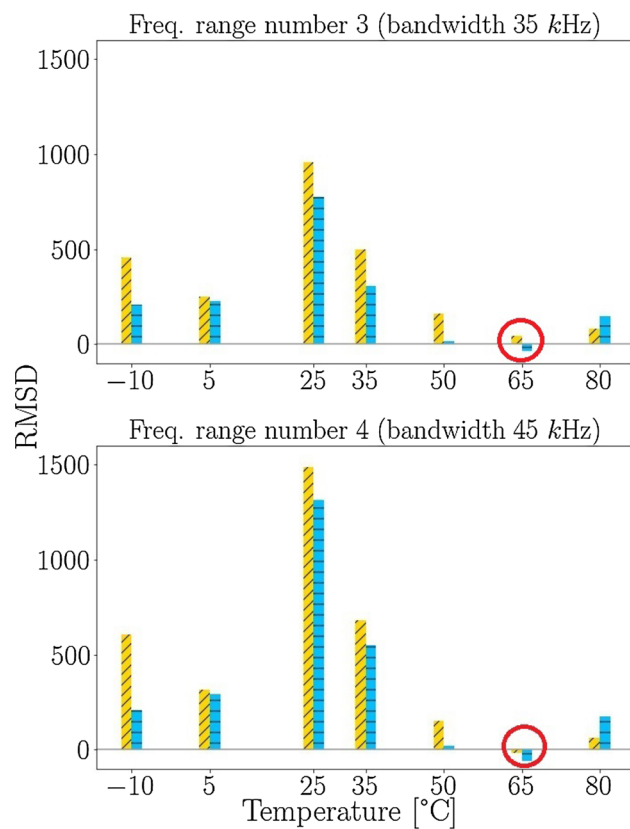


Fig. 16 Difference between the RMSD values computed for the signals in the damaged and undamaged conditions compensated by Park et al. [26] technique for the FR numbers 3 and 4. Yellow slanted bar hatch depicts damage 1, blue bar with horizontal hatch represents damage 2 and red circle indicate the false negatives

On the other hand, if the index is equal to zero, there is no damage, and there is false negative if the index is a negative value, i.e., it does not detect the damage due to the influence of the temperature. The results for the frequency ranges number 1 and 2, which correspond to the bandwidths 15 and 30 kHz, are presented in Appendix 2.

The results for both indexes (RMSD and CCDM) reveal that the Park et al. [26] technique allows one to detect both types of damage in different temperatures. However, in particular at the temperature of 65 °C the RMSD-based index (Fig. 16) fails to detect both damage types using the frequency range number 4. It also fails to detect damage type 2 using the frequency range number 3. In addition, the approach fails when using the CCDM-based index corresponding to the temperature -10 °C for the frequency range with bandwidth 45 kHz (damage 2, Fig. 17). These cases with false negatives in terms of damage detection and their corresponding temperatures are highlighted by red circles in both Figs. 16 and 17. These results demonstrate that the frequency range considered to compute damage detection

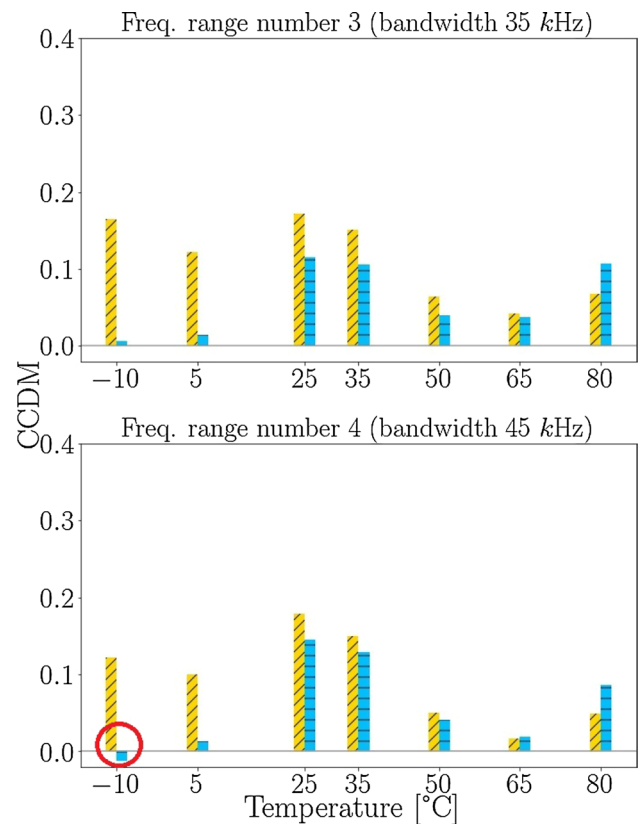


Fig. 17 Difference between the CCDM values computed for the signals in the damaged and undamaged conditions compensated by Park et al. [26] technique for the FR numbers 3 and 4. Yellow slanted bar hatch depicts damage 1, blue bar with horizontal hatch represents damage 2 and red circle indicate the false negatives

indexes affects the accuracy of the structural monitoring when using the Park et al. [26] technique. In addition, the results shown that large bandwidths in frequency are more susceptible to involve low accurate detections, which can imply more false negatives in terms of the damage presence.

3.1 Analysis of the new approach

The new approach proposed in this article is demonstrated by considering the EMI signals presented in Fig. 18, which contains the reference signal (measured at 24 °C). The signals obtained for the temperatures -10 °C and 80 °C are used to employ the approach proposed herein, and the procedure is applied for the frequency range number 3, which corresponds to the bandwidth 35 kHz, without loss of generality. This frequency range is arbitrarily used to compute the more convenient frequency range based on the proposed approach (see Sect. 2.2.2). Figure 18 shows the signals obtained after applying Park et al. [26] technique, and these signals are used to apply the proposed

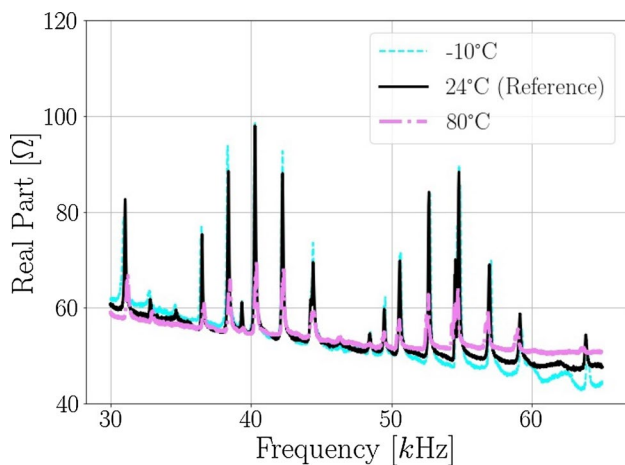


Fig. 18 Real part of the electromechanical impedance (undamaged condition) after applying Park et al. [26] compensation technique in the frequency range number 3 (bandwidth 35 kHz). They are used to employ the proposed approach

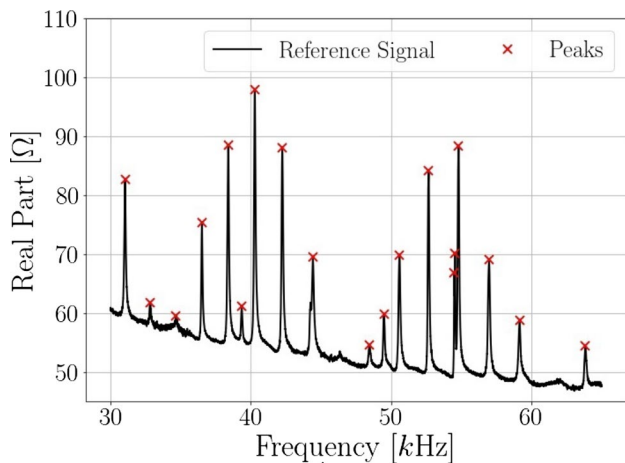


Fig. 19 Reference signal (real part of the EMI) and peak values identified

approach. Then, considering the selected frequency range, the approach is employed for the EMI signals, as shown through the following results.

According to the proposed approach, the important part of the procedure is to identify the peak values in the real part of the EMI. Figure 19 shows the curve for the reference temperature (24 °C), and the peaks are highlighted by red symbols (×). Note that even small peaks are identified by employing the *prominence* equal to 2, and their associated frequencies are accurately determined based on their corresponding position in the frequency vector. Based on the $S \times N_r$ plot, and the proposed parameter S achieves a numerically stable value when considering $N_r \approx 300$ points. The corresponding values are shown in Table 5 (see Appendix 3 for details).

Figure 20 shows the considered signal parts after removing the peak values influence, i.e., the clipped curves. Note that a higher influence of the peak values is still verified for the signals at T_d . The curves of the means differences are obtained by considering N_{dif} equal to 1224 points. Figure 21 shows the vector **Dif** for the temperature -10°C (left-hand side) and 80°C (right-hand side), and note that different behaviors are verified when comparing them with each other. These behaviors suggest that different strategies need to be applied to select the frequency range depending on the temperature in relation to the reference temperature (i.e., if it is higher or lower than the reference temperature). Then, the employed procedure considers the frequency range selection based on the temperature, such that it corresponds to the range in which the values of **Dif** are smaller than its standard deviation σ_{Dif} if $T_d < T_r$. On the other hand, if $T_d \geq T_r$, the selected frequency range corresponds to the range in which the values of **Dif** are smaller than its mean $\bar{Dif}$. Using this strategy of selection, it is possible to evaluate more accurately the EMI signals measured at different temperatures.

The strategy employed to select the frequency range is also applied to those different temperatures for the undamaged system, i.e., 4°C , 36°C , 52°C and 64°C .

Figures 22 and 23 present respectively the re-computed RMSD and CCDM-based indexes considering the selected frequency ranges. Note that the results demonstrate that both types of damages are detected for all those temperatures. i.e.,

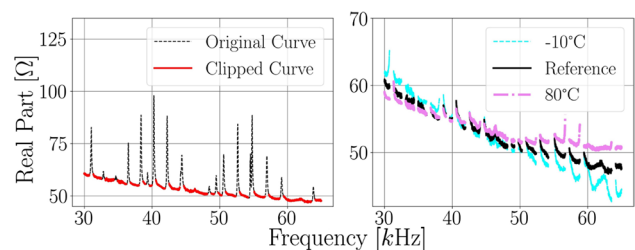


Fig. 20 Clipped EMI curves. Left-hand side: curves at the reference temperature, and right-hand side: curves for three different temperatures

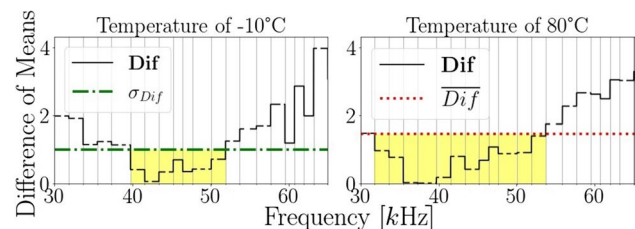


Fig. 21 Curves of the absolute differences of the means for the temperature -10°C and 80°C . The yellow region represents the selected frequency range, which is 39.72 to 51.89 kHz for $T_d = -10^\circ\text{C}$ and 31.82 to 53.71 kHz for $T_d = 80^\circ\text{C}$

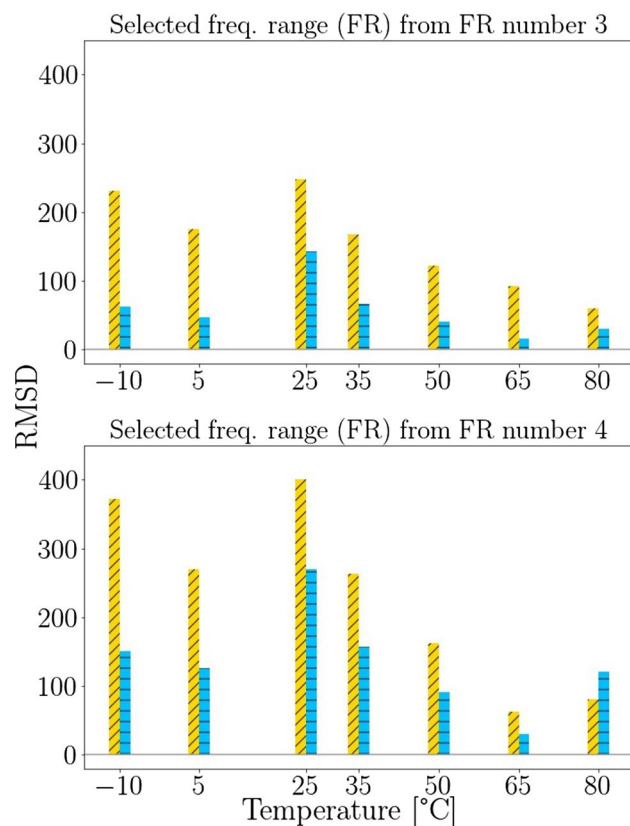


Fig. 22 Difference between the RMSD values computed for the signals in the damaged and undamaged conditions after applying the new approach for the FR numbers 3 and 4. Yellow slanted bar hatch depicts damage 1 and blue bar with horizontal hatch represents damage 2

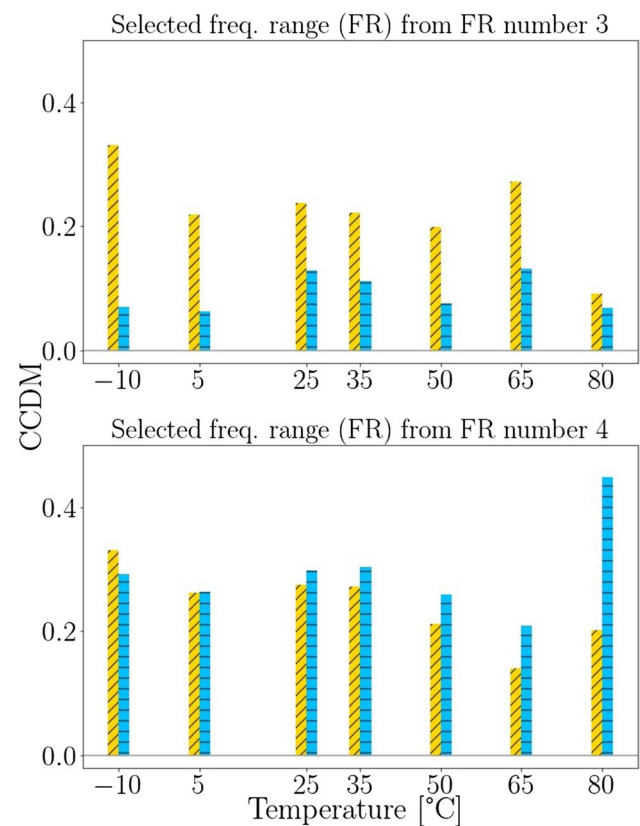


Fig. 23 Difference between the CCDM values computed for the signals in the damaged and undamaged conditions after applying the new approach for the FR numbers 3 and 4. Yellow slanted bar hatch depicts damage 1 and blue bar with horizontal hatch represents damage 2

the false negatives are eliminated. Only the indexes results for frequency ranges number 3 and 4 (i.e., bandwidths 35 and 45 kHz) are shown in this section, since these were the only ones that showed false negatives. The recomputed indices of frequency range number 2 (bandwidth 30 kHz) are presented in Appendix 1. However, the new approach cannot be applied to frequency band number 1 (bandwidth 15 kHz), since its S -parameter curve has not stabilized, as can be seen in Appendix 3.

Theoretically, if the EMI curve is smooth and multiple sharp peaks are not verified in the measured frequency range, the technique performance can be reduced. However, Liang et al. [20] note that the EMI exhibits well defined peaks (resonance) of the electromechanical system occur for each frequency in which the actuator impedance and the structural impedance matches to each other. Then, in practice this proposed approach can be successfully employed if there are matches between the actuator and structural impedance, which requires to properly select the PZT actuator for each particular structure.

4 Conclusions

This work introduced an enhancement in the temperature compensation technique proposed in the literature to use the electromechanical impedance technique for damage detection. The EMI curves for different frequency ranges are evaluated, which allows one to contribute to the practical application of the technique in monitoring real systems. The compensation of the temperature effects were investigated for an aluminum beam including different conditions, which correspond to the damaged and undamaged structure in four different frequency ranges, resulting the bandwidths 15, 30, 35 and 45 kHz.

The experimental results demonstrated that when using a classical technique from the literature, a less effective performance can be observed if the frequency range increases, in the sense of compensating the temperature effects on the EMI curves. However, the proposed approach reduces these effects, and it is demonstrated for the three different structural conditions evaluated herein (non-damage, damage 1 and 2). The findings are observed in both vertical (magnitude) and horizontal (frequency) compensation. Furthermore, both RMSD and CCDM-based indexes demonstrate that the

proposed procedure to select the frequency range for the temperature compensation technique improves the damage detection by eliminating those false negatives obtained through the original technique from the literature. In this sense, the proposed approach can contribute to establishing more efficient structural health monitoring systems involving EMI signals measured in different environmental temperatures.

Table 2 shows that the temperature for undamaged and damaged conditions can exhibit a small difference. The results demonstrate that differences around 1 °C between them do not affect the performance of this proposed technique. However, the maximum limit of this difference is not investigated in this present study. Then, a good practice for applying this proposed approach is to measure the EMI for both undamaged and damaged (i.e., unknown structural condition) conditions at the same temperature.

Appendix 1 Overview on the Park et al. [26] compensation technique

This appendix shows the EMI curves when applying the Park et al. [26] temperature compensation technique. Figure 24 shows the real part of the EMI obtained for the aluminum beam in the undamaged condition in two different temperatures (10 and 30 °C) and 4 different stages of the method (i.e., iterations). The values of V_a and δ^S for each iteration are shown in Table 4. After the first iteration the difference in the vertical axis reduced by summing δ^S to the curve. This parameter presents a small variation even after multiple iterations, as shown in Table 4. This characteristic is verified because δ^S is computed by the difference between Z_R and the measured signal shifted horizontally.

Park et al. [26] verified that it is possible to detect damages in the incipient phases, even considering temperature

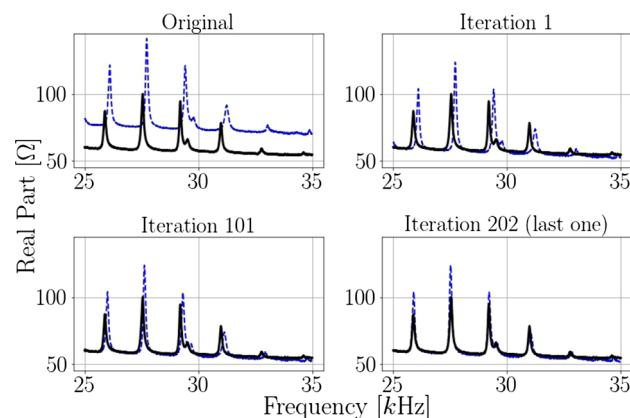


Fig. 24 Real part of electromechanical impedance at different iterations of Park et al. [26] technique: 10 °C (black continuous line) and 30 °C (blue-dashed line)

Table 4 Values of V_a and δ^S in each iteration

Iteration	V_a [Ω^2]	δ^S [Ω]
0	4242589.902	-17.486
1	970046.711	-17.571
101	593727.990	-17.486
202	143901.751	-17.401

variations from 25 to 75 °C, with a step of 12.5 °C. The experiments were carried out in different frequency ranges according to the monitored structure: carbon steel beam (70–80 kHz), bolted pipe joint (70–80 kHz), gears (190–220 kHz), and composite-reinforced structure (54–63 kHz).

Appendix 2 Results for the frequency ranges numbers 1 and 2 (Table 3)

Figures 25, 26 and 27 show the EMI signal after applying the approach proposed by Park et al. [26]. These figures contain, respectively, the signals for the undamaged

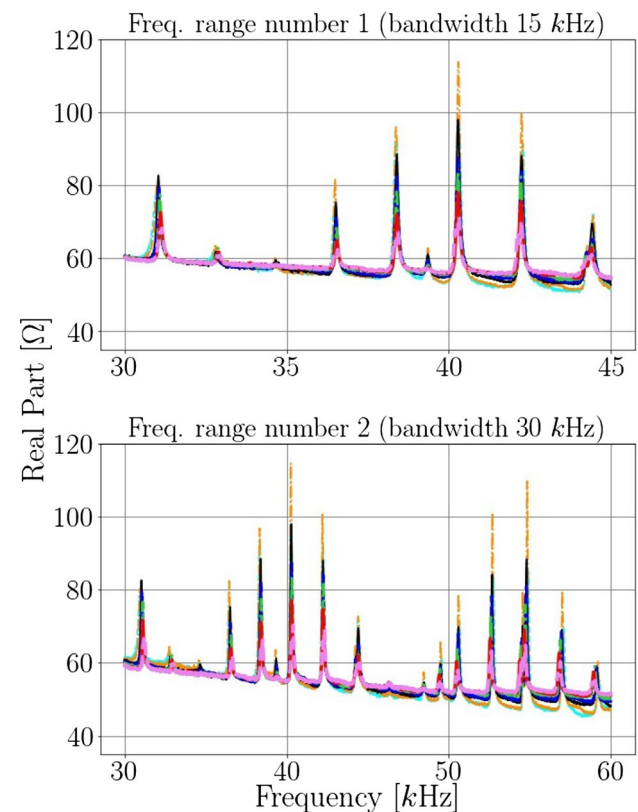


Fig. 25 Real part of the electromechanical impedance (undamaged condition) using Park et al. [26] compensation technique for two frequency bandwidths: 15 and 30 kHz. Curves for the temperatures -10 °C, 4 °C, 24 °C (reference), 36 °C, 52 °C, 64 °C and 80 °C

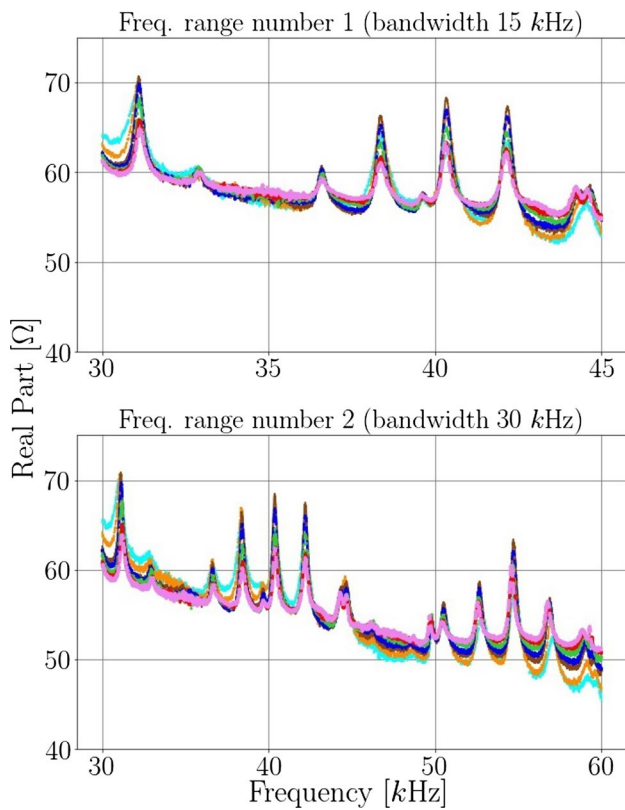


Fig. 26 Real part of the electromechanical impedance (damage 1) using Park et al. [26] compensation technique for two frequency bandwidths: 15 and 30 kHz. Curves for the temperatures -10°C , 5°C , 25°C , 35°C , 50°C , 65°C and 80°C

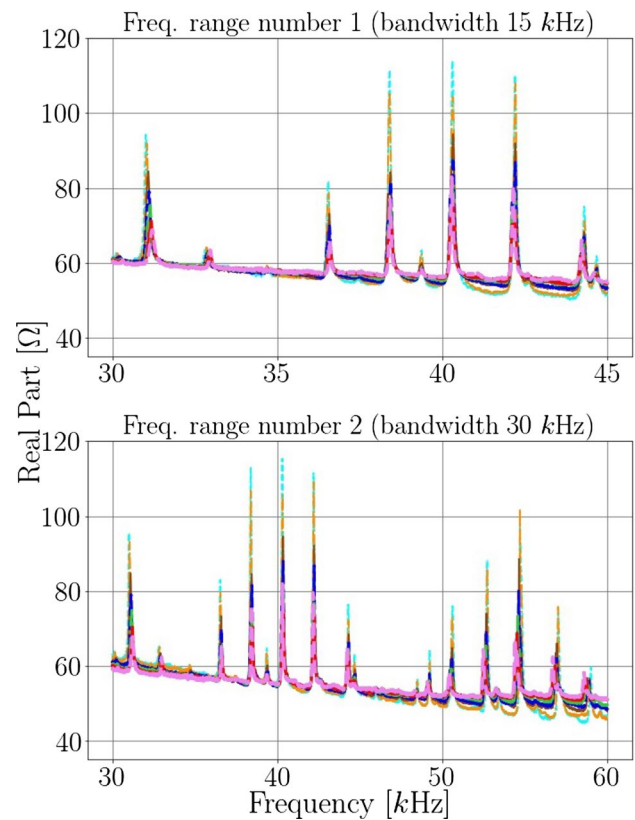


Fig. 27 Real part of the electromechanical impedance (damage 2) using Park et al. [26] compensation technique for two frequency bandwidths: 15 and 30 kHz. Curves for the temperatures -10°C , 5°C , 25°C , 35°C , 50°C , 65°C and 80°C

condition, with damage 1 (added mass) and damage 2 (mechanical cut) for two different frequency ranges, corresponding to the bandwidths 15 and 30 kHz. The values of the difference between the RMSD and CCDM of the signals for both damaged and undamaged conditions are shown in Figs. 28 and 29. Figure 30 shows similar results regarding damage detection (i.e., no false negatives) for

the frequency range number 2 (bandwidth 30 kHz) after applying the new approach. On the other hand, Appendix 3 shows that this approach can not be successfully applied by considering the frequency range number 1 because a stable value of S is not achieved.

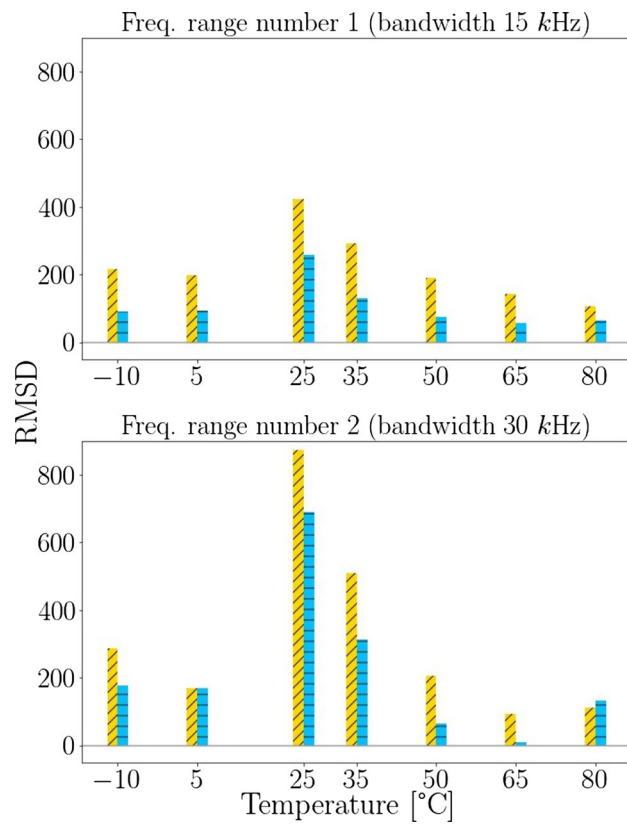


Fig. 28 Difference between the RMSD values computed for the signals in the damaged and undamaged conditions compensated by Park et al. [26] technique for the FR numbers 1 and 2. Yellow slanted bar hatch depicts damage 1 and blue bar with horizontal hatch represents damage 2

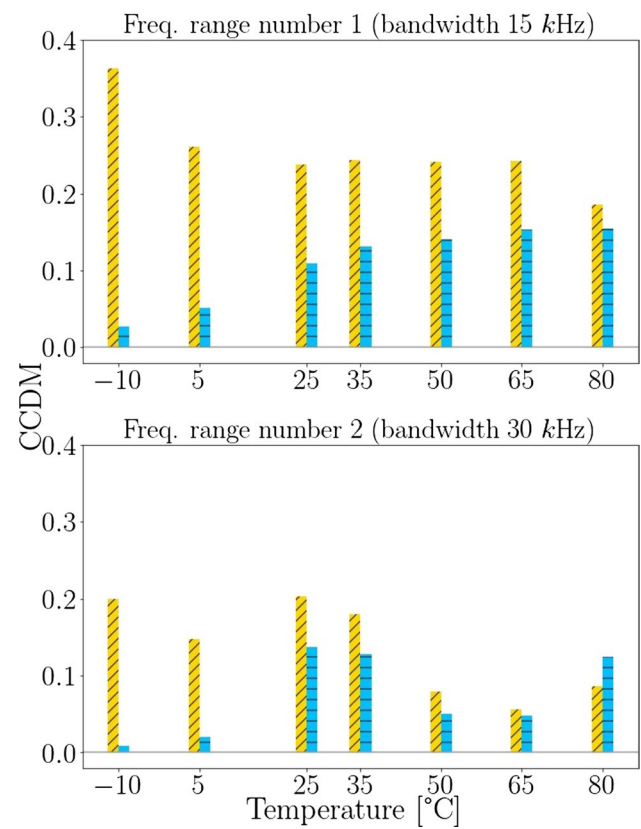


Fig. 29 Difference between the CCDM values computed for the signals in the damaged and undamaged conditions compensated by Park et al. [26] technique for the FR numbers 1 and 2. Yellow slanted bar hatch depicts damage 1 and blue bar with horizontal hatch represents damage 2

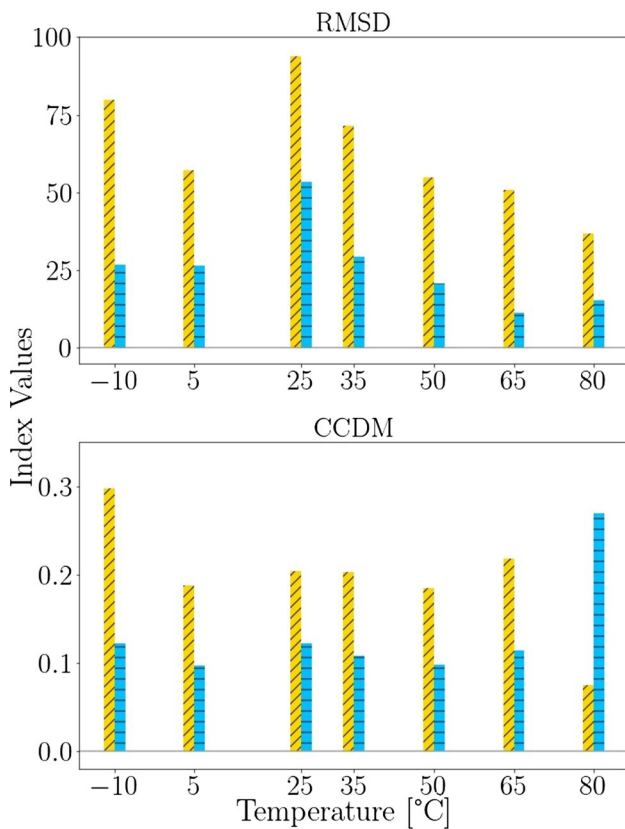


Fig. 30 Difference between the RMSD and CCDM values computed for the signals in the damaged and undamaged conditions after applying the new approach for the FR number 2. Yellow slanted bar hatch depicts damage 1 and blue bar with horizontal hatch represents damage 2

Appendix 3 Analysis of the S-curve

Table 5 shows the values of S for each frequency range. Note that it is numerically approximately a constant value (around 10^3) for the frequency ranges 2, 3 and 4. However, its variation is more significant for the frequency range number 1.

This behavior suggests that the approach can not be successfully applied when using this frequency range. Then, the evaluation of the parameter S is an important part of this proposed strategy to select the frequency range.

Table 5 S and N_r values for the four frequency ranges (FR)

N_r	FR	S			
		1	2	3	4
100		0.3368	0.3989	0.4133	0.4376
200		0.1933	0.2688	0.2863	0.3159
300		0.1812	0.2578	0.2756	0.3056
400		0.1812	0.2578	0.2756	0.3056
500		0.1812	0.2578	0.2756	0.3054
600		0.1761	0.2578	0.2756	0.3054
700		0.1740	0.2578	0.2756	0.3054

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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