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STUDY OF THE TEMPERATURE EFFECT ON THE ELECTROMECHANICAL IMPEDANCE TECHNIQUE APPLIED TO STRUCTURAL HEALTH MONITORING OF A BEAM

Lorena Lopes Dias

lorena.dias@unesp.br

Camila Gianini Gonzalez-Bueno

camila.gg.bueno@unesp.br

Douglas D. Bueno

douglas.bueno@unesp.br

GMSINT - Intelligent Materials and Systems Group, Department of Mechanical Engineering, State University of São Paulo “Júlio de Mesquita Filho” (UNESP) - Ilha Solteira Campus, Av. Brasil Centro, 56 - Ilha Solteira, SP - CEP 15.385-000

Abstract. *Different structures are subjected to operational and external effects which can generate structural damage. The structural performance must be carefully designed to avoid failures because their consequences typically involve economic, social and environmental impacts. Damage detection is then one of the great concerns of the engineers, who have carried out 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, mainly involving signal processing. This technique consists of the use of piezoelectric transducers, which are responsible for exciting the monitored structure and measuring its response. However, the sensitivity of the 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 this point of view, the present article investigates the influence of temperature in a mechanical system characterized by a piezoelectric transducer coupled in a Euler-Bernoulli beam described by the Spectral Elements Method. By the results obtained through numerical simulations, it was possible to conclude that the influence of the piezoelectric transducer in EMI technique is superior than that practiced by the monitored structure. Furthermore, the behavior of EMI curves under temperature variation is in agreement with reference works.*

Keywords: *Structural health monitoring, Piezoelectric transducers, Electromechanical impedance, Beam, Temperature Influence.*

1. INTRODUCTION

Mechanical structures are subject to damage due to the inevitable aging and degradation resulting from the operating environments (Farrar *et al.*, 2005). These damages are responsible for deteriorating the state of conservation of the structure and, consequently, changing its performance and reliability, and may even cause accidents due to structural failure of some equipment. In view of this, different numerical and experimental studies are carried out for developing new techniques to evaluate and monitor structures and systems (Worden and Dullieu-Barton, 2004). This field is known as Structural Health Monitoring (SHM), mainly focused on detecting damage in its early stages. The techniques usually employ sensors to obtain damage-sensitive information from the structural system over time. The obtained measurements are post-processed to determine the system structural state (Farrar *et al.*, 2005).

SHM systems can comprise five main steps. First step consists to place sensors on the structure, from which necessary data are obtained (step 2). Third step comprises to interpret the signals obtained by using computer codes, which allows one to determine the structure condition. Step 4 is the definition of an action plan, i.e., if it is necessary an intervention to avoid damage propagation (step 5) or if no intervention is needed, restarting the operational cycle (Louzada, 2019; Rébillat *et al.*, 2016).

Electromechanical Impedance (EMI) is used in SHM. It was first suggested by Liang *et al.* (1993) and currently there are promising results known in literature, mainly involving real-time signal processing to detect incipient damage. This technique is characterized by the use of piezoelectric transducers, especially ceramics PZT (Leads Zirconate Titanate). Transducers are capable to generate electrical voltage when subjected to mechanical efforts (direct effect), acting as sensors and, conversely, suffer mechanical deformations when they are under the action of an electric field (converse effect), and this behavior works as an actuator (Tebaldi, 2014; Wang *et al.*, 2014). This technique employs the piezoelectric effect,

which is responsible for the electromechanical coupling between the structure and the PZTs installed on it. The transducer works as an actuator and sensor simultaneously, that is, it excites the monitored structure and measures its response. This approach basically consists of measuring the EMI for the no-damage condition known as baseline signal. This data is compared with other EMI signals obtained for unknown structural conditions (Gyuhae Park and Inman, 2003).

There are many works investigating EMI-based techniques, and most of them involve post-processing experimental data. On the other hand, there is a few numbers of articles introducing dynamic models for the electromechanical impedance. Wang *et al.* (2014) investigate the electromechanical impedance of a piezoelectric smart beam with a crack simulated by using spring models. The authors used the Spectral Element Method (SEM) to study the piezoelectric element impedance response to changes in crack depth. Xu *et al.* (2016) also used SEM to develop a model to predict the electromechanical admittance in the surface-bonded piezoelectric wafer and beam structure considering temperature effects. Sepehry *et al.* (2010) analyzed the effects of environmental temperatures in the impedance-based structural integrity monitoring (ISHM) method. The authors developed a temperature-dependent analytical model for a piezoelectric wafer active sensor connected to an aluminum Euler-Bernoulli cantilever beam, and the results are compared with experimental data. Zhang *et al.* (2011) developed an analytical model for damage identification in a Timoshenko beam through the electromechanical impedance technique. The authors analyzed the influence of a crack and inertial forces of PZT patches on damage detection.

EMI signal are affected by external disturbances, as changes in environmental temperature, and this is an important challenge to employ the technique for practical applications. Because of this, there are several studies to address the influences of external effects on EMI. They are focused on developing strategies to minimize the effects on impedance curves. Different methods are proposed in literature, as shown by Baptista *et al.* (2011, 2014), Park *et al.* (1999), Koo *et al.* (2009), Grisso and Inman (2010), Sepehry *et al.* (2010), Abbas *et al.* (2021), among other authors. In general, these researches show that temperature variations introduce shifts in frequency and magnitude in EMI curves.

In this context, the present work employs the Electromechanical Impedance technique to the Structural Health Monitoring of an aluminum beam described by Spectral Elements Method. The EMI curves are investigated considering a working temperature in range 0°C and 70°C. Temperature variations change the properties of the PZT transducer and the structure Young's modulus. The effects of variations in the properties are analyzed separately and combined with each other. Then, the main goal of this article is to analyze the behavior of Electromechanical Impedance curves of a beam due to the influences generated by the variation of the working temperature.

2. METHODOLOGY

Electromechanical Impedance technique consists of using one or more piezoelectric transducers (PZT) as sensor(s) and actuator(s). They are employed for performing the coupling between mechanical and electrical impedance, from which monitoring of the structure is carried out (Na and Baek, 2018). Figure 1 shows a representation of the interaction between the PZT and an arbitrary structure. The transducer vibrates in response to the application of an electrical voltage, $V_{in}(\omega)$; one of its ends is connected to the structure to be monitored and an auxiliary electrical circuit (A. C.) is used to measure the electrical current, $I_{out}(\omega)$.

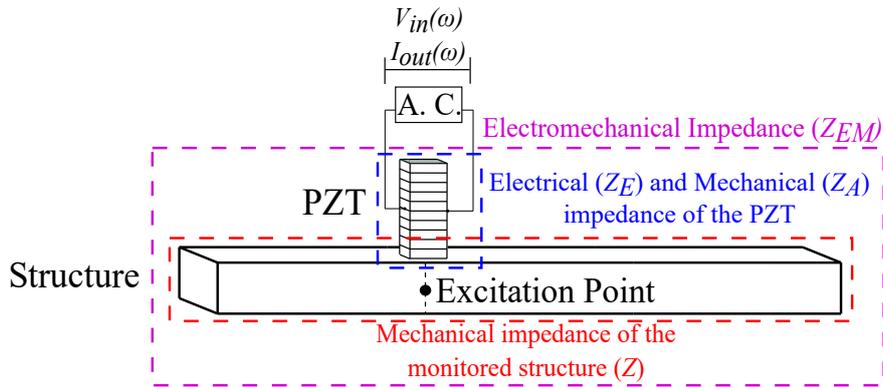


Figure 1. Representation of the Electromechanical Impedance of a PZT stack coupled to an arbitrary structure.

Liang *et al.* (1996) introduces the admittance (Y_{EM}), represented in Eq. (1), and its inverse corresponds to the electromechanical impedance, where $Y_{EM}(\omega)$ is the admittance (inverse of the electromechanical impedance), l_t , b_t and t_t 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, $j = \sqrt{-1}$ represents the pure imaginary number, $Z(\omega)$ and $Z_A(\omega)$ are, respectively, the

mechanical impedance of the structure and the PZT.

$$Y_{EM}(\omega) = j\omega \frac{b_t l_t}{t_t} \left[\epsilon_{33}^T - \frac{Z(\omega)}{Z_A(\omega) + Z(\omega)} d_{31} \bar{Y}_{11}^E \right] \quad (1)$$

2.1 STACK PIEZOELECTRIC TRANSDUCER

The mechanical structure consists to an Euler-Bernoulli beam with longitudinal and flexural degrees of freedom, besides the angular rotation (Achenbach, 1984; Souza, 2000). Then, a stack piezoelectric transducer was used, which is responsible for generate a transversal excitation in the structure. It is characterized by presenting several piezoelectric elements placed in layers on top of each other, as shown in Fig. 2. In this type of PZT, when a voltage is applied, a deformation, or displacement, is induced in the direction of the polarization (Piezo Technology, 2021). Therefore, the desired effect (transverse punctual excitation) is obtained by including a PZT placed on the structure as illustrated in Fig. 1.

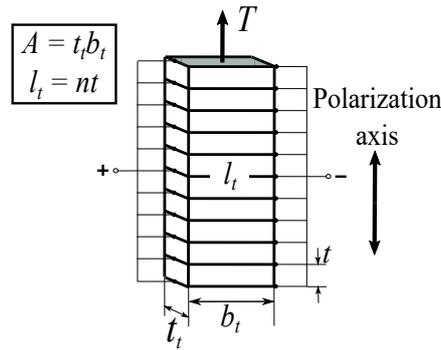


Figure 2. Stack piezoelectric transducer, with l_t , b_t and t_t being the length, width and thickness of the transducer, t the individual thickness of each piezoelectric element, A the cross-sectional area and n the number of piezoelectric elements in the stack.

The equation to determine the mechanical impedance Z_{mt} of the piezoelectric transducer, shown in Eq. (2), was obtained from the model previously developed by Preumont (2006) and Nakano *et al.* (2007). It is given by

$$Z_{mt} = \frac{1}{j\omega C_{mt}} (1 + j\eta_{mt}) \quad (2)$$

where ω is the angular frequency, η_{mt} is the loss factor in the mechanical compliance and C_{mt} is the mechanical compliance with open electrodes (zero electrical charge). This parameter is defined as:

$$\frac{1}{C_{mt}} = \frac{K_\alpha}{1 - \kappa^2} \quad (3)$$

where $K_\alpha = \frac{A}{s^E l_t}$ and $\kappa = \frac{|d_{33}|}{\sqrt{s^E \epsilon^T}}$. κ is the coupling coefficient, s^E is compliance of the material under constant electric field and K_α is the stiffness of the transducer with short-circuited electrodes. In particular for the present work, it was selected the piezoelectric transducer PSI-5H4E from Piezo Systems (2011), whose properties are presented in Tab. 1.

Table 1. Piezoelectric transducer properties.

Property	Symbol	Value
Mechanical loss factor	η	0.03
Young's Module	Y_{11}^E	62 GPa
Density	ρ_t	7800 kg/m ³
Compliance	s_{11}^E	$1/Y_{11}^E = 1.61 \times 10^{-12} \text{ Pa}^{-1}$
Piezoelectric constant in the 3-1 direction	d_{31}	$-320 \times 10^{-12} \text{ m/V}$
Piezoelectric constant in the 3-3 direction	d_{33}	$650 \times 10^{-12} \text{ m/V}$
Dielectric constant	ϵ_{33}^T	$33630 \times 10^{-12} \text{ F/m}$
Width	b_t	5 mm
Thickness	t	5 mm
Number of patches	n	3
Length	l_t	$nt = 15 \text{ mm}$

2.2 MECHANICAL IMPEDANCE OF THE STRUCTURE

A beam composed of a 2024 aluminum alloy is selected and represented by the Spectral Elements Method (SEM). The formulation is presented in details by Lee (2009). The beam is discretized into 3 elements (E1, E2 and E3), as shown in Fig. 3. The approach considers two nodes per element, containing shear force Q_j , momentum M_j , transverse displacement w_j and rotation θ_j at each j -th node. The structural properties are shown in Tab. 2.

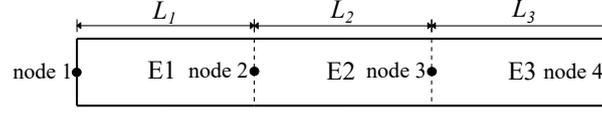


Figure 3. Sketch of the beam considers in the present study.

Table 2. Physical and geometrical properties of the beam.

Property	Symbol	Value
Young's Module	E	73 GPa
Density	ρ_s	2.78 g/cm ³
Width (fixed)	b_s	0.02 m
Thickness	t_s	2 mm
Length of L_1	L_1	0.5 m
Length of L_2	L_2	25 mm
Length of L_3	L_3	0.5 m
Mechanical loss factor	η_s	5.15×10^{-5}

The dynamic stiffness matrix of a spectral element ($\mathbf{S}_B(\omega)$) for the Euler-Bernoulli beam is given by (Lee, 2009):

$$\mathbf{S}_B(\omega) = \frac{EI}{L^3} \begin{bmatrix} S_{B11} & S_{B12} & S_{B13} & S_{B14} \\ S_{B21} & S_{B22} & S_{B23} & S_{B24} \\ S_{B31} & S_{B32} & S_{B33} & S_{B34} \\ S_{B41} & S_{B42} & S_{B43} & S_{B44} \end{bmatrix} \quad (4)$$

where $S_{B11} = S_{B33} = \Delta_B \bar{L}^3 (\cos \bar{L} \sinh \bar{L} + \sin \bar{L} \cosh \bar{L})$, $S_{B22} = S_{B44} = \Delta_B \bar{L}^3 k_F^{-2} (-\cos \bar{L} \sinh \bar{L} + \sin \bar{L} \cosh \bar{L})$, $S_{B12} = S_{B21} = -S_{B34} = -S_{B43} = \Delta_B \bar{L}^3 k_F^{-1} \sin \bar{L} \sinh \bar{L}$, $S_{B13} = S_{B31} = -\Delta_B \bar{L}^3 (\sin \bar{L} + \sinh \bar{L})$, $S_{B14} = S_{B41} = -S_{B23} = -S_{B32} = \Delta_B \bar{L}^3 k_F^{-1} (-\cos \bar{L} + \cosh \bar{L})$, $S_{B24} = S_{B42} = \Delta_B \bar{L}^3 k_F^{-2} (\sin \bar{L} + \sinh \bar{L})$, and

$$\Delta_B = \frac{1}{1 - \cos \bar{L} \cosh \bar{L}} \quad (5)$$

where $\bar{L} = k_F L$, and $k_F = \sqrt{\omega} \left(\frac{\rho A}{EI} \right)^{1/4}$ is the wave number for a flexural wave, I is the area moment of inertia and A the cross-sectional area. The properties, including the length L , match each element. From the local dynamic stiffness matrix of each element, it is possible to obtain the global dynamic stiffness matrix \mathbf{K}_g , and the mechanical impedance is computed by $\mathbf{Z} = \mathbf{K}_g / i\omega$.

2.3 DAMAGE INDEX

Electromechanical impedance curves were also quantitatively evaluated by employing a metric that quantifies the damage influence. The detection index σ is given by Eq. (6), where $Z^b_{EM}(\omega)$ e $Z^d_{EM}(\omega)$ are, respectively, the reference conditions baseline and the unknown one.

$$\sigma = \frac{\left[\sum_{j=1}^n [Z^b_{EM}(\omega_j) - Z^d_{EM}(\omega_j)]^2 \right]^{1/2}}{\left[\sum_{j=1}^n [Z^b_{EM}(\omega_j)]^2 \right]^{1/2}} \quad (6)$$

2.4 EFFECT OF TEMPERATURE

Materials properties vary with temperature. In the electromechanical impedance technique, temperature affects the properties of the piezoelectric transducer and the structure, which can lead to incorrect diagnoses when monitoring the

structural integrity if an unknown structural condition is obtained in a temperature T_{j+1} and then compared with a baseline condition obtained in a different temperature T_j . In view of this, and considering different environments and conditions in which the structure operates, the behavior of the electromechanical impedance curves is analyzed for a temperature range from 0°C to 70°C.

Five particular temperatures are chosen in the range defined above to determine the material properties, and they correspond to: 0°C, 17.5°C, 35°C, 52.5°C and 70°C. The reference temperature is defined equivalent to 25°C. Based on the PZT datasheet, the properties of the transducer which vary with temperature are the dielectric constant $\bar{\epsilon}_{33}^T$, the piezoelectric constant d_{31} and the mechanical loss factor η . On the other hand, it is assumed that only the Young's modulus E of the structures can vary with temperature. This approach is based on the study by Brammer and Percival (1970), who study the variation of elastic constants of a 2024 aluminum rod for temperature from 22°C to 500°C. The properties of both piezoelectric transducer and structure in term of the temperature are shown in Tabs 3 and 4, respectively.

Table 3. Piezoelectric transducer properties in terms of the temperature.

Properties	Temperature [°C]					
	0	17.5	25 (ref.)	35	52.5	70
d_{31} [10^{-12} m/V]	-293.6	-307.2	-320	-329.6	-353.6	-364.8
$\bar{\epsilon}_{33}^T$ [10^{-12} F/m]	26904	30267	33630	35311.5	40356	47082
η	0.032	0.03	0.03	0.03	0.032	0.033

Table 4. Young's modulus of the structure in terms of the temperature.

Properties	Temperature [°C]					
	0	17.5	25 (ref.)	35	52.5	70
E [GPa]	73.8	73.2	73	72.5	71.9	71.3

3. RESULTS AND DISCUSSION

The temperature effect on EMI is investigated by considering three different cases. The first case consists to include the temperature influence only on the PZT, and the second case investigates the temperature affecting only the structure. In the third case, both PZT and structure are affected by the temperature simultaneously. For all cases the influence is included by changing physical properties.

3.1 FIRST CASE - PZT

Figure 5 shows the EMI curves computed by considering the properties of the PZT presented in Tab. 3. The dielectric constant $\bar{\epsilon}_{33}^T$, the piezoelectric constant d_{31} and the mechanical loss factor η change the EMI curves, mainly in the frequency ranges from approximately 15 kHz to 18 kHz and from 27 kHz to 45 kHz. The influence is easily noted in both magnitude (upper figure) and phase (lower figure). Figure 6 shows that the peaks and valleys of the EMI curve vary in frequency (abscissa) and magnitude (ordinate). Note that the amplitude decay almost linearly with temperature, except to zero Celsius degree. Detection indices ranged from such 0.75 (0°C) to 0.3 (35°C), as shown in Fig. 4.

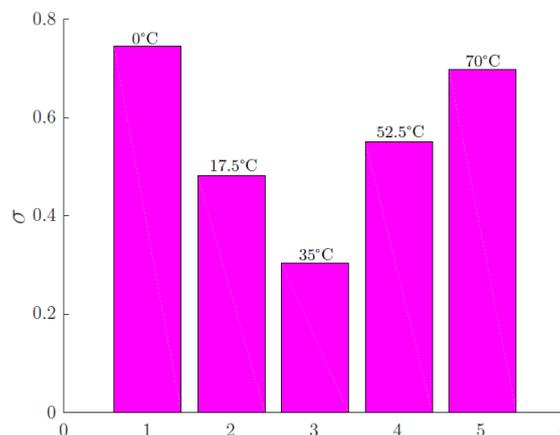


Figure 4. Electromechanical Impedance detection index for different temperatures.

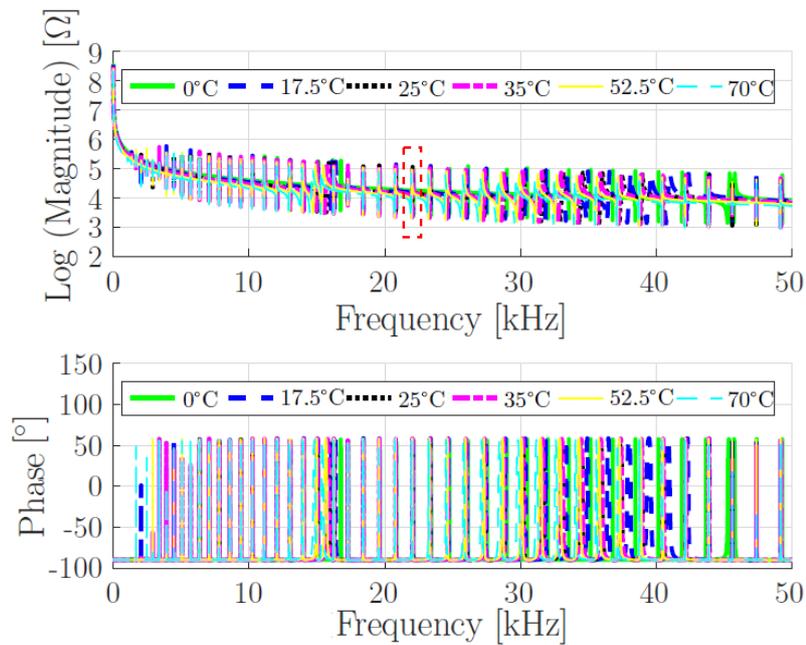


Figure 5. Magnitude and Phase of the Electromechanical Impedance considering temperature variations for the piezoelectric properties ($\bar{\epsilon}_{33}^T, d_{31}, \eta$).

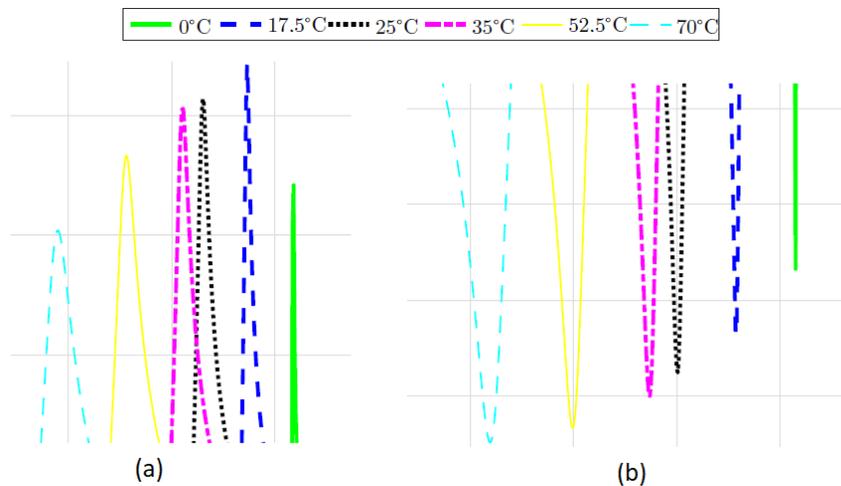


Figure 6. Approximation at the 28th peak and valley of the magnitude of the Electromechanical Impedance shown in Fig. 5 (in red): (a) peak and (b) valley.

3.2 SECOND CASE – STRUCTURE

Figure 8 shows the EMI curves computed by considering the structural properties presented in Tab. 4. The temperature mainly affects the resonance and antiresonance frequencies. With increasing temperature, lower frequencies are obtained. Consequently, changes in the EMI phase are also observed. These variations become more visible and intense in higher frequencies. Besides, unlike in Fig. 5, by varying the properties of only the structure, it was possible to observe differences between the curves during practically the entire selected frequency range. However, the detection indices remained below 0.1 (Fig. 7), much lower than those calculated in the previous case. Therefore, the effect of temperature considering only the changes in the structure is less significant when compared to the values observed in the previous section. By analyzing the Fig. 9, it is noted that the magnitude (ordinate), in all cases, present small changes, whereas the frequency (abscissa) was the one with the higher variations.

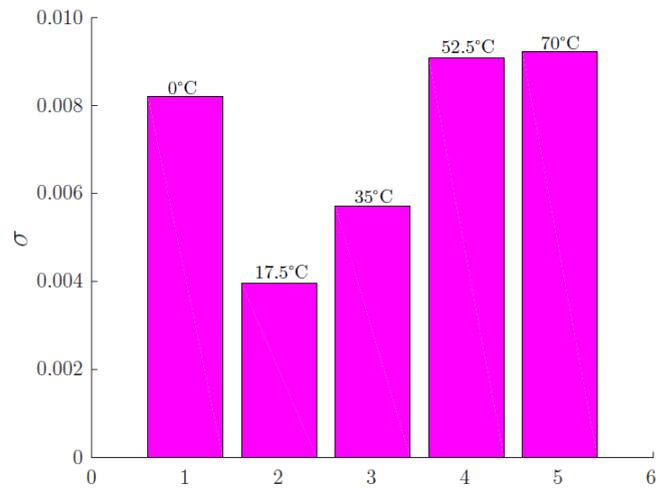


Figure 7. Electromechanical Impedance detection index for different temperatures.

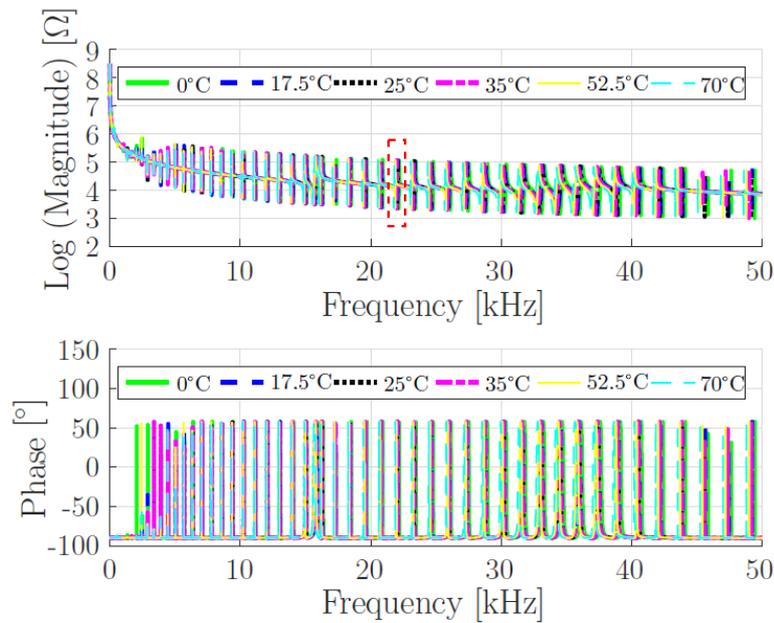


Figure 8. Magnitude and phase of the Electromechanical Impedance considering variations in the elastic property (E) of the structure due to temperature changes.

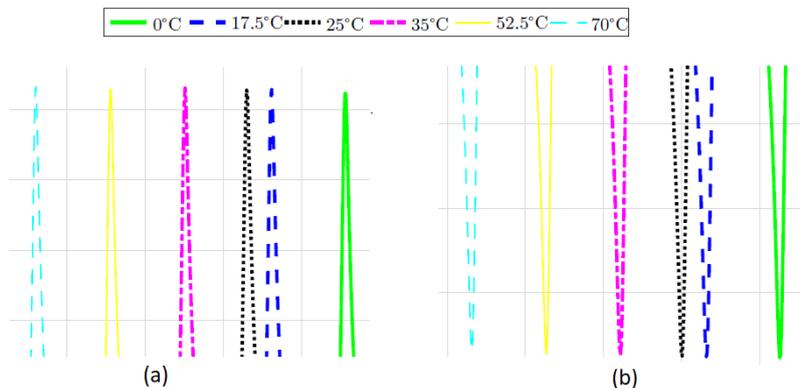


Figure 9. Approximation at the 28th peak and valley of the magnitude of the Electromechanical Impedance shown in Fig. 8 (in red): (a) peak and (b) valley.

3.3 THIRD CASE - MECHANICAL SYSTEM

Figure 11 shows the EMI curves computed by considering the properties of the PZT and the structure presented in Tabs. 3 and 4, respectively. Temperature affects the frequencies and the amplitudes of EMI curves. With increasing temperature, lower frequencies are obtained and variations in amplitude are observed. There is a combination of the behavior observed in each of the previous cases, with the vertical displacement being characteristic of the PZT and the horizontal mainly associated with the structure. Figure 12 shows that both magnitude and frequency vary. Note that the amplitude decay almost linearly with temperature, except to zero Celsius degree, and the frequency of peaks and valleys decreases with temperature. The detection indices, shown in Fig. 10, are very close to those calculated considering only the variations in the PZT properties, demonstrating that EMI curves are mostly influenced by the piezoelectric transducer.

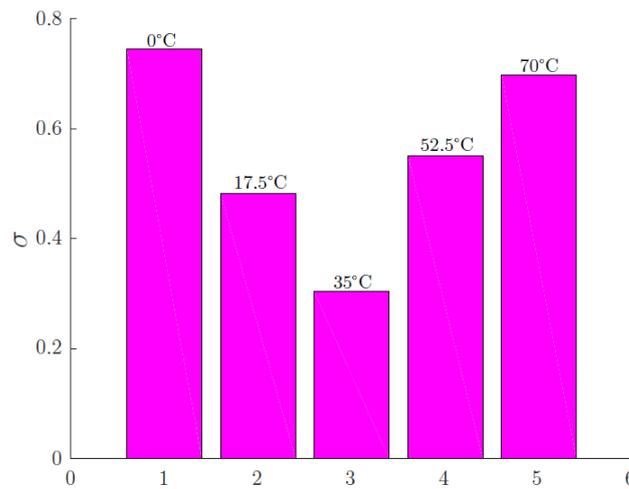


Figure 10. Electromechanical Impedance detection index for different temperatures.

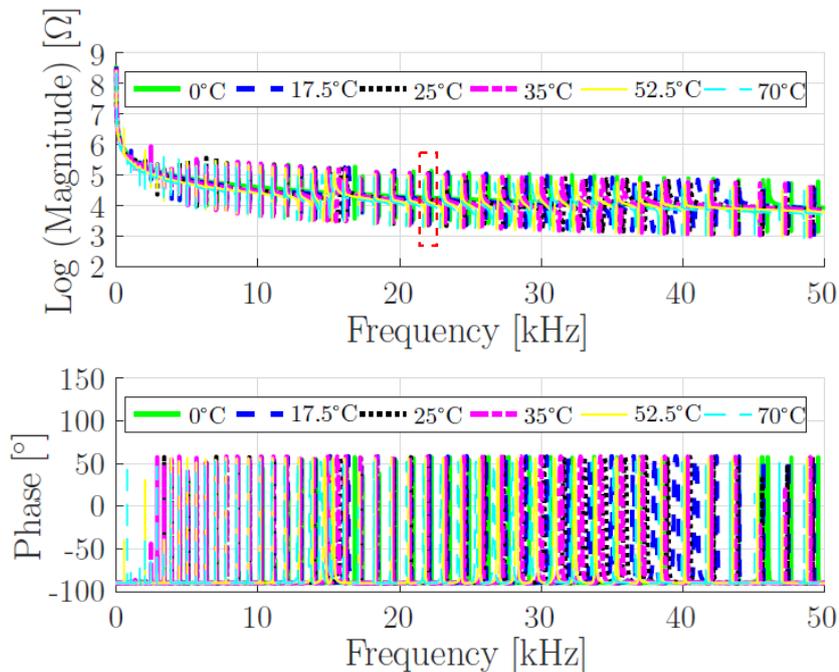


Figure 11. Magnitude and phase of the Electromechanical Impedance considering variations in the piezoelectric properties ($\epsilon_{33}^T, d_{31}, \eta$) and in the elastic property (E) of the structure due to temperature changes.

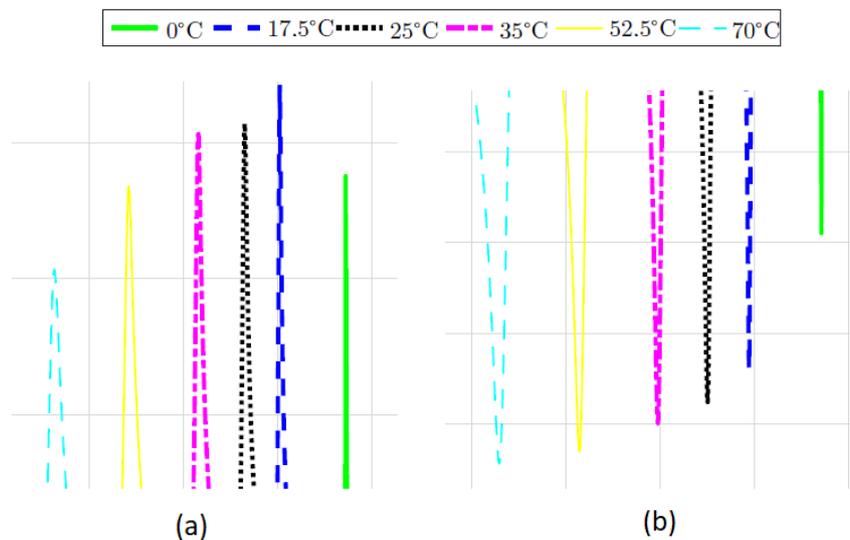


Figure 12. Approximation at the 28th peak and valley of the magnitude of the Electromechanical Impedance shown in Fig. 11 (in red): (a) peak and (b) valley.

4. FINAL REMARKS

This work investigated the electromechanical impedance technique applied to the structural health monitoring. The effect of the environmental temperature on EMI curves is evaluated in an aluminum Euler-Bernoulli beam with PZT transducers. It is noted how temperature affects the EMI if the piezoelectric transducer, the structure or both are affected by temperature changes.

If only the PZT is affected by the temperature, the main effect observed is a vertical shift in the magnitude of EMI curves. In the structure, however, the shift is essentially horizontal, characterized by lower frequencies if the temperature increases. Finally, the combination of these two effects is obtained if temperature changes are considered changing the properties of both (PZT and structure) simultaneously. These behaviors are also verified by other authors, whether through the processing of experimental data (Baptista *et al.*, 2014), dynamic models (Xu *et al.*, 2016) or a combination of both (Sepehry *et al.*, 2010).

By varying the properties of only the structure, it is possible to observe differences between the curves during practically the entire selected frequency range (0 to 50 kHz). However, the detection indices were much lower than those calculated by changing only the properties of the PZT. Therefore, with this study it was possible to conclude in an unprecedented way that the electromechanical impedance curves are mostly influenced by the piezoelectric transducer.

Through the development of the dynamic model in terms of temperature, it was possible to determine how the components of the mechanical system affect the electromechanical impedance curves and also specify the one with the major influence on the final results, which will require more care when applying the technique on real structures. Furthermore, despite the simplifications applied when using the model, it was possible to investigate the behavior of the EMI technique without spending resources on experiments.

5. ACKNOWLEDGEMENTS

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