The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2023

Volume 26, Pages 481-490

IConTES 2023: International Conference on Technology, Engineering and Science

Real-Time Structural Damage Detection Using EMI under Varying Load a and Temperature Conditions

Djemana Mohamed
National Higher School of Technology and Engineering

Meftah Hrairi
International Islamic University Malaysia

Abstract: Structural Health Monitoring (SHM) is a critical aspect of maintaining the safety and integrity of infrastructure. In recent years, there has been a significant shift towards adopting innovative techniques, and one of the most promising methods is Electromechanical Impedance (EMI). EMI involves the utilization of piezoelectric transducers to assess the health of structures in real-time by examining changes in their electrical characteristics. The presence of load causes a change in structural stiffness, which alters the resonant characteristics of the structure. Understanding how external factors like load and temperature influence the electrical impedance of these sensors is essential for its reliable application in damage detection. This article presents an experimental and numerical study to investigate the effects of load and temperature on the electrical impedance of a piezoelectric sensor used in the electromechanical impedance (EMI) technique. The experimental setup uses an impedance analyzer (Agilent 4294A model) to measure the in-situ EMI of piezoelectric wafer active sensors (PWAS) attached to the monitored structure. The numerical model uses ANSYS software to simulate an aluminum beam at varying temperatures. The results show that the load and temperature have a significant effect on the impedance of the transducer. However, it is shown that it is still possible to detect damage using EMI even under varying load and temperature conditions. The results also show that the accuracy of EMI-based damage detection can be improved by using temperature and load compensation techniques.

Keywords: Structural health monitoring, Electromechanical impedance, Piezoelectric sensor, Load detection, Temperature compensation.

Introduction

Structural health monitoring (SHM) is the process of assessing the structural integrity of a structure. SHM can be used to detect damage at an early stage, which can help to prevent catastrophic failure. Electromechanical impedance (EMI) is a promising SHM technique that uses piezoelectric transducers to measure the electrical impedance of a structure. EMI is based on the principle of electromechanical coupling, which is the conversion of electrical energy into mechanical energy and vice versa.

EMI SHM systems typically consist of a network of piezoelectric transducers bonded to the structure. The transducers are used to measure the impedance of the structure at various frequencies. Changes in the impedance of the structure can indicate damage. EMI SHM systems can be used to monitor a variety of structures, including bridges, buildings, and aircraft (Balouchi et al., 2019).

Electromechanical impedance (EMI) is a non-destructive evaluation (NDE) technique that can be used to detect damage in structures. EMI works by measuring the electrical impedance of a piezoelectric sensor bonded to the

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

structure. When damage is present, it changes the stiffness of the structure, which in turn changes the impedance of the sensor.

EMI is a particularly promising technique for structural health monitoring (SHM) because it is sensitive to small changes in damage and can be used to monitor structures in real time. However, EMI measurements can be affected by environmental factors such as load and temperature. Under varying load, the stiffness of a structure can changes, which can affect the EMI readings. This can make it difficult to distinguish between damage and load-induced changes. Similarly, temperature can also affect the stiffness of a structure and the EMI readings. Researchers are developing new techniques to compensate for the effects of load and temperature on EMI measurements. Furthermore, EMI technique has undergone continuous enhancement in recent decades, driven by its appealing characteristics. This method is known for its cost-effectiveness, lightweight nature, noninvasiveness, and its capacity to self-actuate and sense (Zou et al., 2021, 2023).

The effect of temperature and load on the fatigue behavior of steel was investigated by conducting fatigue tests on smooth and notched specimens at different temperatures and load levels. The results showed that the fatigue life of steel decreased with increasing temperature and load level. The fatigue crack growth rate increased with increasing temperature and load level. The fatigue failure mode changed from ductile to brittle with increasing temperature and load level (Wang et al., 2022). The effect of temperature and load on the fracture behavior of concrete was investigated by conducting fracture tests on concrete specimens at different temperatures and load levels. The results showed that the fracture toughness of concrete decreased with increasing temperature and load level. The fracture mode changed from ductile to brittle with increasing temperature and load level (Li et al., 2020). The effect of temperature and load on the creep behavior of polymers was investigated by conducting creep tests on polymer specimens at different temperatures and load levels. The results showed that the creep strain of polymers increased with increasing temperature and load level. The creep rate of polymers increased with increasing temperature and load level (Zhou et al., 2021). developed a damage detection system for aluminum plates using EMI signature monitoring under variable temperature conditions. They found that the EMI signature of a damaged plate is different from the EMI signature of an undamaged plate, even under variable temperature conditions. (Hu et al., 2022) investigated the temperature effect on EMI-based damage detection of aluminum plates with cracks. They found that the temperature effect on the EMI signature of a cracked plate is significant. (Liu et al., 2020) developed a temperature-compensated EMI-based damage detection system for aluminum plates with cracks. They found that their temperature-compensated EMI-based damage detection system was able to accurately detect cracks in aluminum plates under variable temperature conditions.

EMI-based SHM under varying load and temperature conditions is a challenging but promising area of research. By developing new compensation techniques, researchers are making it possible to use EMI to monitor a wide range of structures in real time and to detect damage early, before it leads to failure. This paper makes significant contributions to the field of structural engineering by addressing the intertwined challenges of temperature effects on structural materials and the early detection of small damages in aluminum beams. Our work not only advances the theoretical knowledge in this area but also offers practical solutions with real-world implications, ultimately promoting the safety and longevity of critical structures.

Principle of the Electromechanical Impedance Technique

Electromechanical impedance (EMI) is the measurement of the electrical impedance of a structure under dynamic loading. EMI is based on the principle of electromechanical coupling, which is the conversion of electrical energy into mechanical energy and vice versa. Piezoelectric transducers are used to measure EMI. Piezoelectric transducers are materials that generate an electric charge when they are subjected to mechanical stress.

EMI measurements can be used to monitor the structural health of a variety of structures, including bridges, buildings, and aircraft. EMI SHM systems typically consist of a network of piezoelectric transducers bonded to the structure. The transducers are used to measure the impedance of the structure at various frequencies. Changes in the impedance of the structure can indicate damage (Balouchi et al., 2019). The change is sensed electrically through changes in the apparent EMI of the piezoelectric transducer that is coupled to the host structure and is defined by

$$Z(\omega) = \left[i\omega C \left(1 - k_{31}^2 \frac{Z_{str}(\omega)}{Z_{PZT}(\omega) + Z_{str}(\omega)} \right) \right]^{-1}$$

Where $Z(\omega)$ is the equivalent electro-mechanical admittance as seen at the PZT transducer terminals, κ_{31} is the electro-mechanical cross coupling coefficient of the PZT transducer($\kappa_{31}=d_{13}/\sqrt{\bar{s}_{11}\bar{\varepsilon}_{33}}$), $_C$ is the zero-load capacity of the PZT transducer, Z_{str} is the impedance of the structure, and Z_{PZT} is the impedance of the PZT transducer (Giurgiutiu & Rogers,1998). The piezoelectric sensor-actuators (wafer transducers) are closely bonded to the structure, and their EMI variation is measured across a wide frequency spectrum located in the high kHz band of frequencies. The transducer frequency response, phase, and amplitude, the impedance response (both real and imaginary), and other significant physical parameters act as indicators of potential structure damage and reflect the level of structural integrity. The transducer approach has proven most effective in the ultrasonic range of frequencies, where changes in local dynamics due to the initiation of damage within the structure are captured. Changes at this nascent stage are very small and have minimal effect on the global dynamics of the structure, making them difficult to detect with traditional low frequency vibration techniques (Liu & Giurgiutiu,2007).

Methodology

Experimental Setup

In this section, a series of experiments were conducted using a structure made of aluminum alloy 1100, which had measurements of 500 mm in length, 30 mm in width, and 1 mm in thickness. Additionally, a PIC151 PZT patch, sized at 10 mm × 10 mm × 1 mm, was bonded 20 mm from the specimen's end. The electric impedance spectra of the sensor were examined employing the Agilent 4294A impedance analyzer. The frequency range of 18.5–20.5 kHz was determined based on the presence of piezoelectric resonance peaks observed in the impedance spectra. Figure 1 shows the experimental setup.

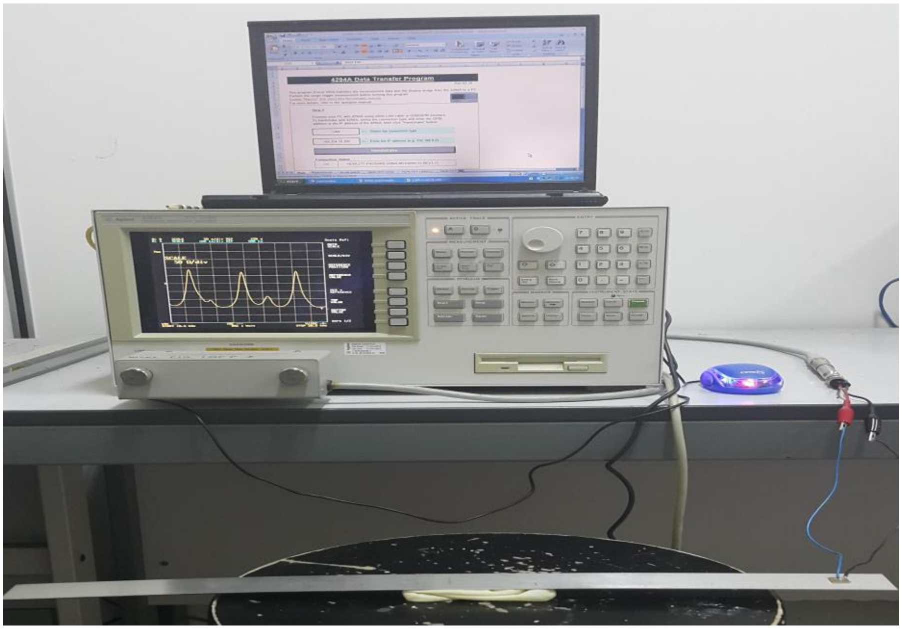

Figure 1. Experimental setup

Finite Element Analysis

Numerical simulation plays a pivotal role in understanding the intricate behavior of complex systems, and our approach involves harnessing the capabilities of ANSYS software to create a detailed model of a piezoelectric (PZT) patch bonded onto an aluminum beam. Within this simulation framework, we employed the versatile three-dimensional (3D) 20-node parabolic SOLID226 element to encapsulate the structural and piezoelectric properties of our system. SOLID226 stands out as an exceptional element within ANSYS due to its status as a coupled-field element. This element is not limited to just mechanical properties; it extends its influence across the domains of thermoelectric, piezoresistive, and piezoelectric phenomena. This unique combination of attributes within SOLID226 allows us to comprehensively capture the intricate interactions between the aluminum beam and the bonded PZT patch. Consequently, it empowers us to investigate a wide array of complex responses, making it a valuable tool in our quest to understand and optimize the behavior of such systems. The model is presented in Figure 2.

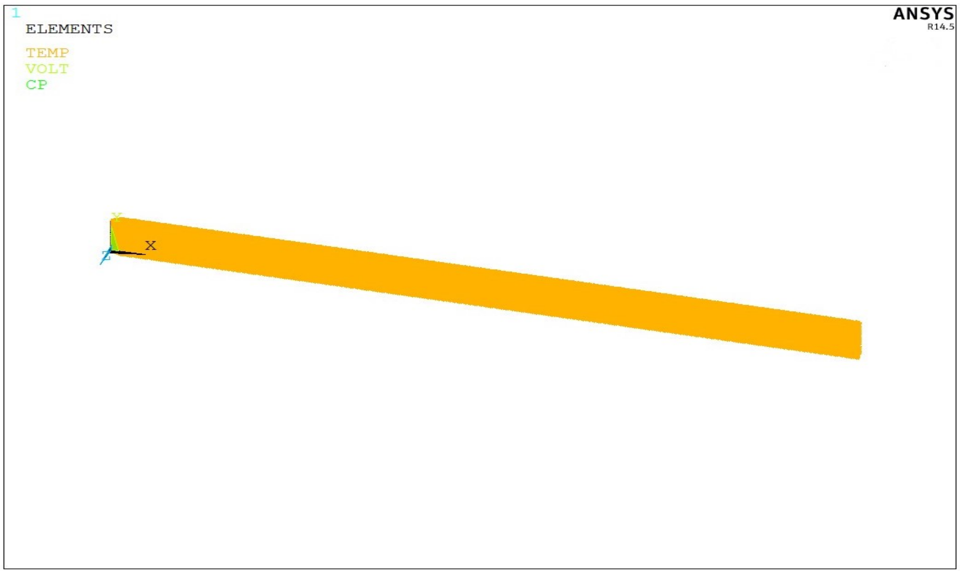

Figure 2. Aluminum beam with the PZT patch and the small steel nut

To generate frequency plots of electromechanical impedance, multiphysics harmonic analyses were performed on an elaborated finite element model with a 1V alternating voltage applied to one of the PZT electrodes. The simulation was extended to include a temperature effect, as temperature variation can affect the host structure properties, the PZT itself, and the bonding layer. This holistic approach allows us to explore the complex and interconnected interactions between electrical, mechanical, and thermal factors in the system, providing valuable insights into its behavior under different temperature conditions. To evaluate the reliability and precision of the finite element model proposed in this study, a validation process was conducted drawing upon experimental results for comparison. Figure 3 shows comparison of real part of impedance between the simulation and experimental results.

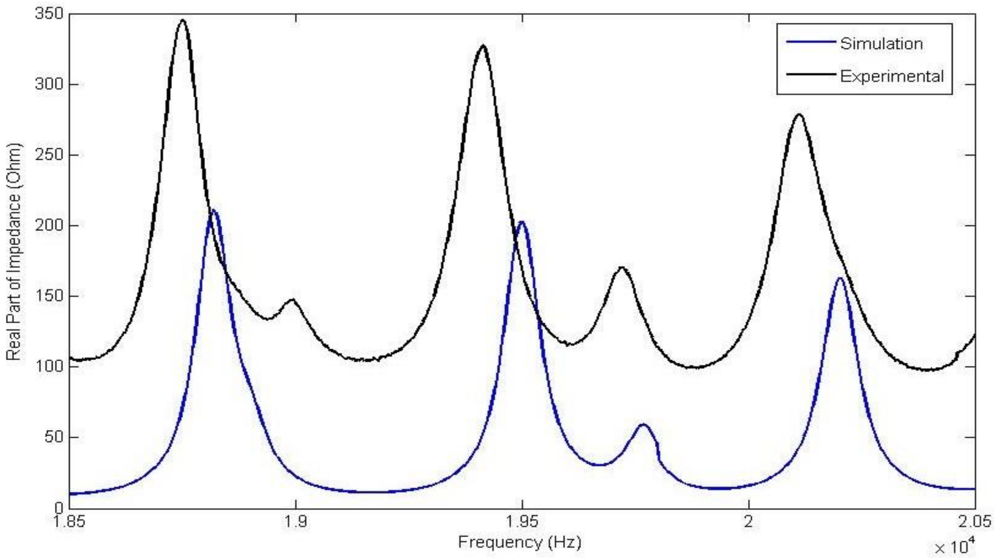

Figure 3. Aluminum beam with the PZT patch and the small steel nut

It is worth noting that the only noticeable deviation in the results was in the form of an upward shift in the experimental data, which can be attributed to the presence of a resistor, as previously documented by Djemana, et al. (2016) This validation procedure stands as a pivotal step in establishing the trustworthiness and appropriateness of the proposed finite element model for effectively simulating and analyzing the behavior of the studied system.

Results and Discussion

Temperature Effect

To thoroughly understand the effect of temperature on the electromechanical impedance (EMI) of aluminum beams, we conducted a systematic series of experiments, applying varying temperature conditions from 27 to 50°C. Figure 4 shows the real part of the EMI signatures for the aluminum beam at different temperatures, at frequencies from 18.5 to 20.5 kHz. This dataset provides a valuable resource for assessing the complex relationship between temperature variations and EMI characteristics of aluminum beams, shedding light on the material's behavior under a range of thermal conditions.

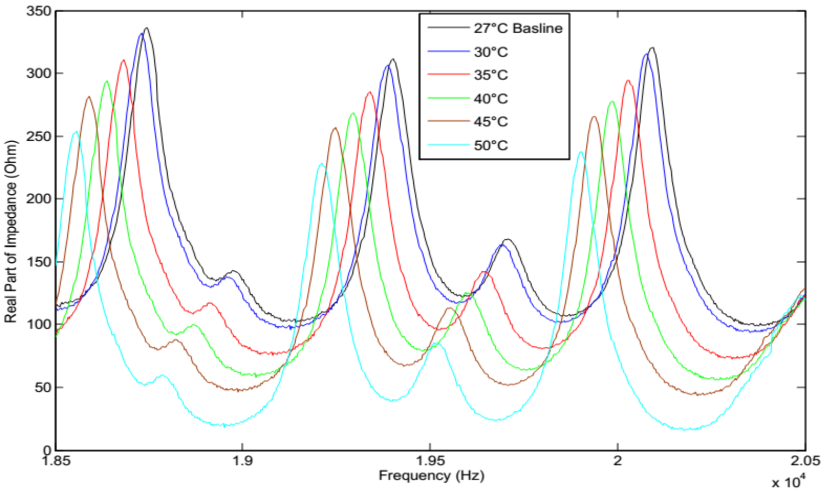

Figure 4. Aluminum beam with the PZT patch and the small steel nut

Figure 4 shows that temperature affects the EMI signature of the aluminum beam, shifting it to the left as temperature increases. This is due to the beam becoming less stiff at higher temperatures. The graph also shows some variation in electrical resistance and vertical shifts in the EMI signature.

Load Effects on EMI

Load is one of the problems occurring to moving components. When small metal particles get attached to the main rotating shaft of these sensitive structures, the changes of the modes of vibration or other negative effects on the working principles can seriously damage the total system. Structural load was induced in the structure by placing a small steel nut with dimensions of 8mm ×6mm×2mm and a mass of 0.6 g at different position from the sensor. The mass loadings of the monitored structure were approximately 14.56%. Figure 5 (a) shows the aluminum beam with the PZT patch and the small steel nut and (b) experimental result for real part of impedance for load attached to a structure. The mass loading produced variations in the mechanical impedance of the structure and could consequently be related to the structural load.

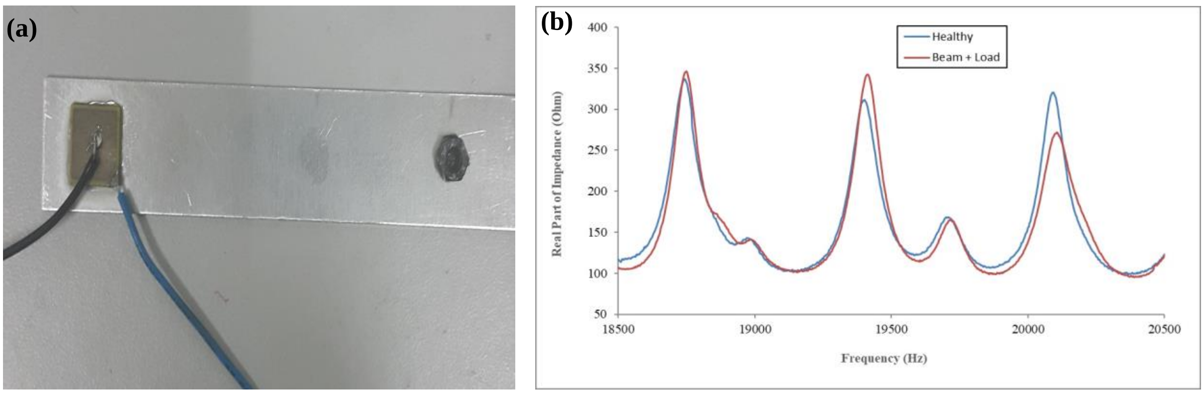

Figure 5. (a) Aluminum beam with the PZT patch and the small steel nut, (b) Real Part of impedance for Load attached to a structure.

Figure 5 (b) shows that the impedance signal amplitude increases with load positioning, but the resonance frequency remains unchanged. This suggests that the overall stiffness of the system is constant. This finding warrants further in-depth investigation.

Co-existence of Load and Temperature

During this part, in order to model more realistic cases and to prove that EMI systems can discover these problems, it was attempted to combine load and temperature damage at the same time. The model was then developed and compared. Apparently, it has the small nail-head with dimensions of 8 mm ×6 mm×2 mm and a mass of 0.6 g and it is then applied by bonding it at a distance of 100 mm from the sensor. The experimental results of real part of impedance can be seen in Figure 6. It depicts the different signals generated by the load and temperature attributed on the beam and the healthy beam.

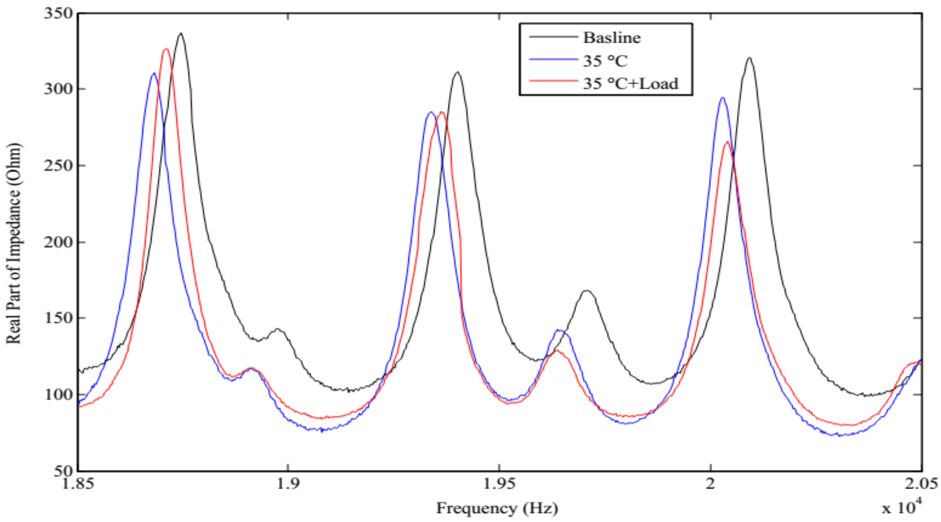

Figure 6. Real part of the electromechanical impedance resulting from temperature changes

Due to the beam signal with the load and temperature co-existence, the amplitudes increase in some frequencies for the electromechanical signature (as seen in Figure 2). However, it is also shifting to the left as the load influences the signal and it gets slightly eased compared to the data with temperature signal. Variations in the electrical resistance and some vertical shifts are also observed.

Compensation Technique

Detecting small damage within a structure becomes notably challenging when temperature variations are introduced into the equation. The reason behind this difficulty lies in the fact that temperature fluctuations can induce changes in the material's mechanical and electrical properties, often overshadowing the subtle signs of early damage. These variations can create a dynamic environment where distinguishing between the effects of temperature and actual structural damage becomes a formidable task. However, to overcome this challenge, a promising solution lies in the application of compensation techniques. These techniques are designed to account for the influence of temperature and isolate the genuine indicators of damage. By utilizing advanced algorithms and sensor networks, compensation techniques enable the identification of even minor structural changes with a high degree of accuracy, offering a practical and reliable means of damage detection within the presence of fluctuating thermal conditions. In doing so, they empower engineers and researchers to enhance the safety and longevity of critical structures and components.

Koo et al. (2009) improved on the Park & Kabeya (1999) method by creating an effective frequency shift (EFS) that countered temperature variations. (Sun et al.1995) compensated for the variations in signatures with a cross-correlation concept. Our approach is instead similar to a previous study (Sun et al.,1995) where similarities in two signals, the updated signatures and the baseline, are revealed to compensate for the frequency shifts. The compensation process involves the application of mathematical equations that can effectively neutralize or reduce the impact of temperature on the measured electromechanical impedance (EMI) signals.
The cross correlation R_{xy} of two signals x (t) and y (t) is defined by.

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T f_x(t) f_y(t+\tau) dt$$

where $f_x(t)$ is the magnitude of the signal at point x, at time t, and $f_y(t+\tau)$ is the magnitude of the signal at a point$y$ at time $t+\tau$. By varying, the relationship between the signals at x and y as a function of time is obtained. The following definition applies for sampled signals:

$$R_{xy}(m) = \frac{1}{N} \sum_{n=1}^{N-m+1} x(n) y(n+m-1)$$

m=1, 2, 3,.., N+1

Figure 7 shows the results of the compensation technique for real part of impedance signatures.

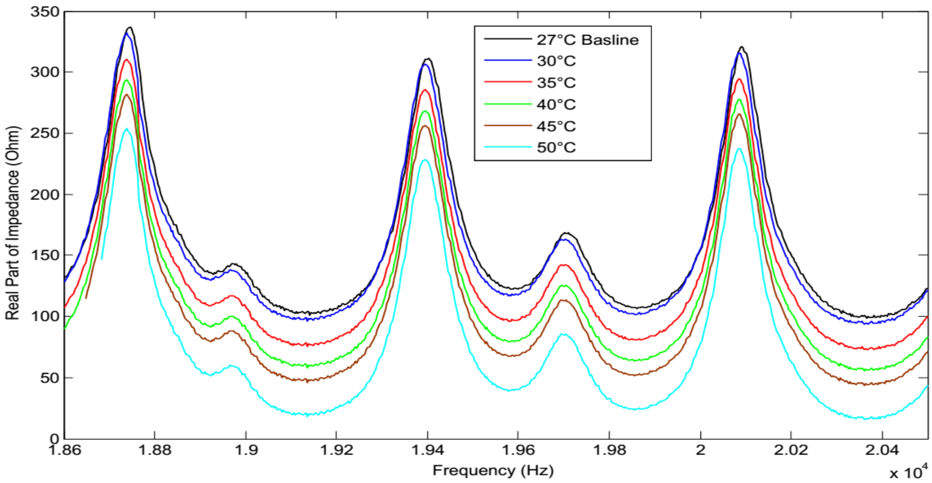

Figure 6. Experimental results for real part of impedance signatures with the proposed compensation method for the temperature effects

In Figure 7, the results of the compensation technique are vividly illustrated. When compared to Figure 4, which lacks the compensation, it is evident that this technique has effectively minimized the influence of temperature variations on the electromechanical impedance (EMI) signature. The primary objective of implementing the compensation method was to eliminate the occurrence of false positive damage detection in healthy structures. By essentially subtracting the temperature-induced variations, the EMI signature of the structure is rendered consistent across different temperature conditions, allowing for a more accurate assessment of structural damage.

The compensation technique was applied across a range of cases, each corresponding to temperatures within the previously mentioned range of 27 to 50°C, with a baseline acquired at 27°C. These results are instrumental in pinpointing the frequencies that exhibit variations due to structural damage rather than temperature effects. By isolating and emphasizing these frequencies, the compensation technique greatly enhances the precision and reliability of damage detection, even in environments where temperature fluctuations are inherent.
The correlation coefficient is the basis for the second index, CCDM, and is calculated by:

$$CCDM = 1 - C_C$$

Where CC is the correlation coefficient calculated using the real part of the electrical impedance signatures for the structure under healthy and damaged conditions, as defined before, in the same frequency range. It's calculated using the following equation

$$C_C = \frac{\sum_{k=\omega_I}^{\omega_F} \left[Z_{E,H}(k) - \overline{Z}_{E,H} \right] \left[Z_{E,D}(k) - \overline{Z}_{E,D} \right]}{\sqrt{\sum_{k=\omega_I}^{\omega_F} \left[Z_{E,H}(k) - \overline{Z}_{E,H} \right]^2} \sqrt{\sum_{k=\omega_I}^{\omega_F} \left[Z_{E,D}(k) - \overline{Z}_{E,D} \right]^2}}$$

Where the subscripts *D* and *H* indicate damaged and healthy conditions, respectively $(Z_{E,D}(k))$ and $R_E(Z_{E,H}(k))$ are the real parts of the electrical impedance signatures acquired by the measurement system of the structure's damaged and healthy states, respectively. The range of frequency *k* is measured between the initial and final frequencies. We use the real part of the impedance because it is known to be more reactive to damage or changes in the structure's integrity, and less sensitive to ambient temperature changes compared to the imaginary part (Djemana et al., 2022).

The shift profile derived from the compensation technique is a valuable tool for assessing the Cross-Correlation Damage Metric (CCDM) index, especially when it comes to distinguishing genuine load-induced variations from temperature effects. The CCDM index is chosen for this purpose due to its unique sensitivity to the shape of the electromechanical impedance (EMI) signature rather than variations in its electrical impedance amplitude.

The reason for selecting the CCDM index lies in its inherent insensitivity to changes in the electrical impedance amplitude. This attribute aligns perfectly with the objective of isolating and quantifying the influence of temperature-induced EMI variations. By focusing on the shape of the impedance signature, the CCDM index can effectively differentiate the alterations caused by changes in temperature conditions from those due to structural loads or damage.

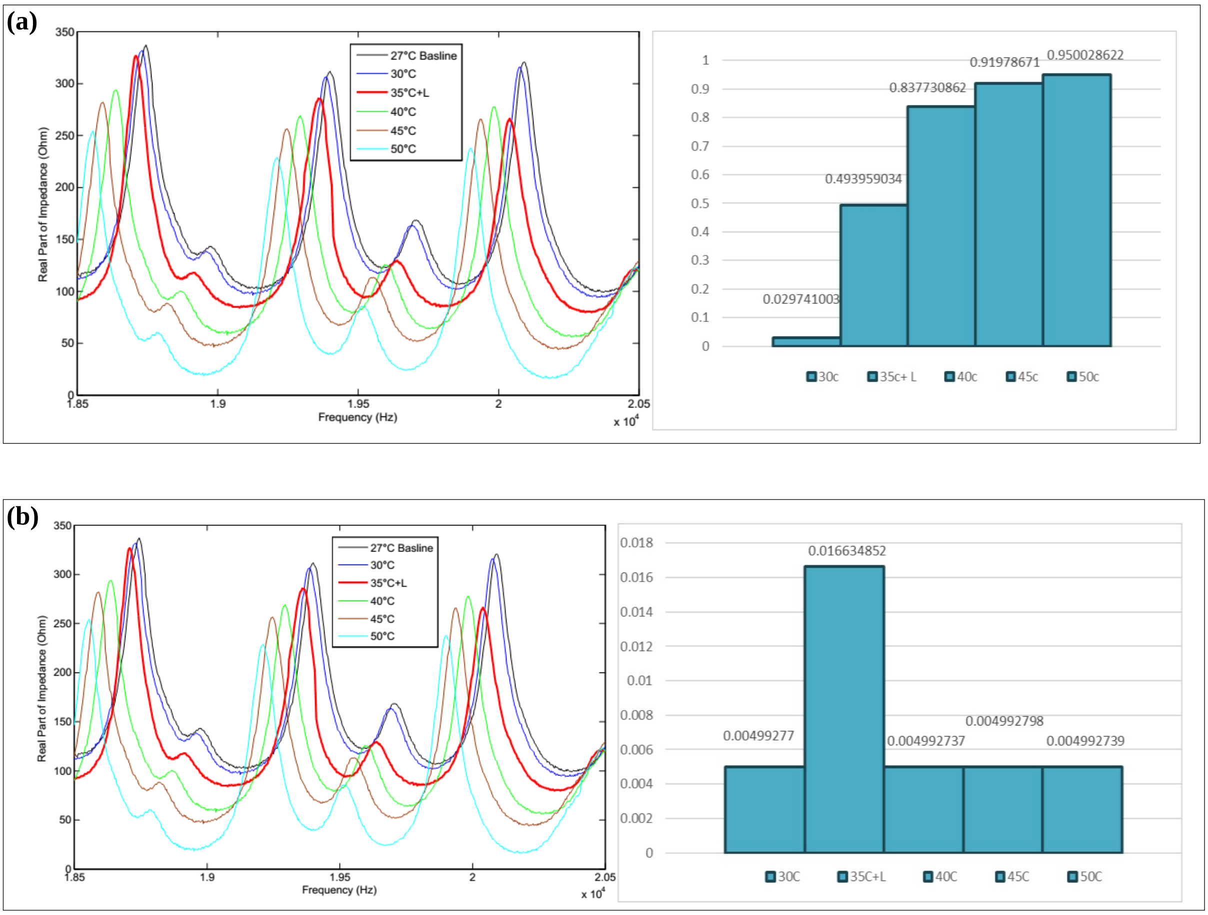

Figure 6. Experimental results for real part of impedance signatures and CCDM indices obtained for load beam (a) structure with load at 35°C without compensation and (b) with the proposed compensation method for the temperature effects.

Part (a) of the Figures vividly illustrates the challenge posed by temperature-induced ambiguities when it comes to diagnosing structural damage(load). At a temperature of 35°C, the electromechanical impedance (EMI) signatures for damaged and healthy specimens exhibit remarkable similarity, making it exceptionally difficult to discern and diagnose damage accurately under these conditions.

However, as depicted in part (b) of the Figures, the application of the compensation technique is transformative. This method substantially enhances the clarity of the results, effectively eliminating the shifts in the signatures induced by temperature fluctuations. The result is EMI signatures with peaks aligned perfectly with the baseline reference. Additionally, the Cross-Correlation Damage Metric (CCDM) indices at 35°C register as notably low, suggesting the potential for detecting even smaller damage provided that the metric index threshold is appropriately set. Importantly, these positive outcomes are consistent across the entire temperature range, including the upper limit.

The introduction of a temperature compensation technique is pivotal in this context, as it serves to measure the precise impact of temperature variations and eliminates the inherent ambiguity in the results stemming from these thermal fluctuations. Such an approach is considered indispensable for enabling real-time health monitoring of structures operating in real-world conditions.

Temperature effects remain paramount concerns in the realm of electromechanical impedance (EMI) structural health monitoring, particularly when it comes to the detection of incipient or small damage. The development and implementation of effective compensation techniques emerge as key drivers for advancing the capabilities of EMI-based structural health monitoring systems. These techniques are instrumental in ensuring the reliability and accuracy of damage detection processes under varying thermal conditions, fostering the continued evolution of this field.

Conclusion

In our experimental model, we investigated the temperature sensitivity of electrical impedance signatures in a conventional PZT sensor used for Structural Health Monitoring (SHM). We focused on an aluminum beam subjected to a range of temperatures and found that the PZT sensor's dynamic response changed significantly. These temperature-induced variations were substantial enough to potentially lead to false positive damage detections, such as notches or applied loads, even when no damage was present. This raises concerns about the structural integrity of systems monitored using PZT sensors under variable temperature conditions.To address this challenge, we developed a temperature compensation technique that precisely measures and eliminates the ambiguity caused by temperature-induced effects. Such compensation techniques are essential for real-time SHM of structures operating in real-world conditions.

Temperature effects remain a critical concern in EMI-SHM, especially for early or subtle damage detection. Effective compensation techniques are linchpins for the ongoing development and refinement of EMI-SHM systems, ensuring accurate and reliable damage detection under variable thermal conditions. These techniques are pivotal in advancing the field of EMI-SHM.

Recommendations

Advanced Data Analytics: Suggest the use of advanced data analytics techniques, such as machine learning and artificial intelligence, to enhance real-time damage detection capabilities. Encourage researchers to explore these approaches. Load-Induced Damage Thresholds: Define load-induced damage thresholds specific to different structural materials and types of damage. These thresholds can serve as reference points for assessing structural health.

Scientific Ethics Declaration

The authors of this article, published in the EPSTEM journal, solemnly affirm our unwavering dedication to upholding the highest scientific, ethical, and legal standards in the conduct and dissemination of our research. We recognize our responsibilities as researchers, not only to advance knowledge but also to do so with integrity and in compliance with established ethical and legal guidelines.

Acknowledgements or Notes

* This article was presented as a poster presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Turkey on November 16-19, 2023.

* This research was funded by a grant from International Islamic University Malaysia Research Management Grant [grant number/project id: RMCG20-032-0032].

* Laboratory of Energy Systems Technologies (LTSE). National Higher School of Technology and Engineering, Annaba, Algeria

References

Balouchi, S., Khaleghian, S., & Gholipour, A. (2019). Electromechanical impedance (EMI) technique for structural health monitoring: A review. *IEEE Access, 7,* 174392-174413.

Djemana, M., & Hrairi, M. (2016). Modelling and simulation of impedance-based damage monitoring of structures. *Int. J. Simul. Model, 15*(3), 395-408.

Djemana, M., Hrairi, M., & Yatim, N. H. M. (2022). Improving Electromechanical Impedance Damage Detection Under Varying Temperature. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 92(*1), 123-133.

Giurgiutiu, V., & Rogers, C. A. (1998). Recent advancements in the electromechanical (E/M) impedance method for structural health monitoring and NDE. In *Smart structures and materials 1998: Smart structures and integrated systems* (Vol. 3329, pp. 536-547). SPIE.

Hu, K., Lin, X., Chen, H., & Liu, Y. (2022). Temperature effect on electromechanical impedance-based damage detection of aluminum plates with cracks. *Mechanical Systems and Signal Processing, 173.*

Li, F., Wang, X., & Zhang, Q. (2020). *Effect of temperature and load on the creep behavior of polymers. Polymer Testing, 90*.

Liu, W., & Giurgiutiu, V. (2007). Finite element simulation of piezoelectric wafer active sensors for structural health monitoring with coupled-filed elements. *In sensors and smart structures technologies for civil, mechanical, and aerospace systems* (Vol. 6529, pp. 1144-1156). SPIE.

Liu, Z., Sun, Z., Wang, S., & Li, X. (2020). Temperature-compensated electromechanical impedance-based damage detection for aluminum plates with cracks. *IEEE Transactions on Instrumentation and Measurement, 70,* 1-10.

Wang, H., Yang, H., & Zhou, Y. (2022). Effect of temperature and load on the fracture behavior of concrete. *Journal of Materials Engineering and Performance, 31*(10), 8698-8711.

Zhang, Q., Chen, X., & Li, Y. (2023). Effect of temperature and load on the fatigue behavior of steel. *Engineering Fracture Mechanics, 270*.

Zhou, Y., Zhang, S., Wu, W., & Yan, Y. (2021). Damage detection for aluminum plate using electromechanical impedance method under variable temperature conditions. *Structural Health Monitoring, 20*(5), 1293-1312.

Zou, X., Li, B., & Dong, T. (2021). Structural damage detection using electromechanical impedance under varying load and temperature conditions: A state-of-the-art review. *Measurement Science and Technology, 32*(9).

Author Information

Djemana Mohamed	Meftah Hrairi
National Higher School of Technology and Engineering, 2000 pedagogical places Sidi Amar, Annaba, Algeria Contact e-mail: *m.djemana@ensti-annaba.dz*	International Islamic University Malaysia P.O. Box 10, 50728 Kuala Lumpur, Malaysia

To cite this article:

Mohamed, D., & Hrairi, M. (2023). Real-time structural damage detection using EMI under varying load and temperature conditions. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 26,* 481-490.