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Numerical and Statistical Analysis of the Influence of Damage and Temperature on EMI for Structural Health Monitoring

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Abstract: Structural health monitoring (SHM) is a process of implementing a system to monitor the structural condition of a structure and assess the structural health. SHM is used to detect damage, predict future performance, and monitor the overall structural health of a structure. Electromechanical impedance (EMI)-based SHM is a non-destructive evaluation (NDE) technique that can be used to detect damage in structures by measuring the changes in the electrical impedance of a piezoelectric transducer that is bonded to the structure. EMI has several advantages over other NDE techniques, including being a passive, local, and relatively inexpensive technique. However, one of the challenges of using EMI for structural health monitoring (SHM) is the effect of damage and temperature on the impedance of the piezoelectric transducer. As the damage and temperature changes, the impedance of the transducer will also change. This can make it difficult to detect small damage if the damage and temperature co-exist on the same structure (aluminum plate). This research presents a numerical and statistical study to investigate the effects of damage and temperature on EMI-based SHM. The numerical model uses ANSYS software to simulate an aluminum plate at different temperatures. The findings have shown that both damage and temperature have a significant effect on the impedance of the transducer. However, the study has also demonstrated that it is still possible to detect structural damage using EMI even under varying damage and temperature conditions. This underscores the robustness of EMI-based damage detection methodologies in practical applications.

Keywords: Statistical analysis, Finite element modeling, Structural health monitoring (SHM), Damage detection, Electromechanical impedance (EMI).

Introduction

Structural Health Monitoring (SHM) has emerged as a critical field within structural engineering and materials science, aiming to enhance the safety, reliability, and longevity of various civil, mechanical, and aerospace structures. Central to SHM is the utilization of advanced techniques for non-destructive evaluation, and one such powerful approach is Electromechanical Impedance (EMI).

EMI is a technique that employs piezoelectric transducers to monitor the structural integrity of systems by analyzing the impedance signatures of materials and structures. It has gained increasing attention due to its capability to provide real-time data and early damage detection, making it a valuable tool in predicting and preventing structural failures. The performance and reliability of engineering structures are intimately linked to the material properties, operational conditions, and the ability to detect potential issues promptly.

Two crucial aspects in this context are the understanding of temperature effects on structural materials and the early detection of small damages, particularly in aluminum plates. The influence of temperature variations on the behavior of materials is a topic of significant importance in fields ranging from aerospace to civil engineering. The mechanical, thermal, and even electrical properties of materials can change in response to temperature fluctuations, which, in turn, can impact the structural integrity and safety of components. Concurrently, the early detection of small damages in aluminum plates is a fundamental concern for ensuring the continued reliable performance of structures.

Recently, there has been a growing focus on addressing the impacts of temperature in scientific experiments. This challenge has been particularly significant in the context of various practical models, some of which include: Tian et al. (2017) investigated the electromechanical impedance (EMI) signature of aluminum plates with small damages under temperature variation. They found that the EMI signature of a damaged plate is shifted to the left as the temperature increases. 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. Chen et al. (2019) developed a modified whale optimization algorithm for temperature compensation in EMI-based damage detection of aluminum plates with cracks. They found that their modified whale optimization algorithm was able to accurately compensate for temperature effects in EMI-based damage detection systems.

Detecting and addressing small damages before they escalate into critical issues is vital in preventing costly repairs or, worse yet, catastrophic failures. This paper serves as a comprehensive exploration of the dual concerns related to temperature effects on structural materials and the early detection of small damages in aluminum plates. We outline the objectives and methodology, which aim to shed light on the complex interplay between temperature and structural materials while offering practical insights into damage detection techniques and mitigation strategies.

Structural Health Monitoring Based on Electromechanical Impedance (EMI)

Principal structural health monitoring based on electromechanical impedance (EMI) is a non-destructive testing (NDT) method that uses piezoelectric transducers to monitor the health of structures. The principle is based on the fact that the electrical impedance of a piezoelectric transducer changes when it is bonded to a structure and the structure undergoes mechanical damage.

EMI-based structural health monitoring systems typically consist of a network of piezoelectric transducers that are bonded to the structure to be monitored. The transducers are excited with an alternating electric field and the electrical impedance of each transducer is measured. The electrical impedance measurements are then compared to a baseline set of measurements taken when the structure is known to be in good condition. If there is a significant change in the electrical impedance of any of the transducers, it indicates that there may be damage in the structure. EMI-based structural health monitoring systems have a number of advantages over other NDT methods. They are non-destructive, relatively inexpensive, and easy to implement. They are also very sensitive to small or incipient damage, making them ideal for detecting damage early on.

Finite Element Model for Aluminum Plate

Finite element (FE) analysis was performed deterministically to model a circular AL2024 aluminum plate in free suspension with PZT transducers bonded to its surface by a thin adhesive layer. The adhesive was factored into the model. The geometry of the thin plate with bonded piezoelectric wafer active sensors (PWAS) was $r = 50.08\,mm, h = 0.835\,mm, r_a = 4\,mm$, and $r_b = 1\,mm$ (Figure 01). The thickness of the adhesive layer was 100 μm. The PZT was made of PZT-5A. A SOLID186 20-node parabolic element was used to build the structure, and a SOLID226 element was used for the PZT models. The SOLID226 element is a coupled-field element with thermoelectric, piezoresistive, and piezoelectric capabilities, making it an excellent choice for modeling complex problems. A SOLID95 element was used to model the adhesive layer, which also includes the same full electromagnetic (EM) coupling as piezoelectric materials. The finite element model of the thin plate with bonded PWAS is shown in the Figure 02.

To assess the accuracy of the proposed FE model, it was subjected to a validation test benchmarked from Rugina et al. (2014) (Figure 03). Validation was accepted based on the approximation of curve trend and magnitude, creating a close reproduction of the experimental results.

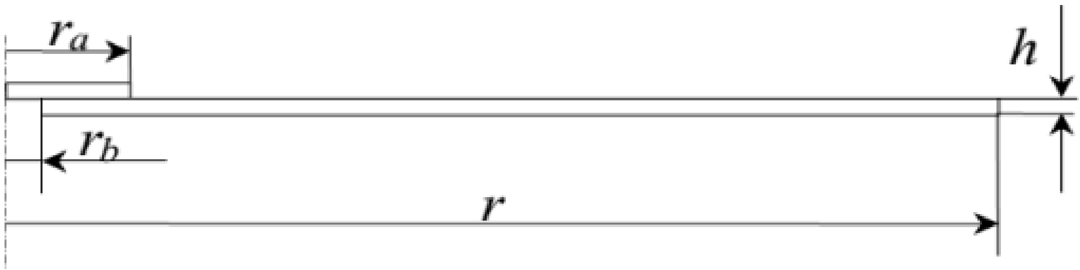

Figure 1. The geometry of the thin plate with bonded piezoelectric wafer active sensors (PWAS)

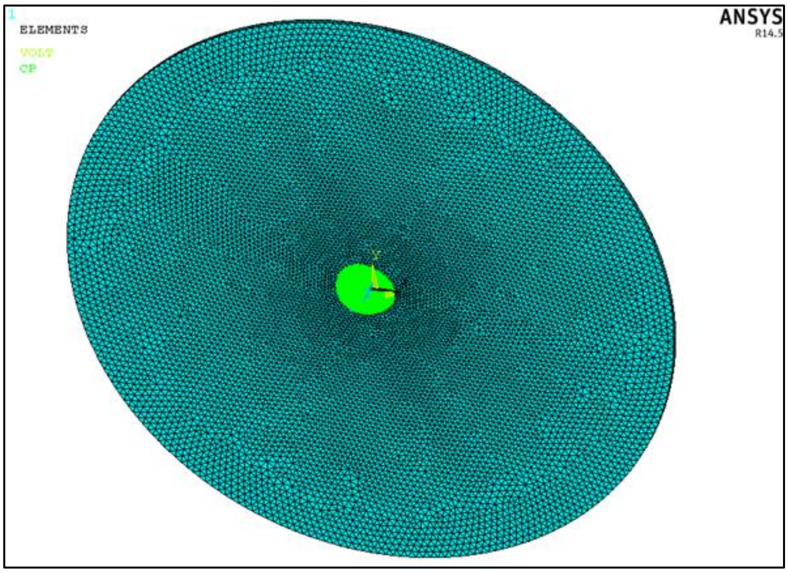

Figure 2. FE model of the thin plate with bonded piezoelectric PWAS

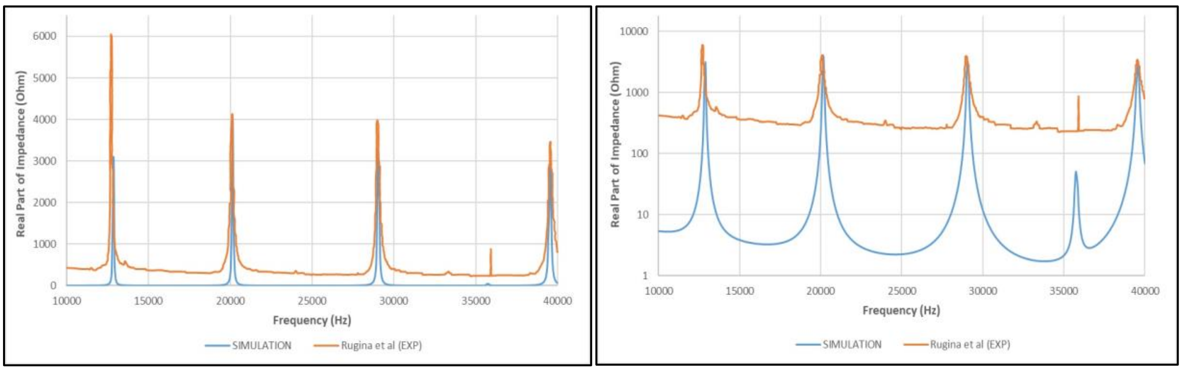

Figure 3. Comparison between the simulation and experimental results (Rugina et al.,2014) for the circular aluminum plate

In order to evaluate the reliability and accuracy of the finite element model proposed in this study, it underwent a validation process, which was based on a benchmark test drawn from the research conducted by Rugina et al. (2014) The validation was deemed successful when the model demonstrated a close approximation of the experimental results, both in terms of reproducing the trend of the data and closely matching the magnitudes observed in the original experiments. The noticeable difference is only observed in terms of the upward shifting of the experimental results due to the usage of a resistor (Djemana et al., 2016) This validation process serves as a critical step in affirming the credibility and suitability of the proposed finite element model for simulating and analyzing the behavior of the studied system.

Effect of Temperature on Aluminum Plate

In the pursuit of a comprehensive understanding of the temperature effects on the electromechanical impedance (EMI) of aluminum plates, a series of experiments was conducted, applying varying temperature conditions to the material between 25 and $70°C$. Figure 04 shows the real part of the electromechanical impedance signatures for aluminum plate with different temperature for frequencies from 10 to 40 kHz.

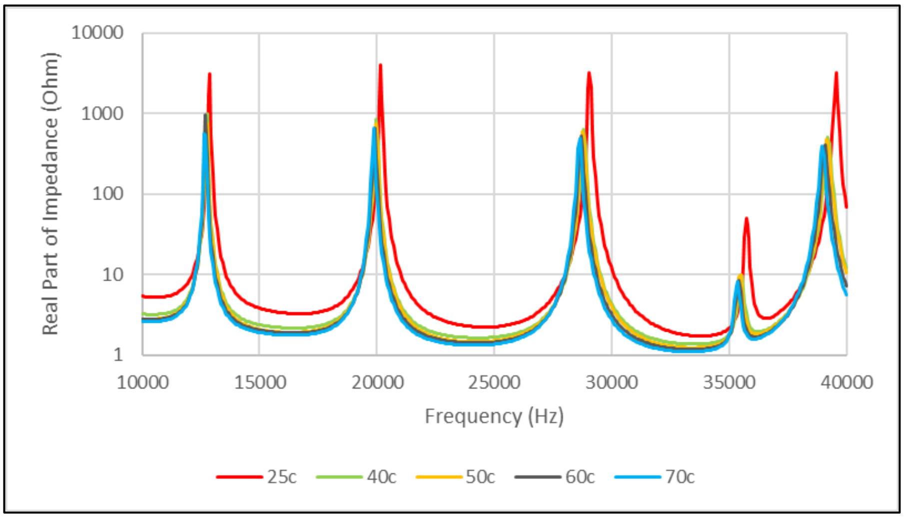

Figure 4. Real part of the electromechanical impedances resulting from temperature changes

In Figure 4, a notable frequency shift can be observed in the electromechanical signature as the temperature is change. Specifically, an increase in temperature leads to a leftward shift in the signature. These shifts are indicative of significant alterations in the material's behavior, which can be attributed to the changing thermal conditions. Additionally, alongside these frequency shifts, variations in electrical resistance are evident, further underscoring the intricate relationship between temperature and the material's impedance characteristics. The presence of vertical shifts in the signature further emphasizes the dynamic nature of the material's response to changing temperature conditions, offering valuable insights into the nuanced effects of thermal fluctuations on its electromechanical behavior.

Co-Existence of Crack Damage and Temperature on Aluminum Plate

The impact of additional types of damage delved into examining, specifically, both structural damage and temperature variations. As part of this exploration, we conducted experiments where we simultaneously introduced crack damage and controlled temperature change with $40°C$. In this sub section, structural damage was simulated. Two different sizes of the cracks took with the form of a 0.3mm wide, 20mm long (**crack 1**) and 0.15mm wide,10mm long (**crack 2**) is the following (Figure 05).

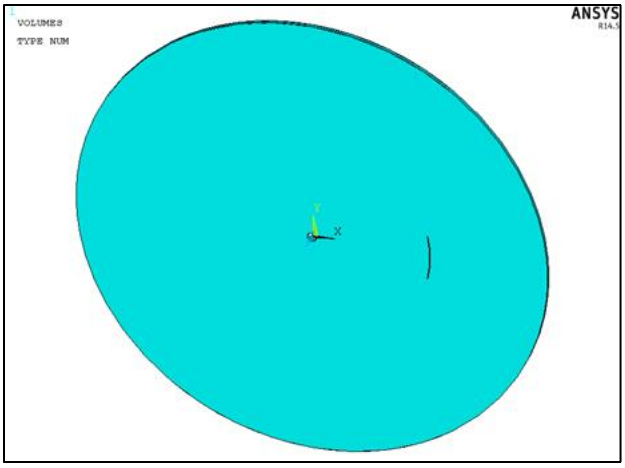

Figure 5. FE model of aluminum thin plate with crack

This approach aimed to simulate more realistic scenarios, mirroring real-world conditions where multiple factors can influence the behavior of structural components. By combining these forms of damage and temperature fluctuations, we sought to demonstrate the capabilities of EMI systems in detecting and characterizing such complex issues. Figure 06 shows the real part of the electromechanical impedance signatures for aluminum plate with different crack damage at $40°C$ for frequencies from 10 to 40 kHz.

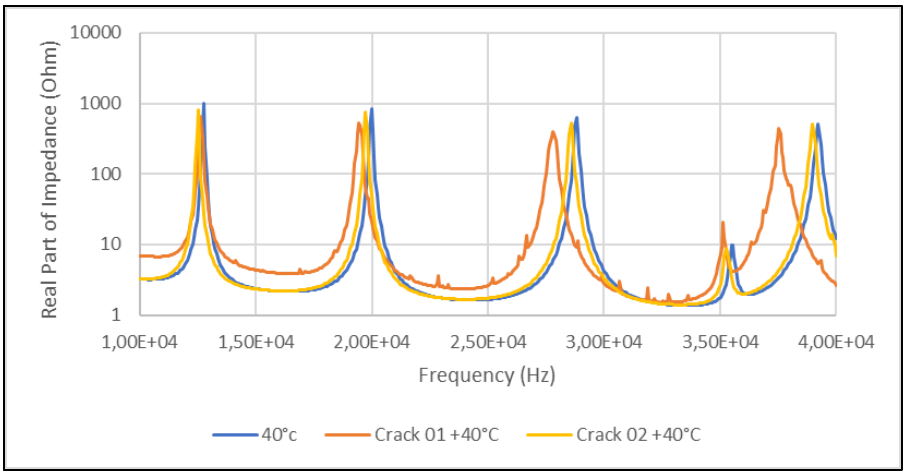

Figure 6. Real part of the electromechanical impedances with different crack damage at 40°C

Observing the data, it becomes apparent that the electromechanical signature associated with the presence of temperature on the cracked plate exhibits a decrease when compared to the signature corresponding solely to temperature variations. Furthermore, this signature undergoes a discernible shift towards the left side. This phenomenon can be attributed to the decreasing stiffness of the structure when subjected to temperature fluctuations. The decrease in stiffness influences the structural response, resulting in alterations in the impedance signature and its leftward shift. This observation underscores the sensitivity of the electromechanical impedance technique in detecting structural changes induced by varying temperature conditions, ultimately contributing to a deeper understanding of the system's behavior and mechanical integrity.

Mathematics and Statistical Analysis

The parameters of clearance factor, crest factor, and impulse factor for three different signals: 40°C and two cracks. This is an interesting observation, as it suggests that these three signals may have a common underlying cause. One possible explanation for this observation is that the three signals are all generated by the same physical process, but under different conditions. For example, the cracks may be caused by the same type of stress, but at different levels of severity. Another possibility is that the three signals are all generated by different physical processes, but that these processes have similar statistical properties. This could be the case, for example, if the three signals are all generated by random noise.

Further research is needed to determine the exact cause of the identical signal parameters in these three signals. However, the observation itself is intriguing and suggests that there may be a deeper connection between these signals than is currently understood. Other signal parameters, such as peak amplitude, mean value, standard deviation, skewness, kurtosis, spectral distribution, autocorrelation function, and power spectral density, may also be identical in the three signals. These parameters can all be used to characterize the shape and frequency content of a signal. By comparing these parameters for the three signals, we may be able to identify additional similarities or differences between them. If the other signal parameters are also identical in the three signals, this would further support the hypothesis that they have a common underlying cause. It would also suggest that the identical signal parameters could be used to develop new methods for crack detection or other diagnostic tasks.

Statistical Analysis

Statistical analysis of impedance signals can be used to detect cracks in materials by identifying changes in the mean, range, standard deviation, skewness, and kurtosis of the impedance signals. These changes are caused by the presence of a crack disrupting the flow of current through the material. By comparing the statistical parameters of the impedance signals for the cracked material to those for a reference material, it is possible to identify the presence of cracks and even estimate their size and severity. This method is non-destructive, relatively inexpensive, and can be used to inspect a wide variety of materials.

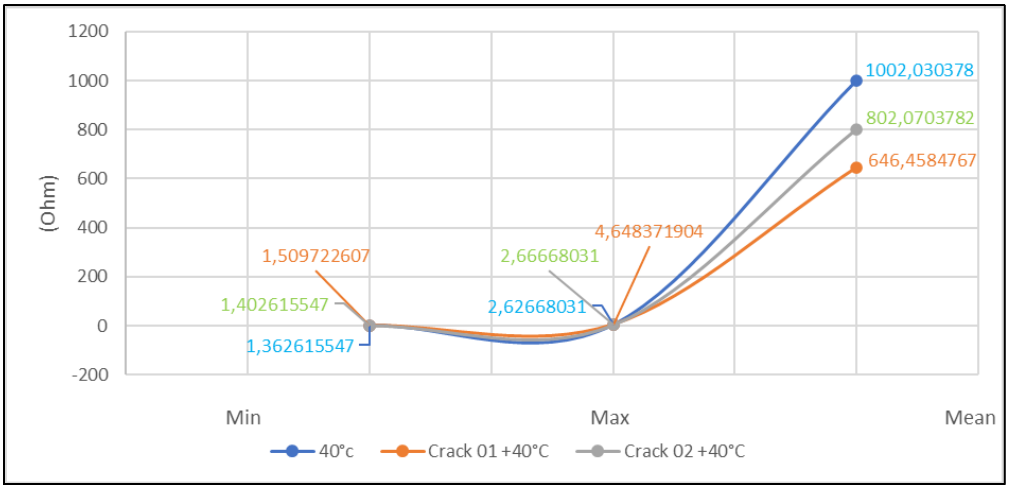

Figure 7. Max, min and mean of signal 40°C, Crack 1 & 2

The graph shows that the mean value of the real part of impedance increases with increasing size of the crack. This is because the presence of a crack reduces the cross-sectional area of the plate, which increases the resistance of the plate. It also shows that the range of the real part of impedance (i.e., the difference between the maximum and minimum values) increases with decreasing size of the crack. This is because the presence of a crack introduces a non-uniformity in the distribution of current, which leads to a wider range of impedance values. An increase in the mean value of the real part of impedance and a decrease in the range of the real part of impedance are both indicative of the presence of a crack. The size of the crack can be estimated by comparing the mean and range values to those for a plate with no crack. This information could be useful for developing non-destructive testing (NDT) methods for detecting cracks in materials. By measuring the impedance of the material at different frequencies and temperatures, it may be possible to identify the presence of cracks and even estimate their size and severity.

Mathematical Analysis

Detecting crack damage in aluminum plates with temperature is a challenging task, as temperature can have a significant impact on the properties of aluminum and the propagation of waves through the material. However, there are a number of methods that can be used to detect crack damage in aluminum plates, even in the presence of temperature variations. Detecting crack damage in aluminum plates with temperature is a challenging task, as temperature can have a significant impact on the properties of aluminum and the propagation of waves through the material. However, there are a number of methods that can be used to detect crack damage in aluminum plates, even in the presence of temperature variations. However, it is important to note that the accuracy and reliability of each method will depend on a number of factors, such as the type of crack damage, the temperature of the plate, and the specific testing method used, alignment technique for the effects of temperature variation can be accomplished through a variety of methods. (Park et al.1999) modified the RMSD index to compensate for shifts in both frequency and amplitude. Our approach is instead similar to a previous study (Park et al.1999).

The root mean square deviation (RMSD) index is a statistical measure of the similarity between two or more sets of data. It is calculated by taking the square root of the average squared difference between the two sets of data. The lower the RMSD index, the more similar the two sets of data are. The RMSD index can be used to compare two signals in a number of different ways. For example, it can be used to compare the waveforms of two signals, the amplitudes of two signals, or the frequencies of two signals. The specific way in which the RMSD index is used depends on the specific application. Here is an equation for the RMSD index:

$$RMSD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2}$$

where:

RMSD is the root mean square deviation
N is the number of samples in the two signals
$\boldsymbol{x_i}$ is the *i*-th sample of the first signal
$\boldsymbol{y_i}$ is the *i*-th sample of the second signal

Figure 08 shows the impedance of the PZT transducer for a healthy beam condition at a regulated temperature of 40°C with the proposed alignment method for the temperature effects.

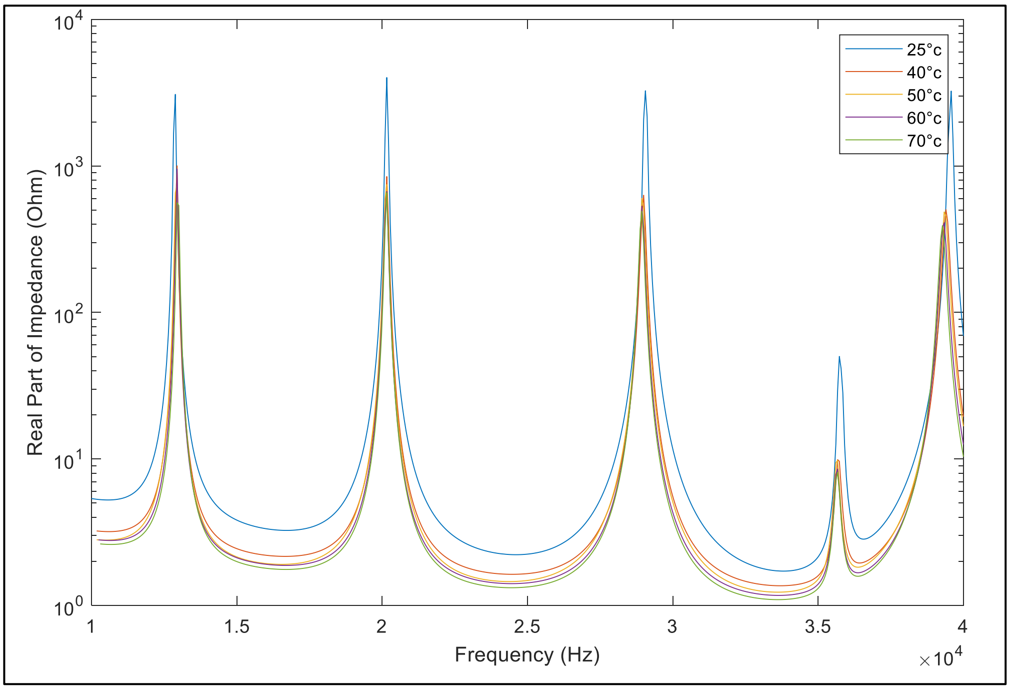

Figure 8. Alignment method for real part of the electromechanical impedances under temperatures varying

The figure shows the impedance of a PZT transducer for a healthy beam condition at a regulated temperature of 40°C, with the proposed alignment method for the temperature effects. This suggests that the proposed alignment method is effective at compensating for the effects of temperature variations on the electromechanical impedance (EMI) signature. Alignment method can be very effective in reducing or eliminating the effects of temperature on EMI signatures. This is important for crack detection in aluminum plates, as it allows crack damage to be detected even in the presence of temperature variations.

The proposed alignment method could be used to develop non-destructive testing (NDT) methods by measuring the impedance of a material at different frequencies and temperatures, and then aligning the impedance spectra using the proposed method, it may be possible to identify the presence of cracks and even estimate their size and severity. The RMSD index is a powerful tool for comparing two signals. It is a simple and robust measure of similarity that can be used in a variety of applications. Its index is selected for this purpose because it is uniquely sensitive to the shape of the electromechanical impedance (EMI) signature, rather than to variations in its electrical impedance amplitude. In other words, the RMSD index is insensitive to changes in the overall strength of the EMI signal, but it is sensitive to changes in the pattern of the signal. This makes it ideal for isolating and quantifying the influence of temperature-induced EMI variations. By focusing on the shape of the impedance signature, the RMSD index can effectively distinguish between the changes caused by changes in temperature conditions and those caused by structural loads or damage.

Figure 09 shows that the EMI signatures of damaged and healthy aluminum plates at 40°C were similar enough to make damage difficult to diagnose at that temperature. According to Figure 11 of Figures, the compensation technique made the results significantly easier to interpret. The shifts in the signatures were eliminated and the peaks were perfectly aligned with the baseline result. Additionally, the RMSD indices at 40°C (Figure 12) were very low, suggesting that smaller damage could be detected with an appropriately set threshold. The results were acceptable across the entire temperature range, even at the upper end. Temperature effects remain a critical issue in EMI structural health monitoring, especially for detecting nascent or small damage. Effective compensation techniques are essential for the continued development of this field.

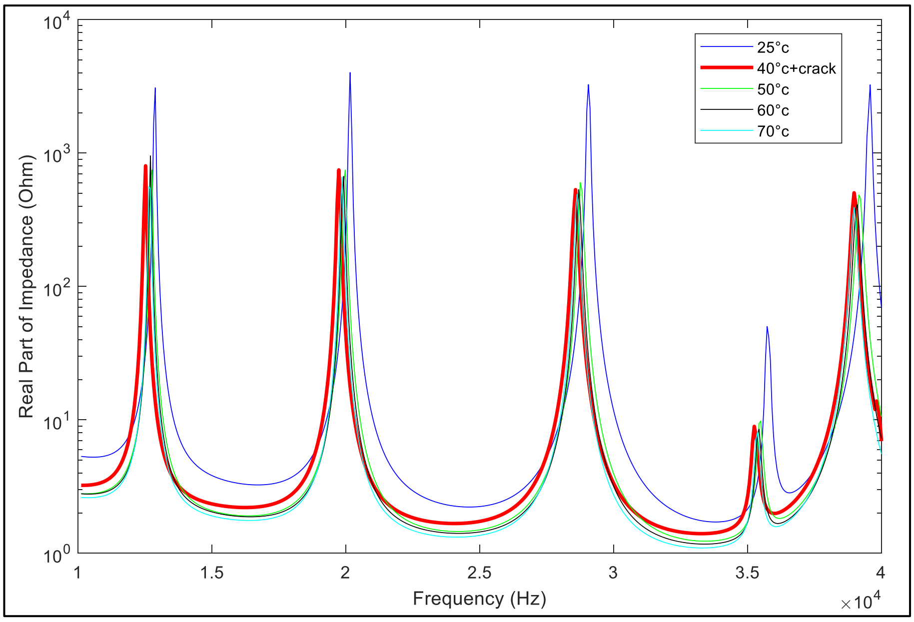

Figure 9. Real part of the electromechanical impedances with crack

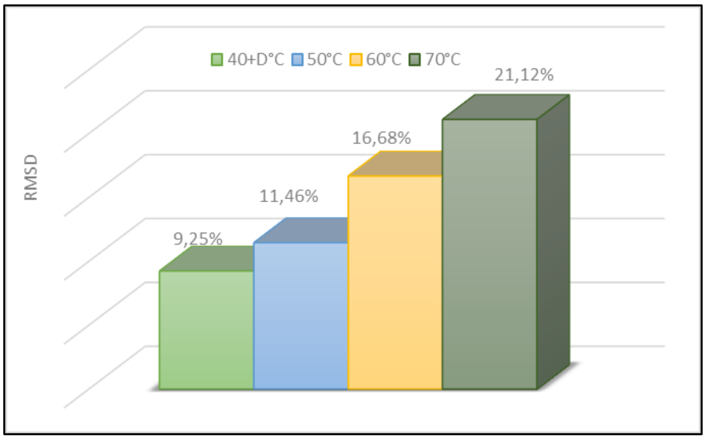

Figure 10. RMSD before alignment under temperatures varying

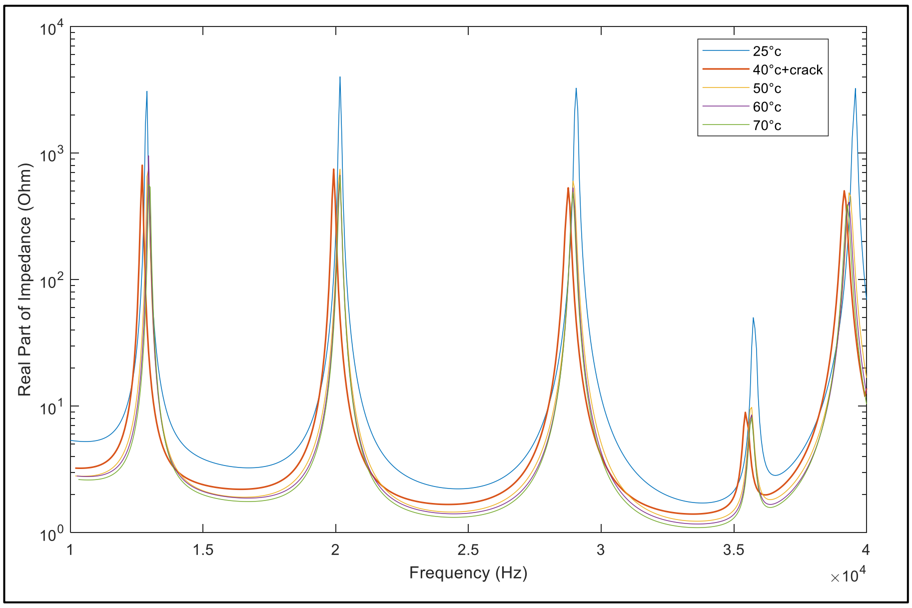

Figure 11. Alignment method for real part of the electromechanical impedances with crack

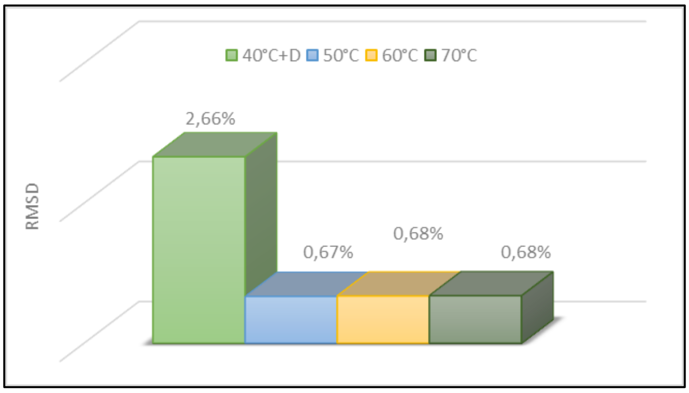

Figure 12. RMSD after alignment with crack

Conclusion

In conclusion, our study has provided valuable insights into the complex interplay between temperature variations and the presence of small cracks in aluminum plates. Through a combination of mathematical and statistical analyses, we have investigated the effects of temperature and damage coexisting in the same structural element, with a particular focus on the early detection of small cracks in the presence of thermal fluctuations. These investigations sought to unravel the intricate interplay between temperature and EMI, recognizing that temperature fluctuations can induce notable changes in the mechanical and electrical properties of structural materials.

By systematically subjecting aluminum plates to different temperature regimes, we aimed to scrutinize how alterations in temperature impact the impedance signatures of the plates. This rigorous approach allowed us to discern the shifts in resonance frequencies, impedance magnitude, and phase characteristics under changing thermal conditions. Furthermore, the study explored the sensitivity of EMI as a non-destructive evaluation technique to temperature variations. The results not only contribute to the fundamental understanding of the temperature-EMI relationship but also have practical implications for the assessment of structural health in real-world applications exposed to varying environmental conditions.

Recommendations

Recommendations for future work on EMI-based SHM and mathematical analysis:

- Develop signal processing and data analysis techniques to extract features from impedance signals that are more correlated with the presence of cracks. This would improve the accuracy and reliability of EMI-based SHM systems.
- Develop theoretical models to predict the impedance of a cracked material in more complex geometries. This would allow EMI-based SHM systems to be used to inspect a wider range of structures and components.

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

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