Improving Electromechanical Impedance Damage Detection Under Varying Temperature

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ARTICLE INFO

ABSTRACT

The field of structural health monitoring has seen a fundamental shift in recent years, as researchers strive to replace conventional non-destructive evaluation techniques with smart material-based techniques. Perhaps the most promising of smart material techniques for developing structural health monitoring (SHM) systems is electromechanical impedance (EMI) which can be used for real-time structural damage assessment. In EMI, mechanical resonances of structure can be seen in electrical characteristics of piezoelectric transducers due to electromechanical coupling of transducer with the structure. Existence of damage will cause a structural stiffness change and therefore the resonant characteristics of the structure will be altered. This article presents an experimental and numerical study to investigate the effects of notch damage with temperature on the electrical impedance of the piezoelectric sensor used in the EMI technique. The practical implementation of the compact EMI method utilizes as its main apparatus an impedance analyser (Model Agilent 4294A) that reads the in-situ EMI of piezoelectric wafer active sensors (PWAS) attached to the monitored structure. The finite element modelling used ANSYS software three-dimensional (3D) capability to simulate an aluminium beam at varying temperatures. Real-time monitoring of the structure is achieved based on harmonic measurements. The results conclusively showed that the proposed temperature compensation technique eliminates the results ambiguity and enabled the EMI system to detect small damages that were otherwise indiscernible.

1. Introduction

Maintaining the safety of a structure can be assured by means of Structural health monitoring (SHM). The assessment of a structural health is particularly important for aged aerospace vehicles and civil engineering structures subjected to heavy periodic loads. For such structures, SHM is a complex activity that involves the interaction of numerous factors. It has been shown that aerospace maintenance and repairs represent about a quarter of commercial fleet's operating costs [1]. One of the possible solutions to decrease these costs is to couple the selective use of condition-based

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maintenance with the implementation of innovative SHM systems, which will continuously assess the structural integrity through online structural health monitoring. Continuous SHM would lead to considerable life-cycle cost reduction since the damaged part can be replaced in time, preventing the failure of the whole structure and the loss of human lives. Another critical feature of a SHM system is its ability to detect the initiation and growth of structural damage at a nascent stage. This would bring a considerable safety enhancement. Such safety enhancement creates a compelling reason to have high-quality online structural health monitoring (SHM) in both modern and aging structures [2].

Focus of intensive study for decades, the electromechanical impedance (EMI) method has demonstrated in several studies that it can be useful for complex and lab-scale structures. There are, however, several practical difficulties that have impeded the application of EMI to real-world structures in a useful and reliable way. Temperatures effects have lately been addressed in the scientific experiments as challenging of many practical models. Sepehry *et al.,* [3] presented theoretical and experimental results by ISHM method in order to validate the proposed model to consider the temperature dependency of PWAS material properties, a temperature-dependent model is developed for a PWAS bonded to a Euler Bernoulli cantilever beam. The comparison of theoretical and experimental results demonstrates a good improvement in ISHM modelling where temperature variation is present. Baptista *et al.,* [4] proposed an EMI system capable of real-time data acquisition from multiple sensors that incorporated a temperature compensation functionality, eliminating one cause of incorrect diagnoses in structural monitoring. The experimental results show conclusively that the proposed methodology is efficient and feasible for real-time SHM. Baptista *et al.,* [5] Studied experimentally the effect of temperature on the electrical impedance of the 5H PZT sensors commonly used in the EMI technique. They found that the temperature effects were strongly frequency-dependent, which may motivate future research in the SHM field. Safaeifar and Karimi [6] looked at how temperature changes affected the natural frequencies of a monitored structure. It has been discovered that as the temperature rises, the inherent resonant frequency of a structure reduces. Wandowski *et al.,* [7] suggested an approach for compensation of temperature influence on damage detection in Carbon fiber–reinforced polymer using electromechanical impedance method. Gianesini *et al.,* [8] established a way to adjust for the temperature effect in the electromechanical impedance technique. The method is particularly general since it may be applied to nonlinear (polynomial) temperature and/or frequency dependences observed on the impedance signatures horizontal and vertical shifts. The compensation is performed via a computer program that may be easily integrated into real-time damage detection systems. In the temperature range of 24C to 80C and the frequency range of 10 to 90 kHz, this compensation technique was successfully applied to two aluminum beams and one steel pipe, limiting the effect of temperature changes on damage detection structural health monitoring systems. Abbas *et al.,* [9] developed an experimental setup using an EMI technique to detect the presence of fatigue cracks in stainless steel (304) beams and assess the effect of temperature fluctuations on the electrical impedance of piezoelectric sensors. They conducted a series of experiments in a controlled temperature setting (25°C–160°C). The dielectric constant ε_{33}^{T} which is known as the temperature-dependent constant of the PZT sensor, has been found to have a significant impact on the electrical impedance signature. Furthermore, the effective frequency shift (EFS) approach was used to provide significant temperature compensation for the current impedance signature of the PZT sensor in comparison to the reference signature over the measurement system's extended frequency bandwidth.

It is known that temperature and stress are two important environmental loads in practical engineering fields, and the correlated EMI research referring to temperature and stress load have also been reported [10-13]. In this paper, the impact of varying temperatures on sensor impedance signatures is experimentally and numerically studied. It is to be noted that, most of the existing works

have considered this problem within the context of experimental set up or otherwise mathematical modelling but none have taken into consideration the effect of temperature with notch damage. This study was carried out experimentally and numerically. In addition, compensation technique presented and discussed for the effects of temperature variation were accomplished through a variety of methods. Therefore, the results presented here are of unique significance and novelty.

2. Electromechanical Impedance Technique
2.1 Theoretical Background

The EMI method for SHM and Non-Destructive Evaluation (NDE) is based upon changes in structural impedance at its drive point that's mean point of concentration or point at which the structural behavior/properties may change. These changes identify damage in the structure. 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

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

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 [14]. 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 [15].

2.2 Damage Sensitive Indexes

Basic structural damage is typically characterized with the use of damage indices. Two of the more commonly used indices include the root mean square deviation (RMSD) and the correlation coefficient deviation metric (CCDM). When a structure is considered healthy, baseline, or reference, EMI signatures are taken. These are compared to later signatures to assess structure health.

The Euclidean norm is the basis for the RMSD index; several variations of this index can be found in the literature. In this study, the RMSD index was calculated by

$$RMSD = \sqrt{\frac{\sum_{k=1}^{N} \left(R_E\left(Z_{E,D}(k)\right) - R_E\left(Z_{E,H}(k)\right) \right)^2}{\sum_{k=1}^{N} \left(R_E\left(Z_{E,H}(k)\right) \right)^2}} \tag{2}$$

where the subscripts D and H indicate damaged and healthy conditions, respectively; $R_E(Z_{E,D}(k))$ 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.

The correlation coefficient is the basis for the second index, *CCDM,* and is calculated by

$$CCDM = 1 - C_C \tag{3}$$

Where C_C 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 is calculated using the following equation [16].

$$C_C = \frac{\sum_{k=1}^{N}\left(R_E\left(Z_{E,H}(k)\right) - \overline{R_E\left(Z_{E,H}\right)}\right)\left(R_E\left(Z_{E,D}(k)\right) - \overline{R_E\left(Z_{E,D}\right)}\right)}{\sqrt{\sum_{k=1}^{N}\left(R_E\left(Z_{E,H}(k)\right) - \overline{R_E\left(Z_{E,H}\right)}\right)^2}\sqrt{\sum_{k=1}^{N}\left(R_E\left(Z_{E,D}(k)\right) - \overline{R_E\left(Z_{ED}\right)}\right)^2}} \tag{4}$$

3. Methodology
3.1 Experimental Setup

The experimental set-up consists of an impedance analyzer (Model Agilent 4294A), a personal computer equipped with data acquisition software, and an interface cable, as shown in Figure 1. Several experiments were performed using an aluminum alloy 1100 structure with dimensions of 500 mm × 30 mm × 1 mm and a mass of 4.12 g. A PIC151 PZT patch with dimensions of 10 mm ×10 mm ×1 mm was bonded 20 mm from the end of the specimen. The beam was heated with a temperature controller and a thermocouple to measure the temperature of the structure. Simultaneously, the impedance analyzer was used to test the electric impedance spectra of the sensor. Experiments were performed at temperatures between 27 and 50°C in steps of 5°C. According to the location of piezoelectric resonance peaks appeared in the impedance spectra, the frequency range of 18.5–20.5 kHz.

An uncertainty analysis was performed to evaluate the accuracy of the data in this study. This analysis was conducted on the temperature which is the only measured quantity. The total uncertainty, u_{total}, for the thermocouple is estimated according to the procedure reported in the literature, and this is given by the relation [17]

$$u_{total} = \sqrt{u_{inst}^2 + u_{rand}^2} \tag{5}$$

where u_{inst} is the instrument uncertainty based on the resolution and the accuracy of the temperature measurement caused by the voltage measurement and u_{rand} is the random uncertainty based on the data fluctuation. Following this procedure, the uncertainty in the temperature was evaluated to be around ±0.25°C which is primarily due to the instrument uncertainty.
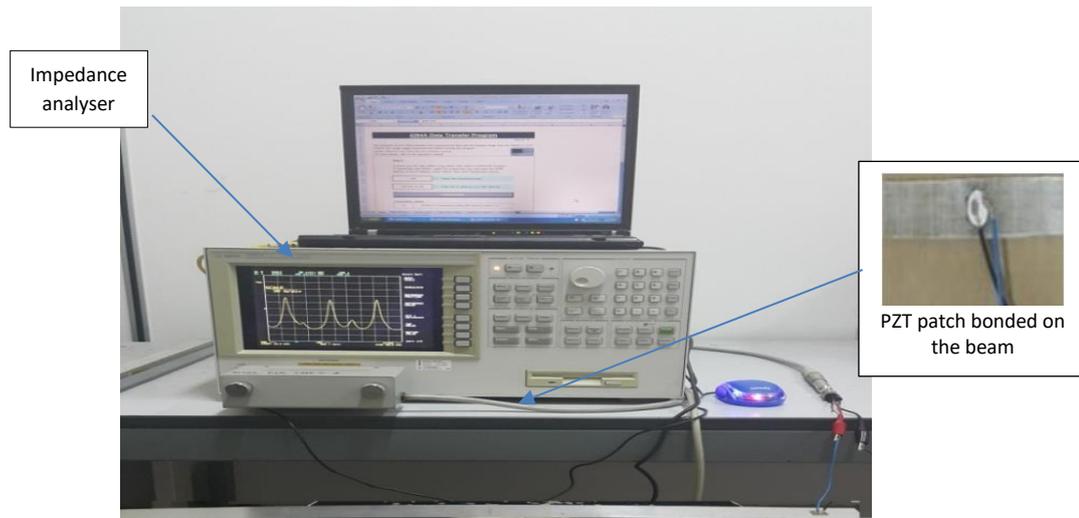
Fig. 1. Experimental setup

3.2 Finite Element Modelling

In this section, FE analysis is performed deterministically. The FE modelling was carried out in ANSYS software where the three dimensional (3D) 20-node parabolic SOLID226 element was used to build the structure and the PZT models. SOLID226 is defined as a coupled-field element with thermoelectric, piezoresistive and piezoelectric capabilities. These properties make SOLID226 an excellent choice to use with the complex problems inherent to our model. Notably, it includes the same full EM coupling that is seen in piezoelectric materials. Figure 2 shows the FE model of the PZT patch bonded on the healthy beam.
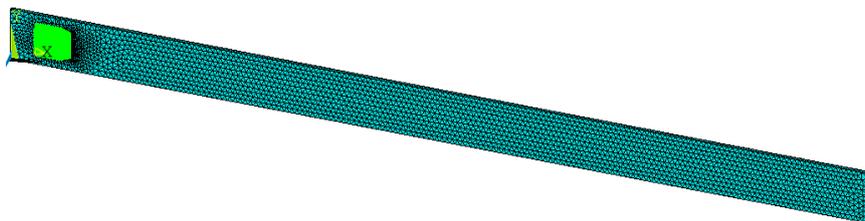
Fig. 2. Finite element model of beam structure

To be more realistic, the bonding layer (measured 0.03 mm) was also simulated. A voltage of 1V was applied on the top master node, whereas 0V was applied on the bottom one (representing the ground contact). Multiphysics harmonic analyses have been performed with elaborated finite element model to generate the frequency plots of electromechanical impedance.

Our simulation was taken a step further with the inclusion of a temperature effect to the FEM dynamic simulation. It is known that temperature variation can not only change certain host structure properties but can also affect the PZT itself and its bonding layer [18]. The complete EMI system which is PZT bonded to the structure with temperature is simulated.

4. Results
4.1 Validation of the FE model

To assess the accuracy of the proposed finite element model, it was subjected to a validation test benchmarked from the experiments. Validation is accepted based on approximation of curve trend, magnitude close reproduction of the experimental results. Figure 3 shows the comparison between the obtained simulation results and experimental results.
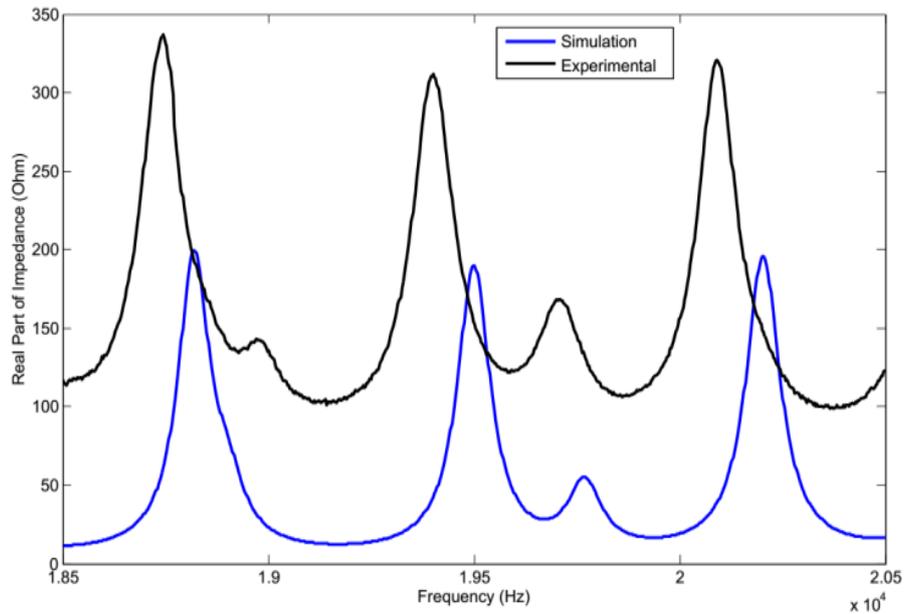
Fig. 3. Comparison between simulation and experimental results for an aluminium beam

4.2 Temperature Effects on EMI

Figure 4 shows the real part of the electromechanical impedance signatures for a healthy beam heated at temperatures between 27 and 50°C for frequencies from 18.5 to 21 kHz. As can be seen in Figure 4, there is a frequency shift to the left for the electromechanical signature due to the increase in temperature due the dielectric constant ε_{33}^T which is recognized as the temperature-dependent constant of PZT sensor has sufficiently influenced the electrical impedance signature [9]. Similarly, as the temperature decreases, the signature shifts to the right. Variations in the electrical resistance and some vertical shifts are also observed.
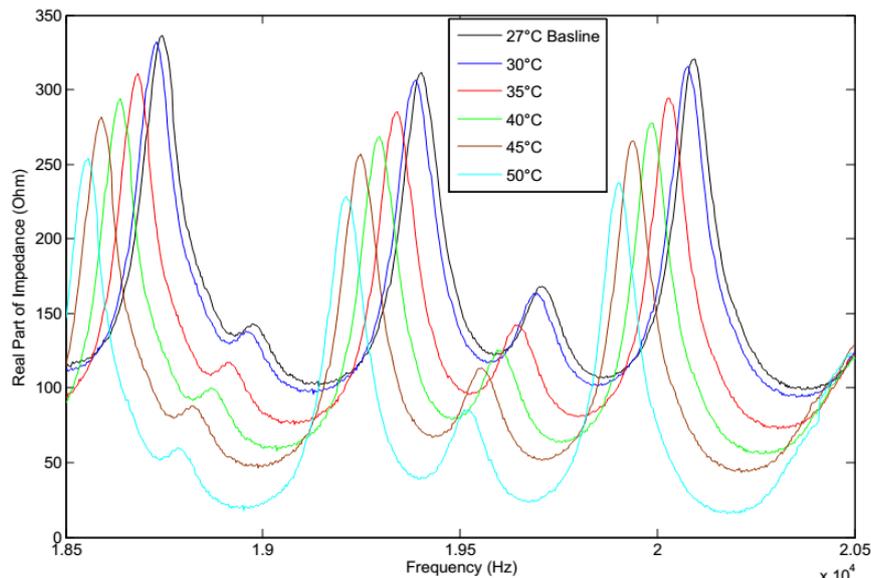
Fig. 4. Real part of the electromechanical impedances resulting from temperature changes

4.3 Co-existence of Damage and Temperature

Upon the inspection of the effect of temperature on EMI, we proceed to the effect of other types of damages, which are damage and temperature. Combining crack and temperature damage at the same time were also performed in this part. This attempt is expected to allow the researcher to model more realistic cases and to show that EMI systems can discover these problems. Figure 5 shows the differences between signals generated by the temperature that exists on the notched beam and the healthy beam. It can be seen that the electromechanical signature of the temperature that exist on the notched beam decrease compared with temperature signature and shifted to the left side. The decrease of the resonant peaks frequencies, which reflect the decreasing of local stiffness, is caused by the existence of local damage (notch). Therefore, the amount of frequency shift increases with the increasing of the notch depth [19].
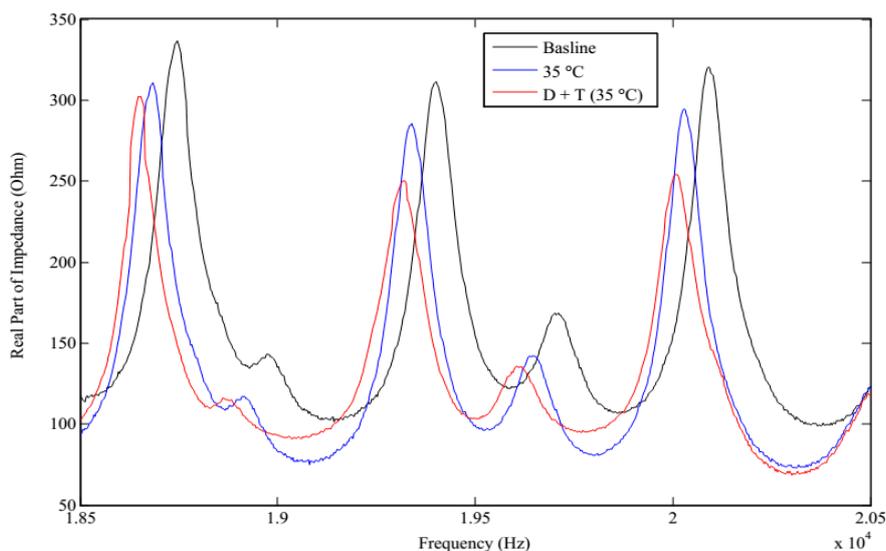
Fig. 5. Real part of the electromechanical impedance resulting from temperature changes

4.4 Compensation for Temperature Effects

One major reason that has kept the EMI technique from being implemented in real world applications is that temperature variations are responsible for significant changes in the EMI signature. As a result, healthy monitored structures can be falsely diagnosed with damage due to a simple change in the surrounding temperature. Implementing real-time EMI monitoring will depend on methods that can automatically neutralize or reduce temperature effects. The model presented here is focused on the real component of the EMI signature since it is more sensitive to structural damage and less susceptible to temperature variation.

Compensation for the effects of temperature variation can be accomplished through a variety of methods. Park *et al.,* [20] modified the RMSD index to compensate for shifts in both frequency and amplitude. Koo *et al.,* [21] improved on the Park *et al.,* [20] method by creating an effective frequency shift (EFS) that countered temperature variations. Sun *et al.,* [22] compensated for the variations in signatures with a cross-correlation concept. Our approach is similar to Sun *et al.,* [22] where similarities in two signals, the updated signatures and the baseline, are revealed to compensate for the frequency shifts. The cross correlation R_{xy} of two signals x (t) and y (t) are defined by.

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T f_x(t) f_y(t + \tau) dt \tag{6}$$

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 $(t+\tau)$, τ is the number of data points delayed. 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:

$$R_{xy}(m) = \frac{1}{N} \sum_{n=1}^{N-m+1} x(n) y(n + m - 1) \tag{7}$$

where m=1, 2, 3, …, N+1. The cross-correlation coefficient is

$$\rho_{xy}(\tau) = \frac{R_{xy}(\tau)}{\sqrt{R_x(0) R_y(0)}} \tag{8}$$

where $R_x(0)$ and $R_y(0)$ are the auto correlation functions of x and y.

MATLAB was the software used to compensate the temperature effects. A MATLAB function is used to implement cross correlation function that obtains the baseline impedance signature of sensor, which is then used as reference to counter temperature variation effects. Additionally, the impedance of the PZT transducer was simulated for a healthy beam condition at a regulated temperature of 35°C (Figure 6).

Figure 6 demonstrates the compensation method result. Using Figure 3 as a reference, it appears that the compensation technique was successful in keeping temperature effects to a minimum. Since the purpose of the method was to eliminate false positive damage detection in healthy structures. The structure's impedance reconducted without temperature variation in order to assess structural damage. A compensation technique shows in different cases obtained over the previously stated range of 27 to 50°C with the step size of 18.6–21 kHz and a baseline acquired at 27°C. The results help identify the frequency shifts that occur with temperature variation. The shift profiles obtained can be used when evaluating the RMSD and CCDM indices in order to separate genuine damage detection from the temperature effects using the correlation coefficient Eq. (3).
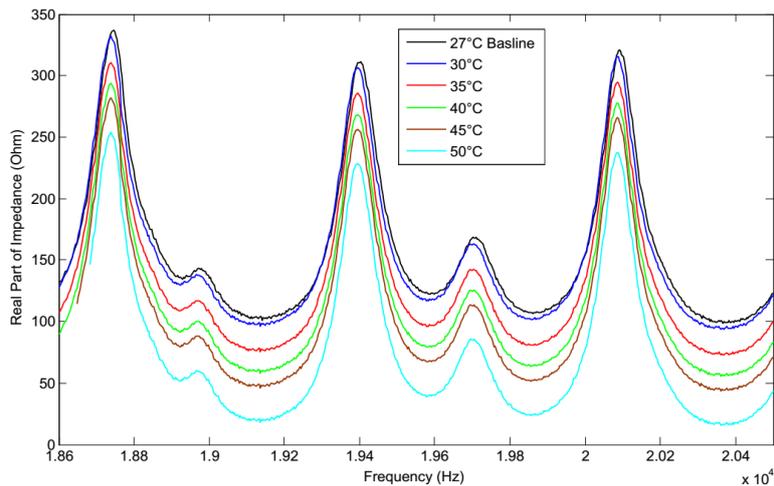
Fig. 6. Experimental results for real part of impedance signatures with the proposed compensation method for the temperature effects

To this end, the CCDM index is selected because it is insensitive to variations in the electrical impedance amplitude and responds instead to the shape of the impedance signature. This insensitivity makes the CCDM index ideal when considering the EMI variations due to temperature change. The part (a) from Figure 7 demonstrates that the signatures for damaged and healthy specimens at 35°C were similar enough to make damage difficult to diagnose at that temperature. According to part (b) from Figure 7, the compensation technique made the results significantly easier to discern. The shifts in the signatures are eliminated leaving peaks perfectly aligned with the baseline result. Also, the CCDM indices at 35°C were very low and it is conceivable that smaller damage could be detected as long as the metric index threshold was accordingly set. Results across the entire temperature range were acceptable, even at the upper end of the range.

(a)
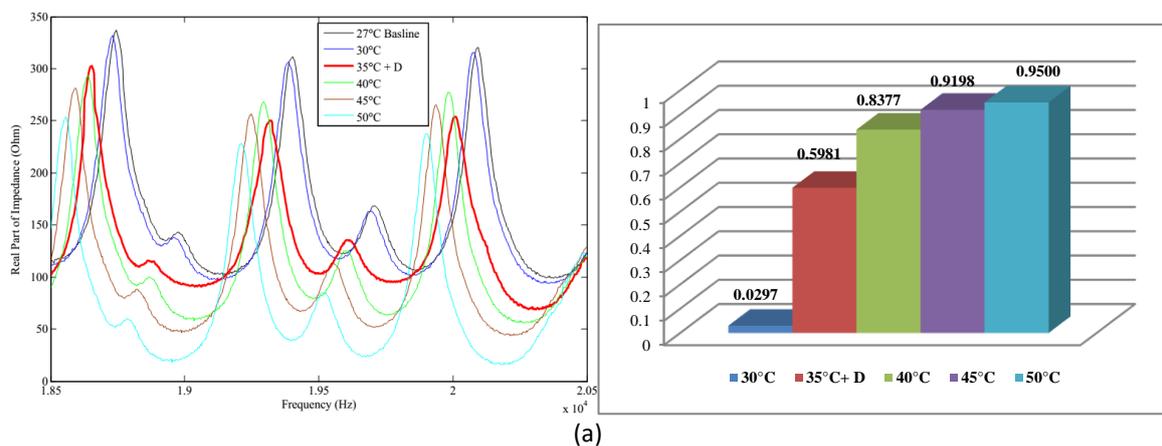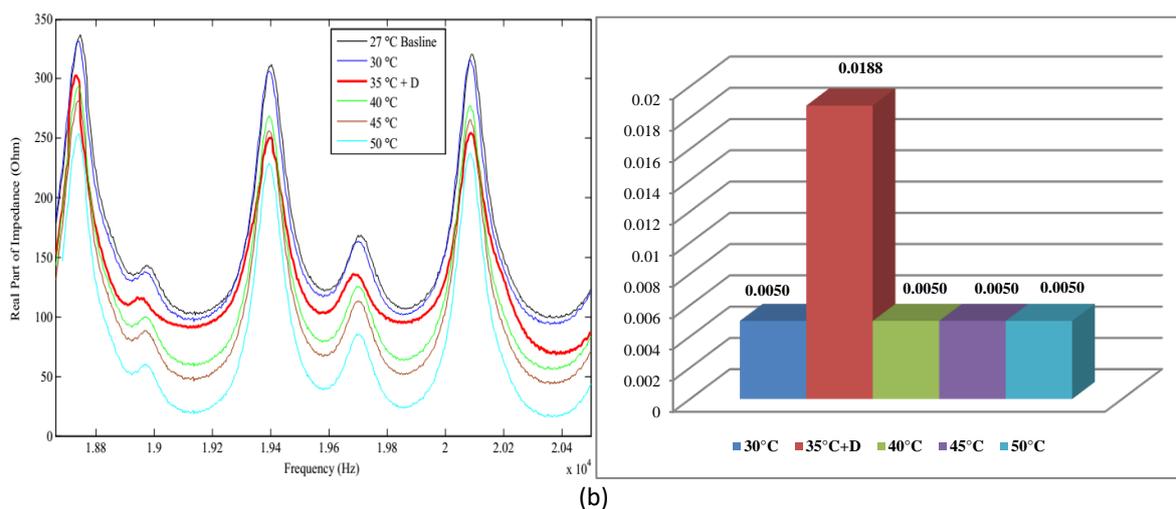
Fig. 7. FE results for Real part of impedance signatures and CCDM indices obtained for the beam (a) damage structure at 35°C without compensation and (b) with the proposed compensation method for the temperature effects

5. Conclusions

In experimental model, electrical impedance signatures of a conventional PZT sensor used in SHM were investigated along with their susceptibility to temperature variation. An aluminium specimen was also tested across a temperature range. As anticipated, the PZT dynamic response changed significantly with temperature variation. The change in the impedance signature was significant enough to cause false positive results, detect the damage that had not occurred and locate the structure's integrity into question because of temperature change. Accordingly, a temperature compensation technique was proposed to measure the exact effect of temperature change and to eliminate results ambiguity due to that temperature variation. This is considered essential to real-time health monitoring of structures in real-world conditions. Temperature effects remain critical issues in EMI structural health monitoring. This is even more obvious when it comes to detecting nascent or small damage. Effective compensation techniques are key to continued development in this field.

Acknowledgement

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