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Numerical Simulation of Electromechanical Impedance Based Crack Detection of Heated Metallic Structures

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ABSTRACT

Among the many health monitoring techniques for structures, one relatively new technique is based on electromechanical impedance (EMI) measurements. The goal of this investigation was to see if the EMI approach could be used to assess the health of metallic structures. In order to achieve this objective, the feasibility of numerical simulation of piezoelectric transducer – structure interaction in the field of the EMI technique to perform structural health monitoring using commercial finite element (FE) software, ANSYS was investigated. The numerical simulations were carried out to find the effect of different types of damage such as crack and to investigate the effect of temperature on the crack detection. When compared to experimental impedance responses found in the literature, where EMI is used to monitor different undamaged and damaged structures made of steel and aluminium, the developed FE models successfully obtained similar results with good agreement. This research revealed that the FEM could be a good alternative to experimentation for studying the EMI approach.

1. Introduction

Structural health monitoring (SHM) has emerged, in recent decades, as an effective means of improving structure reliability and safety thereby reducing operating costs [1]. As a result, multiple SHM techniques are in development, all intended to identify, locate, and quantify structural damage. Techniques in the literature are based on either local or global inspection of the structure [2-4]. Each of these SHM techniques has its own advantages in damage detection as well as its own drawbacks that could limit its applicability. One example of this is with global dynamic techniques, where the structure is subjected to low-frequency excitations but the only mode shapes that can be accurately extracted are the first few that correspond to natural frequencies. Localized damages do not have much effect on global parameters like curvature mode shape, natural frequency, or mode shape data so only large damage have sufficient effect to be detected. Furthermore, ambient vibration noise can contaminate signals obtained by global dynamic techniques at frequencies below 100Hz [4]. On the

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other hand, local techniques, including impact echo testing, acoustic emission, and ultrasound, require complex hardware that must be operation by well-trained professionals and are correspondingly costly [5]. As a promising alternative to these techniques, electromechanical impedance (EMI) based structural health monitoring has successfully monitored structures and detected even minor changes in structural integrity [4–6].

When subjected to high-frequency structural excitations in the presence of an electric field, a piezoelectric (PZT) transducer has recently evolved as an efficient smart material that can interact with the host structure to produce a unique health signature. The piezoelectric effect is the main feature of these transducers There is a direct relationship between electrical impedance and mechanical impedance based on this property. As a result, a structural failure would change the mechanical impedance, which would change the electrical impedance obtained from the PZT bonded in the structure [7]. PZT sensors are inexpensive, small, and lightweight, with low power requirements; they have a low sensitivity to temperature variations and a linear response under low electric fields.

SHM methods based on impedance are useful for detecting damage in critical local members. These methods are sensitive to minor damage. Liang et al., [8] were the first to propose the use of impedance signatures for damage detection. The EMI method is built upon employing PZT patches as actuators and collocated sensors. In order for the PZT, bonded to the structure, to act as a simultaneous actuator and sensor, a fixed alternating electric field must be applied to it. A surface charge is produced in response to an applied mechanical stress (direct effect), and a mechanical strain is produced in response to an applied electric field (converse effect). The electromechanical impedance is essentially the ratio of the resulting current in relation to the applied voltage and it can be measured with an impedance analyzer. Measuring purely mechanical impedance such as stiffness and damping can be difficult, but EMI is measured far more easily and relates to those same properties in a monitored structure and can even be used to detect structural damage [9]. The change in the admittance signature of the bonded PZT transducer is the key indicator of damage in the EMI-based SHM. Most of the research that has been done in this area explored either analytical or experimental solutions. The impedance-based methods have been successfully applied to composites [10], steel [11], aluminum [12], concrete [13], thin plates and aerospace structures [14].

In many cases, doing experiments is very expensive and also very difficult, if not impossible. In this paper, the impact of different damage cases on sensor impedance signatures is numerically studied. It is to be noted that, most of the existing works have considered this problem within the context of experimental setup or mathematical models but none have taken into consideration the finite element method’s perspective and therefore the results presented here are of unique significance and novelty. The feasibility of numerical analyses and simulations using FEM is to understand the concept of the technique and investigate sensitive range of impedance responses. This simulation approach was carried out on different kinds of structural members to detect different kinds of damages and successfully verified with experimental results available in the literature. This study demonstrated that the FEM could be a good alternative to experimentation in the study of the EMI technique.

2. Impedance-based structural health monitoring

The impedance-based structural health monitoring (SHM) technique is based on an electromechanical coupling effect (coupling effect) between the host structure and the PZT patch. As shown in Figures 1 and 2, a 1-D electro-mechanical system serves as a conceptual model to explain the coupling effect. For this model, the main electrical aspect of the PZT patch is its short-circuited impedance, and the main mechanical aspect of the host structure is its driving point mechanical impedance, which includes the effects of stiffness, boundary conditions, mass, and damping.

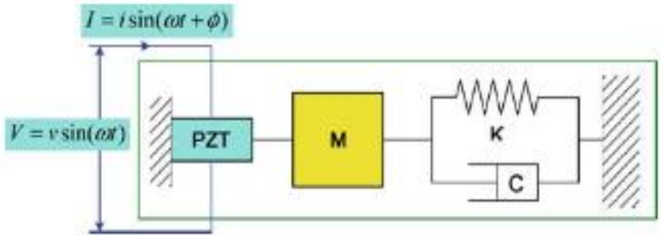


Fig. 1. 1-D electro-mechanical impedance system [13]

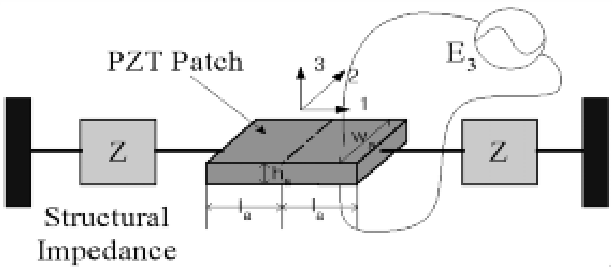


Fig. 2. 1-D Interaction model for a PZT patch and a host structure [15]

A voltage or current is used to power the PZT patch. In the electrical realm, the integrated electro-mechanical system is represented by electrical impedance, which is affected by the interaction between the host structure and the PZT. The mechanical impedance, Z_A, of the PZT patch depicted in Figure 1 is defined as the ratio of a harmonic input voltage V(ω) at an angular frequency ω to a frequency domain current response I(ω). Similarly, the mechanical impedance, Z_S, of the host structure, idealized as a single-degree-of-freedom (SDOF) system, and defined as the ratio of a harmonic excitation force $F_0(\omega)$ at an angular frequency ω to a velocity response $\dot{x}(\omega)$ in a frequency domain. The apparent electro-mechanical impedance of the PZT patch to host structure coupling is then calculated as:

$$Z_{total}(\omega) = \left\{ j\omega \frac{wl}{s} \left[\frac{d_{3x}^2 Y_{xx}^E Z_A(\omega)}{Z_A(\omega)+Z_S(\omega)} \frac{tan\,(kl)}{kl} + \varepsilon_{33}^T - d_{3x}^2 Y_{xx}^E \right] \right\}^{-1} \quad (1)$$

where Z_A, Z_S are obtained as:

$$Z_A(\omega) = \frac{V(\omega)}{I(\omega)} = \frac{kwsY_{xx}^E}{(j\omega)tan(kl)} \quad (2)$$

$$Z_s(\omega) = \frac{F_0(\omega)}{\dot{x}_0(\omega)} = C + j\frac{m\omega^2 - k}{(j\omega)tan(kl)} \quad (3)$$

3. Finite Element Simulation of EMI

A finite element model of different kinds of structural members has been created in ANSYS software. This model considers a thin 0.03 mm layer of adhesive layer between the structure and the patch. Also used within the model were the following element types: 3D 20 nodes SOLID226 for the patch and SOLID186 for the beams. In some cases, element SOLID95 was used and in some of the other SOLID186 was used. The choice between SOLID95 and SOLID186 was determined by which would be the most efficient in each case.

ANSYS software offers a coupling function where a master node links together the nodes on both electrodes (top and bottom surface of the piezoelectric patch). The negative output charge from the patch was obtained at a master node. A voltage of 0V was applied to the bottom master node in order to represent ground contact and a voltage of 1V was applied to the top master node. A mesh size of 0.5mm was fixed for both the patch and epoxy adhesive but a different smart size meshing was chosen for the beam.

Multiphase harmonic analyses were performed with this model in order to generate frequency plots of electromechanical impedance for two structure states: healthy beam and damaged beam by the introduction of crack [16].

In order to demonstrate the capability of the impedance based SHM method, numerical analysis was performed on different kinds of structural members. FE modeling was carried out for different cases using ANSYS software to simulate the impedance response.

4. Results

4.1 Steel Beams

FE simulation was performed on four steel beams of different dimensions in order to compare them to the experimental results from Giurgiutiu and Zagrai [17]. For each beam, a type of transducer was bonded at a distance of 40 mm from its end (Figure 3).

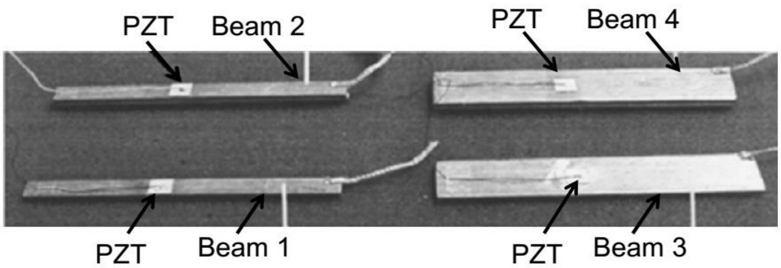


Fig. 3. Steel beams for impedance test [17]

A 3D SOLID226 element type was used for the patch and a SOLID186 was used for the beam. The properties of SOLID186 make it an excellent choice to use with the complex problems inherent to this model. A voltage of 2V was applied to the PZT patch. The beams 'properties and PZT patches ' properties are summarized in Tables 1 and 2 [18].

Table 1
Properties of steel beams

	Dimensions (mm)			Young Modulus, E (GPa)	Density, ρ (kg/m^3)	Damping Coefficient, (%)
Beam	*b*	*l*	*h*			
1	8	100	2.6	200	7750	1
2	8	100	5.2	200	7750	1
3	19.6	100	2.6	200	7750	1
4	19.6	100	5.2	200	7750	1

Table 2
Properties of PZT patches used for steel beams

	Dimensions (mm)			Density, ρ (kg/m^3)	Damping Coefficient, (%)	Dielectric Constant
PZT	*b*	*l*	*h*			
5A	7	7	0.2	7750	0.5	0.02

The beams' boundary conditions were unrestricted. Figure 4 depicts the steel beam's FE model. Figure 5 depicts the comparisons between the FE model and the experiment.

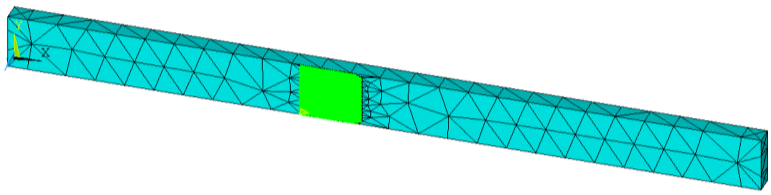


Fig. 4. FE model for steel beam

The resonant frequencies increase proportionally to the thickness of the beam, as illustrated in Figure 5. The numerical impedance responses match the experimental ones well. Resonant frequency differences range from 0.1 to 5.1 percent. As a result, ANSYS showed its capability for simulating E/M impedance responses.

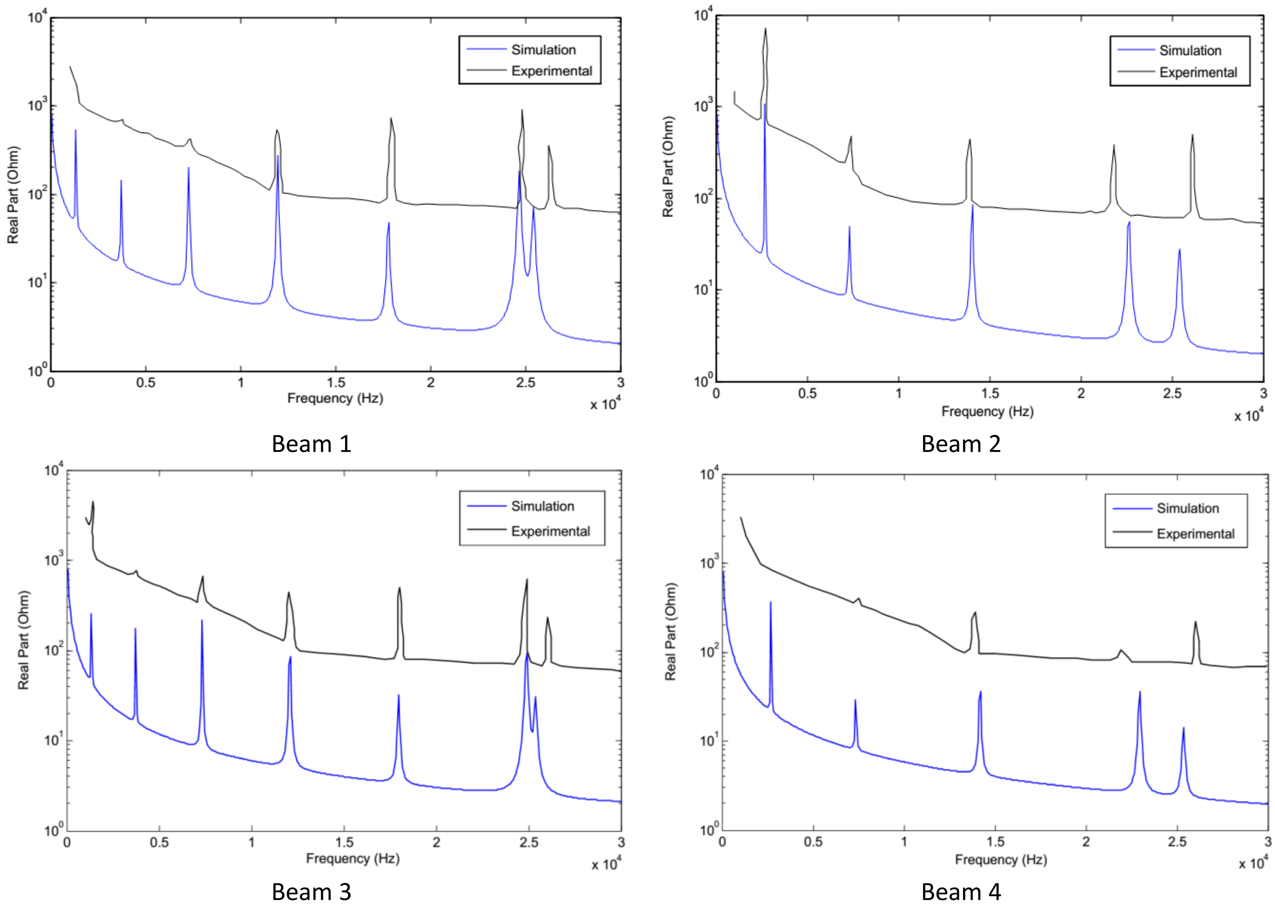


Fig. 5. Real Part signatures of steel beams for FE simulation [current work] versus experiment [17]

4.2 Loading Damage in Aluminium Beam

In this section, a FE model of an aluminum beam was made to detect the occurrence of loading damage on structure. The beam dimension was 500 x 38 x 3 mm, a PZT patch of 15 x 15 x 0.267mm was bonded to the beam at location 30 mm from left end. Structural damage was induced in the structures by placing a small steel nut with dimensions of 11 x 0.5 mm and a mass of approximately 1 g at a distance of 50 mm from the transducers. The mass loading of the beam produced variations in the mechanical impedance of the structure and could consequently be related to the structural damage [18]. For the simulation, the patch was represented by the 3D SOLID226 element type and the beam was represented by SOLID95. A voltage 1 V was applied to PZT patch. Figure 6 shows the FE model.

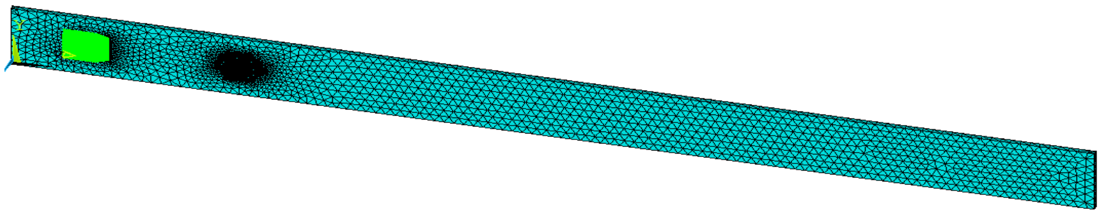
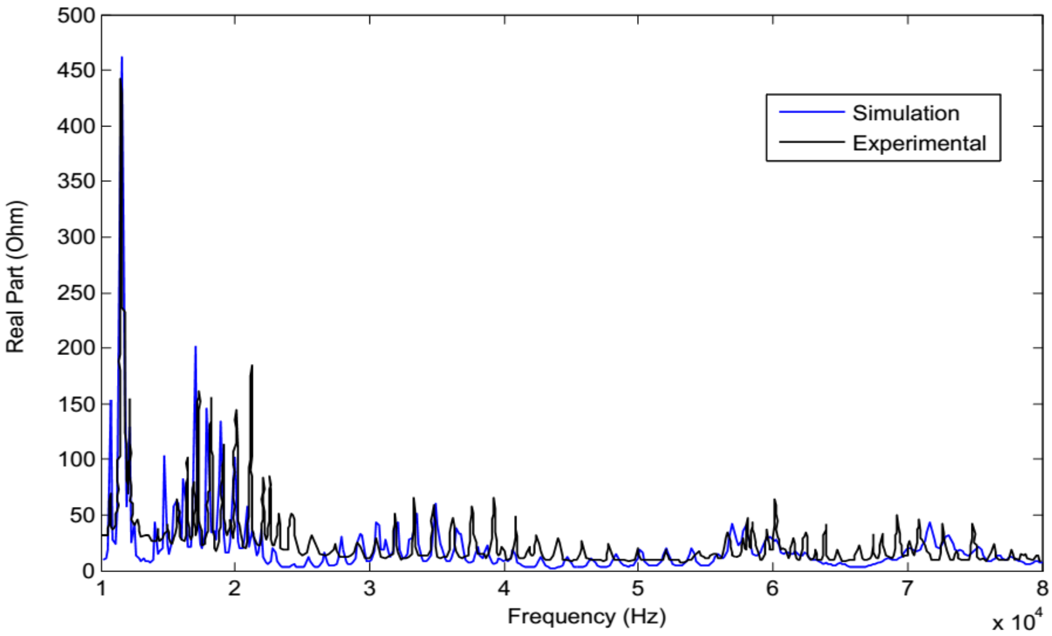


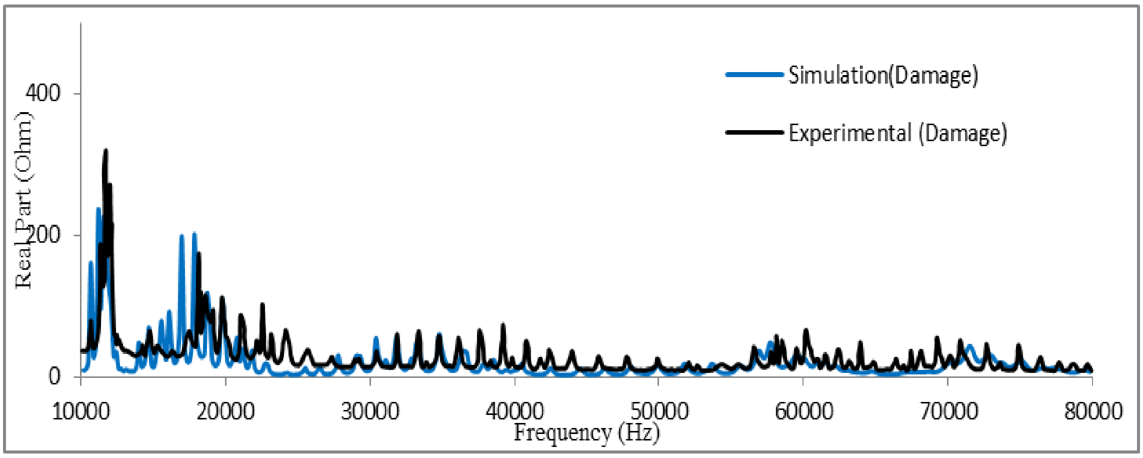
Fig. 6. FE model for aluminum beam

The real part of the electrical impedance signatures obtained from the PZT transducer is shown in Figure 7(a) and (b). The signatures have been acquired in a frequency range of 10-80 kHz.

According to Figure 7(b), there are resonance peaks in the signatures related to the natural frequencies of the structures. Structural damage (nut) causes variations in frequency and amplitude in these peaks, which can be quantified by indices of damage. In addition, the peaks are more significant at low frequencies and tend to decrease as the frequency increases.



(a)



(b)

Fig. 7. Comparison between simulation [current work] and experimental [19] results for an aluminum beam (a) Healthy and (b) Damage

4.3 Circular Aluminium Plate

FE analysis was performed deterministically. The object of examination was a circular AL2024 aluminum plate in free suspension with PZT transducers bonded to its surface by a thin adhesive layer. This adhesive is factored into the current model. The geometry of the thin plate with bonded piezoelectric wafer active sensors (PWAS) was r = 50.08mm, h = 0.835mm, ra = 4mm, rb = 1mm (Figure 8). The thickness of the adhesive layer was 100 µm. The PZT was made of PZT-5A. A SOLID186 element 20-node parabolic was used to build the structure. A SOLID226 element was used for PZT models. It 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 this model. A Solid95 element was used to model the adhesive layer. Notably, it includes the same full EM coupling that is seen in piezoelectric materials. The model is presented in Figure 9.

To assess the accuracy of the proposed finite element model, it was subjected to a validation test benchmarked from Rugina et al., [20] as shown in Figure 10. Validation is accepted based on approximation of curve trend and magnitude creating a close reproduction of the experimental results.

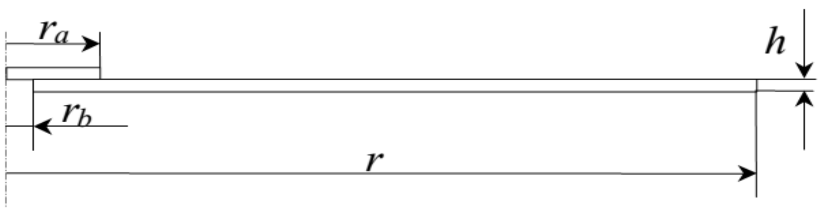


Fig. 8. Geometry of the thin plate with bonded PWAS [20]

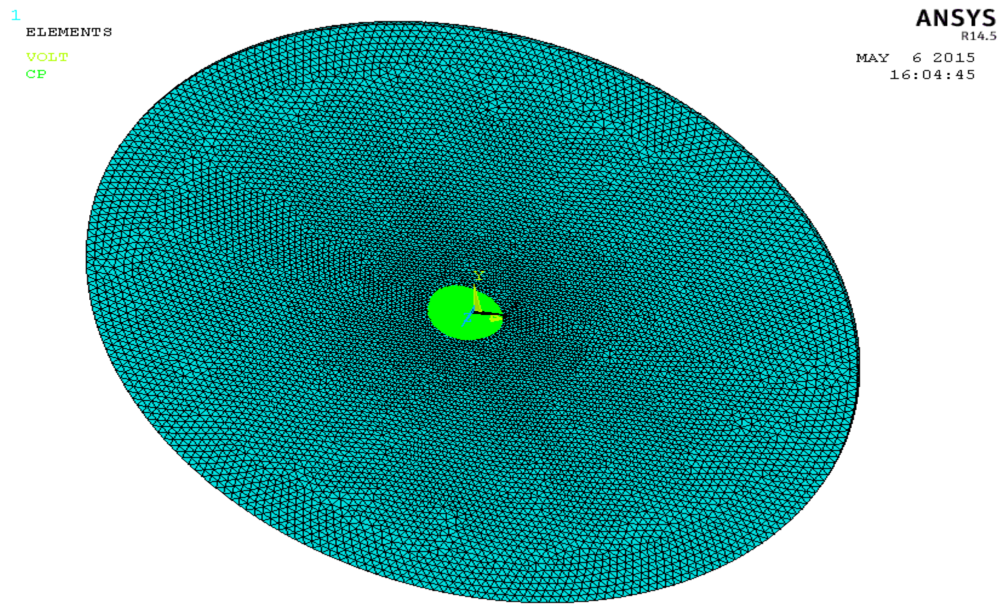


Fig. 9. Finite element model of circular aluminum plate

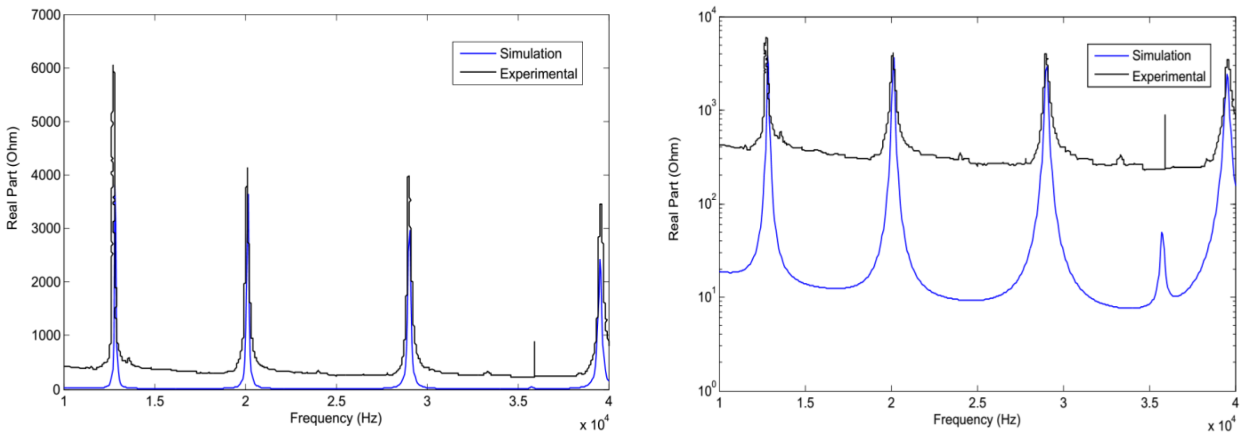
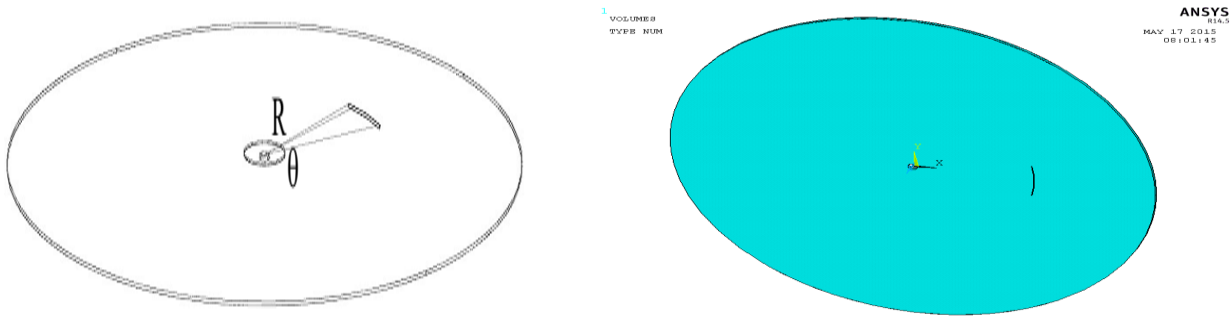


Fig. 10. Comparison between simulation [current work] and experimental [20] results for circular aluminum plate

4.4 Circular Aluminium Plate with a whole in the middle and a crack

In this sub section, structural damage was simulated. The crack took the form of a 0.15mm wide, and 10mm long is the following (Figure 11(a) and (b)). In FEM simulations with a central hole, the central hole was initially used to correctly position the PWAS as centered as possible [20]. It was modeled in order to find the effect of this crack on the output impedance of the system.



(a) (b)

Fig. 11. (a) Geometry of the thin plate with central hole and bonded PWAS [20] (b) Position of the arc-shape crack

This study demonstrated that optimal frequency ranges have a width of 10^4 to $4*10^4$ Hz. Figure 12 shows the EMI plot results of the harmonic analysis for both damaged structures.

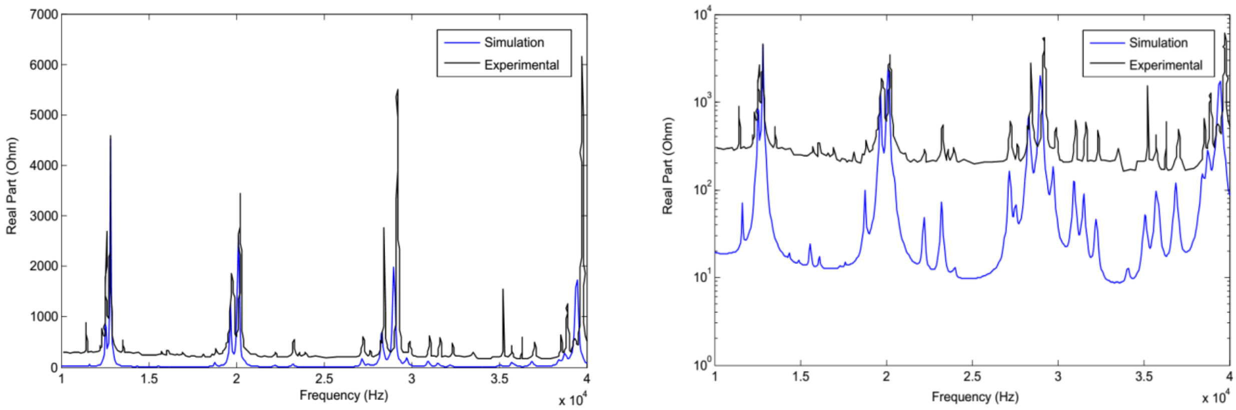


Fig. 12. Comparison between simulation [current work] and experimental [20] results for damage in circular aluminum plate

If a defect is present, many anti-resonance peaks appear (Figure 12), visible on the linear scale. From the logarithmic scale, it can be seen that FEM computations also follow the smaller peaks that are not easy to observe on the linear scale. It can be seen that an ideal adhesive layer of 100 µm with parallel faces, as used in the FEM computations, significantly changes the shape of the EM signature.

4.5 Effect of Temperature on EMI

The simulation was taken a step further, with the inclusion of the temperature effect. It is known that temperature variation can not only change certain host structure properties [21,22] but can also affect the PZT itself and its bonding layer. The object of examination is an aluminium (alloy 2024) beam in free suspension, with PZT transducers bonded to its surface by a thin layer of epoxy. The beam considered is 500 mm x 30 mm x 2 mm. The PZT measures 15 mm x 15 mm x 0.267 mm. It is made of PSI-5H4E and located 20 mm from the end of the beam on its left side. 20-node parabolic SOLID226 element was used to build the structure and the PZT models. To assess the accuracy of the proposed finite element model, it was subjected to a validation test benchmarked from the literature [23] as shown in Figure 13. It can be seen that the results show a good agreement and similar resonant frequencies are observed. However, shifting has occurred for most of the peaks. These shifts are due to the lack of the exact experimental data, so that the missing values were assumed.

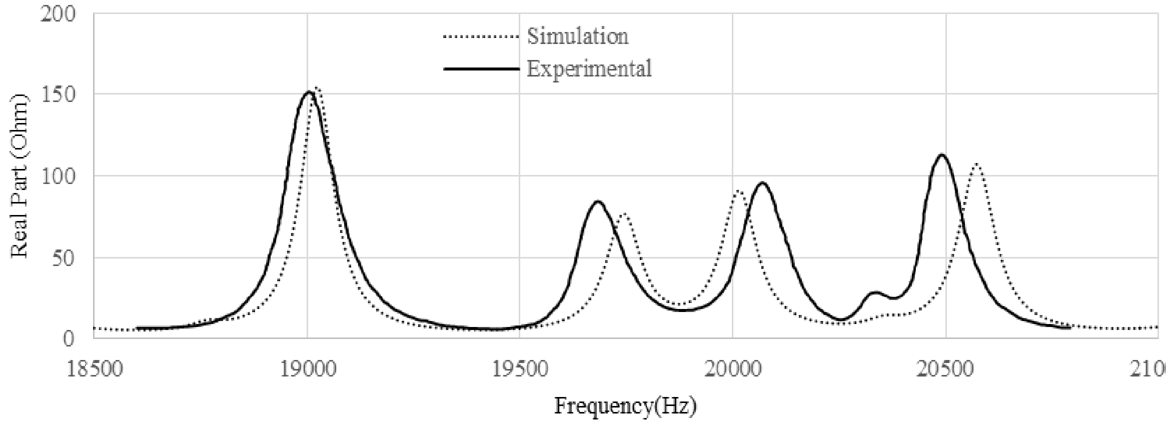


Fig. 13. Comparison between simulation and experimental results for an aluminium beam (25°C)

Simulations were performed at temperatures between 25 and 85 °C. Figure 14 shows the real part of the electromechanical impedance signatures in a healthy beam for frequencies from 18.5 to 21 kHz. As can be seen in Figure 14, there is a frequency shift to the left for the electromechanical signature due to the increase in temperature. Similarly, as the temperature decreases, the signature shifts to the right. Variations in the electrical resistance and some vertical shifts are also observed.

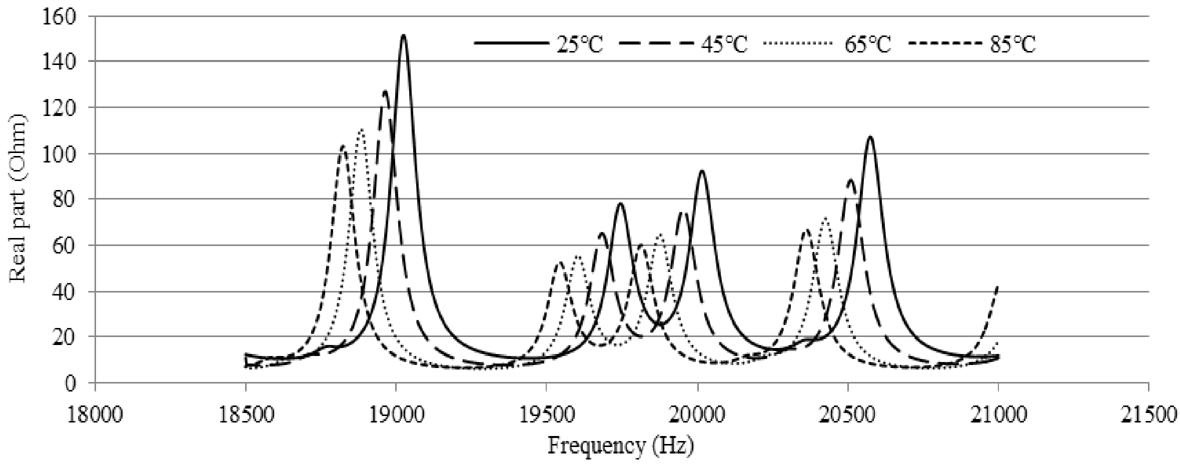


Fig. 14. Real part of the electromechanical impedances resulting from temperature changes

5. Conclusions

The feasibility of numerical simulation of impedance monitoring in structures was investigated in this paper. The results of numerical simulations of electromechanical impedance responses were accurate. The impedance responses demonstrated good agreement between numerical and experimental results. For several previously published experimental examples on steel beams, aluminium beams, and aluminium circular plates, the feasibility of numerical simulation of impedance monitoring was confirmed. Damages such as mass loading and cracks were also detected by the developed simulation module. The temperature effect on the FEM dynamic simulation was also observed. The findings indicate that this finite element simulation model can be used for continuous monitoring of structures using EMI.

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