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Numerical Evaluation of Adhesive Bonding Quality using Electromechanical Impedance Technique

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ABSTRACT

A joint is a crucial approach in the engineering field, especially when it comes to the completion of a structure. Engineers must inspect the structure's quality so that damage can be avoided. Many academic and industry researchers have recently expressed interest in the creation of a real-time, in-service, and smart material-based Structural health monitoring (SHM) technique. Recently, piezoceramic (PZT) transducers have developed into an effective smart material that is frequently used in guided ultrasonic wave propagation and electromechanical impedance (EMI) procedures. This paper will investigate the adhesive bonded structure with the presence of stiffener and lap joint in good and damaged condition. ANSYS software will be used to develop a finite element model to determine the impedance signal of the structure and validate the simulation results with results from the literature. The result will be shown in terms of impedance signal and the differences in the condition will be determined by RMSD value.

1. Introduction

The adhesive bonding technique is vital in several industries, including aerospace, automotive, and civil engineering, where attaching components with adhesives offers significant advantages over standard mechanical fastening methods. Adhesive bonding improves structural integrity, reduces weight, improves stress distribution, and allows the combination of dissimilar materials. However, assuring the quality and dependability of adhesive bonds is critical for bonded constructions' performance and safety. It is essential to detect and monitor the health of adhesive bonds to identify early warning signals of damage, degradation, and failure and take the necessary preventive or corrective measures. Void, discontinuity, delamination, porosity, air bubbles arising from poor curing, variations in glue-line thickness, microcracks, and microfractures are the principal bonding flaws that can affect the quality of the adhesive strength. It is imperative to monitor the health of adhesive

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bonds to spot early indications of deterioration, degradation, and failure and implement the necessary preventative or corrective measures [1].

An effective non-destructive evaluation methodology for determining the caliber of adhesive bonding is the electromechanical impedance (EMI) method. When bonded structures are subjected to mechanical excitation, electrical impedance responses are measured as part of EMI. Information on the bond status, such as debonding, delamination, or degradation, can be gleaned from changes in impedance patterns.

Piezoceramic (PZT) transducers have recently developed into effective smart materials that, when exposed to high-frequency structural excitations in the presence of an electric field, can interact with the host structure to provide a distinctive health signature and method of obtaining such signature as an inverse function of structural impedance is termed as the electromechanical impedance (EMI) technique [2]. The performance of the EMI technique was examined on hollow cylinders to study the influence of different damage types and damage locations on the EMI spectrum and resultant damage metrics. Results from experiments and computer simulations indicated that the orientation and longitudinal distance from the sensor position have an impact on the damage measurements. The findings showed that the mechanical characteristics of the specimen material and thickness, as well as damage intensity in each specimen, have an impact on damage metrics when using the EMI technique [3,4].

Numerical evaluation is vital to damage detection in the early stages. Hind *et al.,* employ numerical and parametric analysis to determine the health of the beam [5]. Beroual and Hrairi [6] presented a numerical analysis of different models, such as free piezoelectric PZT patches of various shapes and several scenarios for healthy and cracked solar cells in order to investigate the capabilities of the EMI technique. The crack was highlighted as a common damage in PV solar cells, and two of its characteristics were investigated namely, the crack location and the crack depth. Gulizzi *et al.,* [7] used a finite element approach to forecast the electromechanical response of PZT attached to adhesively bonded joints. The model was written in MATLAB, and its outcomes were verified by contrasting them with those of a few case studies that were carried out using commercial software. The author concluded that the EMI technique was able to capture the variations in the stiffness of the adhesive layer. The electrical impedance is often tested at high frequencies between 30 and 400 kHz [8]. The excitation's wavelength is short and sensitive enough in this high-frequency band to pick up slight changes in the structural integrity. In the EMI approach, a frequency range with 20 to 30 peaks looks appropriate to select since a larger mode density suggests that the range carries more structural data about the state of a structure [9]. It has been discovered that a frequency range greater than 200 kHz helps localize the sensing, but a frequency range lower than 70 kHz covers a larger sensing area [10].

Roseik *et al.,* [11] performed electromechanical analysis for monitoring cantilever aluminum beams using the finite element method. The model was excited to vibrate at a high-frequency range for the case of the healthy and damaged beam. Numerical results were compared with experimental results and a good agreement was noticed. From the findings, the author stated that the impedance technique can be used successfully for structural health monitoring. Amandas *et al.,* [12] conducted experimental research on the electromechanical impedance technique (EMI) based on piezo ceramic transducers along with the digital image correlation (DIC) method that uses structural surface modifications with monitoring. If there were any structural flaws, the delivery of fatigue would often make the crack worse. Numerous aircraft defects that were brought on by EMI output and the DIC system in the specimens during the weakness test were detected by the neighboring active electrode multiple-crack monitors [13].

Damage is evaluated by comparing measurements from active transmission at a time in its lifespan to the baseline data of the undamaged structure to determine the damage to the structure. The deformation of the beam structure was investigated by Madjid *et al.,* [14], which shows damage in the structure due to temperature change under electrostatic loading. The detection is possible because the damage close to the sensor causes a variation in stiffness and affects the structure's resonant parameters, which will, in turn, change the electrical impedance of the transducer, accordingly, owing to the electromechanical coupling [15]. The author employs a PZT patch and host aluminum plate for analysis; in his work, the relation between the stiffness of piezoelectric patches and host plate is considered, and the best placements of actuators for repair around a plate in a host structure under tension. The author's results conclude that locating the patches at high-stress concentration areas is the best location for piezoelectric patches[16]. A similar method was mentioned in the study [17]. The study simulates different levels of severity of bondline degradation due to kissing bonds. The stiffness of the interfacial element is tuned to different levels (from 10% up to 90% of the original stiffness) to determine the depth of damage. The author studies disbonds between the plate and stiffener along the stiffener length, which have been considered as damage in the stiffened plate structure. A damage detection scheme using the electro-mechanical impedance-based signatures for the detection of multiple damages is presented. Cracks of 1mm width and varying depth have been considered as damages to the beam structure [18].

A recent study on research of electromechanical impedance spectroscopy-based structural health monitoring, specifically emphasizing adhesively bonded joints, is reviewed in detail by Tenreiro *et al.,* [19]. While advances have been made in algorithms for damage detection, localization, and characterization, this technology needs to be mature enough for real-world applications. The study motivates researchers to develop algorithms and models to detect, localize, and characterize damage for real-world scenarios. Very few studies have found that analysis of the beam structure with stiffener and early detection of the damage detection. The above studies focus on damage detection, focusing on the deterioration of the host structure. However, PZT patch bonding and its shape are important parameters to consider. A beam and a stiffened plate with different patch shapes and sizes are considered two example structures in this study. The study aims to identify early indications/detection of deterioration in the adhesive bond between the host beam structure, stiffener, and PZT patch. In the present work, finite element analysis is performed to simulate the impedance response of a piezoelectric patch bonded on an aluminum beam using commercial software (ANSYS).

Furthermore, the electromechanical impedance (EMI) method is utilized to conduct the study for the investigation of adhesive bond quality. The paper is organized with a section one introduction discussing the literature review and research gap, followed by methodology detailing the modeling approach. Section three discusses the results and discussion. Finally, the paper concludes important observations and future work.

2. Methodology

In his paper, we analyze the finite element model of the freely suspended aluminum beam using ANSYS software. The model was built using 3D 20-node elements. The transducer was placed 5mm away from the end of the beam. Also, between the beam and the piezoelectric, there is a thin layer of epoxy glue to attach. The objective is to investigate the probability of the EMI in detecting bond degradation, like poor bond strength. Two cases are studied which use a different value of young modulus, Y, and different mechanical loss factor,η, at fixed young modulus to investigate the ability of the EMI technique to detect degradation

2.1 Background of EMI

Piezoelectric (PZT) transducer is used in Electromechanical Impedance (EMI) to evaluate the structure's state of health. The electrical changes generated by some sort of solid substance will be converted into energy by this PZT transducer, a type of electroacoustic transducer. In this method, PZT is used to apply harmonic forces to structures that have been patched by transducers while they are exposed to an electric field. The process will result in a graph with a peak and a valley where the impedance VS frequency is plotted. As a result, by referring to the transducer's frequency, it may detect damage[3]. The wavelength of the stimulation affects how sensitive the test signal is to damage or cracks. For easy detection, the excitation's wavelength needs to be less than the damage's wavelength. Typically, the damage detection frequency range is between 30 and 400 kHz, with 20 to 30 peaks.

The EMI approach takes advantage of the interaction between a piezoelectric material's electromechanical characteristics and the mechanical characteristics of the host structure into which the material is bonded or inserted. Different frequencies are used to excite a piezoelectric patch using the external voltage. Both the patch and the structure experience a displacement field as a result of the electromechanical interaction. EMI technique uses the changes that take place in the drive point structural impedance to identify developing damage in the structure. The change that happens in the drive-point impedance is detected electrically by the piezoelectric transducer through changes in the apparent electro-mechanical impedance. The apparent electro-mechanical impedance of the piezo transducer as coupled to the host structure is given by

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

From the equation above, Z(ω) is the electro-mechanical admittance which can be seen at the PZT transducer terminals, while C is the zero-load capacitance of the PZT transducer, κ31 is the electro-mechanical cross-coupling coefficient of the PZT transducer (κ 31 = d13 / s11ε 33), Zstr is the impedance of the structure, and Zpzt is the impedance of the PZT transducer. By comparing the impedance spectra taken at various times during the service life of a structure, meaningful information pertinent to structural degradation and the appearance of incipient damage can be extracted.

2.2 Material Properties

Table 1 and Table 2 represent the material properties of Aluminium, adhesive, and Piezoelectric transducers, respectively. Epoxy resin glue adhesive is used as a medium to bond the piezoelectric material with the beam due to its better performance compared to others. Furthermore, it has the lowest probability of damaging the structure. The host structure and adhesive are chosen to be isotropic materials as their mechanical properties are the same in all directions.

Table 1
Material properties for aluminum and epoxy

Parameters	Symbols	Materials	Values	Unit
Density	ρ	Aluminium	2715	[Kg/m³]
		Epoxy	1000	
Poisson ratio	V	Aluminium	0.3	-
		Epoxy	0.4	
Young's Modulus	E	Aluminum	68.95	10^9 [N/m²]
(Isotropic)		Epoxy	5.1	

Table 2
Material Properties for Piezoelectric Transducer PZT PIC151

Parameters	Symbols	Values	Unit
Density	ρ	7800	[Kg/m³]
Compliance	$S_{11}=S_{22}$	19.0	-
Electric permittivity	$S_{11}=S_{22}$	1977	-
coefficient	S_{33}	2395	
Piezoelectric strain	$d_{11}=d_{22}$	-2.10	[10^{18} mV]
coefficient	d_{33}	5.00	[10^{18} CN]

2.3 Finite Element Modelling
2.3.1 Free piezoelectric patch

Two shape models of piezoelectric transducers, circular and square, were modeled using the finite element modeling method in ANSYS Mechanical APDL. ANSYS was able to perform coupled field analysis for piezoelectric patches. SOLID 226 was chosen as the element type for the piezoelectric patch due to its capability to perform coupled field analysis for piezoelectric. This element type has 20 nodes with six degrees of freedom per node. An electric voltage degree of freedom was used to acquire charge accumulation data for the model. APC850 material properties were used to model the piezoelectric transducer for the simulation which are as shown in Table 3.

Table 3
Material properties of PZT APC850 [17]

	Symbols
Stiffness matrix	$C_p = \begin{bmatrix} 97 & 49 & 49 & 0 & 0 & 0 \\ 49 & 97 & 44 & 0 & 0 & 0 \\ 49 & 49 & 84 & 0 & 0 & 0 \\ 0 & 0 & 0 & 24 & 0 & 0 \\ 0 & 0 & 0 & 0 & 22 & 0 \\ 0 & 0 & 0 & 0 & 0 & 22 \end{bmatrix} \text{GPa}$
Dielectric Matrix	$[\varepsilon_p] = \begin{bmatrix} 947 & 0 & 0 \\ 0 & 605 & 0 \\ 0 & 0 & 947 \end{bmatrix} \times 10^{-8}\ \text{F/m}$
Piezoelectric Matrix	$[e_p] = \begin{bmatrix} 0 & 0 & 0 & 0 & 12.84 & 0 \\ 0 & 0 & 0 & 12.84 & 0 & 0 \\ -8.02 & -8.02 & 18.31 & 0 & 0 & 0 \end{bmatrix} \text{C/m}^2$

Both shapes were modeled with the same area and thickness. For the square patch, 7mm × 7mm with a thickness of 0.2mm was modeled while for the circular patch, the dimension was 7mm for the diameter with a thickness of 0.2mm. Both have meshed with the mesh size of 0.0005. Mapped hexagonal elements were used as mesh shapes for a square patch, as shown in Figure 1, whereas sweeping hexagonal elements were used for a circular patch due to the curvature geometric characteristics. To apply voltage to the piezoelectric patch, these patches were coupled, and both sides of the patch were excited with 0 volts (ground) and 1 volt at the master node.

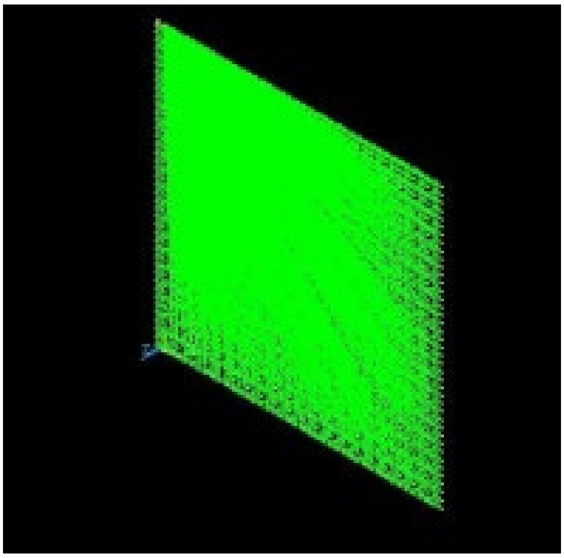


Fig. 1. Coupling the PZT model

As for the frequency selection for the free piezoelectric patch, the range of 0 to 1 MHz with 400 substeps was chosen [20]. This range frequency is a standard range to be used as many cases are performed using the same range. Once the simulation was done, the Reaction force of charge was applied to the master node of the patch, which is located in node 1282, and the data received was calculated to get the value of impedance using the formula in the literature review.

2.3.2 Piezoelectric bonded to the beam

An aluminum beam of dimensions 100mm × 16mm × 1mm was modeled using the SOLID95 element. As a medium to bond the piezoelectric material to the aluminum beam, the adhesive with dimensions of 10mm × 10mm × 0.03mm was modeled using the SOLID95 element. SOLID226 element type was employed for modeling the piezoelectric patch due to its capability to perform coupled field analysis for piezoelectric material. This element has 20 nodes with six degrees of freedom per node. All three volumes were glued by using the Boolean function. Piezoelectric patch and epoxy glue bonding layer were assigned with a mesh size of 0.5mm with a hexagonal shape, while for the case of the beam, the free tetrahedral shape was used with a smart size of 6 as shown in Figure 2. A voltage of 0V and 1V was applied to the master node, and a frequency range between 10KHz to 50KHz, along with a damping coefficient of 0.005, was chosen for the analysis.

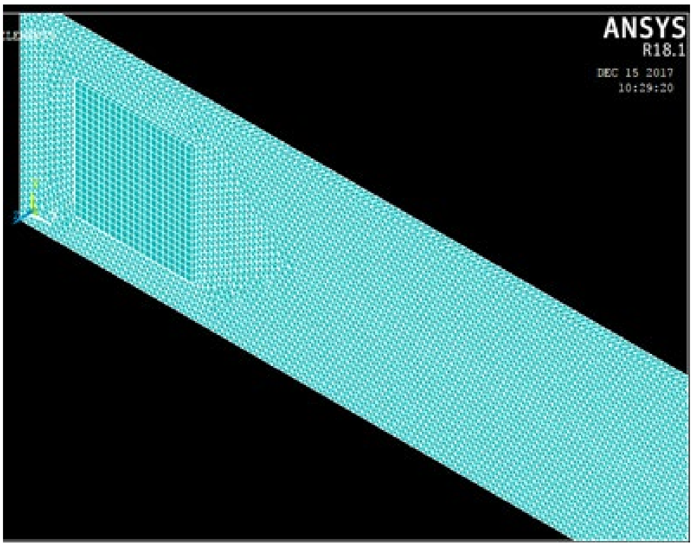


Fig. 2. Meshed model of PZT bonded to the aluminum beam

2.3.3 Beam with stiffener

One of the objectives of this study was to perform structural health monitoring for bonded joint structures. Adhesive bonds have been used as a medium to combine the stiffener with the beam. The piezoelectric patch was placed at the same location as it was placed in the previous case, as in Figure 1, because it can sense large areas and be bonded to the beam using epoxy glue. Table 4 displays the material properties for the adhesive layer, and the material properties for the host structure, epoxy, and piezoelectric patch remain the same, as listed in Tables 1 and 2, respectively.

Table 4
Properties of the adhesive layer

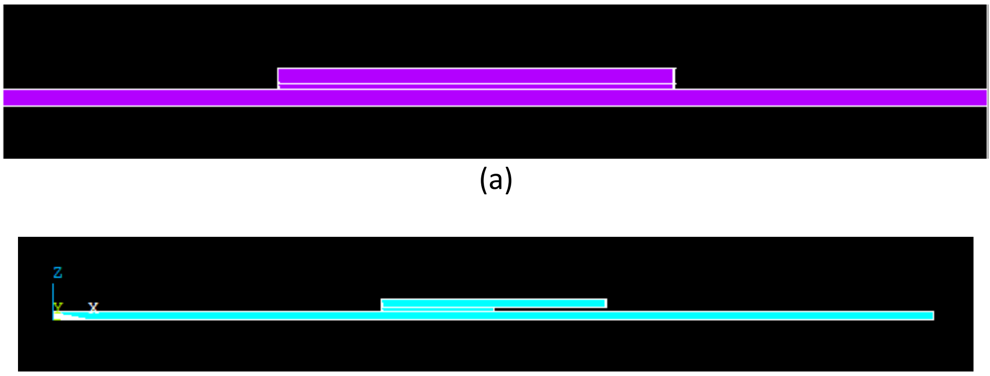
Parameters	Symbols	Values	Unit
Density	ρ	1000	[Kg/m³]
Poisson ratio	V	0.4	-
Young's modulus (Isotropic)	E	2.5	10^9 [N/m²]

The dimensions for modeling the Aluminium beam, adhesive bonding layer, piezoelectric transducer, epoxy glue, and Aluminium stiffener are listed in Table 5.

Table 5
Dimensions for host structure, adhesive bonding layer, piezoelectric transducer, epoxy glue, and stiffener

Dimensions	Aluminium	Adhesive bonding layer	Piezoelectric transducer	Epoxy glue layer	Aluminum stiffener
Height (mm)	16	16	10	10	16
Width (mm)	100	25.4	10	10	25.4
Thickness (mm)	1	0.36	0.3	0.03	1

Two different scenarios were investigated using this model for healthy and damaged structures. For the case of a healthy structure, the adhesive bonding layer covered the whole surface of the stiffener for gluing to the beam whereas for the case of the damaged scenario, the adhesive bonding layer used for bonding the stiffener to the beam covered only half of the volume of the stiffener as depicted in Figure 3.



(a)

(b)

Fig. 3. Bonding of stiffener to the beam (a) Full adhesive bonding layer (b) Half adhesive bonding layer

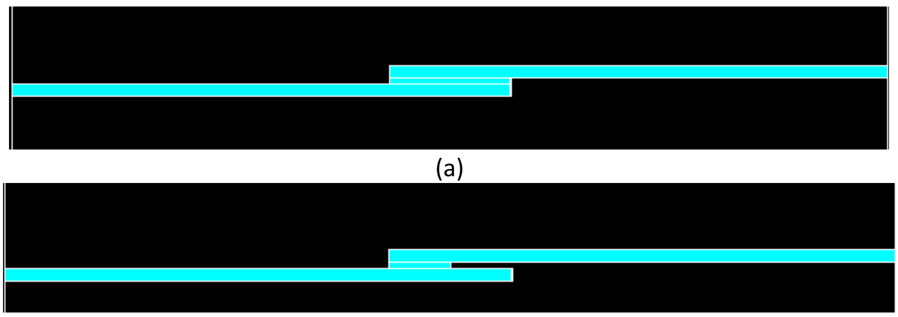
2.3.4 beam with lap joint structure

In this case, the piezoelectric transducer was used to analyze the lap joint structure of the aluminum beam that was joined using an adhesive bonding layer. The same material properties were used for the beam, piezoelectric patch, epoxy glue, and adhesive bonding layer from Tables 1, 2, and 4. The dimensions for the aluminum beam, adhesive bonding layer, piezoelectric transducer, and epoxy glue have been listed in Table 6.

Table 6
Dimensions for Aluminium beam, PZT transducer, adhesive bonding layer, and epoxy glue

Dimensions	Aluminium	Adhesive bonding layer	Piezoelectric transducer	Epoxy glue layer
Height (mm)	16	16	10	10
Width (mm)	50	10	10	10
Thickness (mm)	1	0.5	0.3	0.03

The position of the piezoelectric transducer will be 5mm away from the left of the aluminum beam. An analysis was done for two different scenarios. For the case of healthy conditions, the adhesive bond layer will cover the full lap joint for the bonding of the host structure, whereas, for the case of a damaged structure, the adhesive layer will cover half of the lap joint, as presented in Figure 4.



(a)

(b)

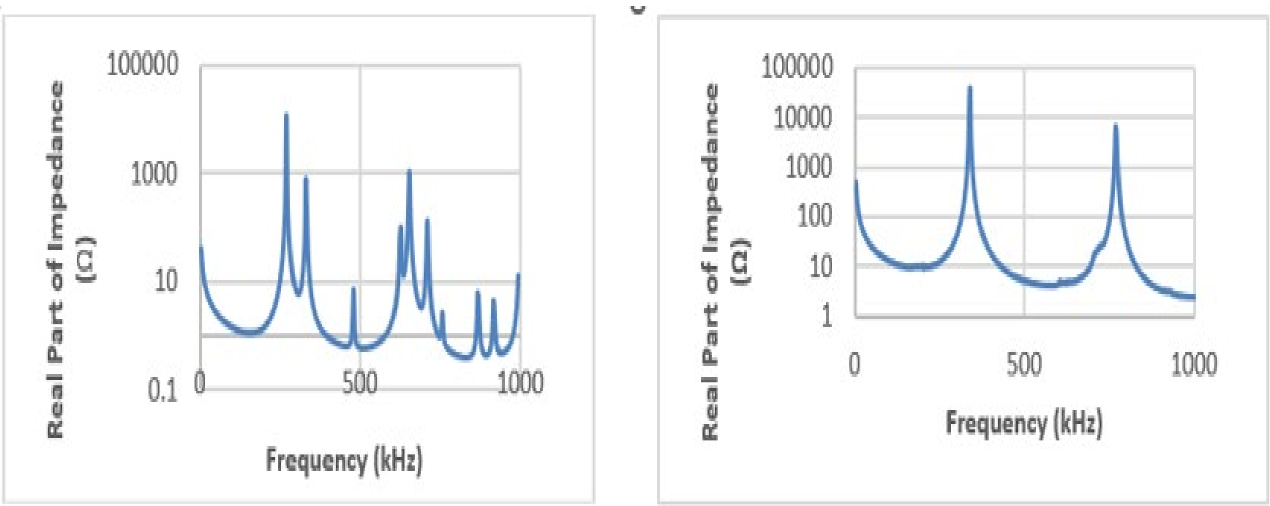
Fig 4. Lap joint bonding (a) Full adhesive bonding layer (b) Half adhesive bonding layer

3. Results and Discussion

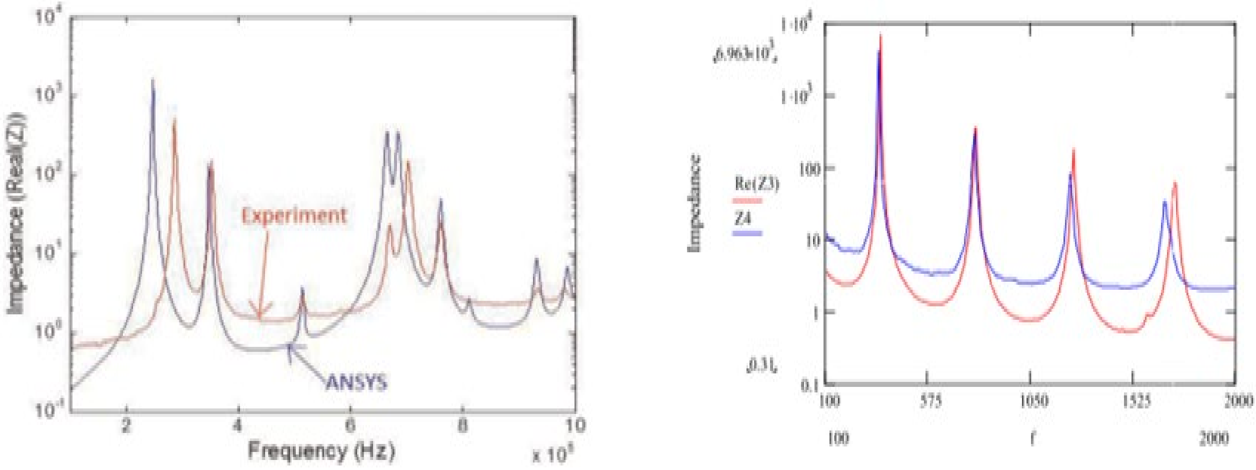
This section discusses the simulation result for a free piezoelectric patch with a different patch that was used for structural health monitoring, and the result focuses on the signal pattern made by piezoelectric sensors for different shapes. Since impedance is a complex number, two results are obtained from the analysis: real value and imaginary value.

3.1 Free Piezoelectric Patch

The real part of the impedance shows more fluctuations than the imaginary part of the impedance value. Therefore, most researchers use the real part of impedance value due to the ease of reading signal fluctuation and recognizing them. The small changes that happen to the signal can be easily determined to see the structural health. Figure 5 depicts the real part of the impedance for the square and circular patches along with similar results from the literature. From the results obtained, for the square shape, the trend of the graph agrees with the literature results. The number of peaks in the simulation matched, whereas there was a difference in the height due to the difference in element length, sub-step, and damping coefficient. The same goes with the circular shape; in literature, the frequency range set was between 100 KHz to 2MHz while the simulation performed was between 0 to 1 MHz. This difference was because of the result of the square shape of PZT. But from the observation, from frequency 0 to 1 MHZ in the literature, there was no difference in terms of the number of peaks when compared with the same simulation results. The difference was in the height due to changes in element length, sub-step, and damping coefficient.



(a) (b)

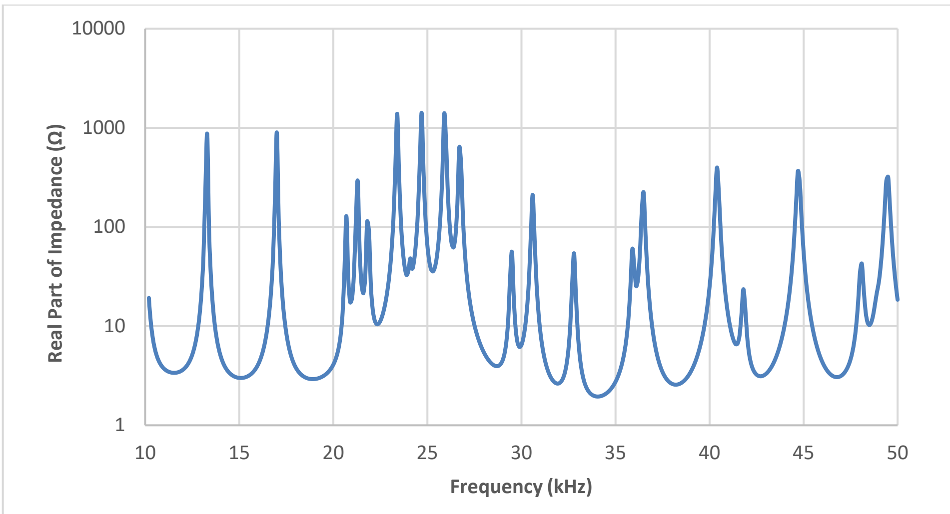


(c) (d)

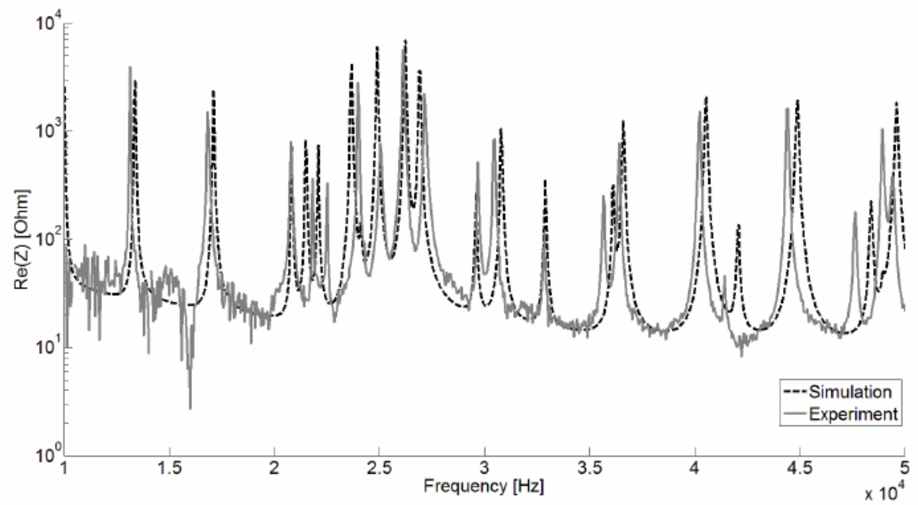
Fig. 5. Results of the real part of impedance for (a) square patch (current work) (b) circular patch (current work) (c) square patch [20] (d) circular patch[21]

3.2 Piezoelectric Patch on Beam

Figure 6(a) depicts the real impedance part of the piezoelectric transducer on the beam. The frequency was set in the range of 10 kHz to 50 kHz. This simulation was required for validation to determine whether the step taken in performing the numerical evaluation for SHM using the EMI technique was correct or incorrect before proceeding to the next step. Figure 6(b) illustrates the real part of PZT on a beam performed numerically and experimentally by [11]. As can be noticed from Figure 6, the result obtained from the simulation is similar to the literature in terms of trend, peaks of excitation, and the number of peaks produced. Thus, it can be verified that the simulation performed is correct based on this result.



(a)



(b)

Fig. 6. Real part of the impedance of PZT bonded to the beam (a) current study (b) [9]

3.3 PZT on Aluminium Beam with Stiffener

An adhesive bonding layer was employed for bonding the stiffener with the beam. The simulation was performed for two conditions. In the first case, the stiffener was bonded to the beam by a full adhesive layer. On the other hand, in the second case, the stiffener was bonded to the beam by a half-adhesive layer. Figure 7 depicts the comparison of the real impedance part of aluminum with stiffener with a fully covered adhesive layer and the half covered adhesive layer. From the results, it can be observed that the resonance of half adhesive (joint failure) has shifted towards the lower values of frequencies. The results comply with what has been stated by [11] when the damage occurred; resonance will shift towards lower frequency values because of increasing structure compliance when introducing a notch. The root mean square index (RMSD) is used to quantify the changes in the EMI signatures, and the value is 0.186. This value showed the equivalent amount of damage experienced with the excellent condition.

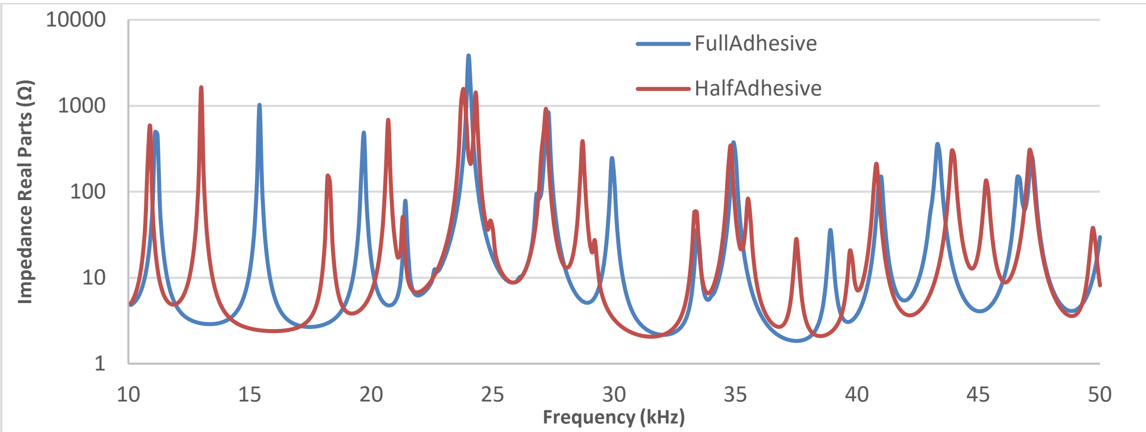


Fig. 7. Comparison between Real Impedance Part of Aluminium with Stiffener when Attach with Full and Half Adhesive

3.4 PZT on Lap Joint Structure

In this case, an adhesive bonding layer was employed to bond two aluminum beams in a lap joint structure. The piezoelectric patch was attached 5mm away from the end of the left beam to investigate the health of the structure. Two cases were studied to differentiate the resonance peak of impedance value and they were adhesive in good condition and bad condition. In the case of good condition, full adhesive was placed to bond the lap joint structure, while in bad condition, only half of the adhesive layer was placed for bonding in the lap joint structure. Figure 8 depicts the comparison of the real impedance of the lap joint structure in good condition (full adhesive) with the real impedance of the lap joint in bad condition (half adhesive). The graph shows resonance tends to shift towards lower frequency due to increased structure compliance when damage is introduced, which can be observed in Figure 8. For the quantification, the RMSD value was 0.072. This value means the amount of damage that occurred when compared to good condition.

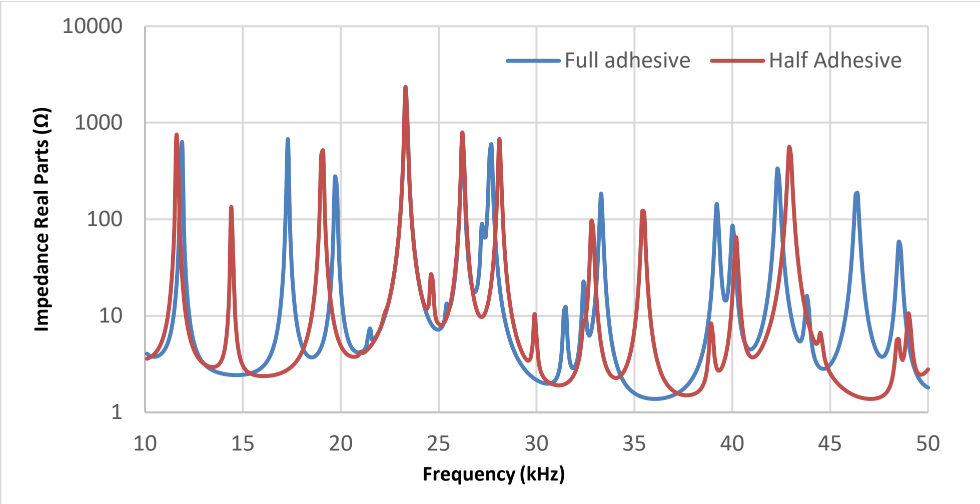


Fig. 8. Comparison between the impedance of lap joint when bonded with full and half adhesive layer

4. Conclusion

This article investigated the effectiveness of the EMI technique for structural health monitoring. The free piezoelectric transducer was modeled under two different shapes and a square-shaped PZT patch was considered for the rest of the study. Finite element analysis was performed for structural health monitoring of an aluminum beam under different scenarios, which included a PZT patch on the beam and PZT on the beam, along with a stiffener under healthy and damaged conditions. The rectangular shape of piezoelectric provided more variance in impedance signal compared to circular, hence making it suitable for analysis for bonded adhesives. Furthermore, the PZT patch on the lap joint structure is bonded by an adhesive bonding layer under healthy and damaged conditions. Thus, the adhesive bond quality of the finite element model was successfully monitored using the EMI technique.

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