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# Examining the Efficacy of Finite Element Method for Detecting Damage in Aluminium Structures

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**ABSTRACT**

Current engineering structures are effectively utilizing monitoring techniques based on electromechanical impedance (EMI) by employing piezoelectric sensors the EMI method is employed to monitor structural health of these systems. This study focuses on performing numerical analyses for structural health monitoring in healthy and damaged aluminium structures. For numerical analysis a finite element-based program in ANSYS commercial tool was utilized to model the beams made of undamaged and damaged aluminium. Additionally parametric studies were done to determine the impedance signal in aluminium structures with Lead-Zirconate-Titanate (PZT). The results obtained indicate that the finite element (FE) modeling with EMI technique is valuable for health monitoring of structures with impedance for healthy and damaged aluminium structures.

## 1. Introduction

Monitoring engineering structures continuously is crucial during both the manufacturing and operational stages to gain valuable insights into their performance. There are several techniques used structural health monitoring (SHM) encompasses various techniques including vibration-based methods, ultrasonic testing, fiber optic sensors for strain monitoring, acoustic emission techniques, and impedance-based approaches [1–3]. Vibration response-based monitoring of structures typically involves applying low-frequency excitations below 100Hz. Conversely the EMI technique operates differently. typically operates within a frequency range of 10kHz to 500kHz [4]. However, for special applications the frequency range employed in the EMI technique can extend to the MHz range. This technique offers several advantages compared to vibration-based techniques including higher sensitivity, simplicity, and ease of implementation [5].

In recent years, the field of mechanical, civil, aerospace engineering, and others has witnessed a growing interest in structural damage identification through the refinement of FE models. Various

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approaches such as direct, sensitivity-based, probabilistic, statistical, and iterative methods, have been explored to update these FE models for accurate structural damage identification. Among these methods, evolutionary algorithms (EAs) stand out as a contemporary approach for FE model updating. Consequently, the application of evolutionary algorithms for FE model updating in structural damage identification has become a thriving and ongoing area of research [6]. Utilizing the inverse finite element method (iFEM) to reconstruct an aluminum honeycomb core was used. The iFEM was fed with complete in-plane strain fields, obtained through a combination of measured strains and an interpolation technique. The interpolation method calculates the overall strain fields on the sandwich panel by leveraging strain distributions acquired from fiber-optic sensors. The results of numerical analysis demonstrate that this fully distributed sensing approach leads to accurate and robust reconstructions of both strain and displacement [7].

The electro-mechanical impedance technique relies on piezoelectric impedance transducers to detect and identify damage in civil and mechanical infrastructure. This method involves deriving the piezo-electrodynamic model evaluates and detects structural damage by analyzing the structural equivalent impedance derived from the admittance signatures of PZT patches. These patches are bonded to the structure through adhesive bonds. The presence of the bonding layer significantly impacts the overall performance of the electro-mechanical admittance signature. The focus lies in utilizing a continuous shear lag model to assess and detect structural damage. To achieve this a three-dimensional finite element is employed to calculate the effective point-driven impedance. Subsequently, this impedance is integrated into the continuum shear lag model resulting in the acquisition of the piezoelectric coupled signature [8]. To explore the potential of the EMI approach for evaluating the condition of metallic structures a study was conducted. The viability of simulating the interaction between piezoelectric transducers and structures using the EMI technique was investigated through numerical simulations. Commercial FE software ANSYS was utilized for structural health monitoring purposes. Numerical simulations were performed to assess the effects of different types of damage including cracks, and to explore how temperature influences the detection of cracks [9].

The aim is to evaluate the efficiency of the EMI technique in detecting damage in hollow cylinders. For this purpose, the EMI technique was implemented in an experimental setup involving hollow cylinders. Damage detection was achieved by comparing damage metrics obtained from the electrical impedance measurements of piezoelectric wafer active sensors (PWAS) for both intact and damaged cylinders. Furthermore, an FE method was developed incorporating the EMI technique to simulate a hollow cylinder. The FE model results are consistent with the experimental data, and similar trends can be observed for the damage metrics [10]. In contrast, FE modal analysis was employed to predict the resonance frequencies that result in concentrated vibrations within the damaged region and to extract the corresponding mode shapes. To validate these numerical predictions electromechanical impedance spectroscopy (EMIS) and scanning laser Doppler vibrometer (SLDV) experiments were carried out using a devised methodology. The EMIS experiment involved measuring the electro-mechanical impedance of a bonded piezoelectric wafer active sensor (PWAS) to anticipate the resonance frequencies associated with cracks [11].

A damage detection approach utilizing signatures based on electro-mechanical impedance to identify multiple instances of structural damage studied. Two example structures, namely a beam and a stiffened plate are investigated for the beam structure, damages in the form of cracks with a width of 1 mm and varying depths are considered. In the case of the stiffened plate structure damages are represented by separation occurring along with the length of stiffener. Drive point and cross conductance data at two piezoelectric patch transducers within a specified frequency range are obtained using the ANSYS software which is based on finite element analysis. The results from ANSYS are verified through experimental testing [12]. A FE simulation model was created for EMI, and numerical analysis was conducted. The simulation results indicated that the peak frequency of the piezoelectric admittance signal corresponds to a specific order resonance frequency of the structure. The effectiveness of the piezoelectric impedance method in detecting the dynamic characteristics of the structure was confirmed. Additionally, a simulation and experimental study involving the piezoelectric admittance of aluminum beams with varying crack sizes were conducted. The results from both the simulations and experiments indicated that the peak admittance frequency decreases as the crack size increases. Moreover, it was observed that smaller-scale damages were more prominently detected by the higher resonance frequencies [13].

An innovative variation of the EMI technique, aiming to enhance damage assessment was introduced. It proposes an approach known as the dual piezo configuration (DPC), involves utilizing a sensor-actuator dual setup. In this arrangement an outer piezoelectric ring functions as the actuator while an inner piezoelectric disc serves as the sensor. Compared to the conventional EMI configuration which employs the same piezo patch for both sensing and actuation the DPC configuration demonstrates superior performance [14]. Furthermore, a boundary element method (BEM) is devised to simulate the electro-mechanical behavior of three-dimensional structures to capture the effects of cracks the host structure is represented using 3D dual boundary element method within an electro-mechanically coupled system. Additionally, the piezoelectric transducers, essential for measuring EMI, are modeled using a semi-analytical finite element approach. This combination of methods allows for an accurate representation of the interactions between the structure and the piezoelectric transducers within the electro-mechanical system [15].

Following an extensive review of structural health monitoring systems employing PZT actuators it has been observed that PZT plays a crucial role in assessing the health condition of aluminum structures using the EMI technique in experimental settings. However, it has also been recognized that simulation using FE-based technology is vital. Consequently, this paper adopts a numerical approach to identify damage in an aluminum structure, offering a cost-effective and energy-efficient solution. The study utilizes FE models to conduct a numerical investigation on damage detection in aluminum. Two types of aluminum, one in a healthy and the other exhibiting damage, are examined within the finite element models.

## 2. Problem formulation

The main objective of this research work is to detect and develop a structural health monitoring system for crack detection based on electromechanical impedance and FE method. This study focuses on examining aluminium samples health monitoring for both healthy and damaged that are attached with PZT patches, where the PZT is attached to the aluminium with epoxy glue. PZT is a piezoelectric material, meaning it can generate an electric charge in response to mechanical stress and vice versa. Where epoxy glue is often used to bond PZT patches to aluminum surfaces due to its strong adhesive properties and compatibility with different materials. Then, we are referring to the use of numerical simulations and the finite element method which is used to solve complex engineering problems by dividing a structure or domain into smaller, simpler elements. These elements are interconnected at specific points called nodes, forming a mesh. The behavior of the entire structure is then approximated by analyzing the behavior of these finite elements to analyze how the impedance of a system or structure changes across different frequencies. Specifically, a PZT patch of type PI151 is employed. which is composed of lead zirconium titanate. And we have taken the density of PZT from previous literature, and it was 7800kg/m$^3$.

The dimensions of aluminium with PZT (Figure 1) patch are shown in Table 1, and material properties of aluminium with PZT and epoxy are presented in Tables 2. The health monitoring for healthy and damaged samples is analyzed using the ANSYS software package.

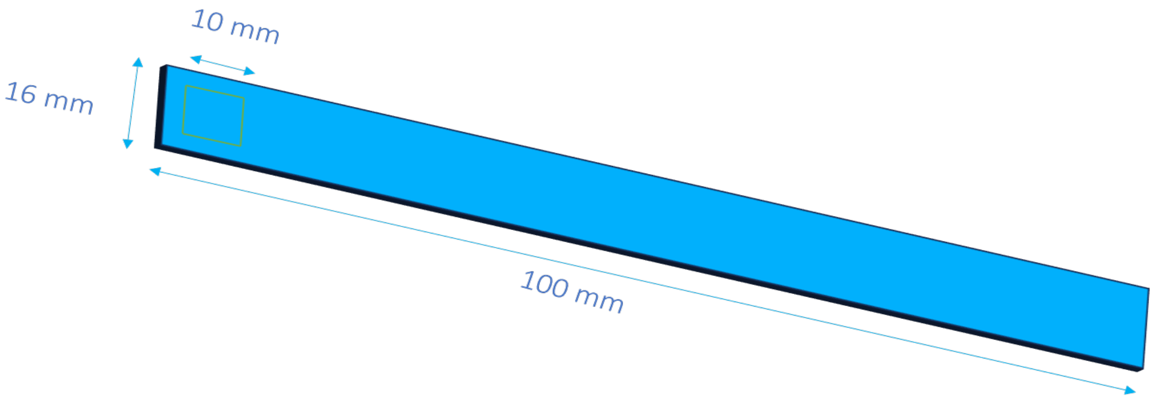



**Fig. 1.** Dimensions of aluminium with PZT

**Table 1**
Dimension of Aluminium with PZT [16]

| Dimensions | Aluminium (mm) | PZT (mm) |
|---|---|---|
| Length | 100 | 10 |
| Width | 16 | 10 |
| Thickness | 1 | 0.3 |

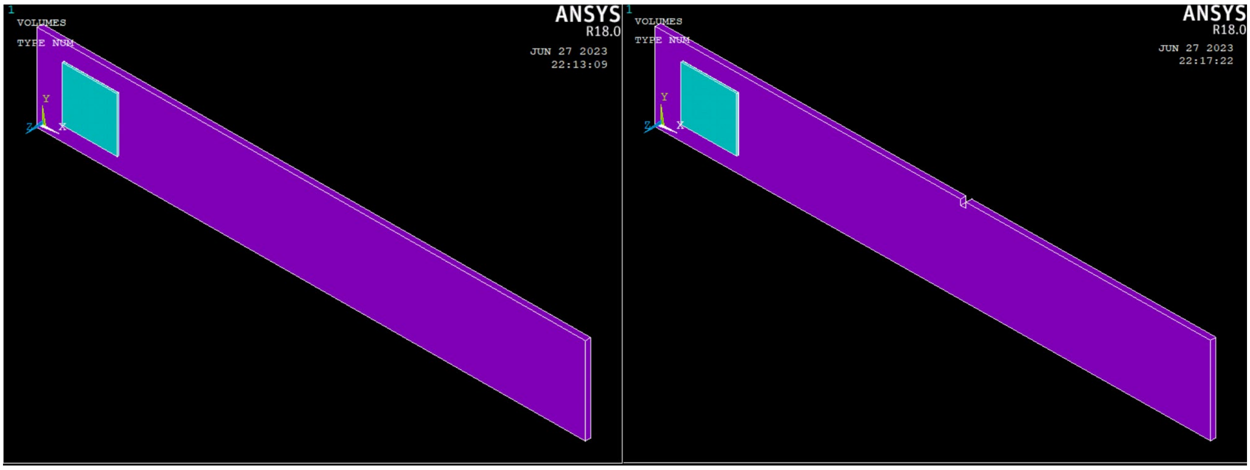
For the PZT patch model in this investigation, piezoelectric material properties of type PI151 were applied. It is necessary to have the following two types of material properties: Table 2 showed the permittivity [$\varepsilon$] (dielectric constant), the piezoelectric strain coefficient matrix [d], These coefficients are crucial in the design of piezoelectric sensors used in applications such as accelerometers, pressure sensors, and force sensors. The inverse piezoelectric effect is also essential. When the material experiences mechanical strain, it generates an electric field. The coefficients $d_{31}$, $d_{32}$, and $d_{33}$ influence the efficiency of this process. Where, compliance matrix represents the relationship between stress and strain in an anisotropic material, such as the piezoelectric material PZT (Lead Zirconate Titanate). The compliance matrix is a mathematical representation that relates the components of strain to the components of stress in a linear elastic material. The dimensions of the PZT patch are also considered for this simulation which is taken as 10 x 10 x 0.3 mm.

**Table 2**
Properties of aluminium with PZT and Epoxy [16]

| Parameter | Aluminium | Epoxy (Adhesive) | PI151 PZT patch |
|---|---|---|---|
| Density (kg/m$^3$) | 2715 | 1160 | 7800 |
| Poisson's Ratio | 0.3 | 0.4 | |
| Young's Modulus (GPa) | 68.95 | 5.1 | |
| Compliance Matrix | | | $S_{11}$= 19.0×10$^{-12}$m$^2$/N<br>$S_{12}$=19.0×10$^{-12}$m$^2$/N |
| Electric Permittivity Coefficient | | | $\varepsilon_{11}^T$=1977<br>$\varepsilon_{33}^T$=2395 |
| PZT strain coefficient (m/V) | | | $d_{31}$=-2.10×10$^{-10}$<br>$d_{32}$=-2.10×10$^{-10}$<br>$d_{33}$=5×10$^{-10}$ |

## 3. Finite Element Method

An ANSYS Mechanical ADPL-18 software was utilized to perform a numerical investigation employing FE models. The objective of this simulation was to create a smart structural system comprising an aluminium component with an attached PZT patch, and to calculate the EMI of the system. The investigation focused on the low frequency range of 20 to 25 kHz, which corresponds to the lateral modes of the PZT patch. To compute the EMI a coupled field analysis approach was employed considering the interaction between various engineering disciplines specifically the structural and electric fields in a piezoelectric analysis. The glue model encompassed with aluminium component attached with the PZT patch representing healthy structure shown in Figure 2 (a). To model for the damaged aluminium, the same procedure as the one used for the healthy aluminium a single PZT patch was attached to the surface of the aluminium specifically positioned 5 mm away from the left edge. The damage was located at 55 mm from the left edge with an incision size of 1 x 1 mm on the aluminium as Figure 2 (b) depicts the damaged aluminium with the applied glue model.

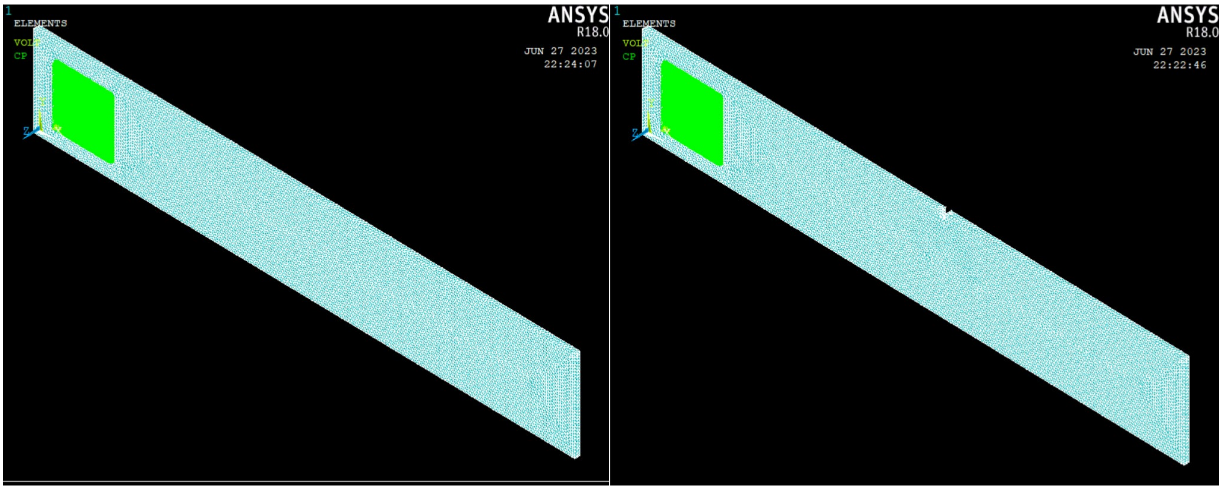



(a) (b)

**Fig. 2.** Glue model of aluminium with PZT (a) Healthy (b) Damaged

To accurately capture the wave characteristics, it is necessary to ensure the FE mesh model is precise and sufficiently fine. The meshing of the aluminium component with the piezoelectric actuator is estimated to have a resolution of 0.0005 mm despite operating in the plane dimension, the PZT patch is polarized in the direction of its thickness. Consequently, the stiffness, dielectric, and piezoelectric matrices must all be orthotropic to accurately describe the material properties. For each of the top nodes of the PZT patch a voltage of 0 V is applied while for each of the bottom nodes a voltage of 1 V is applied. Through harmonic analysis in the low frequency range, the transverse modes of the PZT patch (20 - 25 kHz) are revealed. Figure 3 (a) depicts the healthy aluminium FE mesh model, while Figure 3 (b) illustrates the FE mesh model of the damaged aluminium structure.

The simulation of the PZT patch was conducted using the SOLID226 element which is a three-dimensional (3D) coupled field solid element consisting of 20 nodes and six degrees of freedom (DOF) at each node. This element includes an additional DOF to account for the electrical voltage. For the modelling of the aluminium material the SOLID186 element was employed. It is composed of 20 nodes with three DOF at each node representing translations in the x y and z directions. In the FE analysis the dimensions of the PZT patch were set to 10 x 10 x 0.3 mm while the aluminium structure dimensions in the finite element analysis were set as 100 mm x 16 mm x 1 mm. Figure 4 depicts the FE model of the piezoelectric patch with voltage applied at master node which connects in between the top nodes and bottom nodes.




(a) (b)

**Fig. 3.** FE model of aluminium with PZT (a) Healthy (b) Damaged

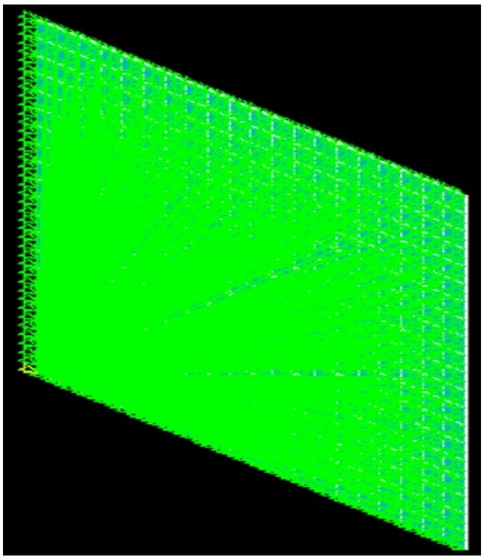


**Fig. 4.** PZT meshing with coupling nodes

Intelligent construction systems were employed to model and calculate the admittance of the system by determining the ratio of the output current to the input voltage from the PZT patch connected to the aluminium structure. A coupled field analysis was utilized to analyze the current flow within the PZT patch effectively managing the interactions between the structural and electric fields while eliminating any interferences between multiple engineering disciplines such as the piezoelectric analysis.

## 4. Results and discussion

### *4.1 Validation of Healthy Aluminium with PZT Patch*

Following the implementation of harmonic analysis during postprocessing structural damping coefficient of 0.005 (No unit for structural damping coefficient) was obtained. When running the simulation model for the healthy aluminium it resulted in a negative polarity charge and a positive polarity charge in relation to frequency by utilizing the frequency and charge parameters the real part of impedance was calculated for different frequencies. Figure 5 illustrates the relationship between the real part of impedance and frequency. So we validated the real part of impedance behavior for healthy aluminium as of [16] simulation results which represents in Figure 5 of frequency vs real part of impedance for healthy specimen. Most peaks in the comparison occurred at identical frequencies, but certain peaks exhibited a leftward shift. This shift might be attributed to the lack of data regarding the properties of the elastic material. Furthermore, distinctions persist between the simulated and measured values, particularly in specific frequency domains. The comparison shows the same behavior of [16] simulation results of the impedance are compared with the results obtained from the (ANSYS 18) simulation of the real part of impedance as a function of frequency. The real part of impedance signatures shows a general similarity in terms of frequency indicating an overall good match. However, certain deviations can be observed with the present results being slightly lower by approximately 5% compared to the previous results. The 5% deviation change observation is due to the ANSYS software package difference. Where the solid element type in preprocessing for aluminium and glue changed. Despite this discrepancy the comparison highlights that the FE technique can yield a reasonable fit, representing a notable improvement over the numerical simulation.

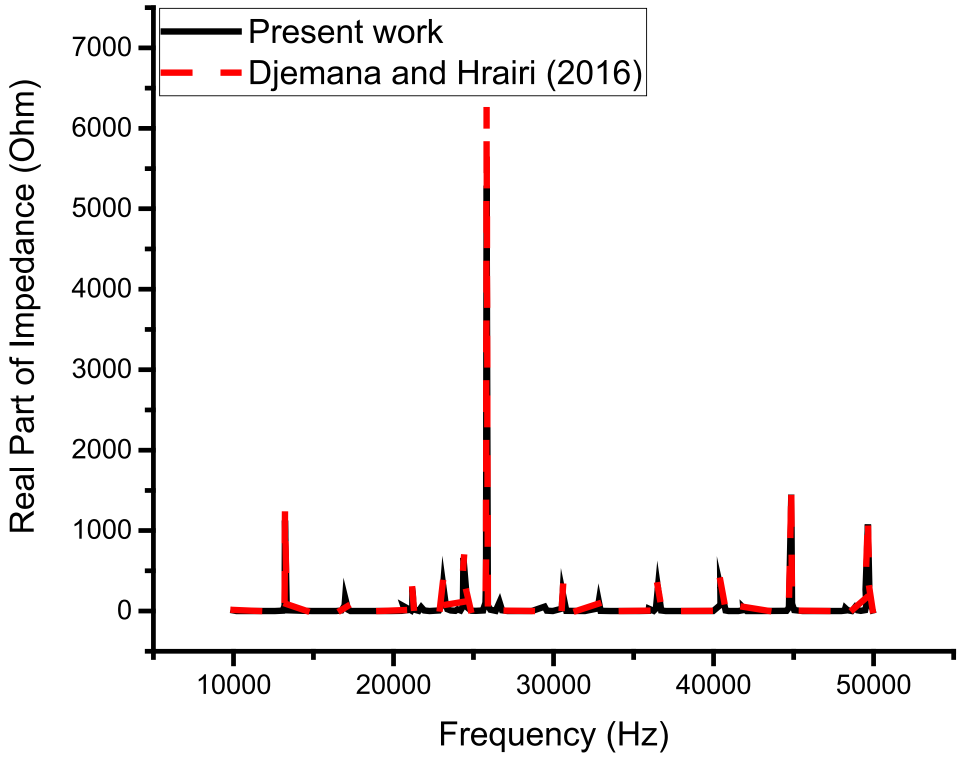



**Fig. 5.** Real part of Impedance for healthy aluminium

*4.2 Validation of Damaged Aluminium with PZT Patch*

Harmonic analysis was chosen with the structural damping coefficient of 0.005. Running the simulation model for the damaged aluminium reveals the generation of both negative and positive charges in relation to frequency. Whereas the electric voltage applied during preprocessing at the nodes of the PZT patch, following the execution of the simulation model, which results in the generation of these charges. Using the charge and frequency parameters we first calculated susceptance, conductance and admittance then calculated the real part of impedance. Figure 6 illustrates the relationship between the real part of impedance and frequency so we validated the real part of impedance behavior for unhealthy specimen as of [16] simulation results. Most peaks in the comparison were observed at the same frequencies. This deviation could be linked to insufficient data on the characteristics of the elastic material. Additionally, variations persist between the values simulated and those measured, especially within certain frequency ranges. The strong agreement between the two results is evident in Figure 6 which demonstrates the accurate and reliable representation of the numerical outcomes by the computational model. However, it should be noted that the present results exhibit a slight deviation of approximately 5% compared to the previous results, which can be attributed to the use of a different version of the ANSYS commercial tool.

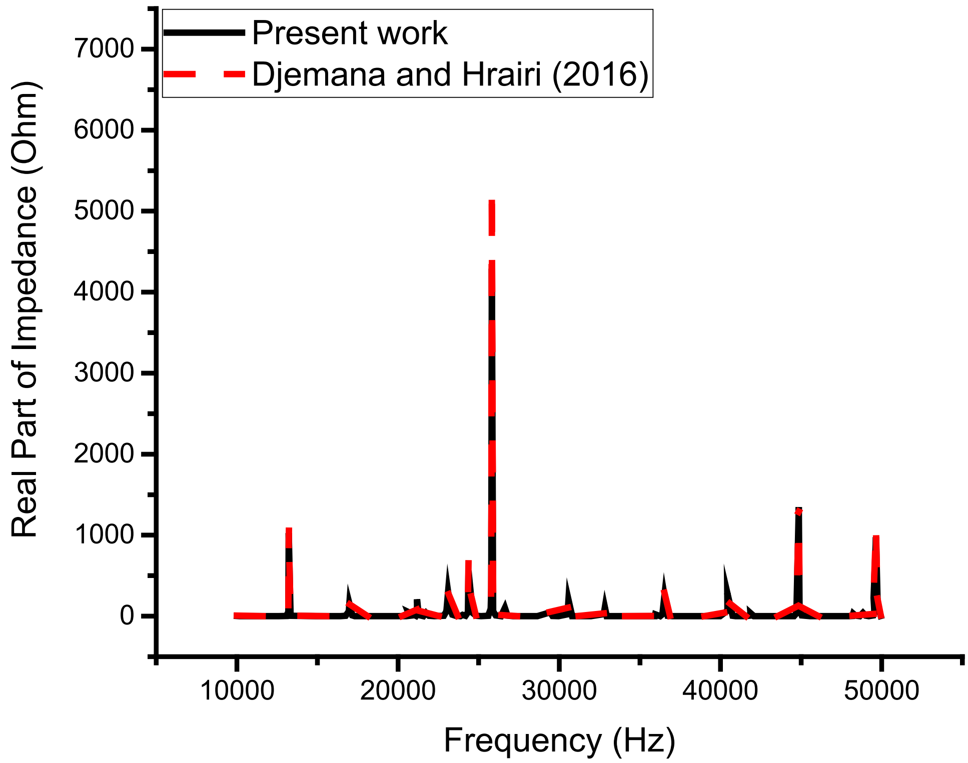



**Fig. 6**. Real Part of Impedance for damaged aluminium

*4.3 Validation of Damaged Aluminium (2mm) with PZT Patch*

A single PZT patch was attached to the surface of the aluminium, specifically positioned 5 mm away from the left edge. Another damage was modeled this damage was located at 55 mm from the left edge, with an incision of 1mm wide and 2 mm depth on the aluminium, and structural damping coefficient is 0.005. Where the structural damping coefficient in the context of a material like PZT (Lead Zirconate Titanate) refers to the ability of the material to dissipate vibrational energy as mechanical vibrations pass through it. We observed the generation of both negative and positive charges at various frequencies. Utilizing these charge and frequency parameters we derived the real part of impedance as a function of frequency. Figure 7 depicts the relationship between the real part of impedance and frequency. This confirms the accuracy of the real part of impedance behavior in the unhealthy specimen as indicated by the simulation results in [16]. Figure 7 demonstrates a strong agreement between the two sets of results, validating the computational model's reliability in accurately representing the numerical outcomes. It suggests that the simulation conducted in the ANSYS software aligns with observed data, encompassing factors such as material properties, element types, simulation procedures, and more. These aligned parameters enhance the case for placing confidence in the model, affirming its ability to generate dependable predictions and output results.

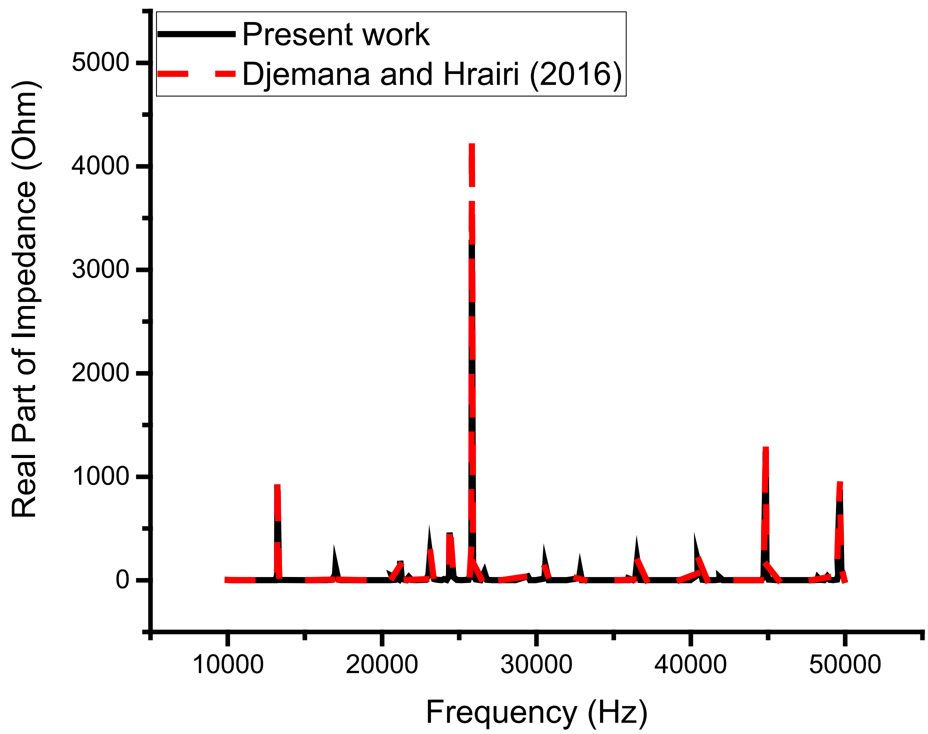



**Fig. 7.** Real Part of Impedance for 2 mm Damage

### *4.4 Comparison between Healthy and Unhealthy Aluminium*

Figure 8 displays the real part of impedance signals obtained from healthy and cracked aluminium specimens. Material properties, boundary conditions, type of mesh are commonalities in cracked and healthy aluminium structures. Whereas damage modelling and non-linear behaviour because of notch present in the aluminium, may be the differences in the damage structure as compared to healthy. Deviations in the real part of impedance behavior signify variations in the structural response between healthy and damaged states. These differences could be indicative of specific damage mechanisms or structural changes affecting the aluminium material. Understanding these deviations is essential for accurately identifying and characterizing the nature and extent of damage within the structure. On the other hand, similarities in the real part of impedance behavior may raise questions about the discriminative capability of the Finite Element Technique. It could suggest limitations or challenges in the technique's ability to distinguish between these conditions accurately. These cracked specimens feature wide notches, each with a depth of either 1 mm or 2 mm. A noticeable observation is that the real part of impedance in the healthy aluminium specimens is considerably higher when compared to the cracked ones. The positioning of the crack on the specimen is 55 mm away from the left side. This discrepancy in impedance between healthy and cracked specimens can be attributed to several factors, with the amplitude and type of incision playing a crucial role in modifying the electrical behavior of a material. Deeper incisions tend to alter the material's electrical conductivity by creating pathways of reduced cross-sectional area for current flow, impacting resistance and conductivity. Additionally, higher amplitude incisions may introduce surface irregularities, affecting the contact area between the material and electrodes, thus influencing electrical resistance. The type of incision, whether a simple cut or a more complex shape, further contributes to changes in localized resistivity and capacitance. So, the presence of the crack alters the electrical behavior of the material, leading to changes in impedance. The potential factors contributing to the observed differences in impedance can be material properties changes in which elastic modulus alterations can be a factor. Where Cracks or damage in the aluminum structure can lead to a reduction in the elastic modulus of the material. This change affects the stiffness of the structure and influences the impedance response. And damping variation which involves damage introduction additional damping mechanisms, affecting the energy dissipation characteristics of the structure. Changes in damping can contribute to differences in the impedance response. Whereas geometric changes, boundary conditions and frequency shift also the factors. Meanwhile, the variables that influence the amplitude and type of incision include the dimensions of the notch and its proximity to the surface of the aluminium material. The variables can be material properties, type of geometry, boundary conditions, material damage and element size. These factors affect the distribution of charges and currents within the material, thereby influencing the impedance response. Material properties, including conductivity, permittivity, and permeability, dictate the ease with which charges move and respond to electric and magnetic fields. The type of geometry shapes the path of charges and impacts impedance, especially in the presence of sharp corners or irregular shapes. Boundary conditions at the interfaces of materials influence how charges interact and propagate, leading to reflections or standing waves that affect impedance. Understanding the impedance behavior of damaged aluminium specimens is significant in various engineering and structural applications, as it can provide valuable insights into the integrity and reliability of the material under different conditions. Aluminum is widely used in aerospace, automotive, and structural engineering due to its favorable strength-to-weight ratio. The ability to assess the impedance behavior of damaged aluminum helps in detecting structural flaws, such as cracks, corrosion, or material degradation, which can compromise the integrity of components and structures. Moreover, impedance-based monitoring provides a non-destructive and efficient means of inspecting structures over time. Continuous monitoring of impedance can reveal the progression of damage, allowing for timely intervention and minimizing downtime or potential risks.

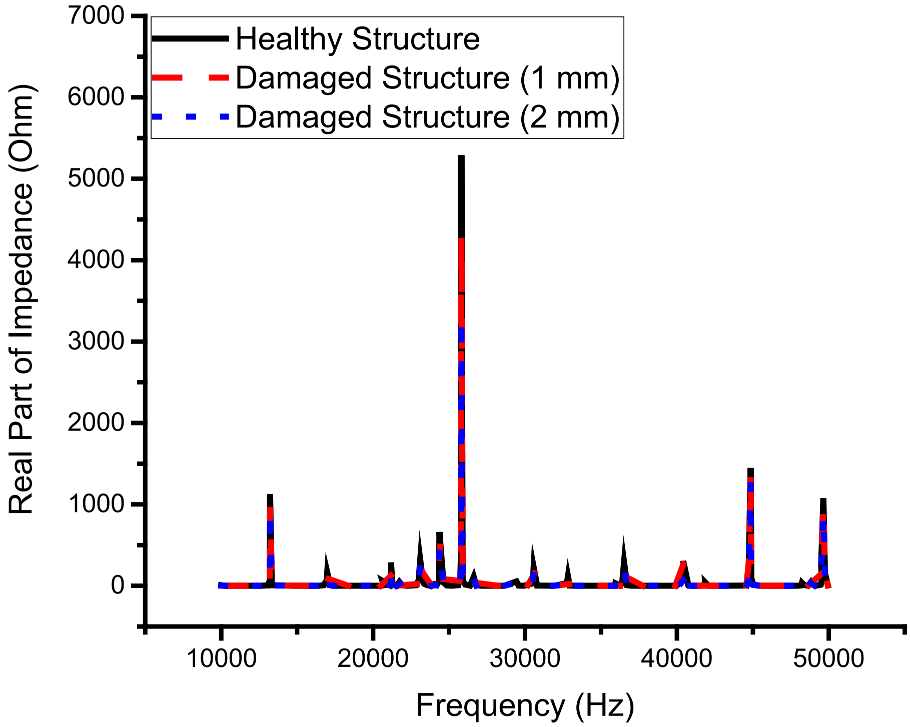



**Fig. 8.** Healthy vs. damaged aluminum

In summary, the viability of numerical simulation for utilizing electro-mechanical impedance sensors for damage diagnosis to monitor condition of mechanical structures was explored.

Investigation involved conducting numerical studies on healthy and damaged aluminium structures to detect and identify damage. The performance and reliability of the present computational model in representing the real part of impedance behavior in healthy versus damaged aluminum structures depend on various factors, including the accuracy of the material model, the fidelity of the damage representation, and the appropriateness of the simulation setup. Meanwhile the objective of this research work is to detect health monitoring in the aluminium structure with healthy and unhealthy conditions using electromechanical impedance and finite element modeling which has been successfully determined. In this research, electromechanical impedance plays a crucial role in evaluating the structural integrity of aluminum components. By analysing the impedance response, which gain valuable insights into the dynamic mechanical behavior of the material. This method allows for the identification of variations in impedance patterns associated with both healthy and unhealthy states, providing a nuanced understanding of structural conditions. The numerical analysis utilizing finite element models successfully predicts damage with consistent trends observed in the fluctuation of impedance signatures recorded by the PZT patches. These trends can indicate the stability or changes in the mechanical and electrical properties of a structure over time. Identifying consistent patterns in impedance fluctuations helps establish a baseline for the healthy state of the structure. Deviations from these trends may signal the presence of damage, defects, or changes in structural conditions. A noticeable observation is that the real part of impedance in the healthy aluminium specimens is considerably higher when compared to the cracked ones. The positioning of the crack on the specimen is 55 mm away from the left side. This discrepancy in impedance between healthy and cracked specimens can be attributed to several factors, with the amplitude and type of incision playing a crucial role. The presence of the crack alters the electrical behavior of the material, leading to changes in impedance. The variables that influence the amplitude and type of incision include the dimensions of the notch and its proximity to the surface of the aluminium material. Furthermore, to gain deeper insights into the topic, like Integration with structural health monitoring systems, crack growth simulations, sensor network optimization, parametric studies, multi-physics coupling can be suggested. additional examinations can be carried out by varying the size and location of cracks at different depths in diverse types of materials. Testing different crack sizes with location helps assess the sensitivity of EMI sensors to cracks of varying magnitudes. This is crucial for understanding the detection limits and capabilities of the sensors. Whereas varied crack depths introducing cracks at different depths provides insights into the EMI sensor's ability to detect and characterize damage at various depths within the material. This is particularly relevant for understanding the depth sensitivity of the technique. This would expand the range of scenarios for investigation, providing a more comprehensive understanding of damage detection using electro-mechanical impedance sensors.

## 5. Conclusion

In conclusion, the study demonstrates the capability of electro-mechanical impedance sensors to differentiate between pristine and damaged aluminum samples through changes in impedance signatures, indicating structural alterations. Finite element modelling validations support the electro-mechanical impedance data, showing precise damage location and extent predictions. This interaction between electro-mechanical impedance sensing and finite element method suggests a significant advancement in structural health monitoring, offering a non-destructive, efficient method for assessing damage in aluminum structures, with potential for further refinement and broader application in damage detection.

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