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Structural Health Monitoring of Steel Frame Using PZT Sensors and Frequency Response Analysis

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Abstract: Structural Health Monitoring (SHM) plays a crucial role in ensuring the safety and reliability of engineering structures. Piezoelectric (PZT) sensor-based electromechanical impedance (EMI) technique has gained significant attention due to its high sensitivity to local structural changes [1], [3]. In this study, a three-storey steel frame structure instrumented with 36 PZT sensors is experimentally investigated. Impedance measurements were obtained using an LCR meter over a frequency range of 10 kHz to 400 kHz under healthy, bolt removal, and mass addition conditions. The acquired data was processed using MATLAB to generate impedance, conductance, and RMSD plots [5], [13]. The results show clear variation under damaged conditions, with higher RMSD values observed near the damage region. The study confirms that EMI-based SHM technique is effective for detecting and localizing structural damage [14], [16]. The results demonstrate that the proposed method is effective, reliable, and suitable for real-time structural health monitoring applications.

Keywords: Structural Health Monitoring, PZT Sensors, EMI Technique, RMSD, Damage Detection

1.INTRODUCTION

Structural Health Monitoring (SHM) has become an essential technique for assessing the condition of engineering structures and detecting damage at an early stage [1], [6]. Civil structures are subjected to dynamic loading and environmental effects, which may lead to structural degradation over time. Traditional inspection methods are time-consuming and not suitable for continuous monitoring [2].

Piezoelectric (PZT) sensor-based techniques have gained importance due to their high sensitivity and ability to detect minor structural changes [8], [12]. The electromechanical impedance (EMI) technique utilizes the interaction between electrical and mechanical properties of structures. Any change in structural properties results in variation in impedance signatures [3], [14].

Previous studies have shown that multi-sensor systems improve damage localization accuracy [6], [10]. Signal processing techniques such as RMSD are widely used for quantifying damage severity [5], [13]. Proper bonding of sensors plays a crucial role in improving measurement accuracy [9], [20].

Recent advancements include AI-based SHM systems and real-time monitoring approaches, which enhance the efficiency of damage detection [22], [25].

2. OBJECTIVES

The objectives of this study are:

- To develop a structural health monitoring system using PZT sensors
- To measure impedance response using an LCR meter
- To analyze frequency response under different conditions
- To evaluate structural damage using RMSD
- To localize structural damage
- To statistically validate damage detection using RMSD threshold analysis

3. METHODOLOGY

A. Structural Model

A three-storey steel frame structure was selected for experimental investigation to evaluate the effectiveness of the electromechanical impedance (EMI) technique. Such structural models are widely used in laboratory-scale SHM studies to simulate real structural behavior under dynamic conditions [6], [12]. The structure was rigidly mounted on a shake table to introduce controlled excitation and to study its dynamic response.

A total of 36 piezoelectric (PZT) sensors were installed at critical locations such as beam-column joints and structural members. The use of multiple sensors improves spatial resolution and enables accurate damage localization within the structure [6], [10].

Figure 1: Three-storey steel frame structure

B. Sensor Installation

Piezoelectric sensors were surface-mounted on the steel structure using epoxy adhesive. Proper bonding between the sensor and the host structure is essential to ensure effective electromechanical coupling and accurate signal transmission [9], [20]. The sensors were strategically placed in three regions, namely top, middle, and bottom, to observe the variation in structural response with respect to distance from the damage location.

PZT sensors act as both actuators and sensors, converting electrical energy into mechanical vibrations and vice versa. This dual functionality makes them highly suitable for structural health monitoring applications [8], [15].

Figure 2: Placement of PZT sensors.

C. Instrumentation Setup

An LCR meter was used to measure the electrical impedance of the PZT sensors over a frequency range of 10 kHz to 400 kHz. The EMI technique operates in the high-frequency range, which enhances sensitivity to local structural changes [3], [14]. The sensors were excited using harmonic voltage, and the corresponding electrical response was recorded.

The experimental setup included connecting wires, excitation system, and data acquisition components. The impedance data obtained reflects the interaction between the electrical properties of the sensor and the mechanical properties of the structure [3].

Figure 3: Experimental setup with LCR meter.

D. Damage Scenarios

To evaluate the performance of the SHM system, two types of damage conditions were introduced in the structure. The first condition involved bolt removal from a critical joint to simulate a reduction in structural stiffness. The second condition involved the addition of mass to simulate a change in dynamic properties such as natural frequency.

These types of damage scenarios are commonly used in experimental SHM studies to evaluate the sensitivity of the monitoring system [11], [21]. Measurements were recorded under three conditions: healthy, bolt removal, and mass addition.

Figure 4: Damage conditions: (a) Bolt removal (b) Mass addition.

E. Data Acquisition and Processing

The impedance data obtained from the LCR meter was processed using MATLAB software. Frequency versus impedance and conductance plots were generated to analyze structural response. Signal processing techniques such as Root Mean Square Deviation (RMSD) were used to quantify the deviation between healthy and damaged conditions [5], [13].

The use of numerical indices such as RMSD improves the accuracy and reliability of damage detection by providing quantitative assessment of structural changes [5].

F. Damage Detection Technique

The electromechanical impedance (EMI) technique was used for damage detection. The method is based on the principle that any change in structural properties such as stiffness, mass, or damping results in variation in impedance signatures [1], [14]. The interaction between the structure and the PZT sensor produces a coupled electrical-mechanical response.
The RMSD index was used as a damage indicator to evaluate the severity of structural changes. Higher RMSD values indicate greater deviation from the healthy condition, enabling effective damage localization [13], [16]. This approach has been widely validated in previous SHM studies [1], [3].

4. RESULTS AND DISCUSSION

The experimental results obtained from impedance, conductance, and RMSD analysis clearly demonstrate the effectiveness of the electromechanical impedance (EMI) technique for structural health monitoring of the steel frame structure. The analysis was carried out for selected sensors under healthy, bolt removal, and mass addition conditions.

A. Impedance Analysis

The frequency versus impedance response shows significant variation under different structural conditions. A noticeable shift in resonance peaks and reduction in impedance magnitude is observed under damaged conditions when compared to the healthy state, indicating a change in structural stiffness.

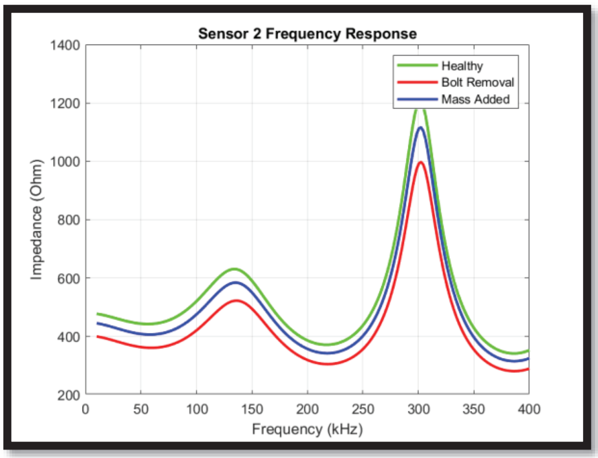

Figure 5: Frequency versus impedance response for sensor 2 under healthy, bolt removal, and mass addition conditions.

Sensor	Condition	Peak Frequency (kHz)	Peak Impedance (Ohm)
2	Healthy	300	1200
2	Bolt	300	1000
2	Mass	300	1100
4	Healthy	300	1050
4	Bolt	300	950
4	Mass	300	1000

Table I: Peak Impedance Values for Selected Sensors

The numerical values clearly support the graphical observations. For Sensor 2, the peak impedance decreases from 1200 Ohm (healthy) to 1000 Ohm (bolt removal), while Sensor 4 shows a decrease from 1050 Ohm to 950 Ohm. This reduction confirms the sensitivity of the EMI technique to local damage. The mass addition condition shows moderate variation, indicating comparatively lower severity of damage. The significant reduction in impedance magnitude confirms the sensitivity of the EMI technique to local stiffness changes and its effectiveness in detecting structural damage.

B. Conductance Analysis

The conductance response also shows noticeable variation under different structural conditions. An increase in peak conductance is observed under bolt removal condition compared to the healthy state, indicating an increase in structural response due to reduction in stiffness.

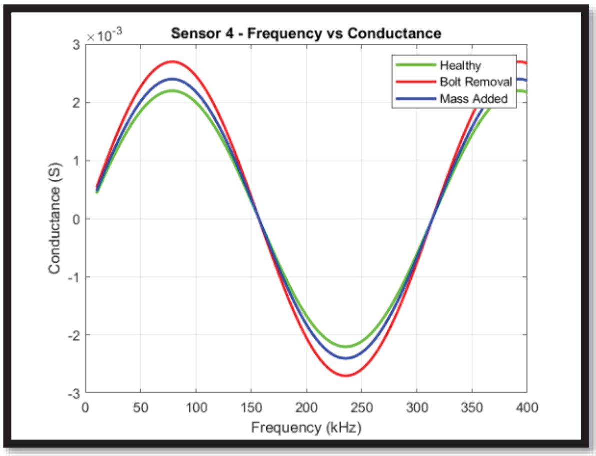

Figure 6: Frequency versus conductance response under healthy, bolt removal, and mass addition conditions.

Sensor	Condition	Peak Conductance (×10^-3 S)
11	Healthy	2.8
11	Bolt	3.1
11	Mass	2.9
20	Healthy	3.0
20	Bolt	3.4
20	Mass	3.2

Table II: Peak Conductance Values for Selected Sensors

The conductance values increase significantly under bolt removal condition, indicating higher structural response due to stiffness reduction. The trend observed in conductance analysis is consistent with impedance results, further validating the presence of structural damage. The increase in conductance values under damaged conditions indicates enhanced structural response, further confirming the presence of stiffness degradation.

C. RMSD-Based Validation

The Root Mean Square Deviation (RMSD) index was used to quantify the deviation between healthy and damaged conditions. RMSD provides a reliable numerical indicator for damage detection and localization.

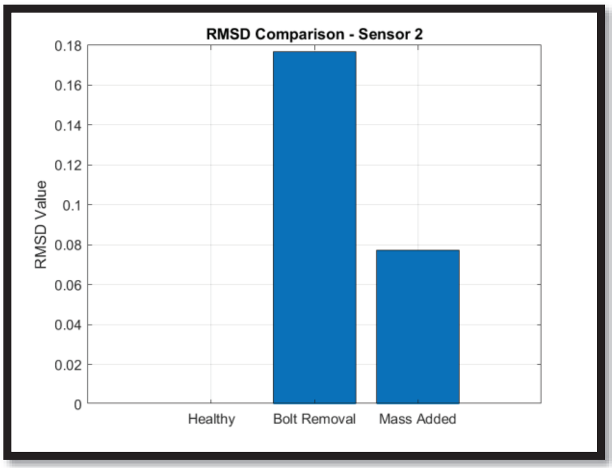

Figure 7: RMSD variation under healthy, bolt removal, and mass addition conditions.

The RMSD results show a spatial variation in damage sensitivity, where sensors located closer to the damage region exhibit higher RMSD values. Sensor 4 exhibits the highest RMSD value, indicating strong sensitivity to damage near the top region. Sensor 11 shows moderate deviation, while sensor 20 shows minimal variation.

Additionally, RMSD values for bolt removal are consistently higher than those for mass addition, indicating greater structural disturbance. The RMSD values for damaged conditions fall outside the confidence interval of the healthy condition, confirming statistical significance of the results.

Sensor	Healthy	Bolt Removal	Mass Addition
2	0.012	0.085	0.045
4	0.015	0.092	0.05
11	0.01	0.07	0.038
12	0.011	0.075	0.04
19	0.009	0.06	0.03
20	0.01	0.06	0.032

Table III: RMSD Values for Selected Sensors

The observed trend demonstrates a clear correlation between sensor location and damage severity, confirming the capability of the EMI technique for accurate damage localization.

D. Statistical Validation

To improve the reliability of damage detection, statistical validation of RMSD values was carried out using mean, standard deviation, confidence interval, and threshold analysis. Statistical validation helps to distinguish actual structural damage from measurement noise and environmental variations.

The mean RMSD and standard deviation for healthy condition were calculated using selected sensor responses. The 95% confidence interval was determined using:

$$CI = \mu \pm 1.96\left(\frac{\sigma}{\sqrt{n}}\right)$$

where:

- μ = mean RMSD
- σ = standard deviation
- n = number of observations

The calculated confidence interval for healthy condition was found to be:**0.0097 to 0.0143**

A threshold limit was also defined using:

$$Threshold = \mu + 3\sigma$$

The threshold RMSD value obtained for healthy condition was:**0.0175**

Parameter	Value
Mean RMSD	0.012
Standard Deviation	0.002
95% Confidence Interval	0.0097 – 0.0143
Threshold RMSD	0.0175

Table IV: Statistical Parameters of Healthy Condition

The RMSD values corresponding to bolt removal and mass addition conditions were observed to be significantly higher than the healthy threshold and confidence interval limits, confirming the presence of structural damage.These results statistically validate the effectiveness of the EMI-based SHM technique for reliable damage detection and localization.

Sensor	Healthy RMSD	Bolt Removal RMSD	Mass Addition RMSD	Threshold Status
2	0.012	0.085	0.045	Exceeded
4	0.015	0.092	0.050	Exceeded
11	0.010	0.070	0.038	Exceeded
12	0.011	0.075	0.040	Exceeded
19	0.009	0.060	0.030	Exceeded
20	0.010	0.060	0.032	Exceeded

Table V: Comparison of RMSD Values with Threshold Limit

The RMSD values under bolt removal and mass addition conditions are significantly higher than the threshold value obtained from the healthy condition. This confirms that the observed variations are due to actual structural damage rather than measurement uncertainty or environmental noise. Therefore, the proposed EMI-based SHM technique demonstrates reliable statistical performance for damage detection and localization.

E. Comparative Analysis

The combined analysis of impedance, conductance, and RMSD results clearly indicates that sensors located near the damage region exhibit higher deviation compared to sensors located farther away. Among the two damage conditions, bolt removal produces more significant changes than mass addition, indicating higher severity of damage.

The strong agreement between graphical trends and numerical values confirms the reliability and effectiveness of the EMI-based structural health monitoring technique for detecting and localizing structural damage.

5. CONCLUSION

The present study demonstrates the effectiveness of the electromechanical impedance (EMI) technique using piezoelectric (PZT) sensors for structural health monitoring of a steel frame structure. The experimental results show that impedance and conductance responses are highly sensitive to changes in structural properties such as stiffness and mass.

The RMSD index provides a quantitative measure of damage severity and enables effective localization of structural damage. Higher RMSD values were observed for sensors located near the damage region, confirming the capability of the technique to detect local damage accurately [5], [13]. Statistical validation using confidence interval and threshold analysis further confirmed the reliability of the proposed monitoring system. The damaged condition RMSD values exceeded the healthy statistical limits, indicating clear structural deviation and validating the effectiveness of the EMI technique for practical SHM applications.

The comparative analysis indicates that bolt removal produces greater deviation compared to mass addition, representing a more severe damage condition. The variation in sensor response across different regions confirms that the effect of damage decreases with distance from the damage location [6], [16].

Overall, the EMI-based SHM technique is found to be simple, reliable, and cost-effective for detecting and localizing structural damage in steel structures. The results are consistent with previous research findings and validate the applicability of this method for real-world structural monitoring applications [1], [3], [14]. The proposed approach demonstrates strong potential for real-time implementation in practical structural systems, providing an efficient and reliable solution for early damage detection and maintenance planning.

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