Structural Health Monitoring Through the Application of Piezoelectric Sensors – State of the Art Review

Aishwarya Thakur and Saurav

Abstract Electromechanical impedance-based (EMI) method is generally utilized for health monitoring. Structural health monitoring (SHM) could show a significant part in keeping up safety of "in-working structures." The EMI method is generally acknowledged as an inexpensive and extremely sensitive procedure for SHM and non-destructive evaluation (NDE) of a variation of engineering organizations. The utilization of piezoelectric sensors (PZT) is one of SHM's intelligent detecting technologies. The piezoceramic materials act simultaneously as an actuator and sensor for SHM. This paper reviews online strength increment monitoring of early age concrete is identified with the service of EMI discovering method. RMSD values for different patches were compared at various frequency ranges (300,400 kHz). Different conductance signature values were also compared and found that with increase in duration RMSD value increases, which provided conclusive evidence in the health monitoring process of a structure by utilizing PZT sensor. Upon connecting PZT sensors in series conductance value subsequently increases from 2.01 at Day 7 to 7.31 after 21 Days of monitoring the beam at different curing region. The root mean square deviation index (RMSD) was additionally used for automatically specifying the change in the impedance of the integrated PZT sensor below temperature and load. Also, it was reviewed that impedance analyzer at range from 40 Hz to 1000 kHz applied at different piezoelectric sensors and showed that integrated PZT sensor can efficiently determine the result in quantification and indication of structural damage; this benefits the accurate assessment of structural damage. Thus, from the study, we can conclude that the proposed strategy for damage recognition is very successful and sensitive to concrete.

Keywords Non-destructive evaluation · Piezoceramic · Concrete · Sensor · EMI technique · Root mean square deviation

A. Thakur (✉) · Saurav
Civil Engineering Department, Jaypee University of Information Technology, Solan, Himachal Pradesh, India
e-mail: 206602@juitsolan.in

Saurav
e-mail: saurav@juit.ac.in

1   Introduction

Civil infrastructure needs timely inspection to assess its reliability and strength for the future advantage of human culture, wellbeing of life, and productivity. Its economic and safe presentation represents a great advantage for the civilization, since it stabilizes financial administration and security. In over-all, their presentation contains a great deal of uncertainties since they are frequently subject to disturbing natural tragedies and heavy use. To conquer these difficulties, numerous independent research associations and entities are devising new methods for large-scale presentation evaluation and clarification of the behavior of structures, which is called SHM. Structural health monitoring is a trending topic today to monitor or certify the complete performance of the organization [1].

An effective SHM system for civil engineering is able to identify the location and quantity of faults (rust, cracks, etc.) in real time, so the building can be fixed and strengthened on schedule to confirm integrity and structural wellbeing [2]. Today, various structural health finding techniques are enforced to different civil structures or their segments. Like as the standard static deformation test, vibration documents techniques and non-destructive test (NDT) techniques: ultrasound, impedance, acoustic emission, X-rays, pulse radar and infrared thermal imaging. But maximum of the methods are qualitative, and real-time detection is difficult. Smart materials, such as PZT materials, cement-based smart composites, fiber optic sensors, and magneto-restrictive materials, offer a new technique for long-term and real-time checking of the health of civil structures [3].

In the middle of the several smart materials, piezoelectric materials, which are mostly signified by piezoelectric ceramics, have the benefits of integrating detection and guidance that makes them fit for SHM [4]. The word "piezo" comes from a Greek word that implies pressure. The phenomenon of piezoelectricity was found in 1880 by Pierre and Paul-Jacques Curie [5]. Piezoelectric Lead Zirconate Titanate (PZT) is an actuator worked framework. It is a solitary PZT that behaves together as an actuator and as a sensor when the PZT head is connected or implanted inside the frame. Among the several smart materials, piezoelectric materials, which are mostly signified through piezoelectric ceramics, have the benefits of integrated sensing and guidance integration, creating them appropriate for SHM. Simultaneously, piezoelectric materials have good linear ratio and quick response, and maximum of piezoelectric materials has low power utilization, minimal cost and easy.

2   Literature Remark

This article includes a brief review of the literature on the various methods available to monitor the structural health of the RC structure.

Bharathi Priya et al. [6] investigate an embedded concrete beam with six PZT covers glued into slabs of expanding thickness by exposing the beam to variance curing. A new process called "sequential detection" is utilized, where patches are associated in sequence, and their admission marks are noted from 10 to 1000 kHz for various frequency varieties from day 2 to day 28. Since the various reaches, 300–400 kHz is ideal with a higher amount of peaks (higher modal density) noticed.

Methodology: RMSD among the signatures was the most suitable index of damage to characterize structural damage.

Expression utilized as given in Eq. 1

$$\mathrm{RMSD} = \left[\frac{\left\{ \sum (G_i^1 - G_i^0) \right\}_{\text{sub - range}}}{\left\{ \sum G_i^{02} \right\}_{\text{full - range}}} \right]^{0.5} \tag{1}$$

where G_i^1 –conductance at the point of the ith dimension in Day of interest; G_i^0– conductance at the point of the ith dimension in Day 2 (baseline).

Patches 5, 3, and 7 situated on the good cure side show higher root mean square deviation (RMSD) values than patches 4 and 6 situated on the poor cure side. RMSD values were calculated from 300 to 400 kHz in patch4 and patch7.

Experimental data: The RMSD values calculated from patch 4 and patch 7 were compared. Patch 4 and patch 7 were linked in series; it is showed in Table 1.

The calculated values are also compared to the RMSD calculated from the patch 4 and patch 7 individual readings. It is showed in Table 2.

Table 1 Percentage change in RMSD values of patches4 and 7 connected in series

Patch	EMSD (%)		
	Day 7	Day 14	Day 21
4 (360–375 kHz)	1.10	2.52	2.01
7 (340–355 kHz)	1.23	5.54	7.31

Table 2 Percentage change in RMSD values of recorded individually from patches 4 and 7

Patch	RMSD (%)		
	Day 7	Day 14	Day 21
4 (360–375 kHz)	5.03	4.10	6.90
7 (340–355 kHz)	2.28	8.09	10.68

From the results, it was clear that the good cure side has a higher RMSD value than the bad curing side. Furthermore, the RMSD of the sequential detection patches was found to follow a similar pattern to the RMSD determined by the information of the individual patch. The results and perceptions from sequential detection and separable record show that the serial detection process utilizing PZT is an efficient, simple, and rapid technique that has surprising and promising utilizes in the field of SHM.

Demi Ai et al. [7] studied that the proposed model was proved through the experimental test outcome of a produced integrated PZT sensor. The inserted PZT sensors were subjectively compared along those fixed to the surface in the investigation of sensing a concrete beam broken shown through means of the subsequent cracking of the concrete covers. As a final point, the efficiency of the integrated PZT sensor was investigated for quantifying structural destruction utilizing the slope-based RMSD index. In addition, a new modifiable RMSD reference index was additionally planned to estimate the impact effect of dual kinds of PZT sensors.

Methodology: The impedance analyzer scanned a PZT patch along measurements of $10 \times 10 \times 0.5$ mm in a free vibration state as of 40 Hz to 1000 kHz, as presented in Fig. 1. A PZT patch along a size of $26 \times 12 \times 0.5$ mm was also measured for comparison in the following experiment. The sizes and the properties of the material used for PZT sensors are additionally presented in Table 3.

Experimental data: A slope situated RMSD list is planned to measure the efficiency of measured destruction values, which (i) displays an extra direct upward trend in destruction quantification; (ii) it can eliminate the value of the suspiciously incorrect damage index of the single PZT sensor, for the benefit of an accurate measurement of the structural damage.

It may also be that the RMSD values of the PZT sensors attached to the surface are almost twice that of the integrated sensors, the slope of the RMSD PZT 2 and PZT 3 values attached to the surface are 0.574 and 0.621 correspondingly, which are additionally greater than PZT integrated sensors. It was originated that the integrated PZT sensor can efficiently filter the impression impact by quantifying and
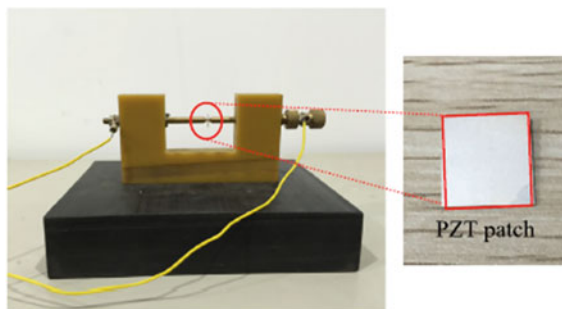

Fig. 1 Experimental arrangement to calculate the PZT patch in a free vibration state

Table 3 Properties of materials and dimensions of PZT sensors

Symbol	Name	Value
l_2	Length	10/25 mm
h_2	Width	10/12 mm
h_2	Thickness	0.5 mm
ε^{33}	Dielectric constant	1.53E−8 facad/m
$\gamma_{33}^{\varepsilon}$	Young's modulus	67 GPa
δ	Dielectric loss factor	0.012
η	Mechanical loss factor	0.003
ρ	Density	7860 kg/m^3
d_{31}, d_{33}	Piezoelectric constant	− 24, 41E−10 m/volt
γ_{13}, γ_{33}	Poisson's ratio	0.38, 1.05

indicating structural damage, benefiting from an accurate assessment of structural damage (Figs. 2 and 3).

Bilgunde et al. [8] mathematical study to arrange the in-situ soundness of piezoelectric sensors utilized for SHM of huge automotive structures, civil, and aeronautical. The system planned in these work activities to demonstrate in-homogeneities in the
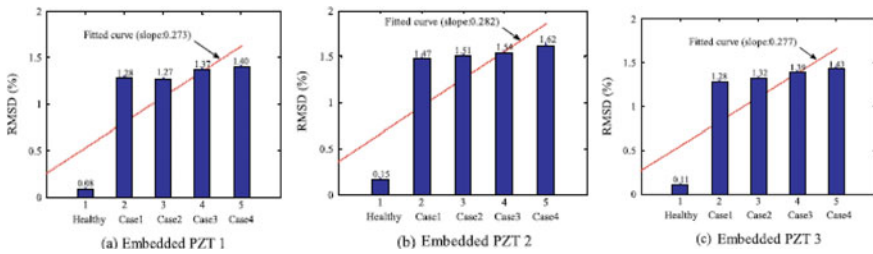

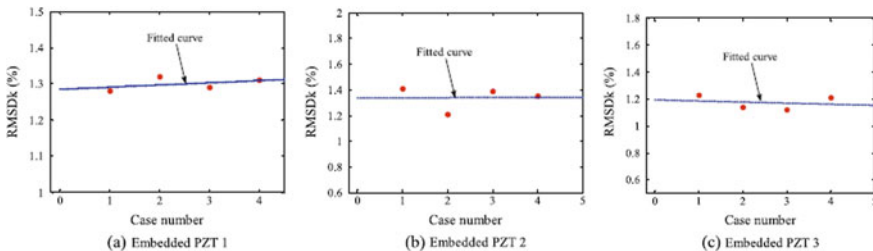**Fig. 2** RMSD values based on the slope of the inserted PZT sensor 1–3

Fig. 3 RMSDk values determined via three inserted PZT sensors in four destruction cases
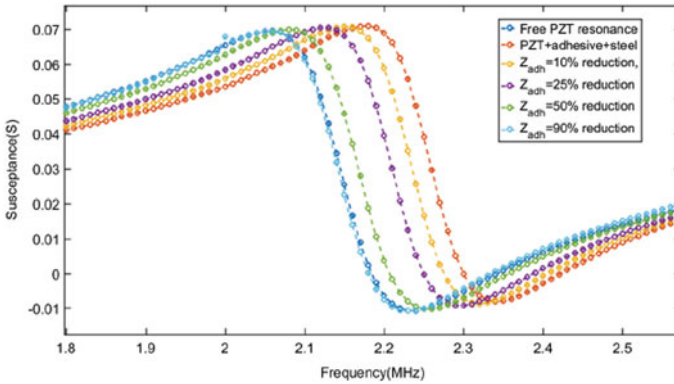
Fig. 4 Decrease in the value of the resonant frequency shown as a function of percentage of decrease in $Z_{adh.}$. In case of 90% decrease, the assemblage starts vibrating at a frequency which equal to the resonant frequency of free PZT-5Adisc

glue along which the sensor is usually attached toward the SHM building. The failure of the connection state was found to justify a discount in resonant frequency of structure and, ultimately, methodologies of the resonance appearances of a PZT material below non-traction limit conditions. These movements in the resonance spectrum are moreover measured utilizing the RMSD-based destruction index. As the outcomes, it was found that EMI technique can be used to monitor the heath of a structure by using an attached sensor.

Experimental data: As per temperature rises, it has been analytically seen that storing modulus of epoxy decreases. The decrease of Z_{adh} reasons an equivalent reduction of the resonant frequency along respect to the base spectrum (presented in Fig. 4). At the point when Z_{adh} is diminished through 90%, comparable to the original binding state, the resonance characteristics are close to the resonance characteristics of a PZT disk.

Changes in the resonance spectrum due to the variation in binding state can also utilize the RMSD-based destruction index. As the percentage of Zadh reduction rises, the destruction rate of the adhesive as well rises. With a 90% decrease in Zadh, the destruction index is 95.7, while free resonance index is 97.80, representing that boundary condition in connected PZT sensor is close to the situation of the situations limit without traction. In this work, we have studied that the decrease of the equal acoustic impedance reasons a decrease of the resonant frequency of the attached group, fundamentally imminent the resonance characteristics of the PZT element however it is in the boundary conditions without traction.

Xu et al. [9] studied in this paper a type of inserted impedance-based PZT sensor that was manufactured utilizing a combination of powdered cement and epoxy as the packing layer. The effects of charge and temperature on the conductance and impedance for the sensor were examined. In the outcomes, a clear temperature dependency is display as the reference point of the conductance spectra keeps on changing by rising the resonance and the temperature heights. Also, RMSD were moreover used here to instinctively visualize the changing impedance for an integrated sensor that is PZT under the effects of load and temperature.

Methodology: The temperature survey was carried out by installing the PZT sensor in a 40 mm × 40 mm × 40 mm mortar sample. The mortar sample with internal the PZT sensor was placed in the temperature examination chamber (Model MPC-710) next restoration on behalf of 28 days. The temperature variety of the experiment is between 2040 °C at a heating degree of 2 °C/min and temperature holding period is one hour each 10 °C. An analyzer was utilized impedance (Agilent 4294A model) to examine electrical impedance spectra of sensor (Fig. 5). The compression load test was performed utilizing a pressure testing instrument, and a growing load with a stage load of 10 kN was enforced to the mortar testers till damage.

Experimental data: The variety of resonance peaks shows that here is a clear temperature dependency of the conductance spectra of integrated PZT sensor (Fig. 6).

The destruction index is generally utilized to visibly specify the characterization of structural destruction. The RMSD index was designed dependent on the calculation given below using Eq. 2

$$\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}\left[|G_i| - |G_i^0|\right]^2}{\sum_{i=1}^{n}\left[|G_i^0|\right]^2}} \tag{2}$$
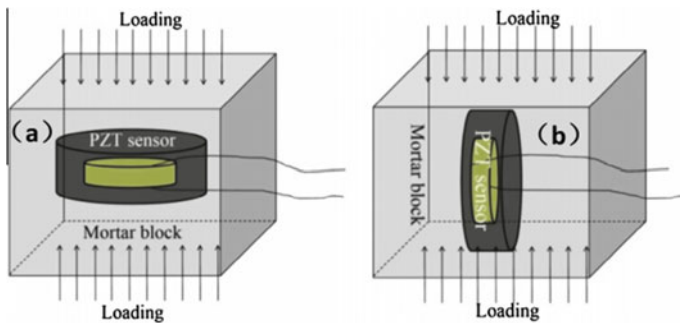

Fig. 5 Pressure being enforced on a mortar sample, **a** alongside the direction of the thick end, **b** beside the direction of flat end of the assigned sensor
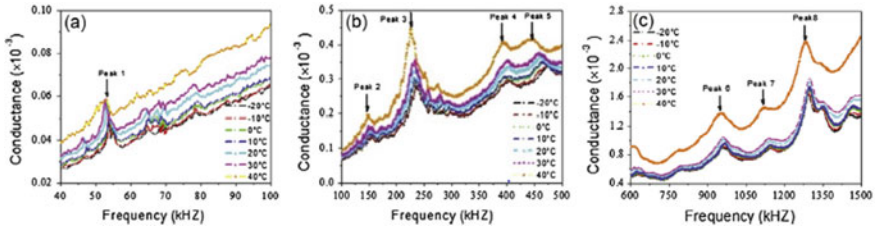
Fig. 6 Conductance spectra versus frequency **a** 40–100 kHz, **b** 100–500 kHz and **c** 600–1500 kHz on various temperature
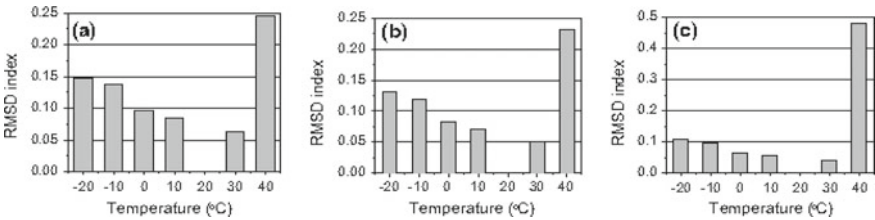

Fig. 7 The RMSD index of the PZT sensor at different temperature in frequency range of **a** 40–100 kHz, **b** 100–500 kHz, **c** 600–1500 kHz

The greater temperature that diverges from the baseline, the greater the dissimilarity in RMSD (Fig. 7). This also obviously specifies the temperature dependence of the EMI method.

The outcomes displayed the sensitivity of the sensor to the primary load at the time the external load was similar to the thickness of the sensor.

Yang et al. [10] this paper deals with the analysis of damage in the RCC structure through the comparative analysis of the sensitivity of the structural mechanical impedance and EM admittance toward damage in a concrete structure. An experiment forced a two-story concrete borderline equipped with 5 PZT sensors. The 5 PZT sensors were constantly associated with one of the segments on the leading flooring of the frame structure. Utilizing impedance analyzer, it is feasible to get conductance and susceptibility signatures from PZT sensors. Prior to destruction and next every of the two destruction stages, these 5 PZT sensors were checked to register PZT EM entry marks. The spaces of the 5PZT sensors as of the primary crack appeared in Fig. 8c were recorded at the 3rd part of Table 4.

Methodology: The loads to be tested were enforced along the base of horizontal motion along changed frequencies. The examination was carry out in a number of stages, and the applied base motion sequences are listed in Table 5.
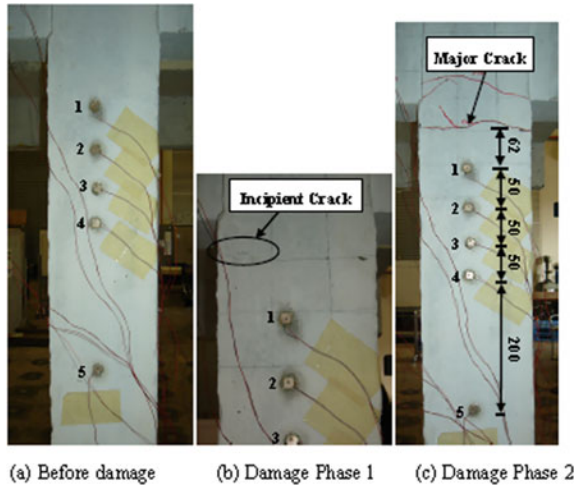
(a) Before damage   (b) Damage Phase 1   (c) Damage Phase 2

Fig. 8 State of the column prior and later destruction (unit mm)

Table 4 Positions of PZT sensors and their distance to primary fissure

Patch Number	Distance from joint O along the column as shown in Fig. 2 (mm)	Distance of the PZT patch from the main crack (mm)
1	100	62
2	150	112
3	200	162
4	250	212
5	450	412

Table 5 Test sequences of the shake table

Phase No	Name	Description	Purpose
1	RND-A	Random, PGA = 0.02 g	Structural identification
2	CHL-	Chile, PGA = 023 g,	Moderate shaking
3	RND-B	Random, PGA = 0.02 g	Structural identification
4	CHL-	Chile, PGA = 0.46 g,	Sever shaking
5	RND-C	Random, PGA = 0.02 g	Structural identification

The 5PZT sensors were scanned prior to loading the base to record reference signatures for health conditions.

Experimental data: The 5PZT sensors were instrumented at positions 62 mm, 112 mm, 162 mm, 212 mm, and 412 mm from the focal crack, respectively, (marked

in Fig. 8c). Curve fitting was performed by plotting Figs. 9 and 10. For every destruction stage, the values of RMSD for the *G* and *x* signatures show reducing tendency as space rises (Table 6).

For both stages of destruction, the highest RMSD values for *G* and *x* are examine in the PZT patch1, which is the closest space to the major break, and the lowermost values in the PZT patch5. This reflects that as the PZT patch destruction space rises, PZT patch's sensitivity to destruction reductions. In addition to Figs. 9 and 10, we can additionally see that the RMSD values on behalf of destruction stage 2 were
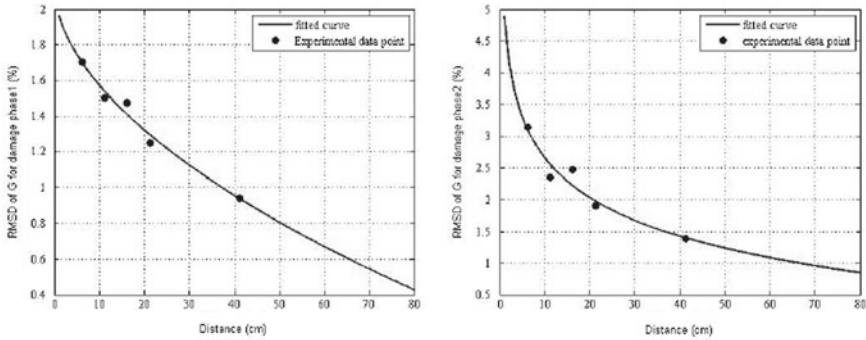

Fig. 9 RMSD values of *G* used for 2 destruction stages with respect to the distance of PZT to the crack

Table 6 Damage rates for entirely PZT sensors at two phase of destruction

| PZT pitch no	RMSD of *G*	RMSD of *B*	RMSD of *x*	RMSD of *y*
Damage phase 1				
1	1.700904	0.079885	15.73118	0.077741
2	1.502574	0.106806	13.34286	0.098003
3	1.473301	0.086287	9.605244	0.063772
4	1.25146	0.11261	7.5918	0.095865
5	0.940053	0.116923	4.747043	0.117208
Damage phase 2				
1	3.139675	0.061062	25.89481	0.049555
2	2.343378	0.073566	20.84959	0.064063
3	2.46278	0.058494	18.08281	0.047549
4	1.898626	0.071459	10.93107	0.054598
5	1.390455	0.056117	8.161555	0.045829
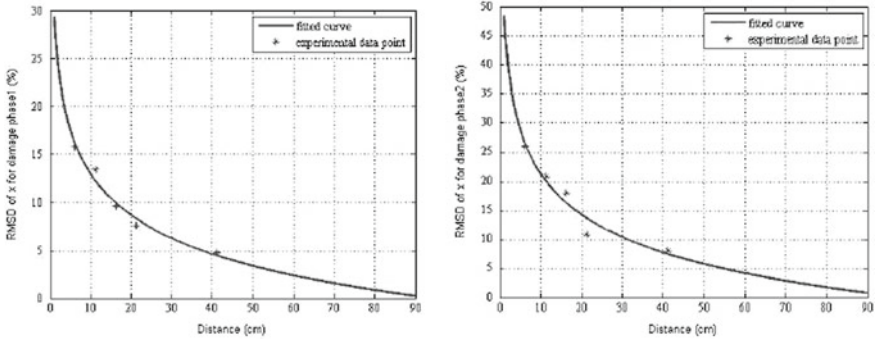
Fig. 10 RMSD values of *x* for two stages of destruction with respect to the PZT distance from the crack

entirely higher as compare to that of destruction stage 1. So, when the destruction is extreme, the sensitive of the PZT sensor also increases.

The results showed that the rate of damage causes an expansion of the damping and a reduction of mass and stiffness at a given point that the model is particularly sensitive to extreme destruction. Furthermore, it was concluded that the PZT sensor along a greater space for destruction is a smaller amount sensitive to destruction.

3 Summary of Data Analysis

Author name	Description	Formulation
C. Bharathi Priya et al.	The technique of localized changes in electromechanical impedance (EMI) along a piezoelectric sensor assembly (PZT), to sense destruction, is accelerated in a series-connected LCR circuit in a large-scale sensor distribution situation. In this research, an embedded concrete beam with six PZT covers glued into slabs of expanding thickness by exposing the beam to variance curing. RMSD among the signatures was the most suitable index of damage to characterize structural damage G_i^1–conductance at the point of the ith dimension in G_i^0–conductance at the point of the ith dimension in	Index of damage to monitor the structural damage, $$\text{RMSD} = \left[\frac{[\sum(G_i^1 - G_i^0)]|_{\text{sub-range}}}{[\sum G_i^{0.2}]|_{\text{full-range}}} \right]^{0.5}$$

(continued)

(continued)

Author name	Description	Formulation
Demi Ai et al.	The report coverers sensitivity in case of a new type integrated active PZT sensor in sensing structural effect destruction by theoretical and experimental studies. The planned model was demonstrated through the result of the experimental test of an integrated PZT sensor produced The RMSD as a scalar destruction metric has been generally acknowledged to assess the severity of destruction through guessing the quantity of variation among two signatures. G_i^0 is the conductance calculated through the PZT sensor previous to destruction to the structure, which is regularly set as a baseline, and G_i^1 is the relating conductance later damage to the ith calculating point. Unlike conventional RMSD, which uses fixed undamaged information as a baseline, RMSDk utilizes data from the previous state as a baseline; therefore, it is changed progressively when the next RMSD value is calculated. Along these lines, absolute variations can be discriminated in every case. Through integrating along the description of the actual admission sign, impact the corresponding effect can be measured utilizing RMSDk. G_i^k is the conductance calculated at the ith calculation, as a base line in previous condition, and G_i^k is the equivalent conductance after the variations	RMSD BASED on slope, $$RMSD\ (\%) = \sqrt{\frac{\sum_{i=1}^N \left(G_i^1 - G_i^0\right)^2}{\sum_{i=1}^N \left(G_i^0\right)^2}} \times 100$$ RMSD via three PZT sensors in four destruction cases, $$RMSDk\ (\%) = \sqrt{\frac{\sum_{i-1}^N \left(G_i^k - G_i^{k-1}\right)^2}{\sum_{i-1}^N \left(G_i^{k-1}\right)^2}} \times 100 \ k = 1, 2, \ldots, n$$

(continued)

Author name	Description	Formulation
Prathamesh N. Bilgunde et al.	Mathematical study to organize the in-situ soundness of PZT sensors utilized for SHM of huge automotive structures, civil, and aeronautical The sensitivity of the material whose characteristics depends upon temperature remains constant w.r.t. to the resonance spectrum is described through metric indices. One of those metrics consists of RMSD. ω_F which is the beginning frequency and ω_I is the completion frequency. $Z_{E,E}$ equal to electrical admittance rate of the set PZT + epoxy + steel; while $Z_{E,T}$ is the admission signature for the equivalent variations in the connection state denoted through the same acoustic impedance Z_{adh}	RMSD for adhesive $$\text{RMSD} = \sum_{n=\omega_I}^{n=\omega_F} \sqrt{\frac{[Z_{E,E}(p) - Z_{E,T}(p)]^2}{Z_{E,E}^2(p)}}$$
Xu Dongyu	A type of impedance-based integrated PZT sensor was made utilizing a mix of powdered cement and epoxy as a fill coating. In this paper a type of inserted impedance-based PZT sensor that was manufactured utilizing a combination of powdered cement and epoxy as the packing layer The destruction index is generally utilized to visibly specify the characterization of structural destruction. The RMSD index was designed dependent on the coming calculation. $|G_i|$ is the amplitude of the conductance of PZT sensor at a various temperature. $|G_i^0|$ is the amplitude of the conductance of PZT sensor at a mention temperature of 20 °C. n is the numeral of frequency sample points in the conductance spectra	RMSD under load at different frequencies, $$\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}[|G_i| - |G_i^0|]^2}{\sum_{i=1}^{n}[|G_i^0|]^2}}$$

(continued)

Author name	Description	Formulation
Yaowen Yang et al	Electromechanical piezoelectric ceramic based on PZT impedance technique for SHM has been effectively enforced in various engineering systems. Comparative examination on the sensitivity of electromagnetic admittance and structural mechanical impedance toward destruction in a concrete design. The destruction index is generally utilized to visibly specify the characterization of structural destruction In the past work, a productive statistical algorithm, in view of frequency-to-frequency comparison, was accessible as RMSD. $G^0{}_i$ is the conductance of the PZT calculated in strong situations of the structure and $G^1{}_i$ is the value after the equivalent destruction at the ith measure point	RMSD for two destruction phases vs distance, $$\mathrm{RMSD}\ (\%) = \sqrt{\frac{\sum_{i=1}^{N} \left(G_i^1 - G_i^0\right)^2}{\sum_{i=1}^{N} \left(G_i^0\right)^2}} \times 100$$

4 Conclusions

This review was carried out to find the utilization of EMI method to carry out the health monitoring of structural. PZT sensor applied on the structure is more efficient in non–destructive evolution technique. The particular benefit of the EMI strategy over the other SHM strategies is its high sensitivity to early harms. The technique has been effectively enforced to different structures alternating from aerospace to civil structures and is ideal for following and web monitoring of damages in different designs or structures. The following conclusions have been made from the research reviews.

- RMSD was the most suitable damage to monitor the damage in structure. Conductance variance is most likely factor to find out the information at different PZT Patches.
- Also, it can be concluded that RMSD calculated with values obtained using impedance analyzer is efficient to find out the destructive values.
- Also, it was reviewed through research papers that impression effect is filtered more efficiently when integrated at PZT than, when integrated on surface. Thus, help to find the accurate assessment of structural damage.
- It was concluded that conductance factor depends upon temperature. Destructive index was also increased with increase in temperature and RMSD index was utilized to specify the characterization of structural destruction. RMSD was moreover used to instinctively visualize the change in impedance in case of integrated PZT sensor at different load and temperature.
- It was also reviewed that for damage detection method, the higher RMSD values sensed by a PZT sensor indicated a greater sensitivity of the PZT sensor to structural destruction.

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