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Electromechanical Impedance Sensing for Next-Generation Structural Health Monitoring Systems

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Abstract

Structural Health Monitoring (SHM) is essential for ensuring the safety, serviceability, and longevity of civil infrastructure through continuous condition assessment. Among various SHM techniques, the Electromechanical Impedance (EMI) method using piezoelectric (PZT) transducers has gained considerable attention owing to its high sensitivity, simplicity, and capability for real-time local damage detection. This paper reviews the fundamental principles, sensing mechanisms, technical requirements, and practical applications of the EMI technique. The effects of key parameters, including PZT dimensions, excitation frequency, adhesive properties, sensing range, temperature variations, and damage assessment metrics, on monitoring performance are discussed. Applications of EMI-based SHM in concrete, steel, composite, bridge, pipeline, aerospace, and retrofitted structures are also reviewed. Recent developments in low-cost instrumentation, wireless sensing, energy harvesting, and dual-PZT configurations are examined, along with existing challenges and future research directions. The EMI technique offers significant potential for robust, cost-effective, and adaptable structural health monitoring and smart infrastructure management.

Keywords: *Structural Health Monitoring (SHM); Electromechanical Impedance (EMI); Piezoelectric Transducer (PZT); Smart Sensors; Damage Detection; Autonomous Monitoring; Energy Harvesting.*

1. Introduction

Infrastructure development is a key indicator of a nation's economic and technological progress. The expansion of infrastructure necessitates effective maintenance, condition assessment, and retrofitting strategies to ensure long-term safety and performance. Conventional non-destructive testing (NDT) techniques, although widely used, are generally application-specific and have inherent limitations [1], [2]. Their implementation often relies on prior knowledge of potential damage locations and engineering judgement. Furthermore, several NDT methods require the inspected portion of a structure to be temporarily isolated or taken out of service, potentially disrupting normal operations and increasing maintenance costs.

Structural Health Monitoring (SHM) provides a systematic approach for continuous assessment of structural integrity using advanced sensing technologies. Unlike conventional inspection methods, SHM does not require prior knowledge of damage location and can be implemented while structures remain in service [3]. Among various SHM techniques, the electromechanical impedance (EMI) method has emerged as a promising approach for damage detection and condition assessment [4]. The technique utilises the electromechanical impedance response of piezoelectric (PZT) transducers surface-bonded to or embedded within structural components. Although PZT transducers are also employed in acoustic emission, ultrasonic pulse, and guided wave-based SHM techniques, the present study focuses primarily on the development and applications of the EMI technique for structural health monitoring.

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2. Health Monitoring Methodology

2.1. Piezoelectric Property

Piezoelectric materials are primarily available in two forms: ceramic materials, such as lead zirconate titanate (PZT), and polymeric materials, such as polyvinylidene fluoride (PVDF). Their unique electromechanical coupling characteristics have led to their classification as smart or adaptive materials. These materials undergo mechanical deformation when subjected to an electric field and, conversely, generate an electrical potential when mechanically strained, as illustrated in Figure 1. This bidirectional electromechanical conversion enables their use as both actuators and sensors. In conventional SHM applications, separate PZT transducers may serve as actuators and sensors for Lamb-wave generation and detection. In contrast, the EMI technique employs a single PZT transducer for both actuation and sensing, and hence it is commonly termed a self-sensing actuator. As shown in Figure 1 Electromechanical sensing and actuation behaviour of a PZT transducer.

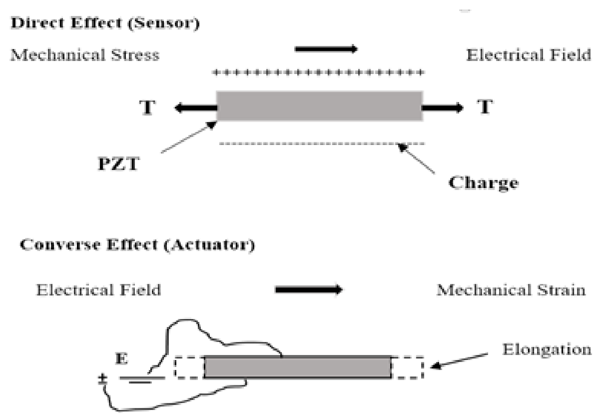

Figure 1 Electromechanical sensing and actuation behaviour of a PZT transducer

2.2. Electromechanical Impedance (EMI) Technique

The electromechanical impedance (EMI) technique exploits the electromechanical coupling of piezoelectric (PZT) transducers by applying an alternating voltage over a high-frequency range. The applied excitation induces mechanical vibrations in the PZT transducer, which may be surface-bonded to or embedded within the host structure, thereby producing localised structural excitation. The resulting electrical response is characterised through the admittance, with the conductance signature corresponding to the real component of the electrical admittance ((Y)) as a function of excitation frequency. These signatures are commonly measured using impedance analysers or LCR meters and provide a basis for evaluating structural condition.

The electrical admittance, defined as the reciprocal of impedance, of a PZT transducer coupled to a host structure has been analytically formulated in previous studies. Considering the host structure as a single-degree-of-freedom (SDOF) system, as shown in Figure 2, the corresponding electrical admittance can be expressed as follows [5]

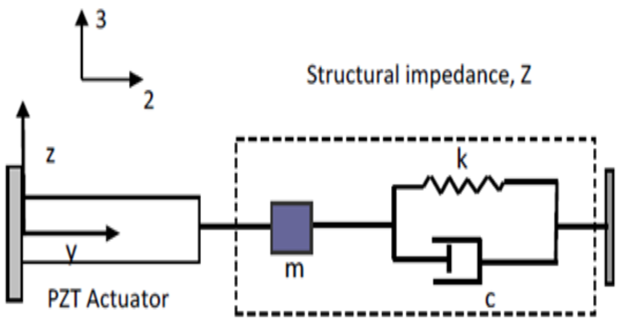

Figure 2 Single-degree-of-freedom (SDOF) structural model with a PZT actuator [5]

$$Y = \omega j \frac{w_a l_a}{h_a}\left[\overline{\varepsilon_{33}^T} + \left(\frac{Z_a}{Z+Z_a}\right) d_{32}^2 \overline{Y_{22}^E}\left(\frac{\tan K l_a}{K l_a}\right) - d_{32}^2 \overline{Y_{22}^E}\right] \quad \text{(Eq. 1)}$$

ω = angular frequency of the applied alternating voltage, wa = PZT width, la = PZT length, ha = PZT thickness, Z = mechanical impedance of the host structure, Za = mechanical impedance of the PZT transdure, (ε_33^T)‾ and d32 are piezoelectric constants, (Y_22^E)‾ = complex Young's modulus. As indicated by Equation (1), the electrical admittance of a PZT transducer is influenced by the electromechanical interaction between the transducer and the host structure. Structural damage locally alters the mass, stiffness, and damping characteristics, thereby modifying the mechanical impedance of the structure. These changes are reflected in the electrical conductance response (Re

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Y) of the PZT transducer, which can therefore serve as a sensitive damage indicator. This principle is equally applicable to two- and three-dimensional PZT–structure interaction models. Figure 3 shows representative experimental admittance signatures obtained before and after structural damage [6]. The conductance signatures, corresponding to the real component of complex admittance, exhibit distinct changes following damage. Here, a signature denotes the admittance response over a specified excitation-frequency range. These responses are analogous to frequency response functions (FRFs) used in structural vibration analysis, although EMI measurements generally employ substantially higher excitation frequencies. As shown in Figure 3 Experimentally obtained conductance signatures of the PZT transducer before and after structural damage (in siemens) [6].

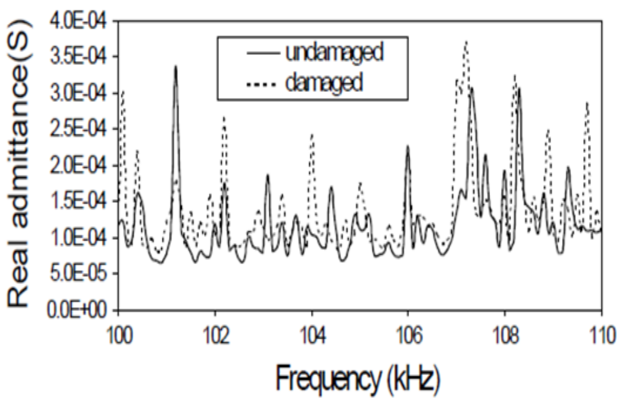

Figure 3 Experimentally obtained conductance signatures of the PZT transducer before and after structural damage (in siemens) [6]

3. Technical Aspects of The Emi (Electromechanical Impedance) Technique

3.1.Test Equipment Requirement

The electrical admittance signatures of PZT transducers are commonly acquired using commercial impedance measurement instruments, such as the HP 4192A Impedance Analyzer, Agilent E4980A Precision LCR Meter, and Wayne Kerr Precision Impedance Analyzer [4], [7]. These instruments facilitate accurate measurement of the admittance response over the selected frequency range for SHM applications.

Figure 4 illustrates a typical impedance measurement setup, in which the PZT transducer is connected to the measurement instrument through electrical wires. The two wires are soldered to the opposite electrodes of the PZT transducer at one end and connected to the corresponding terminals of the impedance measurement device at the other. This configuration enables the acquisition of the PZT admittance response across the prescribed excitation-frequency range. As shown in Figure 4 Typical impedance measurement equipment used for acquiring PZT admittance signatures [6].

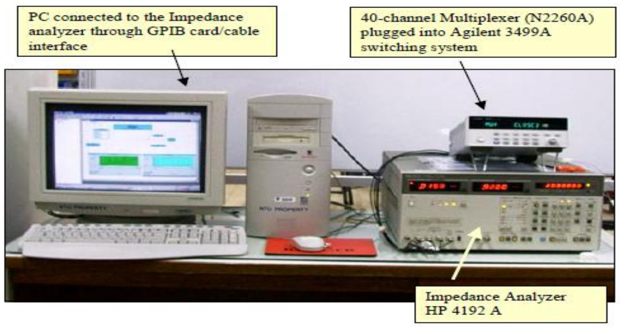

Figure 4 Typical impedance measurement equipment used for acquiring PZT admittance signatures [6]

3.2.Power Requirement

During measurement, the impedance analyser applies an alternating excitation voltage, typically 1 V root mean square (RMS), to the bonded PZT transducer across a predefined frequency range. Studies have shown that variations in excitation voltage have little influence on the resulting conductance signatures. However, higher excitation levels may improve the response of weak structural modes, thereby facilitating their identification in the measured admittance spectrum [8].

3.3.Influence of Adhesive

Epoxy resins are widely employed for bonding PZT transducers to structural surfaces. The adhesive layer facilitates the transmission of high-frequency mechanical vibrations from the PZT to the host structure and ensures effective electromechanical coupling. Hence, the adhesive should exhibit a high shear modulus after curing and be applied uniformly at minimal thickness to reduce energy losses and ensure reliable bonding. The effects of adhesive-layer characteristics on measured admittance signatures, including the real component (conductance) and imaginary component (susceptance), have been extensively investigated [9].

3.4.PZT Dimensions

Annamdas and Soh [10], [11] examined the effect of PZT transducer dimensions on admittance characteristics. Their findings showed that, for constant length and width, decreasing the transducer thickness increased the amplitude of the first dominant admittance peak, whereas increasing the thickness reduced its amplitude. Conversely, for a constant thickness, increasing the transducer length and width shifted the first dominant peak towards lower frequencies, while decreasing these dimensions produced a shift towards higher frequencies.

3.5.Sensing Zone

The effective sensing radius of a typical PZT transducer depends on the properties of the host structure and generally ranges from approximately 0.4 m for composite structural elements to about 2.0 m for metallic beam structures [7], [12].

3.6.Frequency Range of Actuation

The conductance signature of a PZT transducer is first recorded over a high-frequency range under the pristine condition to establish a baseline response. During subsequent inspections, the signature is remeasured and compared with the baseline to assess structural condition and detect potential damage. Selecting an appropriate excitation-frequency range is essential for effective damage detection. Park et al. [13] recommended a frequency range of 30–400 kHz for PZT transducers measuring 5–15 mm. Higher frequencies (>200 kHz) generally provide better damage localisation by reducing the sensing region, whereas lower frequencies (<70 kHz) offer a larger sensing area and are therefore suitable for monitoring broader structural regions.

3.7.Damage Metrics

Structural damage is reflected in conductance signatures through new resonance peaks and shifts in peak frequency and amplitude. Several statistical damage indices, including RMSD, WCC, SAC, ATM, RD, MAPD, CC, and Cov, have been proposed to quantify these changes [7], [8], [12]. However, Naidu and Soh [14], [15] reported that such non-parametric metrics may not adequately capture damage-induced changes in structural dynamic properties, particularly natural frequencies. Parametric metrics, which account for changes in modal properties, can therefore provide more reliable information on damage location and severity.

3.8.Temperature Effect

PZT conductance signatures are sensitive to temperature variations, which can overlap with damage-induced changes and complicate structural assessment. Within a narrow frequency range, temperature effects generally appear as uniform horizontal and vertical shifts in the signature, whereas damage produces more abrupt and localized variations [8]. Appropriate temperature compensation is therefore essential for reliable EMI-based damage assessment [16]. An RBF-based support vector regression model has also demonstrated effective temperature estimation in healthy and damaged steel specimens, highlighting the potential of EMI for multimodal sensing [17].

4. Emi Technique for Shm Application

Numerous studies have demonstrated the feasibility and effectiveness of the electromechanical impedance (EMI) technique for structural damage detection across diverse structural systems [4], [13], [18]. Its localized sensing capability has been validated in laboratory-scale trusses, truss joints, steel bridge and pipe joints [19]–[21], reinforced concrete bridges [22], concrete structures [23], steel and aluminium plates [6], and aircraft components [24], [25]. In these studies, PZT transducers located closer to the damaged region generally exhibited higher damage indices than those positioned farther away, demonstrating the potential of strategically distributed PZT arrays for damage localization and long-term SHM. Moreover, EMI signatures are relatively insensitive to mechanical disturbances such as random impacts and traffic-induced vibrations because the technique operates predominantly in the ultrasonic frequency range (>20 kHz), which is considerably higher than typical environmental vibration frequencies. Beyond damage detection, the EMI technique has been integrated with linear elastic

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fracture mechanics (LEFM)-based prognosis models to estimate the remaining useful life of fatigue-affected structures [26]. It has also been applied to monitor axial and flexural stresses in beams and distinguish stress-induced variations from damage-related changes in conductance signatures [27]–[30]. In concrete structures, EMI has been used for monitoring early hydration [31], [32], strength development during curing [33], [34], corrosion in reinforced concrete [35], and the stress–strain response of concrete [37]. The technique has also enabled simultaneous detection of bolt-loosening location and severity in bolted flange structures [36]. Furthermore, EMI-based monitoring has been employed to assess debonding of carbon fibre-reinforced polymer (CFRP) laminates and fibre-reinforced polymer (FRP) rebars in retrofitted structures [38], [39]. Embedded PZT transducers acting as smart aggregates have additionally shown potential for monitoring concrete strength development and structural condition [40] - [43].

5. Technical Developments of the Emi Technique

5.1.Miniaturization and low-cost variants of EMI technique

Conventional EMI measurements commonly employ HP4192A or HP4194A impedance analysers, with the acquired data transferred to a computer through an I/O interface for subsequent processing. Despite their accuracy, these instruments are relatively bulky, costly, and difficult to deploy for field-based SHM. Although LCR meters provide a low-cost alternative, their sophisticated features are also underutilised for EMI applications, & their cost remains a constraint for scale implementation [18]. To address these limitations, Peairs et al. [44] developed a compact measurement system comprising a PZT transducer, a series resistor, and an HP 35665A digital signal analyser with FFT capability. The system was successfully demonstrated for structural damage detection and offered improved portability and reduced cost. Similarly, Giurgiutiu and Xu [45] developed a compact, field-portable impedance analyser for EMI applications. Panigrahi et al. [46] further simplified the system by replacing the FFT analyser with an Agilent 33220A function generator and an Agilent 54622D mixed-signal oscilloscope for measuring the output voltage at each excitation frequency. The resulting setup reduced the overall cost to approximately US$5,000. Bhalla et al. [47] subsequently developed a lower-cost system, costing approximately US$2,000, using a basic function generator and an Agilent 34411A digital multimeter. However, this configuration measured only the magnitude of admittance and did not provide phase information. Kaur et al. [48] addressed this limitation by incorporating an NI Express Chassis with the function generator to measure both output voltage and its phase difference relative to the excitation voltage. The system could therefore determine the complete complex admittance, providing measurements comparable to those obtained using conventional impedance analysers.

5.2.Energy Harvesting Units for EMI Technique

The length of cables connecting PZT transducers to impedance measurement instruments can adversely affect admittance signatures, particularly for cable lengths exceeding approximately 30 m [4]. Moreover, large-scale deployment of multiple PZT transducers introduces extensive wiring, complicating installation, management, and maintenance. These limitations have motivated the development of wireless EMI-based SHM systems to improve portability and scalability. Mascarenas et al. [49] reported one of the early wireless EMI systems, incorporating a portable, miniaturized, and low-cost impedance measurement chip. The system successfully detected load-induced changes in a bolted frame structure and was integrated with a microprocessor and wireless telemetry for local signal processing and data transmission. Park et al. [50] developed a wireless EMI-based SHM system combining principal component analysis (PCA) for data compression and k-means clustering for pattern recognition. The system employed an AD5933 impedance measurement chip and a self-sensing macro-fiber composite (MFC) transducer. However, its interrogation frequency range was limited to 10–100 kHz, substantially narrower than that of conventional instruments such as the HP 4192A (5 Hz–13 MHz), HP 4194A (100 Hz–40 MHz), and

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Agilent LCR meter (20 Hz–2 MHz), potentially restricting applications requiring higher-frequency measurements. Grisso et al. [51] developed a wireless active sensing system, which was subsequently advanced by Overly et al. at Los Alamos National Laboratory through the Wireless Impedance Device (WID 2.0) [52]. The compact 5.5 × 3.7 cm^2 device integrated an impedance measurement chip, microcontroller, wireless telemetry, and data storage, operating at 2.8 V and interrogating four sensors in approximately 6 s. These developments demonstrated the feasibility of wireless EMI systems for portable and efficient SHM. Further advancements in battery-powered wireless EMI sensor nodes have been reviewed by Annamdas and Radhika [18], highlighting their potential for portable and autonomous monitoring. Further research has developed a portable wireless impedance analyzer for multichannel PZT measurements, incorporating temperature monitoring and low-power operation for field applications. Experimental validation on an unmanned aerial vehicle wing demonstrated its feasibility for wireless EMI-based detection of aircraft structural damage [53]

5.3.Energy Harvesting Units for EMI Technique

Large-scale EMI-based SHM requires continuous sensor interrogation and a reliable power supply. However, PZT transducers installed at remote locations pose challenges for battery replacement and maintenance, while long cables may introduce measurement errors and multiple impedance units are costly. Although wireless sensor nodes reduce wiring requirements, their dependence on batteries limits operational life and long-term monitoring continuity. Energy harvesting can address these limitations by providing supplementary power to wireless EMI systems. Annamdas and Radhika [18] reviewed solar- and vibration-based energy harvesting approaches for EMI-based SHM, although practical implementations remain limited. A low-power, self-powered wireless EMI sensor node based on a Texas Instruments MSP430 evaluation board was developed in [54]. The system performs periodic SHM interrogation and wirelessly transmits data, consuming approximately 0.3 J per interrogation. Its low energy requirement enables potential operation using energy harvested from structural vibrations, although further development is needed for reliable long-term field deployment.

5.4.Ring dual sensor variation of EMI technique

A novel impedance measurement approach based on a dual-PZT configuration, comprising two separate concentric PZT segments, was proposed in [55]. By enabling independent actuation and sensing, the dual-PZT EMI technique can detect structural responses that may be less pronounced in conventional EMI measurements. The resulting resonance peaks are comparable to those obtained using the conventional approach, while the configuration exhibits reduced sensitivity to temperature variations. This makes it particularly promising for monitoring large and massive structures. However, further experimental and field studies are required to establish its effectiveness and practical applicability in SHM.

Conclusion

This paper presents an overview of the fundamental principles of the electromechanical impedance (EMI) technique, its technical requirements, and its applications in structural health monitoring (SHM). The EMI method exploits the impedance characteristics of self-sensing piezoelectric (PZT) transducers for the detection and assessment of structural damage. Recent advancements in the technique, including the miniaturization of measurement systems, the development of cost-effective instrumentation, integration with wireless sensor networks, and the incorporation of energy harvesting technologies, are reviewed. Emerging research trends and future directions for the practical implementation of EMI-based SHM systems are also discussed. Owing to its high sensitivity, adaptability, and potential for continuous condition monitoring, the EMI technique represents a promising approach for the next generation of intelligent structural health monitoring systems.

References

[1]. Hoła, J., and Krzysztof Schabowicz. "State-of-the-art non-destructive methods for diagnostic testing of building structures—Anticipated development trends." Archives of

civil and mechanical engineering 10, no. 3 (2010): 5-18.

[2]. TRAINING COURSE SERIES. "Guidebook on non-destructive testing of concrete structures." Training course series 17 (2002).

[3]. Balageas, Daniel, Claus-Peter Fritzen, and Alfredo Güemes, eds. Structural health monitoring. Vol. 90. John Wiley & Sons, 2010.

[4]. Annamdas, Venu Gopal Madhav, and Chee Kiong Soh. "Application of electromechanical impedance technique for engineering structures: review and future issues." Journal of Intelligent material systems and structures 21, no. 1 (2010): 41-59.

[5]. Liang, Chen, Fan Ping Sun, and Craig A. Rogers. "An impedance method for dynamic analysis of active material systems." (1994): 120-128.

[6]. Naidu, Akshay SK. "Structural Health Monitoring Using Admittance Response of Piezoceramic Actuator Sensors." (2017)

[7]. Tseng, K. KH, and Akshay SK Naidu. "Non-parametric damage detection and characterization using smart piezoceramic material." Smart Materials and Structures 11, no. 3 (2002): 317-329.

[8]. Sun, Fanping P., Zaffir A. Chaudhry, Craig A. Rogers, M. Majmundar, and Chen Liang. "Automated real-time structure health monitoring via signature pattern recognition." In Smart structures and materials 1995: smart structures and integrated systems, vol. 2443, pp. 236-247. SPIE, 1995.

[9]. Bhalla, Suresh, and Sumedha Moharana. "A refined shear lag model for adhesively bonded piezo-impedance transducers." Journal of Intelligent Material Systems and Structures 24, no. 1 (2013): 33-48.

[10]. Annamdas, Venu Gopal Madhav, and Chee Kiong Soh. "Three-dimensional electromechanical impedance model. I: Formulation of directional sum impedance." Journal of Aerospace Engineering 20, no. 1 (2007): 53-62.

[11]. Annamdas, Venu Gopal Madhav, and Chee Kiong Soh. "Three-dimensional electromechanical impedance model. II: Damage analysis and PZT characterization." Journal of Aerospace Engineering 20, no. 1 (2007): 63-71.

[12]. Bhalla, Suresh. "A mechanical impedance approach for structural identification, health monitoring and non-destructive evaluation using piezo-impedance transducers." PhD diss., 2004.

[13]. Park, Gyuhae, Hoon Sohn, Charles R. Farrar, and Daniel J. Inman. "Overview of piezoelectric impedance-based health monitoring and path forward." Shock and vibration digest 35, no. 6 (2003): 451-464.

[14]. Naidu, Akshay SK, and Chee Kiong Soh. "Identifying damage location with admittance signatures of smart piezo-transducers." Journal of Intelligent Material Systems and Structures 15, no. 8 (2004): 627-642.

[15]. Naidu, Akshay SK, and Chee-Kiong Soh. "Damage severity and propagation characterization with admittance signatures of piezo transducers." Smart materials and structures 13, no. 2 (2004): 393-403.

[16]. Park, Gyuhae, Kazuhisa Kabeya, Harley H. Cudney, and Daniel J. Inman. "Impedance-based structural health monitoring for temperature varying applications." JSME International Journal Series A Solid Mechanics and Material Engineering 42, no. 2 (1999): 249-258.

[17]. Dahl, Mads Kofod, Jaamac Hassan Hire, Milad Zamani, and Farshad Moradi. "Multimodal temperature sensing using electromechanical impedance (EMI) for structural health monitoring." IEEE Sensors Journal 24, no. 3 (2023): 3457-3464.

[18]. Annamdas, Venu GM, and Madhav A. Radhika. "Electromechanical impedance of piezoelectric transducers for monitoring metallic and non-metallic structures: A review of wired, wireless and energy-harvesting methods." Journal of Intelligent Material Systems and Structures 24, no. 9

International Research Journal on Advanced Engineering and Management
https://goldncloudpublications.com
https://doi.org/10.47392/IRJAEM.2026.0387
e ISSN: 2584-2854
Volume: 04 Issue: 08
August 2026
Page No: 2717 - 2726

(2013): 1021-1042.

[19]. Ayres, John W., Frederic Lalande, Zaffir Chaudhry, and Craig A. Rogers. "Qualitative impedance-based health monitoring of civil infrastructures." Smart Materials and Structures 7, no. 5 (1998): 599-605.

[20]. Park, Gyuhae, Harley H. Cudney, and Daniel J. Inman. "Impedance-based health monitoring of civil structural components." Journal of infrastructure systems 6, no. 4 (2000): 153-160.

[21]. Park, Gyuhae, Harley H. Cudney, and Daniel J. Inman. "Feasibility of using impedance-based damage assessment for pipeline structures." Earthquake engineering & structural dynamics 30, no. 10 (2001): 1463-1474.

[22]. Soh, Chee Kiong, K. KH Tseng, Suresh Bhalla, and Ashok Gupta. "Performance of smart piezoceramic patches in health monitoring of a RC bridge." Smart materials and Structures 9, no. 4 (2000): 533-542.

[23]. Naidu, Akshay Surendra Kumar, and Suresh Bhalla. "Damage detection in concrete structures with smart piezoceramic transducers." In Smart materials, structures, and systems, vol. 5062, pp. 684-690. SPIE, 2003.

[24]. [24]. Giurgiutiu, Victor, and Andrei Zagrai. "Damage detection in simulated aging-aircraft panels using the electro-mechanical impedance technique." In ASME International Mechanical Engineering Congress and Exposition, vol. 19135, pp. 349-358. American Society of Mechanical Engineers, 2000.

[25]. Rangwala, Husain, Tarak Vora, and Abdullah Baz. "Integrating machine learning with electromechanical impedance for non-destructive detection of bolt looseness in steel structures." Case Studies in Construction Materials (2025): e05430.

[26]. Lim, Yee Yan, and Chee Kiong Soh. "Fatigue life estimation of a 1D aluminum beam under mode-I loading using the electromechanical impedance technique." Smart Materials and Structures 20, no. 12 (2011): 125001.

[27]. Abe, Masato, Gyuhae Park, and Daniel J. Inman. "Impedance-based monitoring of stress in thin structural members." In Proceedings of the 11th international conference on adaptive structures and technologies, pp. 285-292. 2000.

[28]. Ong, Chin-Wee, Yaowen Yang, Akshay Surendra Kumar Naidu, Yong Lu, and Chee Kiong Soh. "Application of the electromechanical impedance method for the identification of in-situ stress in structures." In Smart Structures, Devices, and Systems, vol. 4935, pp. 503-514. SPIE, 2002.

[29]. Annamdas, Venu Gopal Madhav, Yaowen Yang, and Chee Kiong Soh. "Influence of loading on the electromechanical admittance of piezoceramic transducers." Smart materials and structures 16, no. 5 (2007): 1888-1897.

[30]. Lim, Yee Yan, and Chee Kiong Soh. "Effect of varying axial load under fixed boundary condition on admittance signatures of electromechanical impedance technique." Journal of Intelligent Material Systems and Structures 23, no. 7 (2012): 815-826.

[31]. Yang, Yaowen, Bahador Sabet Divsholi, and Chee Kiong Soh. "A reusable PZT transducer for monitoring initial hydration and structural health of concrete." Sensors 10, no. 5 (2010): 5193-5208.

[32]. Visalakshi, Talakokula, Suresh Bhalla, and Ashok Gupta. "Monitoring early hydration of reinforced concrete structures using structural parameters identified by piezo sensors via electromechanical impedance technique." Mechanical Systems and Signal Processing 99 (2018): 129-141.

[33]. Bhalla, Suresh, Akshay Surendra Kumar Naidu, Chin Wee Ong, and Chee-Kiong Soh. "Practical issues in the implementation of electromechanical impedance technique for NDE." In Smart structures, devices, and systems, vol. 4935, pp. 484-494. SPIE, 2002.

[34]. [34]. Annamdas, Venu Gopal Madhav, Yaowen Yang, and Chee Kiong Soh. "Impedance based concrete monitoring using

International Research Journal on Advanced Engineering and Management
https://goldncloudpublications.com
https://doi.org/10.47392/IRJAEM.2026.0387
e ISSN: 2584-2854
Volume: 04 Issue: 08
August 2026
Page No: 2717 - 2726

embedded PZT sensors." International Journal of Civil & Structural Engineering 1, no. 3 (2010): 414-424.
[35]. Talakokula, Visalakshi, and Suresh Bhalla. "Reinforcement corrosion assessment capability of surface bonded and embedded piezo sensors for reinforced concrete structures." Journal of Intelligent Material Systems and Structures 26, no. 17 (2015): 2304-2313.
[36]. Wang, Lintao, Bo Yuan, Zhenbang Xu, and Qingchao Sun. "Synchronous detection of bolts looseness position and degree based on fusing electro-mechanical impedance." Mechanical Systems and Signal Processing 174 (2022): 109068.
[37]. Pan, Huang Hsing, and Jia-Cing Guan. "Stress and strain behavior monitoring of concrete through electromechanical impedance using piezoelectric cement sensor and PZT sensor." Construction and Building Materials 324 (2022): 126685.
[38]. Park, Seunghee, Ju-Won Kim, Changgil Lee, and Sun-Kyu Park. "Impedance-based wireless debonding condition monitoring of CFRP laminated concrete structures." NDT & E International 44, no. 2 (2011): 232-238.
[39]. Li, Weijie, Shuli Fan, Siu Chun Michael Ho, Jianchao Wu, and Gangbing Song. "Interfacial debonding detection in fiber-reinforced polymer rebar–reinforced concrete using electro-mechanical impedance technique." Structural Health Monitoring 17, no. 3 (2018): 461-471.
[40]. Song, Gangbing, Haichang Gu, and Yi-Lung Mo. "Smart aggregates: multi-functional sensors for concrete structures—a tutorial and a review." Smart materials and structures 17, no. 3 (2008): 033001.
[41]. Song, G., H. Gu, Y. L. Mo, T. T. C. Hsu, and H. J. S. M. Dhonde. "Concrete structural health monitoring using embedded piezoceramic transducers." Smart Materials and Structures 16, no. 4 (2007): 959-968.
[42]. Jain, Saumitra, S. Suriya Prakash, and K. V. L. Subramaniam. "Monitoring of concrete cylinders with and without steel fibers under compression using piezo-ceramic smart aggregates." Journal of Nondestructive Evaluation 35, no. 4 (2016): 59.
[43]. Narayanan, Arun, and Kolluru VL Subramaniam. "Experimental evaluation of load-induced damage in concrete from distributed microcracks to localized cracking on electro-mechanical impedance response of bonded PZT." Construction and Building Materials 105 (2016): 536-544.
[44]. Peairs, Daniel M., Gyuhae Park, and Daniel J. Inman. "Improving accessibility of the impedance-based structural health monitoring method." Journal of Intelligent Material Systems and Structures 15, no. 2 (2004): 129-139.
[45]. Giurgiutiu, Victor, and Buli Xu. "Development of a field-portable small-size impedance analyzer for structural health monitoring using the electromechanical impedance technique." In Smart Structures and Materials 2004: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, vol. 5391, pp. 774-785. SPIE, 2004.
[46]. Panigrahi, R., S. Bhalla, and A. Gupta. "A low-cost variant of electro-mechanical impedance (emi) technique for structural health monitoring." Experimental Techniques 34, no. 2 (2010): 25-29.
[47]. Bhalla, Suresh, Ashok Gupta, Sahil Bansal, and Tarun Garg. "Ultra low-cost adaptations of electro-mechanical impedance technique for structural health monitoring." Journal of Intelligent Material Systems and Structures 20, no. 8 (2009): 991-999.
[48]. Kaur, Naveet, Lingfang Li, Suresh Bhalla, and Yong Xia. "A low-cost version of electro-mechanical impedance technique for damage detection in reinforced concrete structures using multiple piezo configurations." Advances in Structural Engineering 20, no. 8 (2017): 1247-1254.
[49]. Mascarenas, David L., Michael D. Todd, Gyuhae Park, and Charles R. Farrar.

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"Development of an impedance-based wireless sensor node for structural health monitoring." Smart Materials and Structures 16, no. 6 (2007): 2137-2145.

[50]. Park, Seunghee, Jong-Jae Lee, Chung-Bang Yun, and Daniel J. Inman. "Electro-mechanical impedance-based wireless structural health monitoring using PCA-data compression and k-means clustering algorithms." Journal of intelligent material systems and structures 19, no. 4 (2008): 509-520.

[51]. Grisso, Benjamin L., Luke A. Martin, and Daniel J. Inman. "A wireless active sensing system for impedance-based structural health monitoring." In Proc. of 23rd Inter. Modal Anal. Conf. (IMAC XXIII). Orlando, FL. 2005.

[52]. Overly, Timothy GS, Gyuhae Park, Kevin M. Farinholt, and Charles R. Farrar. "Development of an extremely compact impedance-based wireless sensing device." Smart Materials and structures 17, no. 6 (2008): 065011.

[53]. Li, Pengfei, Suyu Xu, Dafu Xu, and Chao Xu. "Structural health monitoring of an aircraft wing using a portable wireless electromechanical impedance analyzer." IEEE Sensors Journal 24, no. 14 (2024): 22855-22866.

[54]. Zhou, Dao, Na Kong, Dong Sam Ha, and Daniel J. Inman. "A self-powered wireless sensor node for structural health monitoring." In Health Monitoring of Structural and Biological Systems 2010, vol. 7650, pp. 311-322. SPIE, 2010.

[55]. Song, H., Hyung Jin Lim, and Hoon Sohn. "Electromechanical impedance measurement from large structures using a dual piezoelectric transducer." Journal of Sound and Vibration 332, no. 25 (2013): 6580-6595.