Improving Structural Health Monitoring Techniques Based on Electromechanical Impedance by Exploiting Mutual Impedance Effect

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Abstract The Electromechanical Impedance (EMI) method has been widely employed in several Structural Health Monitoring (SHM) applications. Its basic principle relies on a piezoelectric transducer (PZT) bonded to a host structure, operating simultaneously as both an actuator and a sensor. The PZT is excited over a wide frequency range to compute the EMI. Conventional EMI-based SHM systems sequentially apply this procedure to each PZT when multiple transducers are used. Here, a novel approach is proposed in which all PZT transducers, bonded to the structure, are excited simultaneously, whereas the EMI is individually computed for each sensor, a fundamental distinction from parallel excitation methods that measure only total impedance. Since a PZT transducer can be modelled as a transmission line, the EMI measured at a given transducer includes the effects of crosstalk between adjacent sensors. To assess the proposed method, a simulation study was conducted on OnScale software to model an aluminium plate measuring 200 × 40 × 2 mm instrumented with two PZT transducers. Structural changes were simulated by adding an iron mass, with dimensions of 12 × 4 × 5 mm, to the plate. The EMI was computed from each sensor using both methods. The results obtained indicate that the proposed method increases the sensitivity of the EMI response for damage detection when compared to the sequential EMI approach.

Keywords: SHM; PZT Transducer; Piezoelectricity; EMI; Transmission Line Model

Introduction

Structural maintenance frequently involves procedures that can be risky, time-consuming, and expensive, and may require tedious planning, which can vary and be specific to each case.

However, Structural Health Monitoring (SHM) systems have become an important solution in various engineering subjects such as civil, aerospace, and mechanical. Its main objective is to detect and characterise structural damage at an early stage, enabling preventive maintenance actions and reducing the risk of catastrophic failures. The implementation of SHM systems contributes to improved operational safety, reduced maintenance costs, and extended service life of engineering structures [1].

Among the various SHM techniques, approaches based on Piezoelectric Transducers (PZT) have attracted considerable attention due to their high sensitivity, low cost, and ability to operate simultaneously as sensors and actuators. PZT transducers are widely used because they exploit both the direct and inverse piezoelectric effects, enabling structural excitation and response measurement with the same patch [2]. One of the most widely adopted techniques using PZT sensors is the Electromechanical Impedance (EMI) method [3]. This approach is based on the relationship between the electrical impedance of a bonded PZT transducer and the local mechanical impedance of the host structure. Consequently, changes in structural properties such as stiffness, mass, or damping caused by damage result in measurable variations in the impedance signature. Owing to the high-frequency electromechanical coupling involved, the EMI technique is particularly sensitive to local structural damage [4],[5].

Conventional EMI-based SHM systems typically rely on the sequentially exciting individual PZT sensors, with the impedance of each transducer measured independently. However, practical monitoring systems often employ multiple sensors distributed across the structure to increase spatial coverage. Hence, researchers have proposed various sensor configurations aiming to obtain the most sensitive methods and reduce EMI computation time for structural damage identification. For example, [6] introduced the concept of total EMI, obtained when multiple PZT transducers are connected in parallel, resulting in a single impedance signature representing the collective response of the sensor network. [7] proposed using a transfer impedance between two PZTs in SHM. That new configuration, by adding a capacitor in series with the sensing resistor to reduce the impedance mismatch at low-frequency ranges, plays a fundamental role in the calculation of transfer impedance. [8] investigated the parallel excitation of PZT sensors using multiplexing circuits, enabling simultaneous excitation with signal separation in the frequency domain. [9] compared series and parallel configurations for damage detection, showing that both arrangements can be sensitive to structural changes. A common objective of those mentioned works was to reduce EMI computed time, and some of them also tried to show an EMI more sensitive to detecting damage. Regardless, all of them computed the total impedance as proposed by [6].

When distinct PZT transducers are attached to the same structure, mechanical coupling between them gives rise to electrical interference due to the piezoelectric effect. From an electrical-electronic perspective, this interference is commonly known as crosstalk. Most studies treat it as an undesirable phenomenon and attempt to minimise it through improved isolation or by using sequential excitation strategies. However, it has been shown that, by modelling the transducers as power transmission lines, this crosstalk can be exploited to enhance EMI-based structural damage detection, as it contains useful information related to the structure's condition [10].

The literature still lacks sufficient research on crosstalk effects in SHM applications. Accordingly, this study focuses on further investigating crosstalk between distinct PZT sensors in a parallel excitation configuration based on the transmission line model. Rather than eliminating these interactions, the proposed approach explores them as potential sources of damage-sensitive information. The central hypothesis is that the mechanically-induced crosstalk between sensors may provide additional indicators of structural damage, contributing to the development of improved SHM techniques based on piezoelectric sensor networks. Unlike the methods based on total impedance or parallel configuration, the proposed approach maintains the spatial resolution of the PZT network by computing the individual EMI of each sensor while all transducers are simultaneously excited.

1. Proposed Methodology

The theoretical analysis presented by [10] demonstrated that a PZT transducer can be modelled as an equivalent transmission line. Consequently, coupled transmission lines can represent a network of PZTs bonded to the same structure. The analysis showed that, due to the piezoelectric effects, the mechanical interactions between distinct piezoelectric transducers are analogous to the electromagnetic crosstalk phenomenon, which occurs when the voltage induced in one line by the electrical activity of another can be analysed by means of the concept of mutual impedance. The methodology was applied to EMI-based damage detection in its classical configuration, in which each PZT is excited individually (sequentially), and its electrical response is measured. That approach calculates the voltages induced in the passive sensors (the remaining PZTs) when a specific PZT functions as both an actuator and a sensor. Such voltages modify the global response of the set PZT/Structure and improve the performance of EMI-based damage detection techniques.

Considering a system with N PZTs, each one experiences an additional voltage component due to crosstalk. Therefore, the voltage in the i^{th} PZT can be expressed as below.

$$V_i = V_i^{'} + \sum_{j=1, j\neq i}^{N} Z_{ij} I_i \tag{1}$$

In Eq. 1, Z_{ij} is the mutual impedance between the i^{th} and the j^{th} PZTs and can be measured by using a load resistor. In [10], the objective was only to investigate the effect of mutual impedance, considering the individual (sequential) excitation of each PZT: one active PZT, whilst the other PZTs remained passive. However, a direct analysis of Eq. (1) indicates that the model assumes an additional voltage contribution generated by each PZT. Therefore, if all PZTs are excited simultaneously, the effective excitation voltage applied to each transducer becomes the sum of the source voltage and all induced voltages from the other PZTs. In this situation, from the perspective of EMI-based applications and based on the transmission-line model, the self-impedance of each PZT can be measured individually, and it will naturally incorporate the effect of all interference terms (mutual impedances). This configuration is illustrated in Fig. 1.

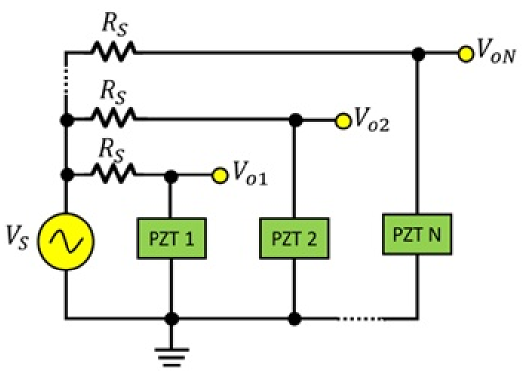

Fig. 1. *Electric circuit encompassing PZT connections for the simultaneous excitation method.*

In Fig. 1, V_s is a single voltage source that excites all PZTs simultaneously, V_{oi} represents the output voltage measured individually in each PZT, and R_s is a resistor used to prevent electrical loading of the transducers. It is crucial to emphasise that this configuration is fundamentally different from the parallel excitation approach proposed in the literature [6], [9].

Whilst those methods measure only the total impedance of the combined sensor network (a single value), the proposed method measures the individual impedance of each PZT (N values for N sensors). This procedure effectively incorporates and simplifies the transmission-line model to simultaneous excitation scenarios.

Consequently, the self-impedance Z_{ii} measured at the i^{th} PZT can be expressed as

$$Z_{ii} = R_s \frac{V_{ts}}{V_{oi}} \tag{2}$$

where V_{ts} corresponds to the total excitation voltage applied to the analysed PZT, which includes the source voltage and all crosstalk-induced. According to the transmission-line model and Eq. (1), the final excitation voltage applied to each PZT can be written as follows:

$$V_{i(ts)} = V_s + \sum_{j=1, j\neq i}^{N} Z_{ij} I_j \tag{3}$$

Therefore, the output voltage measured in each PZT is affected by the voltages induced by the remaining transducers. From an electrical perspective, this behaviour is fully consistent with the theory of coupled transmission lines [11] and the superposition theorem, which means that the induced voltages can be considered as multiple independent voltage sources for the i^{th} PZT analysed. From a mechanical perspective, simultaneous excitation activates the inverse piezoelectric effect in each transducer, given that all PZTs bond to the same host structure. This excitation generates structural vibrations and mechanical waves that propagate through the structure and reach the other PZTs, causing them to behave as secondary actuators. When these waves interact with other PZTs, the direct piezoelectric effect activates, and it generates additional electrical voltages in the transducers. These voltages couple back into the electrical system, producing the induced voltages assumed by the transmission-line model. Any structural modification, such as damage or stiffness variation, modifies this mechanical wave propagation and consequently the induced voltages and the measured impedances, which suggests that the induced voltages may be non-linear.

Although previous studies did not explicitly discuss the transmission-line model for piezoelectric sensors [6],[7],[9], the observed behaviours are consistent with the electrical and mechanical coupling mechanisms described by the transmission-line formulation presented by [10]. Unlike the previous approaches that measure total impedance, this study proposes an analysis of the individual impedance of each PZT whilst all transducers are simultaneously excited, a configuration that emerges naturally from the transmission-line model. By using this strategy, we naturally incorporate the crosstalk effects predicted by the transmission-line model into the measured impedance of each sensor. Besides undoubtedly improving sensitivity, this approach preserves the individual EMI signatures of each PZT, which is essential for damage detection and potentially can be used for damage location. This hybrid strategy, bridging classical EMI measurements and total impedance methods, leverages the reduced acquisition time of simultaneous excitation and the spatial resolution from individual sensor measurements.

2. Simulations and Results

The proposed methodology was evaluated by means of numerical simulations of an SHM system consisting of two PZT transducers attached to an aluminium plate. The procedures for obtaining the EMI signatures are based on [12],[13]. In this work, the analyses were performed directly from the EMI response by considering its magnitude, real part, and imaginary part, which are commonly used features in impedance-based SHM approaches. Wherein, the electrical impedance generated by a coupled PZT–structure system can be expressed as [3].

$$Z_o = \frac{V}{I} = [jwa(\epsilon_{33}^T(1 - j\delta) - \frac{Z_{s(w)}}{Z_{s(w)+Z_a(w)}} d_{3x}^2 Y_{xx}^E)]^{-1} \tag{4}$$

In Eq.(4) Z_s is the mechanical impedance of the structure and Z_a is the electrical impedance of the PZT. The quantities a, ϵ_{33}^T, δ, d_{3x}^2 and Y_{xx}^E are the PZT's geometric constant, the dielectric constant, the loss tangent, the coupling constant, and Young's modulus, respectively. Although this formulation is well established in the literature, it is important to highlight that the structural influence appears in Eq. (4) through the term Z_s, which represents the mechanical impedance of the host structure.

By comparing Eq. (4) with Eq. (2), it can be observed that Z_0 corresponds to the self-impedance Z_{ii} (EMI), while V represents the excitation signal V_s. The current flowing in the circuit, or equivalently, the output voltage, can be measured directly across the resistor R_s (see Fig. 1). The EMI response described in Eq. (4) inherently contains information associated with the coupled PZT–structure system. Therefore, any modification to structural properties, such as stiffness reduction due to damage, will directly affect the impedance signature.

2.1 Simulation Setup

Simulations were performed using OnScale® software [14]. This software provides advanced finite-element numerical models for high-fidelity simulations in several engineering applications. To evaluate the mutual impedance effect upon the PZTs arrangement, simulations were carried out using a set of 2 PZTs type PZT5h4e attached to an aluminium plate structure of 200 × 40 × 2 mm as shown in Fig. 2.

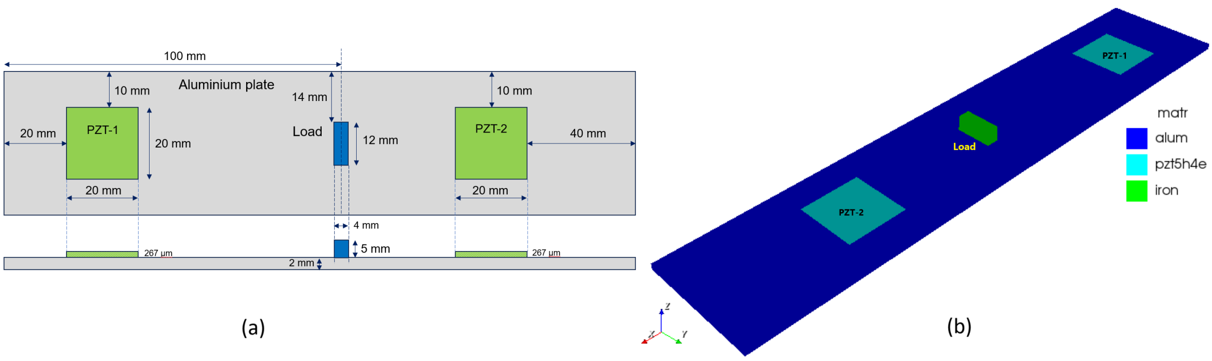

Fig. 2. *Characterisation of the simulation: (a) dimensions and (b) numerical model implemented on OnScale.*

The simulation parameters are: (1) – PZT5h4E with 3800 for relative dielectric constant, 7800 kgm^{-3} for density, and 32 for the mechanical quality factor; (2) - Aluminium plate with 2690 kgm^{-3} for density, 6306 ms^{-1} for bulk velocity, 3114 ms^{-1} for shear velocity, and 3.1 for strain constant (ϵ). The PTZs were excited by a finite duration pulse with an amplitude of $\pm$ 2V, which generates a spectrum like the spectrum of a chirp signal in a frequency range from 1kHz to 300kHz. The load resistor (R_s) value is 1kΩ. Structural damage was simulated by introducing an iron load (an iron block of 12 × 4 × 5 mm) between the two PZT sensors (Fig. 2), which alters the local mechanical impedance of the host structure and consequently affects the electromechanical coupling captured by the PZT transducers.

2.2 Results

To clearly illustrate the difference between the methods, Fig. 3 shows how the EMI, or self-impedances Z_{11} and Z_{22}, are obtained for PZT-1 and PZT-2. For the traditional EMI approach,

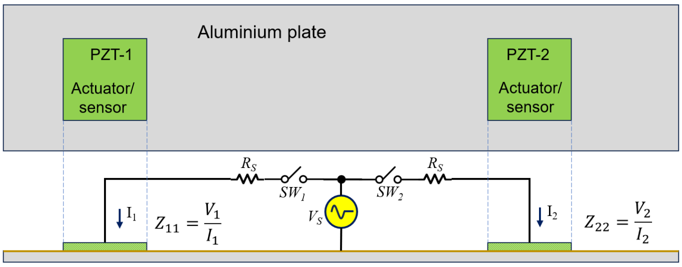

Fig. 3. *Simulation setup for activating a single PZT (1 or 2) or both simultaneously.*

switch SW_1 is closed to measure Z_{11} while SW_2 remains open, and conversely, SW_2 is closed to measure Z_{22} while SW_1 remains open. In this configuration, the response of the PZT–structure system does not consider the influence of the other transducers. In the proposed method, both SW_1 and SW_2 are simultaneously closed, and the EMI is measured at PZT-1 (Z_{11}^{prop}) and PZT-2 (Z_{22}^{prop}). In this case, the measured responses include the effects of mutual impedance, since both sensors are active during the measurements. It is important to note that this quantity does not correspond to the total impedance of the structure–PZT system, but rather to the individual EMI of each transducer under the influence of the others. The main advantage of this approach is that the EMI measured at each PZT inherently accounts for the interaction effects produced by the other transducers through the structure.

The magnitudes of EMI computed for PZT-1 and PZT-2 patches, using both the classical EMI and the proposed approaches, are presented in Figs. 4 and 5, respectively. These results are for a frequency range from 10 kHz to 50 kHz. The figures clearly illustrate the differences between the EMI obtained using our method and the classical approach.

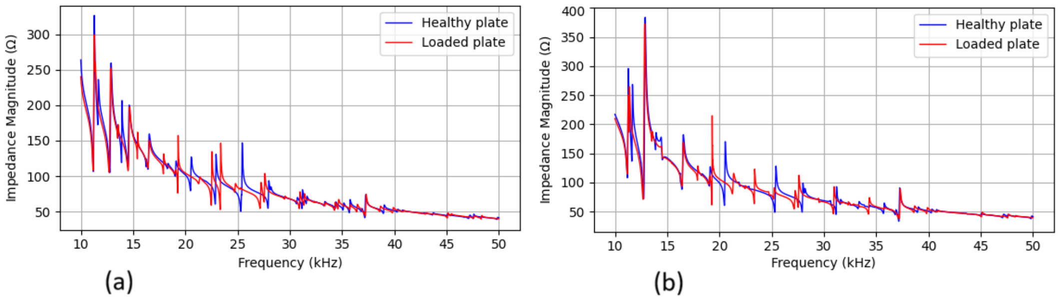

Fig. 4. *Impedance magnitudes for PZT-1 (a) Traditional EMI and (b) Proposed method.*

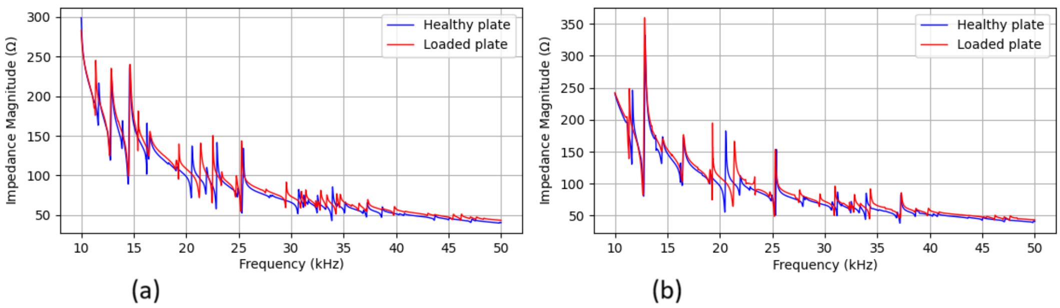

Fig. 5. *Impedance magnitudes for PZT-2 (a) Traditional EMI and (b) Proposed method.*

To compare both methods quantitatively, Root Mean Square Deviation (RMSD) and Correlation Coefficient Deviation Metric (CCDM) indices were computed for both methods across different frequency bands (see Tables 1 and 2) [15]. The results consistently indicate that the proposed methodology (simultaneous excitation) improves the sensitivity of the EMI to detect structural damage when compared with the classical EMI approach (individual excitation) across all bands analysed. It is worth highlighting that the proposed method outperforms the traditional EMI by at least 27% for RMSD and 70% for CCDM, when obtained for PZT-2, considering the frequency range from 10kHz to 50kHz.

Table 1. CCDM and RMSD indices for PZT-1.

Frequency Range (kHz)	RMSD Classical	CCDM Classical	RMSD Proposed	CCDM Proposed	RMSD (%) Increase	CCDM (%) Increase
5– 40	49.067	0.076	52.757	0.089	7.52	16.96
5–200	21.042	0.043	22.746	0.051	8.10	18.07
10– 50	9.800	0.022	13.133	0.038	34.03	72.99
60– 120	5.480	0.367	6.929	0.513	26.44	39.87

Table 2. CCDM and RMSD indices for PZT-2.

Frequency Range (kHz)	RMSD Classical	CCDM Classical	RMSD Proposed	CCDM Proposed	RMSD (%) Increase	CCDM (%) Increase
5– 40	36.605	0.045	56.094	0.094	53.24	110.37
5–200	16.119	0.027	24.629	0.058	52.79	116.82
10– 50	11.039	0.022	14.106	0.038	27.77	70.24
60– 120	7.310	0.491	10.957	0.592	49.91	20.66

3. Conclusion

This paper proposed a novel approach to detect structural damage based on the electromechanical impedance, accounting for crosstalk effects in a PZT arrangement, modelled as a multi-conductor transmission line. The proposed method is based on the simultaneous excitation of all PZTs, with individual impedance measurements for each sensor, a fundamental distinction from parallel excitation methods that measure only the total impedance. That effect was measured using the individual EMIs of each PZT by exciting all PZT transducers simultaneously. Finite element simulations were carried out on an aluminium beam structure containing two attached PZT patches. We took into consideration the structure's healthy and damaged conditions for both methods. When compared with the results for the traditional EMI-based method, our approach showed a significant breakthrough in the sensitivity of the EMI. To illustrate only one successful case, in the frequency range from 10kHz to 50kHz, the improvement is at least by 27% for RMSD and 70% for CCDM, obtained for PZT-2. Rather than employing total impedance methods that compromise spatial detail, our approach maintains individual EMI signatures of each sensor, potentially enabling localisation. It also accounts for mutual impedance effects to improve sensitivity in SHM applications. The results of the ongoing practical experiments are about to be seen, but the signs are promising.

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