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Structural Health Monitoring of Composite Plate using Piezoelectric Transducer

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ABSTRACT: This research proposes an approach for detecting damage in composite structures using the cost-effective electromechanical (EM) impedance method. By employing a piezoelectric transducer driven at high frequencies, the technique facilitates localized damage identification by tracking changes in EM impedance signatures that correspond to alterations in the structural properties caused by damage. A numerical model of a composite plate with a surface-mounted piezoelectric patch is constructed to simulate EM impedance responses under different damage conditions within the composite layers. Damage is represented by localized reductions in stiffness, simulating common failure modes such as delamination or matrix cracking. The simulation results indicate that the EM IMPEDANCE response is highly sensitive to damage within the composite plate across a wide frequency range.

KEY WORDS: Damage detection; Composite plate; Impedance technique; PZT; SHM

1 INTRODUCTION

Composite materials are increasingly adopted across various critical engineering sectors, including aerospace, marine, wind energy, and automotive, due to their exceptional strength-to-weight ratio, resistance to corrosion, and versatility in design. Despite these advantages, the complex, heterogeneous, and anisotropic characteristics of composites pose significant challenges for damage detection, as many types of damage such as delamination, matrix cracking, and fiber breakage typically begin within the material and remain hidden from surface inspection.

To maintain continuous health assessment of composite structures, a variety of structural health monitoring (SHM) strategies have been investigated, ranging from vibration analysis and acoustic emission techniques to guided wave inspection and piezoelectric-based sensing methods. Among these, the electromechanical (EM) impedance approach has emerged as a particularly effective tool for damage detection, especially in civil engineering systems [1]. This technique leverages the capabilities of a compact and economical piezoelectric sensor, which is directly attached to the surface of the structure and driven by high-frequency voltage inputs. The resulting high-frequency actuation enables the system to monitor local variations in structural behavior with high resolution, facilitating real-time identification of damage [2].

When damage occurs, it alters the local mechanical properties such as stiffness and damping, which in turn induces detectable changes in the impedance spectrum of the sensor. The short wavelengths associated with ultrasonic excitations make the method highly responsive to subtle or early-stage damage [3]. Additionally, EM impedance sensing is relatively immune to ambient low-frequency disturbances, enhancing its reliability in environments characterized by complex or fluctuating dynamic conditions. This resilience and sensitivity make the EM impedance method a strong candidate for practical SHM deployment in composite systems in complex real-world conditions.

This work presents a numerical study to evaluate the capability and sensitivity of the EM impedance approach for damage detection in composite structures. Utilizing a detailed finite element model developed in ABAQUS that incorporates accurate material characteristics and simulates local damage effects, the study assesses the detectability of different damage severities. The findings contribute valuable understanding of the practical applicability of this cost-efficient SHM technique and set the stage for future experimental verification.

2 COST-EFFECTIVE EM IMPEDANCE METHOD

As shown in Fig. 1, a standard EM impedance measurement setup typically consists of a piezoelectric transducer, such as a PZT, bonded to the surface of the structure and an impedance analyzer that drives the transducer while recording its impedance response.

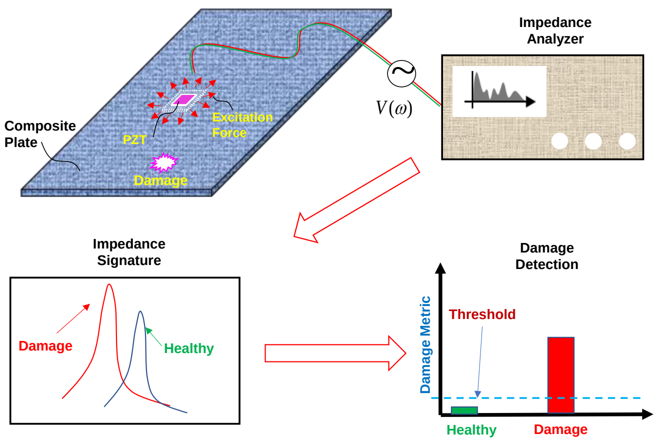

Figure 1. The EM impedance technique for composite plate

When a harmonic voltage V is applied across a range of frequencies ω, the transducer undergoes mechanical vibrations due to the piezoelectric effect, thereby exciting the host structure (Park et al., 2003). The measured EM impedance response depends on the combined effects of the transducer's intrinsic impedance Z_a and the mechanical impedance of the structure Z_s, and it varies as the structural condition changes. For a simplified one-dimensional model, the theoretical EM impedance response Z can be described by the following relationship (Park et al., 2005):

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$$Z = \left\{ i\omega \frac{h_a l_a}{t_a} \left[\hat{\varepsilon}_{33}^{T} - \frac{1}{Z_a / Z_s + 1} d_{31}^{2} \hat{Y}_{11}^{E} \right] \right\}^{-1} \tag{1}$$

where $\hat{\varepsilon}_{33}^{T}$ is the complex dielectric permittivity, and d_{31} is the piezoelectric coupling coefficient; h_a, l_a, and t_a represent the width, length, and thickness of the transducer, respectively; $\hat{Y}_{11}^{E}$ denotes the Young's modulus of the transducer; η corresponds to the structural damping loss factor of the transducer; and i is the imaginary unit.

The EM impedance response is inherently sensitive to the mechanical properties of the host structure, such as its mass, stiffness, and damping characteristics. When damage occurs, these mechanical parameters are altered, which in turn leads to measurable variations in the EM impedance signal. By monitoring such changes using the damage metric, it is possible to reliably detect damage within composite materials (Fig. 1). Furthermore, due to the short wavelengths associated with high-frequency excitation, EM impedance measurements are particularly adept at identifying small-scale defects and early-stage damage in composite structures.

3 NUMERICAL STUDY

A detailed finite element (FE) simulation of a clamped composite laminate was carried out using ABAQUS to investigate the EM impedance response, as shown in Fig. 2. The FE model replicates an experimental model of composite plate with dimensions of 290 mm × 200 mm × 3 mm, rigidly fixed along all four edges, as depicted in Figs. 2a and 2b [4]. The laminate structure consists of 12 layers of T700/M21 carbon/epoxy, arranged in a symmetric stacking sequence of [45/–45/0/90/0/90]S, as shown in Fig. 2c.

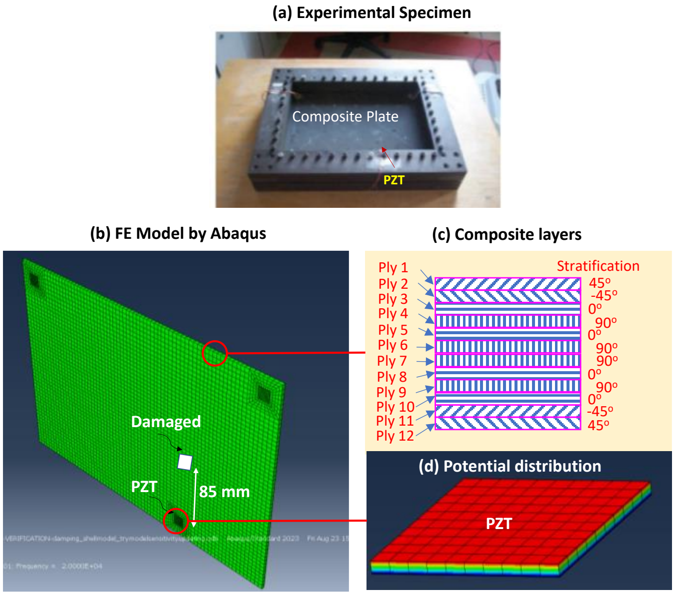

Figure 2. FE modeling

A square piezoelectric patch measuring 10 mm × 10 mm × 0.5 mm is surface-mounted at the center of the plate via a thin adhesive film of 0.04 mm thickness [4]. As shown in Fig. 1b, the composite laminate is discretized using 8-node continuum shell elements (SC8R), while the adhesive layer is represented with 8-node linear brick elements (C3D8). The bonded piezoelectric transducer is modeled using 8-node coupled-field piezoelectric elements (C3D8E), capable of simulating electromechanical interactions.

The material parameters for both the piezoelectric patch and adhesive layer are adopted from established literature [4], and a structural damping ratio of 0.02 is incorporated to simulate energy dissipation. To evaluate the EM impedance response, a sinusoidal voltage excitation of 1 V is applied across the piezoelectric patch, specifically, the upper electrode is subjected to the harmonic signal V(ω), while the lower electrode is grounded. The potential distribution across the transducer's thickness is shown in Fig. 2d. The frequency sweep defined in ABAQUS spans from 10 kHz to 30 kHz with a frequency resolution of 50 Hz to capture relevant impedance dynamics.

To assess damage sensitivity, a localized defect scenario is introduced: a 10 mm × 10 mm square damage zone positioned 85 mm from the piezoelectric transducer. Variations in damage severity are simulated by incrementally reducing the stiffness of the plies to 0.1 Pa within the defect region, mimicking progressive internal damage such as delamination or matrix cracking.

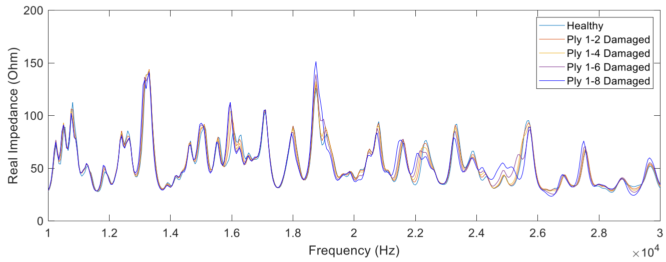

Figure 3. Real part of the EMI response under damage

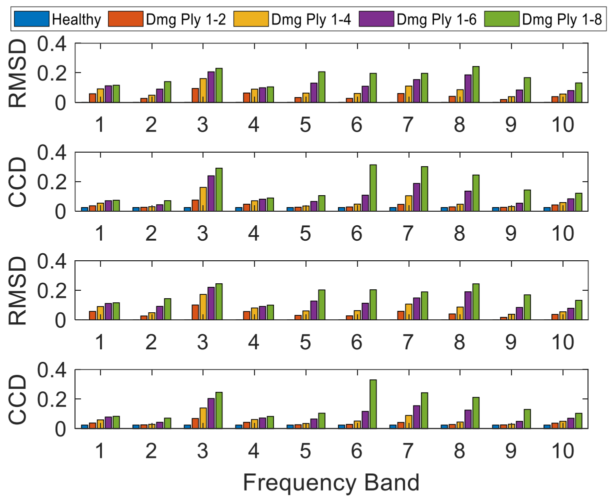

Figure 4. Damage detection results using RMSD and CCD metrics

As illustrated in Fig. 3, the EM impedance spectra recorded between 10 kHz – 30 kHz display multiple well-defined resonance peaks. Upon the introduction of damage to the

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composite plate, these peaks exhibit noticeable shifts, predominantly toward lower frequencies, as the number of compromised plies increases. This frequency shift reflects a decline in local stiffness and a modification of the structure's dynamic behavior.

To systematically capture these changes, statistical damage indices, specifically, the root-mean-square deviation (RMSD) and cross-correlation deviation (CCD) [1] are employed. These indices are calculated across ten 2-kHz-wide sub-bands (see Fig. 4), enabling localized frequency analysis and heightened sensitivity to subtle damage.

The outcomes presented in Fig. 4 clearly illustrate that both RMSD and CCD values increase significantly under damaged conditions, with the magnitude of these indices growing in proportion to the severity of the damage. This trend reinforces the sensitivity of the EM impedance technique not only for detecting the presence of structural degradation but also for quantifying its extent. Such capability is critical in composite materials, where damage often initiates internally and may not be easily visible through traditional inspection methods.

Moreover, the identification of multiple damage-sensitive frequency sub-bands provides additional insight into the damage localization process. These sub-bands exhibit distinct impedance shifts, suggesting that the structural response to damage is frequency-dependent. By isolating and analyzing these sub-bands individually, the detection resolution is substantially improved. This is particularly valuable in real-world SHM scenarios where environmental and operational variability may obscure global trends in the impedance spectrum. The sub-band approach thus offers a practical means to enhance robustness and reduce false positives in damage detection systems.

4 DISCUSSIONS AND CONCLUDING REMARKS

This study presents a preliminary numerical investigation into a low-cost SHM approach for composite structures using the EM impedance technique. A FE model of a clamped composite plate with a bonded piezoelectric transducer is developed to simulate EM impedance responses under different damage conditions, introduced as localized stiffness degradation at the ply level. To enhance sensitivity, the analysis applies frequency sub-band decomposition combined with RMSD and CCD damage indices. Results show that the EM impedance signatures are highly responsive to structural damage, with clear impedance shifts and increasing index values correlating with damage severity. These findings validate the effectiveness of combining EM impedance-based sensing with sub-band analysis and statistical damage indices.

The EM impedance technique offers a low-cost and sensitive approach for real-time damage detection, particularly suited to laminated composite structures in aerospace panels, and turbine blades, where internal damage is often undetectable by surface methods. Its compact size and high-frequency resolution make it ideal for embedded sensing in such systems.

While the current numerical model assumes fixed boundary conditions to isolate damage effects, real-world applications may involve boundary variability due to thermal or operational effects. Future work will therefore include parametric studies accounting for changes in boundary conditions, plate deformation, and internal stress states, to assess the robustness of EM impedanace-based damage indicators under practical uncertainties.

Future efforts will also focus on experimental validation to confirm the numerical findings under realistic conditions. Parametric studies involving different layups, damage types, and sensor placements will help generalize the method. Additionally, integrating EM impedance features with machine learning could improve damage classification and quantification. Extension to complex geometries and real-world structures is also planned to support practical SHM applications.

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