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NUMERICAL MODELING OF STRESS-BASED FATIGUE MODEL FOR EMI TECHNIQUE UNDER FATIGUE LOADING

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ABSTRACT

Structural Health Monitoring (SHM) has become a vital approach for ensuring the safety and longevity of engineering structures. The Electro-Mechanical Impedance (EMI) technique, which employs piezoelectric sensors bonded to host materials, provides a reliable method for detecting fatigue-induced damage. In this study, a numerical fatigue model was developed in COMSOL Multiphysics to simulate cyclic loading on a copper host structure. The model incorporated a stress-based fatigue approach to assess damage evolution under progressive loading conditions. Piezoelectric transducer interaction with the host medium was simulated, and variations in conductance signatures were analyzed. Results indicated that fatigue damage in copper significantly influenced the EMI response, leading to resonance shifts and reduced admittance peaks. This confirms the feasibility of EMI as an efficient non-destructive evaluation technique for monitoring fatigue progression in copper-based structures.

Keywords: Structural Health Monitoring, Electro-Mechanical Impedance (EMI), COMSOL, Admittance signature, Numerical Modeling.

1. INTRODUCTION

Fatigue damage in metallic structures is one of the leading causes of service failures in aerospace, mechanical, and civil engineering applications. Traditional non-destructive evaluation (NDE) methods often require manual inspections and may not capture early stages of fatigue damage. In contrast, Structural Health Monitoring (SHM) techniques provide continuous or periodic monitoring of structural integrity, enhancing safety and reducing maintenance costs [1], [2].

Among SHM approaches, the Electro-Mechanical Impedance (EMI) technique has gained attention due to its high sensitivity to incipient damage. In EMI, piezoelectric sensors are bonded to the host structure, and their electrical impedance response is correlated with the mechanical condition of the structure [3]. This study focuses on numerical modeling of fatigue in copper using EMI, with a stress-based fatigue model applied under cyclic loading.

Fatigue damage is a primary cause of unexpected failures in metallic components subjected to cyclic loading. Traditional inspection techniques often miss small-scale damage or require downtime for manual inspection. The EMI technique — where a piezoelectric transducer is bonded to the structure and its electrical impedance is monitored — is sensitive to local changes in stiffness and damping and therefore well suited for early fatigue detection. Copper is widely used in numerous engineering and electronic applications where fatigue and reliability are critical; modeling its fatigue behavior and corresponding EMI response provides insight for practical monitoring.

This paper develops and documents a numerical framework in COMSOL for coupling a stress-based fatigue model with piezoelectric-electromechanical simulation. The objective is to simulate fatigue progression in a copper plate of specified dimension (48 × 48 × 10 mm), calculate EMI admittance signatures at progressive damage states.

Recent literature includes numerical models that explicitly simulate the PZT patch and host structure in FEM (including COMSOL) and obtain admittance through harmonic response analyses; others used admittance changes to infer anchor forces, crack presence, or local stress states. Surveys on piezoelectric impedance-based SHM categorize approaches as physics-based (FEM + mechanics) or data-driven; combining stress/fatigue modeling with EMI-based observation remains an active research area.

Copper is widely used in engineering applications because of its excellent ductility, conductivity, and fatigue resistance [8]. Understanding its fatigue behavior under EMI monitoring is crucial for extending applications in electrical, mechanical, and aerospace domains.

1.1 EMI technique and piezoelectric transducers

Park et al. first established EMI (impedance-based) monitoring as a practical approach to sense local stiffness changes via piezoelectric transducers bonded to structures; the method couple electrical impedance of the transducer with the mechanical impedance of the host. Giurgiutiu and Rogers and others extended the approach to a broad set of structures and loading conditions, showing high sensitivity to boundary changes, cracks, and debonding [9].

1.2 EMI for fatigue detection

Multiple studies have applied EMI for detection of incipient fatigue damage. Research shows that the emergence and growth of fatigue cracks reduce local stiffness — producing measurable downward shifts in resonance frequency and reductions in conductance peak magnitude. Bhalla, Soh and co-workers demonstrated numerical and experimental implementations of impedance-based monitoring for fatigue scenarios and provided metrics for damage quantification such as RMSD and frequency shift.

1.3 Numerical modeling approaches

COMSOL and similar Multiphysics platforms have been used to couple piezoelectric electromechanics and structural degradation models. Approaches typically combine a continuum fatigue model (stress-life or strain-life) with progressive stiffness degradation implemented as a reduction in elastic modulus or element stiffness. Miner's linear damage accumulation rule is commonly used to step the model forward under cyclic loading.

1.4 Copper as host material

Prior work supports both the sensitivity of EMI to fatigue and the feasibility of numerical modeling of coupled electromechanical responses. This study builds on that foundation by presenting a detailed COMSOL workflow and interpretation for a small copper plate geometry under cyclic loading.

Research objective

To present a reproducible COMSOL workflow to:

Model a copper host block (48 × 48 × 10 mm) instrumented with a PZT patch bonded by an adhesive layer. Simulate harmonic electromechanical response (admittance) of the bonded PZT across a chosen frequency band. Map the computed fatigue damage to changes in local stiffness/properties and predict how the admittance signature (especially conductance peaks) evolves with accumulated fatigue.

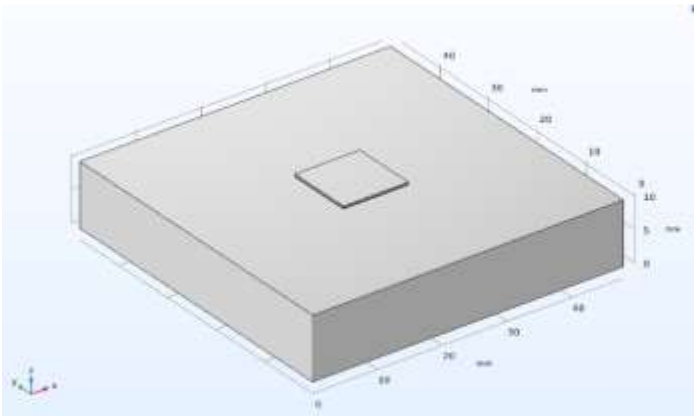
2. METHODOLOGY

2.1 Model Geometry and Material Properties

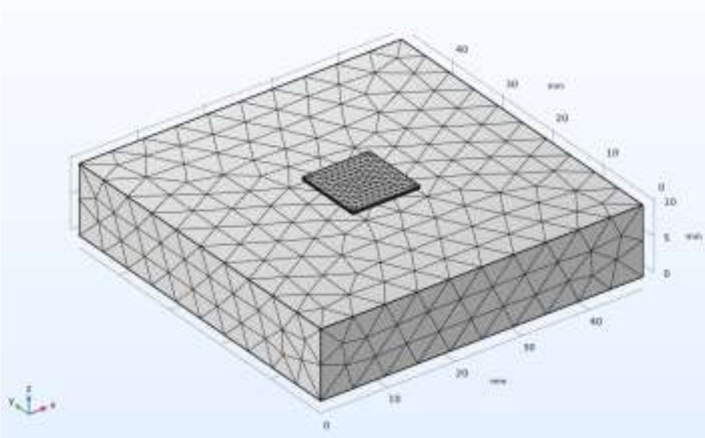
A copper host structure with dimensions 48 × 48 × 10 mm was modeled in COMSOL Multiphysics v.6.2. A PZT-5H piezoelectric sensor was bonded to the surface using a thin adhesive layer to simulate realistic EMI interaction. Material properties of copper (elastic modulus, Poisson's ratio, and density) were adopted from COMSOL library. Material properties of PZT sensor is described in table-2.

Table-1: Properties of host structure

Parameter	Value	Unit
Size	50*50	mm^2
Young's modulus	$11*10^4$	N/mm^2
Density	8960	Kg/m^3



(a)



(b)

Figure 1: (a) Geometry of host structure, PZT patch and adhesive, (b) Meshing plot.

2.2 Fatigue Model

The stress-based fatigue model was implemented under cyclic loading conditions. The fatigue damage was evaluated using the stress-based approach, considering Findley criteria. Progressive damage accumulation was simulated through Miner's rule, enabling prediction of fatigue usage factor [12].

Table-2: Material Properties of PZT sensor

Parameter	Value	Unit
Density	7500	Kg/m^3
Youngs Modulus	$68.78*10^9$	N/mm^2
Poisson's ratio	0.4	-
Relative permittivity	{1704.4,1704.4,1704.4}	-

2.3 EMI Simulation

The coupled-field analysis incorporated the structural and electrical domains. The piezoelectric sensor was excited with a harmonic voltage sweep across a frequency range of 30–300 kHz. The admittance response (real part: conductance, imaginary part: susceptance) was recorded at multiple fatigue stages. Variations in resonance peaks were studied to assess the sensitivity of EMI signatures to fatigue damage.

Use "Piezoelectric Devices" or the Solid Mechanics + Electrostatics (coupled) interface to account for electromechanical coupling and to compute electrical admittance from mechanical interaction. For harmonic response use the Frequency Domain study to sweep the frequency band of interest (e.g., 30 kHz–300 kHz depending on PZT/host dimensions)

3. RESULTS

Baseline Response: The pristine copper host structure showed clear conductance peaks corresponding to its natural modes. **Fatigue Damage Evolution**: As cyclic loading increased, fatigue cracks initiated and propagated, leading to stiffness reduction.

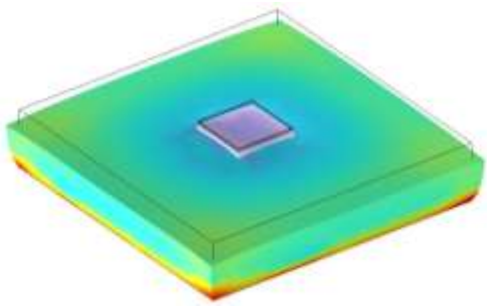


Figure 2: Stress plot.

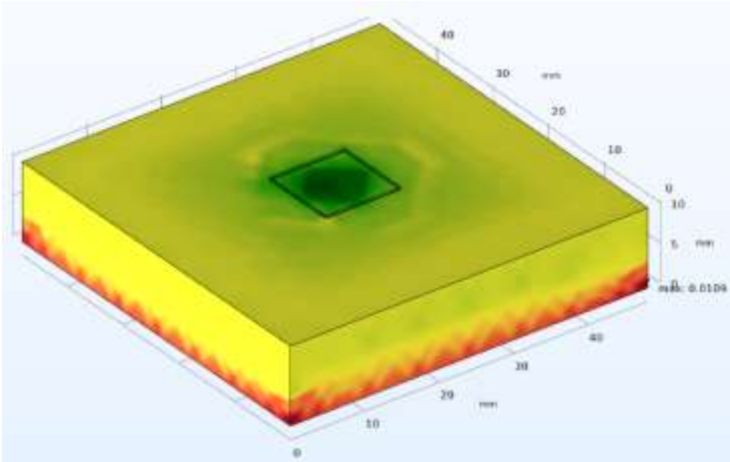


Figure 3: Fatigue usage factor plot.

Admittance Signature Variation: Progressive fatigue caused: Downward shift in resonance frequencies, Reduction in peak amplitude of conductance. Increase in RMSD (Root Mean Square Deviation) between healthy and damaged states.

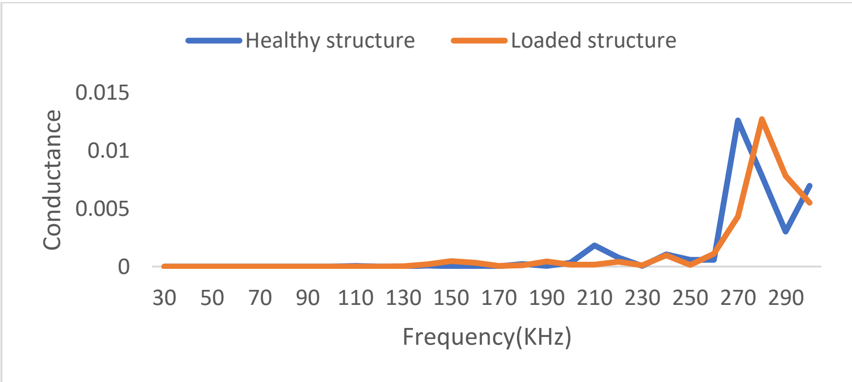


Figure 4: Conductance vs frequency signature

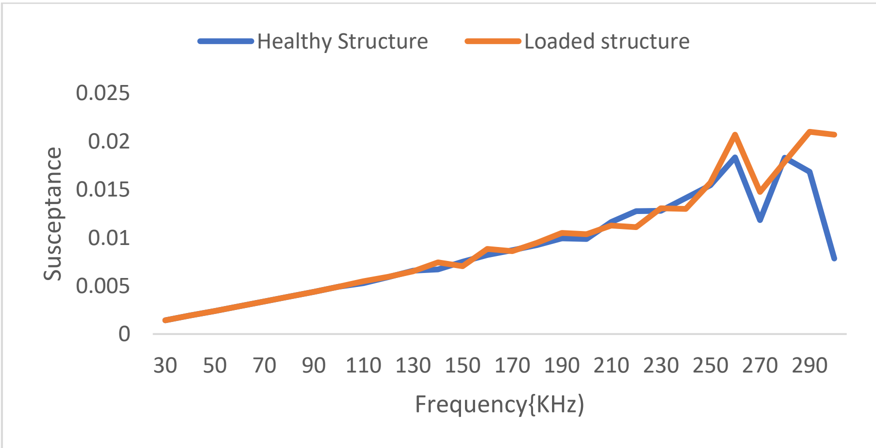


Figure 5: Susceptance vs frequency signature

These results confirm that EMI signatures are directly influenced by fatigue damage in copper, making it a promising method for early-stage damage detection.

4. DISCUSSION

Thicker adhesive or softer glue reduces electromechanical coupling and hence damage sensitivity. PZT size and placement relative to high-stress regions significantly affect detectability. Environmental effects (temperature, preload) must be compensated or normalized.

The FEM-based approach allows parametric exploration (sensor size, adhesive thickness, host thickness, frequency band) without expensive experiments, and the COMSOL environment simplifies coupling piezoelectric harmonic response with fatigue accumulation via the Fatigue Module.

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5. CONCLUSION

This paper presents a clear COMSOL-based methodology to couple piezoelectric admittance (EMI) simulations with stress-based fatigue modeling. Using the Piezoelectric/Multiphysics harmonic analysis and the Fatigue Module, the workflow enables prediction of how fatigue accumulation modifies the PZT admittance signature. The approach supports parametric design of sensor placement, adhesive choice, and frequency band selection. Limitations include the need to empirically map fatigue damage to stiffness degradation and account for environmental influences; experimental validation remains essential.

This research established a numerical framework for modeling stress-based fatigue in copper structures under cyclic loading using the EMI technique. The findings confirm that: Fatigue damage leads to resonance frequency shifts and amplitude reduction in EMI signatures. EMI is sensitive enough to capture early fatigue stages in copper. Numerical modeling provides a predictive tool for extending EMI-based SHM in real-world copper applications.

Future work may include experimental validation and comparative studies with other host materials. The coupled numerical framework effectively links a stress-based fatigue model to EMI admittance predictions for a copper plate 48 × 48 × 10 mm. EMI signatures (resonance shifts, conductance attenuation, RMSD) provide reliable indicators of progressive damage in the modeled scenario. For practical deployment, calibrate the fatigue parameters and stiffness-damage mapping against laboratory fatigue tests on copper coupons and include environmental compensation. Experimental validation on the same geometry, parametric study of patch size/position and adhesive properties, and extension to strain-life models or fracture mechanics for crack propagation

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[14] (For copper fatigue data) — consult metallurgical handbooks or fatigue data handbooks such as ASM Handbooks (Properties and Selection: Nonferrous Alloys) and experimental S–N curve datasets relevant to your copper alloy.