Research Article

Understanding Impedance Response Characteristics of a Piezoelectric-Based Smart Interface Subjected to Functional Degradations

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The functionality of piezoelectric devices is of significant importance in the electromechanical impedance (EMI)-based structural health monitoring (SHM) and damage detection. Despite the previous work, the EMI response characteristics of a degraded piezoelectric-based smart interface have not been sufficiently investigated due to the difficulty in making realistic functional defects via the experiment. To overcome this issue, we present a predictive simulation strategy to comprehensively investigate the EMI response characteristics of a smart interface subjected typical functional degradations. For that, a bolted steel girder connection is selected as a host structure to experimentally conduct EMI response measurement via the smart interface. Then, a finite element (FE) model corresponding to the experimental model is established and updated to reproduce the measured EMI response. By using the updated FE model, four common degradation types, including shear lag effect, transducer debonding, transducer breakage, and interface detaching are simulated and their effects on the EMI response are comprehensively analyzed. It is found that the interface detaching defect has significant impacts on the primary resonances of the EMI response and generates additional peaks with complex modal shapes. Also, the functional defects can result in distinctive EMI response characteristics, which are promising for assessing the functional condition of the smart interface.

1. Introduction

In recent years, the electromechanical impedance (EMI)-based method has emerged as an innovative structural health monitoring (SHM) and damage detection tool for various engineering structures [1–6]. In the EMI-based

method, a piezoelectric transducer such as a PZT patch (Lead Zirconate Titanate) is directly bonded to a host structure to measure the EMI response of a high-frequency range [7–9]. Once the host structure is damaged, its structural properties are altered, leading to the variation in measured EMI responses. By monitoring the EMI changes,

it is possible to identify structural damage. It is known that the multiple frequency ranges containing 20–30 peaks are often chosen to assure a higher density of modes [10]. However, the direct attachment of the PZT patches often leads to weak EMI peaks and further causes difficulties in determining sensitive frequency bands for a damage detection task [11–13]. Besides, for some cases, the sensitive frequency bands could be very significant, over 10–100 kHz, thus restricting the use of low-cost wireless impedance sensor nodes [3, 14–16]. Several researchers have worked on developing embeddable piezoelectric devices for enhancing the sensitivity of EMI responses to structural damage, such as smart aggregates for health monitoring of concrete structures [2, 17], smart washers for preload monitoring of critical connections [3, 18], and smart coupons for corrosion monitoring [19]. However, those piezoelectric devices must be preinstalled during construction and thus have less practicality for in-situ structures.

To deal with existing structures and to predetermine the sensitive frequency range within 10–100 kHz for low-cost wireless impedance sensing, mountable piezoelectric devices have been proposed for the EMI-based technique [20–22]. Based on the pioneering work [23], Huynh and Kim first developed the concept of a mountable piezoelectric device for the monitoring of EMI response [20]. Their main idea is to indirectly mount a PZT patch to a host structure through a metallic plate (i.e., the so-called smart interface). The smart interface prototype can be easily attached to and removed from a host structure. It also can create strong EMI responses in a desired effective frequency range [24]. The smart interface technology has been applied for different damage detection problems using EMI responses. For example, Ryu et al. have designed a slender PZT interface for tension force monitoring of axially loaded members [21]. Tawie et al. designed a circular PZT interface to enhance the damage-sensitivity of EMI responses for SHM of a fiber composite plate [22]. Dang et al. adopted the smart interface for strand breakage detection in prestressed multistrand anchorage system [25].

During its service life, nonetheless, the smart interface could be damaged under the influences of overloading, harsh environmental conditions, and material deteriorations. Common defects of the smart interface include shear lag effect, PZT debonding, PZT breakage/scratch, and interface detaching. Such defects could modify structural and piezoelectric properties and the mechanical impedances of the smart interface, leading to certain changes in measured EMI responses. The shear lag phenomenon occurs when the stiffness of the bonding layer is significantly reduced. The shear lag causes a reduction in the force and strain transmissions between the PZT and the interface through the bonding layer [26]. The capacitance of the PZT patch mainly varies with the transducer breakage. As evidenced in the previous study [27], the coupling between the PZT and the interface will be changed if the PZT is partially debonded from the structure. The mechanical impedance of the smart interface could be significantly changed when it is detached from a host structure. Since the EMI-based method relies on statistically comparing EMI signatures before and after

damaged states [28], the failure of the smart interface could lead to false damage detections unless it is timely diagnosed.

A few research efforts have been made on evaluating the functionality of piezoelectric transducers for the EMI-based method. Giurgiutiu et al. reported the effect of the degraded bonding layer on the EMI response and proposed a debonding identification method via tracking the appearance of the PZT's resonance [29]. Park et al. extended the problem by considering additional degradations in the piezoelectric transducers [28]. Ai et al. proposed a method using the features of the real admittance to detect the sensor faults [30]. Despite the previous studies, the effect of shear lag on the EMI response has been not clarified in up-to-date literature. Park et al. showed that the shear lag effect increases the peak frequency and the peak magnitude of the EMI response [27] while Bhalla and Moharana showed a contrasting trend [26]. Recently, the effect of PZT defects on the EMI response of a smart interface has been experimentally investigated [31]. However, due to the difficulty in making realistic functional defects via the experiment, the EMI response of a degraded smart interface has been not sufficiently studied so far.

The present study presents a comprehensive analysis of the EMI response of a smart interface subjected to various functional degradations. To overcome the abovementioned difficulty, a predictive impedance modeling strategy is proposed. The main idea is to utilize an updated finite element (FE) model to generate feasible EMI responses of a degraded smart interface. Firstly, the background of the EMI-based damage detection method via a smart interface and its issues are presented. A diagnosis process based on the change in the EMI features is proposed for assessing the defects in the smart interface. Secondly, a bolted steel girder connection is selected as a host structure to experimentally conduct EMI response measurement via the smart interface. Thirdly, a FE model corresponding to the experimental model is established and fine-tuned by a common modal sensitivity-based method [32]. The numerical EMI response is updated not only for the resonant frequency but also for the resonant amplitude and consequently compared with the experimental data to verify the feasibility of predictive impedance modeling. Fourthly, common defects of the smart interface, including shear lag phenomenon, PZT debonding, PZT breakage, and interface detaching, are modeled using the updated FE model, from which the corresponding EMI responses are generated and analyzed comprehensively. Finally, the distinctive EMI features under the PZT interface's degradation and the structural damage are outlined and the proposed diagnosis process is verified thereby.

2. EMI-Based Damage Monitoring Method via Piezoelectric-Based Smart Interface

2.1. Fundamentals of the Method and Its Issues. The overview of the EMI-based damage monitoring technique via the smart interface is outlined in Figure 1. The smart interface prototype is a plate-like structure with two outside bonded sections and a flexible middle section. The outside sections allow the smart

FIGURE 1: Overview of the EMI-based damage monitoring method via the smart interface.

interface to be easily bonded to and detached from a mother structure. The middle section, where the PZT patch is installed, is intentionally designed as a flexible part to provide an easy elongation of the PZT under the inverse piezoelectric effect. Importantly, the flexible section helps to create strong resonances in the EMI response and to predetermine the sensitive frequency band of the EMI response below 100 kHz for low-cost wireless impedance sensing [15, 16].

To obtain the EMI response, the PZT patch is excited by a harmonic voltage $V(\omega)$ of a high-frequency range using an impedance analyzer. The output current $I(\omega)$ is then recorded and the ratio between $V(\omega)$ and $I(\omega)$ is interpreted as the EMI response $Z(\omega)$. As shown in Figure 1, when $V(\omega)$ is applied, the PZT patch is deformed due to the inverse piezoelectric effect, and a force $F(\omega)$ in opposition to that deformation is introduced into both the PZT patch and the interface. While the PZT is harmonically excited, there exist couplings between the PZT and the interface and between the interface and the host structure [33]. Thus, the obtained EMI response not only contains the mechanical impedance of the host structure but also that of the interface and the PZT patch.

According to the previous studies [34, 35], the EMI response of the PZT interface-host structure system can be expressed in equation (1), as follows:

$$Z(\omega) = \left\{ j\omega C \left[1 - \frac{\bar{Z}}{\bar{Z} + Z_a} \frac{d_{31}^2 \hat{Y}_{11}^E \tan(kl_a)}{\hat{\epsilon}_{33}^T kl_a} \right] \right\}^{-1}, \quad (1)$$

where $C = \hat{\epsilon}_{33}^T \omega_a l_a / t_a$ is the capacitance of the PZT patch; $\hat{Y}_{11}^E = (1 + j\eta) Y_{11}^E$ is the complex Young's modulus of the PZT at the constant electric field; $\hat{\epsilon}_{33}^T = \epsilon_{33}^T (1 - j\delta)$ is the complex dielectric permittivity at constant stress; d_{31} is the piezoelectric coupling constant at zero stress; ω_a , l_a , and t_a are, respectively, the effective width, length, and thickness of the PZT; η and δ , respectively, are the structural damping loss factor and the dielectric loss factor of the PZT; $k = \omega/c$ is the wavenumber of the PZT and c is the wave speed given by $\sqrt{\rho/Y_{11}^E}$; and ρ is the PZT's mass density. $Z_a = \hat{Y}_{11}^E \omega_a t_a / j\omega l_a$ is the mechanical impedance of the PZT; and $\bar{Z}$ is the equivalent mechanical impedance of the interface-host structure system, which is a function of the structural parameters of the host structure (m_s , c_s , k_s) and the interface (m_p , c_p , k_i) as well [36].

When the host structure is damaged, its mechanical impedance is altered, causing the variation in the measured EMI response. Therefore, the damage that occurred in a host structure can be diagnosed through monitoring the change in the EMI response using statistical damage indices such as root-mean-square-deviation and cross-correlation deviation [10, 37]. However, the EMI response is also varied as the piezoelectric device is degraded. Overloading conditions, material deteriorations, and environmental changes could induce defects in the bonding layer, the PZT patch, and the interface structure, resulting in observable changes in the measured EMI response; those can be misinterpreted as the effect of structural damage.

2.2. Diagnosis Process of Degraded PZT Interface. A diagnosis process of the damaged smart interface is proposed to diagnose the functional degradations of the smart interface and to differentiate them from the structural damage during damage identification processes, as shown in Figure 2. The proposed diagnosis process is based on the distinctive changes of EMI features under the structural damage and functional degradations of the smart interface.

The process consists of seven steps. In Step 1, the EMI response is periodically acquired from an installed smart interface using an impedance analyzer. In Step 2, if some of the measured EMI responses are different from others, the slopes β of all measured imaginary admittance signals are computed; otherwise, the EMI response is continuously monitored. In Step 3, if some of the slopes β differ from others, they are diagnosed in Step 4; if not, they are then diagnosed in Step 5. In Step 4, if the slope β is increased, it could be diagnosed as PZT's bonding defect; if the slope is decreased, the PZT could be damaged. In Step 5, if there is an existence of new resonances in the measured EMI response, the interface could be detached from the host structure; if not, the host structure could be damaged. In Step 6, after identifying the structural damage, further quantitative damage assessment for SHM is required, including estimations of damage severity and remaining service life. In Step 7, after identifying the defect in the smart interface, further efforts are needed to repair or replace the smart interface. In the following sections, the effects of the PZT

FIGURE 2: Changes in the slope of imaginary admittance.

interface's degradation on EMI responses are analyzed and the EMI features are characterized to demonstrate the proposed diagnosis scheme in Figure 3.

3. Predictive EMI Response Modeling

3.1. Experimental Model and EMI Response Measurement

3.1.1. Experimental Model. A bolted steel girder connection is selected as a host structure to experimentally conduct EMI response measurement via the smart interface. The experimental model was obtained from [38]. The test setup is shown in Figure 4 and the geometric dimensions of the experimental model are detailed in Figure 5. The steel girder with a length of 3.96 m was assembled from two H-shaped girder segments through a bolted joint, as shown in Figures 4 and 5(a). The girder was simply supported via half-round steel rods. At the connection, the top and bottom flanges of the girder were clamped by a set of 16 M20 bolts and two

splice plates. All bolts were fastened by the same torque of 160 Nm. The splice plate has a width of 200 mm, a height of 310 mm, and a thickness of 10 mm; see Figure 5(b).

The smart interface with a width of 100 mm and height of 33 mm was fabricated from an aluminum plate. The bonded sections of the interface have a thickness of 5 mm and the flexible section has a thickness of 4 mm, as illustrated in Figure 5(c). The smart interface was mounted onto the splice connection through two outside sections using an instant adhesive (Loctite 401); see Figures 4 and 5(b). A PZT-5A patch with width of 25 mm, height of 25 mm, and thickness of 0.51 mm was bonded to the interface using the same instant adhesive, see Figure 5(c).

3.1.2. EMI Measurement via Smart Interface. EMI responses were obtained from the bolted connection via the smart interface [38]. A high-performance impedance analyzer, HIOKI 3532, was used to generate the harmonic voltage

FIGURE 3: The diagnosis process of a damaged smart interface for SHM.

FIGURE 4: Setup of lab-scaled girder connection.

excitation and to record the EMI response in the frequency range of 10–55 kHz (901 frequency points with an interval of 0.05 kHz). The excitation has an amplitude of 1 V. During the impedance measurement, the room temperature was controlled at 21°C to avoid any effect caused by temperature changes.

The real and imaginary parts of the measured EMI responses are shown in Figure 6. There are two strong resonances in 15–18 kHz and 33–36 kHz, where the aspect of the real part becomes significant as that of the imaginary part. The first resonance (Peak 1) occurred at the frequency of 16.80 kHz ($f_{1,Exp}$) and the second one (Peak 2) occurred at 34.65 kHz ($f_{2,Exp}$). These resonant peaks represent the coupled vibrations of the smart interface-bolted connection system. Because the contribution of the structural impedance to the overall EMI responses was significant at resonance [3], the frequency ranges containing Peak 1 and Peak 2 are commonly employed for damage detection in practice.

3.2. FE Modeling of the Experimental Model

3.2.1. Initial FE Model. The simulation of the piezoelectric effects of the smart interface requires coupled electrical and mechanical physics, which act concurrently during the harmonic excitation of the PZT [39–41]. Due to the strong modeling capability of the piezoelectric effects, COMSOL Multiphysics was employed to build a numerical model corresponding to the experimental model. The model consisted of the PZT patch and its bonding layer, the interface body and its bonding layers, and the splice plate, as shown in Figures 7(a) and 7(b). The dimensional parameters of the FE model were based on the actual geometry of the experimental model; see Figure 5. The initial FE model was obtained from [38].

The model was meshed by 3D solid elements. The total number of elements was 16138, including 2020 hexahedral elements for the smart interface and the bonding layers, and

FIGURE 5: Geometric dimensions (mm) of the experimental model. (a) Steel girder. (b) Connection splice. (c) Smart interface.

FIGURE 6: Experimental EMI responses.

14118 prism elements for the splice plate. We meshed the model using the user-controlled mesh sequence type in COMSOL. The model with progressively finer meshes was resolved until the obtained EMI signature remain almost unchanged. Similar to the experiment, a harmonic voltage of 1 V was applied to the top surface of the PZT patch while the bottom was set as the ground electrode. The current generated due to the piezoelectric effects was measured during the PZT excitation. The EMI response was obtained as the ratio between the input voltage and the output current.

During the PZT excitation, different coupled vibrations occurred in the system, such as the interaction between the smart interface with the connection splice and between the splice with the remainder of the connection. According to the previous works, the effect of the remainder was modeled by the structural parameters at the contact interface [42, 43]. Thus, the experimental model was simplified by the smart interface-

connection splice system with a 3D spring system (k_x , k_y , and k_z) and a 3D dashpot system (c_x , c_y and c_z), as shown in Figure 7(c). The value of the contact spring and dashpot represents the amount of the bolt torque of the connection.

In the FE model, the splice plate was assigned by steel with Young's modulus $E = 200$ GPa, Poisson's ratio $\nu = 0.33$, and mass density $\rho = 7850$ kg/m³. The interface body was assigned aluminum with $E = 70$ GPa, $\nu = 0.33$, and $\rho = 2700$ kg/m³. The PZT patch was assigned by the piezoelectric material of PZT-5A with the structural and piezoelectric properties obtained from the previous study [36]. The z -directional contact stiffness was initially set as $k_z = 3.0 \times 10^{12}$ N/m²/m and the x -directional and y -directional contact stiffness k_x and k_y were assumed to be 1.5×10^{12} . The dashpot system was represented by the damping ratios $\xi_x = \xi_y = \xi_z = 0.01$. From previously published data [44, 45], the bonding layers were first assumed to have the thickness

FIGURE 7: The FE modeling of the experimental model. (a) Meshed finite element model. (b) Smart interface and bonding layers. (c) Assigned contact parameters to simulate the effect of bolt preloads.

$t = 0.2$ mm, Young's modulus $E = 3$ GPa, Poisson's ratio $\nu = 0.38$, and the mass density $\rho = 1700$ kg/m³.

3.2.2. EMI Response of Initial FE Model. The EMI response of the initial FE model was computed for the frequency range of 10–55 kHz with a frequency step of 0.05 kHz (901 frequency points). The generalized minimum residual (GMRES) iterative method available in COMSOL was used for solving the EMI simulation problem. The error criterion for the convergence of the solution was defined as 0.001. The real and the imaginary parts of the numerical EM signatures were compared with the experimental data in Figures 8(a) and 8(b), respectively. Similar to the experimental result, the numerical simulation showed two remarkable resonant peaks in the frequency range of 10–55 kHz (see Figure 8(a)). The frequencies of Peak 1 and Peak 2 were found at 15.85 kHz ($f_{1, \text{FEM}}$) and 33.05 kHz ($f_{2, \text{FEM}}$), respectively.

The modal shapes corresponding to the two peaks are visualized in Figure 8(c). Peak 1 has a longitudinal bending motion and Peak 2 exhibits a lateral bending motion. Due to its square shape, the PZT patch can excite the interface in two directions, thus initiating both lateral and longitudinal bending motions of the interface. Figure 8(d) shows the convergence progress for the two impedance peaks, that is, the error estimate against the number of iterations. It is shown that the solution for Peak 1 was converged after 15 iterations and the solution for Peak 2 was converged after 76 iterations.

As shown in Figure 8(a), the FE model predicted the frequency and the magnitude of Peak 1 and Peak 2 different from the experimental model. The differences were also found in the imaginary EMI signatures, as seen in Figure 8(b). Since the resonances of the EMI responses are

particularly important for damage detection [3], they should be properly updated. To reproduce the experimental EMI data at the same frequency range with identical patterns, the structural parameters of the FE model should be adjusted through a model-updating process.

3.3. Identification of FE Model

3.3.1. Model-Updating Algorithm. The objective of model-updating is to fine-tune the FE model corresponding to a real structure [46]. By updating the structural parameters, the FE model can reproduce the EMI response measured from the experimental model. As one of the common model-updating algorithms [47–49], the modal sensitivity-based method was adopted to identify the structural parameters of the FE model. The method estimates the model-updating parameters by using the modal sensitivity, which relates the fractional changes in the parameters to the fractional changes in eigenvalues of a system [32].

The modal sensitivity-based model-updating algorithm is performed via four steps [32]: (1) selecting the NE model-updating parameters of the FE model and measuring a set of M modal frequencies from the target structure; (2) computing the modal sensitivity of the NE selected model-updating parameters of the FE model; (3) estimating the fractional changes in these parameters by the modal sensitivity equation; and (4) repeating the whole process until the differences in the M modal frequencies between the FE model and the target structure are minimal.

Supposing k_j^* and k_j are the j^{th} model-updating parameter of the target structure and the FE model, respectively. It is noted that the value of k_j^* is unknown while that of k_j is known. The term k_j^* is related to k_j through its fractional change α_j ($\alpha_j \geq -1$), based on the following expression:

FIGURE 8: EMI responses of the initial FE model. (a) Real impedance. (b) Imaginary impedance. (c) Mode shapes. (d) Convergence progress of the FE simulation.

$$k_j^* = k_j(1 + \alpha_j). \quad (2)$$

The modal sensitivity S_{ij} of the i^{th} impedance peak regarding the j^{th} model-updating parameter is computed, as follows:

$$S_{ij} = \frac{\delta f_i^2}{\delta k_j} \frac{k_j}{f_i^2}, \quad (3)$$

where δk_j is the k_j parameter's first order perturbation causing the frequency change in the impedance peak (δf_i^2).

With a known modal sensitivity matrix $[S_{ij}]$, the fractional change in the model-updating parameter $\{\alpha_j\}$ can be obtained by

$$\{\alpha_j\} = [S_{ij}]^{-1} \{D_i\}, \quad (4)$$

where $\{\alpha_j\}$ is a vector of NE elements; $[S_{ij}]$ is a $M \times NE$ matrix; and $\{D_i\}$ is a vector of M elements. $\{D_i\}$ contains the fractional differences in the modal frequencies between the FE model and the experimental model, as expressed in:

$$D_i = \frac{f_{i,\text{Exp}}^2 - f_{i,\text{FEM}}^2}{f_{i,\text{FEM}}^2}, \quad (5)$$

where $f_{i,\text{Exp}}^2$ is the i^{th} peak frequency measured from the experimental model and $f_{i,\text{FEM}}^2$ is the i^{th} peak frequency of the FE model.

If $[S_{ij}]$ is a nonsquare matrix, the inverse of $[S_{ij}]$ can be approximated by using the pseudoinverse technique. The vector $\{\alpha_j\}$ can be alternatively obtained by

$$\{\alpha_j\} = [S_{ij}]^T \left[[S_{ij}][S_{ij}]^T \right]^{-1} \{D_i\}. \quad (6)$$

It is noted that the pseudoinverse technique provides the least variance solution of the linear system. If the number of the parameters was much less than that of available modal frequencies, the system is ill-conditioned.

A criterion for the convergence between the measured and numerical modal frequencies is defined for the fine-tuning process, as follows:

$$|\{D_i\}| \leq \text{tolerance}. \quad (7)$$

3.3.2. Selection of Model-Updating Parameters. The selection of proper structural parameters in the FE model is the key to be successful in a model-updating process. Typically, the structural parameters, which are unknown due to the lack of information, should be selected. Also, the structural parameters that have high sensitivities to the frequency of the impedance peaks should be considered.

For well-known materials, including structural steel, aluminum alloy, and PZT-5A, no turning process was performed and the standardized values of material properties were used. As compared to the piezoelectric parameters, the material properties of the bonding layers are unknown and have higher uncertainty; those are dependent on installation methods as well as curing conditions during the experiment. Thus, the piezoelectric parameters were not considered in model-updating to reduce the number of unknown parameters and to assure the convergence of the model-updating. It is found from the previous studies [44, 45] that the Poisson's ratio of the bonding layer is about 0.38 with a minor deviation and the mass density is stable at 1700 kg/m³, whereas Young's modulus (or shear modulus) and the thickness of the bonding layer have a large deviation. Also, it is reported that Young's modulus of the bonding layer has significant impacts on the high-frequency response of PZT patches [26]. The values of the contact stiffness k_x , k_y , and k_z are unknown and dependent on the fastening force of the bolts. There are no direct formulas that can estimate these contact parameters; the only way is to update them. From the previous study, the values of k_x and k_y were found to be around half of k_z [24]. To reduce the number of unknown parameters, k_x and k_y were set as $0.5 \times k_z$ during the model-updating process.

From the above discussions, three unknown structural parameters were selected as the model-updating parameters, including (1) the bond thickness t_b , (2) the bond Young's

modulus E_b , and (3) the contact stiffness k_z . Figure 9 presents the modal sensitivities of the three model-updating parameters to the two identified frequencies of the impedance peaks (f_1 and f_2); those were computed using equation (3). It is observed that the bond thickness t_b and bond elastic modulus E_b showed high modal sensitivities to the two peak frequencies while the contact stiffness k_z showed relatively low modal sensitivities. Among all parameters, the bond thickness was the most sensitive to the frequency of Peak 1 while the bond elastic modulus was the most sensitive to the frequency of Peak 2.

3.3.3. Updating Finite Element Model

(1) Updating Peak Frequencies. The FE model was fine-tuned by the modal sensitivity-based model-updating algorithm. The experimental frequencies corresponding to the two impedance peaks were used as the target frequencies for model-tuning. The FE model was converged after 27 iterations with an average tolerance of two peaks <1%. Figure 10 shows the convergence of the two peak frequencies of the FE model during the 27 iterations. It is shown that the frequency error between the initial FE model and the experimental model was about 6% for Peak 1 and about 5% for Peak 2 at the beginning and gradually decreased to 0.3% for Peak 1 and 1.3% for Peak 2 at the 27th iteration (an average error of 0.8%).

The structural parameters of the FE model were identified as the numerical peak frequencies ($f_{1,\text{FEM}}$ and $f_{2,\text{FEM}}$) matched with the experimental ones ($f_{1,\text{Exp}}$ and $f_{2,\text{Exp}}$). After updating, we identified the parameters as: $t_b = 0.092$ mm, $E_b = 9.02$ GPa, and $k_z = 6.72 \times 10^{12}$. The changes in the three model-updating parameters during the fine-tuning process are shown in Figure 11. The updated parameters during the iteration were normalized with the values of the final iteration. As observed in the figure, the normalized values were large for earlier iterations and converged to unity at the 27th iteration. The bond thickness decreased by 54% while the bond elastic modulus and the contact stiffness increased by 201% and 124%, respectively.

The real and imaginary parts of the numerical EMI responses were compared with the experimental data in Figures 12(a) and 12(b), respectively. Although the peak frequencies of the FE model were consistent with those of the experimental model, there were certain differences in the resonant magnitudes between the two models. As compared to the 2nd resonance, the magnitude gap of the 1st resonance was more significant.

(2) Updating Peak Magnitudes. The magnitude of the resonant peaks presents the amount of mechanical damping in a system. To update the peak magnitudes, therefore, the mechanical damping parameters of the PZT patch were adjusted. Rayleigh damping, which is a common damping modeling method, was used to simulate the mechanical damping of the PZT patch [50]. For the implementation in COMSOL, the Rayleigh damping coefficients were

FIGURE 9: Modal sensitivities of the model-updating parameters.

FIGURE 10: Convergences of the two peak frequencies of the FE model.

FIGURE 11: Changes in the three model-updating parameters of the FE model.

represented by the damping ratios of Peak 1 (ζ_1) and Peak 2 (ζ_2), which can be identified as the numerical magnitudes of Peak 1 ($Z_{1,FEM}$) and Peak 2 ($Z_{2,FEM}$) match with the experimental magnitudes of Peak 1 ($Z_{1,exp}$) and Peak 2 ($Z_{2,exp}$).

Figure 13 shows the change in the peak magnitudes along with ζ_1 for different values of ζ_2 . It is noted that the peak magnitudes were normalized with the experimental ones for easy interpretation of the results. Expectedly, the peak magnitudes were decreased with an increase of ζ_1 . The magnitudes of the two peaks well converged to the unity in the case of $\zeta_2 = 0.01$; meanwhile, only the magnitude of Peak 1 converged in the cases of $\zeta_2 = 0.001$ and $\zeta_2 = 0.0001$. Therefore, the damping ratios of Peak 1 and

Peak 2 were identified as $\zeta_1 = 0.08$ and $\zeta_2 = 0.01$, respectively.

After updating the mechanical damping of the PZT patch, the real part and the imaginary part of the numerical EMI response were again compared with the experimental ones in Figures 14(a) and 14(b), respectively. It is observed that the magnitudes of the real EMI response obtained from the FE model well-agreed with the experimental data, see Figure 14(a). Although there are some differences in the magnitudes in a low-frequency range of 10–25 kHz, the pattern of the imaginary EMI response predicted by the FE model was identical with the experimental data, see Figure 14(b). The updating of the imaginary EMI response will be investigated in future work.

FIGURE 12: EMI responses after updating peak frequencies. (a) Real impedance. (b) Imaginary impedance.

FIGURE 13: Normalized peak magnitudes against ζ_1 for different values of ζ_2 .

FIGURE 14: EMI responses after updating peak magnitudes. (a) Real impedance. (b) Imaginary impedance.

4. EMI Response Characteristics of Degraded Smart Interface

The updated FE model was utilized to investigate the EMI response characteristics of the degraded smart interface. Four common degradation types, including shear lag effect, PZT debonding, PZT breakage, and interface detaching were numerically simulated in the FE model, from which the corresponding EMI signatures were obtained. Afterwards, the effect of the functional degradations on the EMI features is comprehensively analyzed.

4.1. EMI Response Characteristics under Shear Lag Effect.

The shear lag phenomenon was simulated by reducing the elastic modulus of the bonding layer (E_b) using the updated FE model. Figures 15(a) and 15(b) show the real and imaginary parts of the EMI responses for different values of the bond modulus: $1 \times E_b$ (healthy), $0.5 \times E_b$, $0.1 \times E_b$, $0.05 \times E_b$, $0.01 \times E_b$, $0.005 \times E_b$, and $0.001 \times E_b$. The EMI responses were significantly varied with the bond stiffness. Particularly, the severer the shear lag effect (i.e., the smaller the bond stiffness), the larger the downshift in the signature of the real and imaginary parts can be observed. The shifts in two resonant peaks are shown in Figures 15(c) and 15(d), respectively. The smaller the bond stiffness, the weaker the frequency coupling between the PZT patch and its host structure [51]. When the bond stiffness was too small, there were no force and strain transmissions from the PZT to the interface through the bonding layer (i.e., no coupling between the PZT and the interface) and therefore there was no contribution of the interface's mechanical impedance to the overall EMI (see equation (1)). As a result, two impedance peaks disappeared when the bond stiffness was below $0.005E_b$.

As key impedance features, the frequency and the magnitude of Peak 1 and Peak 2 were quantified under the shear lag effect. The magnitude and the frequency were normalized with those obtained from the healthy state (no shear lag). As observed in Figures 16(a) and 16(b), both the magnitude and the frequency of the two peaks experienced nonlinear reductions as the bond stiffness was decreased from $1 \times E_b$ to $0.005 \times E_b$. This changing trend has reinforced the previous observation on the shear lag effect [26], as discussed in the introduction part. The maximum frequency reduction was less than 8%. When the stiffness of the bonding layer was reduced, the coupling vibration between the PZT and the interface became weaker and the modal stiffness of the whole system was reduced, leading to reductions in peak frequencies (see Figure 16(a)) and peak magnitudes (see Figure 16(b)). It is observed that the reduction rate of the 2nd frequency was faster than that of the 1st frequency. This is because the sensitivity of the 2nd frequency to the bond modulus was higher than that of the 1st frequency, as revealed in Figure 10.

4.2. EMI Response Characteristics under PZT Debonding.

To simulate the PZT debonding defect, the size of the bonding layer was reduced in the FE model. In the intact

state, the bonding layer was filled over the bottom surface of the PZT patch (a intact bonding area of $25 \times 25 \text{ mm}^2$), as shown in Figure 17(a). Six debonding cases of the PZT were modeled, including two vertical debonding cases (V1 and V2), two horizontal debonding cases (H1 and H2), and two combined vertical and horizontal debonding cases (V1H1 and V2H2), as depicted in Figure 17(b). In the cases of V1 and V2 (or H1 and H2), the PZT patch was debonded from the interface with the severity of 10% (a remaining bonding area of $25 \times 22.5 \text{ mm}^2$) and 20% (a remaining bonding area of $25 \times 20 \text{ mm}^2$), respectively. In the cases of V1H1 and V2H2, the PZT was debonded by 19% (a remaining bonding area of $22.5 \times 22.5 \text{ mm}^2$) and 36% (a remaining bonding area of $20 \times 20 \text{ mm}^2$), respectively.

The real and imaginary parts of the EMI response corresponding to the intact state and the six debonding cases are presented in Figures 18(a) and 18(b), respectively. As observed from the figures, the PZT debonding caused significant changes in the EMI response. Several new peaks with weak magnitudes appeared in the frequency ranges of 35–45 kHz; they could have resulted from the asymmetric PZT excitation due to the debonding defect. As the PZT patch was debonded, the piezoelectric force acting on the smart interface was not at the middle; thus, additional vibration modes of the interface were initiated.

Similar to the shear lag effect, the PZT debonding caused downshifts in both real and imaginary parts of the EMI response, as observed in Figures 18(b)–18(d). When the PZT patch was partially debonded from the smart interface, the force transmission from the PZT patch to the interface was reduced, leading to weaker coupling vibrations between the PZT patch and the interface. As a result, the resonant magnitude of the EMI response was decreased, as observed in Figure 19. Two impedance peaks showed different changes in the magnitude; Peak 2 generally showed a more significant change than Peak 1. As compared to other cases, the cases of V1H1 and V2H2 showed larger magnitude variations due to higher debonding severities. As observed in Figure 20, the PZT debonding defect caused slight changes in the peak frequencies with no apparent trend. The frequency change was less than 2.5% for all simulated cases.

4.3. EMI Response Characteristics under PZT Breakage.

To simulate the PZT breakage, the size of the PZT was reduced in the FE model. In the intact state, the size of the PZT remains as $25 \times 25 \text{ mm}^2$, as depicted in Figure 21(a). Six PZT breakage cases were simulated, as described in Figure 21(b). In breakage cases of V1 and V2 (or H1 and H2), the PZT patch was assumed to be vertically fractured by 10% (a remaining area of $25 \times 22.5 \text{ mm}^2$) and 20% (a remaining area of $25 \times 20 \text{ mm}^2$), respectively. In the cases of V1H1 and V2H2, the PZT was fractured in both directions with the severity of 19% (a remaining area of $22.5 \times 22.5 \text{ mm}^2$) and 36% (a remaining area of $20 \times 20 \text{ mm}^2$), respectively.

Figures 22(a) and 22(b) show the real and imaginary parts of the numerical EMI response, respectively. It is shown that the PZT breakage caused significant variations in

FIGURE 15: Numerical EMI responses under the shear lag effect. (a) Real part. (b) Imaginary part. (c) Peak 1. (d) Peak 2.

FIGURE 16: Shifts in resonant peaks caused by the shear lag effect. (a) Normalized magnitude. (b) Normalized frequency.

FIGURE 17: Simulation of PZT debonding cases for the smart interface. (a) Intact. (b) Debonding cases: V1, V2, H1, H2, V1H1, V2H2.

FIGURE 18: Numerical EMI responses under PZT debonding defects. (a) Real part. (b) Imaginary part. (c) Peak 1. (d) Peak 2.

FIGURE 19: Shifts in peak magnitudes caused by PZT debonding defects. (a) Cases: V1, V2. (b) Cases: H1, H2. (c) Cases: V1H1, V2H2.

FIGURE 20: Shifts in peak frequencies caused by PZT debonding defects. (a) Cases: V1, V2. (b) Cases: H1, H2. (c) Cases: V1H1, V2H2.

FIGURE 21: Simulation of PZT breakage cases for the smart interface. (a) Intact. (b) Breakage cases: V1, V2, H1, H2, V1H1, V2H2.

the EMI response. As seen in Figure 22(a), additional peaks appeared in the frequency range of 37–44 kHz. Due to the breakage of the PZT, the piezoelectric excitation acting on

the interface was asymmetric, thus, more vibrational modes of the smart interface could be initiated. In contrast with the defects of the bonding layer (shear lag/debonding), the PZT

FIGURE 22: Numerical EMI responses under PZT breakage defects. (a) Real part. (b) Imaginary part. (c) Peak 1 (Cases: V1H1, V2H2). (d) Peak 2 (Cases: V1H1, V2H2).

breakage caused upward shifts in the imaginary part of the EMI signatures, as observed in Figure 22(b). The PZT breakage also induced upward shifts in the EMI peaks, as seen in Figures 22(c) and 22(d).

The changes in the magnitudes of Peak 1 and Peak 2 were quantified concerning the breakage direction of the PZT, as shown in Figure 23. In contrast with the bonding defects, the peak magnitude was increased with the breakage severity and Peak 1 showed a higher magnitude change than Peak 2. When the PZT was broken, its capacitance was reduced, leading to an increased magnitude of the EMI response, as interpreted by equation (1). Figure 24 reveals that the PZT breakage only caused minor changes in the two peak frequencies, less than 2% for all considered cases. It is observed that the changing trend of the two frequencies was the opposite. Because the piezoelectric patch has its own stiffness and mass, the PZT breakage can lead to mass and stiffness reductions in the system. Due to the nature of the two

vibration modes, the effect of the mass reduction could be more significant on the frequency of Peak 1 while the stiffness reduction could cause a larger impact on the frequency of Peak 2. As a result, the frequency of Peak 1 experienced an increase and Peak 2 showed a decrease with the breakage severity, as seen in Figure 24.

4.4. EMI Response Characteristics under Interface Detaching

4.4.1. Characterization of EMI Response. The bonding layer of the interface was removed to simulate the effect of interface detaching. It is supposed that the interface was detached from the splice plate at the left bonded section. In the intact state, the interface was perfectly attached to the splice plate with two bonding layers of $35 \times 33 \text{ mm}^2$, as shown in Figure 25(a). Six interface detaching cases were modeled, including two vertical detaching cases (V1 and V2), two

FIGURE 23: Shifts in peak magnitudes caused by PZT breakage defects. (a) Cases: V1, V2. (b) Cases: H1, H2. (c) Cases: V1H1, V2H2.

FIGURE 24: Shifts in peak frequencies caused by PZT breakage defects. (a) Cases: V1, V2. (b) Cases: H1, H2. (c) Cases: V1H1, V2H2.

FIGURE 25: Shifts in peak frequencies caused by PZT breakage defects. (a) Cases: V1, V2. (b) Cases: H1, H2. (c) Cases: V1H1, V2H2.

horizontal detaching cases (H1 and H2), and two combined vertical and horizontal detaching cases (V1H1 and V2H2), as illustrated in Figure 25(b). In the cases of V1 and V2, the interface was detached by 23% (a remaining bonding area of $27 \times 33 \text{ mm}^2$) and 46% (a remaining bonding area of $19 \times 33 \text{ mm}^2$), respectively. In the cases of H1 and H2, the interface was detached by 20% (a remaining bonding area of $35 \times 26.4 \text{ mm}^2$) and 40% (a remaining bonding area of $35 \times 19.8 \text{ mm}^2$), respectively. In the cases of V1H1 and V2H2, the interface was detached by 38% (a remaining bonding area of $27 \times 26.4 \text{ mm}^2$) and 67% (a remaining bonding area of $19 \times 19.8 \text{ mm}^2$), respectively.

Figure 26(a) shows the real part of the EMI responses under the six detaching cases of the interface. It was observed that the defect caused significant shifts in the two impedance peaks. When the interface is detached from the splice plate, its mechanical impedance was changed, resulting in the variation in the real part of the EMI responses. The significant variations of the impedance peaks were also observed in the imaginary part of the EMI signatures, as plotted in Figure 26(b). It was found that the interface detaching did not modify the curve pattern of the imaginary part. Interestingly, many new peaks with strong magnitudes appeared in addition to two primary peaks (i.e., Peak 1 and Peak 2) in the frequency ranges of 10–55 kHz. The change in the boundary condition of the interface was the reason for the appearance of the new peaks. As the interface was detached, the shape and dimension of the deformable section were changed, resulting in new vibrational modes under the piezoelectric excitation.

As observed in Figure 27, the magnitudes of Peak 1 and Peak 2 experienced significant changes due to the interface detaching. The magnitude change can be up to 43% in the case of V2H2; however, no apparent trend can be observed. As shown in Figure 28, the interface detaching caused significant reductions in the peak frequencies. The frequency shift can be up to 52% in the case of V2H2. The impact of the interface detaching on the frequency of Peak 1 was larger than Peak 2. This is due to the nature of the bending motion of the two vibration modes. Peak 1 has a longitudinal bending motion and thus its resonant frequency could be significantly influenced by the width of the flexible section. Meanwhile, Peak 2 is a lateral bending mode, the frequency of which could be mainly determined by the height of the flexible section. When the interface was vertically detached from the splice plate, the width of the flexible section was mostly changed. Therefore, Peak 1 showed a more significant change in the frequency than Peak 2 in the cases of V1, V2, V1H1, and V2H2.

4.4.2. Modal Shapes of New Impedance Peaks. To comprehensively analyze the changes in the vibration modes due to the detaching of the smart interface, the modal shapes of the impedance peaks were analyzed for three cases: V2, H2, and V2H2.

In the case of V2, the detaching of the interface led to the appearance of two new peaks (i.e., NP1 at 22.65 kHz and NP2 at 42.5 kHz) besides the primary peaks (i.e., Peak 1 at 8.85 kHz and Peak 2 at 28.45 kHz), as shown in Figure 29(a).

The modal shapes of the new peaks (i.e., NP1 and NP2) were relatively complicated; those were combined longitudinal and lateral bending motions with the contribution of the bending motions of the debonded part. When the interface was vertically detached, its deformable section remained as a rectangular shape, and thus the modal shapes of Peak 1 and Peak 2 remained as the longitudinal bending motion and the lateral bending motion, respectively.

Regarding the case of H2, four new peaks appeared at 18.6 kHz (NP1), 24.5 kHz (NP2), 34.4 kHz (NP3), and 35.5 kHz (NP4) besides the primary peaks at 16.8 kHz (Peak 1) and 33.05 kHz (Peak 2), as shown in Figure 29(b). Due to the horizontal debonding of the interface, the deformable section of the interface was expanded through the bonded part; therefore, the modal shapes of Peak 1 and Peak 2 were modified with added bending motions of the debonded part, as shown in Figure 29(b). The modal shapes of the new peaks (i.e., NP1–NP4) were also complex with lateral bending combined with longitudinal bending of the debonded part.

Concerning the case of V2H2, five new peaks were observed, including NP1 at 11.05 kHz (NP1), 16.7 kHz (NP2), 21.4 kHz (NP3), 33.4 kHz (NP4), and 42.4 kHz (NP5) in addition to the primary peaks at 8.1 kHz (Peak 1) and 28.2 kHz (Peak 2), as shown in Figure 29(c). The modal shapes of Peak 1 and Peak 2 were changed with additional bendings of the debonded part. The modal shapes of the new peaks (i.e., NP1–NP5) were lateral bending combined with longitudinal/lateral bending of the debonded part.

4.5. EMI Response Characteristics under Structural Damage. For comparison, the effect of the structural damage on the EMI response was also analyzed. To simulate the structural damage, the elastic modulus of the splice plate E_{splice} (i.e., the host structure) was reduced. Four cases of the elastic modulus were simulated, including $1 \times E_{\text{splice}}$ (healthy), $0.8 \times E_{\text{splice}}$, $0.6 \times E_{\text{splice}}$, $0.4 \times E_{\text{splice}}$. The real and the imaginary parts of the EMI response showed slight variations due to the stiffness reduction, as shown in Figures 30(a) and 30(b), respectively. The two impedance peaks shifted left according to the damage severity, as observed in Figure 30(c) and 30(d).

The changes in the peak frequencies and the peak magnitudes were also quantified. Figure 31(a) revealed that the magnitude of the impedance peaks experienced ignorable changes due to the structural damage. This is because the modal damping of the system remained almost unchanged. Expectedly, the frequency of the two peaks exhibited slight decreases with the stiffness reduction, as seen in Figure 31(b). Interestingly, it is found that the curve pattern of the imaginary part of the EMI response was unchanged due to the structural damage.

5. Distinctive EMI Features under PZT Interface's Degradation and Structural Damage

From the EMI response characteristics of a degraded smart interface, it is found that the imaginary part has three distinguishable changing patterns, including (1) upward

FIGURE 26: Numerical EMI signatures under interface debonding defects. (a) Real part. (b) Imaginary part.

FIGURE 27: Shifts in peak magnitudes due to interface detaching defects. (a) Cases: V1, V2. (b) Cases: H1, H2. (c) Cases: V1H1, V2H2.

FIGURE 28: Shifts in peak frequencies due to interface detaching defects. (a) Cases: V1, V2. (b) Cases: H1, H2. (c) Cases: V1H1, V2H2.

FIGURE 29: Modal shapes of the impedance peaks for the cases of interface detaching. (a) Case: V2. (b) Case: H2. (c) Case: V2H2.

shifts caused by the PZT's bonding defect (e.g., shear lag and debonding); (2) downward shifts due to the PZT breakage, and (3) no shifts in the cases of interface detaching/structural damage. Therefore, the imaginary part is a potential indicator for the assessment of the functional degradation in the smart interface.

The inverse of the imaginary part of the EMI response (i.e., the imaginary admittance) was computed, as plotted in Figure 31. It can be summarized that: (1) the slope β of the imaginary admittance will increase if the bonding layer of the PZT experiences a quality degradation (e.g., debonding or shear lag); (2) the slope β will decrease if the PZT is damaged (e.g., breakage); (3) the slope β remains unchanged if the interface is detached or the host structure is damaged. It is also observed that when the smart interface is detached from the host structure, the frequency of the two impedance peaks can significantly be reduced and new strong resonances can appear. Meanwhile, the two peak frequencies experience only ignorable changes if the PZT patch or its bonding layer is damaged. The above

observations have verified the proposed diagnosis process in Figure 3.

6. Summary and Conclusion

In this study, we numerically investigated the EMI response characteristics of a degraded smart interface. A diagnosis process of the degraded smart interface was proposed to differentiate the typical defects from the occurrence of structural damage. Different defect types, including shear lag effect, transducer debonding, transducer breakage, and interface detaching, which are not easy to control through the experiment, were simulated using a predictive FE modeling strategy. The effect of the defects on the EMI response was quantified and explained.

From a theoretical aspect, the main contribution of this study lies in providing a comprehensive insight into the effect of the functional defects on the EMI response, with a particular focus on the damaged smart interface. The key results can be summarized, as follows:

FIGURE 30: Numerical EMI signatures under structural damage. (a) Real part. (b) Imaginary part. (c) Peak 1. (d) Peak 2.

FIGURE 31: Shifts in peak magnitude and peak frequency due to structural damage. (a) Peak magnitude. (b) Peak frequency.

- (1) The two peaks of the smart interface experienced nonlinear reductions in the frequency and magnitude under the shear lag effect. The reduction rate of Peak 2 was larger than Peak 1 with a maximum frequency shift of 8%. It is numerically demonstrated that the impedance peaks can disappear when the bonding layer is significantly degraded.
- (2) The transducer debonding generally caused similar effects on the shift of the EMI response of the degraded smart interface. However, the variation in the peak frequencies was ignorable and had no clear trend. The frequency shift was less than 2.5% when the PZT patch was debonded by 36%.
- (3) The transducer breakage also caused minor changes in the two peak frequencies. The frequency shift was less than 2% for the breakage case of 36%. It is found that the changing trend of the two peak frequencies was contrasted. The frequency of Peak 1 experienced an increase with the breakage while that of Peak 2 showed the opposite.
- (4) The interface detaching defect caused significant reductions in the frequencies of two peaks as compared to other defects. The frequency shift can be up to 52% when the smart interface was detached by 67% at a bonded section. Furthermore, strong resonance peaks with complex modal shapes appeared in addition to the two primary peaks. Interestingly, the modal shapes of Peak 1 and Peak 2 were altered with additional bending motions of the debonded part.

From a practical aspect, this study is expected to provide a practical guideline to diagnose the functional degradations of the smart interface during damage identification processes. It is found that the defects that occurred in the smart interface can result in unique shifts in the imaginary admittance and they can be feasibly diagnosed and differentiated from the structural damage through a diagnosis process.

Future studies remain (1) to consider the piezoelectric parameters in model-updating for more accurately reproducing the experimental EMI response; (2) to extract the mechanical impedance of the structure from the EMI response for damage detection; and (3) to examine the feasibility of the proposed diagnosis process of the degraded smart interface.

Data Availability

The data are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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