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Depolarization diagnosis of PWAS used for EMI based structural health monitoring system for composite plates

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Abstract: Implementation of Electromechanical Impedance (EMI) as a technique to carry out Structural Health Monitoring (SHM) has been proved to be such effective tool in the last two decades, especially for structures made of composite material. EMI technique is the revolutionary evolution of the conventional Vibrational Based Damage Identification (VBDI) techniques. Unlike VBDI techniques, EMI technique has the privilege of employment tinny permanent piece of equipment which is known as Piezoelectric Wafer Active Sensor (PWAS). Although it has such advantage, it brings the necessity of continuous and robust diagnosis process of the PWAS used in the SHM system to ensure that output signals are caused by real variation of the modal parameters for the host structure rather than being occurred due to degradation and-or physical damage of the PWAS system itself. The study presented in this paper is focused on the self-diagnosis of PWAS used to carry out SHM via implementation of EMI technique. The main concern of this research is to study the ability of EMI technique to determine depolarization of PWAS and its influence on the performance of EMI based SHM system employed for structures made of composite plates. The used specimen (s) is / are underwent controlled excitation over desired frequency range, the imaginary part of admittance is plotted over desired frequency range. The whole process is then repeated for different levels of depolarization for the same specimen (s). The modeling process is carried out using a finite element commercial package, ANSYS v.15.0 in which multi-physics-based modeling can be used for such coupling field of piezoelectricity. MATLAB code is written to process the output data received from numerical simulations into counterpart spectrum and to calculate the statistical damage index Root Mean Square deviation (RMSD) that is used in damage detection. The calculated RMSD found to be non-zero values, which means false prediction. These results shows how important to have self-diagnosis for PAWS used in SHM system for further reliable measurements and data interrogation using EMI technique.

Keywords: Structural Health Monitoring – Electromechanical Impedance – Piezoelectric waver active sensor – Depolarization – Finite element modeling – composite plates.

Nomenclature

$[c^E]$	Piezoelectric material stiffness matrix at fixed field
$\{D\}$	Electric displacement
$[d]$	Piezoelectric constant strain matrix

d_{31}	Piezo electric constant in C/N
$\{E\}$	Electric field vector
E_1, E_2, E_3	Young's moduli in directions x,y, and z
$[e]$	Piezoelectric constant stress matrix
G_{13}, G_{12}, G_{23}	Shear moduli
K	Wave number
l_a	PWAS/Actuator length
$\{S\}$	Strain vector
$[s^E]$	Elastic compliance coefficient matrix at fixed field
$\{T\}$	Stress vector
t_a	PWAS/Actuator thickness
w_a	PWAS/Actuator width
$Y(\omega)$	Admittance
$\hat{Y}_P^E$	PWAS complex young modulus at constant field
Z_i^o	The impedance of the PWAS measured at healthy conditions
Z_i	The impedance of the PWAS after measured damage occurre
$Za\ (\omega)$	Actuator mechanical impedance
$Zs\ (\omega)$	Structure mechanical impedance
$Z(\omega)$	Electro mechanical impedance
$[\varepsilon^S]$	Permittivity at fixed strain in F/m
$[\varepsilon^T]$	Permittivity at fixed stress in F/m
$\hat{\varepsilon}_{33}^T$	Complex dielectric permittivity component in z direction
ν	Poisson ratio
Y	Admittance
ρ	Mass density
ω	Angular frequency

1. Introduction

Structural Health Monitoring (SHM) using electro-mechanical impedance (EMI) method has implied a new wide perspective rather than conventional mechanical impedance concepts. This achieved by 'tiny' wafer piezoelectric active sensors (PWAS) mounted permanently to the monitored structure. The coupling exhibited by piezoelectricity between mechanical variables and electrical variables was introduced by Tzou and Tseng [1] via plane formulas which were generalized by Ikeda[2, 3] in main forms of 3D piezoelectric constitutive equations. Equations (1) and (2) are the most used formulas in the piezoelectric analysis

$$\begin{bmatrix} \{T\} \\ \{D\} \end{bmatrix} = \begin{bmatrix} [c^E] & -[e]^T \\ [e] & [\varepsilon^S] \end{bmatrix} \begin{bmatrix} \{S\} \\ \{E\} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \{S\} \\ \{D\} \end{bmatrix} = \begin{bmatrix} [s^E] & -[d]^T \\ [d] & [\varepsilon^T] \end{bmatrix} \begin{bmatrix} \{T\} \\ \{E\} \end{bmatrix} \tag{2}$$

Very small permanent (surface attached / embedded) patch that has the ability to produce sufficient excitation force ranges from few KHz's to several hundreds of KHz's instead of using heavy expensive temporal equipment, as well as the magnificent ability to sense at the same time as excitation action is going on, avoiding the non-stationary problems in measurements. The availability of wide frequency range enables damage detection as the contribution of the first lower few natural modes in the strain energy have a great influence on damage identification Amin[4]. Also, the advantage of decreased cost of PWAS's gives the possibility of minimizing the distances between the attached PWAS's. As far as the sensing area can be close to the PWAS source it would be very beneficial to detect the damage existence as well as its location, Salem [5].

Furthermore, the post-sensing process in the EMI technique is much easier; it can be almost done directly, whereas in the mechanical impedance method, post-processing of separately measured force and acceleration or velocity data are required. This advantage was shown by Liang et al [4] mathematical 1-D model introduced in Equation (3).

$$Y(\omega) = j\omega \frac{w_a l_a}{t_a} \left(\hat{\varepsilon}_{33}^T - {d_{31}}^2 \hat{Y}_P^E + \frac{Za(\omega)}{Za(\omega)+Zs(\omega)} \times {d_{31}}^2 \hat{Y}_P^E \left(\frac{\tan kl_a}{kl_a} \right) \right) \tag{3}$$

where

$$Z(\omega) = 1/Y(\omega) \tag{4}$$

Many other mathematical models were introduced to describe some of the 2-D limited geometrical configuration models, among them, those that are introduced by Giurgiutiu, and Zagrai [5] and Bhalla [6].

In addition to the above mentioned advantages, the EMI has the capability of capturing a wide range of structural damage from incipient damage [7] to severe one, feasibility of inspection during structure service, ease of implementation into an in-situ automated SHM system, and minimization of inspection time and effort as well as required expertise to operate SHM systems using such technique.

2. Difficulties associated with EMI techniques

Although such revolutionary potential capabilities offered by EMI technique, the application of such tiny permanent PAWS faces some challenges to maintain the whole SHM process reliability and integrity, rejecting incompetence due to any hardware component failure of the SHM system.

The EMI-based SHM systems employed for structures made of composite plates [8] are subjected to dramatic operating conditions which widely varied from simple weather effects to harsh environmental and sever operational conditions. Subsequent degradation in the PWAS reliability is considered as one of the major threats in active in SHM system. There are two possible PWAS destructive forms that may affect and influence its performance in damage detection. The first is the direct mass losses of the PWAS due to any hard impact that causes the loss of some part [9]. The second is the degradation of PWAS 'coupling' properties or what is called depolarization. The last takes place either due to normal aging or due to extensive operational conditions which involve temperature, exceeding power limitation, or hard mechanical stresses.

Park et al [9, 10] denoted that PWAS defects due to direct breakage or piezoelectric properties degradation, can be caught directly through continuous observation of the imaginary part of the admittance $Y(\omega)$. This can be achieved throughout direct compensation in the equation (3), either by decreasing the geometrical dimensions (w_a,l_a, t_a) just as breakage case, or by decreasing electrical properties ($\hat{\varepsilon}^T_{33}$, d_{31}) as degradation case. Both cases show downward shift in the slope of imaginary part of admittance spectrum. Figure 1. illustrates the study offered by Park et al [10] based on experimental comparison between free and surface-bonded PAWS showing upward shift in the base line of the admittance imaginary part spectrum due to adhesive degradation, this result found to be consentient with that obtained numerically by Salem[7] as shown in Figure 2.

Park et al [9] followed a well-known method to reduce the coupling effect of PZT material as he conducted a series of laboratory experiments in which mechanical impacts are applied on surface mounted PWAS. This approach is followed aiming to investigate the depolarization effect of PWAS on imaginary admittance spectrum [10]. The followed mechanical impact methodology affected the coupling capability of the PWAS material as well as the bonding layer. Consequently, the acquired results cannot be solely attributed to the depolarization effect only as the accompanied de-bonding and the possible fracture of the PWAS shared the influence on imaginary admittance spectrum.

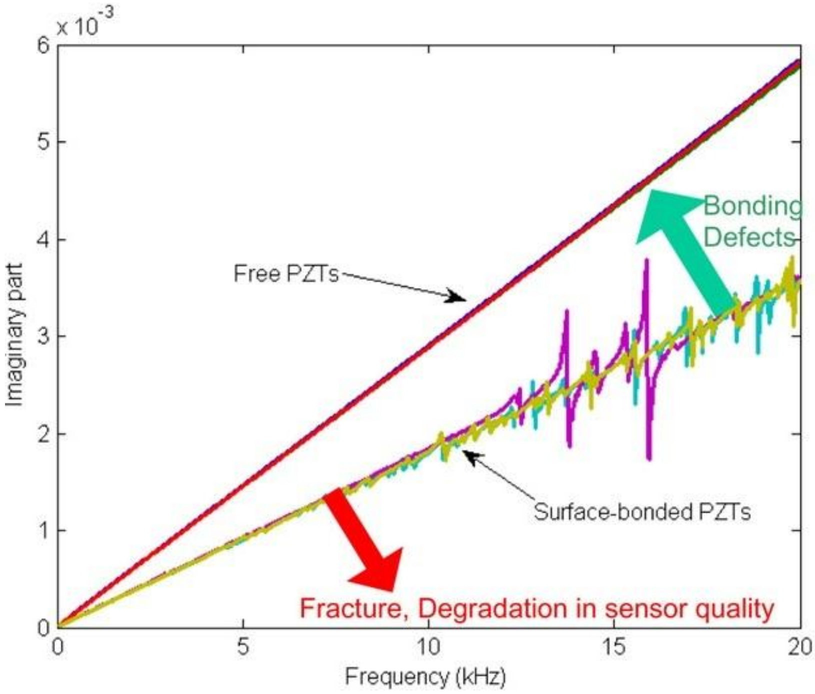


Figure 1. Electrical admittance measurement from PZT patches under free and surface-bonded conditions by Park et al [10].

Gresil et al [11], used 2D numerical model to simulate breakage of 1 mm from PWAS Figure 3. which introduces obvious downward shift in the imaginary part of the admittance received from defected PWAS rather than spectrum of the non-damaged PWAS .Nevertheless Chang [12] studied the effect of adhesive degradation under cyclic fatigue load, experimentally and numerically, the results show the behavior of real part of impedance spectrum due degradation of adhesive layer subjected to ascending cyclic fatigue load that increases the percentage of degradation as shown in Figure 4.

With reference to the above mentioned researches, the efforts to simulate the degradation of PWAS piezoelectric properties localized around, the plane analytical approach, that are limited to simple geometry models such as beams and isotropic materials [5, 13, 14]; or experimental implementations such as [8, 9, 12].

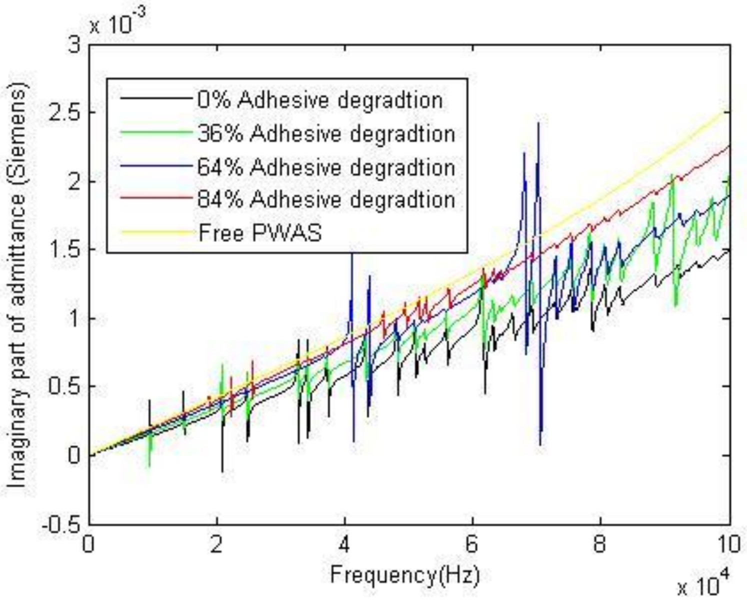


Figure 2. Numerical model results for degradation of adhesive layer, after Salem [7].

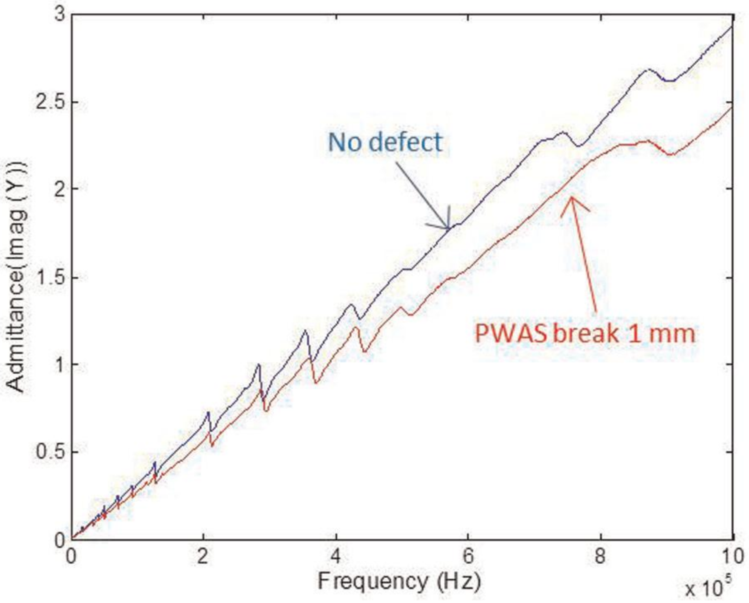
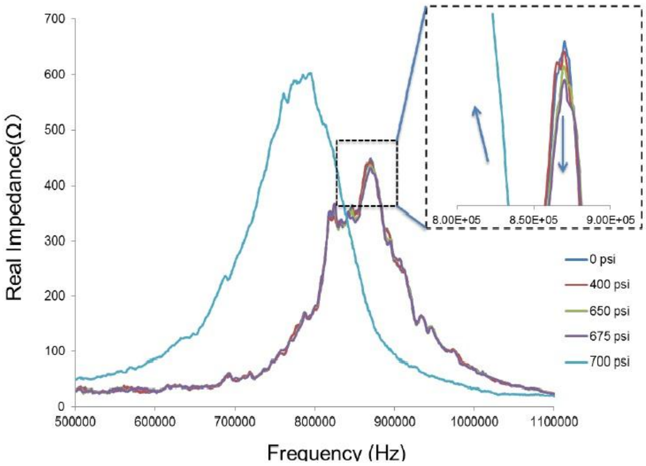
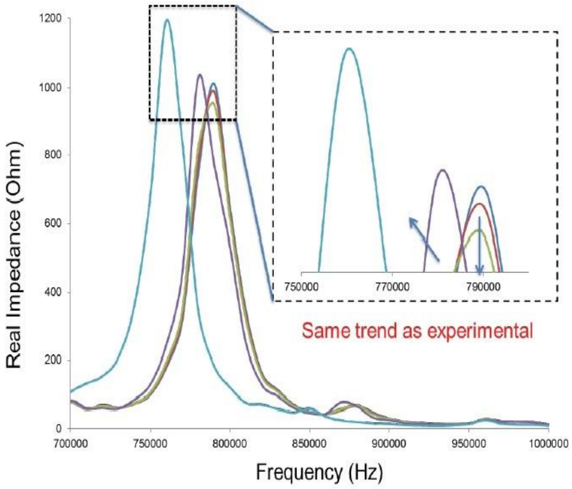


Figure 3. Gresil numerical model results for breakage of PWAS[11].

Consequently, the main objective of the approach proposed in the current research is to study the ability of EMI technique to determine depolarization of PWAS and its influence on the performance of EMI based SHM systems employed for structures made of composite plates. This issue has been handled during the current research using FEM commercial software ANSYS that has coupled features capabilities in which multi-physics-based modeling is presented to achieve effective solutions to analytical limitations. ANSYS numerical model of SHM system was validated effectively by Gresil [11] ,Salem[7], and Chang[12].



(a) Experimentally



(b) Numerically

Figure 4. Study for effect of adhesive degradation under cyclic fatigue load, after Chang [12].

3. Mathematical analysis of the piezoelectric constitutive equations

Mathematical decomposition of Equations (1) and (2) gives the following mathematical expression for the related physical matrices.

$$[S] = [s^E][T] + [d][E] \tag{5}$$

$$[T] = [c^E][S] - [e][E] \tag{6}$$

$$[D] = [d][T] + [\varepsilon^T][E] \tag{7}$$

$$[D] = [e][S] + [\varepsilon^T][E] \tag{8}$$

Considering Equations (5) and (6), it is noticed that the coupling capability of piezoelectric materials is introduced in the second term of the right-hand side of both equations. The main parameters in these two terms are [e] and [d] which are defined as piezoelectric stress and strain matrices respectively. Decreasing the values of those parameters will reduce the interference of electric field (E) in these (strain – stress) equations, subsequently reducing coupling efficiency of PWAS.

If (e/d) are further reduced to zero value, Equations (5), and (6) would be just ordinary (strain-stress) equations without any coupling capabilities. Similarly if (e/d) are decreased in Equations (7) and (8), the coupling effect of (stress- strain) would be reduced until these formulas became just ordinary permittivity equations (in case of e/d =0), based on Ikeda [3], the following mathematical expression for the piezoelectric constant stress matrix.

$$[e] = [d][c] \tag{9}$$

Equation (9) explains the linear relationship between $[e]$ and $[d]$ matrices, from which it can be concluded that any variation may happen to any of both constant matrices, will cause a correspondent variation to the other constant matrix.

4. Numerical simulations studies

Numerical simulation studies are planned and carried out to investigate the influence of the degradation of the coupling capability of piezoelectric materials.

The influence of [e] and [d] matrices on the coupling capability of piezoelectric materials is employed to study the effect of losing the piezoelectric significant coupling of PWAS due to any of the factors introduced earlier. In which, the degradation of PWAS coupling capabilities is numerically simulated by reducing the numerical value of matrix [e] gradually by (10%, 20%, 40%, and 80%) of its original value.

Harmonic analysis has been performed for healthy PWAS as well as each of the four numerically depolarized PAWS's (10%, 20%, 40%, and 80%). This analysis was performed using a load of 1 volt on the terminal of PWAS over frequency range from 0 to 400 KHz. The thickness of adhesive layer simulation is neglected for feasibility. MATLAB code is developed and used to process the output data received from numerical analysis that is carried out using ANSYS into counterpart frequency based spectrum.

4.1. Finite element model for PAWS

The proposed PWAS assigned for the current parametric study made of APC850 material with characteristics illustrated in Table 1. in accordance with the American Piezoelectric Ceramics APC [15]. The PWAS is modeled using element (SOLID5) cubic coupled element that has eight nodes as shown in Figure 5. The element node has 6 DOFs (thermal, magnetic, and electric DOFs in addition to translations in the nodal x, y, and z directions). In the current study, only 4 DOFs / node are assigned, which are electric DOFs in addition to translations in the nodal x, y, and z directions [16].

To study the ability of EMI technique to determine depolarization of PWAS and its influence on the performance of EMI based SHM systems employed for structures made of composite plates.

4.2. Finite element model for test article

A 100×100×3 mm plat made of composite material is assigned as the proposed monitored host structure test article, shown in Figure 6. The plate is composed of six layers of Epoxy_Carbon_Woven_395GPa_Preprege $[0]_s$ whose mechanical properties are illustrated in Table 2. The composite plate layers are modeled using element (SHELL181) element that has eight nodes as shown in Figure 7., each node has 6 DOFs (three translations and three rotations) [16]. The boundary conditions are considered as fully fixed along the four edges. The plate is simulated as healthy plate in all parametric studies.

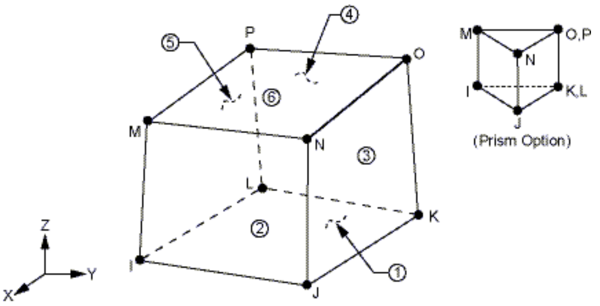


Figure 5. SOILD5 element.

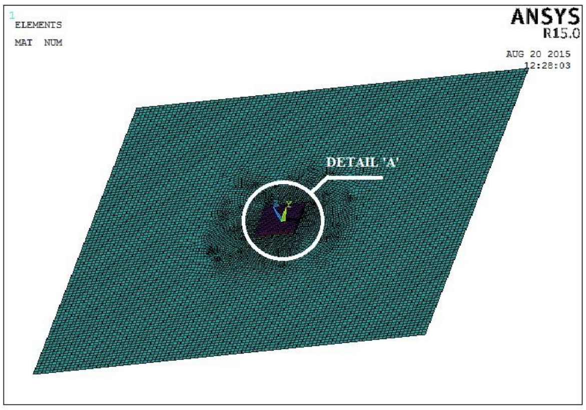


Figure 6. Proposed mesh test article with PWAS [detail (A)) in the center].

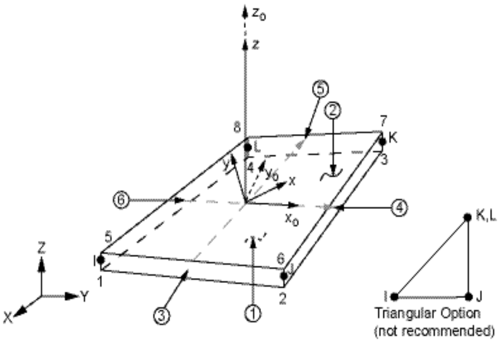


Figure 7. (SHELL181) element.

5. Results and analysis

Five parametric studies were carried out to investigate the effect of depolarization of the PAWS's on its performance for healthy plate structure. Figure 8. shows the relevant impedance real part spectrums for each degraded case study compared to the healthy one. The results demonstrate obviously the sever effect of PZT depolarization on the received EMI offered by sensors and subsequently on the proceeded data.

Among the successful mathematical algorithms used to identify damage in structures made of composite materials is the statistical damage index Root Mean Square deviation (RMSD), Salem [7], expressed by equation (10). The RMSD for the healthy plate with healthy PAWS is found to be (0%). The RMSD is implemented to the acquired results in the current research due to change in piezoelectric capabilities gave the indices (4.4%, 9.6%, 26.4%, and 85.5%) respectively for each degraded case of study for the shown frequency interval in Figure 8. Those results can be introduced as structural potential damage of ascending severity in any SHM system algorithm; meanwhile the integrity of the SHM system itself is compromised leading to false conclusion about the structural integrity of monitored specimen.

$$\mathrm{RMSD}\,\% = \sqrt{\frac{\sum[\mathrm{Re}(Z_i)-\mathrm{Re}(Z_i^o)]^2}{\sum[\mathrm{Re}(Z_i^o)]^2}} \times 100 \tag{10}$$

Studying the imaginary part of admittance for each case of degradation percentages in comparison to the healthy state shows dramatic downward shifting in the slope of base line of imaginary part plot as the [e] matrix values are reduced as stated earlier. The change in the slope was (11%, 19%, 35%, and 53%) respectively for each case of [e] matrix degradation as shown in Figure 9. The downward shift of the admittance imaginary spectrum obtained in this study is clear to be matching with analytical analysis conducted by park [9, 10].

Table 1. Properties of APC850 material

Properties	APC850
E_1, E_2	63.24 GPa
E_3	54.00 GPa
G_{13}, G_{23}	22.00 GPa
G_{12}	24.00 GPa
ν_{13} , ν_{23}	0.41
ν_{12}	0.3
ρ	7600 kg/cm^3
ε_{11}^s	0.968e-8 F/m
ε_{33}^s	0.668e-8 F/m
e_{31}	-8.02 C/m^2
e_{33}	18.31 C/ m^2
e_{15}	12.84 C/ m^2

Table 2. Mechanical Properties of Epoxy_Carbon_Woven_395GPa_Preprege

Properties	Epoxy_Carbon_Woven_395GPa_Preprege
E_1, E_2	91.82 GPa
E_3	9.00 GPa
G_{13}, G_{23}	3.00 GPa
G_{12}	19.5 GPa
ν_{13} , ν_{23}	0.3
ν_{12}	0.05
ρ	1480 kg/cm^3

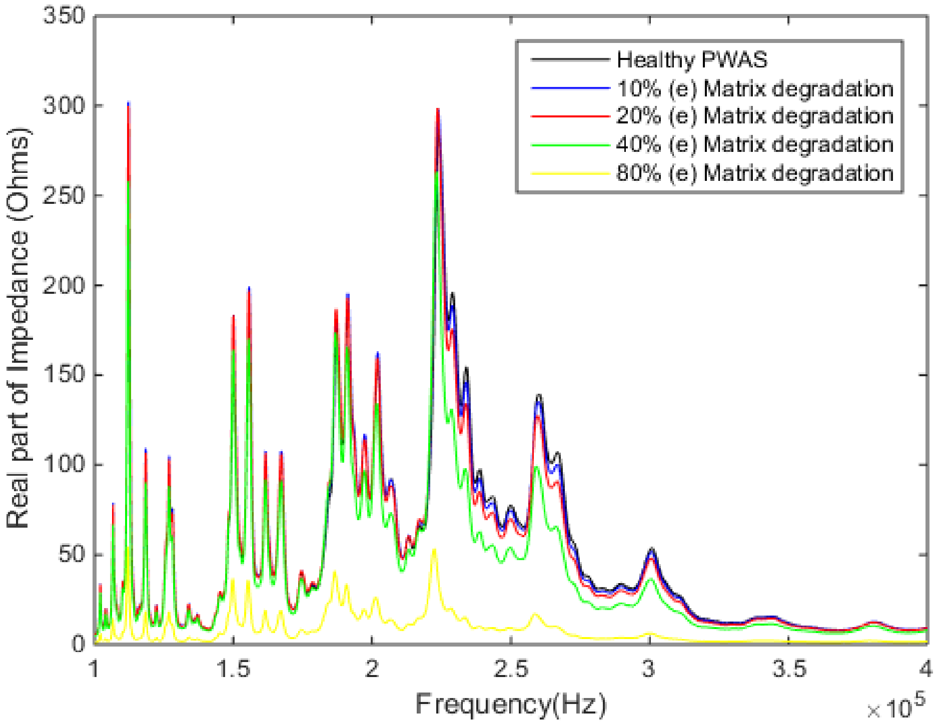


Figure 8. Real part of impedance vs. frequency for degradation of piezoelectric capabilities.

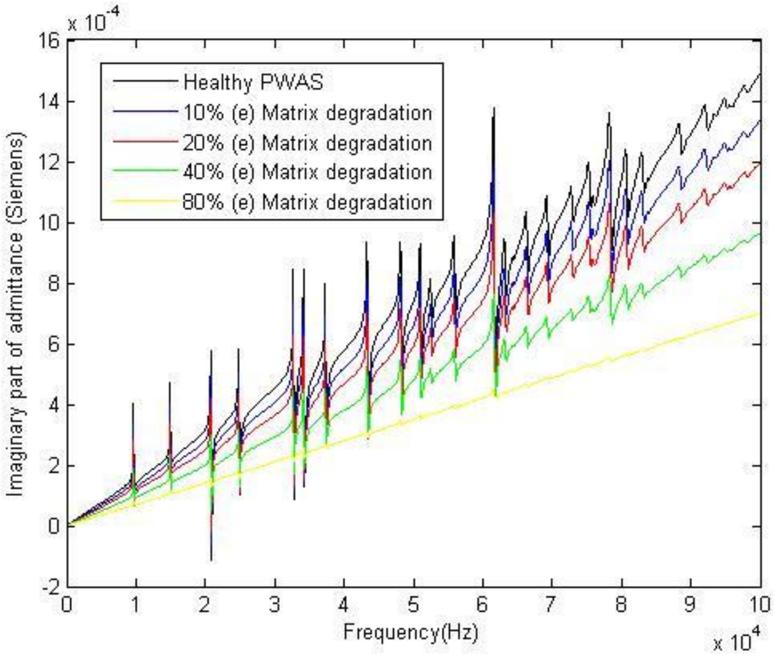


Figure 9. Imaginary part of admittance vs. frequency for degradation of piezoelectric capabilities.

6. Conclusion

Degradation of the coupling capability of piezoelectric material itself by percentages of (10%, 20%, 40%, and 80%) of its original capacity was studied simulating depolarization stages of functional PWAS. The acquired deteriorated EMI may lead to false predictions about integrity of the monitored composite plate structure, as the calculated RMSD indices found to be (4.4%, 9.6%, 26.4%, and 85.5%) respectively compared to (0%) for the healthy PAWS and healthy plate structure. Also, the base line of imaginary part of admittance spectrum was shifted downward with percentages of (11%, 19%, 35%, and 53%) respectively. The calculated non-zero values of RMSD means, physically, determination of damage in the plate structure, which is not the case, in other words false prediction. These results shows how important to have self-diagnosis for PAWS used in SHM system for further reliable measurements and data interrogation using EMI technique.

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