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Electromechanical Admittance Signature Analysis of Piezo-ceramic Transducers for NDE

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Abstract

Of the multiple applications of the piezoelectric ceramics transducers such as Lead-Zirconate-Titanate (PZT), one prominent one is in the field of non-destructive evaluation (NDE) using the Electromechanical Impedance method (EMI). In this method a piezo-ceramic transducer (PZT) is bonded on to the structure and actuated using a harmonic voltage at ultrasonic frequency ranges. The dynamics of the PZT-structure interaction is captured in the frequency response of the electrical admittance of the PZT, popularly called as the admittance signature. A mechanical damage in the structure alters the mass, stiffness and damping properties locally, which in turn alters the admittance signature. Many analytical and semi-analytical models of the EMI method that have been used are limited in application to simple systems. The coupled-field finite element modeling has been demonstrated to quite accurately predict the admittance signatures as obtained by the experimental EMI technique. This paper presents the results of identification and quantification studies of damage using the analysis of admittance signatures obtained by coupled-field FE model of a simple cantilever type plate in ANSYS™.

Keywords: Piezoelectric ceramic transducer; Lead-Zirconate-Titanante (PZT), Electromechanical Impedance (EMI) ; Non-Destructive Evaluation (NDE); Coupled-field FE analysis

1. Introduction

An emerging non-destructive evaluation (NDE) technique with the potential of real time, online and automated monitoring of the health of machinery and structures is the electromechanical impedance (EMI) method. The

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diagnostic signal in this method is the electrical admittance response over frequency of the piezoelectric ceramic transducer, such as the Lead-Zirconate-Titanate (PZT), surface-bonded to the structure, obtained over high frequency ranges in the order of kHz. Upon being subjected to high-frequency alternating voltage, the PZT vibrates and transfers the vibrational energy to the structure. If bonding is strong between the PZT and the structure, there exists a dynamic coupling between the mechanical impedances of the PZT and the structure, which is reflected in the electrical admittance of the PZT transducer. The diagnostic signal generated is the frequency response of the electrical admittance of the surface-bonded PZT, ranging anywhere between 1kHz – 100kHz, which is called as the admittance signature. Defects, deteriorations and damages in the machinery components or structural members change the dynamic parameters of the system, such as mass, stiffness and damping. These in turn change the natural frequencies of the system and get reflected in the pattern changes of the admittance signature, which serves as the indicator of damage [1]–[4].

In this paper, a numerical study is carried out to generate admittance signatures for a cantilever beam subjected to material damage at the fixed end. The change in the admittance signature pattern is quantified by statistical quantification techniques [5].

2. Electromechanical Impedance (EMI) Technique

2.1. Experimental Approach

The typical experimental set-up has the following components: (a) test specimens to be tested or the portion of the structural/machine component to be diagnosed (b) PZT transducers bonded onto or embedded within the specimen, (c) impedance measuring instruments such as impedance analyzer (HP 4192A, 4194A), LCR meter (Agilent E4980A Precision LCR meter) or a Digital Multimeter (d) electrical wire connections connecting the PZT to the impedance measuring device, (e) a desktop or a laptop computer equipped with a data acquisition software and (f) a PC-impedance instrument interface cable. The transducers available in the market are usually so designed that after its bottom surface is bonded to the surface of the host structure, both the electrodes of the transducer are accessible from its top surface for soldering the wires. Two-part epoxy adhesive consisting of hardener and resin is used for bonding the transducers on to the surface of the specimens or embedding between two materials as in a composite. The electrodes of the transducers are then soldered by electrical wires of desirable lengths. The soldered wires connected to a PZT transducer are then plugged into the impedance measuring equipments for the acquisition of the admittance signatures (both real and imaginary parts), extracted as a function of exciting frequency. A program, functional in the interface software is run on the computer to operate the process of diagnosis automatically.

The PZT transducer is excited through an alternating voltage signal of rms amplitude of 1 V using an impedance analyzer or an LCR meter, over a frequency range within 1 - 200 kHz. This induces a high frequency vibration in the PZT. The PZT, which is surface-bonded onto or embedded within the structural element, induces actuation in the structure, locally. The PZT actuates the structure at any particular frequency and the structural response is simultaneously sensed by the PZT. The current in the circuit divided by the applied voltage is the electrical admittance, which is extracted for every frequency step, as per-determined and commanded through the software input. This frequency response curve or the admittance response versus the excitation frequency range is called as the electromechanical admittance signature. The full details of the set-up can be obtained in the literature [1]–[4], [6]
.

For an healthy state of the structure, the admittance signature is extracted, which becomes the reference or the baseline or the pristine state signature. As desired, at a later point of time, the admittance signature is again extracted to diagnose the structure. Comparing the latest signature with the pristine state signature gives an idea of the changes in the signature.

Any damage, such as a crack, debond or corrosion in the structure, alters the mass, stiffness and damping parameters locally around the damage. The mechanical impedance of the structure accordingly gets altered as it is a function of the structural mass, stiffness and damping parameters. Due to the impedance coupling that exists between the PZT and the structure, the changes in mechanical impedance reflects in the change in the admittance signature of the PZT attached to the structure. Thus, change in the pattern of the admittance signature serves as the damage indicator. The changes in the admittance signatures can be statistically quantified or measured by parameter-based damage metrics [3], [11].

2.2. Analytical and Semi-Analytical Models of EMI technique

Several analytical or semi-analytical models of the EMI method have been developed and tested against the experimental investigations [7]–[11] . Researchers have proposed a semi-analytical modeling approach incorporating the FE model and the impedance based model, commonly known as finite element analysis (FEA)-based impedance model. This model enables the modeling of PZT-structure interaction without the presence of PZT patch in the model, as it has been simplified and represented by a force or moment. This approach retains the simplicity of the impedance based model while utilizes the strength of FEM including the ability in modeling generic distributed structures possessing anisotropic material, mass loading and non-uniform boundary conditions. However, this is not the full numerical simulation and has the limitations in approximating the actuator force transmitted to the structure as acting only at the boundary of the PZT transducer.

2.3. Coupled Field FE Modeling of the EMI technique

However, these have been restricted only to very simple structures with simple boundary conditions. When the structure to be studied is relatively complex or with complicated boundary conditions, or when the targeted model involves a system of structures interacting with each other, analytical modeling is usually impossible. Numerical models turn up to be a viable option, which often provide close enough approximation to the exact solution, satisfactory for engineering applications. Recent developments of various finite element (FE) method based software packages and advancement in computing technology render the numerical modeling technique more attractive option.

In recent years, a full numerical simulation of the EMI technique has been demonstrated using the coupled field finite element modeling and analysis of the PZT in ANSYS^{TM} [12]–[14]. Using this numerical simulation, the admittance signatures can be directly obtained just as we get in the experimental results. Thus, the coupled field FE simulations can help in examining the various pattern changes of the admittance signatures under various conditions of damage without the need of complex experimental set-up. Recently, a study has been carried out on the influence of the PZT material and geometric parameters on the admittance signatures [15]. It has been observed that the susceptance (imaginary admittance) signatures are more indicative of the PZT characteristic changes than the conductance (real admittance) signatures.

In ANSYS^{TM}, piezoelectric analysis comes under the category of coupled field analysis. Coupled-field analysis considers the interaction or coupling between two or more disciplines of engineering. Piezoelectric analysis caters for the interaction between structural and electric fields. Coupled-field analysis derives solutions to problems not possible with the usual FE methods, by simplifying the modeling of coupled-field problems. Piezoelectric analysis makes use of direct coupling method, which involves only one analysis with the use of one coupled-field element containing all necessary degrees of freedom.

This formulation is very convenient for evaluating the admittance signatures used in the EMI technique. The complex electrical admittance signature, which is the ratio of electric current to voltage, expressed as: $Y = I / V$, where Y is the complex electrical admittance of the PZT, V is the sinusoidal voltage applied and I is the modulated current in the PZT, all being complex terms. When the voltage is taken as 1 volt, the output current directly gives the electrical admittance. By performing Harmonic Analysis and extracting the current as output we can obtain the admittance signature. The details of the steps involved in modeling and harmonic analysis were similar to those used in the literature [10], [14].

Yang and co-researchers [9] studied the ability of coupled-field FE model in simulating the PZT-structure interaction. PZT patch surface-bonded onto aluminium structures of various shapes were simulated and compared with the experimental counterparts. The overall outcome of the numerical simulation showed excellent agreement with the experimental tests up to a frequency as high as 1000 kHz.

Advantages of FE simulation using coupled elements include: results in terms of electrical admittance can be readily obtained and compared with the experimental counterparts, higher accuracy can be achieved as the entire PZT patch can be simulated instead of being replaced by a force or moment, local modes omitted in the analytical model can be excited in the coupled field model, and the bonding layer and shear lag effect can be physically simulated.

Lim and Soh [13]showed that by adjusting material parameters and choosing an appropriate Damping Model the results obtained from the couple field. FE Simulations can have very close arrangement with the experimentally obtained signatures. In this work, the same simulation method was adopted.

3. Numerical Simulation of Damage

The objective of this numerical simulation is to study the changes in the admittance signatures due to damage induced in the material of a cantilever plate like structure. For this study, a thin metallic plate of dimensions 300 mm length, 20 mm width and 2 mm thickness, is considered as shown in the Figure 1. This is constrained at one end to form a cantilever type end conditions.

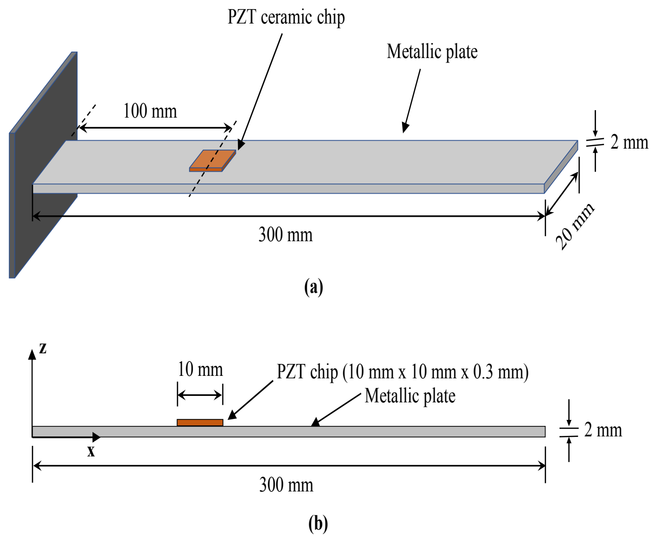

Fig. 1. Cantilever Metallic Plate bonded by a PZT (a) 3D view (b) Side View

The piezoelectric ceramic (PZT) is assumed to be bonded at 100 mm from the fixed end of the plate. The dimensions of the PZT chip are chosen to be 10 mm length, 10 mm width and 0.3 mm thickness. The PZT is bonded symmetrically over the width of the top surface of the thin metallic plate as shown in the Figure 1 (a). In this analysis, the thickness of the bonding adhesive layer is ignored and the PZT is assumed to be perfectly bonded to the structure.

The material properties considered for the PZT are based on catalog of PI Ceramic for PI 155, commonly considered in the literature, as shown in Table 1. Hysteretic damping ratio is chosen as used by Lim and Soh [13]. The properties of the metallic material of the plate are listed in Table 2.

Parameters	Symbols	Values	Units
Density	ρ_{PZT}	7800	kg/m^3
Compliance	$s_{11} = s_{22}$	15	10^{-12} m^2/N
	s_{33}	19	
	$s_{12} = s_{21}$	-4.5	
	$s_{13} = s_{31}$	-5.7	
	$s_{23} = s_{32}$	-5.7	
	$s_{44} = s_{55}$	39	
	s_{66}	49.4	
Electric permittivity (Relative values)	ε^T_{11}	1980	
	ε^T_{22}	1980	
	ε^T_{33}	2400	
Piezoelectric strain coefficients	d_{31}	-210	10^{-12} C/N
	d_{32}	-210	
	d_{33}	500	
	d_{24}	-	
	d_{15}	580	
Mechanical quality factor	Q_m	100	
Damping ratio (Hysteretic)	$\xi_{PZT} = (2Q_m)^{-1}$	0.005	
Dielectric Loss tangent	$\tan\delta$	0.02	

Table 1: Properties of the Piezoceramic (PZT) material

Property	Notation & Value
Young's Modulus	$E = 6.89 \times 10^{10}$ N/m^2
Density	$\rho = 2600$ kg/m^3
Poisson's ratio	$\nu = 0.3$
Hysteretic damping ratio	$\xi = 0.0005$

Table 2 Properties for the Host Structure (Metallic Plate) material

FE meshing and Damage Model

The meshing for this model is done using 8-noded solid brick elements, SOLID 45 for the plate and SOLID 5 for the PZT transducer. The mesh sizes for both PZT and the cantilever chosen were 1 mm. This was so as to get exact overlapping of nodes. The two elements, i.e. the plate and the PZT, were bonded in the model by using the feature of merging the nodes that coincide. The size of the mesh was taken from the previous works [12], [13], which showed that for the chosen frequency range of excitation, 1mm mesh size would give quite accurate results. For this size of the mesh, the plate thickness would accommodate two elements along the depth. As the maximum bending stresses would occur usually at the fixed end of the cantilever, the damage is induced by reducing the stiffness of the top elements of the beam along the boundary near the fixed end. The reduction in stiffness that is considered is as given in Table 3.

Plate Material Property Altered	Pristine State (D0)	Damage State 1 (D1)	Damage State 2 (D2)	Damage State 3 (D3)
Material Stiffness (x 10^{10} N/m^2)	6.89	5.1675	3.445	1.7225
Percentage Reduction in stiffness	-	25%	50%	75%

Table 3: Reduced Stiffness Values to Induce Damaged States

Modal Analysis is done for the above cases to obtain the system natural frequencies. The admittance signatures are obtained by performing Harmonic Analysis in ANSYS^{TM} ([12], [13]) in the frequency range of 0 – 5 kHz, which covers first few resonant frequency peaks about 10 natural frequencies of the structure.

4. Results and Discussion

The natural frequencies for first 20 modes covering the first modal frequency of 18.6 Hz to 20th modal frequency of about 5700 Hz were extracted and studied for all the four cases of damages as shown in Table 3. There were natural frequency reductions observed with progressive damage states. The reduction in natural frequencies of the damaged states D1, D2 and D3 were obtained with respect to the pristine or undamaged state. The results of the reduction in natural frequencies for the three damaged states for the first 20 modes are shown in Figure 2. The immediate observation is that for the same state of damage the higher frequency modes show greater values of frequency reduction. Thus, higher natural frequencies are more favourable and sensitive for providing indications of damage as compared to the low frequency modes. It can also be observed that for the same mode, with increase in damage severity, the frequency reduction values are higher. Thus, progressive states of damage severity can be monitored by proportionate reduction in natural frequencies for all the modes. Further, it may be observed that the modal frequency reduction values for mode numbers 9, 12, 15, 17 and 19 are lower than their immediate neighbouring modes. This is due to the fact that the vibration nodes (zero displacement points) are either coinciding or in the close vicinity of the location of the PZT transducer for these modes.

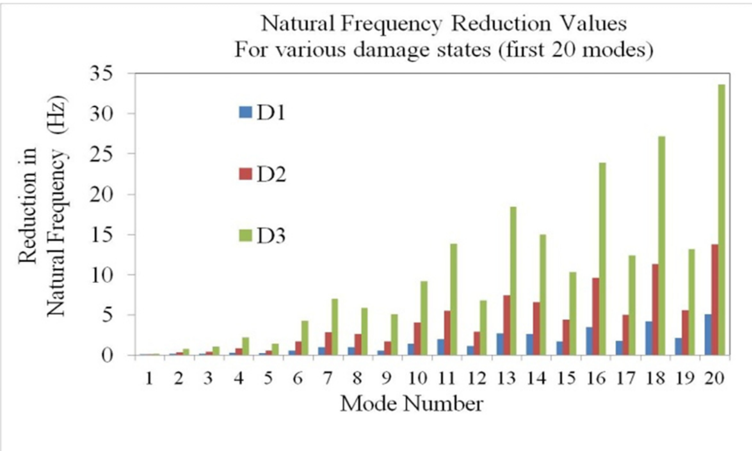

Fig. 2. Reduction in Natural Frequencies with increasing Damage Severity

The real and imaginary parts of the admittance signatures, namely conductance signatures and the susceptance signatures, for the pristine state and the damaged state for the frequency range of 0 – 5 kHz are shown in Figures 3(a) and 3 (b), respectively. The frequencies of the peaks in the signatures correspond to the structural natural frequencies that resonate with the actuating frequency. Preliminarily, we can observe that there is hardly any significantly noticeable change in the signatures, particularly in the lower frequency regions. However, when zoom in to a few peaks i.e. say around 2900 Hz and 3700 Hz, as shown in Figures 4(a) & 4(b) and 5(a) & 5(b), respectively, we can observe significant peak shifts towards the left. This indicates that natural frequencies are reducing for those modes of vibration, and this is an indication of damage.

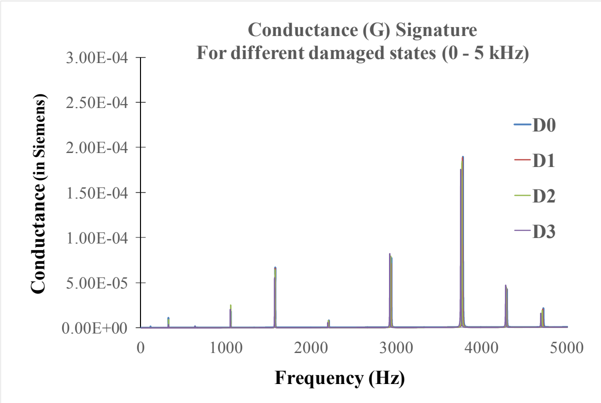

Figure 3(A): Conductance Signatures over frequency range of 0 – 5000 Hz

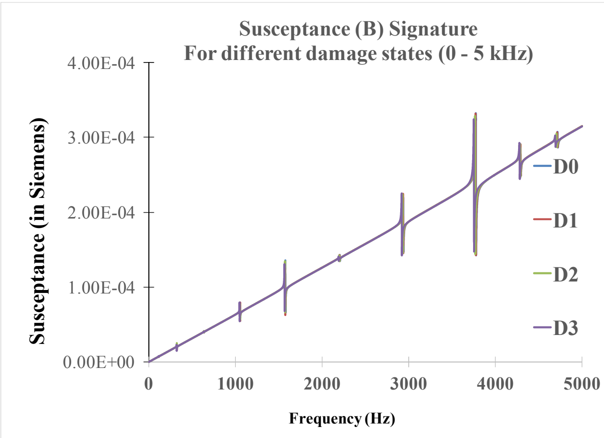

Figure 3(B): Susceptance Signatures over frequency range of 0 – 5000 Hz

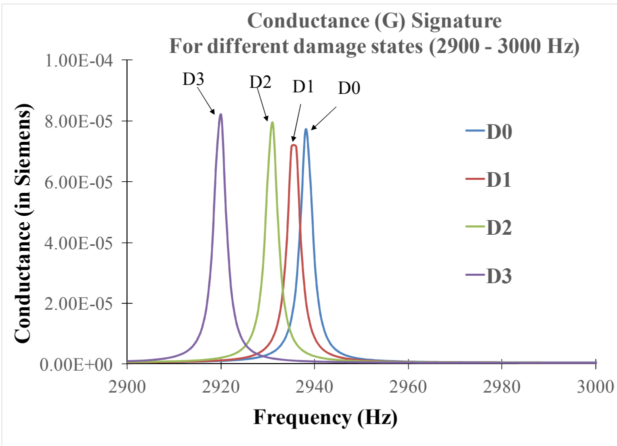

Figure 4(A): Conductance Signatures over frequency range of 2900 – 3000 Hz

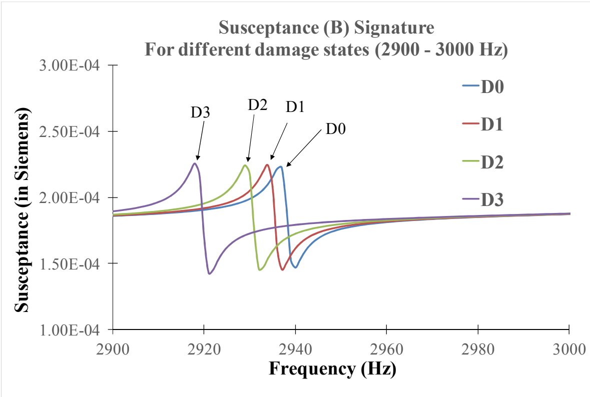

Figure 4(B): Susceptance Signatures over frequency range of 2900 – 3000 Hz

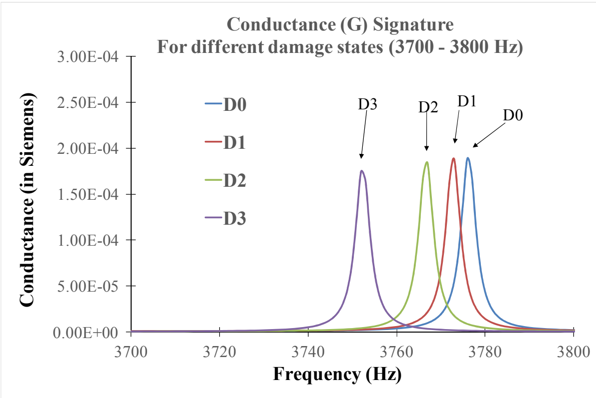

Figure 5(A): Conductance Signatures over frequency range of 3700 – 3800 Hz

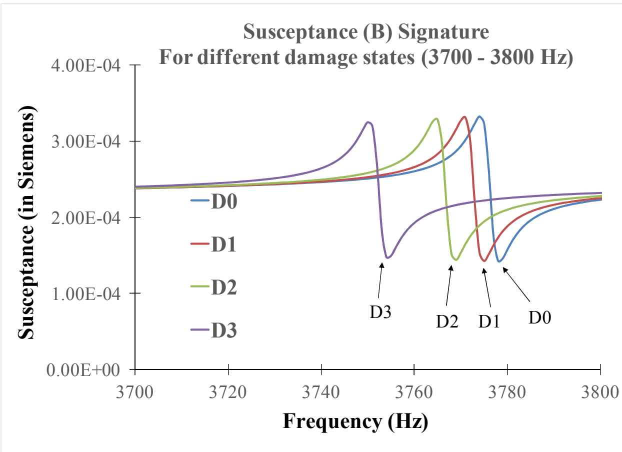

Figure 5(B): Susceptance Signatures over frequency range of 3700 – 3800 Hz

With the increase in the severity of the damage, there is a greater shift of the peaks in the signatures towards the left. For NDE and continuous monitoring purposes, these progressive shifts of the peaks are indicative of increasing severity of the localized damages. We can observe that the amplitude or the magnitude of the peaks do not change much. In experimentally obtained admittance signatures we do observe drastic changes in the magnitudes of the peaks as well, which is because of local changes in the damping parameters at the location of the damage. In the numerical simulations considered here the damping parameters are not modeled in relation to the damage location and severity. Thus, in the signatures in Figures 4 and 5, we do not observe significant amount of change in the magnitudes of the peaks.

To be able to quantify the changes in the admittance signatures, suitable statistical tools need to be adopted. The most commonly used damage metric in the research literature on EMI is the root mean square deviation index which is defined as follows.

$$\text{RMSD (\%)} = \sqrt{\frac{\sum_{i=1}^{i=N}(y_i - x_i)^2}{\sum_{i=1}^{i=N} x_i^2}} \text{ x } 100 \quad (1)$$

where x_i and y_i (I = 1,2,3…N) are digital signatures obtained from the PZT bonded to the structural before and after the damage is incurred.

The same is adopted here to quantify the observed changes in the damage states. The RMSD values for the damaged states are calculated for (a) the full range of actuating frequency, i.e. 0 – 5000 Hz, (b) the subrange of the actuating frequency between 2900 – 3000 Hz and (c) sub-range of the actuating frequency between 3700 – 3800 Hz. The RMSD values obtained for conductance signatures are shown in Table 4 and the RMSD values for susceptance signatures are shown in Table 5.

Damage Index (RMSD) for Conductance Signatures			
Damage State	**D1**	**D2**	**D3**
Full Range (0.0 - 5.0 kHz)	90.7	126.8	134.8
Sub-Range 1 (2.9 - 3.0 kHz)	92.5	131.1	143.2
Sub-Range 2 (3.7 - 3.8 kHz)	90.9	127.8	134.2

Table 4: Damage Index (RMSD) for Conductance Signatures

Damage Index (RMSD) for Susceptance Signatures			
Damage State	**D1**	**D2**	**D3**
Full Range (0.0 - 5.0 kHz)	2.7	3.8	4.1
Sub-Range 1 (2.9 - 3.0 kHz)	6.1	8.6	9.4
Sub-Range 2 (3.7 - 3.8 kHz)	12.9	18.1	19.0

Table 5: Damage Index (RMSD) for Susceptance Signatures

Quick comparison between Tables 4 and 5 reveals that RMSD values for characterizing difference in the conductance signatures are much higher than those for susceptance signatures. Although it is observed that susceptance signatures are shifting towards left, the RMSD index does not effectively capture this change. The nature of most of the statistical indices, including RMSD index, is that they quantify the magnitude of the vertical shifts of the signatures, averaged over the entire frequency range. RMSD values for conductance signatures are high due to high peak values at resonant frequency over a small interval of frequency. According to conclusions of past work, conductance signatures are more sensitive and better indicators of damage than the susceptance signatures [1]. However, observations here show that it is dependent on the type of damage index that we chosen for quantification. It has been noted however that conductance signatures are more sensitive to the changes in structural parameters while susceptance signatures are more sensitive to the changes in PZT's electrical and mechanical parameters.

Further observation shows that for both conductance and susceptance signatures the RMSD values increase proportionately to the damage severity, i.e. as we move from left to right along any row of the Tables 4 and 5. This indicates that RMSD index captures increase in severity for both conductance and susceptance signatures.

Choosing a smaller sub-range of frequency for RMSD quantification of signature changes does not help much for conductance signatures, as observed when we move top to down along the columns of Table 4. However, choosing the smaller sub-range of frequency in the vicinity of the structural natural frequencies increases the RMSD index for susceptance signatures, as can be observed by moving top to down along the columns of Tale 5. If only conductance signatures are used for damage diagnosis, then the band of the frequency range chosen for quantification does not affect the results much.

5. Conclusions

This paper presented a Coupled-field finite element (FE) modeling and analysis of the Electromechanical Impedance (EMI) method using Piezoelectric ceramic (PZT) transducers. This method has a potential for Non-destructive evaluation (NDE) for machine components and structures, with the capability of real-time continuous online monitoring. The numerical study included inducing damage at the fixed support of a cantilever plate by reducing the stiffness of the material of the plate, locally. The electrical admittance signatures of the PZT ceramic chip bonded onto the plate were used as the diagnostic signals for evaluation of the condition of the plate. Modal analyses and harmonic analyses for all the damage states, including the pristine or undamaged state of the plate were carried out in ANSYS^{TM}. The modal analysis results show that higher frequency ranges capturing the higher modes of the structural vibration are better suited for damage diagnosis compared to the lower ones. The conductance (real admittance) signatures and susceptance (imaginary admittances) signatures both show leftwards shifts of the natural frequencies, seen by shifts of the resonant peaks. These peak shifts appear to be insignificant over a large frequency range. However, these are clearly perceivable over smaller sub-ranges of the frequency in the vicinity of the resonant peaks. With the increase in damage severity, the degree of leftward shifts of the peaks is also higher. This serves as an indicator for damage severity growth. The commonly used Root Mean Square Deviation (RMSD) index is used to quantify the changes in the signatures. It is shown that the RMSD index could be used more effectively for quantifying conductance signature changes than the susceptance signature changes.

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