A FINITE ELEMENT ANALYSIS OF PIEZOELECTRIC EFFECT IN SMART BEAM FOR STRUCTURAL HEALTH MONITORING

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Abstract: *Structural health monitoring is nowadays more significant. There will be a significant loss of life as well as a significant loss of economy by the failure of any infrastructure. Important structure should be observed at a regular interval of time. A common method used for structural health monitoring is visual inspection which require knowledge as well as experience. So many studies carried out to find the alternative method for visual inspection method. One of the methods established is using smart material which is advanced method. This is a non-destructive evaluation method. The main aim for developing this method is to reduce maintenance and inspection costs. In this study finite element studies interaction between piezoelectric patch and structure by using EMI method using ANSYS software in a high frequency range. This study shows that finite element method is one of the most emerging field and it's a great alternative to visual inspection method in structural health monitoring.*

Keywords: **Structural-health monitoring, finite-element method, piezoelectric-effect and-smart material**

1. INTRODUCTION

Structural-Health Monitoring (SHM) is a rising field have-numerous applications. -Structural health monitoring used to express the healthy-condition of structure and by appropriate-data processing and interpretation, it can predict the remaining-structures life. Smart-structures is one of the alternative-method to the visual inspection methods-from last two decades, because it's-in-built 'smartness', the smart materials-exhibit high sensitivity to any changes in the-environmental condition. Structural-Health Monitoring is a new and-improved way to conducting Non-Destructive Evaluation.

There is a decrease in construction now a days and also need for maintenance of structure increasing nowadays. Suitable maintenance will increase the life span of the structure and also prevent catastrophic failure. By providing continuous and quantitative data, the monitoring system helps you in assessing the quality of structure during construction, operation, maintenance and repair phase of structure, therefore eliminating the hidden costs of damages caused by non-achieving the required designed standards. Early discovery of performance degradation can save lives and property in time. This assurances the safety of the structure and its users. It also gives us a way to assess the possible damages after a natural calamity or any other type of major event which can affect the structural properties and condition.

There are basically two methods of health monitoring. They are Visual inspection and automated health monitoring. In the Visual inspection method, inspections are made by experienced staff. In case of further study, test samples may be taken from the structures and which is examined in the laboratory. An automated health monitoring the detection of damage is done by various smart materials which is having the features that makes them to react to the changes in their loading environment in a predetermined manner.

Smart materials will be materials which have capability to modify their physical properties, such as shape, stiffness, viscosity, etc. Smart materials are the portion of smart structure. “In the recent year, Lead Zirconate Titanate (Pb_2ZnO_3), Piezo-ceramic (PZT) materials have emerged as important smart materials for SHM. PZT patches utilize the well-known piezoelectric effect discovered by Pierre Curie and his brother in 1880.” Because it has in-built capability of detecting the any variation in structure, smart materials, systems and structures are being used for SHM. Piezoelectric materials to play the dual roles as actuators and sensors. It is utilized in this specific project. “Piezoelectricity is the effect of interaction between electrical and mechanical systems.” Piezoelectric material which generates a surface charge because of an applied mechanical pressure.

The electromechanical impedance (EMI) technique which uses piezoelectric (PZT) sensors, has been successfully applied to structural health monitoring. In this technique, PZT transducer is excited at a particular frequency range by applying harmonic voltage, in order to measure the electrical charges at the sensor. The PZT, which is surface-bonded or embedded within the structural element, interact with the structure at any particular frequency range and acquires electric admittance signature. If the bond between the PZT and the structure is strong, there exists a coupling between the mechanical impedance of the structure and the mechanical impedance of the PZT material. In the EMI technique based SHM, the PZT patches are either inserted or attached with adhesive to the main structure which has to be monitored. When attached on the surface of the structure, the adhesive bond forms an interface layer of finite thickness between the patch and main structure.

In this study making use of high frequency dynamic response technique employing smart piezo-ceramic (PZT) actuators and sensors which excite the structure, which is having higher sensitivity to emerging damage. In order to examine model, the electro mechanical connection between the PZT transducers and host structures with or without the intermediate bonding layer in PZT smart systems. To investigate and model the key electro-mechanical interaction between the PZT transducer, the intermediate bonding layer and the host structure in PZT-based smart systems. To perform fundamental examination for the shear lag effect of bond layer on piezo-impedance model numerically by performing FE coupled-field piezoelectric analysis. To conduct comparative study on PZT smart beam consist of two different bond thickness. To investigate performance of smart beam by changing PZT patch length and comparing model having two different PZT patch length. To study conductance signature of simple beam with PZT patch and structure interaction by changing element size.

2. METHODOLOGY

The finite element model consist of aluminium block, bond layer and PZT layer. This model is build up in ANSYS 2020 R1. This software can be used for structural modelling and analysis. Dimension of aluminium block consist of 48x48x10mm, bond layer consist of 10x10x0.03mm and PZT layer consist of 10x10x0.3mm. $1/4^{th}$ of the system is modeled since model is symmetric in all direction. While defining materials, material 1 is the properties of aluminium block, material 2 is the properties of bonding layer and material 3 is the properties of PZT layer. Since model is symmetrical, only $1/4^{th}$ of the model is considered and the block modelled in ANSYS that is 24x24x10mm and PZT layer consist of 5x5x0.3mm and bonding layer consist of 5x5x0.03mm. Element used for aluminium is solid 45 and for PZT patch that is solid 5. Solid 45 in noded 3D element having three degree of free freedom that is translation in x, y and z axis in each node. Along the inner edge and base of the model approximate boundary condition are applied. In y-z plane displacement in z direction set to be zero. At the bottom of the specimen the displacement in all three direction i.e x, y and z were set to zero. Properties of aluminium listed in the table used to prepare the model.

In this coupled field investigation of PZT patch and aluminium block to consider shear lag effect of bonding layer is also done. In this piezoelectric analysis it was assumed that the nodes at the top of PZT have the same voltage and nodes at the bottom of the PZT patch are expected to have the same voltage so as to create a uniform potential difference throughout the PZT patch. Also the top and bottom nodes were separately coupled with VOLT degree of freedom. The excitation of the PZT patch in this study is well within the linear range, as in the EMI technique, due to the use of very small voltage (typically 1V). Hysteresis effect is assumed to be negligible due to the use of relatively thin and small pitch with very low voltage of excitation. For piezoelectric analysis, one needs to couple the bottom and top nodes of the PZT patch with "VOLT" degree of freedom. Performing the full harmonic analysis, the resultant output can be obtained as reaction force (-Q) labelled as AMPS from time history post processor of ANSYS.

For obtaining current, one has to consider the negative of the charge and differentiate charge with respect to time that is simulation of shear lag effect by coupled field finite element method.

$$-Q= -(Q_r+Q_i\, j)e^{jwt} \qquad (1)$$

$$I= d(-Q)/dt=(-I_r\ \ -I_i\, j)e^{jwt} \qquad (2)$$

Finally, the electro-mechanical admittance can be obtained by,

$$Y= I / V \qquad (3)$$

With the support of ANSYS, the electric current can be directly computed for the admittance signature from the EMI technique (with V = 1V), saving all the effort of converting the mechanical impedance into electrical admittance through the impedance based electromechanical coupling equation (equation 3) as, required in the FEA based semi analytical impedance models. The mechanical and electrical properties of PZT patch have been enlisted in Table.

Table 1: Properties of specimen (Aluminium block) and adhesive bond (Moharana 2013 and Adhekeri 2015)

Parameter	Material	Values
Modulus of elasticity(E)	Aluminium	68.95GPa
	Epoxy	1GPa
Poisons ratio (υ)	Aluminium	0.3
	epoxy	0.4
Density (ρ)	Aluminium	2715kg/m^3
	epoxy	1000kg/m^3
Mass damping factor (α)	Aluminium	0
	epoxy	0
Stiffness damping factor (β)	Aluminium	3X10^{-9}
	epoxy	6X10^{-9}

Table 2: Properties of Piezoelectric PIC 151 (PIceramics, 2010)

PARAMETERS	SYMBOLS	VALUES	UNIT
density	ρ	7800	Kg/m^3
Dielectric loss factor	tan δ	0.02	
Compliance	S_{11}	15.0	10^{-12}m^2/N
	S_{22}=S_{33}	19.0	
	S_{12}=S_{21}	-4.5	
	S_{13}=S_{31}	-5.7	
	S_{23}=S_{32}	-5.7	
	S_{44}=S_{55}	39.0	
	S_{66}	49.4	
Electric permittivity	ε^T_{11}	1.75	10^{-8}F/m
	ε^T_{22}	1.75	
	ε^T_{33}	2.12	
Piezoelectric strain coefficient	d_{31}	-2.10	10^{-10}m/V
	d_{32}	-2.10	
	d_{33}	5.0	
	d_{24}	5.8	
	d_{15}	5.8	

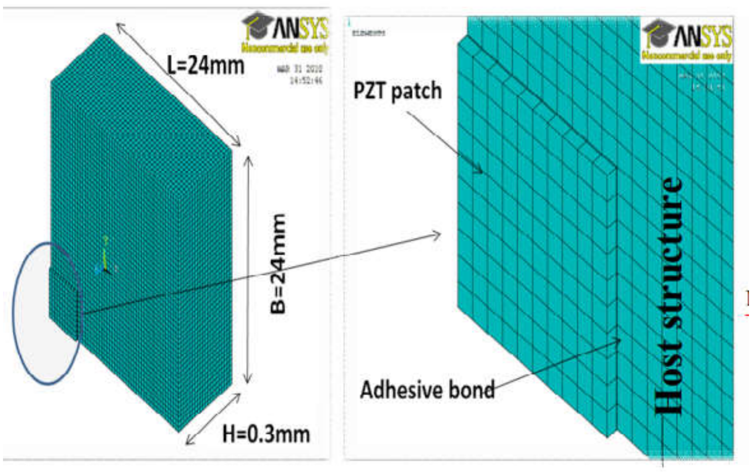

Figure1: Isometric view of aluminium block (24mm x 24mm x10mm) ¼ th adhesively bonded with the PZT patch is modelled using ANSYS 20.0 workspace.

3. RESULT AND DISCUSSION

3.1 Modal analysis:

Modal analysis was done to recognize the natural frequencies of the beam mounted with the PZT, and to study the changes in the natural frequencies due to changes in the element size. First 20 modal frequencies were considered for this purpose and compared. When beam is perfectly bonded to PZT patch, which shows that an element size of 1mm is sufficient to ensure satisfactory results.

Table 3: Modal frequencies of the host structure

No of modes extracted	**Modal Frequency (kHz)**		
	Element Size		
Mode number	**2mm**	**1.5mm**	**1mm**
1	83	82.4	81.5
2	89.5	89.64	89.06
3	91.29	91.26	91.72
4	107.01	108.2	106.7
5	126.45	125.9	124.2
6	138	135.8	137.2
7	140.4	138.8	139.2
8	142.9	140.1	141
9	145.2	142	143
10	149.4	145	148.2
11	150.67	150	149
12	155.2	155	154.4
13	158.3	157	155.8
14	165.3	158	163.4
15	169.6	165	173.5
16	178.5	169	170
17	182.5	176	182
18	183.4	185	183
19	187.5	185.3	184
20	192.9	191	189

3.2 Harmonic Analysis:

The following results were obtained from Harmonic Analysis. In this project PZT bonded to structure with adhesive layer subjected to harmonic excitation of up to 250 kHz, the modal was extended to simulate the interaction of a PZT with the host structure. The reaction charge Q was obtained for frequency range. Electro-mechanical admittance can be calculated as I/V where I is the current value and V i.e. the applied potential voltage.

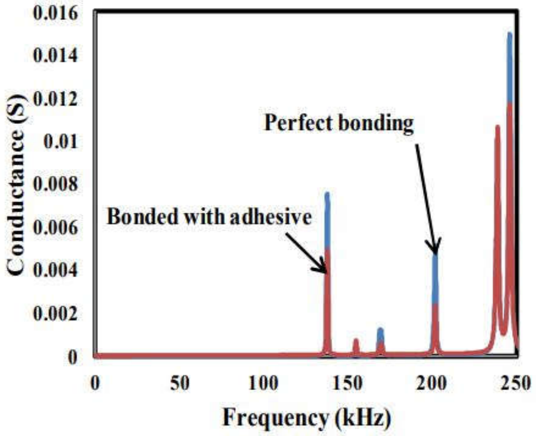

Figure 2: Plot between conductance signature and operating frequency for PZT bonded to structure with adhesive layer and perfect bonded to structure

From the above figure, it can be observed that in conductance(S) plots, the conductance curve has acquired much lower value as compared to perfect the bonding condition (where the adhesive is completely ignored). It can be clearly observed from the figure that the presence of the bond layer has a significantly influenced the admittance signature in terms of shifting of peaks downwards in the conductance (G) plot. The bonding layer is important for optimal coupling between PZT and host structures. Due to bonding there is a reduction in signal strength. It is observed that peak of adhesively bonded on PZT structure is lower than perfectly bonded PZT structure due to additional damping introduced by adhesive layer. Since adhesive layer is an important parameter that has significant effect on EMI system.

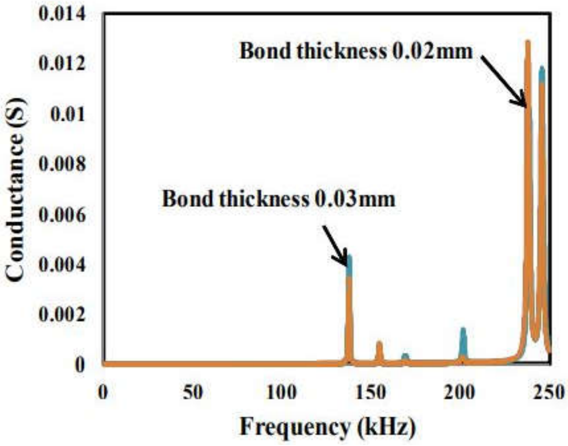

Figure 3: Effect of varying bond thickness on electro mechanical admittance signature on the plot of conductance signature v/s operating frequency

The adhesive bonding layer has a significant effect on EMI system. This layer transfer the signal bi-directionally between PZT patch and structure. It is observed that by changing thickness to lower value, the peak of conductance plot has decreased significantly. Hence it is better to take adhesive bond thickness as 0.03mm. Shear lag effect become more dominant when thickness of adhesive layer increases. Time delay for the wave to reach sensor increase with increase in thickness of adhesive layer.

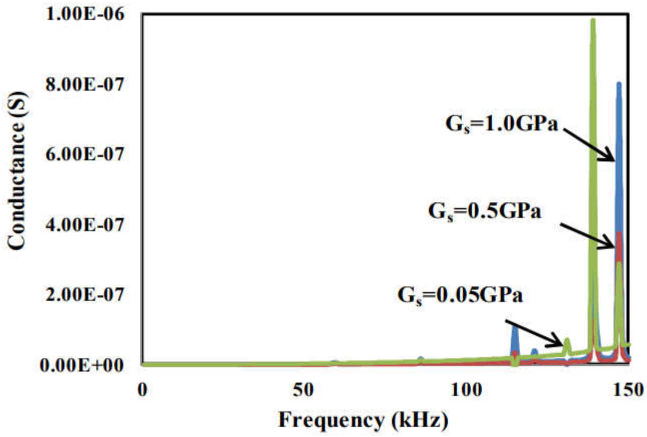

Figure 4: Effect of shear modulus of adhesive on conductance signature obtained through 3D coupled field analysis

It is observed that as the shear modulus decreases, the peaks of conductance subsides down and as more decreases in shear modulus, conductance plot move leftwards. The shear lag effect become more dominant with lower shear modulus, resulting in less effective shear transfer between PZT layer and host structure.

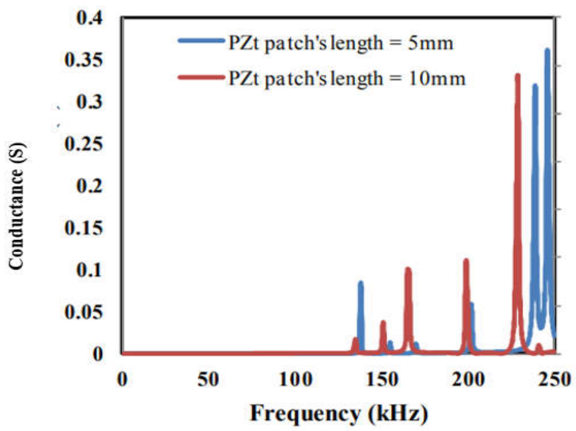

Figure 5: Effect of length of the sensor on the electro mechanical admittance signature

In conductance, the resonance peaks are shifted towards the left with *a* higher peak value as the sensor length increase. Hence, it can be stated that the change in sensor length affects the mechanics of the PZT-structure interaction has changed.

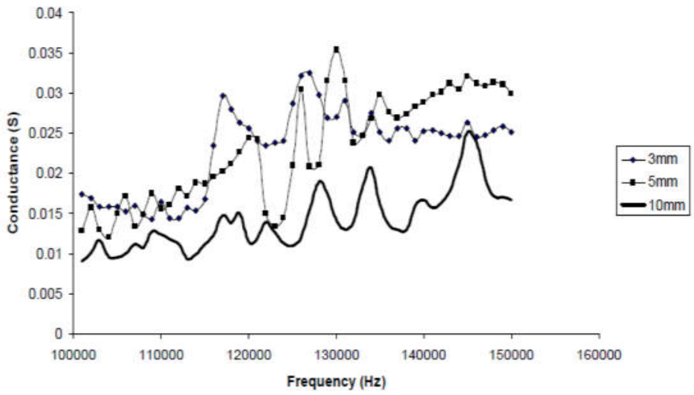

Figure 6: Conductance signature of Simple beam with PZT patch -structure interaction using 3mm, 5mm, and 10mm element size

A simple aluminium beam which is rectangular in cross-segment (dimension 230mm x 20mm x 2mm) utilized as the test specimen in this investigation. A PZT patch of measurement 10mm x 10mm x 0.2mm. The admittance signatures which is named conductance signatures, for the pristine state of different element size 3mm, 5mm and 10mm and frequency range of 0-150kHz are shown in figure 6. This graph of conductance signature of the undamaged structure used in determining presence of damages in terms of location and its extent.

4. CONCLUSION

This method has more potential in non-destructive evaluation (NDE) for the structures, which help in real time online monitoring continuously. This numerical study includes finite element modelling of part of beam which is bonded to PZT layer with or without adhesive layer. Harmonic analysis for undamaged state of the beam was carried out using ANSYS. The electrical admittance signature (conductance signature) help in evaluation of condition of the beam. The effect of different EMI parameter, such as patch geometry (length and thickness) and bonding layer thickness were studied. The conductance signature was obtained for the undamaged beam. So when there will be any damage in the beam, the conductance signature of the beam will be different. By comparing the conductance signatures of the undamaged structure with those of the damaged one, the presence of the damage in terms of its location and extent may be predicted. This numerical simulation is the most useful in future research work in smart structures study. By using this simulation method, we can avoid the tedious experimental works. It will save time and economic means. For large civil structures require more number of PZT patches and impedance analysers are required. Using simulation method, conductance signature for various types of structure can be studied without subjecting any type of cracks in the structure.

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