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Investigation of Shear Lags Effect for EMI and PZT Technique by using Analytical Approach

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Abstract-
The birth of smart devices such as piezoelectric (PZT) transducers has helped to transform the structural health monitoring system (SHM) based on non-destructive testing methods (NDT). Currently, the effect of adhesion layer adhesion (Shear lag effect) is considered to be negligible in the actual application of the EMI process. Although the new NDT method known as electromechanical (EMI) technique has been investigated for more than two decades, there are still a variety of problems that need to be resolved before it can be applied to real buildings. The strategy, which has great potential to contribute to the development of one of the most efficient SHM systems, involves the use of a single PZT to entertain and experience the host structure. In this paper, studies that have applied over the past decade related to the EMI approach have been reviewed to understand its trends. In addition, new ideas and ideas proposed by various authors are also explored, and the paper concludes with a discussion of possible guidelines for future activities.
Keywords: Structure health monitoring; Electro-Mechanical impedance technique; PZT patches; Shear lag effect etc.

1. Introduction

SHM involves testing the response of any structure under current loading, taking into account environmental conditions. It assesses the malfunction, deterioration affecting the safety or usefulness of any part of the structure [1]. Continuous monitoring, response, analysis and evaluation data to facilitate decisions are key features of SHM [2]. Detecting local or early damage prevents serious damage. The severity of the damage ranged from local damage to severe damage. Medium to large damage is easily recognizable and this type of damage significantly alters the vibration response to the structure. In contrast to the vibration response i.e. changes in mode mode, modal frequencies are identified by global strategies.

It is difficult to diagnose environmental damage with global strategies because frequency or climate change is less important for environmental damage. Thus, in order to compensate for the loss of space, local strategies are highly relied upon. Local classroom techniques Ultrasonic Pulse Velocity Techniques techniques acquire structural strength, Acoustic Emissions, Impact Echo Testing etc. These are often great strategies and lead to the release of other information, which is a history of the load used and the formation of difficulties, which does not provide much information about initial or local damage.

Investigating the shear gap effect of PZT nerves bound or embedded in a structure is a complex task because the thickness of the binding layer of the PZT sensor attached to the actual structure cannot be altered. This paper focuses on investigating the effect of coagulation on a composite layer using a numerical method. Therefore, the integrated system model and binding layer were developed using the FEM-based numerical model in the ANSYS. The signature of the integrated system was digitized and further analysis of the signature change was performed to study the effect of the thickness of the bond layer in order to accurately predict the life of the structure.

2. Problem Formulation

Several researchers have investigated the effect of the bond layer and found that the effect of the adhesive layer is significant. Therefore, it is important to calculate the error in the signature of the integrated system due to the binding layer. Monitoring a building after its construction is just as important as it is during design or construction. A well-maintained building can prevent many dangerous accidents. Structural Health Monitoring (SHM) plays an important role. Preliminary analysis of systems by specialist technicians was performed visually.

Various Non-Destructive Tests (NDT) such as Rebound Hammer, Ultrasonic Pulse Velocity Test, etc. are used for testing. As well as these piezoelectric transducers have proven to be an alternative to structural testing. Electromechanical Impedance (EMI) method using piezoelectric material has been developed extensively for structural feedback at various stages. EMI has the ability to detect damage, corrosion and the potential of any part of the structure.

3. Objectives

The primary objectives of this project can be summarized as follows:

1) To study the different that evolved from the past decade related to EMI dealing with new concepts and ideas.
2) To study the Structural Health Monitoring is to identify position and severity of the damage and the estimation of remaining life of the host structure.
3) To study the thickness of bonding layer.
4) To analyzing the effect of thickness of bonding layer numerically using finite element method (FEM) based software.

4. Literature Review

Smart content has become a new way for SHM and NDT. Smart materials have a tendency to detect changes. One smart material is the piezoelectric material. The word piezo is a Greek word which means pressure. Pierre and Paul Jacques Curie discovered the piezoelectric effect in 1880. Lead zirconate titanate (PZT), is a kind of piezoelectric material.

Structure Health Monitoring (SHM) has been used to assess the health of structures such as bridges, high-rise buildings, cable bridges, trusses, and other infrastructure.

There are several techniques that are used to predict the health of the structure for SHM (Spencer, Nagayama and Rice, 2008; Moreno-Gomez et al., 2018; Maura et al. 2020). EMI technology is one of the SHM techniques which has been used by various researchers. Piezoelectric properties are used in EMI technology to assess the health of the structure. A number of experimental and analytical studies have been reported in the field of application of PZT sensors for SHM.

PZT sensors are used to assess the health of structures (Kaur et al., 2017; Maurya et al., 2019; Maurya et al., 2020). In EMI techniques PZT sensors are bonded to the structure using adhesive materials. These patches are used as sensors or actuators in structures.

The materials used in the bonding layer of the PZT sensor have different shear modulus, inertia, geometry and dynamic properties, etc. (Han et al. 2008). Because of these inherent properties of the adhesive material, the signature of the coupled system differs from the actual signature.

This difference of the recorded value of the signature from the actual signature (i.e. on the surface of the host structure) is due to the shear lag effect (Han et al. 2008). In recent times, many researchers have studied the effect of the bonding layer on the signature of the coupled system based on different properties of the bonding layer.

It was observed that the adhesive layer properties significantly affect the signature of the coupled system (Bhalla and Gupt, 2010; Islam and Huang, 2014; Moharana and Bhalla, 2014, 2015).

5. Methodology

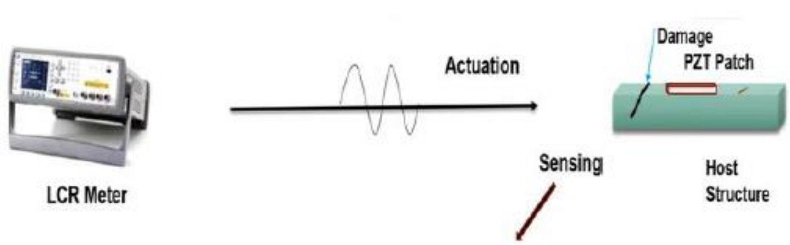

Fig. 1 EMI technique

In EMI surface waves are generated through the vibrations or excitations of the PZT patches. These waves travel outward radially. The waves play detects any defects or damage which tend to hinder its course. The technique involves the use of PZT either bonded on the host structure or embedded in. The patch is excited using alternating.

- The patch is excited using alternating electric field through an impedance analyzer or an LCR meter. The analyzer then measures the electro-mechanical response of the patch in form of admittance. The analyzer plots real and imaginary parts of the admittance against the frequency range and are known as signatures.
- Fig. 1 shows the mechanism of the EMI technique through an LCR meter. The pristine signatures are considered as the baseline indicator. The damage occurring in the structure changes the signatures and the damage is then detected.
- In this project, the EMI technique and its various characteristics are focused. Various studies are mentioned that are conducted over the past few years in order to provide readers with a sight of how the technique has developed so far.

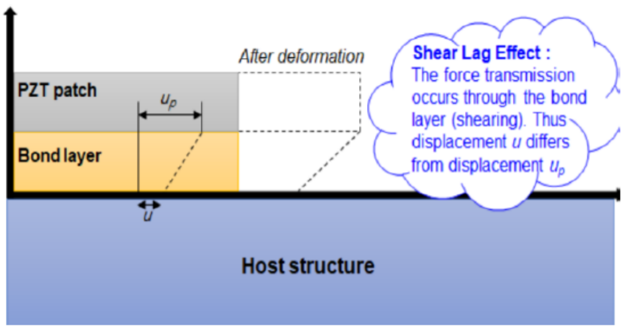

Fig.2. Shear Lag Phenomena

- Some accurate analytical solution was formed considering the shear lag phenomena analytically. Fig. 2 shows the shear lag phenomena. The earlier models overlooked the inertial effect of the PZT but here was taken into account to form shear lag model.
- The new model considered both the shear lag and inertia effects simultaneously. The predictions of the new model matched more accurately with the experiment.

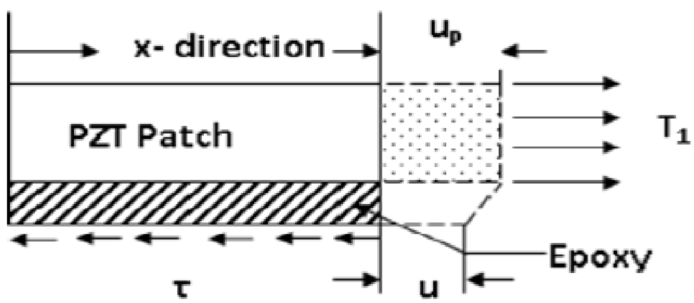

Fig. 3 Deformation in bond layer and PZT patch

- As bond layer is solely responsible for changing the coupled signature, the bond characteristics (shear deformation, inertia, mechanical damping) and geometry (bond thickness and bond length) must be chosen so as to ensure best performance of the PZT transducer.
- However, the existing shear lag models do not account for shear and inertia effects simultaneously as well as the continuous bond deformation variation along bond length These understandings will play significant role to apply the EMI technique on practical structures more effectively.

6. Analytical Modelling Of Shear Lag Effect

- Crawley and de Luis (1987) and Sirohi and Chopra (2000b) respectively modelled the actuation and sensing of a generic beam element using an adhesively bonded PZT patch.
- The typical configuration of the system modelling the actuating and sensing of a generic beam element using an adhesively bonded PZT patch is shown in Fig 4.
- The patch has a length 2l , width p w and thickness p t while the bonding layer has a thickness s t . The beam has depth b t and width b w . Let p T denote the axial stress in the PZT patch and τ the interfacial shear stress.

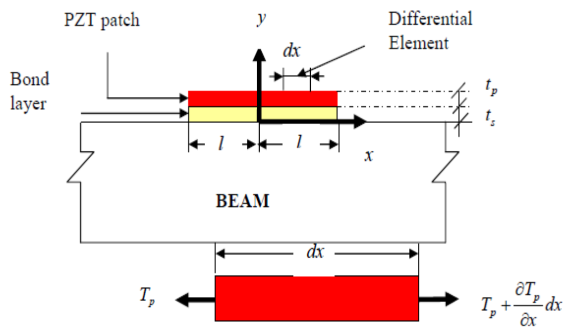

Fig.4. A PZT patch bonded to a beam using adhesive bond layer (Bhalla, 2004).

6.1. PZT Patch as Sensor

- Let the PZT patch be instrumented only to sense strain on the beam surface and hence no external field be applied across it. Considering the static equilibrium of the differential element of the PZT patch in the x-direction, as shown in Fig. 5 , Bhalla (2004).
- The phenomenon of the difference in the PZT strain and the host structure's strain is called as the shear lag effect.

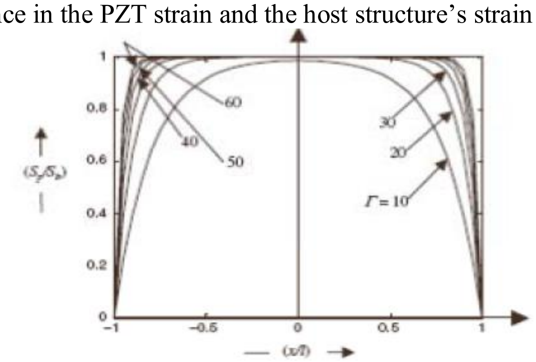

Fig. 5. Strain distribution across the length of the PZT patch for various values of Γ (Bhalla, 2004).

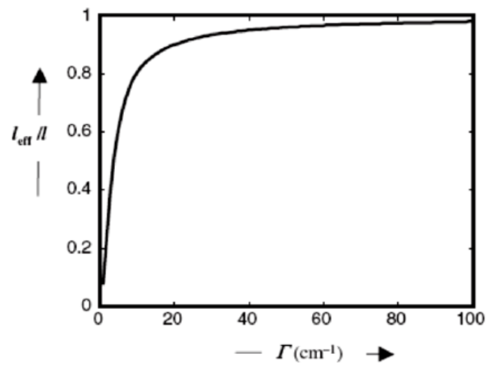

Fig. 6. Variation of effective length with shear lag factor (Bhalla, 2004).

Fig. 6 shows a plot of the effective length (Eq. 3.8) for various values of the shear lag parameter Γ. From the figure it can be observed that typically, for Γ > 30cm−1 , (/) 93% eff l l > , suggesting that shear lag effect can be ignored for relatively high (> 30cm−1) values of Γ.

6.2. PZT Patch as Actuator

- If a PZT component is hired as an actuator in a beam structure, it can be displayed (Bhalla, 2004).
- It is noted that as in the sensory area, as Γ increases, shaving is effectively transferred to a smaller area near the end of the pond. Typically, at Γ> 30 cm-1, the gravity force found in the basement by the PZT actuator is within 5% of the fully sealed case.

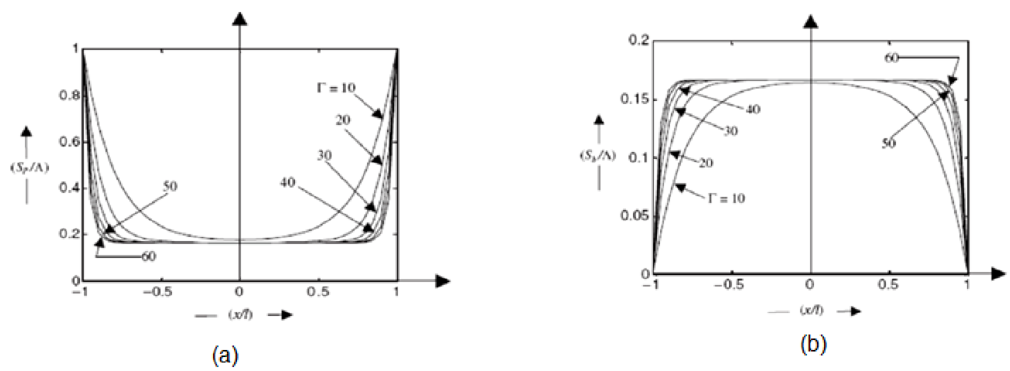

Fig. 7. Distribution of piezoelectric and beam strains for various values of Γ: (a) strain in PZT patch and (b) beam surface strain (Bhalla, 2004).

7. Integration Of Shear Lag Effect Into Impedance Models

When acting as an actuator and / or sensor, there is a shear object associated with the power transfer between the PZT patch and the host structure through the adhesive bond layer. This feature was first investigated by Xiu and Liu (2002) on the EMI strategy where the same patent operates simultaneously both as a sensor and an actuator. Later Bhalla and Soh (2004) developed a robust model that incorporates the 18th effect of the bond layer on EMI signatures.

7.1. Modified 1d Impedance Model By Xiu And Liu (2002)

Xu and Liu (2002) proposed a modified 1D impedance model in which the binding layer was modeled as a single degree of freedom (SDOF) system connected between the PZT patch and the host structure.

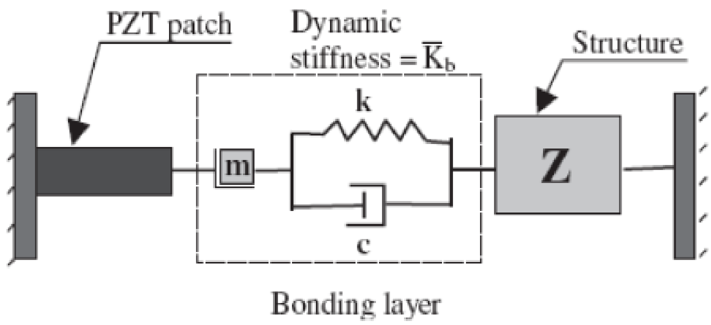

Fig. 8. Modified impedance model of Xu and Liu (2002) including bond layer (Bhalla, 2004).

7.2. Inclusion Of Shear Lag Into Impedance Model By Bhalla And Soh (2004)

Bhalla and Soh (2004) applied the shear lag effect, first to the 1D model and then expanded it into a functional 2D based model.

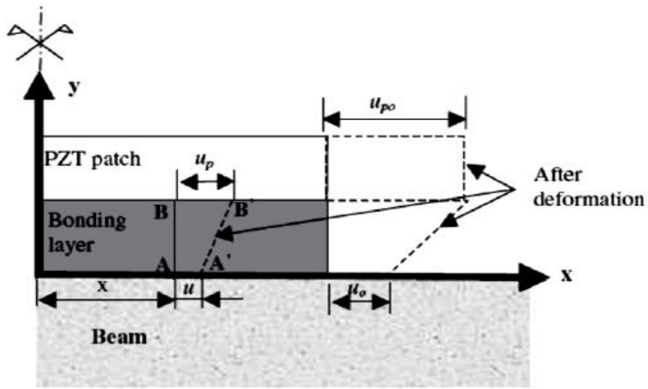

Fig. 9.Deformation in bonding layer and PZT patch.

7.3. Kumar, Bhalla And Datta (KBD) 1d Impedance Model

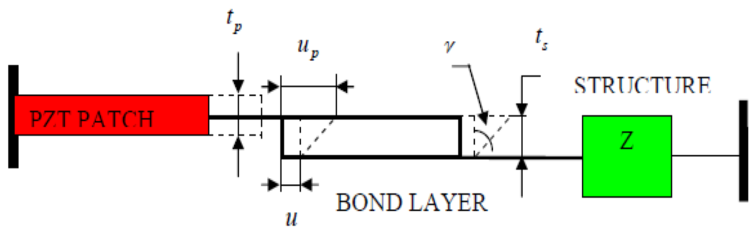

Fig. 10. Diagram showing the KBD model.

Figure 10 shows the proposed KBD model. The conversion of the PZT episode is indicated by p u. Due to the effect of the same shear lag deformation will not be transferred to the handle structure. Modifications to the host structure are indicated by u. The mechanical impedance of the host structure is defined by Z. The thickness of the PZT reservoir is indicated by p t while that of the adhesive bond layer by s t. It is assumed that the transfer of power between the PZT component and the host structure takes place in the simple manner of pure shear shown by Fig.10.

From the above discussion, it can be noted that the model presented by Bhalla and Soh (2004) is robust. Therefore, extracting conductance signatures and doubts using their model will be very difficult. This requires the development of a simple model, which can include the effect of shear lag on the 1D impedance model.

7.4. Verification Of KBD Model

- ***Generation of Finite Element Model :***

The Cantilever beam was manufactured in ANSYS 9. The frame was thought to be made of aluminum grade Al 6061-T6 whose main mechanical properties are set out in Table 4.1.The beam was used with PZT patch between A&B points as shown. in Fig.11 Fig.12 shows a mesh produced using the preprocessor of ANSYS 9, with an element size of 2.0mm.

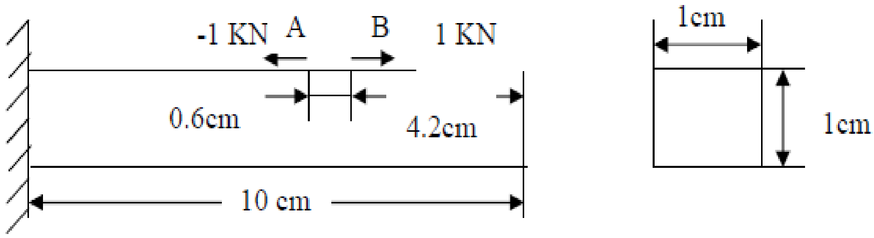

Fig.11..A cantilever model in ANSYS 9

Table 1 Physical properties of Al 6061 – T6 (Bhalla, 2004)

Physical Parameter	Value
Density (kg /m^3)	2715
Young's Modulus, Y_{11}^E (N/m^2)	68.95 x 10^9
Poisson ratio	0.33
Mass damping factor , α	0
Stiffness damping factor, β	3 x 10^{-9}

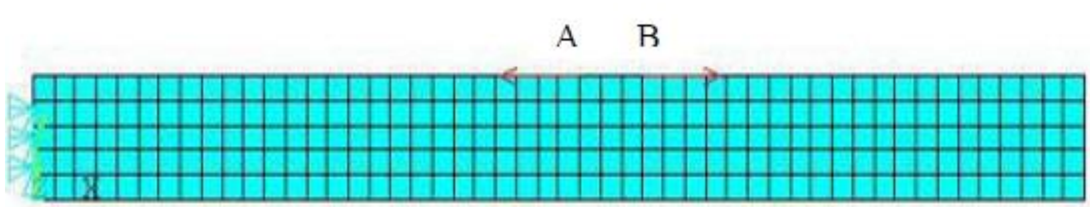

Fig.12. ANSYS Model

A set of equal and horizontal loads of 1 KN was applied to two points, A and B (the end points of the PZT section) at 6mm respectively at the top surface of the model as shown in Fig. 12. 1 KN load is used. at node number 160 (point A) and load 1 KN is applied to node number 154 (point B).

The materials used were considered as a stretch and isotropic line. Harmonic analysis of the model structure constructed in this way was performed to determine the actual and hypothetical migration components at node 160. The estimated frequency range was 100 - 150 kHz. By performing the above analysis we have the required data of the power transferred to the host structure (1KN in the current model) and the corresponding shift in the host structure to the various frequency frequencies. This data was continuously processed to extract conductance signals and susceptance in different 1D impedance models i.e.. without considering the effect of shear lag, using the Bhalla and Soh model, and using the KBD model..

7.5. Convergence Test

For dynamic harmonic problems, in order to obtain accurate results, a sufficient number of nodal points (3 to 5 in the length of each wave) should be present in the standard feature net (Bhalla, 2004). To confirm this requirement, modal analysis was performed again. Frequency range of 0–150 kHz was found to contain a total of 18 modes. The modal frequencies are listed in Table 2, calculated in 3, 5mm, 2mm and 1mm different size sizes. It can be noted that a good combination of modal frequencies is achieved at a size of 2mm (which is the size of the element used in the current analysis). Thus, fairly accurate results are expected in the analysis using FEM.

Table 2. Details of the modes of vibrations of the test structure

MODE	MODAL FREQUENCIES (Hz)		
	5mm	2mm	1mm
1	860.59	858.49	857.78
2	5191.1	5136.8	5125.9
3	13410	13392	13388
4	13802	13494	13440
5	25400	24461	24308
6	39312	37244	36918
7	40255	40114	40089
8	55019	51236	50656
9	67164	66052	65123
10	72203	66637	66552
11	90665	81435	80056
12	94143	92783	92576
13	0.11026E+06	97207	95271
14	0.12114E+06	0.11323E+06	0.11062E+06
15	0.13080E+06	0.11830E+06	0.11788E+06
16	0.14800E+06	0.12934E+06	0.12597E+06
17	-	0.14282E+06	0.14106E+06
18	-	0.14523E+06	0.14206E+06

- ***Visual Basic Programs***

Two VB systems were used to generate conductance and susceptance sites from the ANSYS exit. The first system may determine the continuation and signing of a 1D impedance model without the inclusion of a shear lag effect (Bhalla, 2004). The second system can determine the driving signals and suspicions of the KBD model developed in the current study. The two programs are listed in Appendix A and B respectively. The visual properties of the PZT patch used in the analysis are listed in Table 2.

- ***MATLAB Program***

The MATLAB system, listed in Appendix C, may determine conductance signatures and ANSYS output signals. The system is based on a 1D impedance model with a shear lag effect embedded in it, according to the Bhalla and Soh model (2004).

Table 3 Physical Properties of PZT patch (Bhalla, 2004).

Physical Parameter	**Value**
Density (kg / m^3)	7650
Thickness (m)	0.0002
Length (m)	0.006
d_{31}	-1.66E-10
Young's Modulus , Y_{11}^E (N/m^2)	6.3E+10
ε_{33}^T	1.5E-8
η	0.1
δ	0.012

8. Results

The conductance and susceptance signatures are extracted from three impedance ID models namely the model without the shear lag effect (shown wsle in graphs), the KBD model and the Bhalla and Soh model (2004) for 1D (identified by BSM in graphs). Figures 13, 14 and 15 show the conductance signatures of the different sizes of the bond layer. The effect of changing the bond layer thickness on the conductance signatures given to the three models can be easily seen in these calculations. As the bond thickness of the bond decreases, the performance given by the KBD model and the Bhalla and Soh model (2004) is very close.

Fig 13.shows the susceptance plots given by the three models. The curves are quite close to each other. This part has a weak interaction with the structure and bond layer does not seem to influence the susceptance signatures much.

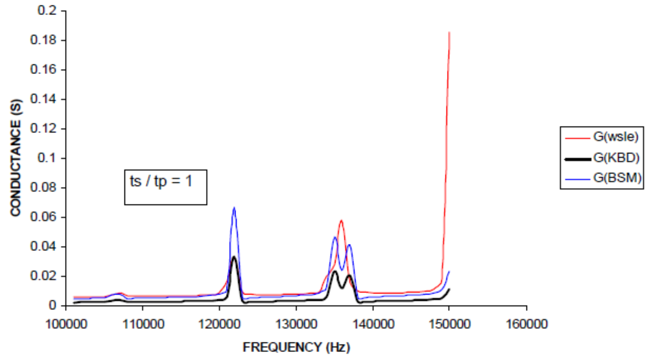

Fig. 13 Comparing conductance signatures obtained by three models for bond layer thickness *ts* = *tp* .

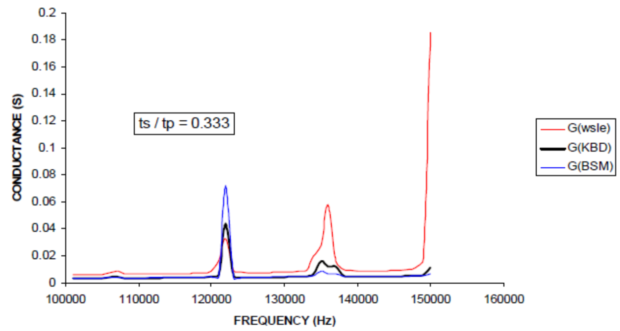

Fig. 14 Comparing conductance signatures obtained by three models for bond layer thickness $t_s = t_p / 3$

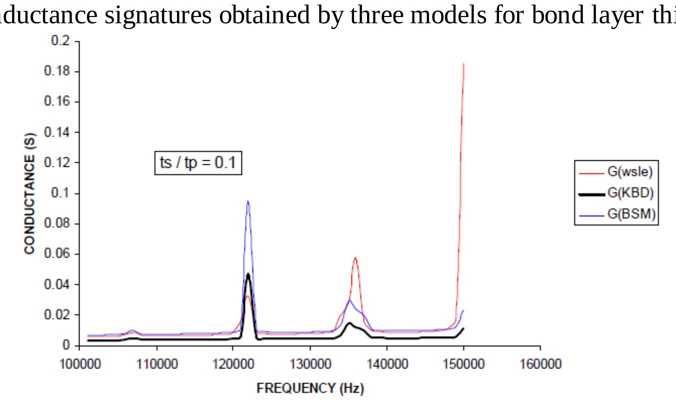

Fig. 15 Comparing the conductance signatures obtained by three models for bond layer Thickness $t_s = 0.1t_p$.

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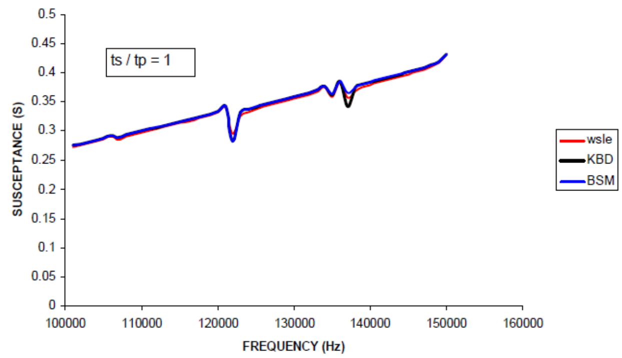

Fig. 16. Comparing susceptance obtained by three models for bond layer thickness $t_s = t_p$.

9. Conclusions

(i) In the current research work a new simplified 1D model that combines the shear lag effect is developed and introduced, called the Kumar, Bhalla and Datta models or just the KBD model. The conductance and susceptance signatures obtained using the KBD model are comparable to those obtained using the Bhalla and Soh 1D impedance model (2004). In addition, detailed parametric research on the process and signing of signatures was performed using the KBD model. In addition, a new method of predicting shear pressure in a bond layer that adheres to different wave frequencies is developed based on the KBD model. Major research conclusions and contributions can be summarized as follows,

(ii) The KBD model developed in this report is found to predict behavior and signature signals close to those provided by the Bhalla and Soh 1D impedance model (2004). However this approach is not taken into account in all frequency frequencies. Next to the noisy peaks, there is a significant difference in performance rates predicted by these models. But for high-frequency sound waves, the difference in performance values predicted by the KBD model and the Bhalla and Soh model (2004) is very small.

(iii) Suspected signatures of three models are found close to each other at different thicknesses of the bond layer. This component has a weak reliance on the bond layer.

(iv) Parametric studies performed using the KBD model suggest that the apparent resonant frequency increases due to a decrease in shear modulus (i.e., the deterioration of the bond layer quality) and due to an increase in the thickness of the bond layer. It is suggested that in order to achieve the best results, the PZT clip should be bonded to the structure using a shear high modulus adhesive and the least possible thickness.

(v) The most important result based on the shear stress distribution study is the layer of adhesion bond that the shear stress distribution is slightly affected by the frequency of happiness except the peaks near the resonance. This result is confirmed by both the KBD model and the Bedla and Soh 1D impedance model. Therefore, it can be argued that the shear stress distribution is generally independent of the excitation frequency, with the exception of imminent resonance.

(vi) Another important result found in the analysis of shear stress distribution in the adhesive bond layer is that the high shear pressure obtained using the Bhalla and Soh model (2004) is close to the average shear stress obtained using the KBD model. This result suggests that the KBD model can be used to create the first design in problems related to structural control.

(vii) The benefits of the KBD model developed in this report are clear. This model is a simplified model of the complex shear lag component associated with the power transfer between the PZT patch and the handle structure connected to each other by a layer of adhesive bond. The main advantage of this model is that it does not involve solving different complex scales. It may be simpler, however, it does not replace the Bhalla and Soh model (2004) especially if accuracy is paramount.

Each nation spends a lot of money on construction. All sectors of society play an important role in the lives and development of citizens living in the country. Any damage to such structures and systems contributes to the production of the whole country, costing many lives and halting the growing development of the country and its citizens. Structural strength decreases with continuous loading and environmental effects. Therefore, the performance of the structure should be evaluated to determine whether the performance is satisfactory or not. By monitoring the proper structural failures can be prevented.

The study included an EMI approach and focused on the latest research in the field. There are still many usage issues that need to be addressed such as a limited PZT sensor list, proper choice of frequency interval, need to report temperature fluctuations, accurate mathematical metrics, etc., should be overcome in order to monitor damage. The EMI method has great potential. However, because most tests are performed under laboratory conditions, future work should focus more on real-life structures. The integration of the EMI approach with computer simulation and FEM is effective in bringing the approach closer to marketing.

10. Future Work

The use of the EMI method using drones is in the first phase of research. While drone surveillance technology focused on visual inspection continues, this app with drones cannot detect internal damage as it is difficult to detect with the camera. Another visually based SHM comprising drones is being investigated.

The importance of emerging a smart city is becoming increasingly important. Sensory use is one factor in which this can be done. Using multiple sensors is called multi-functional sensors. As mentioned in the previous section, it has been proven by experiments that impedance signatures during an EMI strategy vary with temperature changes. This gives the EMI method the possibility of simultaneous detection to determine the temperature of the host system.

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