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Vibration Analysis of Smart Viscoelastic Cantilever Beam

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ABSTRACT

Modeling and control of a viscoelastic beam are considered. Piezo electrical elements are bonded to the beam and used as actuators and sensors the beam. A finite element model has been developed for the three layer viscoelastic beam. Viscoelastic beam is modelled using linear displacement field at face layer and non-linear displacement field at core layer. The equation of motion for the viscoelastic beam is derived by using the Hamilton's principle. Specimens have been modelled by varying the face layers and core layers and studied under the cantilever boundary conditions for modal analysis. The Natural frequencies are obtained for various models using different core layers and boundary conditions. Finally LQG control theory is applied to control the vibration. The results obtained are validated with experimental results.

Key words : Viscoelastic beam, damping, Finite Element, Piezoelectric

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I. INTRODUCTION

Active vibration control is defined as a technique in which the vibration of a structure is reduced or controlled by applying counter force to the structure that is appropriately out of phase but equal in amplitude to the original vibration. As a result two opposite force cancel each other and structure stops vibrating.

Active vibration control is a modern approach towards vibration control at various places; classic control techniques are becoming too big for modern machines where space is limited and regular maintenance is not possible and if possible, it's too expensive, at such conditions AVC techniques comes handy, it is very cheap requires no manual maintenance and the life expectancy is also much more than the passive controllers.

Active vibration control makes use of smart structure . The system mainly requires actuators, sensors, source of power and a compensator that performs well when vibration occurs. Smart structure are used in the bridges, trusses, buildings, mechanical systems etc. analysis of a basic structure can help in improving the performance of structure under poor working conditions involving beam vibrations

The Major components are

1. Sensor patch- it is bonded to the host structure (beam). It is generally made up of piezoelectric crystals. It senses the disturbance of the beam and generates a charge which is directly proportionally to the strain. Direct piezoelectric is used.
2. Controller- the charge developed by the sensor is given to the controller, the controller lines are charged according to the suitable control gain and charge is fed to the actuator. Controller also forms the feedback functions for the system.
3. Actuator patch- the lined up charge from the controller is fed to the actuator causes pinching action (Or generates shear force) along the surface of the host which acts as a damping forces and helps in the alternating vibration motion of the beam. Converse piezoelectric is used.

Active vibration control finds its application in all the modern day machines, Engineering structures, automobiles, gadgets, sports equipment's, ceramics, electronics etc. As it needs only a little actuation voltage hence it does not requires any external power source, the power can be directly derived from the host machine itself. As the electronics is also developing at a very fast rate hence the size of a processor is also reducing, which is very useful in the design of the control system.

In this work a smart viscoelastic beam with one pair of piezoelectric lamination is used to study the active vibration control. The smart viscoelastic beam modeled in cantilever configuration with surface bonded piezoelectric patches. The study uses ANSYS-13 software to derive the finite element model of the smart beam. Based on this model, the optimal sensor locations are found and actual smart beam is produced. In this experiment we find a suitable control methodology by which we optimize the controller gain to get more effective vibration control with minimum control input.

Normally Sandwich construction includes a relative thick core of low density material, sandwiched between the bottom and top face sheets (face layers) of relatively thin in size. The schematic diagram of a sandwich beam is shown in Figure 1.

Figure 1. Sandwich beam model

Core Material

The core layer consists of some typical features as given below,

- Lower density
- Damping of vibration and noise
- Shear strength and shear modulus
- Stiffness perpendicular to the top and bottom faces
- Thermal insulation

Face Material

The face layer consists of some typical features as given below

- High impact resistance
- High compressive and tensile strength
- Wear resistance
- Resistance to different conditions (chemical, heat, etc.)
- High stiffness giving high flexural rigidity
- Good surface finish

Various types of materials are as follow :

Metals and alloys: Metals and their alloys possess all most all required properties of face materials. Conventional materials and their alloys such as steel, stainless steel and aluminum are often used as face material.

Composites: Most composites offer properties similar to or even higher than those of metals, they have been substantially used in construction of sandwich structures. Particularly fiber reinforced composites are suitable for sandwich structures even though the stiffness is often lower in magnitude. Thus with a light core, the composites produce high rigidity. Even wood also can used as face material in sandwich structures.

Aim and Objectives of Works

In the present work, a number of papers published so far have been surveyed, reviewed and analyzed.

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- The literature review for the various studies carried out with reference to this work has been enlisted along with a critical discussion of investigations conducted.
- The mathematical modeling of sandwich model is shown.
- The procedure for modeling Viscoelastic sandwich beam using finite element package ANSYS 13.0, has been described stepwise and the finite element formulation for the solution of vibration problem has been presented.
- Results obtained from the present investigation have been presented and discussed in detail. Finite element results obtained for the above parameters using ANSYS has also been included and conclusion drawn on the above studies have been described
- The Natural frequencies are obtained for various models using different core layers and boundary conditions. Finally LQG control theory is applied to control the vibration. The results obtained are validated with experimental results.
- The conclusion of the present study has been presented.

II. LITERATURE REVIEW

Amirani et al. [2009], studied the free vibration analysis of sandwich beams with functionally graded material as core material. For the analysis, the element free Galerkin method and Galerkin formulation for two dimensional elasticity problems are considered. Penalty method is used for modeling of interface between the face sheets and the core in the sandwich beam. Using the similarity of materials for the face sheets and core, applicability of the model is tested. The first ten natural frequencies of sandwich beam with elastic core are derived. The results have shown good agreement with those obtained by the finite element method. Finally, the natural frequencies of sandwich beam with functionally graded core are obtained and discussed.

Banerjee et al.[2007], has developed an accurate dynamic stiffness model for a three-layered sandwich beam of unequal thicknesses is developed and subsequently used to investigate its free vibration characteristics. Each layer of the beam is idealised by the Timoshenko beam theory and the combined system is reduced to a tenth-order system using symbolic computation. An exact dynamic stiffness matrix is then developed by relating amplitudes of harmonically varying loads to those of the responses. The resulting dynamic stiffness matrix is used with particular reference to the Wittrick–Williams algorithm to carry out the free vibration analysis of a few illustrative examples. The accuracy of the theory is confirmed both by published literature and by experiment.

Banerjee et al. [2004], searched A dynamic stiffness theory of a three-layered sandwich beam is developed and subsequently used to investigate its free vibration characteristics. This is based on an imposed displacement field so that the top and bottom layers behave like Rayleigh beams, whilst the central layer behaves like a Timoshenko beam. Using Hamilton's principle the governing differential equations of motion of the sandwich beam are derived for the general case when the properties of each layer are dissimilarThe boundary conditions for responses and loads at both ends of the freely vibrating sandwich beam are then imposed to formulate the dynamic stiffness matrix, which relates harmonically varying loads to harmonically varying responses at the ends.

Daya et al. [2003], suggested an elementary theory for non-linear vibrations of viscoelastic sandwich beams is presented. The harmonic balance method is coupled with a one mode Galerkin analysis. This results in a scalar complex frequency response relationship. So the non-linear free vibration response is governed by only two complex numbers. This permits one to recover first the concept of linear loss factor, second a parabolic approximation of the backbone curve that accounts for the amplitude dependence of the frequency The amplitude equation is obtained in closed form for a class of sandwich beams. The effects of the boundary conditions and of the temperature on the response are discussed.

Fei Lin and Mohan [2013], present a modeling technique to study the vibroacoustics of multiple-layered viscoelastic laminated beams using the Biot damping model. In this work, a complete simulation procedure for studying the structural acoustics of the system using a hybrid numerical model is presented. The boundary element method (BEM) was used to model the acoustical cavity, whereas the finite element method (FEM) was the basis for vibration analysis of the multiple-layered beam structure. Through the proposed procedure, the analysis can easily be extended to another complex geometry with arbitrary boundary conditions. The nonlinear behavior of viscoelastic damping materials was represented by the Biot damping model taking into account the effects of frequency, temperature, and different damping materials for individual layers. The curve-fitting procedure used to obtain the Biot constants for different damping materials for each temperature is explained. The results from structural vibration analysis for selected beams agree with published closed form results, and results for the radiated noise for a sample beam structure obtained using a commercial BEM software is compared with the acoustical results of the same beam by using the Biot damping model.

Grewel et al. [2013], searched that the dynamic properties of sandwich beam type structure are analyzed using finite element method based on a nonlinear model for displacement field in the viscoelastic core layer of the beam structure. Results obtained for the nonlinear and linear models are compared to the test data available in literature. It is revealed that the nonlinear model provides more accurate results than the linear one. Parametric studies are carried out on the nonlinear model to illustrate the effect of viscoelastic core thickness on the loss factor and natural frequencies of structure. These results are also compared with those obtained for the linear model. Parametric studies on the nonlinear model revealing the sensitivity of the location of untreated and treated patch and the length of treated patch are presented

Mohammadi and Sedaghati [2012], explained damping properties of viscoelastic sandwich structure can be improved by changing some parameters such as thickness of the layers, distribution of partial treatments, Slippage between layers at the interfaces, cutting and its distribution at the top and core layers. Since the optimization problem may result in a thick core layer, for achieving more accuracy a new higher-order Taylor's expansion of transverse and in-plane displacement fields is developed for the core layer of sandwich cylindrical shell in which the displacement fields at the core layer are compatibly described in terms of the displacement fields at the elastic faces. The presented model includes fewer parameters than the previously developed models and therefore decreases the number of degree of freedom in the finite element modeling. The transverse normal stress in the core layer is also considered.

Won et al. [2013], studied the numerical implementation of Mead and Markus's two sets of differential equations of motion governing the damped forced vibration of three constrained layer sandwich beam requires C^2-basis Functions or the mixed formulation. To resolve this problem, a damped beam element for three-layered symmetric straight damped sandwich structures is derived according to the virtual work principle, in which both the virtual kinetic and strain energies are expressed in terms of the lateral displacement and the transverse shear strain of a core layer. Because the forced vibration equations of three constrained layer damped beam are equipped with three pairs of boundary conditions, the rotation of the mid surface which is directly derived from the lateral displacement is added for the damped beam element to have three degrees of freedom per node. The shape functions are analytically derived using the compatibility relation between the lateral displacement and the transverse shear strain. The validity of the proposed beam element is verified through the benchmark experiments, and furthermore the DOF-efficiency is justified through the comparison with Nastran 3-D solid element.

Jingjun Zhang[2010], study of the applications of piezoelectric materials in the active vibration control of flexible structures has been ongoing for more than a decade. Based on the Linear Quadratic Gauss (LQG) optimal control method, the paper introduces an effective procedure to suppress the vibration of flexible structures with the sensors/actuators are symmetrically collocated on both sides of the same position on the host structure. The model of a piezoelectric intelligent cantilever beam is built by the application of ANSYS software, and through the modal analysis, the first 4 ranks of modal frequencies and vibration shapes are extracted.

Najeeb ur Rahman [2012], Vibration suppression of smart beams using the piezoelectric patch structure is presented in the present work. The smart system consists of a beam as the host structure and piezoceramic patches as the actuation and sensing elements. An experimental set-up has been developed to obtain the active vibration suppression of smart beam. The set-up consists of a smart cantilever beam, the data acquisition system and a Lab View based controller. Experiments are performed for different beam specimen. The experimental results obtained by using the active vibration control system have demonstrated the validity and efficiency of PID controller. Experiments are conducted to compare the controlling of various cantilever beams of different sizes.

III. FINITE ELEMENT AND EXPERIMENTAL ANALYSIS OF VISCOELASTIC BEAM

In this step we define the analysis type and options, apply loads and initiate the finite element solution.
This involves three phases

1. Pre-Processor Phase
2. Solution Phase
3. Post-Solution Phase

Pre-Processor is an interactive model builder to prepare the finite element model and input data. The solution phase utilizes the input data developed by the pre-processor and does solution according to the problem definition. It creates input files to the post processor. The post processor provides complete visualization of results on graphics screen. It displays the displacement, stresses, forces, temperatures etc, on the screen in the form of contours.

Before the vibration control of smart structures for minimizing structural vibration, it need to understand the vibration analysis of the structure. Once the vibration analysis is understood, a good performance controller can be designed and implemented. In this section, Natural frequencies of smart structures are found out by experimental method.

In this case, a simple cantilever viscoelastic beam is tested for vibration analysis. To actuate the beam, piezoelectric actuator is used and for sense the changes in the beam sensor is used. The system parameters are listed in Table 3.1. Dynamic signal analyzer, DASY-Lab version-11.00 software (Data Acquisition System Laboratory) and Spectra-PLUS version 4.0.24.0 (FFT Spectral Analysis System) were used to obtain frequency responses and time responses from the piezoelectric laminate beam. Figure 2 shows the experimental setup to find out the amplitude of natural frequencies for different modes.

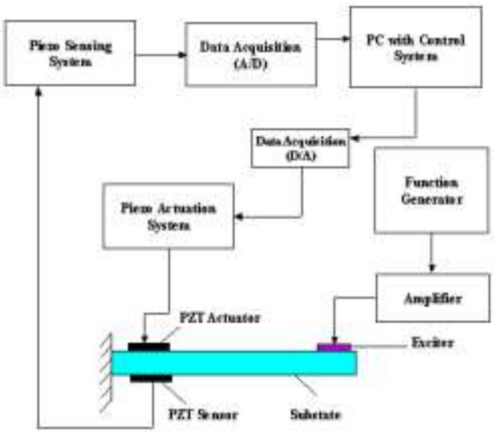

Figure 2. Schematic Diagram of Experimental setup

Preparation of Sandwich Beam Specimens:

Sandwich beams are made with the aluminium and steel sheets as the face layers and the core layers as rubber and neoprene. In preparing the sandwich beam specimens the face layers are made free from grease, dirt etc by cleaning their surface with acetone and carbon tetrachloride. The adhesive used for bonding the layers was commercially available Araldite. After application of thin layer and equal amount of adhesive on surfaces of all layers, the specimens were allowed to settle down for 24 hrs for perfect bonding under the load and proper care was taken to avoid the slippage between the layers by providing the positioning guides at all the edges of the specimen. The details of physical and geometrical properties of specimen are given as: the thickness of top and bottom layers 1.5 mm, core layer thickness as 1.5 mm, the length and width of beam are taken as 300 mm and 100 mm respectively. The material properties of sandwich beam considered here are given in Table 1

Table 1: Specification of Beam

Plate dimension	
Materials For beam	1) Alluminium 2) Mild Steel 3) Rubber 4) Neoprene
Length of Beam	450 mm.
Thickness (t)	4.5mm.
Width	50 mm

Four different types of sandwich beam specimens were made for experimental investigation which consists of
Specimen 1: Aluminium – Rubber- Aluminium
Specimen 2: Steel- Rubber- Steel
Specimen 3: Aluminium- Neoprene – Aluminium
Specimen 4: Steel-Neoprene-Steel

Table 2: Material properties of sandwich beam for face and core layers

Type of material	Young's Modulus E (GPa)	Shear Modulus G (GPa)	Density ρ in Kg/m^3	Poisson's Ratio ν
Aluminium	69	27.3	2766	0.33
Steel	210	80	7850	0.3
Rubber	0.00154	0.005	950	0.45
Neoprene	0.0008154	0.000273	960	0.49

The natural frequencies for all the specimens were determined experimentally for the cantilever boundary conditions.

IV Vibration Control of viscoelastic beam by using PZT Actuator and LQG Controller

The effect of position of actuator at different locations for controlling the amplitude of vibration of the Viscoelastic beam is tested using simulations (FEM) and experimental methods. The location of the sensor has been fixed throughout the simulation, where the actuators are placed at different locations. The LQG controller has been used to study the effect of the actuator positions. The LQG controller have been implemented such that the amplitude of vibration for the closed- loop system should be minimized. An LQG controller is added to the system as shown in

Figure 3. The output voltage of the sensor is fed to the LQG controller. The signal from sensor is controlled by controlled gain parameters gc and Tc in controller.

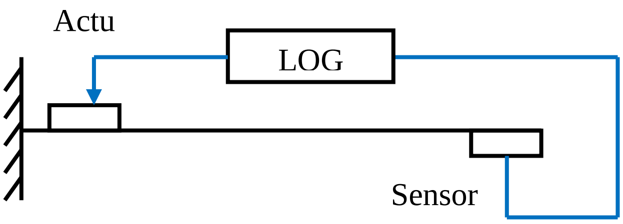

Fig. 3. Smart Viscoelastic beam with LQR Controller for Cantilever

V. RESULT

1. Al-Ru-Al Sandwich Beam

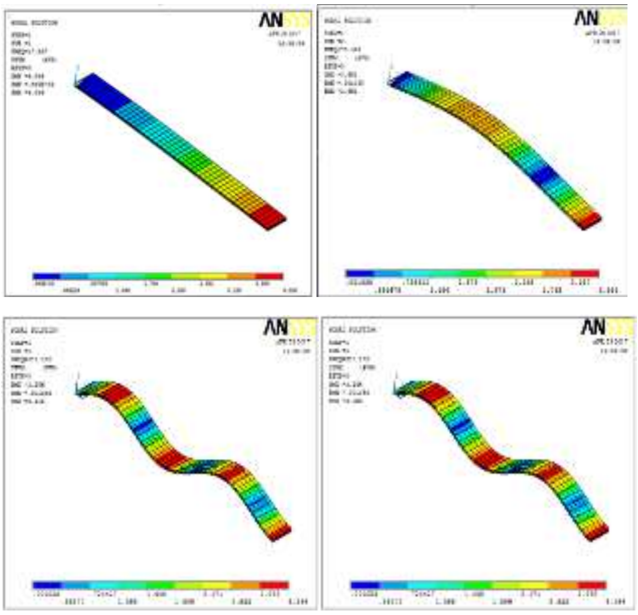

Figure 4. Mode Shapes of Al-Ru-Al Beam in Cantilever Condition

Table 3. Result for Al-Ru-Al (4.5mm) Sandwich Beam for cantilever condition

ANSYS Result			
1st Nat. Freq.	2nd Nat. Freq.	3rd Nat. Freq.	4th Nat. Freq.
17.537	70.493	145.746	217.872

2. Al-Ne-Al Sandwich Beam

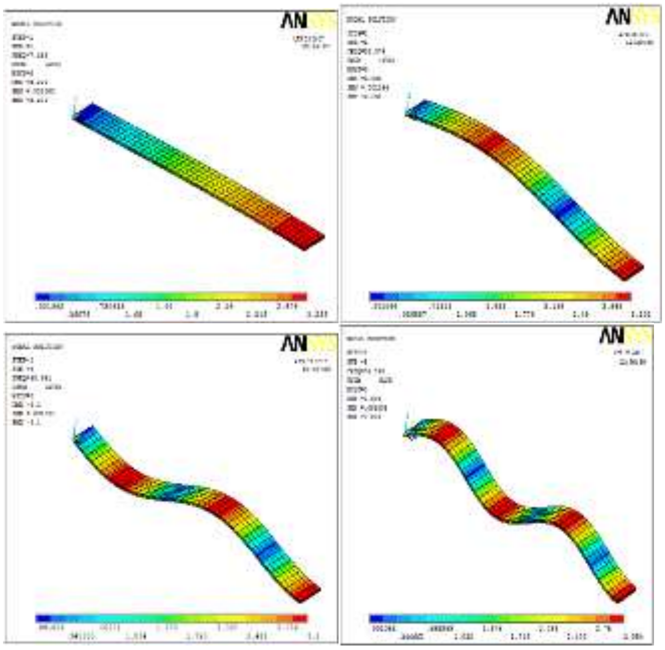

Figure 5. Mode Shapes of Al-Ne-Al Beam in Cantilever Condition

Table 4 Result for Al-Ne-Al (4.5mm) Sandwich Beam for cantilever condition

ANSYS Result			
1st Nat. Freq.	2nd Nat. Freq.	3rd Nat. Freq.	4th Nat. Freq.
7.385	22.374	38.941	54.843

3.St-Ru-St Sandwich Beam

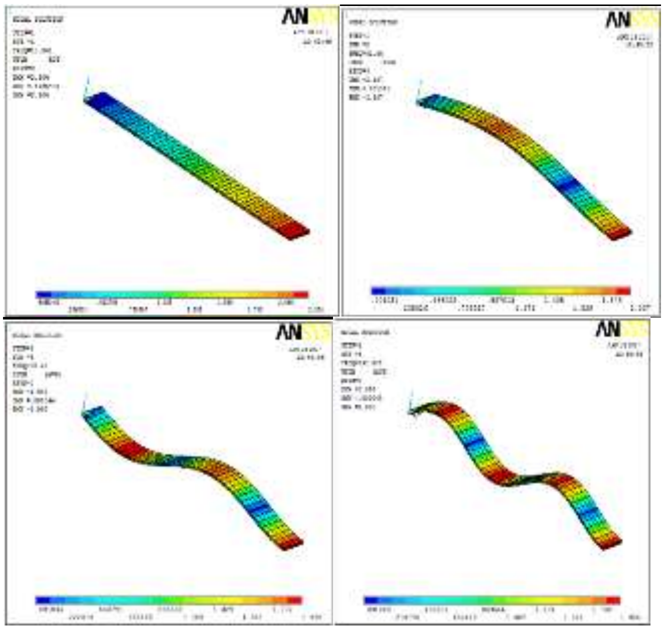

Figure 6. Mode Shapes of St-Ru-St Beam in Cantilever Condition

Table 5. Result for St-Ru-St (4.5mm) Sandwich Beam for Cantilever

ANSYS Result			
1st Nat. Freq.	2nd Nat. Freq.	3rd Nat. Freq.	4th Nat. Freq.
15.241	51.060	98.230	141.388

4.St-Ne-St Sandwich Beam

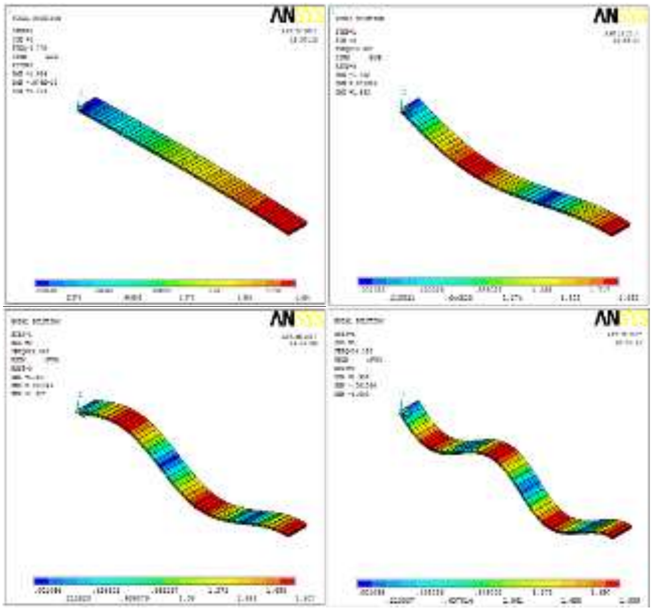

Figure 7. Mode Shapes of St-Ne-St Beam in Cantilever Condition

Table 6. Result for St-Ne-St (4.5mm) Sandwich Beam for Cantilever

ANSYS Result			
1st Nat. Freq.	2nd Nat. Freq.	3rd Nat. Freq.	4th Nat. Freq.
4.778	14.367	24.347	34.182

Table 7.Reading of Impact Hammer Test

Cantelever Condition	Experimental Result(Nat. freq. in Hz)			
Al-Ru-Al	18.787	71.743	146.996	219.12
Al-Ne-Al	8.635	23.624	40.191	56.093
St-Ru-St	17.131	52.95	100.12	143.27
St-Ne-St	6.668	16.257	26.237	36.07

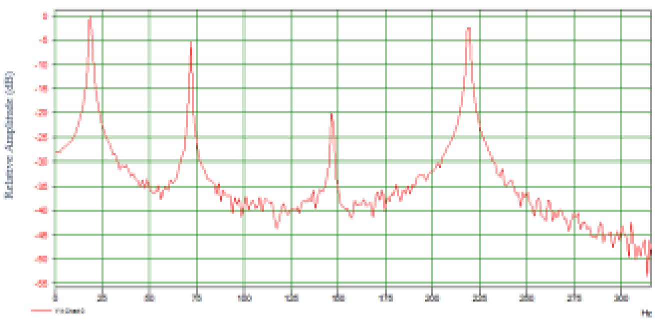

Figure 8. Frequency Response Curve for Al-Ru-Al Beam in Cantilever Condition

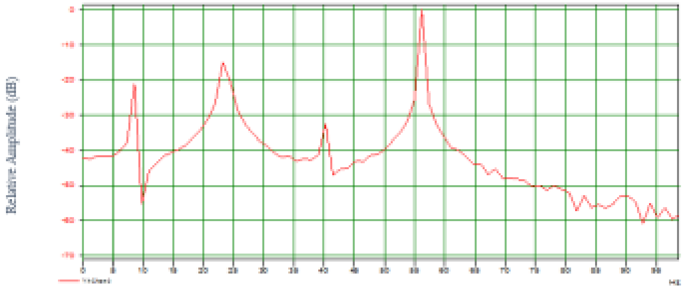

Figure 6. Frequency Response Curve for Al-Ne-Al Beam in Cantilever Condition

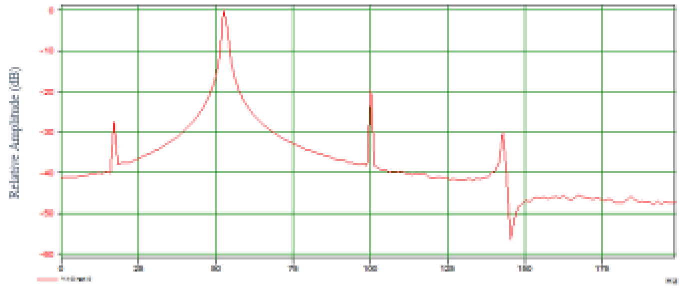

Figure 10. Frequency Response Curve for St-Ru-St Beam in Cantilever Condition

Figure 11. Frequency Response Curve for St-Ne-St Beam in Cantilever Condition

The beams are considered for analysis that is aluminum, with Rubber and Neoprene as core material are compared and tested experimentally and analytically. The natural frequencies are found out by both methods and tabulated. The tabulated result shows that there is a close result between the both methods.

The mild steel beam with viscoelastic material as a core layer, when tested The ANSYS results obtained are compared with experimental results which are have very low percentage variation under the simply supported and cantilever conditions. The results obtained in the form of natural frequency are very close to each other.

Overall Comparison Graph between Viscoelastic Sandwich Beam with Rubber and Neoprene as Core Material :

1. For Alluminium as a Face Layer :

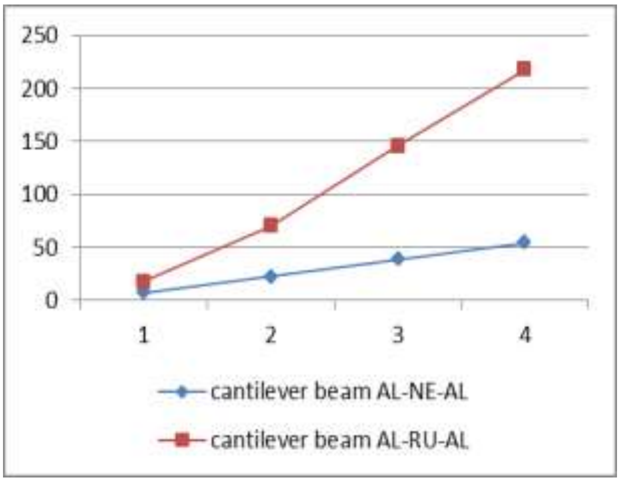

Figure 12. Comparison Graph of ANSYS results between Al-Ru-Al and Al-Ne-Al beam in cantilever Condition for Natural Frequency

2. For Mild Steel as a Face Layer

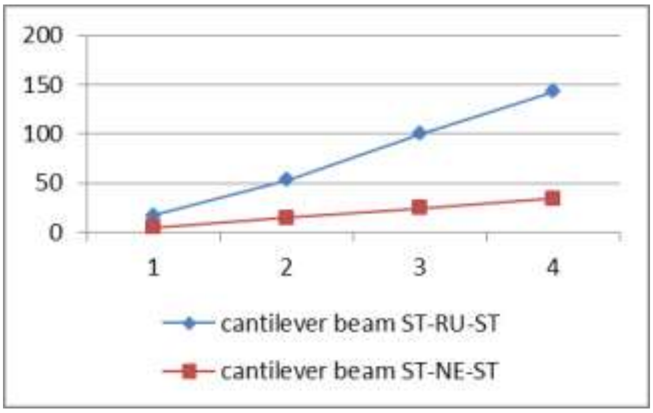

Figure 13. Comparison Graph of ANSYS results between St-Ru-St and St-Ne-St beam in cantilever Condition for Natural Frequency

Overall Comparison Graph between Viscoelastic Sandwich Beam with Rubber and Neoprene as Core Material for Experimental Results :

1. For Alluminium as a Face Layer

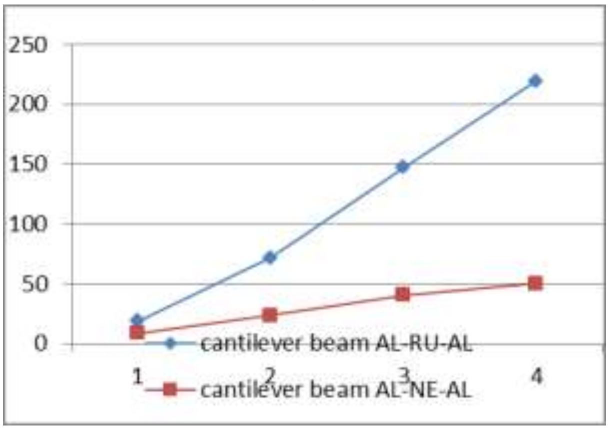

Figure 14 Comparison Graph of experimental results between Al-Ru-Al and Al-Ne-Al beam in cantilever Condition for Natural Frequency

2. For Mild Steel as a Face Layer

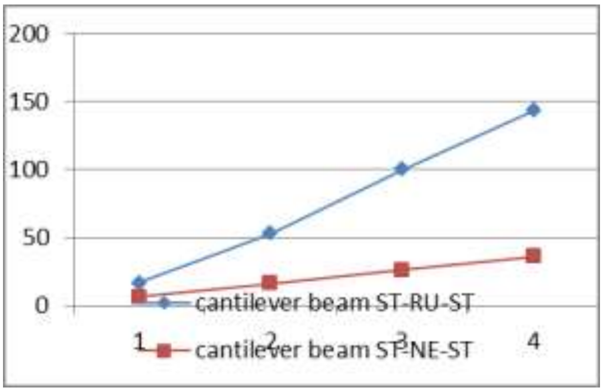

Figure 15 Comparison Graph of experimental results between St-Ru-St and St-Ne-St beam in cantilever Condition for Natural Frequency

The results obtained clearly shows that the beams modeled with Neoprene as a core layer has more damping effect as compared to the rubber for the fixed-fixed and cantilever boundary conditions under the same load. The graphs for ANSYS and Experimental results are of similar nature.

VI. CONCLUSION

The viscoelastic sandwich beam has been successfully modeled using finite element method. The developed model have been validated with the earlier theory, experimental verification has also been done for the different types of sandwich beams modeled. The sandwich beams modeled here with varying of face and core layers. The sandwich beams modeled here are carried out for modal analysis using finite element method by varying the core layer to study the damping effect on the beams for the fixed-fixed and cantilever boundary conditions. The results obtained from the modal analysis clearly shows that Neoprene as a core layer provides less natural frequency than that of Rubber for the same mode. From the results one can infer that damping characteristics for neoprene viscoelastic material has significant effect when compared with the rubber viscoelastic material. Finally the frequency responses of the modeled sandwich beams have been plotted for the fixed-fixed and cantilever boundary conditions. Results show that the viscoelastic constrained layer damping treatment has a great significance in controlling the vibration of structures like beams, plates, etc.

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