International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 4 (2015) pp. 10233-10251

http://www.ripublication.com

Study on Active Vibration Control In Smart Aluminium and Mild Steel Cantilever Beams

Ravindra prasad.J[1] and Dr.P.K.Palani[2]

[1] *Ph.D. Research Scholar 24A, Kumaran street, 5th Cross Vinayakapuram,*
Coimbatore-641 035, Tamil Nadu, India
E-mail: ravindraprasadj@gmail.com
[2] *Associate Professor in Mechanical Engineering, Govt. College of Technology,*
Coimbatore, Tamil Nadu, India.

Abstract

When a system is subjected to dynamic loading, it causes vibratory motion. For the better stability of the system, this vibration should be eliminated. But practically vibration can be brought down to some extent, and cannot be eliminated completely. It can be control by appropriate control methods. The passive and active vibration control techniques can be used for control. This can be achieved by modification of the system's structural response. The objective of the present work is to carry out modeling, analysis and simulation of active vibration control of Aluminium and mild steel cantilever beams using piezoelectric sensors and actuators. The mathematical model of the cantilever beam bonded with piezoceramic actuator is formulated as a multilayer piezo composite beam. The finite element modeling and analysis of the beam with sensors and actuators is done using the finite element package ANSYS. The location of the piezo is determined based on maximum deflection of beam obtained in ANSYS coupled field analysis. Modal analysis is performed in ANSYS and the natural frequencies and mode shapes of the beam are found out for the applied voltage. Proportional-integral controller was developed and experiments were carried out by using Labview software

Keywords: Active vibration control, smart structure, sensor, Proportional-integral controller and actuator

Nomenclature

$\{T\}$ = stress vector

{E} = electric field vector
{D} = electric displacement
[e] = piezoelectric stress
[C] = elasticity matrix
ρ = Density of beam
[εS] = dielectric permittivity matrix at constant strain
[M] = Structural Mass
[C] = Structural Damping
[K] = Structural Stiffness
{L} = Electrical Load Vector

Introduction

Piezoelectric materials are used as actuators and sensors for vibration control in flexible structures. Piezoelectric ceramics provide cheap, reliable and no intrusive means of actuation and sensing in structures. When used in flexible structures, the piezoelectric ceramic films are bonded to the body of the structure using strong adhesive material. A distinct characteristic of piezoelectric actuators or sensors is that they are spatially distributed over the surface which is being sensed or controlled. This property makes them different from the discrete actuators and sensors which are often used in the control of flexible structures. When a piezoelectric element is stressed electrically by a voltage, its dimensions change and when it is stressed mechanically by a force, it generates an electric charge. A piezoceramic is therefore capable of acting as either a sensing or transmitting element, or both.

Actuators and sensors are widely used in various applications and are generally integrated with main structures via surface bonding or embedding. When building the beam, it is taken into consideration that piezoelectric materials must be bonded to the beam in a uniform fashion along with the fact that both materials must have electrical contact on each side of the material. These facts bring about the controversy between surface bonding and embedding. Surface bonding for piezoelectric actuators is advantageous in that there is better access for fabrication, easier access for inspection, and less maintenance cost. However, since these materials are exposed, they are more vulnerable and more prone to be damaged. In this experiment, it is necessary for the piezoelectric components to be on the surface because it was the only way it could be easily manufactured.

Linear Quadratic Gaussian (LQG) controller was developed to control the vibrations caused by various sources including human activity and nearby motorized equipment [3].

Spatial H∞ controller for the active vibration control of a cantilevered smart beam was developed in order to determine the modal damping ratios of the smart beam [2].

A finite element model based on the third order theory is presented for the active vibration control of composite beams with distributed piezoelectric sensors and actuators. A modal superposition technique and a Newmark-β method are used in the numerical analysis to compute the dynamic response of composite beams [4].

Active vibration control of a smart flexible cantilever beam was devloped by using mode theory and μ synthesis method by taking account into uncertainty of the external disturbance and measurement noise, and uncertainty of natural frequency, damping ratio[5].

Finite element modeling of cantilever beam and active vibration control implemented within MATLAB environment [6]. Two strategies: position control and vibration control for attenuation of vibration effects in active cantilever beams was identified [7]. Method of minimizing the effect of higher modes, which lie out of the bandwidth of interest, on low frequency modes of the truncated model of a piezoelectric laminate beam by adding a zero frequency term to the low order model of the structure [8] and suggested a considerations in placement of piezoceramic actuators that are used in structural vibration control [9].

The design and analytical study of piezoelectric active vibration control of beam structures using piezoelectric actuators and sensors [10]. The active vibration control of beams with constrained layer damping treatment.

Numerical Analysis

1. Uniform along its span, or length, and slender.
2. Composed of linear, homogeneous, isotropic, elastic material without axial loads.
3. Such that plane sections remain plane.
4. Such that the plane of symmetry of the beam is also the plane of vibration so that rotation and translation are decoupled.
5. Such that rotary inertia and shear deformation can be neglected.

For the present investigation an Aluminum and Mild steel beams of length 250 mm, width 25mm and thickness 1mm is considered.

The material property of Aluminum and Mild steel was given in Table I.

Table 1:

Material property	ALUMINUM	MILD STEEL
Young’s modulus, E,N/m2	6.75E+10	2.00E+11
Poisson’s ratio	0.32	0.303
Density, ρ,Kg/ m3	2800	7850

The material property of PZT creamic used is given below:

$$[C] = \begin{bmatrix} 12.6 & 7.95 & 8.41 & 0 & 0 & 0 \\ 0 & 12.6 & 8.41 & 0 & 0 & 0 \\ 0 & 0 & 11.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.35 \end{bmatrix} \text{X } 10^{10}\, \text{N / M}^2$$

$$[e] = \begin{bmatrix} 0 & 0 & -6.5 \\ 0 & 0 & -6.5 \\ 0 & 0 & 23.3 \\ 0 & 17 & 0 \\ 17 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{c/M}^2$$

$$[\varepsilon] = \begin{bmatrix} 27 & 0 & 0 \\ 0 & 27 & 0 \\ 0 & 0 & 29 \end{bmatrix} \text{x } 10^8\, \text{F/m}$$

ρ =7500 kg/m ^{3}

Applied voltage: 20 Volt

The beam is modeled in ANSYS using SOLID 45 element. SOLID 45 is used for the 3-D modeling of solid structures, where eight nodes having three degrees of freedom at each node define the element: translations in the nodal x, y, and z directions. The beam volume is meshed using mapped hexahedral elements. The beam is discretized into 9elements, each of size 25mm x 25mm x 1mm.

A three dimension electromechanical coupled-field finite method is used to accurately predict the resonant frequency and harmonic response of the system subjected to a step voltage input. Several cases are studied and the dynamic response of the system, such as deflections and electric equivalent circuit analysis, is presented as function of time. Fig 1 presents the equivalent system of clamp-free piezoelectric beam.

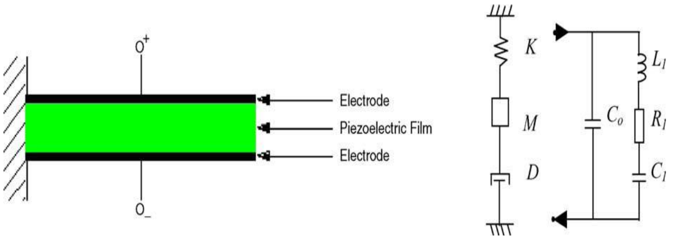


Figure 1: Equivalent system of clamp-free piezoelectric beam

The Piezoelectric coupled-field analysis is represented as

$$\begin{Bmatrix} \{T\} \\ \{D\} \end{Bmatrix} = \begin{bmatrix} [C] & [e] \\ [eT] & -[\varepsilon] \end{bmatrix} \begin{Bmatrix} \{S\} \\ -\{E\} \end{Bmatrix}$$

A modal analysis is used to determine the natural frequencies and mode shapes of the structure for a given voltage. These are important parameters in the design of a structure for dynamic loading conditions. They are also required for carrying out a spectrum analysis or a mode superposition harmonic or transient analysis. The coupled-field with given boundary conditions and the applied voltage is given in Fig. 2.

Table II shows the natural frequencies of the beam for the given voltage of 20 V and the corresponding mode shapes are shown in Fig. 3

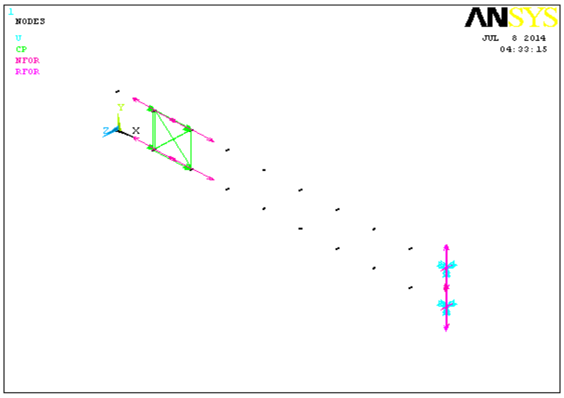
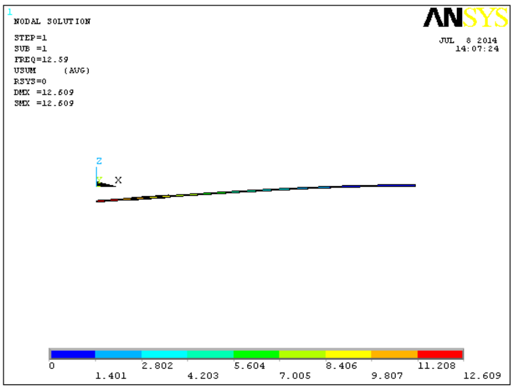


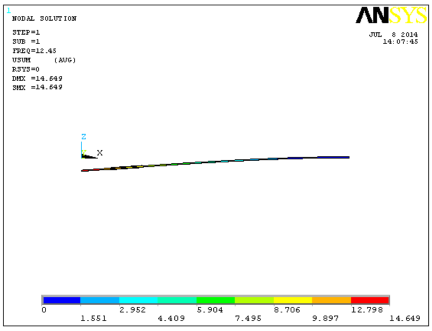
Figure 2: Coupled-field with Boundary condition and applied voltage

Table 2: Natural Frequencies of the aluminum & MILD STEELBeam

Natural Frequency of Beam		
Mode	ALUMINUM	MILD STEEL
1	12.59	12.45
2	99.33	99.04
3	299.86	299.64
4	302.29	302.18
5	365.18	364.85



(a)First mode shape of Aluminum beam



(b) First mode shape of Mild steel beam

Figure 3: Mode shapes for Beam

Placement of sensor

In the present work, the beam is considered to be made up of 9 elements. The analytical study using ANSYS is carried out by keeping the sensor for the entire length of the beam (9 elements) and observed the place where the maximum sensibility occurs. It is found the maximum sensibility occurs near to the clamped end. Fig. 4 shows the sensed voltage at different position of sensor.

```
         4    0.0000
         5    0.0000
         6    0.0000
         7    0.0000
         8    0.0000
         9    0.0000
        10   7.30751
        11   9.11742
        12  11.85612
        13  12.19608
        14  14.30254
        15  15.42624
        16  15.51147
        17  15.74444
        18  15.55248
        19    20.000

 MINIMUM VALUES
 ELEM          10
 VALUE    7.30751

 MAXIMUM VALUES
 ELEM          19
 VALUE     20.000
```

Figure 4: Sensed voltage at different positions

The dynamic response of structure under the action of any general time-dependent loads can be determined by using transient analysis. The results of the transient analysis in the present study for the uncontrolled and controlled vibration are given in Tables III and IV and are shown respectively in Figs. 5 and 6.

Table 3: Uncontrolled Vibrations at 20 V

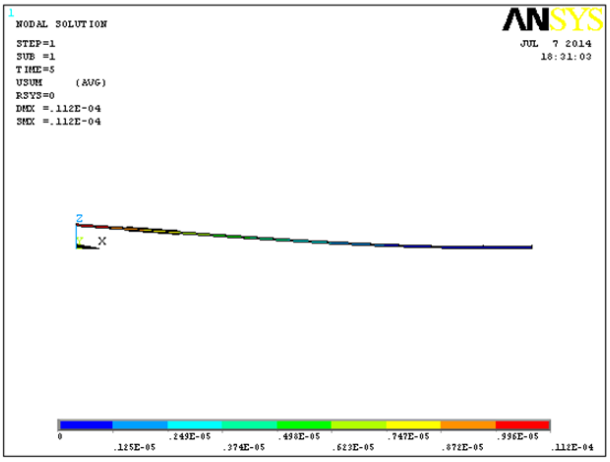
Applied volt (V)	Displacement (m)	
	Aluminum	Mild Steel
20	9.23E-05	8.40E-05

Table 4: Controlled Maximum Values

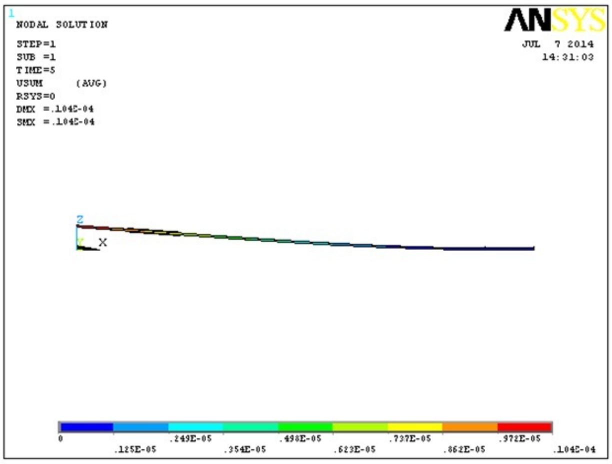
Position	Distance of controller from free end (m)	Displacement (m)		Controllability (%)	
		Al	M S	Al	M S
1	0.025 m	1.12E-05	1.04E-05	87.86	87.73
2	0.05 m	2.96E-05	2.75E-05	67.93	67.23
3	0.175 m	6.97E-05	6.41E-05	24.48	23.66
4	0.2 m	5.91E-05	5.44E-05	35.96	35.27

a)Max disp of Al beam 0.923e-4 m b)Max disp of MS beam 0.840e-4 m

Figure 5: Mode uncontrolled vibration



(a) Max displacement of Al beam : 0.112e-4 m



(b).Max displacement of MS beam : 0.104e-4

Figure 6: Controlled vibration at 0.025m

The comparison between controlled and uncontrolled peak values of the response was tabulated. The graph between the controller position and displacement was drawn for the applied voltage (20 V) and is shown in Fig. 7 (Figs 5, 6 and Tables III, IV). From the result it is observed that the use of a controller reduced the vibration by an amount of 87% approximately.

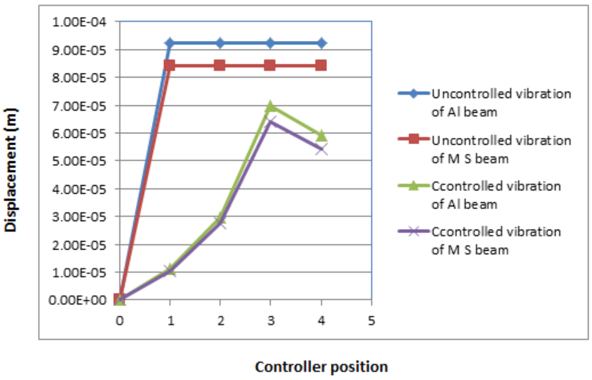


Figure 7: controllability chart

Experimental Setup

A schematic representation of the experimental setup is shown in Fig 8. The computer based Labview develops sine waveform. This waveform is sent to the function generator which generates the voltage signal. These signals were amplified by a piezoelectric drive amplifier. The PZT drive amplifier is a special device which is used to amplify the voltage from the order of ± 10V to ± 200V. The amplified signals were fed into the actuator by the ARB output channel in the PXI chassis. As the voltage was setup in the actuator in the form of sine wave, the actuator deflection continuously changes and vibration was created.

Once the beam starts vibrating, the time varying deflection was sensed by the sensor placed below and near to the clamped edge. As the beam deflected, the voltage was setup which is sensed by the sensor. These voltage signals were received by the oscilloscope through sensor. The computer received the voltage signal from the oscilloscope. A photograph of the experimental setup is shown in Fig. 9. Then the control voltage was fed to the controller through the NI-DAQ card. The controller controlled the vibration created in the beam.

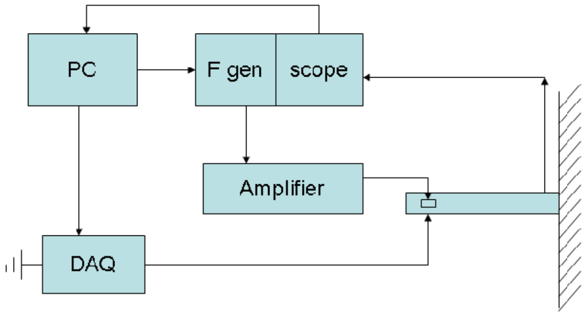


Figure 8: Schematic Representation of Experimental Setup

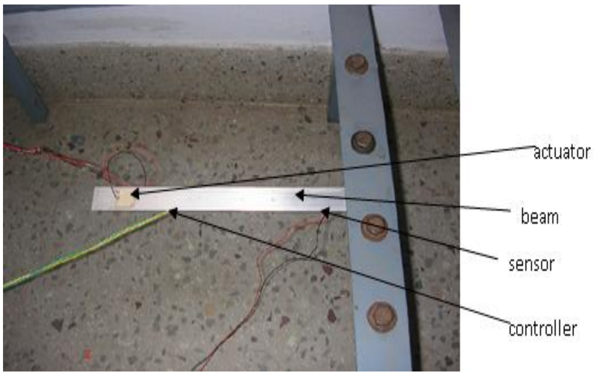


Figure 9: Experimental Setup

The location of the actuator, sensor and controller are given below Location of Actuator - Actuator is to create vibration of the beam. (top of the beam and 2.5cm way from free end)

Location of Sensor – Sensor is to sense the response of the vibration created by actuator. (below the beam and near fixed end)

Location of Controller – Controller is to control the vibration which is sensed by the sensor.(bottom of beam and exact position have to find)

Development of Control Algorithm

For the purpose of the overall smart structure design and simulation, besides the active sensor/actuator elements, an appropriate model of the controller is required. The procedure of the control law design, testing and verification in the framework of the finite element analysis represents a complex process.

A Linear Coupling Control was developed for a clamped – free beam model with surface bonded piezoceramic actuators is being used as the basis for the design of the control system. This model can be used for piezoceramics placed anywhere along the beam and can be used for the control of free and forced vibrations. One of the advantages of this approach is that the control strategy is ultimately capable of controlling free and forced vibrations in the structure. The model provides flexibility in actuator location and dimensions.

The piezo actuated cantilever beam is modeled as a primary and secondary systems coupled to each other. The primary structure is a cantilever beam modeled as a single-degree-of-freedom system. Consistent with the assumptions for an Euler Bernoulli theory, it is assumed that axial loads and rotary inertia are negligible and that plane sections remain plane and normal.

The controller or the secondary system is modeled as a single-degree-of-freedom linear oscillator which is coupled to the structure via linear terms. The result is a small actuating force, or weak coupling between the structure and controller which lends it well to piezoceramic actuation. This system is solved as a linear eigenvalue problem which provides a computationally efficient means of finding the response.

Determination of actuator gain

The controller gain of the active control system is determined by performing a set of analysis this is common for both beams. The tip deflections produced for applied actuation voltage are tabulated in Table V. From the tabulated results the actuation voltage to be applied to the actuator to produce a unit tip deflection is calculated. It is termed as control gain of the system. The voltage that was sensed when vibrating under an electrical disturbance is tabulated in Table VI.

Table V: Determination of Controller Gain

Test	Applied Voltage (v)	Displacement (m)
1	5	2.07E-04
2	10	4.14E-04
3	15	6.21E-04
4	20	8.28E-04

Actuator gain (Ga)=2.412 e4 V

The actuator requires 2.412 e4V to produce a unit deflection, when it is stressed by electric field.

Table 4: Determination of Sensor Gain

Sl. no	Applied Voltage	Displacement	Voltage from
	Va (V)	(m)	Sensor Vs (V)
1	5	2.07E-04	-0.3344
2	10	4.14E-04	-0.6678
3	15	6.21E-04	-1.0017
4	20	8.28E-04	-1.3356
5	40	1.66E-03	-2.6713

Sensor Gain G_s = -6.1992e -04 m. (i.e.) The Sensor requires 6.1992e -04 m to give a unit volt while stressed by mechanical strain.

Therefore,

Actuator gain G_a =2.412 e4 v/m

Sensor Gain G_s = -6.1992 e -04 m /v

Proportional-integral controller

The controller is the closed-loop system that processes information needed to perform the decision-making function. The controller can be considered the brain that enables automated systems to operate without human intervention.

The input applied to the controller is the error signal, which is the difference between the desired set point and the feedback signal. The controller calculates changes needed in the controlled variable to compensate for disturbances that upset the process, or changes in the set point. The controller responds to these changes by producing an output signal that drives the actuator to alter the controlled variable until the error signal is reduced to zero.

The integrals mode of control is designed to eliminate the offset inherent in proportional-mode control. It develops a control signal that depends on the absolute value of the offset. The integral mode does not function by itself. It is used along with the proportional control mode in the controller section of closed-loop system.

When an error signal first appears, the controller is tuned so that the proportional control signal returns the process to the desired control point. This proportional-control signal is immediate and fast acting. If a deviation between the set point and controlled variable is present after the operation of the proportional control mode is completed, an additional corrective is required, which is supplied by the integral control mode function. A small corrective action is developed slowly to reduce the deviation to zero only after it is certain that there is a definite steady-state error. Here the controller gain is 1.

Block diagram (Control Diagram)

The program is developed in Labview to perform the operation. The block diagram was used as a control diagram. The signal stimulator icon developed the sine wave signal. The frequency and number of samples per second is given as input parameter. The simulated wave was written to the LVM (Labview measurement file). These signals were fed to the NI-FGEN. It created the vibration in beam. From sensor voltage is sensed by oscilloscope and received by the software through NI-Scope Express. These sensed signals are in voltages and are to be converted into displacements by using the actuator gain. The displacement was written to the LVM file. Then displacement is covert into voltage signal by multiplying with sensor gain. Finally this voltage is sent to controller through DAQ. The controller responds to these changes by producing an output signal that drives the actuator (controller) to alter the controlled variable until the error signal is reduced to zero. The block diagram is show in Fig. 10.

In the present study, the investigation is carried out in two phases for both beams:

1. without controller (uncontrolled vibration)
2. with controller (controlled vibration)

Without controller:

Here actuator (top of the beam and 0.025 m way from free end) is placed on the beam and sensor is placed near to the clamped end, applied voltage is 20 v and readings are taken. The results of the study are shown in Fig.11 and in Table VII.

With controller:

Here actuator and sensor placed on the beam, the controller is placed at different position. The applied voltage is 20 V and readings are taken.

The positions of controller are:
Position 1: 2.5 cm from free end
Position 2: 5 cm from free end
Position 3: 17.5 cm from free end
Position 4: 20 cm from free end

The results of the study at different positions are shown in Fig. 12 and in Table VIII.

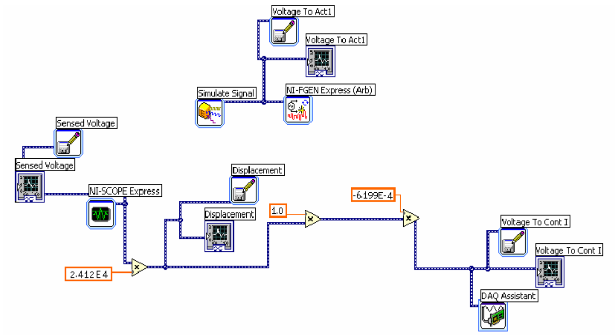
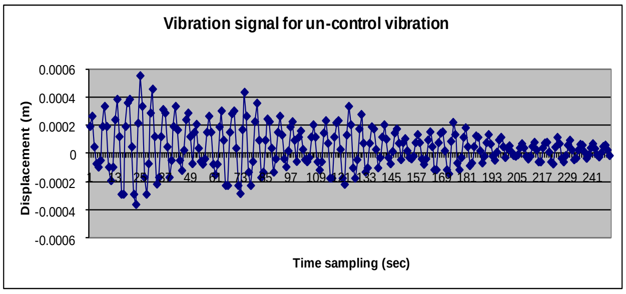


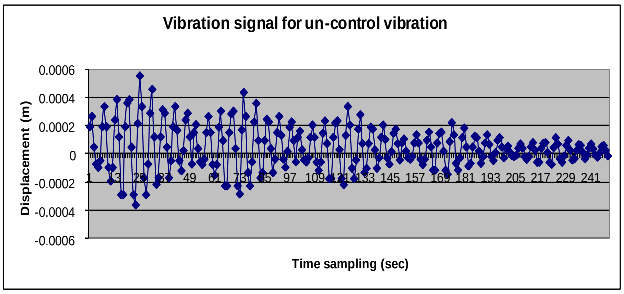
Figure 10: Block Diagram

Without controller



(a) Maximum uncontrol displacement of Al beam = 0.9725e-4 m

Figure 11: uncontrolled Vibration



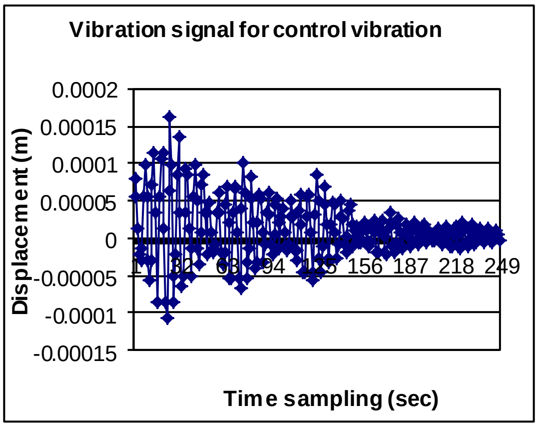
(b) Maximum uncontrol displacement of MS beam = 0.8753e-4 m

Figure 11: uncontrolled Vibration of beams

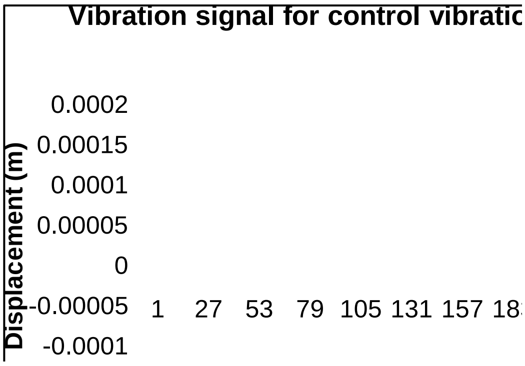
Table 7: Uncontrolled Maximum Displacements

Uncontrolled Vibrations at 20 V		
Applied volt (V)	Displacement (m)	
	Aluminum	Mild Steel
20	9.73E-05	8.75E-05

With controller



(a) Position 1: Max Controlled Disp = 1.67e-5 m of Al beam



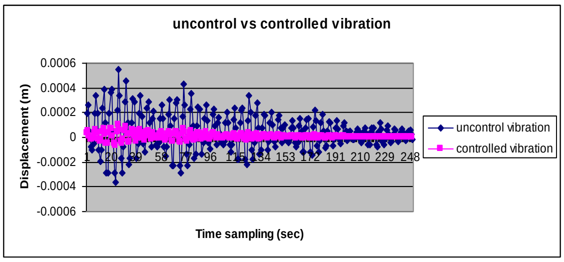
(b) Position 1:Max Controlled Disp = 1.6e-5 m of M S beam

Figure 12: Controlled Vibration at Position 1 of beams

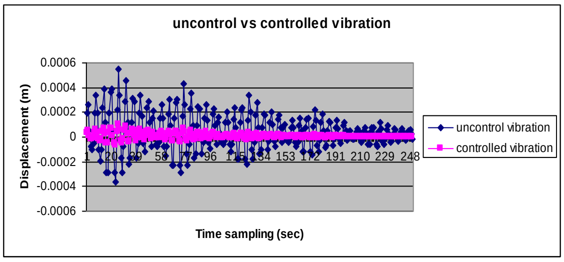
Table VIII: Controlled Maximum Displacements

Position	Voltage	Displacement (m)		Controllability (%)	
		Al	M S	Al	M S
1	20V	1.67E-05	1.60E-05	82.83	81.68
2	20V	2.75E-05	2.53E-05	71.72	71.09
3	20V	7.21E-05	6.56E-05	25.81	24.21
4	20V	6.54E-05	5.95E-05	32.75	32

A comparison between the maximum displacement of uncontrolled vibration and control vibration were shown Fig. 13



(a)Uncontrolled vs. Controlled Vibration of Al beam



(b)Uncontrolled vs. Controlled Vibration of MS beam

Figure 13: Uncontrolled vs. Controlled Vibration

The experiment was conducted with an applied voltage of 20 V. The vibration was setup and the response of the structures increased until the controller starts developing the control force. Once the control force was developed the vibrations were controlled by the control actuator. This vibration continued till the block diagram was aborted. The comparison of controlled and uncontrolled peak values of the response was tabulated and is shown in Fig.14. Hence, from the experiment it can be concluded that the maximum controllability occurs at position 1 and is found to be the optimal place for the controller in the present study.

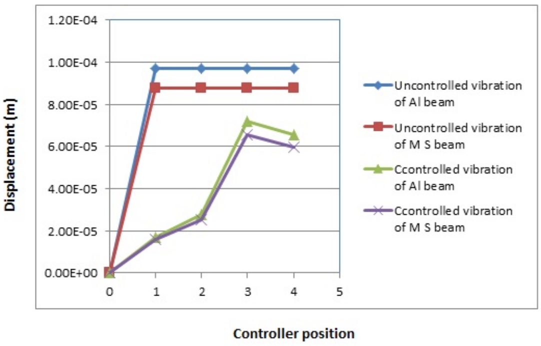


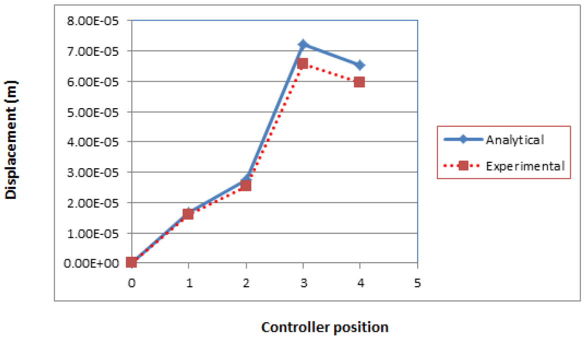
Figure 14: Maximum Controllability

Comparison of Result

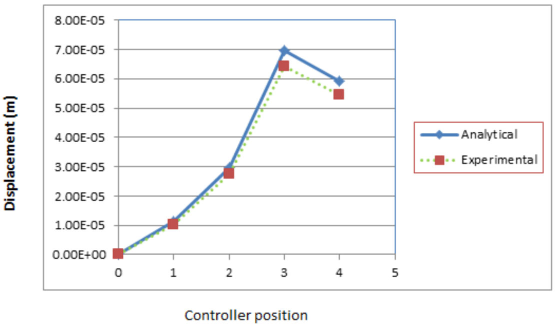
For the present study, cantilever beam of size 0.23 X 0.025 X 0.001 m is used in aluminum and mild steel beam. The actuator is placed at 0.025 m from free end on the topside of the beams. This actuator is used to induce the vibration. This vibration response is called as uncontrolled vibration. To sense the vibration signal sensor is sought place on the beam near to the clamped bottom end. The controller, which is used to control vibration, is placed at different locations, from which the optimum one is found out.

The uncontrolled vibration can be reduced by automatic modification of the system structural response. For automatic modification, system needs an active vibration control. For active vibration control a controller is needed and the controller should be placed in the position where the performance of the overall system is optimized. To find the optimum position of the controller the study has been carried out for the four different positions.

The experimental and analytical investigations (ANSYS) are carried out for these positions of controller and the results are given in Figs. 15 and 16.

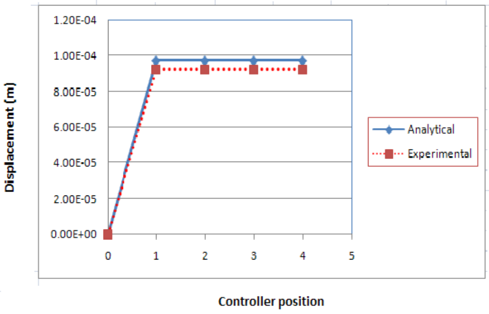


(a) Controlled Vibration of Al beam

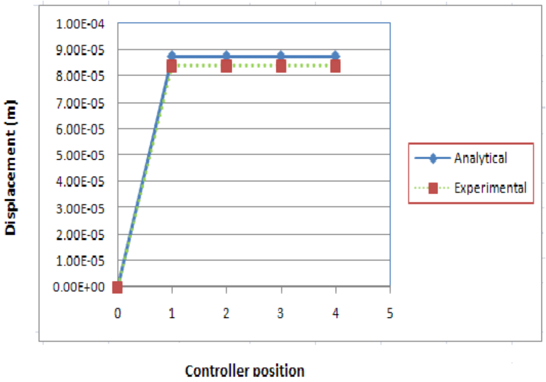


b) Controlled Vibration of MS beam

Figure 15: Controlled Vibration



a) UnControlled Vibration of Al beam



b) UnControlled Vibration of MS beam

Figure 16: Uncontrolled Vibration

Conclusions

In the present investigation, modeling, analysis and simulation of active vibration control on aluminum and mild steel cantilever beams using piezoelectric actuator are carried out and result are compared. The finite element model of the piezo actuated beams are developed using the finite element software package ANSYS. A modal analysis is carried out to find the natural frequencies and the first natural frequency is given as an input parameter for experimental setup. A transient analysis was carried out to investigate the dynamic behavior.

The experimental setup is made by interfacing the software and hardware and the instruments are calibrated. A state feedback algorithm is developed, which gave better results. A Labview block diagram was developed, which is found to be suitable for vibration control of structures. Labview software was used to interface the computer based control of the beam.

First experiment was conducted to simulate the beams to find the uncontrolled vibration, and then the experiment is carried out by placing the controller at different position to find maximum controllability position and finally controller is placed on that position.

This principal is common for both beams. Similar work is carried out in FEA package ANSYS. Experimental and ANSYS models were compared to find maximum controllability.

In the experimental investigation, the study is carried out at four different positions of the controller and in analytical studies; it is carried out at all the nine elements considered in the analysis. The results of both the Al and MS beam show that the position of the controller to get maximum controllability is at a distance of 0.025 m from the free end. The result also shows that the use of controller at this position reduced the vibration by an amount of 87 % approximately.

References

[1] Junfeng, H.U., and GUITANG, X.U., 2013, “Vibration control of piezoelectric flexible structure using robust control methodology,” Journal of theoretical and Applied information Technology., Vol. 50 (2), pp. 309-318.

[2] Waghulde, K.B., and Kumar, B., 2012, “Active vibration control of a cantilevered smart structure by using spatial h∞ control technique,” International journal on smart sensing and intelligent systems., Vol. 3 (1), pp. 64-69.

[3] Waghulde, K.B., and kumar, and B., Sinha., 2010, “Vibration control of cantilever smart beam by using piezoelectric actuators and sensors,” International Journal of Engineering and Technology., Vol.2(4), pp. 259-262.

[4] Pratik, K., Gandhi, J.R., Mevada., 2013, “A finite element model and active vibration control of composite beams with distributed piezoelectrics using third order theory.,” International journal of engineering research and application.,Vol.3(3), pp.940-945.

[5] Junfenu, H.U., and Gulyang, X.U., 2013 “Vibration control of piezoelectric flexible structure using robust control methodology,” Journal of theoretical and applied information technology., Vol.50(2), pp. 309-318.

[6] Michel, G.H., and Daniel**,** N., 1998, “Finite Element Analysis and Active Vibration Control of a Cantilever Beam,” IEEE Proceedings., pp. 37-40.

[7] Gaudenzi, Palo., 2000, “Control of Beam Vibrations by Means of Piezoelectric Devices: Theory and Experiments,” Composite Structures., Vol. 50(4), pp. 373-379.

[8] Moheimani., 2000, “Experimental Verification of the Corrected Transfer Function of a Piezoelectric Laminate Beam,” IEEE Control systems.,Vol. 8(4), pp. 660-665.

[9] Moheimani., and S.O.R. yall.T., 1999 “Considerations in placement of piezoceramic actuators that are used in structural vibration control,” Proceedings 38th IEEE conference Decision Control, Phoenix,AZ, pp. 1118-1123.

[10] Trindade., and jue, J., 2002, “An Electromechanically Coupled Finite Element to handle passive damped multilayer sandwich beams,” Composite Structures., Vol. 52(6), pp. 376-382,.

[11] Balamurugan,V.,and Narayanan,S., *2003, “*Finite Element Modeling of Piezo laminated Smart Structures for Active Vibration Control with distributed Sensor and Actuators,” Journal of Sound and Vibration.,Vol.183(5), pp. 797-817.