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STUDY ON VIBRATION CHARACTERISTICS OF PZT ACTUATED MILDSTEEL AND ALUMINIUM CANTILEVER BEAMS

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ABSTRACT: Considerable attentions have been devoted recently to active vibration control using smart materials as actuators. This study presents an active vibration control technique applied to a smart beam. The smart beam consists of Aluminum and mild steel beams modeled in cantilevered configuration with surface bonded piezoelectric (lead-Zirconium-Titanate-PZT) patches .The natural frequency of smart beams were found using finite element code for first four modes by varying the location of actuator from the fixed end of the structure, and it has good agreement with analytically found natural frequency. An experimental apparatus has been developed to study the vibration suppression of the smart beams. The free vibration of the mild steel and aluminum beams were carried out by varying the initial displacement and input voltage to the PZT in order to find out the settling time and the damping factor of both of the beams. The results shows that the aluminium beam will have little more damping effect than mild steel leads to less settling time of aluminum.

KEYWORDS: Active Vibration Control (AVC), piezoelectric (PZT), Actuator, ANSYS

❖ INTRODUCTION

Flexible structures usually have low flexible rigidity and small material damping ratio. A little excitation may lead to destructive large amplitude vibration and long settling time. These can result in fatigue, instability and poor operation of the structures. Vibration control of flexible structures is an important issue in many engineering applications, especially for the precise operation performances in aerospace systems, satellites, flexible manipulators, etc.

When a structure is undergoing some form of vibration, there are a number of ways in which this vibration can be controlled. Passive control involves some form of structural augmentation or redesign, often including the use of springs and dampers, which leads to a reduction in the vibration. Active control augments the structure with sensors, actuators and some form of electronic control system, which specifically aim to reduce the measured vibration levels.

Advances in smart materials have produced smaller and effective actuators and sensors with high integrity in structures. Many types of smart materials are well accepted for consideration as actuating and sensing devices: they include piezoelectric (PE), electrostrictive (ES), magnetostrictive (MS), shape memory alloy (SMA), electrorheological and fibreoptic materials. In general, PE and ES materials have low saturation strain and force generation, and large percentage of loss of strain unless operated within a very small range of temperature.

On the other hand, MS actuators provide better saturation strain, moderate force, fast response and low power requirements compared with actuators made from the PE and ES materials. However, due to the need for permanent magnets and magnetic return path, an inherent advantage of this type of material actuators is that both coils and magnetic return adds an additional weight and volume.

Among the many materials, piezoelectric and shape memory alloys are most suitable for active control of the development of smart composite structures. They are able to generate a relatively large deformation. The drawbacks of SMA based actuators are comparatively slow response time [5, 6]. Piezoelectric materials like (lead-Zirconium-Titanate) can be used effectively in the development of smart systems. So far a large amount of work has been devoted exploring smart structures with piezoelectric actuation. Some of them suggested strategies have already found in practical applications in vibration control. Materials with piezoelectric properties have been found to exhibit pyroelectric and electrocaloric properties for the possible conversion of thermal energy into electrical energy, and vice versa. Conversion of thermal in to mechanical energy and vice-versa by means of thermal expansion together with piezo-caloric effect can be observed in piezo-thermoelectric materials. These effects can be used to increase the efficiency of the control actuation. The corresponding interaction of mechanical fields certainly represents an increase in the complexity of the problem [1].

A finite element formulation of vibration control and suppression of intelligent structures with a piezoelectric plate element with a help of negative velocity feedback control law is presented and validated using numerical examples by Chen et all [2]. An analytical formulation for laminated composite beams with piezoelectric actuator (PVDF) and sensor has been developed based on first order shear deformation theory [3].

Kermani et all, [4] suggested that decreasing the PZT thickness improves its performance even if it is accompanying some voltage reduction. They also concluded that the placement of the PZT actuator in the beam is a function of nodes to be controlled. The use of PZT actuator has been proposed as an alternative, where the electric field is perpendicular to the direction of polarization to cause shear deformation of the material. Active vibration suppression is implemented with positive position feedback (PPF) and velocity feedback [7]

Hu YR and Vukovich G [8] investigated on robust shape control of flexible aluminium plate with bonded PZT actuators and strain sensors. They have developed a mathematical model using Hamilton's principle and experimentally validated for robustness.

The adaptive shape control for vibration suppression of a cantilever beam using piezoelectric damping -modal actuator/sensor has been presented [9]. The dynamic behaviour of the smart system is described with linear equations with modal actuator. The importance and effect of the fiber orientation and appropriate actuator location had been explained. A dynamic model has been developed for vibration control in a silicon dioxide micro-cantilever beam with surface mounted PZT actuators [10]. Mode shapes and variation of natural frequency have been studied using ANSYS. The actuator placed close to the beam centre performed better than those located at the other position. The optimal placement of PZT patches has been done using genetic algorithm technique [11].

In the research paper [12], they have been studied analytically about optimizing the thickness and width of the PZT actuators. They concluded that the width is better design variable than the thickness. Experimental study on active vibration control of cantilever beam with PZT actuator is done and simulated using ANSYS.

The proposed work is to study the vibrational characteristics of Aluminium and Mild steel beams with surface bonded PZT. Also to find out the optimum location of the actuator to have a better vibration suppression.

❖ ANALYSIS OF VIBRATION ON BEAMS

For a simple elastic beam problem with uniform cross-sectional area, a well-known natural frequency can be calculated by

$$\omega_n = \frac{1}{2\pi}(\beta l)^2 \sqrt{\frac{EI}{\rho A l^4}} \tag{1}$$

where A and l are the area of cross-section and the length of the flexible beam, respectively. Bl is a constant relative to the vibration bound condition. The constant Bl for first four modes of a cantilever configuration are 1.87504, 4.690491, 7.854757, and 10.995541 respectively. EI is the equivalent bending stiffness.

The natural frequency of the steel and aluminium beams are found by the well known Finite Element (FEM) Software. Modal analysis and harmonic analysis are carried out using ANSYS software for finding the natural frequencies. The first mode shape of the mild steel and aluminium is shown in Figure1 and Figure2 respectively. The first four natural frequencies of the steel and aluminium beams are shown in the Table 1.

Table 1. First four natural frequencies of steel and aluminium beams

Mode	Mild steel		Aluminium	
	f Analytical (Hz)	f ANSYS (Hz)	f Analytical (Hz)	f ANSYS (Hz)
1	2.546	2.5444	2.572	2.5683
2	15.942	15.946	16.092	16.096
3	44.706	44.659	45.126	45.079
4	87.606	87.575	88.430	88.398

A beneficial characterization of the smart materials is their good damping property. Several damping parameters, such as inner fraction, loss factor and loss tangent tan Δ have been used individually or combined for metals, ceramics, and rubbers, according to the material properties and test methods. For the smart materials, the logarithm attenuation coefficient is used, which can be evaluated by measuring the vibration amplitude during the experiment. A classical damping equation for vibration beams is expressed in the form of

$$\Delta = \frac{\ln x_n}{x_{n+1}} \tag{2}$$

where x_n and x_{n+1} are the amplification of sine wave with logarithm damping in different intervals.

$$\xi = \frac{\Delta}{\sqrt{(2\pi)^2 - \Delta^2}} \tag{3}$$

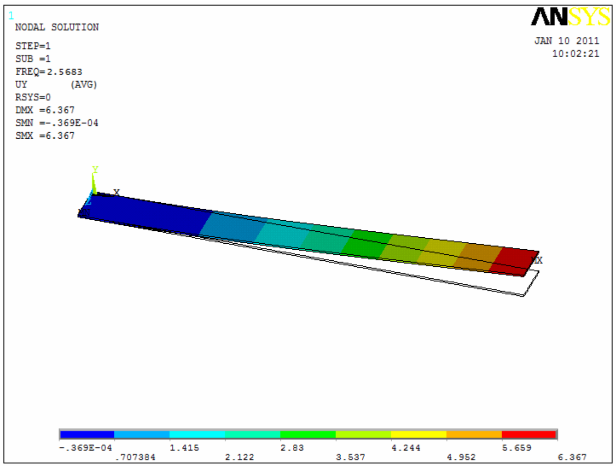

Figure 1. First Mode shape of Mild steel beam

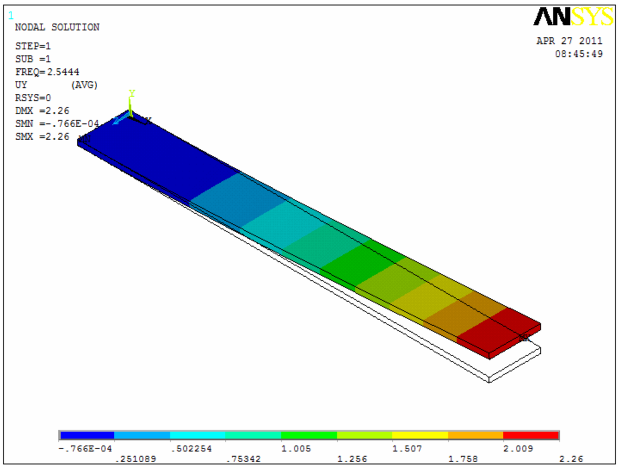

Figure 2. First Mode shape of Aluminium beam

❖ EXPERIMENTAL WORK

In order to verify the effectiveness of vibration control strategies, the real time experimental setup shown in Figure1 is designed and built. The setup consists of the following four main parts: if) the beam under test with the externally bonded piezoelectric actuators and, the fixture ii) time and actuation circuit iii) shaker system with the controller iii) computer with interfaced Lab VIEW software to process the measured signal and issue the appropriate control signal. The vibrations are picked up using an accelerometer pickup and the values are given to the Lab VIEW software. The interface is done by using a PXI module. The Lab VIEW block diagram is shown in fig 4.

A clamped-free beam fixed horizontally along its width is considered in this study. The dimensions and material properties of the steel and aluminium beams, PZT are listed in Table 2 and Table 3 respectively. PZT (Lead Zirconate Titanate) of type SP-5H from Sparkler Ceramics Pvt. Ltd is used in this study.

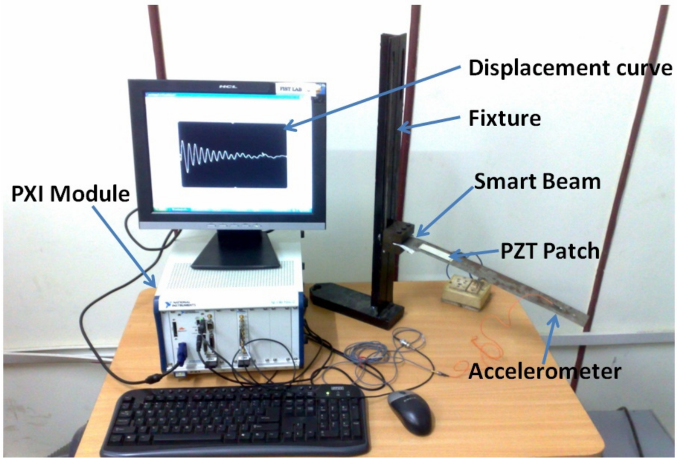

Figure 3. A real-time experimental setup

Table 2. Material Properties and Dimensions of a Aluminium and Mild steel beam

Dimensions/Properties		Mild steel	Aluminium
Length (m)	*l*	0.4	0.4
Width (m)	*b*	0.05	0.05
Thickness (m)	*t*	0.005	0.005
Young's modulus (GPa)	*E*	200	70
Density (kg/m^3)	*ρ*	7850	2700

Table 3. Material Properties and Dimensions of a PZT Actuator

Material Properties	Piezoelectric Coupling Co-efficient	K_p	0.63
		K_{33}	0.73
	Piezoelectric Charge Constant (X10^{-12} C/N)	D_{33}	550
		D_{31}	-247
	Piezoelectric Voltage Constant (X10^{-12} C/N)	G^{33}	20
		G^{31}	-9
	Relative Dielectric Constant, (Low Signal)	K^t_3	3100
	Dissipation Factor	tan δ	0.020
	Density (kg/m^3)	ρ	7500
	Curie Temperature (^{o}C)	T_C	190
	Mechanical Quality Factor	Q_m	65
	Frequency Constants (Hz-m)	N_p	1950
		N_t	2000
Dimensions	Patch length (mm)	P_l	76.2
	Patch width (mm)	P_w	25.4
	Patch thickness (mm)	P_t	0.5

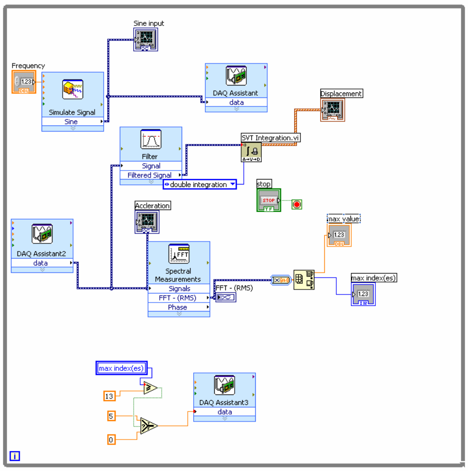

Figure 4. Block diagram of the LabVIEW program

Using the experimental setup as described the beam was vibrated freely for preset displacement values say 40, 50, 60 mm and the graphs for settling time were obtained. First the PZT patch was glued to the surface of the beam at a distance of 25 mm from the fixed end using araldite. The beam was then clamped in the fixture at a desired height. The accelerometer pickup was placed over the beam at the free end for sensing the displacement in that position. The signals from the accelerometer were sent to the PXI module where it was interfaced with Lab VIEW for displaying the displacement curves.

The PZT patch was actuated by means of an auto transformer whose output can be varied from 0-100V AC. The input for the transformer given was 220V AC. The voltage given to the patch was varied as 0, 25, 50, 75 V for various displacement values and the settling time was found out.

Results And Discussions - Influence Of Position Of PZT Actuator On Natural Frequency

PZT actuator patch is surface bonded at different locations from the fixed end. The vibration characteristics of the Aluminum and Mild steel beam with PZT actuator is investigated by bonding the PZT patches at different locations and voltage given to PZT actuator is varied.

The influence of location of PZT patch onto the surface of the beam was studied separately for mild steel and aluminium. The smart beam was divided into eight equal segments. The first segment, located on the fixed end of the beam had the high stiffness. The eighth segment, located on the free end of the beam had the low stiffness. The beam and the PZT patch were modeled in ANSYS and were glued together and analyzed for natural frequency with fixing the beam at one end. The ANSYS models of beam with PZT patches at various locations are shown Figure 5. Due to addition of PZT patch on the mild steel and aluminium beams the mass and stiffness of the beam gets increased but not proportionally. So the natural frequency of the beam is also gets increased. The percentage of increase of the mass and stiffness is tabulated in the Table 4.

Table 4. Mass and stiffness of smart beams

Beam materials	Mass (Kg)		% Increase in mass	Stiffness (N/m)		% Increase in stiffness
	Passive beam	Smart beam		Passive beam	Smart beam	
Mild Steel	0.0786	0.08588	9.26	0.5095	0.6447	26.53
Aluminium	0.0270	0.03428	26.96	0.1786	0.2540	42.21

Table 5. Natural frequencies in Hz for various PZT Actuator positions in mild steel beam

Modes	Location of PZT Actuator (centre point) in mm							
	58	96	134	172	210	248	286	324
First mode	2.7132	2.7223	2.7411	2.8111	2.7483	2.7176	2.6903	2.6963
Third mode	20.646	22.504	22.851	30.192	18.831	18.528	18.093	17.976
Third mode	43.780	51.169	48.092	44.127	44.192	42.630	42.418	42.341
Fourth mode	59.814	65.849	75.886	86.990	68.047	61.039	57.626	56.703

Table 6. Natural frequencies in Hz for various PZT Actuator positions in aluminium beam

Modes	Location of PZT Actuator (center point) in mm							
	58	96	134	172	210	248	286	324
First mode	2.7389	2.7413	2.7666	2.8375	2.7744	2.7430	2.7156	2.7216
Third mode	20.840	22.542	23.066	30.476	19.008	18.702	18.263	18.145
Third mode	44.192	51.860	48.544	44.542	43.598	43.031	42.817	42.739
Fourth mode	60.377	67.479	76.600	87.808	68.687	61.613	58.168	57.236

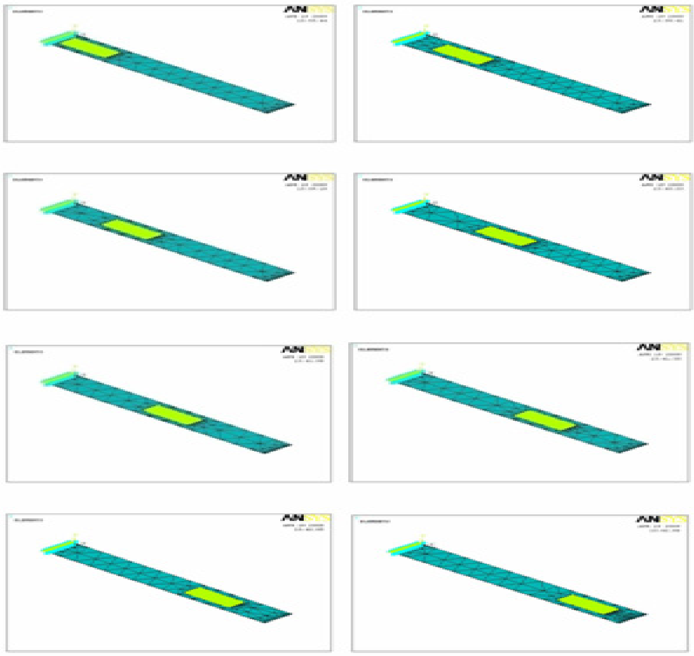

Figure 5. PZT patches at various locations on the beam

It is well known that location of actuators has a significant influence on vibration control of mechanical structures. In order to do so, the PZT actuator was shifted from the fixed end to the opposite end. In every step (repeated 8 times), the first four natural frequencies are calculated. The calculated for mild steel and aluminum beams with surface bonded PZT actuators at various locations are listed in Table 5 and Table 6 respectively. From the Table 5 & 6 it can conclude that the natural frequency of the steel and aluminum beams are high when the PZT actuator is bonded near the centre of the beam.

Results And Discussions - Damping Characteristic

Using the experimental set up shown in Figure3, the beam was vibrated freely for preset displacement values say 40, 50, 60 mm and the graphs for settling time were obtained. The PZT patch was glued to the surface of the beam at a distance of 25 mm from the fixed end. The Figure6-9 shows that the settling time of the Aluminium with PZT patches at 0V, 25V, 50V and 75V respectively for initial displacement of 40mm. From these figures it can be inferred that as the voltage for the PZT patches increases the Aluminium beam's settling time decreases.

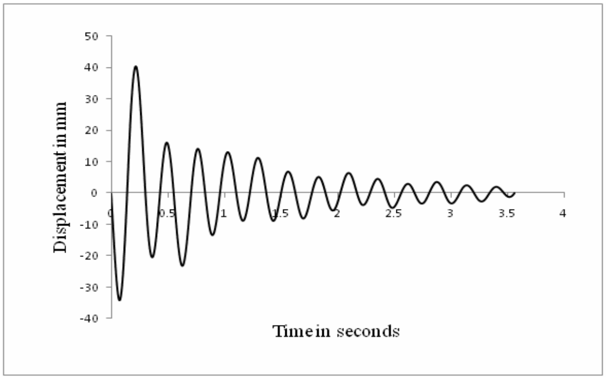

Figure 6. Settling time of Aluminium beam with initial displacement of 40 mm at 0V input

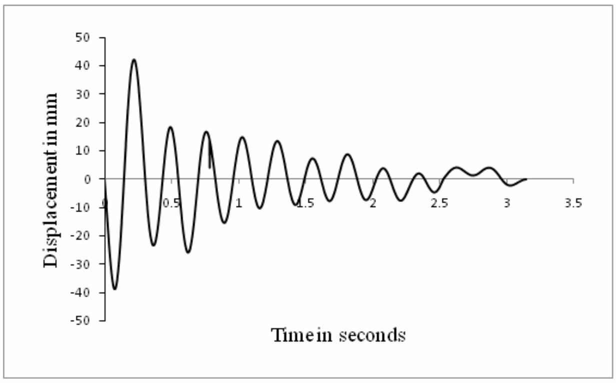

Figure 7. Settling time of Aluminium beam with initial displacement of 40 mm at 25V input

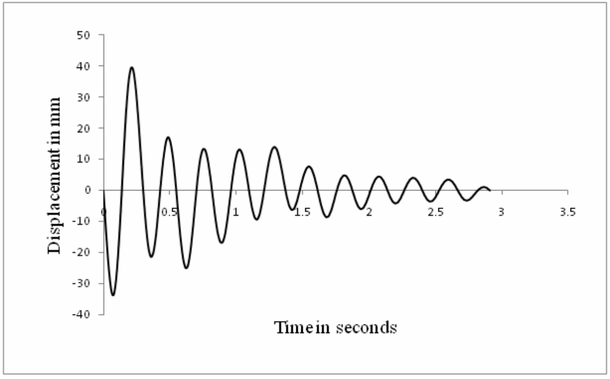

Figure 8. Settling time of Aluminium beam with initial displacement of 40 mm at 50V input

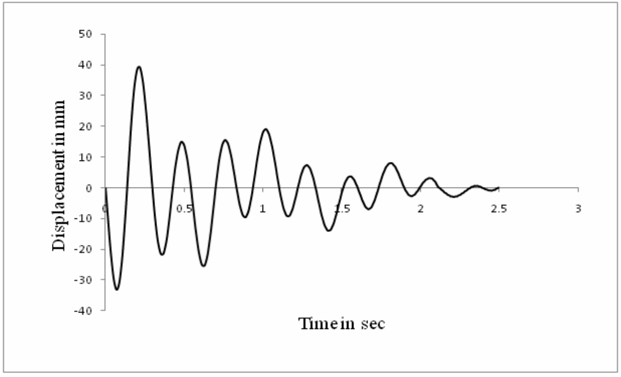

Figure 9. Settling time of Aluminium beam with initial displacement of 40 mm at 75V input

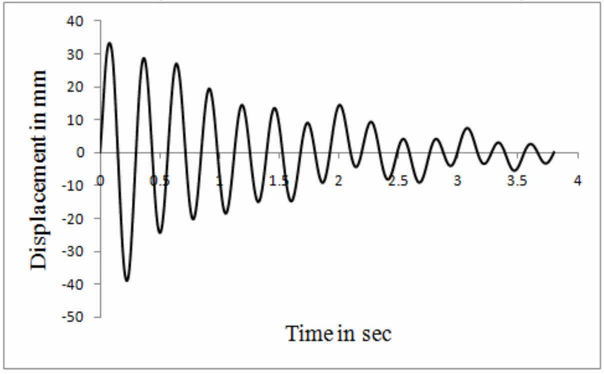

Figure 10. Settling time of Mild steel beam with initial displacement of 40 mm at 0V

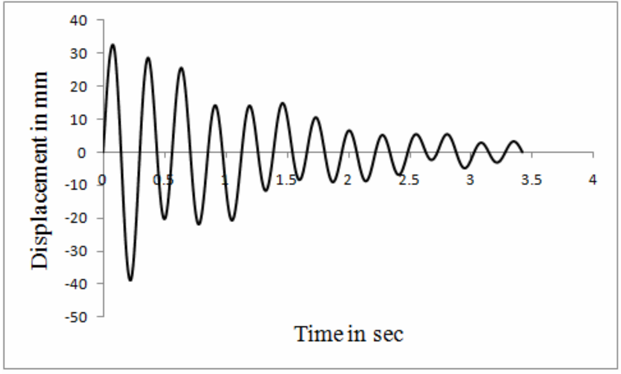

Figure 11. Settling time of Mild steel beam with initial displacement of 40 mm at 25V input

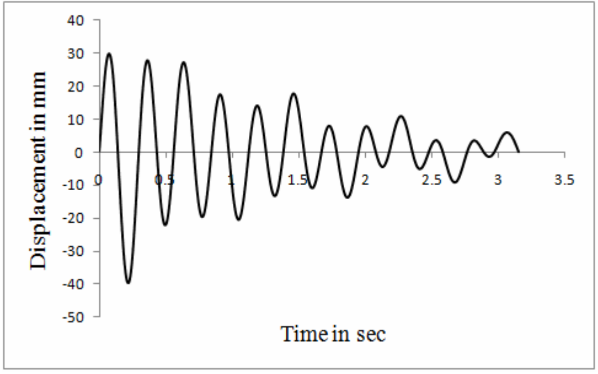

Figure 12. Settling time of Mild steel beam Actuator with initial displacement of 40 mm at 50V input

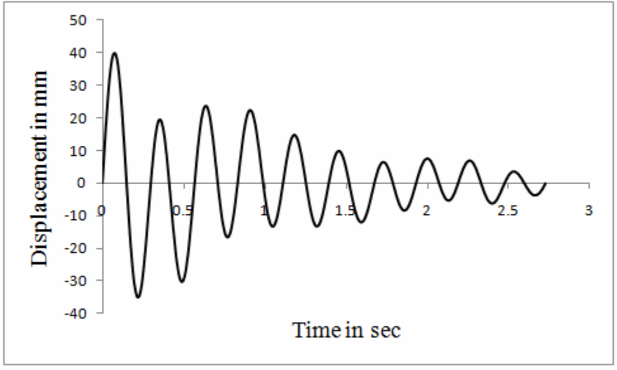

Figure 13. Settling time of Mild steel beam with initial displacement of 40 mm at 75V input

The Figure 10 -13 presents the settling time of the Mild steel beam with PZT patches at 0V, 25V, 50V and 75V respectively for the initial displacement of 40mm. From these figures it can be inferred that as the voltage for the PZT patches increases then the settling time decreases.

The settling times for various initial displacements were compared in Table 7 for various voltage input to the PZT patch. The settling times were found to decrease for increase in the voltage input to the PZT for a constant initial displacement. But it kept increasing when the initial displacement was increased for a constant voltage input to PZT.

Table 7. Settling time for varying voltages and displacements

Settling time in Seconds						
Voltage/ displacement	40 mm		50 mm		60 mm	
	M S	Al	M S	Al	M S	Al
0 V	3.800	3.559	4.037	3.855	4.585	4.147
25 V	3.412	3.145	3.567	3.431	4.101	3.816
50 V	3.151	2.909	3.300	3.198	3.838	3.442
75 V	2.730	2.494	2.968	2.838	3.372	3.222

The beam has a constant damping factor for free vibrations. So, the vibrations which decay exponentially will have higher settling times for higher initial displacement values.

Table 8. Damping Factors for various voltages

Beam materials	Damping factor ζ			
	0V	25V	50V	75V
Mild Steel	0.0376	0.0434	0.0440	0.0452
Aluminium	0.0389	0.0448	0.0465	0.0480

Using equation (2) and (3) the logarithmic attenuation coefficient i.e damping factor were calculated for Aluminum and Mild steel beams with PZT actuator at 0, 25, 50, and 75 volts which is listed in the Table 8. From the Table 8 it can be inferred that the logarithm attenuation coefficient of the smart beam increases with increasing the voltage to the PZT patches.

The damping factor for aluminum is greater than that of mild steel (Table 8) which causes the vibrations to decay sooner. Due to the higher mass of mild steel than aluminum (Table 4), the inertial forces will be high, resulting in higher settling time. Also the higher stiffness of mild steel (Table 4) reduces the effect of PZT actuator in vibration damping. All these reasons account for greater settling time in mild steel than in aluminum.

❖ CONCLUSIONS

Smart materials will control the system in terms of reducing the vibrations amplitude and frequency so as to improve the efficiency of the system. The design, characterization and testing of PZT actuator for vibration control applications has been presented. In this study, it can be found that the PZT actuators can be used for active vibration control. The settling time of the smart structures is decreased and logarithmic attenuation coefficient is also increased by increasing the input voltage to the PZT actuators. The positions of actuators have a critical influence on the natural frequencies of smart structures. For maximum effectiveness the actuators must be placed in high strain regions and away from areas of low strains. Thus the vibrations in a cantilever beam were suppressed by applying variable voltage to the piezoelectric actuator.

❖ ACKNOWLEDGEMENT

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❖ REFERENCES

[1.] Irschik H, 2002, "A Review on static and dynamic shape control of structures by piezoelectric actuation", Engineering Structures 24: 5 - 11.

[2.] Chen SH, Wang ZD, LiuXH, 2002, "Active Vibration control and suppression for intelligent Structures", Journal of Sound and Vibration 2: 167 - 177

[3.] Sun B, Huang D, 2001, "Vibration Suppression of laminated beams with piezoelectric damping layer" Composite Structures 53: 437 – 447.

[4.] Kermani MR, Moallem M, Patel RV, 2002, "Optimizing the performance of piezoelectric actuators for active vibration control". Proceedings of the 2002 IEEE Conference on Robotics and Automation, Washington DC: 2375 - 2380.

[5.] Yuvaraja M., Senthilkumar M., 2010, "Vibration Control Of GFRP Composite Beam Using SMA-Flexinol Actuators", Annals of Faculty Engineering Hunedoara - International Journal of Engineering, Fascicule 3: 288 – 295.

[6.] Yuvaraja M., Senthilkumar M., 2010 "Active Vibration Control of SMART Composite structure - A Review", National Journal of Technology 6: 27 - 24.

[7.] Hu YR, Vukovioch G, 2002 "Active robust shape control of flexible structures", Mechatronics, 288: 43-56.

[8.] Vel SS, Baillargeon B.P, 2004, "Active vibration suppression of smart structures using piezoelectric shear actuators", proceedings of the 15th international conference on Adaptive structures and technologies, Bar Harbor, Maine.

[9.] Lin JC, Nien MH, 2005, "Adaptive control of a composite cantilever beam with piezoelectric damping-modal actuators/sensors", Composite Structures 70: 170–176.

[10.] Zhang W, Meng G, Li H, 2006, "Adaptive vibration control of micro cantilever beam with piezoelectric actuator in MEMS" International Journal of Advanced Manufacturing Technology 28: 321–327.

[11.] Moita JS, 2008, "Optimal dynamic control of laminated adaptive structures using a higher order model and a genetic algorithm" Computers and Structures 86: 198-206.

[12.] Donso A, Sigmund O, 2008, "Optimization of bimorph actuators with active damping for static and dynamic loads", Sturct Multidisc Optim-Springer Verlag 3: 375–386