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Comparative study on Vibration Characteristics of a Flexible GFRP Composite beam using SMA and PZT Actuators

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Abstract

Shape memory alloy and piezoelectric based composites are presented for investigating the vibration characteristics. In former case, GFRP beam modeled in cantilevered configuration with externally attached SMAs. In later case, GFRP beam with surface bonded PZT patches are analysed for its vibration characteristics. The experimental work is carried out for both cases in order to evaluate the vibration control of flexible beam for first mode, also to find the effectiveness of the proposed actuators and verified numerically. As a result the vibration characteristic of GFRP beam is more effective when SMA is used as an actuator.

Keywords: GFRP, SMA, PZT, Vibration Control

1. Introduction

Composite 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, composite 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.

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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 fibre optic materials. A good start has been made in the field of SMA research in developing the models of describing the shape memory behaviour. Tanaka [1] modelled the shape memory behaviour first in terms of exponential function. He developed a consecutive equation to get the stress-strain curve for SMAs isothermal conditions. This concept is maintained but Liang and Rogers [2] developed the concept by changing the consecutive relations for the martensite volume fraction. Liang and Rogers modelled the martensite volume fraction as cosine models. Liang and Rogers have found that the four cases for the applications of SMAs in Vibration control. (i) By utilizing the high damping characteristics of SMA, (ii) Utilizing the hysteretic damping of SMA, (iii) Utilizing the variable stiffness of SMA and (iv) Using shape memory effect.

Baz, Imamand and Levent [3] studied theoretically and experimentally, the feasibility of utilizing SMA in the flexural vibrations of a composite cantilever beam. They concluded that the use of two Nitinol actuators for each degree of freedom will effectively damp the vibration. They also indicated that increasing the input power to the actuators is found to be in damping out the structural vibrations but at the expense of degrading the stability of the control system. Baz, Poh and Gilheany [4] studied the control of natural frequencies of Nitinol-reinforced fibreglass composite beams. They also demonstrated that control in natural frequencies of composite fibre glass could be achieved by activating optimal set of SMA wires which are embedded along the neutral axis of the beams (simply supported).

Baz, Chen and Ro [5] studied the shape control of Nitinol reinforced composite beams. They consider an alternate way of controlling the shape of the Nitinol reinforced composite such that the full potential of the shape memory effect can be utilized without considering the stiffness of the composites. They developed the shape control action for the Nitinol reinforced composite beams. They also demonstrate control action by actuating the SMA strips which are embedded along the neutral axis of the composite beam (Cantilever). Hashemi and Khadem [6] studied the vibration behaviour of the SMA beam. They used the Aurcchio's SMA model for modelling the superelastic behaviour of the SMA beam. They found the free and forced response of the SMA beam. They concluded that the presence of different elastic modules at austenite and martensite phases causes a change in system stiffness and consequently variation in natural frequencies, which leads to an escape from resonance conditions.

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 was discussed by Irschik [7]. 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 [8]. An analytical formulation for laminated composite beams with piezoelectric actuator (PVDF) and sensor has been developed based on first order shear deformation theory [9]. Kermani et all, [10] 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 was investigated by Vel and Baillargeon [11].

Yuvaraja and Senthilkumar [12-13] have studied the importance of SMA in controlling the vibration of flexible structures of GFRP with different fiber orientations. In this proposed work the vibrational characteristics of GFRP beam with SMA and PZT are compared to find the effectiveness of the above smart materials in damping out the vibration.

Nomenclature

A	Area of cross section of laminated beam in m^2
l	Length of the beam in m
b	Width of the beam in m
h	Thickness of the beam in m
D	Diameter of the SMA wire in mm
E_c	Young's modulus of GFRP in GPa
E_s	Young's modulus of lamina composed of SMA and GFRP in GPa
EI	Equivalent bending stiffness in N-m
βl	Constant relative to vibration bound condition
V_{SMA}	Volume fraction of SMA

2. Smart Materials

2.1. Shape Memory Alloys

Shape memory alloys (SMA) having the composition in the range of 53-55% of nickel. SMA's have been widely employed as actuators and sensors in applications including smart structures, biomedical devices, and robotics. SMA's have the ability to return to a predetermined shape when heated. When an SMA is cold, or below its transformation temperature, it has a very low yield strength and can be deformed quite easily into any new shape which it will retain. However, when the material is heated above its transformation temperature it undergoes a change in crystal structure which causes it to return to its original shape. If the SMA encounters any resistance during this transformation, it can generate extremely large forces. This phenomenon provides a unique mechanism for remote actuation.

SMA has very good electrical and mechanical properties, long fatigue life, and high corrosion resistance. As an actuator, it is capable of up to 5% strain recovery and 345MPa restoration stress with many cycles. By example, a Nitinol wire 0.50mm in diameter can lift as much as 7.25kg. Nitinol also has the resistance properties which enable it to be actuated electrically by joule heating. When an electric current is passed directly through the wire, it can generate enough heat to cause the phase transformation. In most cases, the transition temperature of the SMA is chosen such that room temperature is well below the transformation point of the material. Only with the intentional addition of heat can the SMA exhibit actuation.

SMAs has a low temperature and a high temperature phase and its unique characteristics arise from change its phase. The phase change is between two solid phases and involves arrangement of atoms with crystal lattice. The internal structure is different at different temperatures. The low temperature phase is called martensite, with a highly twinned martensite and high temperature phase is called austenite phase with a body centred cubic structure. The martensite transformation phase starts at Martensite start temperature which is denoted by M_s and ends at martensite finish temperature which is denoted by M_f. The austenite transformation phase is starts with austenite start temperature which is denoted by A_s and ends with austenite finish temperature A_f. The recovery of the SMAs begins at A_s and ends at A_f. Any method of heating is adequate for the SMA wires. The dimensions and material properties of the SMA actuator are listed in Table-1.

Table 1. Dimensions and properties of the NITINOL wire actuator

Properties Of SMA	Specification	Nomenclature	Range
Thermal	Austenite Start Temperature (°C)	A_s	88
	Austenite Finish Temperature (°C)	A_f	98
	Martensite Start Temperature (°C)	M_s	62
	Martensite Finish Temperature (°C)	M_f	62
	Annealing Temperature (°C)		300
	Melting Point (°C)		1300
Material	Density (g/cc)	ρ_{SMA}	6.45
	Maximum Recovery Force (MPa)		600
	Recommended deformation force (MPa)		35
	Breaking Strength (MPa)	γ_{SMA}	1000
	Poisson's Ratio		0.33
	Energy conservation efficiency (%)		5
	Young's Modulus at Austenite (GPa)	E_A	82
	Young's Modulus at Martensite (GPa)	E_M	28
Dimensions	Length (m)	l_{SMA}	0.45

2.2. Piezoelectric Crystals

The word 'Piezo' is derived from the Greek word meaning pressure. The phenomenon of piezoelectricity was discovered in 1980 by Pireer and Paul-Jaques Curie. It occurs in non-centro symmetric crystals. Piezoelectric actuators are transducers that convert electrical energy into a mechanical displacement or stress using a piezoelectric effect. Using piezoelectric actuators large amount of displacement can be obtained with a low driving voltage. Actuators from piezoceramic materials have established themselves in a large number of applications ranging from active vibration control to nano-scale positioning tasks. This is due to their high-frequency response behavior and their essentially infinite resolution. Smart structures with surface mounted or embedded piezoelectric ceramic patches have received much attention in vibration control of structures in recent years, because piezoelectric ceramic materials have mechanical simplicity, small volume, light weight, large useful bandwidth, efficient conversion between electrical energy and mechanical energy, and easy integration with various metallic and composite structures. PZT (lead zirconate titanate) is a commonly used piezoelectric ceramic. The dimensions and material properties of the PZT actuator are listed in Table 2.

Table 2. Dimensions and properties of the PZT actuator

Properties of PZT	Specification		Range
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,	K^t_3	3100

	(Low Signal)		
	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

3. Analysis of Vibration

For a simple elastic beam problem with uniform cross-sectional area, a well-known natural frequency can be given by [7],

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

βl is a constant relative to the vibration bound condition is shown in Table-3. EI is the equivalent bending stiffness. For case (i) using the concept of classical composite-beam theory, the equivalent bending stiffness of the smart beam can be easily approximated. Moreover, the stiffness of a composite beam and attached discrete SMA fibers can be given [8] by the rule of mixtures.

The equivalent bending stiffness EI for smart beam with SMA wires, obtained according to the classical composite-beam theory can be given as [8],

$$EI = \frac{E_s b D^3}{12} + \frac{E_c b(h^3 - D^3)}{12} \quad (2)$$

$$EI = \frac{2E_s b}{3}\left[\left(\frac{h+4D}{6}\right)^3 - \left(\frac{h-2D}{6}\right)^3\right] + \frac{2E_c b}{3}\left[\frac{h^3}{8}\left(\frac{h-2D}{6}\right)^3 - \left(\frac{h+4D}{6}\right)^3\right] \quad (3)$$

The lamina thickness is considered to be the diameter of SMA wires, thus the elastic modulus of the composite lamina can be given by the rule of mixtures

$$E_s = E_{SMA}V_{SMA} + E_c(1 - V_{SMA}) \quad (4)$$

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

$$\Delta = \ln\frac{x_n}{x_{n+1}} \quad (5)$$

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

$$\xi = \frac{\Delta}{\sqrt{(2\pi)^2 - \Delta^2}} \quad (6)$$

Table 3. Vibration bound condition of a beam in cantilever configuration.

MODE	*Bl*
1	1.87504
2	4.690491
3	7.854757
4	10.995541

Table 4. Natural frequencies of GFRP beam

MODES	Analytical Results In Hz	ANSYS Results In Hz	% of Deviation
1	6.643	6.642	0.015
2	41.563	41.627	0.48
3	116.556	116.000	1.22
4	228.403	265.720	5.01

The natural frequency of the GFRP composite beam is found by the well known Finite Element (FEM) Software called ANSYS. Modal analysis and harmonic analysis are carried out using ANSYS software for finding the natural frequencies. The first mode shape of the GFRP beam is shown in Fig.1. The first four natural frequencies of the GFRP beam are shown in the Table 4. By comparing the ANSYS and theoretical results, the percentage of deviation of natural frequency is very less. We consider the first natural frequency for this entire study. So the deviation of the first natural frequency is negligible.

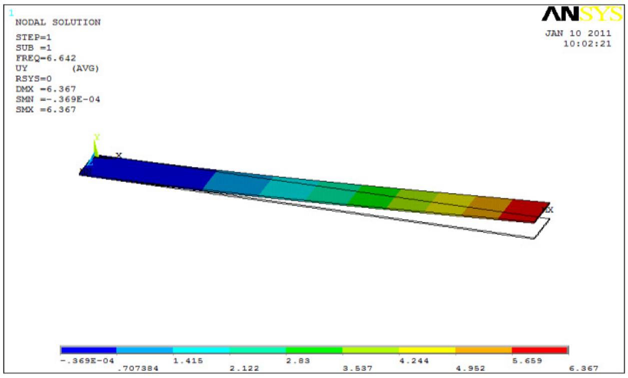

Fig.1. First mode shape of the GFRP beam

4. Experimental Setup

In order to verify the effectiveness of vibration control strategies, the experimental setup shown in Fig.2 is developed. The setup consists of the following four main parts: i) the smart beam under test and, the fixture ii) time and actuation circuit iii) shaker system with the controller iv) computer with interfaced LabVIew software to process the measured signal and issue the appropriate control signal. The smart beam is modeled in two cases. In both cases the beam is made freely vibrated at the free end. The vibrations are picked up using an accelerometer and interfaced with LabVIew software through PXI module.

Fig. 2. Experimental Set up

A clamped-free GFRP beam fixed horizontally along its width is considered in this study.The SMA wires used in this work are in the trade name Flexinol® was procured from Dynalloy Inc., USA. Flexinol is a binary alloy (Ni-Ti: 50.5–49.5%) with a one-way shape memory effect. The SMA actuator is placed at the neutral axis of the beam then the flexible composite beam is made to vibrate freely. The Flexinol wire is heated intermittently by a VI (Voltage to current) converter. The SMA wire is tends to lose its property when continuously heated for a longer period of time, the wire is subjected to intermittent heating. Cooling of the wire occurs due to natural convection. The wire was heated for 2 seconds and then cooled for 2 seconds. A Timing and actuation circuit is specially designed for the heating and cooling process. The settling time of the beam with and without SMA wire is plotted. Also the temperature dependent natural frequency of GFRP with one and two SMA wire is presented in Fig 3.

PZT (Lead Zirconate Titanate) of type SP-5H is used in this study. The PZT actuators are surface bonded at different locations from the fixed end. The vibration characteristics of the GFRP beam with PZT actuator is investigated by varying the input voltage to the PZT.

5. Results and Discussion

5.1. Natural Frequencies:

The density of the GFRP beam is about 1.98 g/cm^3 is much lesser than the density of the SMA wire. Therefore, the natural frequencies of the GFRP with SMA wire beams are decreased accordingly due to the increase of the overall density of the beams. However, this phenomenon can be changed by using composite materials with high tensile modulus. The natural frequencies of the composite beams with different numbers of SMA wires at different temperatures are plotted in Fig.3. In these diagrams, it is clearly shown that the natural frequencies initially decrease for the beam with low SMA wire fraction. The decrease of the natural frequencies is due to an internal compressive stress induced by the thermal expansion of the glass fibber composite and SMA materials. The frequencies are then increased with continuously increasing the number of SMA wire fraction.

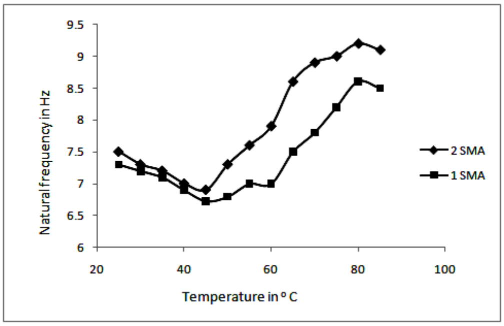

Fig.3 Experimental comparison of natural frequency of the smart beam by varying number of SMA wires

The natural frequencies of the GFRP beam with PZT actuator at various locations are shown in Table 5. The natural frequency of GFRP with PZT actuator is little more than the natural frequency of GFRP beam alone. The reason for increase in frequency is increase in mass and stiffness of the beam due to the bonded PZT over the beam. But still the mass and stiffness is varied proportionally there will not be change in natural frequency. From the Table-5 it can be inferred that the natural frequency of the smart beam is high when the PZT actuator is bonded at centre of the beam.

Table 5.Natural frequencies for GFRP beam with PZT Actuator at various locations

Location of PZT Actuator (center point) in mm	Natural Frequency in Hz
58	6.724
96	6.798
134	6.815
172	6.893
210	6.912
248	7.164
286	6.863
324	6.807
368	6.786
414	6.713

5.2. Damping Property:

The damping property of the beam is analysed by comparing the settling time with and without SMA, And different input voltage such as 25V, 50 V and 75 V to the PZT actuator. The Fig.4 shows the free vibration of the GFRP beam. Fig.5(a)&(b) shows the Settling time of the GFRP beam with one and two SMA wires respectively. From these Figures it can be inferred that as the number of SMA wires increase the settling time decreases due to the increase in force generated by the SMA.

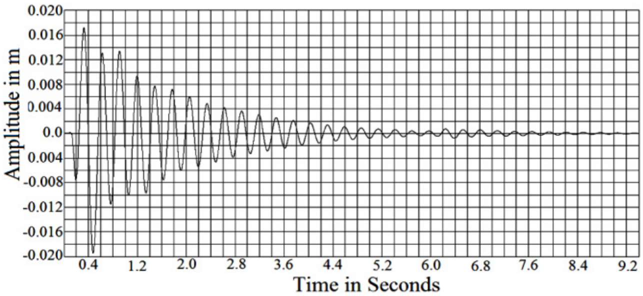

Fig.4 Free Vibration of a GFRP beam

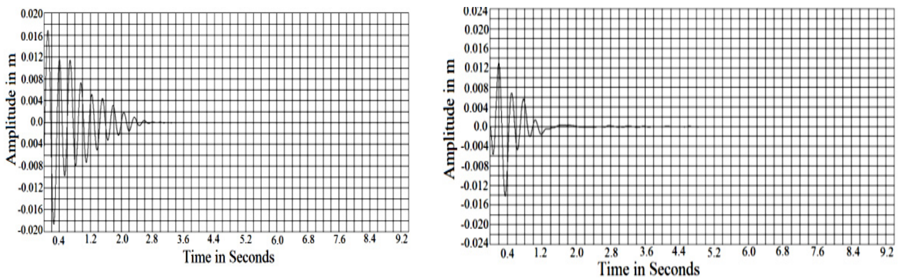

Fig.5.(a) Settling Time of a GFRP beam with one SMA wire; (b) Settling Time of a GFRP beam with two SMA wires

Using equation (5) and (6) the logarithmic attenuation coefficient was calculated for GFRP beam with one SMA wire and two SMA wires. Temperature dependent logarithmic attenuation co efficient is shown in Fig.6. The logarithmic attenuation coefficient of the SMA laminated beams increases with increasing volume fraction of the SMA wires. The logarithmic attenuation coefficient of the beam is high before the austenite phases transformation temperature, because the stiffness of the SMA wires increases with increasing temperature.

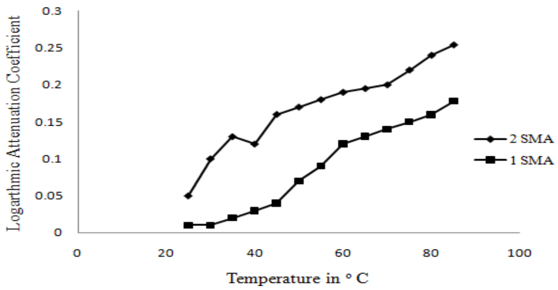

Fig.6 Comparison of logarithmic attenuation coefficient of the smart beam by varying number of wires

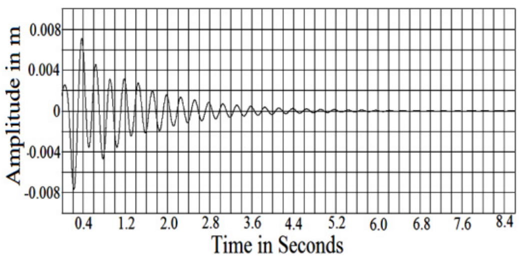

Fig.7.(a). Settling Time of a GFRP beam with PZT patches at 25V

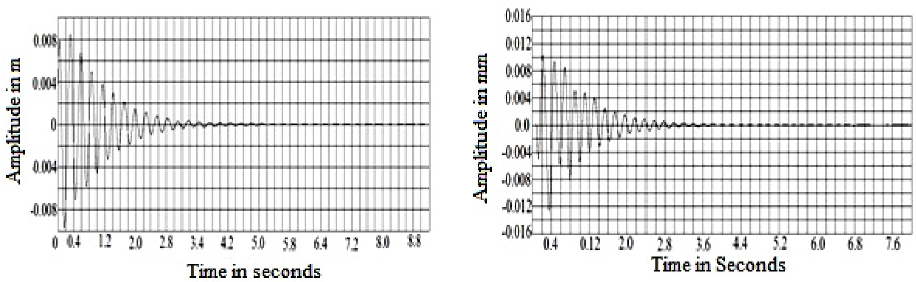

Fig.7.(b) Settling Time of a GFRP beam with PZT patches at 50V; (c) Settling Time of a GFRP beam with PZT patches at 75V.

Similarly Fig.7(a,b &c) shows the Settling time of the GFRP beam with PZT patches at 25V, 50V and 75V respectively. From these Figures it can be inferred that as the voltage for the PZT patches increases the settling time decreases. Again logarithmic attenuation coefficient was calculated for GFRP beam with PZT patches at 25, 50, and 75 volts. A Graph plotted from this data is shown in Fig.8. The logarithm attenuation coefficient of the PZT patches increases with increasing the voltage to the PZT patches.

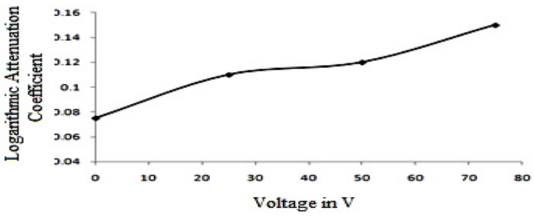

Fig.8. Comparison of logarithmic attenuation coefficient of the smart beam by varying number of wires

Table 6.Settling time for Various Specimens

Specimens	Settling Time in Seconds
GFRP beam	7.6
GFRP beam with one SMA wire	2.5
GFRP beam with two SMA wire	1.4
GFRP beam with PZT at 25V	4.4
GFRP beam with PZT at 50V	3.5
GFRP beam with PZT at 75V	3.0

The settling times for the various specimens used in the both cases are listed in the Table 6. From the table it can be found that the Settling time for the SMA Actuator is less compared to the PZT actuator. So the vibration can be effectively controlled having SMA with composite beam, Also the natural frequencies and logarithmic attenuation coefficient are higher when compared to the PZT actuator. These results prove that the SMA wire is more efficient than the PZT actuator.

6. Conclusion

The design, characterization and testing of SMA and PZT actuators for use in active vibration control applications has been presented. In this study SMA and PZT actuators behaviour is compared. Both SMA and PZT actuators can be used for active vibration control, but from the results it is found that the SMA actuator is comparatively more efficient than the PZT actuator because the voltage required for actuation of SMA is very less. It was also discovered that the use of SMA minimizes the large amplification circuits. The cost of the SMA is also less when compared with PZT.

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