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VIBRATION CONTROL ON CANTILEVER BEAM USING SHAPE MEMORY ALLOYS

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Abstract

This articlehas been made to control the vibration level of cantilever beam by selecting suitable damping material, recently shape memory alloys shows its superior mechanical and thermal properties suitable for many structural and material science application. Since Shape memory alloys are novel materials that have the ability to return to a predetermined shape when subjected to the appropriate thermal procedure. This property provides use of this material will be much suitable for controlling the vibration of structures and machines.

The vibration control of cantilever beam is achieved by heating of NiTinol wire. By using the experimental setup retaining force of NiTinol wire can measure at varies temperature under known strain. The temperature of NiTinol is increased by supplying known quantity of current by using current controller kit. By supplying the required current the temperature of the NiTinol wire is increased uniformly to induce martensitic phase transformation. Due to the phase transformation, NiTinol wire retains back to its initial position. When the retaining force acts on the cantilever beam structure, stiffness of the cantilever beam structure is increased, there by the natural frequency of the cantilever beam structure and amplitude of vibration is reduced. Hence the vibration of the cantilever beam can be reduced up to20 % by supplying the required current on NiTinol wire. The results were obtained by theoretical calculations and also ANSYS.

1. Introduction

First observations of shape memory behaviour were in 1932 by Olander in his study of “rubber like effect” in samples of gold–cadmium and in 1938 by Greninger and Mooradian in their study of brass alloys (copper–zinc). Many years later (1951) Chang and Read first reported the term “shape recovery”. They were also working on gold–cadmium alloys. In 1962 William J. Buehler and his co–workers at the Naval Ordnance Laboratory discovered shape memory effect in an alloy of nickel and titanium. He named it NiTinol (for nickel–titanium Naval Ordnance Laboratory)

Buehler’s original task was finding a metal with a high melting point and high impact resistant properties for the nose cone of the Navy’s missile SUBROC. From among sixty compounds, Buehler selected twelve candidates to measure their impact resistance by hitting them with hammer. He noted that a nickel–titanium alloy seemed to exhibit the greatest resistance to impact in addition to satisfactory properties of elasticity, malleability and fatigue. One day he took some NiTinol bars from melting furnace and laid them out on a table to cool. He intentionally dropped one on the floor out of curiosity. The bar produced a bell–like quality sound. Then he ran to the fountain with cold water and chilled the warm bar. The bar was once again dropped on the floor. On his amazement it exhibited the leaden–like acoustic response.

Buehler knew that acoustic damping signaled a change in atomic structure that can be turned off and on by simple heating and cooling near room temperature, but he did not yet know that this rearrangement in the atomic structure would lead to shape memory effect. It was in 1960 when Raymond Wiley joined Buehler’s research group. He worked on failure analysis of various metals. He demonstrated to his management the fatigue resistance of a NiTinol wire by flexing it. The directors who were present at this meeting passed the strip around the table, repeatedly flexing and un flexing it and were impressed with how well it held up. One of them, David Muzzey, decided to see how it would behave under heat. He was a pipe smoker, so he held the compressed NiTinol strip in the flame of his lighter. To the great amazement of all, it has stretched out completely.

When Buehler heard about that, he realized that it had to be related to the acoustic behavior he had noted earlier. After this moment, NiTi alloys increased interest of developing applications based on a shape memory alloys.

2. Literature Review

A shape memory alloy (SMA) is an alloy that "remembers" its original shape and that when deformed, it returns to its pre-deformed shape when heated. This phenomenon results from a crystalline phase change known as "thermoelastic martensitic transformation"[1]. Shape Memory Alloys (SMAs) have the ability to change their shape, stiffness, natural frequency, damping, and other mechanical characteristics in response to changes in temperature, magnetic field or electric field [2]. It is in the form of rod, plate, wire, etc. Wire shape NiTinol is used in many applications such as an anaconda endovascular device, stents, dental clips [3, 4], reinforcement with composite structure [5], vibration control of structures [6,7], self actuator on fire sprinkler [8] etc. In SMAs, the modulus of elasticity changes with respect to temperature, i.e. the elasticity of a SMA in the high temperature phase is up to four times larger than that of the low temperature phase. Therefore, the stiffness of the structure can vary by a factor of three to four times. Hence, an antagonistic force (pre-stress) will be created in the SMA structure [9]. G.Song, explained various methods of implementation of SMA actuators in the applications of the passive, active, and semi-active vibration control of civil structures [10].Future large space systems will require improved structural performance to meet serious vibration and control issues. Active vibration suppression, precision pointing and shape control techniques will have to be developed to accurately control and position large flexible space structures in the space environment. The overall spacecraft designs will rely on distributed structural control methods to minimize local vibration and jitter, and maintain the high accuracy pointing and shape requirements. To meet these requirements, structural members which contain their own local sensors, actuators, and computational/ control capabilities need to be investigated. Current state-of-the-art sensors and actuators are being researched throughout the aerospace industry. New design concepts using electrorheological fluids [11], piezoelectric ceramics [12], and shape memory metal alloys as methods of actuation are being studied. Some of these same designs involving piezoelectric ceramics and shape memory metals along with other concepts that use fiberoptics [13] and acoustic waveguides [4] are being developed for sensing. The purpose of this paper is to present the results of an IR&D study performed by Boeing Aerospace and Electronics to investigate the feasibility of using NiTiNOL shape memory metal materials for both local sensing and actuation to minimize vibrations of a simple structure. The results of this investigation verified that the NiTiNOL shape memory metals could be used for active vibration suppression. Shape memory alloys (SMA), because of their unique mechanical characteristics and shape memory effect (SME), have been widely used as force and displacement actuators in many fields [14,21]. Some shape memory alloys like NiTi show noticeable high damping property in pseudoelastic range. Due to its unique characteristics, a NiTi alloy is commonly used for passive damping applications, in which the energy may be dissipated by the conversion from mechanical to thermal energy[15].A high damping capacity is considered as one of the important functional properties of shape memory alloys. Those properties are related to a thermo elastic martensitic transformation. As a consequence of this transformation, the internal friction or damping can be investigated for three different states: 1. during thermal transformation cycling, **2.** during martensite induced strain cycling at constant temperature, **3.** in the martensitic state.[16,20].The aim of this paper is an introduction to shape memory alloys, the materials that change shape by applying heat. This paper contents a brief history and a description of general characteristics of the shape memory alloys. At the end are described groups of most widely used commercial applications[17,22].A damper device based on shape memory alloy (SMA) wires is developed for structural control implementation. The design procedures of the SMA damper are presented. As a case study, eight such SMA dampers are installed in a frame structure to verify the e_ectiveness of the damper devices.[18,23].A new approach to the design and control of shape memory alloy (SMA) actuators is presented. SMA wires are divided into many segments and their thermal states are controlled individually as a group of finite state machines[19].

3. Materials & Methods

The wire form is used in this work to control the vibration occurred in our experimental arrangement. The following materials will have shape memory effect Zinc, Copper, Gold, Iron, Nickel, and Titanium. Material is chosen based on the mechanical and electrical properties as well as corrosion resistance.

This chapter focuses on selection of shape memory alloy material for controlling the vibration in our experimental arrangement.

3.1 Nickel Titanium Based Shape Memory Alloy:

Nickel–titanium alloys have far greatest recoverable strains of commercially available shape memory alloys. Fully recoverable strains of 7% are easily achieved with these alloys. The temperature at which the phase change associated with the memory effect takes place can be adjusted from −200℃ to +100℃ by altering the propositions of nickel and titanium around the equi–atomic ratio of 50 % nickel and 50 % titanium. Differences of just 0.1 atomic percent can easily change transformation temperatures by 20℃ or more. For this reason production and processing of NiTi alloys must be very strictly controlled.

The manufacture of NiTi alloys follows closely the procedures of conventional titanium alloy manufacture. Because titanium easily forms oxides, carbides and nitrides a vacuum melting process is essential. This ensures good homogeneity of the alloy, and enables transformation temperatures to be controlled to within 5°C. Because of this careful fabrication and often small production are NiTi alloys rather expensive. The greatest benefit of NiTi alloys over other commercial shape memory alloys is its excellent corrosion resistance.

3.2 Methods:

Flexible structures usually have low flexible rigidity and small material damping ratio. A little excitation may lead to destructive large amplitude of vibration and long vibration decay 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. Advances in smart materials have produced smaller and effective actuators and sensors with high integrity in structures.

Smart material systems offer great possibilities in terms of providing novel and economical solutions to engineering problems since they offer potential technological advantages over traditional ones.

Smart materials like shape memory alloys (SMA) have been used in diverse areas. Varieties of actuators are developed from smart materials but the more promising are the one based on the shape memory effect of metallic alloys. NiTinol is the most widely used shape memory alloy due to its superior properties that are suitable for actuation.

The significant advantages of SMA wires in actuator are the relatively low voltage to generate a displacement, larger recovery force generated per unit volume by phase transformation, small size, high output excitation actuation for vibration control, its large displacement, the complete recovery deformation, high stiffness and electrical heating.

By using the accelerometer with two channels the vibration signals are captured in the system through data acquisition card.

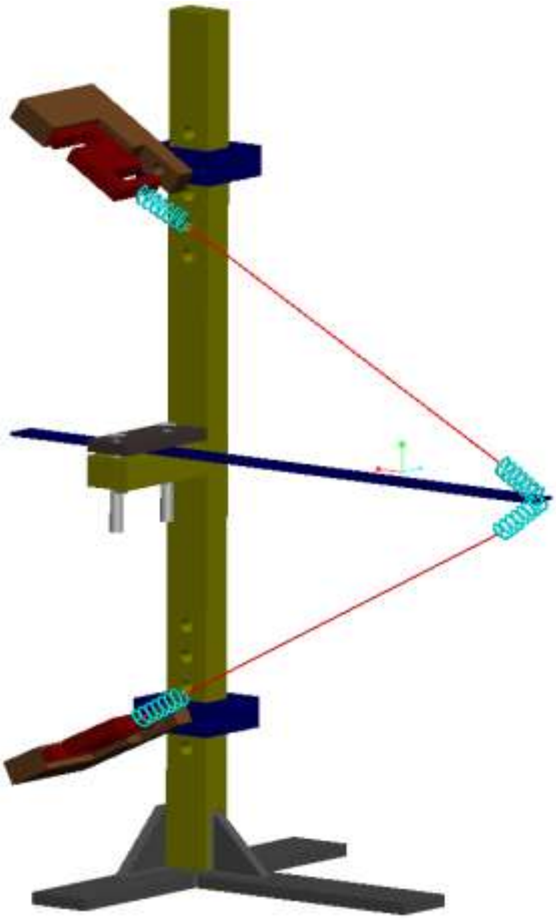

Figure 1. Experimental setup for Methodology of vibration control

Table 1. Specification ofExperimental Setupof Vibration Control

Sl. No	Item	Specification	Quantity
1	Shape memory alloy wire NiTinol	ength = 0.325m iameter =0.5mm	2 no’s
2	Accelerometer		1 no
3	“K” Type Temperature Sensor	ength = 5m	6 no’s
4	Force sensors		1 no

6	DEWE 43 Data acquisition box	8 Channel analog input 8 Channel Counter input 24 Channel Digital input 2 CAN bus port	1 no
7	Thermocouple amplifier	Thermocouple type K, accuracy ±0.4 °c,	1 no

In this experimental setup a 0.5mm diameter of NiTinol wire is stretched and it's both ends are fixed at vertical column as shown in Figure1, equidistant from the cantilever beam such that if passes through the later. NiTinol wire is to be stretched to make a strain 2% of its length by using cable adjusting screws in the vertical column. Two vibration sensors(accelerometer) attached the in the cantilever beam which senses the vibration and generate respective electrical signal which are fed to CPU through DEWE 43. By analysisng the signal the natural frequency and modes can be determined. The two force sesnors fixed beetwean shape memory alloy wire amd column. It helps to measure the force acting on the cantileverbeam for controlling the vibration

By supplying required current, the temperature of NiTinol wire is increased uniformly to induced martenside phase transformation. Due to the phase transformation, NiTinol wire generates retaining force to regain back its initial position. When the retaining force act on cantilever beam structure, the stiffness of the cantilever beam is increased. Hence the vibration of the cantilever can be controlled by supplying required current on Shape memory alloy wire.

4. Experimental procedure

The experiment is conducted in the following operating procedure.

Table 2. Experimental Procedure

Step 1	The cantilever beam setup is brought to the working table.
Step 2	A variable frequency oscilloscope is set under the cantilever beam connected with the beam to generate the desired vibrations.
Step 3	The oscilloscope is switched on and the natural frequency of the cantilever beam is recorded using computer interface.
Step 4	Now the frequency of the oscilloscope is varied in steady increments and the natural frequency is recorded for the cantilever excited using a vibratory source.
Step 5	The cantilever beam setup is hinged with NiTinol wire using lock nut and screw and the other end of the wire is connected to transducer.
Step 6	The terminals of ‘K’ type temperature sensor are connected with the NiTinol wire.
Step 7	The temperature controller unit and thermocouple amplifier are switched on.
Step 8	By adjusting the supply voltage to the variable frequency oscilloscope, the cantilever beam with NiTinol wire is made to vibrate at desired higher frequency.
Step 9	The temperature is kept considerably low to ensure that the smart material is in martensitic phase.
Step 10	The values of frequency are recorded using computer interface.
Step 11	Now, the temperature of the system is gradually increased by varying the supply voltage to the temperature controller unit.
Step 12	The rise in temperature assists the phase transformation from martensitic phase to austenitic phase.

Step 13	With the rise in temperature, it may be noted that the frequencies recorded using computer interface gets reduced considerably.
Step 14	The readings recorded after rising the temperature is the natural frequency when NiTinol wore is in austenitic phase.
Step 15	The natural frequency values obtained in this experiment are tabulated.

5. Results and Discussion

5.1 Determination of natural frequency of the cantilever beam using newton's method (Theoretical Method)

The cantilever beam can be considered as a vibratory system having mass and elasticity with single degree of freedom. The equation of motion for a single degree of freedom system can be found by employing many methods such as Newton's method, Energy method and Rayleigh's method. Here Newton's method is used to develop equations of motion to determine the natural frequency of the system.

The cantilever beam may be considered as a spring – mass system, with the beam's self weight as mass (m) and beam's stiffness as spring stiffness (k). let the displacement of the beam be

According to Newton's second law,

Mass × Acceleration = Resultant force on the mass

$$m\ddot{x} = -kx$$

$$m\ddot{x} + kx = 0$$

Where, $\ddot{x} = \frac{d^2x}{dt^2}$ is the acceleration of mass, m. This is recognized as the equation for simple harmonic motion. The solution is

$$x = A\,\cos\omega_n t + B\,\sin\omega_n t$$

Where A and B are constant which can be found by considering the initial conditions, and is the circular frequency of the motion.

Substituting Eq 2 in Eq 1 and solving we get,

$$-\omega_n{}^2 + \left(\frac{k}{m}\right) = 0$$

$$\omega_n = \sqrt{\frac{k}{m}} \quad (rad/sec)$$

The frequency of vibration, $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}\,Hz$

5.1.1 Geometrical and Material Properties of The Beam

Dimensions : 500 × 25 × 3 mm

Density : 2.7×10^{-9} kg/mm^3

Young's Modulus : 70×10^3 N/mm^2

5.1.2 Derived Values

Self mass of the beam (m)

Density = $\frac{Mass}{Volume}$

Mass = $\frac{500 \times 25 \times 3 \times 2700}{10^9}$ = 0.10125kg

Self Weight of the beam (W) = 0.10125 × 9.81 = 0.9932N

Mass per unit length (w) = $\frac{Mass}{Length}$

$$= \frac{0.9932}{500}$$

= 0.00199 N/mm

5.1.3 Calculation of Natural Frequency of the Cantilever Beam

The natural frequency of the cantilever beam can be calculated from the expression

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (Hz)$$

Where,

k- Stiffness of the spring (N/mm)

m – Mass of the beam (kg)

The value of stiffness of spring (k) can be calculated from

$$k = \frac{W}{\delta} \ (N/mm)$$

Where,

W- Weight of cantilever beam (N)

δ – Deflection (mm)

Deflection is calculated from the expressions

$\delta = \frac{wl^4}{8EI}$ (for uniformly distributed load)

$\delta = \frac{Wl^3}{3EI}$ (for point load)

Deflection is calculated for both the self weight of the beam as uniformly distributed loadspread throughout the length and loads as point loads.

5.1.4 Theoretical Results

Natural frequency of beam, considering only the self weight of beam

Deflection, δ = 0.01787 mm

Stiffness of spring, k = 1825.61 Newton/mm

Circular frequency, ω_n= 60.42 rad/sec

Natural frequency f_n= 9.617 Hz

5.2 Modal Analysis Using Ansys

Modal analysis is carried out to study the natural frequency cantilever beam with and without NiTinol wire at austenite and martensite. In Ansys Solid185 elements is used for cantilever beam and Beam 4 element is used for NiTinol wire. Cantilever beam is discretized to 3155 elements with 1226 nodes. Frequency and mode shape are given below.

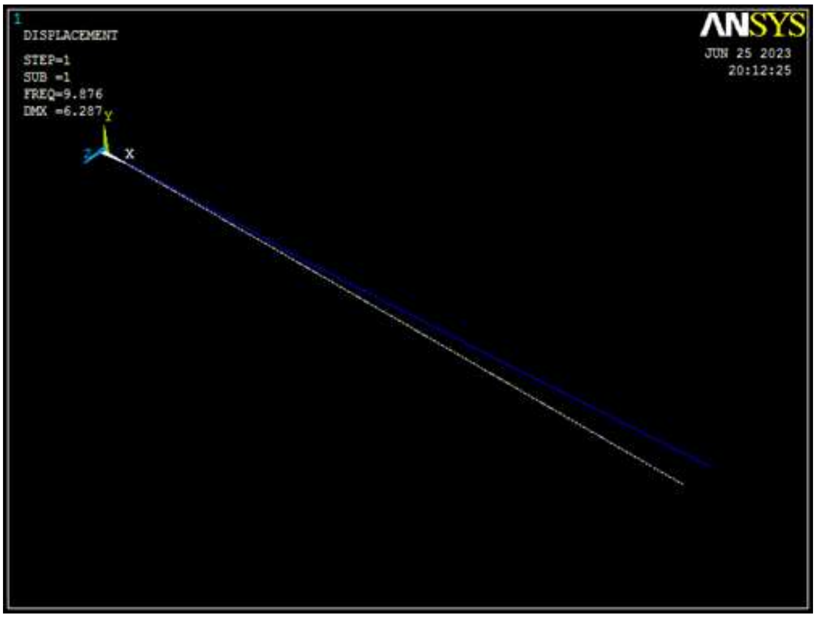

Figure 2. First set modal solution for cantilever beam

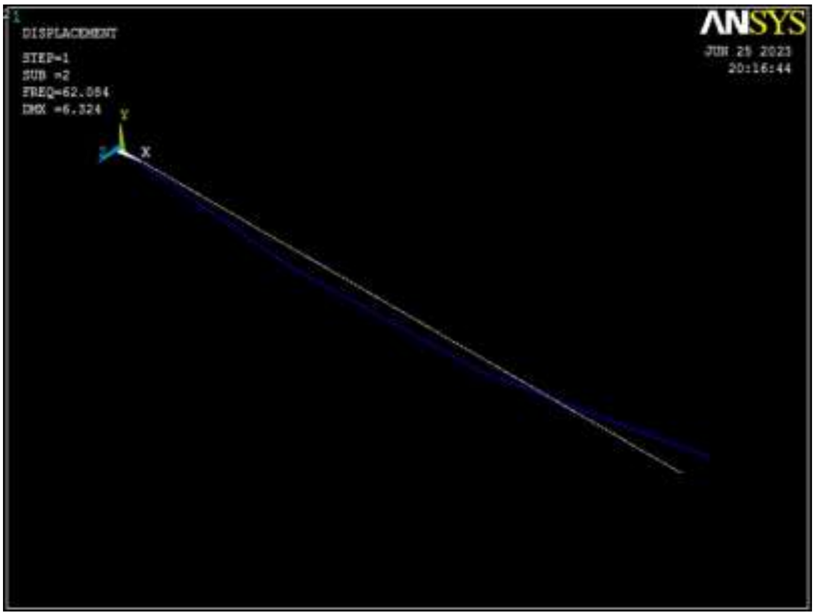

Figure 3. Second set modal solution for cantilever beam

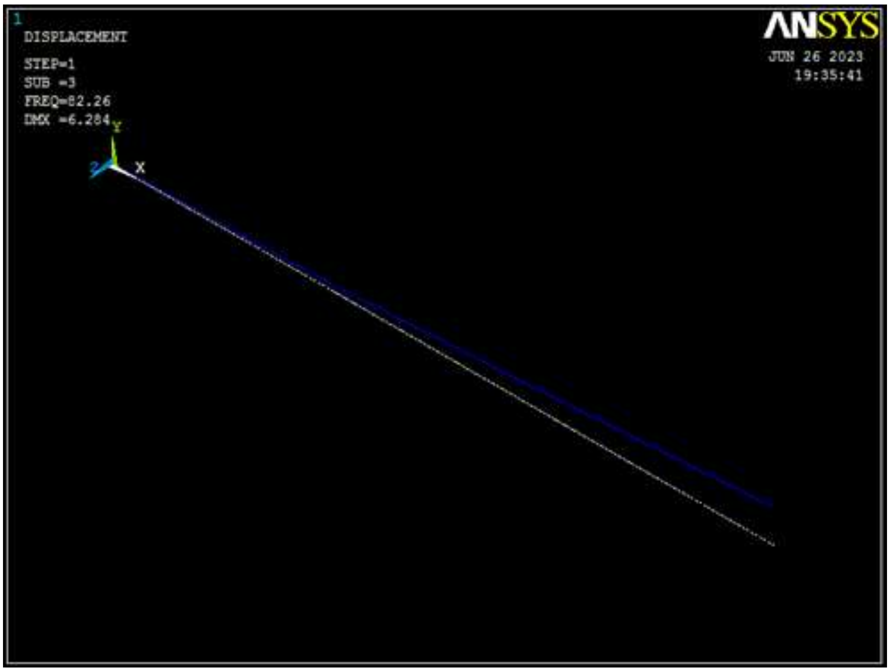

Figure 4.Third set modal solution for cantilever beam

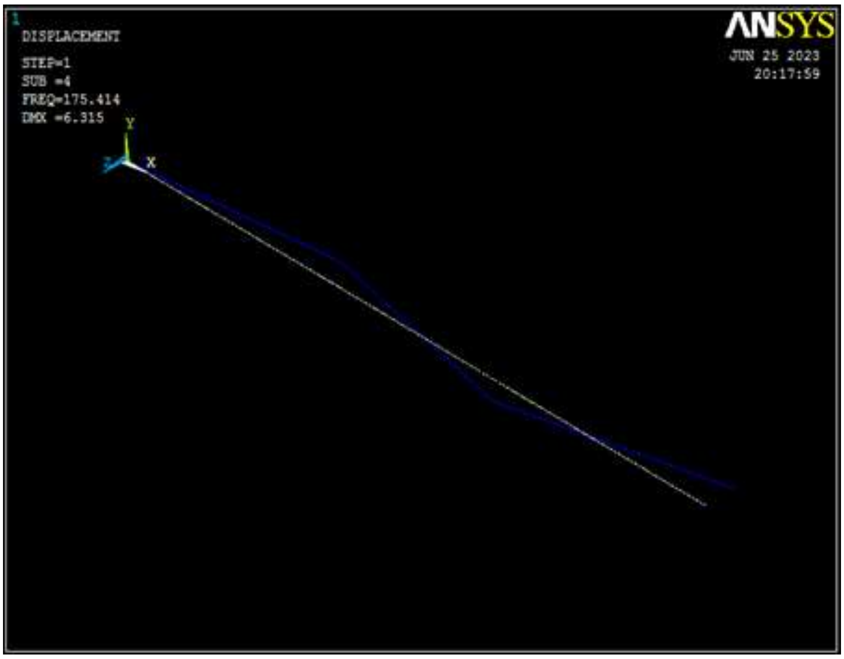

Figure 5.Fouth set modal solution for cantilever beam

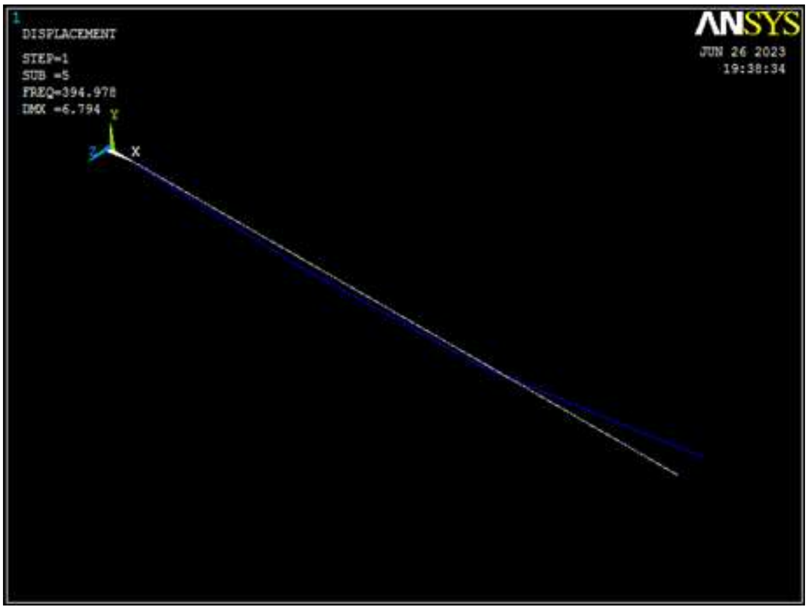

Figure 6.Fifth set modal solution for cantilever beam

Table 3. Model Analysis Results

INDEX OF DATA SETS ON RESULTS FILE				
SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	9.876	1	1	1
2	62.084	1	2	2
3	82.26	1	3	3
4	175.414	1	4	4
5	394.978	1	5	5

CONCLUSION

In this work the vibration control of cantilever beam is achieved by heating of NiTinol wire. By using the experimental setup retaining force of NiTinol wire can measure at varies temperature under known strain. The temperature of NiTinol is increased by supplying known quantity of current by using current controller kit. By supplying the required current the temperature of the NiTinol wire is increased uniformly to induce martensitic phase transformation. Due to the phase transformation, NiTinol wire retains back to its initial position. When the retaining force acts on the cantilever beam structure, stiffness of the cantilever beam structure is increased, there by the natural frequency of the cantilever beam structure and amplitude of vibration is reduced.

Calculating the frequencies theoretically using equations of motion for vibration analysis. Frequencies are theoretically calculated separately for cantilever beam hinged with NiTinol wire.

Theoretical values also prove that the values obtained from this experiment is valid and hence becomes a proof for the good damping characteristics of shape memory alloy wire (NiTinol)

The results obtained theoretically and by experiment is further validated by performing harmonic analysis using ANSYS. The experimental setup is modelled in ANSYS and analysis is performed. Analysis results also prove to the good damping characteristics of shape memory alloy wire.

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