VIBRATION ANALYSIS OF NITINOL SHAPE MEMORY ALLOY IN CARBON FIBRE REINFORCED POLYMER COMPOSITES

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Abstract: Owing to high specific strength and stiffness, composites find wide applications in automobile and aerospace industry. In this paper, an attempt has been made to study the vibration characteristics of embedded shape memory alloy wire (SMA). Earlier, experimental modal analysis was carried out on the carbon fiber reinforced epoxy composite beams (CFRP beam) embedded with shape memory alloy wire manufactured by hand lay-up process. Increased levels of pre-strain up to 4% on shape memory alloy wire resulted in maximum increment in natural frequency when activated at 75°C. The experiment also investigates change in modal frequencies in CRPF plates embedded with the SMA wires. The selected pre-strain for experimentation was 4% pre-strain actuated at 75°C.

1. Introduction
Composite materials, which have low density and high strength, results in very high specific stiffness to and increased quality of strength-to-weight ratio, are used for high performance operations [1]. In addition to all this, a lot of parameters in composite materials, for example, fiber angle, range of layers, successions provided to the stacks and the volume of fiber in the composite are bespoken to adequately fulfill the outline necessities of quality and firmness [2]. The requirement for outside damper can be kept away through adapting dynamic control strategies. Adaptive composites are structural materials that integrate actuating and detecting capabilities frequently under the type of inserted dynamic materials. Dynamic control enhances the structure with actuators, sensors and some type of electronic control framework which is customized to diminish the measured vibration levels. Frequency, stiffness and damping capacity is related in such a way that the natural frequency is directly proportional to the square root of the stiffness whereas the damping ratio is indirectly proportional to the stiffness of the material. Technological advances in smart materials have made them smaller and successful actuators and sensors with high integrity in their structure. Numerous sorts of smart materials are very much acknowledged for actuating and sensing devices: they include piezoelectric (PE), electrostrictive (ES), magnetostrictive (MS), Shape Memory Alloy (SMA), electrorheological and fibre optical materials. Shape memory alloys are great contenders for conferring these versatile abilities. The currently available composites have low damping properties, thus the idea of smart hybrid composite with embedded shape memory alloy elements/SMA composites has pulled in a wide intrigue [3&4]. SMA composite materials are made by implanting SMA components as wires, strips or particles intro matrix metals, for example, polymers, metals or composites. The CRPF’s properties can be enhanced by the SMA elements or by controlling martensitic transformation of the pre-strained SMA elements that is embedded in it [5-7].

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In this work an alloy of Nickel and Titanium, which is known Nitinol, is used as shape memory alloy because of its high strength and stiffness. It is pre-strained to 4% to achieve the twinned martensite structure. Nitinol is used as SMA in this experiment because of its excellent damping capacity, super elasticity and shape memory effect. The term ‘shape memory’ states that the ability of the material to bring it from a plastically deformed shape to its original shape by the application of heat or stress. Nitinol has a high temperature parent austenite phase and a low temperature martensite phase. Phase transformation from austenite to martensite and vice versa due to applied stress or heat makes Nitinol a suitable material for applications that requires better properties as mentioned earlier. The change from austenite to martensite and the invert change from martensite to austenite don’t occur at the same temperature [8]. The entire transformation cycle is described by the following temperatures: austenite start temperature (\( A_s \)), austenite finish temperature (\( A_f \)), martensite start temperature (\( M_s \)) and martensite finish temperature (\( M_f \)). Nitinol in its as-received stage has twinned martensite structure, which is a soft martensite state [9]. When stress is applied it deforms and becomes a detwinned martensite structure. Nitinol gains in strength on heating it beyond the austenite finish temperature and also simultaneously it recovers its shape. The SMA wires used in this study have an activation temperature of 75°C [10] where the SMA wire reaches the Austenite final stage which improves the damping property of the composite and makes its use in high speed applications possible [11&12].

Nitinol alloys are manufactured widely by adopting the method of either Vacuum Arc Re-melting (VAR) or Vacuum Induction Melting (VIM). In vacuum inducted melting process, the charge material is placed in a crucible of graphite and heat is applied through the external induction coils. Homogeneous melting then occurs due to the stirring effect of induction field. The material is likely to absorb carbon from the graphite container and could result in formation of Titanium Carbon inclusion which is one of the main drawbacks of the VIM process. Vacuum arc re-melting (VAR) is the other type of method adopted where the charge materials are compacted into a consumable electrode after which an arc is stroke in the middle of the electrode and the base of the container. The container is then lined with copper and water cooling is also provided which takes away the risk of carbon contamination, due to the formation of the molten metal there is adjustment in relative electro deposition as the molten zone is moved along the length.

Aeronautical and automotive applications lend operations in the supercritical regime and therefore vibration characteristics of composites embedded with SMA wire is required so that vibration stability can be maintained [13&14]. An attempt has been made in this work to find out the natural frequency of a CFRP beam embedded with inclusion and without inclusion of SMA wire and the effect of heating on the natural frequency of CFRP beam with SMA wire through experimental modal analysis.

2. Experimental procedures

2.1. Material preparation
Carbon fibre was cut according to the dimension. Cold curing method was adopted in this process, since any exothermic process might lead to the activation of the SMA wire during the fabrication. EP306 resin and EH758 hardener was used as a binder in the ratio 10:1. The composite was made using hand lay-up method. At first, a single sheet of carbon fibre is placed on the mould and the resin mixture was applied to it and one more sheet of carbon fibre is placed over it. This process is repeated till it reaches the mid-level of the mould. Then SMA wires are place parallel to each other in the neutral axis along the length of the carbon fibre in a continuous manner and it is again covered with the carbon fibre and resin mixture alternatively till it reaches the top position. The specimen is rolled in order to remove the air bubbles present in it. It is ensured that the SMA wire are not in contact with each other since it might result in short circuiting because of the electrical heating. Additional weight is kept over the setup in order to ensure the flatness and it was kept overnight for drying up. The data, specimen size and other specifications are given in the table 1.
Table 1. Composite Plate Specifications.

| Parameter                                      | Specification       |
|------------------------------------------------|---------------------|
| Length of Plate (l)                            | 300mm               |
| Width of Plate (w)                             | 300mm               |
| Thickness of Plate (t)                         | 3mm                 |
| SMA Wire Diameter (d)                          | 0.4mm               |
| Young’s Modulus of SMA in Martensite Phase (E<sub>en/m</sub>) | 25GPa               |
| Young’s Modulus of SMA in Austenite Phase (E<sub>aua</sub>) | 75GPa               |
| Young’s Modulus of Specimen (E<sub>specimen</sub>) | E<sub>CFRP</sub>V<sub>CFRP</sub> + E<sub>res</sub>V<sub>res</sub> |
| Density of CFRP Fabric (ρ)                     | 1600kg/m<sup>3</sup> |
| Mass of Plate (M)                              | 1.44kg/m            |

2.2. Fundamentals of Vibration

Vibration occurs because of the oscillation of the mass and forces acting inside the system. Any mass which has elasticity can be vibrating. Vibrations can be classified into two sorts: fixed and forced vibration. The former is happening at time when the system swings away freely after some excitation provided formerly and the latter happens when surrounding external forces energize the system [16]. In the event that the frequency of the external forces coincides with the natural frequency of the system, resonance occurs, influencing the system to vibrate at higher amplitude. High vibrations at resonant conditions lead to wastage of energy, environmental damage, commotion pollution and potential damage.

2.3. Vibrational Analysis

Vibration analysis setup is discussed for testing natural frequency of CFRP beam with and without activating SMA wire under clamped condition. During Shape recovery, modulus of elasticity of shape memory alloys increases, which raises the yield stress values in transformed austenite phase. Constraining recovery of shape memory alloys also generate axial stresses. This constrained recovery force provides the mechanism to alter the natural frequency of the beam. The natural frequencies of a composite beam with SMA wire inserted into embedded sleeves depend upon beam parameters and SMA wire parameters. The beam parameters are its length, thickness, width, material and boundary conditions. The vibrational analysis for free vibration is done on the composite plate. The setup for free vibration is given below in figure 1.

Figure 1. Free Vibration Setup.
2.4. Modal Analysis
Investigation of dynamic characteristics of a part under vibration excitation is called modal analysis. Every structure has absolute properties like modes. Material properties like content, firmness and damping features dictate resonance properties. Each mode has a mode shape, modal damping and natural frequency [17]. The modal shape changes if the material characteristics or structural constraints change. The mode shape of the resonance has a tendency to command the vibration shape of a machine or structure, when near to the natural frequency of a mode [18]. The building blocks that describe the excitation of the structure to natural and forced excitation are modal parameters like natural frequency, damping ratio and mode shape.

2.5. Experimental Modal Analysis

![Experimental Modal Analysis Process](image)

Figure 2. Experimental Modal Analysis Process.

To measure the dynamic response of a structure when excited by stimuli, modal analysis is used. The step involved in modal parameters using Experimental modal analysis are (i) Heating up of the wire. The SMA wire was heated more than the activation temperature, for getting it activated. (ii) Providing a cantilever support to the beam. It is so done so that hammer force can be applied for vibrating the plate. (iii) Connecting the hammer to the DAC. Its purpose is to collect and convert the analog signals of the vibrations into digital value. (iv) The digital values are then converted to graphs, depicting the natural frequency of the system. [19]

3. Result and Discussion

3.1. Frequency Response
The software recorded the vibrations, and the graphs were plotted, which was done by the DAC, which converted the vibrations into digital signals. The plotted graphs are given below in Figure 2 & 3.

![Frequency Response Before Actuation](image)

Figure 3. Frequency Response Before Actuation.

In the figure 2 and 3, the graphs are plotted for the frequency response function, which tell about the natural frequencies of the composites, without actuated wire and with actuated wire. As we can see from the above graph in figure 2, the natural frequency of the plate without the actuated wire is 38.75Hz. This explains that the vibration is high in that plate. The subsequent values depict the 1st, 2nd, 3rd and so on, the modal frequencies of the plate.
In the next figure in Figure 3, we can clearly see that the natural frequency has reduced drastically, (from 38.75Hz to 15Hz). This depicts the damping action of the wire, which also shows that the wire had been actuated. Also, if we compare the modal frequencies of the graphs, we can see that they have also reduced a lot in their respective modes (165Hz to 133.7Hz for 1st mode, 326.25Hz to 216.25Hz for 2nd mode, and so on). Hence, we can conclude from the graphs that the damping effect of an SMA wire has a huge impact on its frequency, and consequently its vibrational properties, which is clearly visible in the above graphs.

3.2. Theoretical Calculations

Since all the data for the specimen, regarding the size of the plate, its weight and density are known. Theoretical calculations were done to find the natural frequency [15]. All the values given are taken for the ideal conditions, taking into considerations that the mass is uniform throughout the plate, and the density is constant.

\[ I = \frac{wt^3}{12} \]  
\[ \frac{\pi^2}{4} d^4 \times N / (w \times t) \]

Moment of inertia (I) is found from eqn (1) is 8.54 mm\(^4\) and the volume fraction (\(V_n\)) from eqn (2) values 1.39\times10^{-4} for the nitinol.

\[ T = A \times V_n \times E_{\text{sh}} \times 0.5 \times 0.02 \]

\[ f = \frac{\pi^2 \times E_{\text{sh}} \times \sqrt{I} / \left[ I + \left( T \times d^2 / EI \times \pi^2 \right) \right]}{(m_s \times d^4)} \]

Tensile recovery force from eqn (3) appears to be 0.187 KPa by assuming 50% strain recovery and the strain applied on wire as 0.02. And the calculated frequency (f) from eqn (4) is 52.82 Hz whereas the natural frequency of the plate without the wire is 38.75 Hz.

| S.No | Mode          | Experimental (Hz) |
|------|---------------|-------------------|
| 1    | Natural Frequency | 38.75            |
| 2    | 1             | 165               |
| 3    | 2             | 326.25            |
| 4    | 3             | 531.25            |

**Table 2:** Frequency Tabulation of Plate without Wire.

| S.No | Mode          | Experimental (Hz) |
|------|---------------|-------------------|
| 1    | Natural Frequency | 15                |
| 2    | 1             | 133.7             |
| 3    | 2             | 216.25            |
| 4    | 3             | 342.5             |

**Table 3:** Frequency Tabulation of Plate With Actuated Wire.
As we can see, we are getting a deviation of about 36% in the theoretical value from the experimental value. However, the frequencies for the first three modes without and with wire, as taken from the graphs are given below in table 2&3.

4. Conclusion
Natural frequency of CFRP plate embedded with SMA wire after actuation were recorded experimentally and compared with the values of natural frequency of CFRP plate without SMA wire. From the experiment it can be concluded that SMA wire after actuation increases the damping property of CFRP composite and therefore, increases the stability and life of the specimen. Also, there is a vast difference in the natural frequency of the plates, without SMA wire and with actuated SMA wire. The frequency of the plate without the wire is 38.75Hz, whereas the natural frequency of the plate with the actuated SMA wire turned out to be 15Hz, which shows a decrease in the natural frequency of about 61%. The theoretical calculation for vibration analysis of the CFRP plate was done and it was in accordance with experimental results; experimental value came out to be 38.75Hz, whereas the theoretical value, from the experimental value. The reason in this deviation is due to the fabrication imperfections incurred, which lead to a few randomly arranged arrays of carbon fibre, which is not constant throughout. Also, since it is made using hand lay-up method, the composition mixture is not uniform, which also added to the irregularities.

5. References
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