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VIBRATION CONTROL OF GFRP COMPOSITE BEAM USING SMA-FLEXINOL ACTUATORS

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ABSTRACT
This paper deals studying vibration control of Glass Fiber Reinforced Plastics (GFRP) flexible composite beam using shape memory alloy (SMA). Tip displacement of the beam was measured to study the extent of vibration control. The parameters investigated in the present study includes the effects of wire diameter of SMA, current input to the SMA, fiber orientation in the beam, and the excitation frequency on the tip displacement. A mathematical model is developed to describe the behavior of this composite. The model describes the interaction between the elastic characteristics of the composite beams and the thermally induced shape memory effect of the FLEXINOL wire. The results obtained demonstrate the potential of the SMA in shape control and damping out the vibration of flexible beams.
KEYWORDS
Shape Control, Shape Memory Alloy, Composite beam.

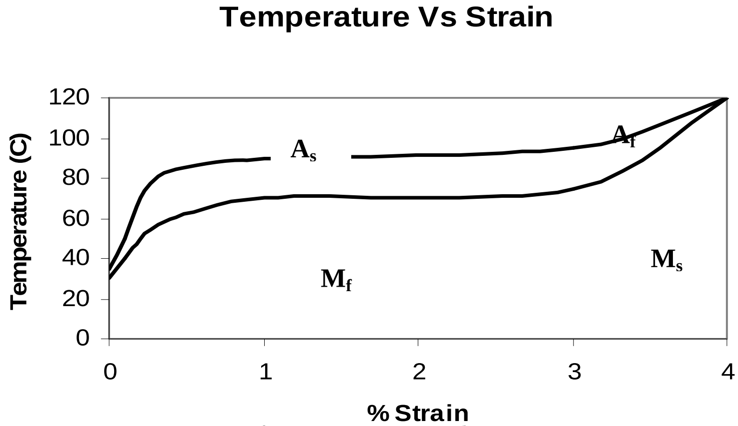
1. INTRODUCTION

In the recent years, there has been considerable interest in the study on smart materials and structures to develop adaptive structures. In order to obtain shape control and active vibration suppression of the flexible composite structures under unanticipated loading and environmental conditions, the use of smart materials becomes specifically important. Various actuators have been used in shape control. Among the smart materials, SMA in particular is receiving much attention. This is because of the unique characteristics of SMA which has a distinct strain recovery effect. Also, the SMA is capable of generating forces during shrinkage as it undergoes its unique phase transformation by temperature change. also SMA has good potential to be used as an actuator in smart structures due to the reason that, the voltage required for actuation is very less when compared to other actuation techniques. Free vibration analysis of composite structures is found in the research papers [1-3]. Use of parametric system identification technique for the modeling of flexible beam is discussed by Bai [4]. Peng et al [5] have developed a finite element model, based on third order laminate theory for the active position control and vibration control of composite beams with distributed piezoelectric sensors and actuators. Mathematical models for beams using surface mounted PZT actuators have been used in various research papers [6-10]. Active vibration suppression and shape control using piezo-ceramic materials is discussed in the literature [11-15].

Baz et.al [16] studied theoretically and experimentally, the feasibility of utilizing SMA in controlling the flexural vibrations of a flexible cantilevered 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 would be effective in damping out the structural vibrations, but at the expense of degrading the stability of the control system Baz et.al [17] studied the control of natural frequencies of Nitinol-reinforced fiberglass composite beams. They also demonstrated that control in natural frequencies of flexible fiberglass composite beams could be achieved by activating optimal sets of shape memory alloy wires which are embedded along the neutral axes of the beams (simply supported). This paper deals with the study on shape and vibration control of GFRP composite beam using SMA.

2. SHAPE MEMORY ALLOY

FLEXINOL is a shape memory alloy wire provided by M/s. Dynalloy Inc., USA. FLEXINOL has a unique property (i.e) when it is heated beyond the austenite transformation temperature, the wire contracts about 4% of its original length. FLEXINOL wires of various dimensions were procured and wires of diameter 0.020” and 0.016” have been used for experimentation and testing purposes. The electrical and mechanical properties of FLEXINOL wire are shown in Table 1.The complete phase transformation characteristics of the FLEXINOL wire, during a complete heating and cooling cycle, are given by the strain-temperature characteristics, which is shown in Figure 1.



A_s = austenite start temperature
A_f = austenite finish temperature
M_s = martensite start temperature
M_f = martensite finish temperature

Figure 1. Variation of temperature with percentage strain for flexinol wire

Table 1. Properties of flexinol wire

Wire diameter size (in)	Resistance (Ω per in)	Maximum Pull force (g)	Applied current at room temperature (mA)
0.001	45	7	20
0.0015	21	17	30
0.002	12	35	50
0.003	5	80	100
0.004	3	150	180
0.005	1.8	230	250
0.006	1.3	330	400
0.008	0.8	590	610
0.010	0.5	930	1000
0.012	0.33	1250	1750
0.016	0.2	2000	4000
0.020	0.020	3560	5000

3. THE DYNAMICS OF COMPOSITE BEAMS REINFORCED WITH FLEXINOL WIRE

The dynamic characteristics of beams reinforced with FLEXINOL wire are determined by considering the interaction between the elastic characteristics of the composite beams and the thermally induced shape memory effect of the FLEXINOL wire.

3.1. Beam Dynamics

Consider the following strain-displacement relations for a beam undergoing large transverses deflection w and longitudinal displacement μ. [18,19,20]

$$\varepsilon_1 = \mu^1 + w'^2/2 \text{ and } \varepsilon_b = yw'' \quad (1)$$

where ε_1 and ε_d denote the longitudinal membrane strain and the bending strain, respectively. Also, the primes denote the spatial derivatives with respect to x.

The strain and kinetic energies of the beam are given by:

$$\text{elastic strain energy} = \frac{1}{2}\int_0^{L_e}(E_t A_t \varepsilon_1^2 + EI\varepsilon_b^2)\,dx \quad (2)$$

$$\text{kinetic energy} = \frac{1}{2}\int_0^{L_e} m_t(\mu^2 + w^2)\,dx \quad (3)$$

where E_t, A_t, I_t and m_t, represent Young's modulus, cross sectional area, area moment of inertia and mass per unit length L_e, of the composite beam respectively.

Forming the Lagrangian, as the difference between the elastic strain and the kinetic energies, and applying the classical Lagrangian dynamics, the following dynamic equation is obtained:

$$[M_e]\{\ddot{\delta}\} + [K_e]\{\delta_e\} = \{F_e\}, \text{ for } e=1, \ldots\text{ n}, \quad (4)$$

where n denotes the number of finite elements and $\{\delta_e\}$ denotes the nodal deflection vector of element e, which is bounded by nodes i and j, such that:

$$\{\delta_e\} = [u_i\, u_j\, w_i\, w_{xi}\, w_j\, w_{xj}]^T, \quad (5)$$

with u_i, w_i and w_{xi} being the deflections of node i in the axial, transverse and angular directions. The nodal deflection vector $\{\delta_e\}$ is related to the axial deflection u and the transverse deflection w at any location x by the following interpolating equations:

$$\begin{bmatrix} u \\ w \end{bmatrix} = \begin{bmatrix} A_1 & A_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_3 & A_4 & A_5 & A_6 \end{bmatrix}\{\delta_e\} = \begin{bmatrix} A_7 \\ A_8 \end{bmatrix}\{\delta_e\} = [A]\{\delta_e\} \quad (6)$$

where the elements of matrices [A_1] through [A_6] are function of x [19].

In Equation (4), $[M_e]$ and $[K_e]$ are the mass and the stiffness matrices of the beam element e which are given by:

$$[M_e] = m_t \int_0^{L_e} [A]^T [A] dx \text{ and } [K_e] = [K_e]_L + [K_e]_{NL} \quad (7)$$

where $[K_e]_L$ and $[K_e]_{NL}$ denote linear stiffness matrix and the non-linear stiffness matrix due to large deflections which are given by:

$$[K_e]_L = \int_0^{L_e} \{[A_{7''}]^T [A_{8''}]^T\} \begin{bmatrix} E_t A_t & 0 \\ 0 & E_t I_t \end{bmatrix} \{[A_{7''}] A_{8''}\} dx \quad (8)$$

$$[K_e]_{NL} = E_t A_t \int_0^{L_e} \{[A_{7'}]^T [A_{8'}]^T\} \begin{bmatrix} 0 & f_1 \\ f_1 & f_2 \end{bmatrix} \{[A_{7'}][A_{8'}]\} dx \quad (9)$$

where

$$f_1 - [A_8]\{\delta_e\} \text{ and } f_1 = 2([A_{8'}]\{\delta_e\})^2 + [A_{7'}]\{\delta_e\}/2 \quad (10)$$

with primes denoting spatial derivatives with respect to x,

In Equation (4), (F_e) is the vector os control moments developed by the FLEXINOL wire (M_{ci} and M_{cj}). It is given by:

$$\{F_c\} = [0 \;\; 0 \;\; 0 \;\; M_{ci} \;\; 0 \;\; M_{cj}]^T \quad (11)$$

These moments are to be determined by considering the constitutive equations of the SMA.

3.2. Constitutive Equations For The Shape Memory Effect

The martensitic phase transformation process of the FLEXINOL wire is governed by the following constitutive Equation [21]:

$$(\sigma - \sigma_0) = E_s(\varepsilon - \varepsilon_0) + \Theta(T - T_0) + \Omega(\xi - \xi_0) \quad (12)$$

where σ, ε and T denote the stress, strain and temperature respectively. Also E_s, Θ and Ω define Young's modulus, the thermal expansion modulus and phase transformation modulus of FLEXINOL. Subscript '0' corresponds to the initial conditions. In Equation (12), the martenstitic fraction ξ is defined as follows:

3.2.1. During Transformation From Martensite to Austenite (M→A)

$$\xi = \xi_M e^{[a_A(A_s - T) + b_A\sigma]} \quad (13)$$

$$a_A = \text{In } (0.01/\xi_M)/(A_s - A_f) \text{ and } b_A = a_A/C \quad (14)$$

with ξ_M, A_s, A_f and C denote the initial martensitic fraction, austenite start temperature, austenite finish temperature and slope of stress-transition temperature characteristics.

The domain of the M→A transformation is defined by:

$$\text{In } (0.01/\xi_M)/b_A + a_A/b_A(T - A_s) \le \sigma \le a_A/b_A(T - A_s) \quad (15)$$

3.2.2. During Transformation From Austenite to Martensite A→M

$$\xi = (1 - \xi_A)\left[1 - e^{[a_M(M_s - T) + b_M\sigma]}\right] \quad (16)$$

$$a_M = \ln [1 - 0.99 / (1 - \xi_A)]/(M_s - M_f) \text{ and } b_M = a_M/C \quad (17)$$

with ξ_A, M_s, M_f and C denote the initial martensitic fraction, martensite start temperature, martensite finish temperature and slope of stress-transition temperature, martensite finish temperature and slope of stress-transition temperature characteristics.

The domain of the A→ M transformation is defined by :

$$a_M/b_M(T - M_s) \le \sigma \le \ln [1 - 0.99/(1 - \xi_A)]/b_M + a_M/b_M(T - M_s) \quad (18)$$

The constitutive Equations (12)-(18) can be used to determine the stress – strain – temperature characteristics of a one-dimensional (ID) SMA fiber. These relationships have been utilized to compute the recovered strain or stress of the SMA, resulting from the shape memory effect.

3.3. Shape Memory Control Action

Figure 2, presents the schematic diagram of flexible composite beam with FLEXINOL actuator.

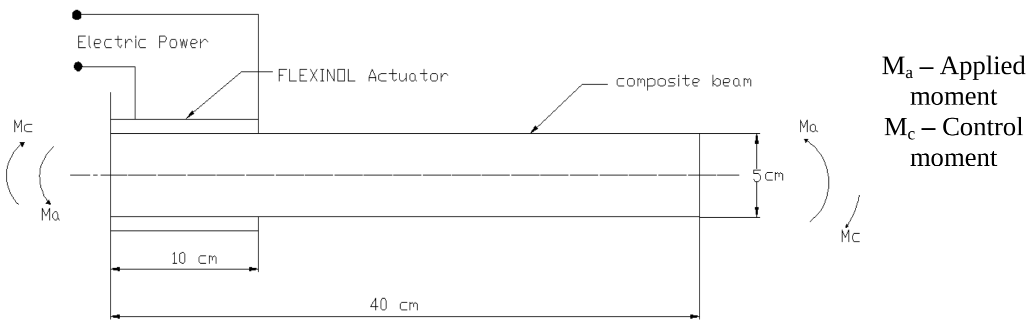


Figure 2. Schematic Diagram Of Flexible Composite Beam

The control moment can be written as a product of the actuator force F_a and the distance d_i between the actuator axis and the beam neutral axis.

$$M_c = F_a d_i \tag{19}$$

The force-deflection characteristics of the individual elements of the beam-actuators system is given in Equation (20), are combined to determine the overall stiffness of the system.

$$F_i = K_i \delta_I \tag{20}$$

where F_i is the vector of resultant forces and moments acting on the beam element I, K_i is the stiffness matrix of the beam actuator element, and δ_I is the deflection vector of the nodes.

The equilibrium conditions of the beam require that the sum of the external forces and moments and of the internal forces and moments acting on the beam are in balance; i.e.,

$$F= \sum^{N+1} F_1 = \sum^{N+1} K_i \, \delta_i = K\delta \tag{21}$$

where K and δ represent the overall stiffness matrix and deflection vector of the beam –actuators system, respectively.

4. EXPERIMENTAL SET UP

The experimental setup used in this work is shown in Figure 3. The actuator is attached to the beam with the help of screws. at the fixed end of the beam. The SMA wire is heated intermittently by a power supply with a help of a timing and actuation circuit. The control system takes care of automatic switching ON/OFF of the power supply (0-30V DC, 0-30A) to the SMA wire, thus aiding in intermittently heating of the SMA wire. Cooling of SMA wire is taken care of by natural convection.

Experiments were performed on composite beams by varying the following parameters such as wire diameter (0.020" and 0.016"), currents rating (2A and 4A) and various excitation frequencies (2Hz, 4Hz and 8Hz). The length of SMA was maintained constant but different stacking sequences of ply were employed. The sequences are $(0^o)_3$, $(0^o/90^o/0^o)$ and $(60^o/0^o/30^o)$ with the volume fraction of 0.6. The natural frequency of the beam subjected to load at the end is determined by Equation (22). The first natural frequency of the beam is 5.9 Hz. Hence, in order to avoid resonance, it was necessary to consider the excitation frequencies as 2 Hz, 4 Hz and 8 Hz.

$$\omega_n = (\beta I)^2 \sqrt{EI / \rho A l^4} \tag{22}$$

where, ω_n- Natural frequency of the system in rad/s

β- Constant that varies with the order of frequency being found out

E- Young's Modulus of the material in GPa

I- Area moment of inertia of the beam in m^4

ρ- Density of the beam material in kg/m^3

A - Area of cross section of the beam in m^2

L- Length of the beam in m

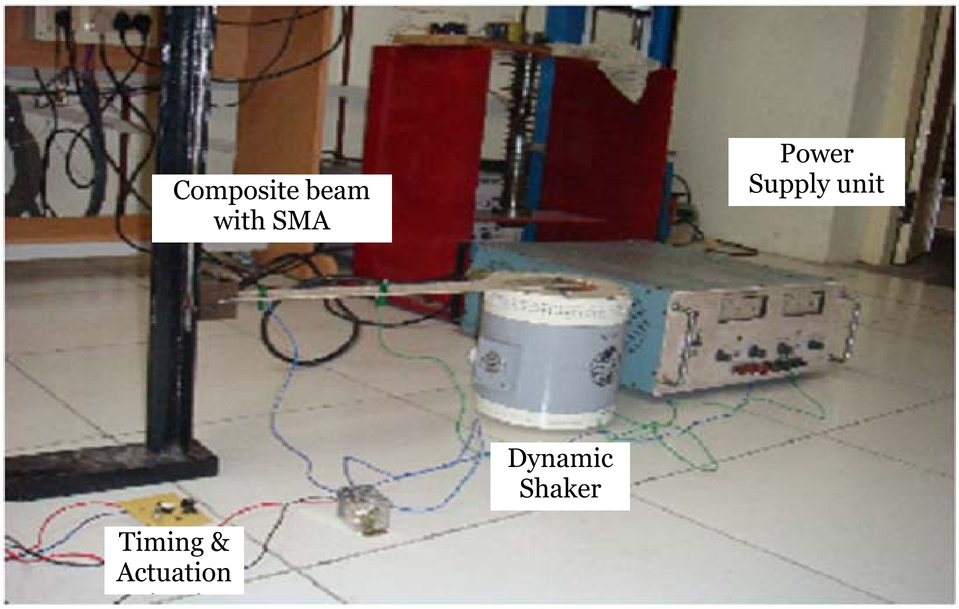


Figure 3. Experimental setup

4.1. Timing and Actuation circuit

Since the FLEXINOL wire 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. An electrical circuit was specially designed for the heating and cooling process. The schematic representation of which is shown in Figure 4. An output voltage of 5V DC from the Data Acquisition Card (DAQ), switches on the transistor in the opto-coupler (U1) – MCT2E. As a result, 5V from the power source V2 is grounded through this opto-coupler. Hence, the power transistor (Q1) – 2N1711 remains switched off. So, the 12V from the power supply V3 closes the NO (Normally Open) contact of the relay S1. When the relay contacts are closed, the preset current from the constant voltage variable current power supply (V5) is passed to the SMA wire and the wire is heated. The reverse logic is followed when there is no output from the DAQ card. The relay is switched on once in 3 seconds using a timer control through Lab VIEW software.

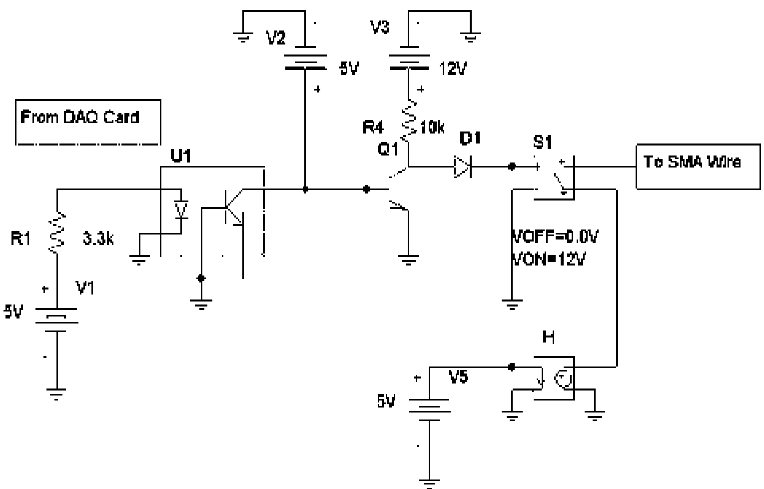


Figure 4. Circuit diagram of the control and actuating circuit

5. RESULTS AND DOISCUSSION

The displacement plot of 0°/0°/0° stacking sequence for the current rating of 2A and 4A is given in Figures 5-6. The corresponding cycle time taken for contraction and relaxation of SMA is shown in Figure 6.

From the Figrures 5-6 it can be inferred that the current input to the wire is ON, the FLEXINOL gets contracted during in which the contraction tip displacement of the GFRP beam is considerably reduced likewise the current input to the wire is OFF, the wire gets relaxed .Hence, the tip displacement tends to increase during this period.

The tip displacements for various orientations at different levels of frequencies are presented in Figures 7-9.

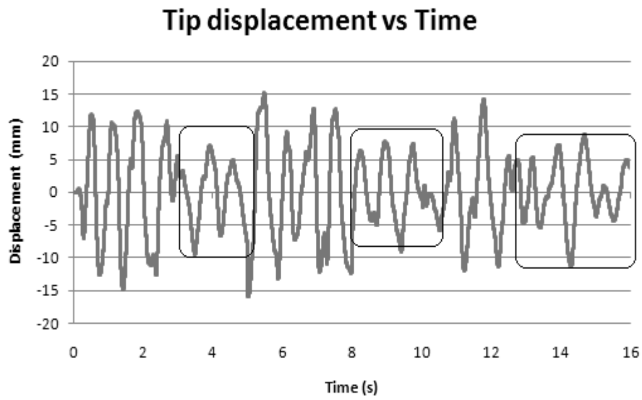
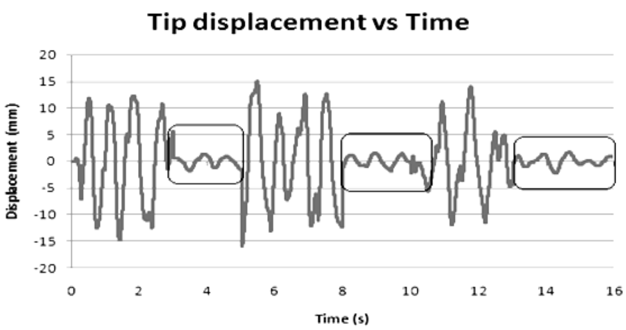


Figure 5. Displacement plot for 0°/0°/0 ° composite beams for excitation frequency 2hz with two SMA 0.020” diameter wires and 2a current rating



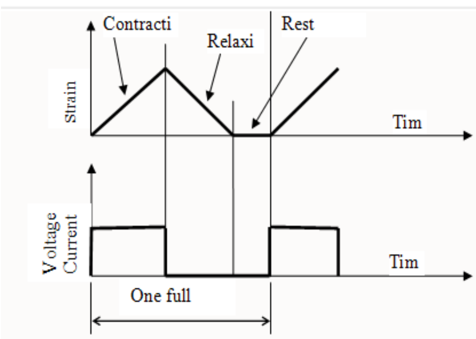


Figure 6. Displacement plot for 0°/0°/0 ° composite beams for excitation frequency 2hz with two SMA 0.020” diameter wires and 4a current rating

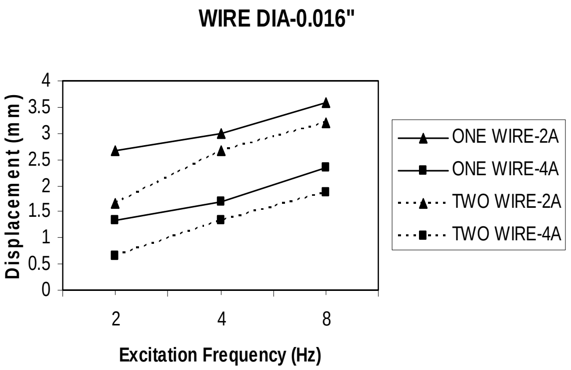


Figure 7. Effect of current and number of actuators on beam shape for 0°/0°/0° ply orientation

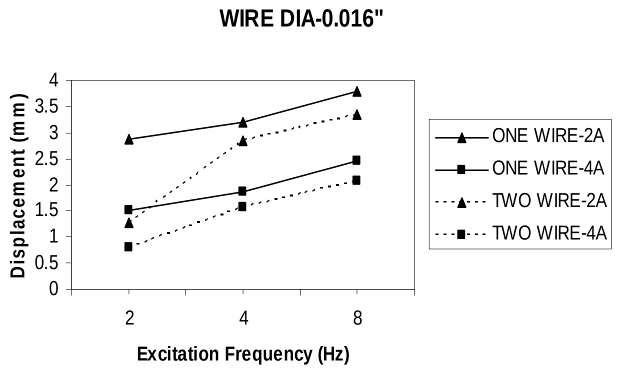


Figure 8. Effect of current and number of actuators on beam shape for 0°/90°/0° ply orientation

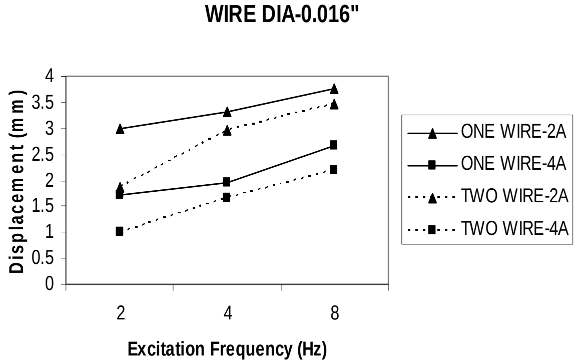


Figure 9. Effect of current and number of actuators on beam shape for 60°/0°/30° ply orientation

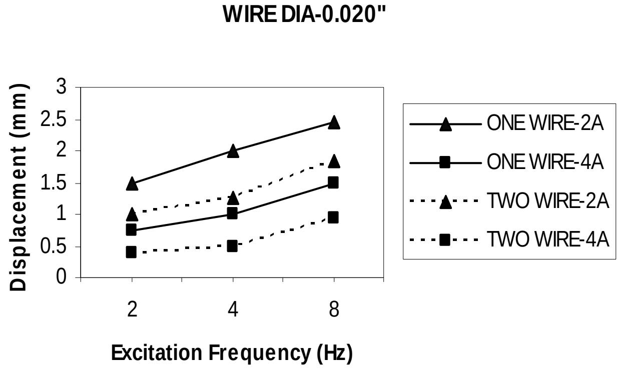


Figure 10. Effect of current and number of actuators on beam shape for 0°/0°/0 ° ply orientation

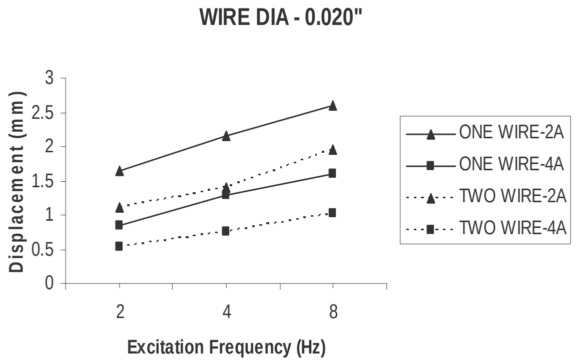


Figure 11. Effect of current and number of actuators on beam shape for 0°/90°/0° ply orientation

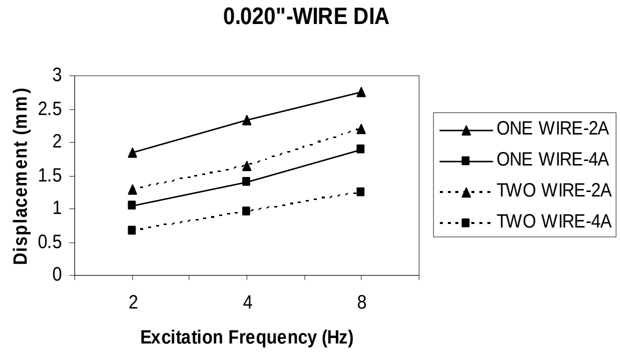


Figure 12. Effect of current and number of actuators on beam shape for 60°/0°/30° ply orientation

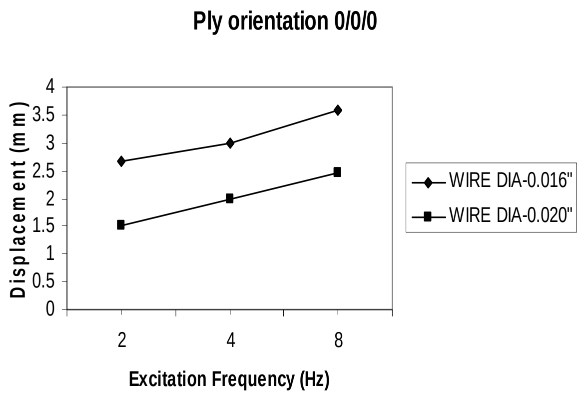


Figure 13. Effects of wire diameters on shape control

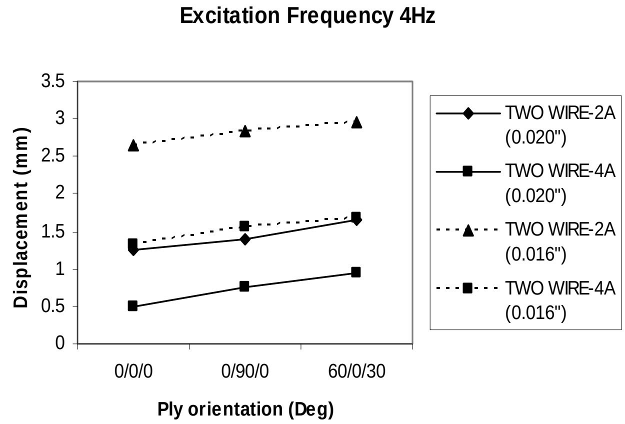


Figure 14. Comparison between different ply orientations

From experiments conducted the effects of current, number of actuator and the diameter of FLEXINOL wire on shape control of the GFRP beams are shown in Figures 7-9. From the characteristic curves it can be inferred that as the current is increased, the force generated by the wire is more and hence the tip displacement of the cantilever beam is less for the current rating of 4A, when the frequency is constant. The use of multiple SMA wires gives better results when compared to that of using a single wire. The tip displacement of the beam with two SMA wires is less than that of the beam with one SMA wire. As the excitation frequency increases, the percentage reduction in tip displacement also decreases.

Similarly, from the Figures 10-13, it can be observed that the larger diameter wire (0.020") significantly reduces the displacement for the same current rating and excitation frequency when compared to a wire of smaller diameter (0.016"). As the excitation frequency increases, the percentage reduction in tip displacement decreases; this is because the cycle time of the large diameter wire is lesser when compared to that of the small diameter wire. But if lesser diameter wire is used, a compromise has to be made on the force generated by the wire. A better alternative would be to employ forced cooling methods to improve the cycle time of SMA wire.

From Figure 14, it can be understood that, the shape control is more effective in case of 0°/0°/0 ° glass fiber/epoxy beams. This is primarily because the resultant forces and moments developed by all fibers are exactly balanced by the control force and moment developed by the SMA wire, since they are in the same longitudinal direction.

The percentage reduction in tip displacement value was maximum in the case of beam with two SMA 0.020" diameter wires, 4A current rating and excitation frequency 2Hz; it was minimum in the case of beam with one SMA 0.016" diameter wires and 2A.

6. CONCLUSION

The shape and vibration control of composite beam composite beam using SMA was intensively studied. The results obtained indicated that SMA has good potential to be used as an actuator in smart structures due to the reason that, the voltage required for actuation is very minimum when compared to other actuation techniques. Experiments were performed on composite beams for various excitation frequencies and the effect of variation of input current, wire diameter, ply orientation of the fibers in composite beams and beam material were recorded. It was also discovered that the use of SMA minimizes the need for large amplification circuits. Since the voltage required for actuation is very less which is in the order of 4V.

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