

Application of Shape Memory Alloy Wire Actuator for Precision Position Control of a Composite Beam

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In this paper are presented the design and experimental results of using a shape memory alloy (SMA) wire as an actuator for position control of a composite beam. The composite beam is honeycomb structured, having wires of SMA embedded in one of its face sheets for the purposes of active actuation. Nickel-titanium SMA wires were chosen as actuating elements due to their high recovery stress (>700 MPa) and tolerance to high strain (up to 8%). A simple proportional and derivative controller plus a feed-forward current is designed and implemented for controlling the tip position of the composite beam. Experiments have demonstrated the effectiveness of the SMA wire as an actuator for active position control of a composite beam.

Keywords shape memory alloys, Nitinol, Ni-Ti alloys, hysteresis

1. Introduction

Discovered about 50 years ago, shape memory alloys (SMAs) are smart materials, which 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.

The most common shape memory material is an alloy of nickel and titanium called Nitinol, or NiTi, which was discovered at the Naval Ordnance Laboratory in the 1960s. This particular alloy has very good electrical and mechanical properties, long fatigue life, and high corrosion resistance. As an actuator, it is capable of up to 8% strain recovery and 700 MPa restoration stress with many cycles. By example, a Nitinol wire 0.508 mm in diameter can generate as much as 70 N blocked force. Nitinol also has the resistance properties that 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 be actuated.

The unique properties of SMA make it a potentially viable choice for actuators. The SMA actuators have over the years been used in a spectrum of applications, such as (a) active shape control of space antenna reflectors, (b) vibration reduction for rotorcraft with active flap control, and (c) active deicing systems for fixed-wing aircraft. When compared to the piezoelectric actuators, the SMA actuators offer the salient advantage of being able to generate either larger deformations or forces. The SMAs can be conventionally fabricated into different shapes. The most widely used are the SMA wires.[1,2] The SMA wires can be precisely embedded into the face sheet of a structure of interest, such as a helicopter blade, and can actively alter the shape of the structure in a desired fashion. As illustrated in Fig. 1, a shape memory wire actuator is used to lift a weight.

The special properties of SMAs result from a phase transformation (Fig. 2) in their crystal structure when cooled from the stronger, high-temperature form (austenite) to the weaker, low-temperature form (martensite). The alloy undergoes a martensitic transformation of a type that allows the alloy to be deformed by a twinning mechanism below the transformation temperature. The deformation is then reversed when the twinned structure reverts upon heating to the parent phase. The transformation exhibits a hysteretic effect, in that the transformations on heating and on cooling do not overlap.[3] This unique ability, of a reversible crystalline phase transformation, enables a Nitinol SMA object to either recover its initial heat-treated shape (up to 8% strain) when heated above a critical transformation temperature or alternatively generate high recovery stresses (in excess of 700 MPa).

This paper discusses the salient attributes when embedded SMA wires are used as actuators for tip position control of a composite beam. The wire actuators are embedded within a low modulus elastomeric face sheet attached to a honeycomb core. Supplying direct current, ranging from 1.5 to 3 A, to the wires of SMA deforms the composite beam. The tip of the beam can move up to 1.5 cm when the base end is fixed. The primary motivation for the experimental study was to have a basis to demonstrate and validate the concept of using SMAs as actuators for aerospace-related applications and to concurrently develop control methods for SMA actuators. A proportional and derivative controller with feed-forward current is designed for active control of the SMA wire actuators. A real-time code is developed and implemented to control the tip position of the composite beam with the base end fixed. The experimental results demonstrate the effectiveness of using SMA wires as actuators.

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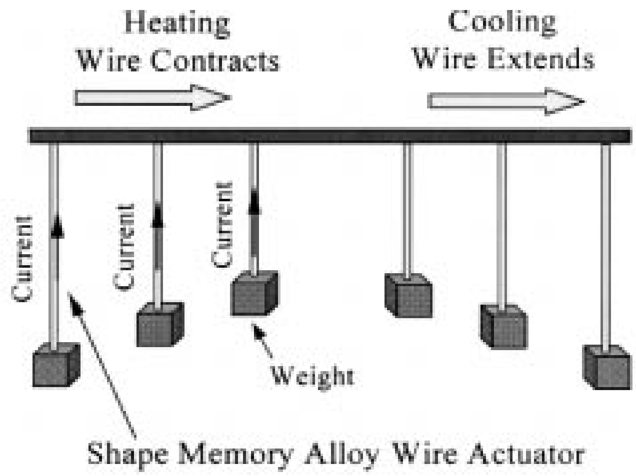

Fig. 1 Demonstration of a SMA wire actuator lifting a weight

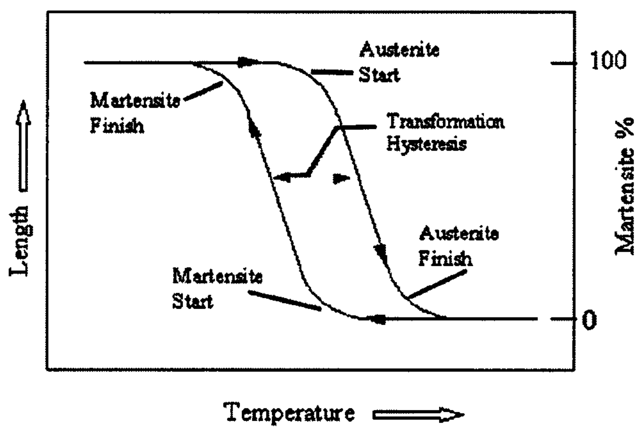

Fig. 2 Transformation hysteresis vs temperature for an SMA actuator under constant load (stress) as it is cooled and heated

2. Composite Beam with Embedded SMA Wire as Actuator

Considering the potential applications of SMA actuators, a composite beam having embedded SMA wire actuators is fabricated for this study and is shown in Fig. 3. When heated, the shape memory wire actuators tend to deform the composite structure. For purposes of simplicity, the SMA wire actuators are embedded on one side of the composite beam. A composite beam is chosen and used because of its light weight coupled with the convenience to embed actuators. Wires of Nitinol SMA were chosen as the candidate actuating elements due to their high recovery stress (>700 MPa) and high strain (up to 8%). The detailed properties of this Nitinol SMA material are shown in Table 1.[4]

There are two types, direct and indirect, of embedding of SMA wire actuators into structures for the application of active control of flexible structures.[5] Direct embedding of SMA wires means that the SMA wires are embedded directly without any covering, while indirect embedding of SMA wires means that SMA wires, for example, secured in sleeves or face sheets, are

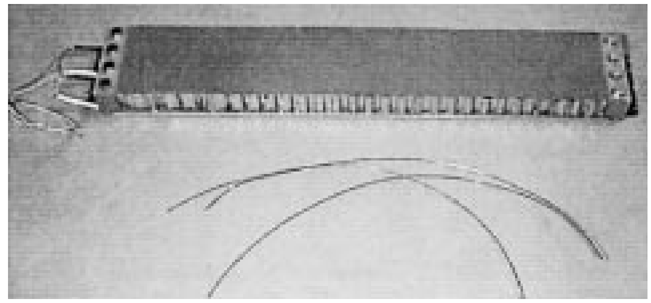

Fig. 3 The composite beam with embedded SMA wire actuators and some SMA wires

embedded within composite laminates. In this research, the method of indirect embedding is used to secure the SMA wire actuators to a honeycomb-cored composite beam *via* a face feet.

The composite beam measures 30.48 cm in length, 5.08 cm in width, and 1.32 cm in thickness. Figure 4 provides a top view of the beam, while Figure 5 shows a side view of the beam. The beam is constructed of a 1.27 cm thick honeycomb core made from aluminum alloy (AA5052). The thickness is 0.81 mm G-10 backbone with a 2.54 mm thick Conathane urethane casting system (UC-49) as the compliant face sheet and two termination blocks (type: ultem 2300). The SMA wires are embedded within a low modulus elastomeric face sheet, which is attached to the honeycomb core. The opposing side of the beam consists of a high modulus glass epoxy bonded to the core of the honeycomb. The elasticity of the beam provides the restoring force. There are in all 16 ($d = 0.381$ mm, and $L = 30.48$ cm) nickel-titanium shape memory wires (two sets of eight wires electrically wired in parallel) embedded in the compliant face sheet. The effective circuit resistance of the wires is 10.3 ohms.[4]

Supplying current ranging from 1.5 to 3.0 A to the SMA wires can conveniently deform the composite beam. The exact amount of current is dependent on the mutually interactive influences of desired response time and degree of actuation. Degradation of the urethane face sheet can result from current in excess of 3 A or extended hold times at maximum deflection. The potential applications of this experiment include the following: (a) thermodistortion compensation for precession space structure, (b) stern shape control for submarines, and (c) flap shape control for aeronautical applications.

3. Experimental Setup

The purpose of the experiment is to actively control the tip motion of the composite beam actuated by SMA wire actuators. A diagram of the overall composite beam experiment is shown in Fig. 6. Major components of this experiment include the following: (a) a programmable power supply (model 6542A), (b) a high-power low-voltage power supply, (c) a composite beam, (d) a laser analog sensor (model LM100), (e) an oscilloscope, and (f) a tabletop computer. The computer (not shown in Fig. 6) is loaded with Matlab/Simulink and dSPACE data acquisition and real-time control system. The dSPACE system (Germany) employs a Texas Instruments (Dallas, TX) C-30 DSP.

Table 1 Properties of the nitinol wire actuator

Transformation properties	
Transformation temperature	–200 to 110 °C
Latent heat of transformation	5.78 cal/g
Transformation strain (for polycrystalline material)	
For a single cycle	8% maximum
For 100 cycles	6%
For 100,000 cycles	4%
Hysteresis	30 to 50 °C
Physical properties	
Melting point	1300 °C
Density	6.45 g/cm^3
Thermal conductivity	
Austenite	0.18 W/cm °C
Martensite	0.086 W/cm °C
Specific heat	0.20 cal/g °C
Corrosion performance	Excellent
Electrical properties	
Resistivity(ρ) [resistance = $\rho \times$ length/cross-sectional area]	
Austenite	~100 $\mu\Omega$ cm
Martensite	~80 $\mu\Omega$ cm
Magnetic permeability	<1.002
Magnetic susceptibility	3.0×10^6 emu/g
Mechanical properties	
Young's modulus	
Austenite	~83 GPa
Matensite	~28–41 GPa
Yield strength	
Austenite	195–690 MPa
Matensite	70–140 MPa
Ultimate tensile strength	
Fully annealed	895 MPa
Work hardened	1900 MPa
Poisson's ratio	0.33
Elongation at failure	
Fully annealed	25–50%
Work hardened	5–10%
Hot workability	Quite good
Cold workability	Difficult
Machinability	Difficult

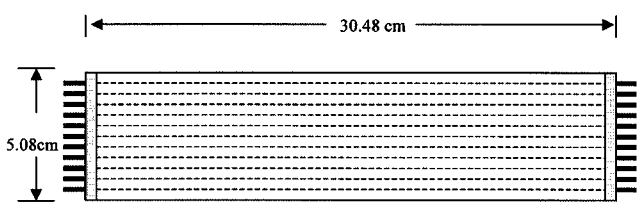

Fig. 4 The top view of the shape memory composite beam

As shown in Fig. 6, one end of the composite beam is fixed to the supporting structure, while the other end is free to move once the embedded SMA wires are supplied with current. The laser analog sensor is used to detect displacement of the tip of the beam. The output signal is sent to the dSPACE digital data acquisition system for feedback control.

A real-time control design environment with Matlab/Simulink and dSPACE interface software is used to design controllers and to concurrently generate real-time codes. The real-time code is then downloaded to the DSP for real-time control. The control signal from the dSPACE system is amplified by the programmable power supply (model 6542A) and forwarded to the SMA wire actuator to activate the composite beam. The output voltage from the dSPACE system serves as the input voltage to the power supply. Throughout this experiment, the power supply is operated in the voltage control mode. The power supply delivers a current proportional to the control voltage to the SMA wires and gradually heats it. Heating of the wire promotes the occurrence of a phase transformation coupled with shrinkage of the wire, thereby causing the beam to be bent and its tip to move. The laser sensor detects the movement. An oscilloscope is used to display both the displacement output voltage from the laser sensor and the output voltage from the real-time control system.

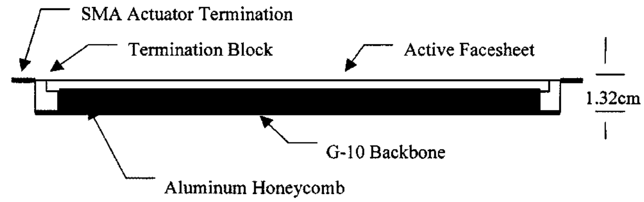

Fig. 5 A side view of the shape memory composite beam

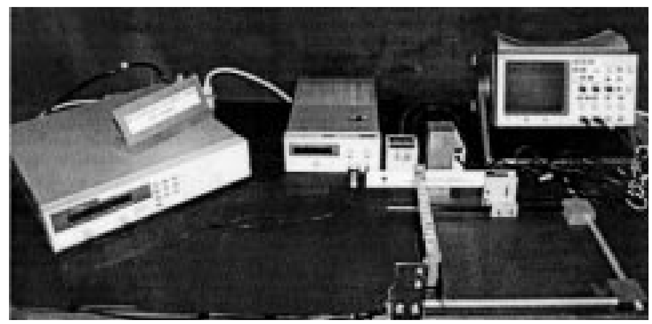

Fig. 6 The setup of the SMA beam experimental

4. Control System Design

To test the smart composite beam with SMA wire actuators, a control system is designed. The co-ordinate system is defined to assist control design. In Fig. 7 is shown a top view of the SMA composite beam. The end at point "O" is constrained, while the end at point "A" (tip of the beam) is free to move in the Y direction. The SMA wires are embedded on the side face facing the $+Y$ direction. As current is applied to the SMA wire actuator, the tip of the beam will displace toward the $+Y$ direction. However, when the current is removed, the beam tip will move in the $-Y$ direction toward its starting point.

The control errors are defined to be the following:

$$e = y - y^d, \quad \dot{e} = \dot{y} - \dot{y}^d \qquad \text{(Eq 1)}$$

where y^d and $\dot{y}^d$ are the desired tip position and velocity, respectively. Since the problem of a regulator is considered, $\dot{y}^d = 0$. Therefore, $\dot{e} = \dot{y}$.

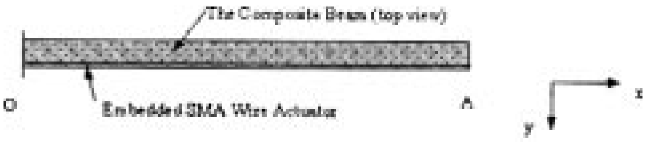

Fig. 7 Top view of the SMA composite beam

The controller is proposed as

$$i = i_f - k_p e - k_d \dot{e} \qquad \text{(Eq 2)}$$

where k_p and k_d are positive gain constants. The functions of each control action in Eq 2 are as follows. It is worthwhile to point out that the value of the control current i is set to zero if $i < 0$.

- The $-k_p e - k_d \dot{e}$ term is the proportional plus derivative (PD) controller. Proportional control is used to decrease steady-state error and increase responsiveness of the actuator. The derivative control facilitates increasing damping and concurrently stabilizing the actuator.
- The i_f term is a feed-forward action. This control action is used to supply the SMA actuator with the appropriate amount of current to compensate for environmental heat losses.

5. Testing Results and Observations

The controller is implemented using Matlat/Simulink and dSPACE real-time interface software. The proportional and derivative gains are set to 20, and the bias voltage is set to 0.02 V. The bias voltage effectively corresponds to a current of 0.77 A applied to the SMA beam. During the process of control, the tip of the beam is required to move from 4 to 7.5 mm. In Fig. 8 is shown the time history of the position of the beam tip, when the controller uses the robust compensator. It is clear from this figure that an accurate control of the position of the tip is now achieved. There is no overshot. This experiment demonstrates the feasibility of using SMA wire actuators for precision position control.

6. Conclusions

The following are the key observations resulting from this study.

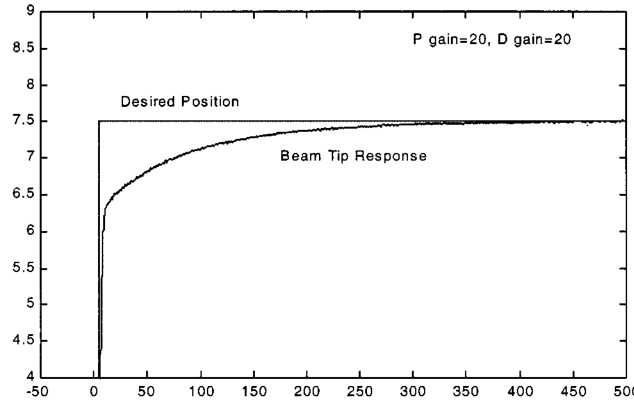

Fig. 8 Position control of the tip of the composite beam

- Wires of SMA were embedded into a composite beam for purposes of achieving active position control.
- The composite beam is honeycomb structured having wires of SMA embedded in one of its phase sheets for the purposes of inducing active actuation. The controller includes a feed-forward action and a PD control action.
- The controller is designed in Matlab/Simulink and implemented in real-time using a dSPACE data acquisition and control system.
- An experiment was conducted and the results demonstrate the ability of SMA actuators to precisely control the tip position of a composite beam.

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