ACTIVE SHAPE CONTROL OF A BEAM BY MEANS OF SHAPE MEMORY ACTUATORS

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Abstract. *Among the functional materials the Shape Memory Alloys - SMA – have received special attention in applications where high loads and large strains are required from the actuators. In this paper, a basic experimental work on the application of SMA for active shape control of structures is presented. The deflection of a flexible beam is actively controlled through resistive heating of NiTi wires fixed on its upper and bottom surfaces. The heating is accomplished by a electric current and the deflection of the beam is measured by means of strain gauges sensors. A feedback control system was implemented to investigate the dynamic response of the beam in some basic feedback control experiments. The preliminary experimental results illustrate the potential of shape memory actuators for the development of adaptive structures.*

Keywords: *Shape Memory Alloy, memory actuators, adaptive structures, active control;*

1. Introduction

In the last three decades, the application of Shape Memory Alloy (SMA) has attracted much attention from many fields as industrial, medical and aerospace (Borden, 1991; Yang et al, 1994; Stanewsky, 2001; Norbert et al, 1992; Hagermeister et al, 1995). In the field of adaptive structures, SMA has been mainly proposed for shape control (Elzey et al, 2005) and vibration control (Shahin et al, 1997).

Considerable attention has been devoted to the development of hybrid composite structures based on the thermomechanical behavior of SMA elements. They are often incorporated to host materials or structures in the form of wires or thin films by either directly embedding or inserted into to pre-embedded sleeves to control vibration or shape of the host structures. The use of these composite structures for the development of adaptive structure is one of the most promising applications of SMA (Baz and Tampe, 1989; Baz et al, 1990; Shahin et al, 1997; Elzey et al, 2005; Rogers and Giurgiutiu, 1999; Hesselbach and Stork, 1994). In this kind of application shape memory elements are used as reinforcements in a matrix and the control of the composite is accomplished by electric heating of them. This trend is due to the unique thermomechanical behavior of the SMA such as strain and stress recovery and large changes in some of their physical properties such as stiffness, damping ratio and viscosity in response to thermomechanical stimuli. All these changes are associated with a martensitic phase transformations (Krishnan et al, 1975).

In 1988, Rogers and Robertshaw proposed for the first time the application of SMA actuators in a composite laminate. Turner (2001) and Jia and Rogers (1989) proposed two concepts for structural control based on the thermomechanical behavior of SMA: Active Properties Tuning (APT) and Active Strain Energy Tuning (ASET). The APT concept relies on unstrained shape memory wires embedded in composite structures. Upon heating the memory wires above the austenite start temperature (A_s) they undergo a stark increase in elastic modulus, which may undergo changes by a factor of 350% in transforming from the martensite to the austenite phase, and the yield stress may change by a factor of ten (Krishnan, 1975). The modulus shift of the memory wire causes a shift in stiffness of the composite as a hole, and this causes a change in the dynamical behavior of the structure. In the ASET concept the memory wires are pre-strained before to being embedded. Upon heating the recovery stress developed at the composite matrix-wire interface causes a change in the modal response of the structures. The APT and ASET concepts have been intensively investigated (Wei et al, 1998; Turner, 2001).

In addition to APT and ASET concepts Schetky (1992) considers the Shape Control concept by means of shape memory actuators. In this case the shape memory fibers may be embedded or fixed on the surface of the structure at a certain distance from the neutral axis, so that upon heating the resulting tensile forces produce local moments, which cause out of plane bending and shape change. In the embedded case if the shape memory fibers are free to contract by separating them from the matrix by means of a sleeve for instance (Chaudhry and Rogers, 1991), then a concentrated moment is produced by the shape recovery of the memory wires and causes bending and shape change of the structure. Some applications exploiting the Shape Control concept have been proposed (Chaudhry and Rogers, 1991; 1992; Baz and Tampe, 1989; Musolff, 2005).

In a previous work Da Silva (2004) presented some basic control experiments exploiting the Shape Control concept for shape control of a simply supported flexible beam actuated by one shape memory actuator. The actuator was fixed on the upper surface of the beam and its deflection was actively controlled. In the present work similar control experiments are extended to a simply supported beam actuated by two NiTi shape memory actuators: one on the upper surface and the other on the bottom surface of the beam. A feedback control system is implemented and the beam time response is investigated for different reference functions. The deflection is measured by means of strain gauge sensors placed on the surfaces of the beam. The main goal of this study is to illustrate the application of shape memory actuators for shape control of structures.

In section 2 the experimental apparatus is presented and in section 3 the feedback control system is described. The obtained experimental results are presented and discussed in section 4.

2. Experimental apparatus

The system investigated in this work is illustrated in Figure 1 and the experimental apparatus is shown in Figure 2. The adaptive system consists of a flexible beam of steel (Da Silva, 2000) with the following dimensions: 220mm x 20 x 1,5mm. The experimental apparatus is the same used by Seelecke at al (1999), but the material of the beam is steel intead of Epoxy. The memory actuators 1 and 2 are NiTi memory wires with 90mm length and of 0.29mm diameter. The actuators 1 and 2 are fixed on the upper and bottom surfaces of the beam respectively, parallel to the beam neutral axis. Between the wires and the holders isolating sleeves are used to prevent that electric current flows through the beam. The beam deflection is measured by means of the strain gauges *SG1* and *SG2*. The actual electric signals *D1* and *D2* measured by the strain gauge sensors are used to calculate the beam deflection *Z(t)* by means of an experimentally obtained relationship. The two electric reference resistors *Rr1* and *Rr2* have known values and are used to calculate the electric currents that flow through the actuators 1 and 2 respectively.

The actuating principle relies on the unique properties of SMA. The actuator configuration exploited here is of the bias-type, whereby the bias function is exerted by the beam stiffness. The wires are pre-strained and assembled into the beam holders as shown in Figure 1. Upon heating the wires begin to recover the pre-strain and assume their high temperature shape (shorter length) as the austenite start temperature A_s is reached. The shape recovery upon heating is completed at the austenite finish temperature A_f.

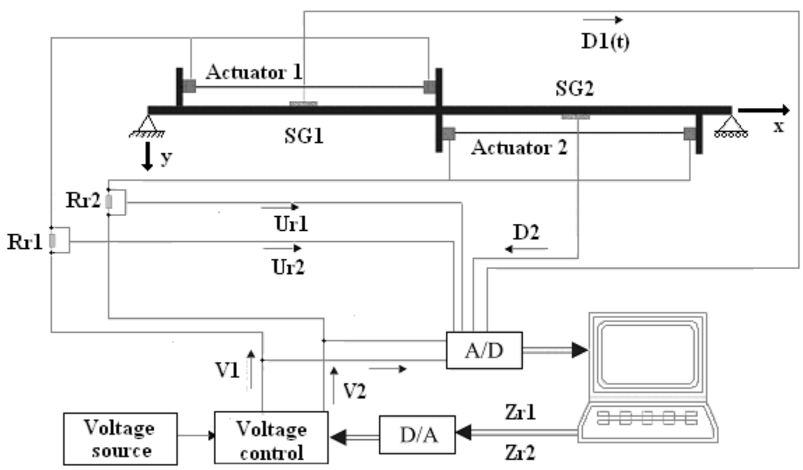

Figure 1. Adaptive system actuated by shape memory actuators – Schematic.

Figure 2. Experimental apparatus – Beam and voltage source.

The phase transformation from martensite to austenite upon heating produces uniaxial forced as the wired recover their high temperature shapes. Because they are fixed at the ends these forces generate moments that deflect the beam. The active beam shape control is accomplished by controlling the heating of the wires. The shape recovery of the beam is due to the restoring moments generated by the stiffness of the beam that strain back the memory wires. In the next section the feedback control system implemented to control the beam shape is described.

3. The feedback control system

The block diagram of the feedback structure under consideration is shown in Figure 3. The input of the control system is the variable *Zr(t)*. This is the reference value (desired value) for the beam deflection *Z(t)* that is the output of the control system and is measured by the strain gauge sensors. *Zd(t)* is the control error and corresponds to the difference between *Z(t)* and *Zr(t)*. *V(t)* stands for the control variables generated by the controller and *M* for the moments generated by the actuators 1 and 2.

The control strategy considered in the experiments is as follows: if the control error *Zd(t)=Z(t) - Zr(t)* is negative the actual beam deflection *Z(t)* is smaller than *Zr(t)* and the controller generates the signals *V1(t)* and *V2(t)* which turns the actuators on allowing electric current to flow through the shape memory wires. Due to the Joule effect the temperatures of the wires start to increase. As the phase transformation start temperature A_s is reached, the wires start to recover their high temperature shape (shorter length) generating forces against the holders. This force multiplied by the distance between the wires and the neutral axis of the beam generates moments, which deflect the beam, in order to reach the reference value *Zr(t)*. On the other hand, if the actual beam deflection *Z(t)* is larger than *Zr(t)* the controller turns the actuators off cutting the electric currents and letting they to be cooled by the surrounding air.

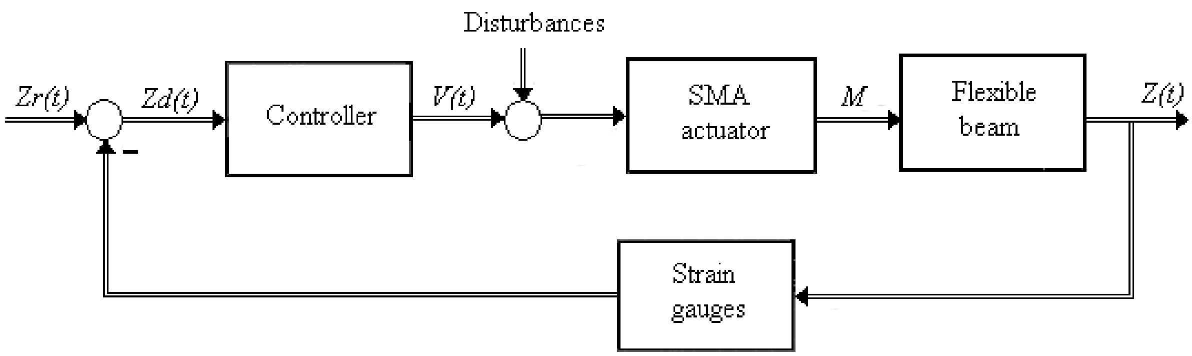

Figure 3. Block diagram of the feedback structure of the system.

Due to the nonlinear behavior of the SMA the choice of the variable to be measured and fed back is a very important point by the application of SMA as electrically activated actuator (Ikuta, 1990). In this work the beam deflection is fed back. However, the temperature or electric resistivity could be fed back. In both cases it would be necessary to know the relation between beam deflection and temperature or electric resistivity and temperature respectively. This would require extensive experimental measurements and be out of the scope of the present work.

4. Experimental results and discussion

In this section the closed loop behavior of the system shown in Figure 1 is examined under a controller of the proportional type. Given the illustrative nature of the present work, the simplicity of the controller allows emphasis on the study itself rather than on the controller design. The controller output is given by

$$V(t) = Kp[Zr(t) - Z(t)], \tag{1}$$

where *Kp* is the proportional gain. The closed loops for the wires are independent, so that the Equation (1) must be considered for each memory actuator. The desired beam deflection was prescribed in millimeters at the positions where the strain gauge sensors SG1 and SG2 are bounded. The parameters of the P-controller were tuned manually for all reference functions considered.

Figure 4 shows the step response of the system for *Kp* = 3,5. The time to reach the target value for the first time is approximately 1s. In stationary state the deflection tracks the target value with a small deviation that can be ignored as well as the overshoot. As expected, by cooling the system takes much more time and the control error is considerably greater. It depends on the cooling rate between the memory wires and the surrounding air, and is a well known limitation of SMA for their application as electrically activated actuators (Hashimoto et al, 1985).

Three others closed-loop experiments were carried out. In the first experiment both sides of the beam were required to track a square wave with varying amplitude. In the second experiment the side 1 was required to track a ramp wave and side 2 a square wave. And in the third experiment both sides were required to track a ramp wave. Figures 5, 6 and 7 show the experimental tracking responses of the system for *Kp* = 3,5. In all three cases, a similar behavior is observed. The overshoot can be neglected and the time to reach the target values upon heating is relatively small. On the other hand upon cooling the systems needs much more time to react. Figure 8 shows the beam under action of the memory actuators.

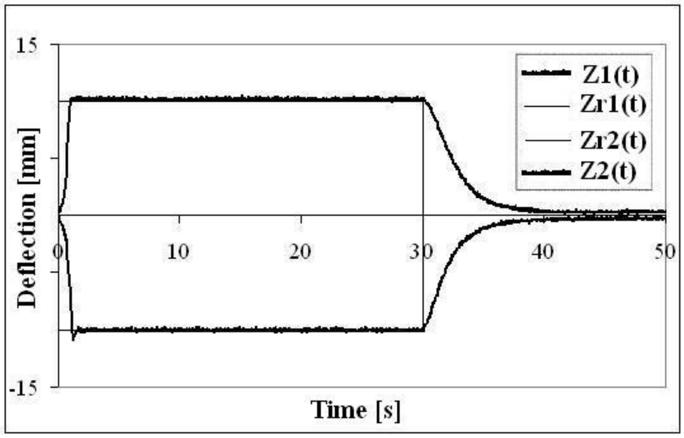

Figure 4. Step response of the system.

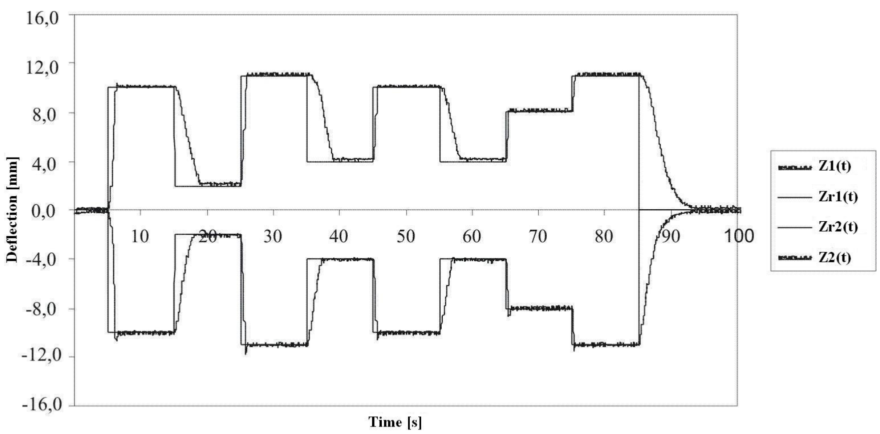

Figure 5. Multi step beam response.

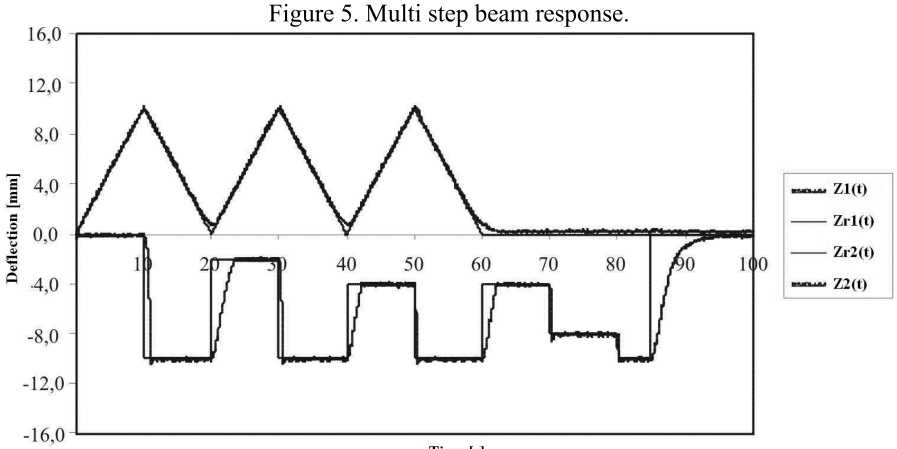

Figure 6. Multi step combine with multi ramp beam response.

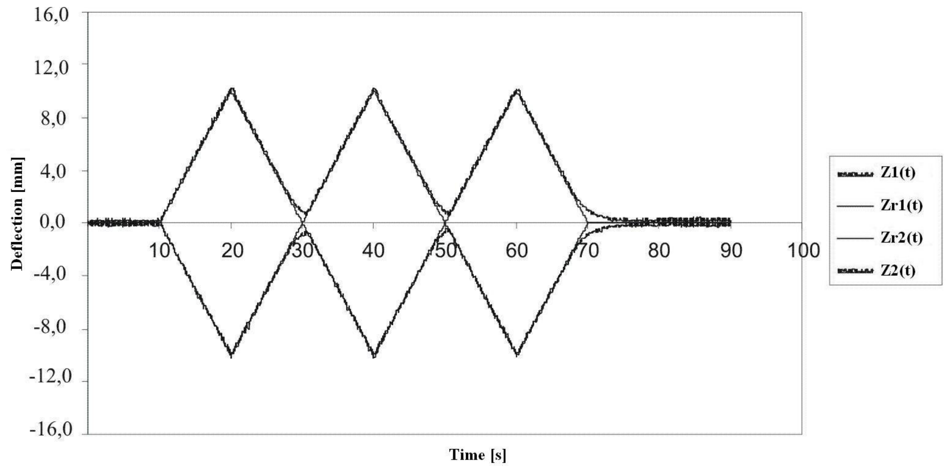

Figure 7. Multi ramp beam response.

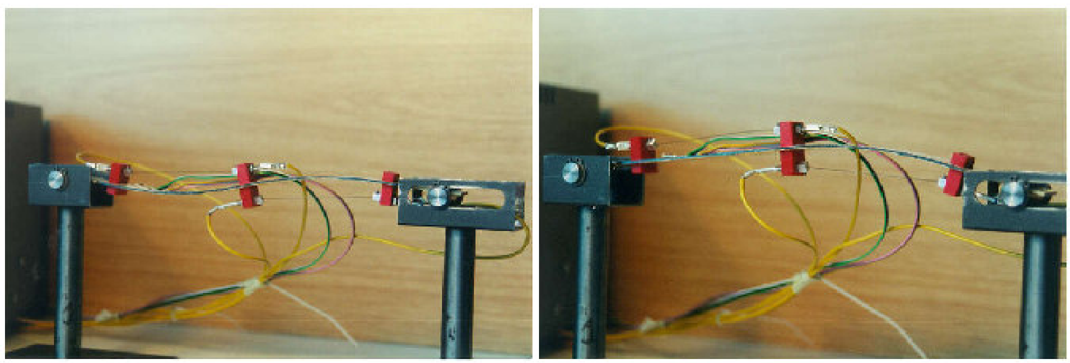

Figure 8. Response of the adaptive beam under action of the memory actuators.

5. Conclusion & future work

This paper has addressed some basic aspects of the application of Shape Memory Alloy for active shape control of structures. A simply supported adaptive beam actuated by means of NiTi shape memory wires was presented. Exploiting the thermomechanical characteristics of the SMA the beam was actively deflected through resistive heating of two memory actuators. A feedback control system was implemented and some basic closed-loop control experiments were carried out. Some preliminary results illustrated the potential and some problems of SMA for the development of adaptive structures. A surprising result is the fact, that even though the thermomechanical behavior of the shape memory actuators is highly nonlinear and hysteretic, a simple proportional control seems to function sufficiently for different target functions. In general the response of the system upon heating is satisfactory. On the other hand the results show that the cooling rate is a very important point to be considered in applying SMA in adaptive structures.

In the present work the main objective was merely to illustrate how shape memory actuators could be exploited in the sense of the Shape Control concept. In order to be able to apply this concept for the development of adaptive structures the future research work include:

- mechanical modeling of the simply supported beam coupled with a thermomechanical model for shape memory model in order to simulate the closed loop behavior of the beam;
- generalization of the modeling for multiple shape memory actuators;
- application of the Shape Control concept based on SMA to develop a prototype of an adaptive wing.

The development of adaptive structures is a promising field for application of advanced actuators. This work represents a small step towards the development of reconfigurable structures based on Shape Memory Alloys.

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