APPLICATION OF SHAPE MEMORY ALLOY FOR THE DEVELOPMENT OF AN ADAPTIVE BEAM

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Abstract. This work presents some basic experimental investigation of an adaptive flexible beam actuated by means of an actuator made of Shape Memory Alloy (SMA). The deflection of a flexible beam is controlled by means of resistive heating of a shape memory actuator and cooling in the surrounding air. The shape memory actuator consists of a NiTi wire fixed on the upper side of the beam. The heating of the wire causes its contraction, which in turn deflects the beam. A feedback control system was implemented to control this deflection taking the Joule heat as the control variable. Some control experiments were carried out considering a proportional controller. The results obtained illustrate the potential of the Shape Memory actuators for the development of such applications.

1. Introduction

In the last years the application of Shape Memory Alloys (SMA) for the development of adaptive structures have been intensively investigated (Rogers et al, 1990; Rogers and Giurgiutiu, 1999; Hesselbach, 1999). This trend is due to their unique properties of these alloys 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, undergoing a martensitic phase transformation (Funakubo, 1987; Otsuka K et al, 1998). In Figure 1 Mavroidis (2002) and Ikuta (1990) present a comparison based on weight and output power-to-weight between SMA, electrorheological and conventional actuators. The SMA have a high power to volume ratio that allows the development of compact and light systems in comparison to the conventional actuators.

For applications where high forces and high strains at low frequencies are required the actuation by means of SMA actuators is a promising option. An example is the bending of a flexible beam that must have its shape modified in response to environmental conditions that do not change abruptly. In such cases the shape memory actuators may be applied as fibres in composite structures (Epps and Chandra, 1987), or placed directly on the surface of the structure which shape should be controlled. This is the method considered in the development of the present work.

In this work the deflection of a flexible beam is controlled by means of a NiTi wire, which is placed directly on the upper surface of the beam. A feedback control system, which takes the Joule heat as the control variable, is implemented to investigate the beam time response to different reference functions. The deflection is measured by means of a strain gauge placed on the upper surface of the beam. The main goal of this work is to illustrate the application of shape memory actuators for the development of adaptive structures.

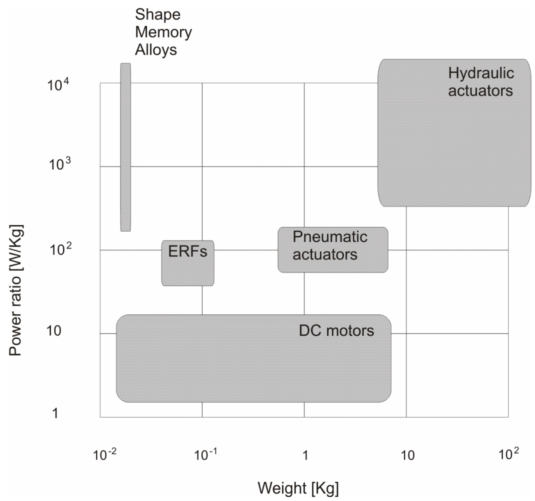

Figure 1. Comparison based on weight and output power-to-weight between shape memory, electrorheological and conventional actuators (Mavroidis, 2002; Ikuta, 1990).

2. Experimental setup

The system under consideration in the present work is illustrated in Figure 2. It consists of a flexible beam made of steel and has the following dimensions: 150mm x 20 x 1,5mm. The shape memory actuator is made of Ni 49 at. % Ti. It is 90mm length and has a diameter of 0.29mm. The actuator is fixed on the upper side of the beam, parallel to its neutral axis. Between the wire and the holders isolating sleeves are used to prevent that electrical current flows through the beam.

The deformation of the beam is measured by means of a strain gauge located in the middle of the upper side of the beam surface, as illustrated in Figure 1. From the actual electrical signal of the strain gauge the current beam deflection *Z(t)* is calculated by means of an experimentally obtained relationship and stored in the computer, in which the actual beam deflection *Z(t)* is compared to a reference value *Zr(t)* (desired value) and a controller calculates the amplitude of the control variable *V(t)* that must be applied to the wire. This process is explained in details in the next section.

The actuation principle relies on the unique properties of SMA. The wire shows Two-Way Memory Effect (Perkins and Hodgson, 1990). It means that the material was trained to show a shape change upon cooling too. When it is cooled below the martensite start temperature M_s, it begins to stretch out due to the two-way memory effect, and has its length enlarged. As the martensite finish temperature M_f is reached the shape change by cooling is completed.

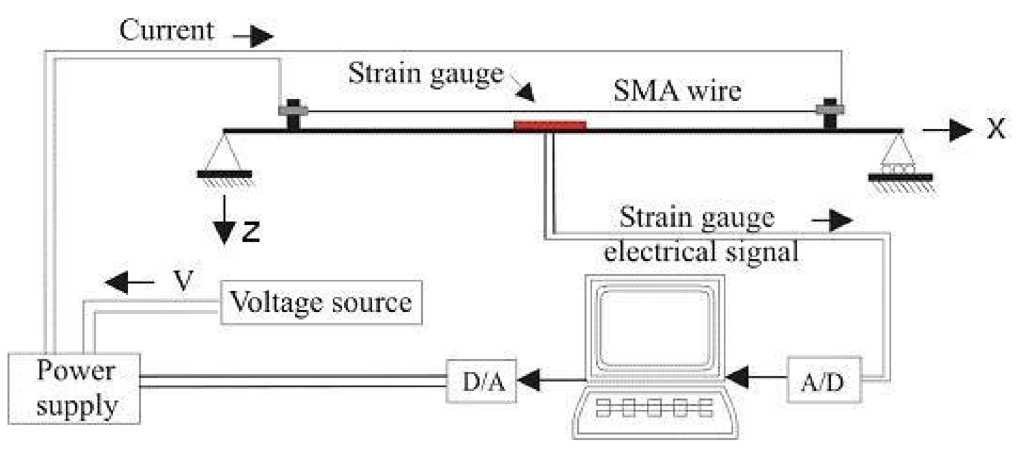

Figure 2. Experimental setup - Flexible beam and the SMA actuator.

Upon heating it begins to return back to its high temperature shape (shorter length) as the austenite start temperature A_s is reached. The shape recovery upon heating is completed as the austenite finish temperature A_f is reached.

The phase transformation from martensite to austenite upon heating produces a uniaxial force as the wire recovers its high temperature shape, since the wire is fixed at the ends, and this force generate a moment that deflects the beam. Controlling the heating of the wire it is possible to control the deflection of it. The recovery of the beam deflection is due to the restoring moments generated by the stiffness of the beam. Simultaneously to the deflection recovery the wire returns to its longer length due to the Two-Way Memory Effect. In the next section the control system implemented to control the beam deflection 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 for the deflection of the beam. *Z(t)* stands for the actual output of the control system. This variable corresponds to the deflection value in the middle of the beam, where the strain gauge is placed. *Zd(t)* is the control error and corresponds to the difference between *Z(t)* and *Zr(t)*. *V(t)* stands for the control variable generated by the controller and *M* for the moment generated by the SMA actuator on the holders.

The control strategy considered is as follows: if the control error *Zd(t)=Z(t) - Zr(t)* is negative, that is, the actual beam deflection *Z(t)* is smaller than the desired one, *Zr(t)*, the controller generates a signal *V(t)* which turns the actuator on allowing a electrical current to flow through the shape memory wire. Due to the Joule effect, generated by the electrical current, the wire temperature starts to increase. As the martensite to austenite phase transformation start temperature A_s is reached, the wire starts to recover its high temperature shape (shorter length) generating a force against the holders. This force multiplied by the distance between the wire and the neutral axis of the beam generates a moment, which deflects the beam, in order to reach the reference value *Zr(t)*.

On the other hand, if *Zd(t)* is positive, that is, the current beam deflection *Z(t)* is larger than the desired one, *Zr(t)*, the controller turns the actuator off cutting the electrical current and letting it be cooled by the surrounding air.

Due to the non-linear behaviour of the SMA the choice of the variable to be measured and fed back is a very important point by the development of SMA applications (Ikuta K, 1990). In this work the beam deflection is fed back. However, one could feedback the temperature or electrical resistivity. In both cases it would be necessary to know the relation between beam deflection and temperature or electrical resistivity of the wire respectively. This would require extensive experimental measurements and would be out of the scope of the present work.

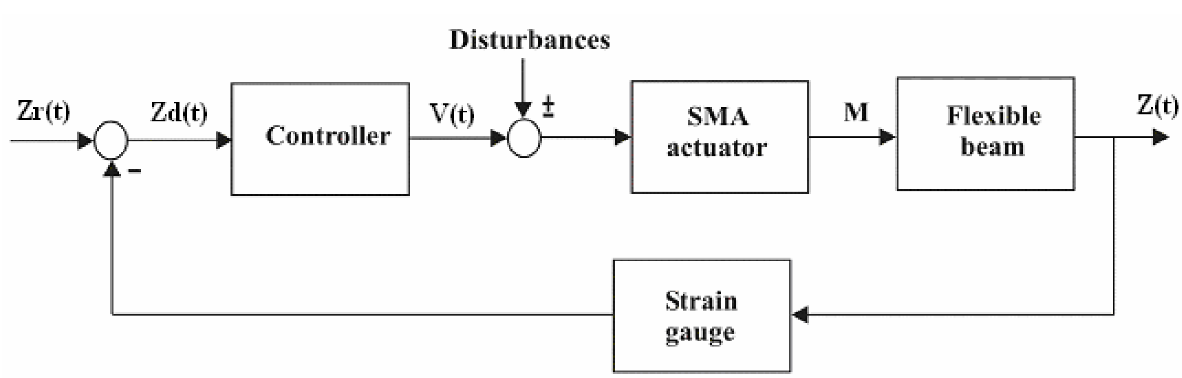

Figure 3. Block diagram of the feedback structure under consideration.

4. Experimental results and discussion

In this section, the closed loop behaviour of the system is investigated. The controller used in closed-loop control is 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. For the proportional controller the relation between the control variable *V(t)* and the controlled variable is given by:

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

Three sets of closed loop experiments were carried out. The beam deflection was prescribed in millimetres at *L/2* = 75mm. In the firs set of experiments the beam was required to track a step deflection function of 2mm for 10s. For a *Kp* = 5 the results are presented in the Figures 4 and 5. In stationary state the deflection tracks the target with a small deviation of approximately 6%. The time to reach the target for the first time is approximately of 1.7s. During this time period, in an effort to meet the target, the controller rapidly saturates the voltage *V(t)* and consequently the electrical current, see Figure 5. At the beginning the error is very large and the wire is heated with the maximal electrical power, it means the voltage is maximal and the current that flows is maximal too, as shown in Figure 6.

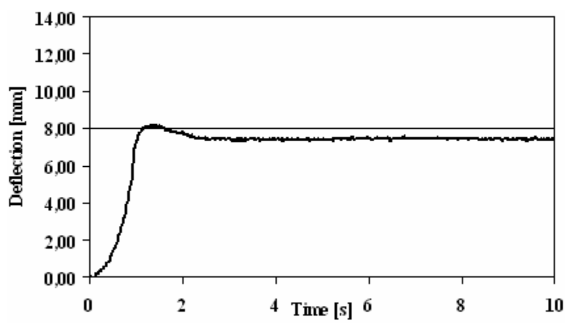

Figure 4. Beam deflection behaviour for *Kp*=5 for step target function.

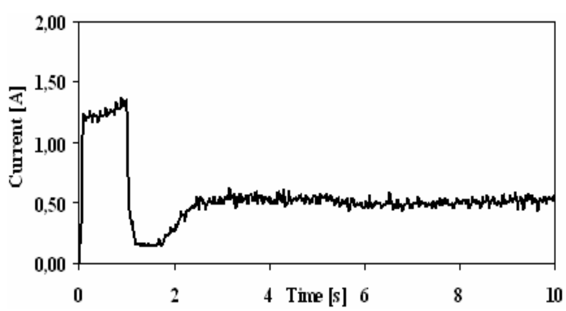

Figure 5. Electrical current behaviour for *Kp*=5 for step target function.

The same closed loop experiment was carried out for a greater gain factor, namely *Kp*=20. The Figures 6 and 7 show the results obtained. A substantial performance improvement of the system is observed. Although the overshoot is now greater, approximately 10%, the control error in stationary state is almost eliminated.

In the second set of closed loop experiment the system was required to track a triangular wave input and a sinusoidal function at different frequencies. The Figure 8 and 9 show the prescribed deflection (thinner line) and the response of the beam (thicker line) for a triangular function at 0.05 and 0.1Hz respectively. For 0.05Hz, apart from small deviations at the end of the cooling phases (descended parts of the curve), the control error is very small. For 0.1Hz one can observe that the system cannot track the target function in the cooling phases.

The importance of the cooling rate is well clear in this type of experiment. This is one of the greatest limitations by the application of shape memory actuators in developing adaptive structures when relative higher frequencies are required.

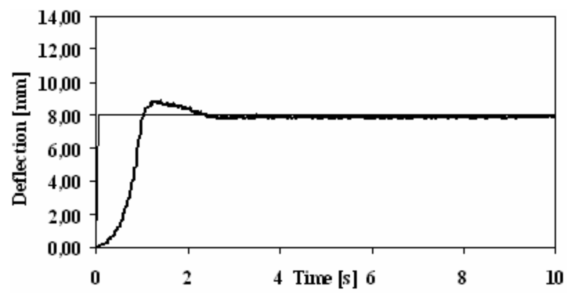

Figure 6. Beam deflection behaviour for *Kp* = 20 for step target function.

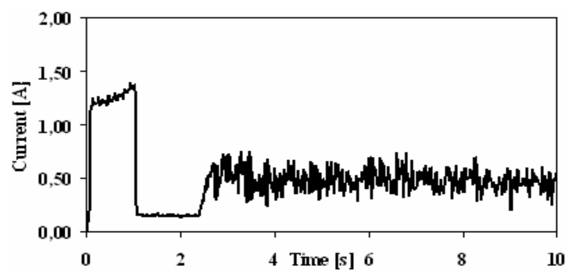

Figure 7. Electrical current behaviour for *Kp*=20 for step target function.

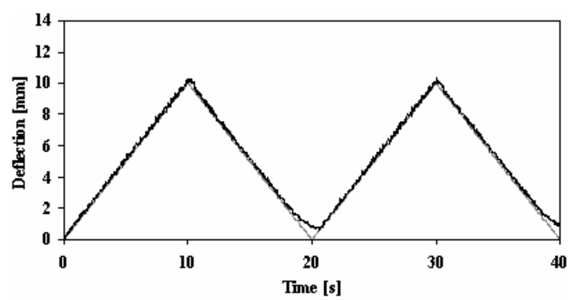

Figure 8. Beam deflection behaviour for a 0.05Hz and 10mm triangular wave target function.

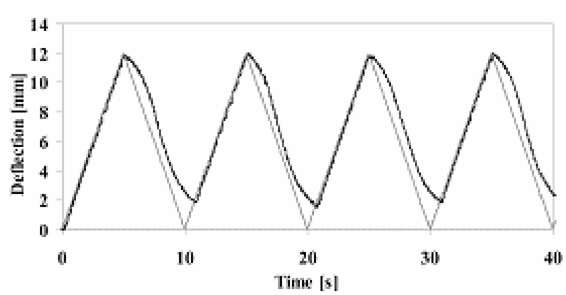

Figure 9. Beam deflection behaviour for a 0.1Hz and 10mm triangular wave target function.

5. Conclusion

This work has addressed some basic aspects of the application of Shape Memory Alloys for active shape control of a beam. A flexible beam actuated by means of a NiTi shape memory wire was constructed and its closed loop behaviour investigated. Exploiting the characteristics of the SMA actuator the beam was actively deflected through resistive heating of the actuator. A feedback control system was implemented and some basic closed loop control experiments were carried out. The results illustrate the potential of the SMAs for the development of adaptive structures. The results show also that the cooling rate is a very important point to be considered in applying Shape Memory Alloys in such cases.

6. References

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