Researches about Parameters Stabilization for Long-time Functionality of Shape Memory Alloy Active Elements

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Abstract: - The increment number of the applications based on thermo-mechanical properties causes a need for a mathematical model able to describe all thermo-mechanical properties of shape memory alloy (SMA) by relatively simple final set of constitutive equations that could be helpful for development of further sophisticated shape memory applications. Thus, the present paper presents the designed and developed temperature control system used for a gripper actuated by two pairs of differential SMA active springs. An experimental setup was established, using electrical energy for actuator’s springs heating process. As for holding the temperature of the SMA springs at certain level for a long time was developed a control system in order to avoid the active elements overheating. The experimental stand was designed in order to be able to test the prehension process model function of thermo-mechanical transfer.

Key-Words: - actuator, shape memory alloy, active element, temperature control, thermo-mechanical transfer

1 Introduction

In the recent past period a lot of effort has been performed to the design, the construction and the control of the robotic grippers. Even so, actuators of the grippers have still been mostly low in energy density (power-to-weight ratio), inflexible in the design parameters, and complex in structure and transmission agent.

In order to overpass these disadvantages of the conventional actuators, as driving elements for the actuator were chose shape memory alloy (SMA) springs.

Basically, SMAs are functional materials sensing changes in the ambient temperature, being able to convert their shape to a pre-programmed structure. They are more important for what they do (as an action) than for what they are (as a material). SMAs recover their original induced shape after they exceed a transition temperature (a narrow temperature band, not a single point) between a low-temperature phase and a high-temperature phase [1].

Shape memory alloys possess highly nonlinear and hysteretic constitutive behaviours showing a strong dependence on strain, temperature, and strain rate, making them viable as actuators in many applications, particularly those that are weight critical, that require a high force and high stroke under severe space restrictions. The “shape memory” effect offers these materials an inherent actuation capability combining high strains with an exceptional specific work output [2].

Shape memory alloys lead the list in maximum actuation stress and rival even hydraulics in specific work output, approaching 108 J/m$^3$. This is the highest specific work output amongst all known smart materials.

While NiTi is soft and easily deformable in its lower temperature form (martensite), it resumes its original shape and rigidity when heated to its higher temperature form (austenite). This is called the one-way shape memory effect. The presence of permanent deformation, related to plastic strains or to the residual martensite variants occurring during the material training, allows reversible spontaneous shape change to be obtained during cooling and heating processes without application of any external stress, known as the two-way memory effect [3].

The occurrence of these unique properties is originated from a molecular rearrangement related to a solid state phase variation, the values of these variables being strongly affected by the alloy’s composition.

Researches on the electro-thermo-mechanical characteristics of SMA material have already confirmed that SMA actuators have some advantages compared with conventional actuators [4]. Thus, the recovering force per unit weight of an SMA actuator is higher than that of the conventional actuator, while the design of an SMA actuator can be very simple and flexible.

The structure of an SMA actuator is fairly simple in comparison with the conventional actuators. Another advantage of SMA actuators is that they are easy to be controlled due to the fact that they are heated by electric current device (AC or DC) [5].
2 Problem Formulation

In order to obtain the necessary force and displacement developed by the actuator for long time period functionality, was designed and developed an experimental stand pretty simple, but sufficiently precise.

The necessary condition to avoid damage of the active elements and still to perform a prolonged prehension action is to remain between certain limits of temperature. Overheating of springs leads in the first phase to diminish their lifetime and even, if the overheating is maintained for longer period, to lose their initial trained shape.

The exterior temperature perturbation will be avoid in the final form of the actuator by covering all the active elements with silicon flexible tubes in order to obtain a stable temperature environment, knowing that the cooling system will utilise a fluid flux as cooling agent.

It is well known that for achieving the martensite estate as quick as possible is necessary to use a cooling agent in order to overcome the active element thermal inertia.

2.1 Behaviour of the model

Results of displacement controlled simulations of the SMA model at various temperatures are presented in the diagrams below. The displacement is prescribed in the manner shown in figure 1, except in the quasi-plastic case.

![Fig. 1](image1)

Starting from an un-stretched condition, the simulated material is drawn out to some maximum extent and then permitted to return to a zero load condition [6]. To effectively remove the self-heating and self-cooling phenomena associated with the release and absorption of latent heats, the simulation strain rate is very low, allowing ample time for temperature equilibration. This produces a nearly isothermal response. Further, the maximum displacement is chosen to guarantee a full phase transition to M+ at full extension for the temperatures chosen.

At a low temperature, the quasi-plastic material behaviour is intrinsically captured by the model. Figure 2 (model stress-strain curve 20°C) shows the simulated load-deformation result in the tensile quadrant only. The initial phase composition is assumed to be equal proportions of the two martensite variants.

Clearly, there is a remnant deformation as the material returns to a zero load condition, which dictates an early termination of the displacement curve of figure 1.

![Fig. 2](image2)

As shown in the figure, the initially linearly elastic material response is followed by a large displacement coinciding with a single load value, and then regains its elastic behaviour on further displacement. The zero slope region of the plot corresponds to the phase transition where M- lattice layers flip to the M+ orientation. Upon unloading, these newly formed M+ layers do not retransform to their original orientation, but instead find equilibrium in this configuration, leading to the remnant deformation. That the slope of the curve starting from the origin is the same as the slope along which the material returns to a zero load condition indicates that the initial phase composition was purely martensitic.

![Fig. 3](image3)

Figure 3 (model stress-strain curve 40°C) shows the load-deformation curve at a higher temperature, where the material shows a pseudo-elastic response. Austenite is the stable phase under no load. Here again the initial response is linearly elastic, though the slope of the elastic region is much steeper than that observed at the lower temperature. This reproduces experimentally observed behaviour and indicates that a purely austenitic
phase composition is significantly stiffer than a purely martensitic composition. Note that the load at which the A → M transformation occurs is higher than that shown for the quasi-plastic case. This demonstrates the model’s ability to capture the temperature dependence of the transition stress. Once the A → M phase transition is complete, further deformation traces the same linear path as the lower temperature. However, as the deformation returns to zero, the material spontaneously undergoes a retransformation to austenite at a low load level. At the end of the simulation, the material has returned to its original, un-stretched and unloaded condition, at the same time regaining a purely austenitic phase composition. The hysteresis loop circumscribed by the prescribed deformation is quite clear.

The next plot (model stress-strain curve 50°C) shows the load-deformation curve of a simulation at yet a higher temperature. The salient differences in this case are the increases in the transition stresses. Both the A → M and the M → A phase transitions occur at substantially higher load levels than either of the two previous cases. However, the width of the hysteresis loop remains the same as the lower temperature, reproducing the experimentally observed behaviour.

These three simulations clearly demonstrate that the model is capable of reproducing the temperature-dependent nature of the material behaviour, as well as the hysteresis loops produced during cyclic loading where phase transformations occur. It is the model’s intrinsic ability to capture the temperature dependence of the material response, as well as its ability to calculate that response from a prescription of deformation, that makes it particularly suitable for use in representing a SMA actuator in a deformation-based finite element environment.

2.2 Actuator design
The main input and output parameters and which characterise the SMA actuator state are the material characteristics (chemical composition, mechanical and electrical characteristics, size of memory effect), their geometrical characteristics (form, length, section) and specific parameters of the heating and cooling process. Function of these input parameters, the active elements are in one of the already presented estates, characterised by certain values of the state parameters (strain-stress state, electrical resistivity, instantaneous temperature) [8].

The output parameters of the actuators are the displacement value, the developed force or torque and working cycle’s frequency.

Function of all these parameters, the developed actuator driven by the two pairs of Nitinol active springs working in antagonistic way, based on the experimentally observation of thermo-mechanical transfer, aim to improve the real-time response of the SMA actuator in grasping processes.

The actuator was able to perform a maximum stroke of 35 mm, lifting a weight of 400 grams. The relations between the characteristics of the gripper and the cooling methods, the heating current and the action frequency were studied experimentally. Furthermore, the position’s control of the SMA actuator will be developed.

2.3 Temperature command
The actuator control system based on SMA current should ensure optimal parameters necessary for prehension, but has not exceed the maximum power dissipated in the active element, which would lead to overheating and loss induced effect.

Respecting the imposed energy restriction, SMA’s control systems can be achieved by implementing circuits in pulse width modulation (PWM). Such a
circuit has been proposed in the literature [9] and is shown in figure 6 (control circuit principle diagram). Figure 7 shows extensive control circuit’s functional blocks, where EC - electric current, HT- heating temperature, PhT - phase transfer, F - force, D – displacement, R - SMA resistivity and T - SMA temperature.

![Fig. 7](image)

SMA behavior can be described by four variables: temperature, electrical resistance, generated force and displacement. In figure 8 is presented a block diagram of a simple SMA’s control system but able to meet the requirements of this stage of experimentation, leading to the establishment of a long time current variation and consequently the variation of resistance depending on time, where PC - computer, µP - microcontroller, PT - power transistor, SMA - shape memory alloy, TS - temperature sensor and LR - limitation resistivity.

Implementing a control system with the internal variable resistance has the following advantages: small hysteresis, the behaviour is approximately linear, easy to avoid the alloy overheating.

In practice it is proposed a control method that combines internal resistance and the size of the displacement to implement a feedback control algorithm. It also uses a control model to compensate shape memory alloys high hysteresis. This is done by using the feed-forward predictive power involving active element so as to achieve the desired movement.

![Fig. 8](image)

The literature [7] treats several types of controllers for shape memory alloy actuators. The classic controller used is PI (proportional - integrative) but the controller's performance is determined by hand applied settings.

PI algorithm involves two distinct parameters, proportional and integral value, determining the proprotionate amount response to current error and determining the response to the integrated value sum recent errors. Weighted sum of these two measures is used to adjust the process via a control element such as mains electricity to a heater.

By "setting" of the two constants in the PI algorithm's controller, it can carry out checks for specific requirements of process. Controller's response can be described according to a reactivity controller's error, the degree of overshoot of the reference point and the oscillation of the system. It must be emphasized that use PI as an element of control algorithm guarantees an optimal control on the system or system stability.

3 Experimental Analysis

At this stage of experimentation, the microcontroller is used only for adjusting the active element SMA transmitted energy.

The control system contains a ATmega8 AVR microcontroller, which allows the generation of PWM pulses on three separate channels. The operating principle stands as follows: - PWM pulses are applied to a IRFL640xxx MOS FET transistor in order to activate the SMA spring, the MOS FET transistor withstanding a maximum current of 17 A and a voltage of 200 V.

For proper functioning of the microcontroller it has been used the reset circuit and an oscillator circuit with a 4MHz quartz. Two voltage supplies of 12V and 5V were provided. The scheme also contains an XTEMP series electronic temperature measuring laser equipment which is able to transmit values via USB. The microcontroller could be programmed using the STK200 programmer, communication with the PC being via RS232 protocol.

The working values for the two types of used active springs are presented in the table below:

<table>
<thead>
<tr>
<th></th>
<th>Tension</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifted weight [gr]</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td>Dynamic acting period [sec]</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Voltage [V]</td>
<td>1.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Current variation [A]</td>
<td>1.75 → 2</td>
<td>2.65 → 3</td>
</tr>
<tr>
<td>Resistance variation [Ω]</td>
<td>1.03 → 0.9</td>
<td>1.07 → 0.9</td>
</tr>
<tr>
<td>Strain [mm]</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Variation type</td>
<td>hyperbolic</td>
<td>hyperbolic</td>
</tr>
</tbody>
</table>

As results of experiments was obtained that the tension springs have to be supplied for 10 sec at 2 A in order to reach the 52\(^\circ\) C, followed by a value of 0.9 A as long as necessary for prehension, while for compression springs, the values are 12 sec at 3 A in order to reach the 64\(^\circ\) C, followed by a value of 1.6 A.
4 Conclusion

SMA thermal actuators are much simpler and much easier to be realized that other types of actuators, the control of temperature being possible to be realised in a simple manner, but present the disadvantage of a reduced operating speed. The specific actuator designing steps are: dimensioning active elements in function of the imposed source and force; dimensional and structural synthesis of the associated mechanical structure; designing the activation (heating and cooling) and the command and control system. Important to notice is that the design of shape memory applications always require a specific approach, completely different from the design with structural materials.

Progress over the past is promising which can be specifically related to understanding and analytically describing SMAs' constitutive behaviour.

The SMA actuator, whose main components are two pairs of SMA springs, is presented in this study. The experimental device was realized to investigate the characteristics of the SMA springs and finally, the actuator for the robotic gripper, which can achieve the opening and closing motion of the two jaws easily.

Performances of the SMA gripper have been observed experimentally, whose dependence on the cooling methods, the heating current, and the action frequency has been investigated. The output displacement amplitude can increase by increasing the heating current and decreasing the action frequency during the SMA transformation process.

A PI controller is presented to control the output temperature of the springs, in which a control method was developed in order to reduce the overshooting of the system. Based on the acquired results, the temperature control can be realised very precise, in this way being possible to predict the actuator’s developed displacement and prehension force.

The following researches will take into consideration the displacement feedback, the proposed position controller to achieve a good control performance and high positioning accuracy, which are typical requirements for a gripper’s actuators.

Acknowledgement


References:

[9] N. Ma, G. Song, Control of shape memory alloy actuator using pulse width modulation, 2003, Smart Materials & Structures 12 712