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INNOVATIVE MODULAR SMA ACTUATOR

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Abstract. A modular design for a shape memory actuator is proposed. The actuator is able to perform linear movements, while the modularity allows force and/or stroke improvements. Experimental results show how the behavior of the proposed implementation is sufficient for a wide class of problems and can be improved with proper developments.

Introduction

The shape memory alloys (SMA) represent a class of metallic materials with particular thermo-mechanical and electrical properties, high power density and ability of producing comparatively large actuation strains/stresses [1]. Their actuation properties originate from a solid-state phase transformation, which is affected by changes in temperature or stress, and strain. SMA actuators are widely used in wire or spring configurations, but upcoming applications in, e.g., medical instrumentation or microsystems also demand more complex shapes [2,3]. However, designing SMA actuators is a challenging task, due to the complex material behavior and also electrical, thermal and mechanical aspects have to be considered simultaneously.

SMAs are intermetallic compounds able to recover, in a continuous and reversible way, a predetermined shape during a heating/cooling cycle. From a microscopic point of view, this transformation consists in a transition from a crystallographic phase stable at low temperature, i.e. martensite, to a different crystallographic phase stable at high temperature, namely austenite [4]. When the SMA is deformed by an external force, instead of breaking crystallographic bonds and damage its structure, starts a progressively arrangement of planes which close the deformation without achieving significant atomic displacements. During this mechanism, atoms have moved only slightly from original positions, when, due to an imposed stimulus, atoms move to restore the previous crystal structure before the deformation and then the recovery of macroscopic original shape.

The current state of the art on SMA have mainly focused on two items. One is the characterization of the thermo-mechanical behavior of SMA materials [5] and the other is the actuator application of one-way shape memory effect (SME). The one-way effect cannot provide suitable mechanism of SMA actuator because the host structure does not return to its initial shape after it is cooled. In order to aligning at SME issue, different researches [6] proposed some designs of SMA muscles for a robot hand and also [7] demonstrated that it is possible to build a hand actuated by SMAs. In most cases, a model based controller will not perform in a satisfying way because it is an open loop system. The control problem (e.g. hysteresis) was partially solved by restricting displacements to a range of a few tenths of a millimeter [6] and could thus simplify the problem to a linear one. This behavior could also be linearized by using two counteracting shape memory elements. That solution was further improved by mounting a temperature sensor in direct contact with the shape memory element. Electrical resistance position feedback was also used in common practice [8]. Most authors use a kind of Pulse Width Modulation (PWM) power amplifier in combination with a classical PID controller [9].

Problem definition

A peculiar topic that drives SMA selection is operative temperature range. All memory alloys have temperatures that characterize the internal structure [4]. Temperatures of phase transformations for the adopted alloy (NiTiCu5) are: Temperature at end of martensitic transformation (MF) 26°C; Martensitic transformation start temperature (MS) 37°C; Austenite transformation start temperature (AS) 48°C; End temperature austenitic transformation (AF) 59°C and Hysteresis 24°C [10]. The temperature of 59°C indicates the maximum operative temperature for SMA material, in fact for higher temperature no transformation phase are pointed out. The SMA element remains in the same position and all exceeded power is dissipated. Temperature of 26°C indicates the lower limit of the resting phase of SMA element and internal structure of alloy is all in the martensitic phase.

This paper presents the study and realization of a SMA actuator able to achieve linear movements in a coil spring configuration. SMA material has an high electrical resistance, it can be heated to its transition temperature simply by passing current through it. This opens up many possibilities for providing mechanical actuation (movement) without any moving parts [4]. The purpose of research is the realization of SMA actuators which perform in defined operating temperature a specified movement. Temperatures must meet limits due to actuator structure and application. The duty cycle for current application should be in agreement with user's needs, so as to allow a movement in a short time. For these reasons, authors have as primary objective the shortest working cycle with imposed temperature constraint, especially during the cooling phase. A robust approach (Design of Experiment) is accepted for performing tests in order to achieve a required output for thermal, voltages, stroke and time point of view [11]. The experimental tests developed permit a performance comparison between different operating conditions.

Design of the actuator

The actuator is designed to have a linear movement along horizontal axis of SMA elements. The drive to the development of this device was the final use. This means that the importance to meet certain specific functional requirements, severely affected the designers’ choices regarding the shapes and configuration that actuators should possess in order to produce predefined strokes and output forces [12,13]. Cartesian geometry (Fig. 1) develops electrical and mechanical function on several layers. This configuration is a result of movement optimization as shown in the followings.

The actuator need to moves along an horizontal axis or a plane to perform a linear movement. The intuitive geometry for this type of movement is the cylinder, where all the components are positioned around the main axis of movement. In this case functional axes (mechanical constraints, electrical contacts, movements, thermal heating and cooling) are coincident with movement axis and the model is very compact. On other hand, a cylindrical geometry does not permit the geometrical diversification of the contact points that characterize the different functions.

Different functions can need different materials and different physical connections. In order to design properly the single elements of the actuator, it is useful separate functions i.e. with Concentric cylinder geometry (separate elements, on concentric surfaces) or a Cartesian geometry (different functions on different parallel plans). The physical model is more complex, but the design phase and maintenance activities are simplified by isolating geometrical features, with independent functional behaviors.

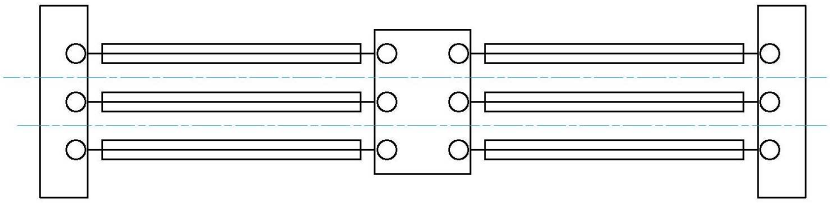

Figure 1 - Modular actuation system.

From a Cartesian geometry is possible to develop a modular model (Fig. 2). SMA model is designed to have more actuator elements in parallel without changing the conformation of the individual components, but increasing overall dimensions, developed force and energy consumption, this represent an important benefit compared with concentric cylinder geometry. This refers to modularity of the system [14] and allows, in the configuration in Fig. 1 an increment of the nominal force of the actuator.

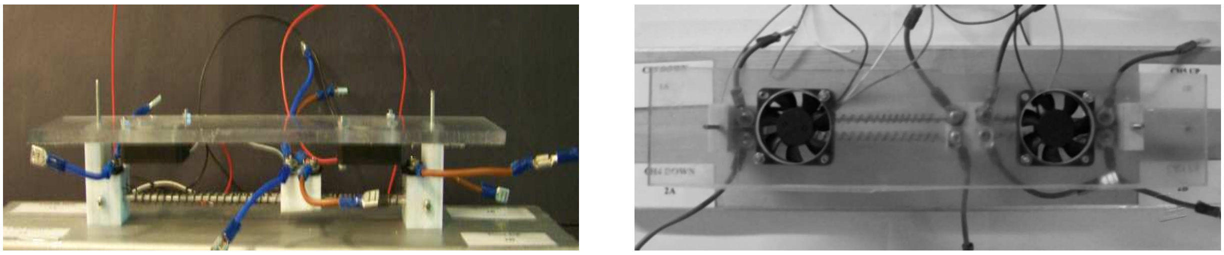

Figura 2 - Representation of SMA prototype composed by two module.

In that prototype, functional electrical and mechanical plans are separate. Electrical function is located in the upper part of the SMA actuator (Fig. 2) while the plane of the mechanical function is located on the axis of SMA elements. The number of springs has been chosen in order to have better control and stability in the movement. In this study are used four SMA elements, positioned on each side between central slider and wall. The spiral diameter is equal to 4 mm and a wire thickness of 0.4 mm, as shows Fig. 4.

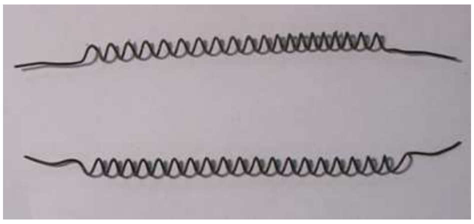

Figure 3 - SMA spring actuator elements.

Experimental results

The tests were carried out perturbing two main parameters [15]: current and operating times. Table 1 summarized result of input values: supplied current of two SMA elements (I), total cycle time (Tc), cycle time in which SMA element is active (Ton), number of cycles which elements have been subjected (Nt), initial value of cursor position (Xo) and the position reached by cursor at the end of test (Xf).

Table 1. Results of input-output values.

I [A]	Tc [s]	Ton [s]	Nt	Ne	Xo [mm]	Xf [mm]
1	10	10	10	10	0	2
1.5	10	5	10	10	0	0
1.5	20	10	5	5	0	10
1.5	20	10	10	10	0	36
2	5	3	5	5	0	10
2	5	3	10	10	0	35
2	10	5	5	5	0	21
2	10	5	10	10	0	60
2	20	10	5	5	0	55
3	5	3	5	3	0	60
3	5	3	10	3	0	60
4	3	3	5	3	0	60

For current equal to 1 ampere, has been carried out that operating time is not in compliance with expected 60-90 seconds, a transformation phase needs more power in input. For values of current of 2 - 3 - 4 and 5 amperes have been carried out complete experimental campaign, with data acquisition related to voltage, temperature and position. Results analysis of first trials led to supply current higher to 3 amperes, as they have been achieved output in accordance with defined performance. In order to search for an optimal cycle time with selected values, first were chosen high time of heating and cooling and then gradually reduce them until finding optimal times that meet restriction criteria relating to temperature (maximum temperature at the end of cooling phase as 35°C) and actuator position (SMA element must reach its maximum stroke). The results obtained with supply current of 2 amperes were not considered satisfactory for the required performances.

Table 2 shows data relating to current (indicated I), activation time of SMA elements (Ton), maximum temperature reached during test (Tmax), cooling time of SMA actuators (Tr), minimum temperature reached during the test (Tmin) and test duration (Ttot).

Table 2. Experimental results for optimizing current and operating times.

I [A]	Ton [s]	Tmax [°C]	Tr [s]	Tmin [°C]	Ttot [s]
2	20	76.28	30	33.59	100
3	15	78.23	25	33.98	80
4	10	87.14	25	31.10	70
5	7	75.94	25	32.47	64

For each supply current has been chosen value of activation and cooling time considered the best ones. For each test configuration, data were acquired, processed and used to create different graphs.

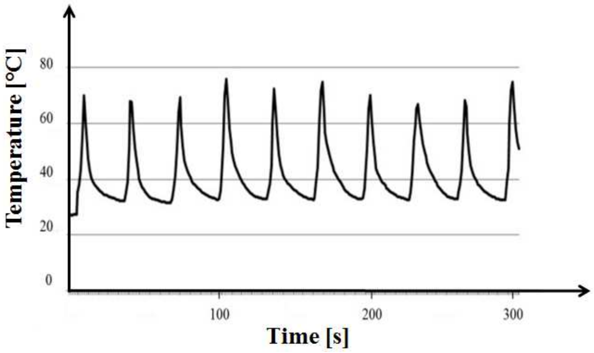

Figure 4 - Maximum temperature on SMA element.

Fig. 4 refers to a test where SMA activation time is 15 seconds, SMA cooling time is 25 seconds and supply current is 3 amperes. The trend refers to temperature that occurs along SMA element obtained by IR camera during test campaign. These temperature charts were used to determine correct input time in agreement with selected criteria.

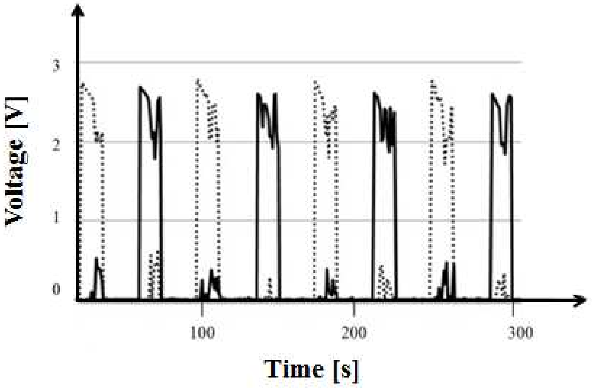

Figure 5 - Voltage present on SMA elements during the work cycle.

Solid line represents the SMA element connected to right of cursor, dotted line represents voltage on SMA element at left of cursor. Fig. 5 refers to test with SMA activation time of 7 seconds and cooling time as 25 seconds and supply current to 5 Amperes. Trend in Fig. 5 represents the voltage on SMA elements during the test. Data were acquired at a sampling frequency of 1 Hz. Fig. 5 shows slightly decrease of Voltage during the cooling phase after magnitude is reaching maximum value. The detected volt is a product between current established in input and resistance of SMA spring. The voltage grows means that electrical resistance increases, consequently increasing the temperature.

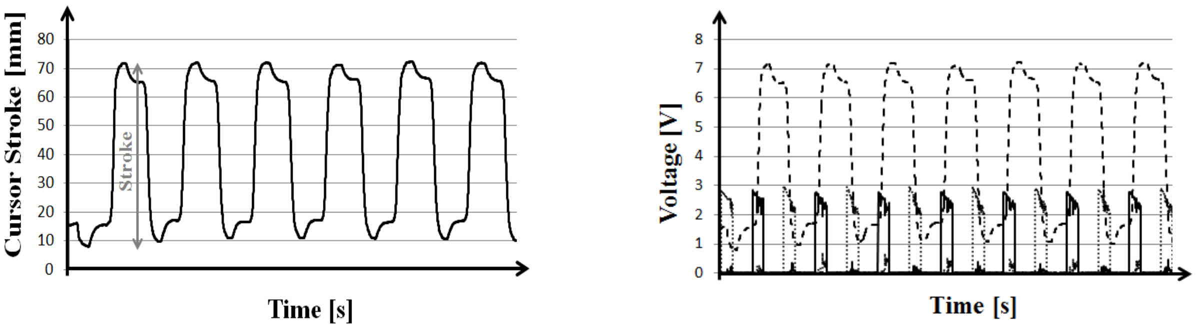

Figure 6 – Stroke of central cursor (left), Comparison between cursor stroke and voltage input of SMA element (right).

In Fig. 6 is represented the evolution of mechanical tests relating to output of potentiometer during SMA elements movements. The frequency of sampling data for these tests were 10 Hz. Potentiometer and Voltage have been showed on the same figure to compare and highlight their performance.

During the active phase of SMA elements, voltage on the potentiometer changes because it follows the movement imposed by SMA transformation of springs. During the cooling steps the potentiometer has a minimum deviation from reached position due to hysteresis, a phenomenon which allows SMA element to reproduce the memorized shape but not to maintain it over time.

Conclusions

The design of a modular actuator was analyzed in this work where some practical aspects are deepened and a hint of theoretical observations is shown especially on relations between functional and geometrical properties of this device. Some experiments are performed and preliminary results stress some peculiar aspects of this actuator (i.e. hysteresis) and some design tricks (i.e. connections).

Finally the first optimization produced acceptable results for some applications (i.e. medical or home). Thus we suppose to improve some theoretical aspects and to develop the mechanical design of the system.

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