Applied Mechanics and Materials
ISSN: 1662-7482, Vol. 783, pp 69-75
doi:10.4028/www.scientific.net/AMM.783.69

Submitted: 2015-03-17
Accepted: 2015-04-13
Online: 2015-08-10

Design and Experimental validation of a Shape Memory Alloy actuator for Linear Motors

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Keywords: shape memory alloy actuator, linear motor, design of experiment

Abstract. This paper presents an innovative mechanical actuator using a shape memory alloy (SMA) with a cooling system based on combined thermoelectric effect and forced air cooling systems. The main advantages of using SMAs include the reduction of the system weight, the ease and reliability in application, and a simple control strategy. This study focuses on the development of the system highlighting the mathematical model of the actuator, and an experimental prototype was implemented. Several experiments are used to validate the model and to identify best SMA actuator configuration parameters. Experiments were used to evaluate the actuator closed-loop performance, stability, and robustness properties.

Introduction

One of the main requirements that an actuator needs to satisfy is to guarantee high mechanical performances in a limited space. In this way, SMA actuators play an important role to provide the highest power-to-weight ratio among light-weight technologies [1,2]. They have become a very attractive option for uses in actuators and they are implemented in a broad range of commercial applications (consumer electronics, fashion, fasteners, …). SMA actuators can be actuated remotely with a low actuation voltage [3-5] guaranteeing reliable performances and ease in installation.

SMA actuators are widely used in wire or spring configurations, but upcoming applications (e.g. medical instrumentations or microsystems) also demand more complex shapes [6,7]. Designing a SMA actuator is a challenging task due to the complexity of the material selection and behavior. In this manner, the electrical, thermal and mechanical aspects have to be considered simultaneously.

SMAs are intermetallic compounds able to recover, in a continuous and reversible way, a previously defined shape when subjected to an appropriate thermomechanical load. From a microscopic point of view, this transformation consists in a transition from a crystallographic stable phase at low temperature (e.g.. martensite) to a different crystallographic stable phase at high temperature (e.g. austenite). When the SMA is deformed by an external force, instead of breaking crystallographic bonds and damaging its structure, it starts a progressively arrangement of planes which closes the deformation without achieving significant atomic displacements. During this process, atoms have moved only slightly from original positions. When an imposed stimulus occurs, atoms move to restore the previous crystal structure before the deformation and then the recovery of macroscopic original shape.

SMAs application to linear motors

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 approach opens up many possibilities for providing mechanical actuation (movement) without any moving parts. The purpose of this research is the realization of SMA actuators which perform in defined operating temperature a specified movement. Temperatures have to 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 [8]. The developed experimental tests permitted a performance comparison between different operating conditions.

This paper focuses on two main issues in SMAs assessment and selection. The first one is the characterization of the thermo-mechanical behavior of SMA materials [9] and the other is the actuator application of one-way shape memory effect (SME). The selection of the operative temperature range is a crucial point in SMA selection [10]. All memory alloys have temperatures that characterize the internal structure [11]. In this study, the main temperatures of phase transformations for the adopted alloy (NiTiCu5) include the temperature at end of martensitic transformation (MF) 26°C, the martensitic transformation start temperature (MS) 37°C, the austenite transformation start temperature (AS) 48°C and the end temperature austenitic transformation (AF) 59°C (Hysteresis 24°C) [12]. 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.

Generally, the one-way effect does not provide suitable mechanism of SMA actuator due to the host structure that is not able to return to initial shape after cooling process. However, different researches [13,14] proposed some designs of SMAs applied to muscles of robot hands demonstrating that it is possible to realize a hand actuated by SMAs. In this case, a model based controller does not perform in a satisfying way due to the open loop configuration. The control problem (e.g. hysteresis) can be partially solved restricting the displacements to a specific range simplifying the problem to a linear one. This behavior is linearized using two counteracting shape memory elements. This solution is further improved by a temperature sensor on the shape memory element. Electrical resistance position feedback is also used in common practice [15]. An example of this application has been developed in the proposed actuator system.

Design of SMA actuator module

The actuator is designed to obtain a linear movement along horizontal axis of SMA elements. The shortest duty cycle was the primary objective in designing the device. This assumption highlights that the importance to meet 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 [12-14]. 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 needs 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 the movement axis and the model is very compact. A cylindrical geometry does not permit the geometrical diversification of the contact points that characterize the different functions.

These functions need of different materials and physical connections. In order to design properly the single elements of the actuator, it is useful to separate functions with Concentric cylinder geometry (separate elements, on concentric surfaces) or 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.

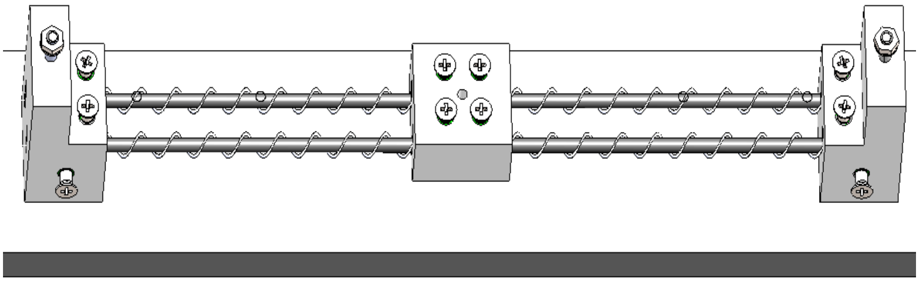


Fig 1. The modular actuation system.

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 approach represents an important benefit compared with concentric cylinder geometry. In particular, this configuration permits an increment of the nominal force of the actuator as shown in Fig.1 [15].

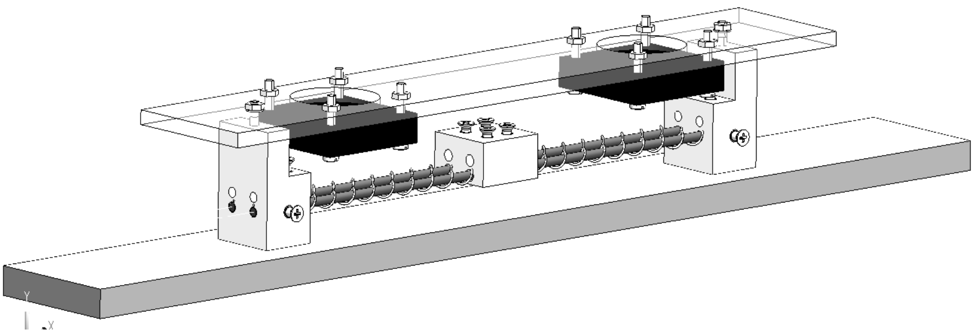


Fig. 2. The SMA prototype based on two modules.

Fig. 2 describes the developed prototype, electrical and mechanical functional 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 obtain the best control and stability in the movement. In this study four SMA elements are used, positioned on each side between central slider and wall. The spiral diameter is equal to 4.00 mm and the wire thickness is 0.40 mm.

The experimental test campaign

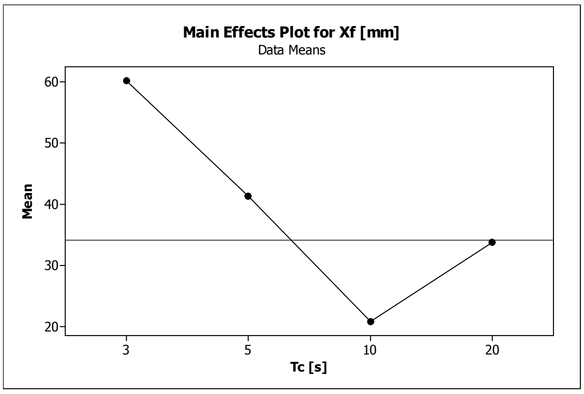
The experimental test campaign has been designed perturbing the input current and operating times. Table 1 summarized the obtained results of the position reached by cursor at the end of test (Xf) stratified by the main inputs (supplied current of two SMA elements (I), total cycle time (Tc), cycle time in which SMA element is active (Ton), number of cycles which elements have been subjected (Nt)).

Tab. 1. Summary of the test campaign results.

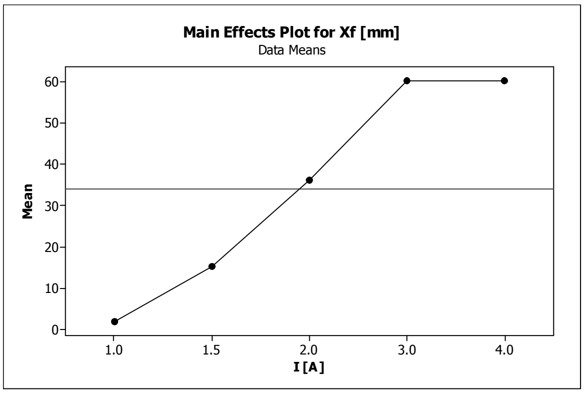
I [A]	Tc [s]	Ton [s]	Nt	Ne	Xf [mm]
1.00	10.00	10.0	10.00	10.00	2.00
1.50	10.00	5.00	10.00	10.00	0.00
1.50	20.00	10.00	5.00	5.00	10.00
1.50	20.00	10.00	10.00	10.00	36.00
2.00	5.00	3.00	5.00	5.00	10.00

2.00	5.00	3.00	10.00	10.00	35.00
2.00	10.00	5.00	5.00	5.00	21.00
2.00	10.00	5.00	10.00	10.00	60.00
2.00	20.00	10.00	5.00	5.00	55.00
3.00	5.00	3.00	5.00	3.00	60.00
3.00	5.00	3.00	10.00	3.00	60.00
4.00	3.00	3.00	5.00	3.00	60.00

In particular, when the input current is equal to 1.00 A, the tests show that the operating time is not able to satisfy the requirements (expected in 60-90 seconds). This result suggested that the transformation phase needs to increase the power in input. Fig. 3 shows the effect of the main inputs (Tc and I) on the response (Xf). It is noted that a input current greater than 3A guarantees a response (Xf) able to satisfy the defined requirements.



(a)



(b)

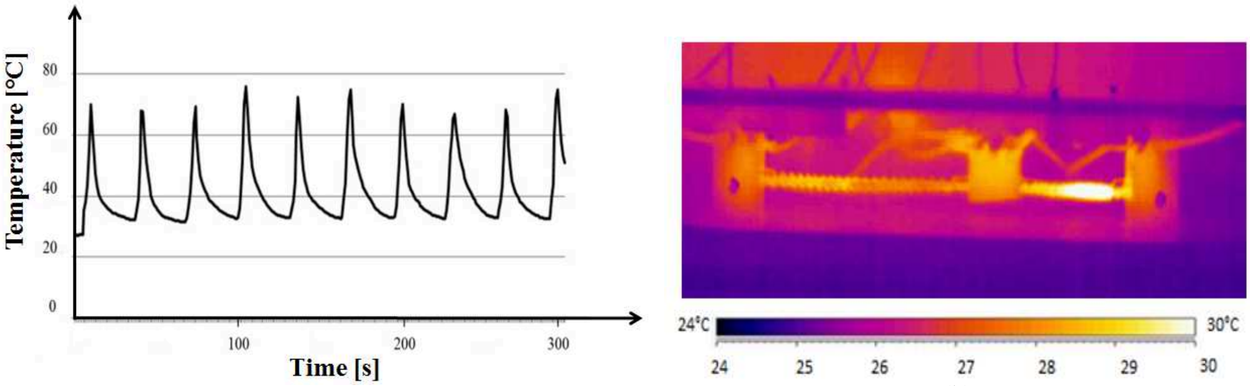
Fig. 3. Experimental test results: inputs (Tc (a), I (b)) vs. output (Xf).

In order to identify the optimal cycle time, the highest time values of heating and cooling were selected and then gradually reduced to find the best time in satisfying the restriction criteria on the temperature (maximum temperature at the end of cooling phase equal to 35°C) and the actuator position (SMA element has to reach its maximum stroke). In this way, Tab. 2 lists data relating to input currents (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).

Tab 1. Experimental results for optimizing input current and operating times.

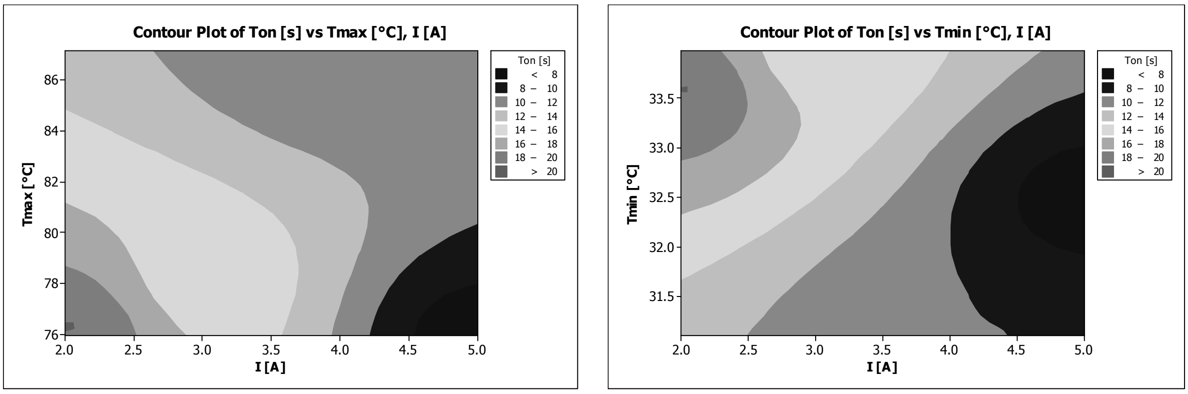
I [A]	Ton [s]	Tmax [°C]	Tr [s]	Tmin [°C]	Ttot [s]
2.00	20.00	76.28	30.00	33.59	100.00
3.00	15.00	78.23	25.00	33.98	80.00
4.00	10.00	87.14	25.00	31.10	70.00
5.00	7.00	75.94	25.00	32.47	64.00

The activation and cooling times have been considered and analyzed for each input current level. Fig. 4 describes the temperature on SMA element when the SMA activation time is equal to 15 seconds, SMA cooling time is equal to 25 seconds and input current is equal to 3A. This configuration is able to satisfy the required performance and constrains. To study the problem in detail and optimize the system configuration for the control strategy, Fig. 5 underlines the relations between the main inputs (i.e. Ton, Tmax and I) to maximize the position reached by the cursor at the end of test (Xf).



(a) (b)

Fig. 4. The temperature behaviour (a) on the SMA element and IR data collection (b).



(a) (b)

Fig. 5. Input correlation for control strategy optimization.

Using the temperature charts, it was possible to determine correct input time in agreement with the selected criteria. Fig. 6 shows the decrease of Voltage during the cooling phase. The detected Voltage is defined as the multiplication between the established input current and the resistance of the SMA spring. The Voltage growth means that both electrical resistance and temperature are increasing. In this test (Fig. 6) the SMA activation time is equal to 7 seconds, cooling time is 25 seconds and supply current is equal to 5 Amperes.

Fig. 7 shows a summary of the SMA actuator performance. The relation between the operating time (s), the central cursor stroke (mm) and the test voltage (V) is highlights in Fig 7b. These results confirm that the developed actuator is able to satisfy the functional requirements optimizing the input setting.

Conclusions

This paper presents the development of a modular actuator based on shape memory alloy material. Starting from theoretical observations, this study wants to highlight the main relations between the functional and geometrical properties of this device. A set of experiments perturbing the main inputs have been executed in order to analyze the actuator performances and features (i.e. hysteresis). The preliminary prototype shows acceptable results in terms of functionalities and potential application (i.e. rehabilitation medical devices). The next steps include to improve some theoretical aspects and develop new prototypes to optimize the required perfomances.

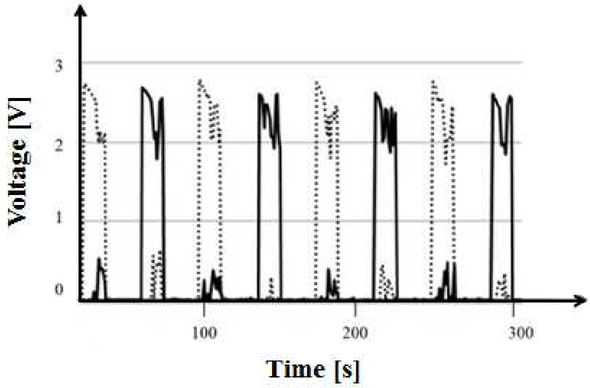


Fig. 6. Voltage on SMA elements during the work cycle.

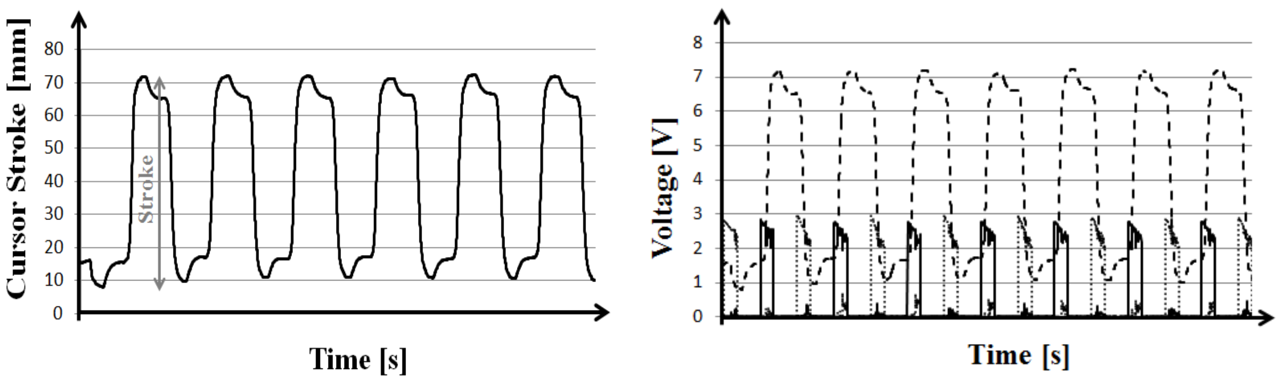


Fig. 7. The cursor stroke (a) and the comparison between cursor stroke and voltage input (b).

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