SHAPE MEMORY ALLOY ACTUATOR: MODELING IMPROVEMENTS AND POSITION CONTROL USING A TEMPERATURE INNER LOOP

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Abstract: Shape Memory Alloy (SMA) actuators have interesting properties as high energy density, high compactness, silent operation, biocompatibility and strain self-sensing ability. These characteristics make SMA actuators suitable for a large range of applications (such as in biomedical, aerospace and automotive). This paper presents modeling improvements and new control approach for SMA actuators. The model presented takes into account the temperature influence in the SMA resistivity and this consideration lead to a more precise simulation model. A temperature inner loop control is used to improve the controller performance, and this strategy allows operation in higher frequencies. Simulations are conducted in order to evaluate the controller performance.

Keywords: Shape Memory Alloy, Smart Sensors and Actuators, Position and Temperature Control

1. INTRODUCTION

Shape Memory Alloy (SMA) is a class of material with the ability to recover large deformation when the temperature is increased. This effect allows the development of actuators based in SMA, since its deformation recovering can be made in a controllable manner (Elahinia, 2016). Over the past few years, several applications have been explored in a wide variety of industrial sectors (Lagoudas, 2008), as for example in biomedical (Pittaccio and Viscuso, 2012), aerospace (Harlt and Lagoudas , 2007), automotive (Langbein and Czechowicz, 2012) and civil engineering (Debbarma and Saha, 2012).

The SMA's memory effect is associated with a reversible phase transformation. Phase transformation is a microscopic change in the material crystalline structure. In SMA case, this transformation is reversible and dependent of the temperature. A SMA wire deformed at low temperature (martensite phase) can be recovered to its original shape when heated to a higher temperature (austenite phase). This phase transformation induces strain recovery associated with large force and mechanical work. It is worth noting that physical properties that are dependent of crystal structure, as electrical resistance, are also affect by this transformation. These changes in phase transformation results in a temperature hysteresis and it takes SMA to present a non-linear behavior (Eisakhani *et al.*, 2014). In general, the SMA actuators use the alloy in the wire form, although other forms are also known. In most of applications the temperature can be increased when electrical current is applied through the SMA.

Regardless of its final application, it is always important to have a representative model of the SMA dynamic behavior. This dynamic model can be used to investigate mechanical effects and also can be used to obtain an efficient control. SMA modeling and control are complex due to its intrinsic non-linear behavior.

There are at least two approaches to model a SMA and its hysteresis: phenomenological or physical. Phenomenological models describe the hysteresis as an input-output operator. No physical insight is necessarily required (Kannan, 2012). In the other hand, physical models are based on physical laws, which allows to obtain more precise modeling, despite its greater complexity. The two physical basis to describe the SMA dynamics are the phase transformation process and its mechanism of heat exchange. Phase transformation is a process directly linked to the material temperature. This relationship is described for Tanaka (1986), Ikuta *et al.* (1991) and Liang (1990). General description for thermomechanical behavior were given in Leclercq and Lexcellent (1996), Brailovski *et al.* (1996) and Benzaoui *et al.* (1999). The main base for the SMA thermomechanical modeling is the classical differential equation of heat transfer. According to this approach, the heat exchange in the SMA wire depends on a few set of parameters. The wire electrical resistance is among these parameters. The resistance is temperature dependent, although most works in the literature do not take this into consideration. The current work will present a model taking this temperature dependency in consideration, improving simulation results.

SMA control strategies can be classified in three different groups. Inverse control, nonlinear control and linear control. If it is possible to obtain a phenomenological model to describe the SMA hysteresis, a feedforward controller can be implemented to compensate this non-linearity. This strategy is called inverse control and it was used in Nguyen and Ahn (2009) and Zhang *et al.* (2013). Another possibility are the nonlinear methods. The hysteretic behavior of the SMA can also be conveniently treated by methods such as feedback linearization (Benzaoui *et al.*, 1999) or slide mode control (Elahinia and Ashrafiuon, 2002) (Ianagui and Tannuri, 2015), despite its greater complexity. Lastly, conventional linear PID controller is also an option to be adopted due to its simplicity. Different variants of PID control were applied in Guo *et al.* (2013), Nguyen and Ahn (2006), Shameli *et al.* (2005) and Silva (2007). Temperature is a key variable in SMA operation. Phase transformation and others important aspects of SMA dynamics are temperature dependent. Overheating increases the time required to the shape memory recovery. Large overheating can include permanent damage the alloy. Linear control using PID traditionally does not look to the temperature. A modified PID strategy using an inner loop to temperature control is proposed in this work. This inner loop is used to improve SMA position control since overheating can be avoid. This is also important because it make possible to work in higher frequencies of actuation.

2. SMA MODEL

The dynamics of the SMA can be described in a modular approach where the three main phenomenons can be analyzed in a sequential way, as presented in Fig. 1: heat transfer exchange, phase transformation and mechanical behavior.
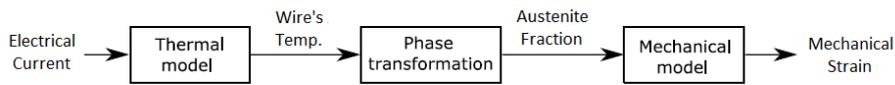

Figura 1: SMA modular model block diagram

The SMA thermal model define the relationship between the electrical power applied and the wire's temperature using thermal balance equation. The SMA phase transformation links the temperature and the martensite fraction. The SMA mechanical model establishes the relationship between the martensite fraction and the induced mechanical strain.

2.1 Thermal model

The classical differential equation of heat transfer can be obtained from the thermal balance of the SMA. The heat transfer dynamics can be conveniently written as:

$$\rho C V \frac{dT}{dt} = \frac{v^2}{R} - h A_s (T - T_e). \tag{1}$$

where ρ is the density of the SMA wire, C is its specific heat, V is the volume of SMA material, T is the SMA temperature at a time t, v is the voltage applied in the wire, R is the wire's electrical resistance, h is the heat exchange coefficient, A_s is the wire surface area, and T_e is the environment's temperature (Velazquez and Pissaloux, 2012).

This SMA thermal model can be improved considering that the heat convection coefficient is temperature dependent. In order to improve the heat transfer model, as reported by (Elahinia and Ashrafiuon, 2002) and (Jayender *et al.*, 2008), h can be approximated using a second order polynomial as:

$$h = h_0 + h_1 T + h_2 T^2 \tag{2}$$

where the parameters h_0, h_1 and h_2 can be obtained through experimental procedure. An experimental procedure to h estimation based in step response experiments was reported in (Barbosa *et al.*, 2016).

2.2 Phase Transformation and Mechanical Model

SMA phase transformation is a complex and nonlinear process. The transition between martensite and austenite phases is a temperature dependent behavior, highly hysteretic. Dissipation and assimilation of latent heat due the phase transformation causes the hysteresis. The amount of martensite fraction $\xi(T)$ in SMA material, under constant load conditions, can be described using a differential hysteresis model. This model follow a phenomenological approach as described in (Dutta and Ghorbel, 2005). The hysteresis model proposed by (Dutta and Ghorbel, 2005) is a Duhem differential model and it is given according to:

$$\xi(T) = \begin{cases} \frac{h_-(T) + \xi - 1}{h_+(T) - h_-(T)} g_+(T); & \dot{T} \geq 0 \\ \frac{h_+(T) + \xi - 1}{h_+(T) - h_+(T)} g_-(T); & \dot{T} < 0 \end{cases}, \tag{3}$$

where g_+ and g_- are slope functions and h_+ and h_- represents the hysteresis major loop:

$$g_\pm(T) = \frac{1}{\sigma_\pm \sqrt{2\pi}} exp(-\frac{(T - \mu_\pm)^2}{2\sigma_\pm^2}) \tag{4}$$

$$\begin{aligned} h_\pm(T) &= \int_{-\infty}^{T} g_\pm(T')dT' \\ &= \frac{1}{2}[1 + erf(\frac{T - \mu_\pm}{\sigma_\pm \sqrt{2}})] \end{aligned} , \tag{5}$$

where the subscripts $+$ and $-$ represent increasing and decreasing curves, respectively; μ is the mean and σ^2 is the variance, and this two parameters can be experimentally defined.

Mechanical is responsible to link phase transformation and actuator strain. For this work it was considered an actuator directly connected to a single load. In the case the martensite fraction is directly related to the mechanical strain.

2.3 SMA wire resistance

Another important parameter dependent on the temperature is the wire electrical resistance. The current work presents a new approach to be used in simulations. This consideration improves simulation results. Moreover, since the wire resistance can be easily measured through current and voltage measurements, this variable can be used to self-sensing purposes.

The electrical resistivity is intrinsic property of the material and it can be considered linearly related to the temperature. Moreover the total resistivity of SMA can be estimated as a summation of the resistivities of each phase. According to (Ikuta *et al.*, 1991), the variable sublayer model defines the SMA resistivity in terms of martensite fraction as following:

$$\rho = \xi(T) \rho_M + (1 - \xi(T)) \rho_A \tag{6}$$

where ξ is the martensite fraction, ρ_M and ρ_A are the resistivities of martensite and austenite phases, respectively.

The following equation presents the traditional relationship between electrical resistance and resistivity:

$$R = \rho \frac{l}{A_\phi} \tag{7}$$

where R is the electrical resistance, ρ the electrical resistivity, l the wire length and A_ϕ the wire cross section area. SMA actuator movement is created due to the wire strain. When the wire is deformed, its length and transversal section also change. Besides that variation, it is reasonable to consider the volume as a constant in this process. In that way the Eq. 7 can be rewritten as:

$$R = \rho \frac{l^2}{V_{ol}} \tag{8}$$

where V_{ol} represents the wire volume.

The Eq. 6 and 8 are used to simulate the SMA variable resistance using only information available in the material data sheet. The complete block diagram proposed here is presented in Fig. 2. The Eq. 8 can also be easily manipulated to be used in a self-sensing control strategy with a reduced computational effort.

2.4 Simulation parameters

The SMA actuator used as reference is a commercial type made by Miga Motors Company, available under the name MigaOne-15 (Fig. 3). It is a credit-card-sized memory metal actuator, weighing less than 13 grams, with 8 mm of stroke, and actuation time of $\sim$1.0 second at 5.0 V. The MigaOne-15 provides 11 N of force (22 N peak), using 0.015" diameter SMA elements.
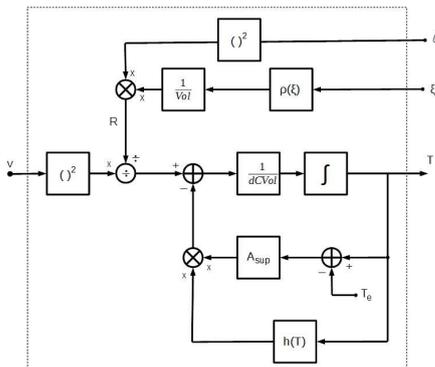

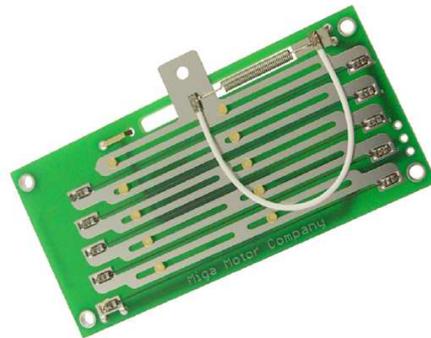Figura 2: SMA thermal model for simulation

Figura 3: MigaOne-15 SMA actuator

Table 1 presents the parameters used to simulation in this work. Manufacturer's data sheets is available at (MigaMotors, 2014).

Parameter	Value	Unit
Density ρ	6450	$kg.m^{-3}$
Specific heat C	320	$J.kg^{-1}.oC^{-1}$
Environm. temp.	26	oC
Wire diameter	0.038	mm
Surface area	$3.26e^{-5}$	m^2
Volume	$3.10e^{-10}$	m^3
Heat Coef. h_0	42.53	-
Heat Coef. h_1	0	-
Heat Coef. h_2	0.0029	-
Resistivity Mart. ρ_M	80	$\mu\Omega.cm$
Resistivity Aust. ρ_A	100	$\mu\Omega.cm$

Tabela 1: Intrinsic and geometric SMA properties

3. SMA CONTROL

Different control strategies were investigated. Traditional PID controller can be used to control the SMA position, although with limited actuation frequency. In order to improve the operational frequency, this work proposes a control strategy using a PID outer loop position control and a PID inner loop temperature control, as illustrated in Fig.4.
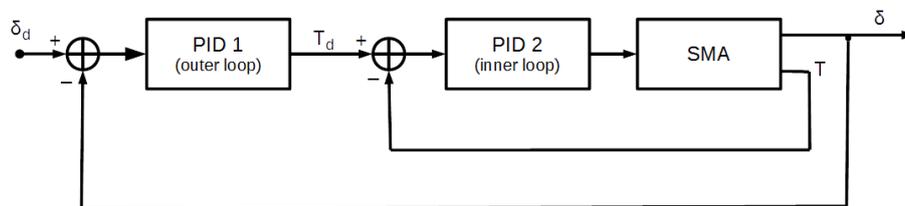

Figura 4: SMA control using a temp. inner loop

Sinusoidal tracking response was used to compare the control strategy proposed against a conventional PID control. The SMA simulation model presented in the previews section was implemented in the Matlab / Simulink environmental, and it was used to test three different frequencies: 0.005Hz, 0.01Hz and 0.02Hz. The results can be seen in Fig. 5a, Fig. 5c and Fig. 5e.

It is possible to see that the performance of the proposed position control is better than a traditional PID controller. The cascade strategy used allows a more appropriate tuning, using more aggressive gains. As the actuation frequency increases this difference became even more evident and the proposed controller can be used in higher frequencies where the simple PID would not be acceptable.

The difference between the controllers performances is due to the overheating. The inner loop temperature control is able to minimize that undesired behavior. The temperature profile can be seen in the Fig. 5b, Fig. 5d and Fig. 5f. It is clear that the simple PID strategy allow a unnecessary overheating.

4. CONCLUSION

In this work it was presented an improved SMA model for simulation. The presented approach is suitable for control developments. This model consider important aspects such as the temperature dependency of the heat exchange coefficient and the electrical resistance, and this lead a more accurate simulation results. Based on that model, it was possible analyze the SMA behavior and to propose a SMA control strategy using an inner loop temperature control. Position control performance was increased for higher frequencies. Future works intent to implement a temperature estimator in order to avoid the temperature measurement in real applications. This control strategy will be implement in SMA biped robot.

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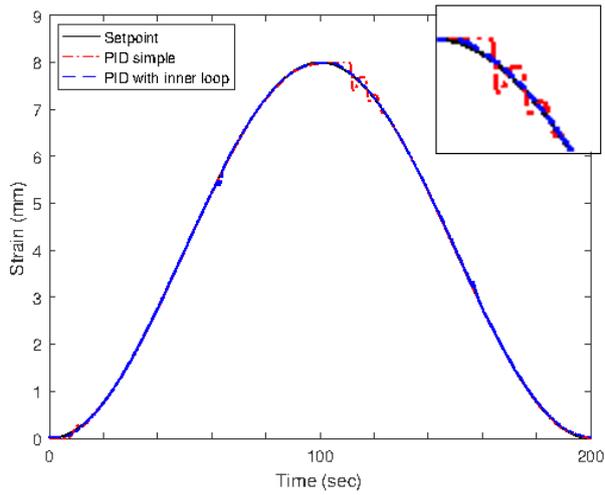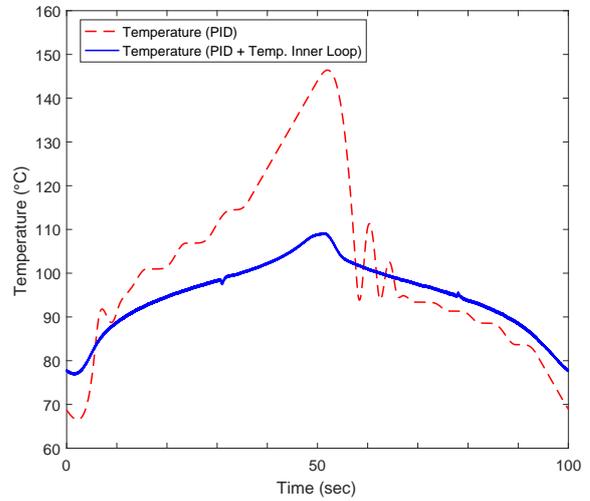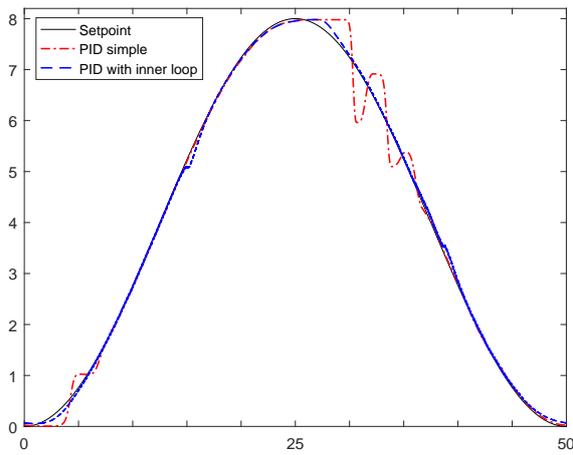
(a) Sin. tracking resp. at 0.005 Hz
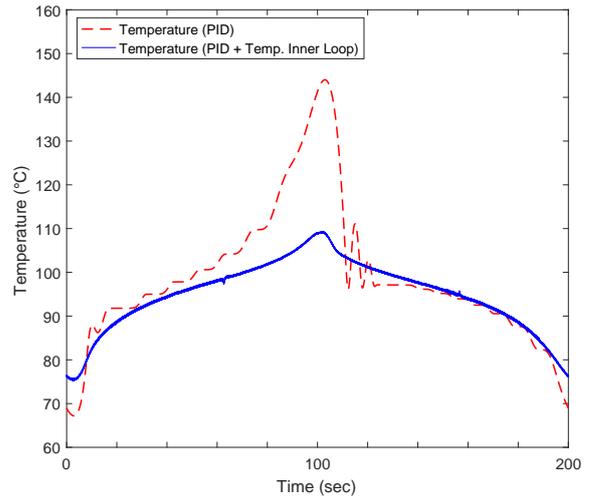
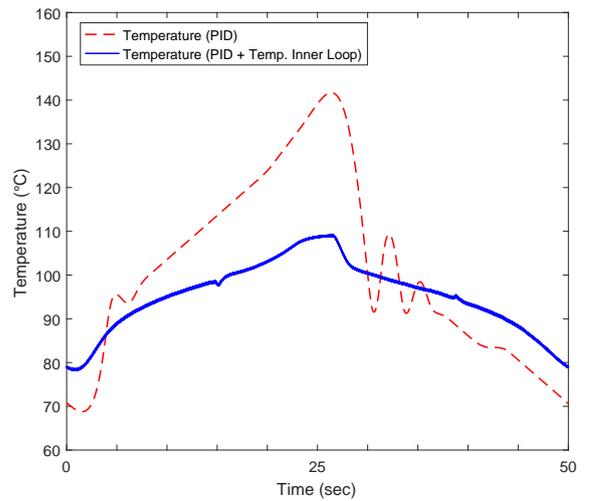(b) Temp. in sin. tracking resp. at 0.005 Hz
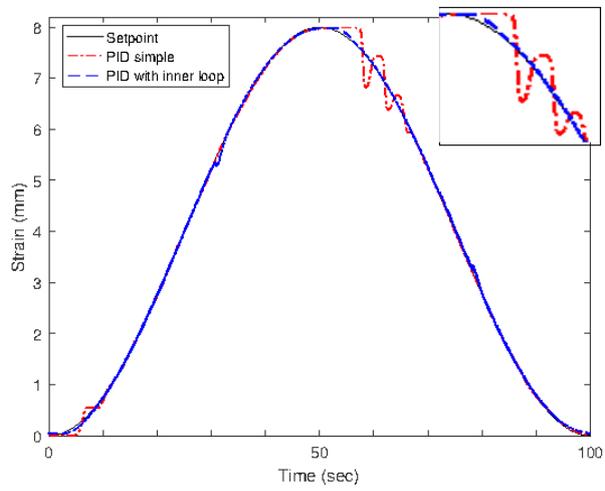
(c) Sin. tracking resp. at 0.01 Hz

(d) Temp. in sin. tracking resp. at 0.01 Hz

(e) Sin. tracking resp. at 0.02 Hz

(f) Temp. in sin. tracking resp. at 0.02 Hz

Figura 5: Results

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6. AUTHORS RESPONSIBILITY

The authors are solely responsible for the content of this work.