SHAPE MEMORY ALLOY MODELING AND SIMULATION

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Abstract— Shape Memory Alloy (SMA) is a special class of material with great potential to be used as actuators. There are a significant number of recent development especially on robotic application area. Part of SMA actuators development is related to modeling and control. The objective of this paper is to present a model of the SMA behavior suitable to be used on simulation control studies. The heat transfer coefficient considered on the model is obtained using an experimental procedure. Experimental tests are performed in order to evaluate simulation model results.

Keywords— Shape Memory Alloy; Modeling and Control; Heat Transfer Coefficient

1 Introduction

Development of high functional density and smart materials is certainly a current technological need due to tie technical and commercial restrictions. (Jani et al., 2014). Active materials, a group of multifunctional material exhibiting sensing and actuation capabilities, can be considered smart materials. Some examples of active materials are piezoelectrics, piezomagnetics and shape memory materials (Lagoudas, 2008).

Shape memory alloy (or SMA) is a kind of active materials. Its shape memory effect (SME) allow the material to recover the original shape at the presence of the right stimulus (Sun et al., 2012). SMA is capable of create motion from electricity, transforming electrical energy on mechanical energy. Usually this is a function cover by an electrical motor, however SMA has important characteristics that make it more suitable than motors in a variety of applications (Gilbertson, 2000).

The SMA's great power to weight ratio is one of its major advantages. SMA can lift loads a lot of times heaviest that its own weight. Besides that, it has a silent operation and it is also a biocompatible material. SMA has already been used in medical applications. It is even common to call SMA as artificial muscle (Gilbertson, 2000).

The large range of applications where SMA can be used as actuator make its study a subject of interest in many research centers around the world. Regardless of its final application, it is always important to have a representative model of the SMA dynamic behavior. This dynamic model is used to investigate mechanical effects and also can be used to obtain an efficient control for this kind of actuator. However, modeling and control are not easy tasks in SMA case, mainly because SMA presents a very non-linear behavior. All that makes a SMA actuator research a very challenging subject.

A summary of SMA modeling and control methods is presented on (Kannan, 2012). The classification used divide modeling methods in three different groups: Phenomenological, Linear or No Model, and Physical. Phenomenological models are formulated by weighted aggregate of all possible elementary hysteresis operators. This group include Preisach, Krasnosel'skii-Pokrovskki, Prandtl-Ishlinskii and Duhem differential models. In the other hand, Linear or No Model group uses a very simply approaches to model the SMA hysteretic behavior, considering, for example, the hysteresis as phase lag between input/output. Physical models describe the given hysteretic SMA system base on physical laws. This approach make possible to obtain more precise modeling, despite its greater complexity. Some important works are basic reference for physical model approach. The thermomechanical and heat convection behavior are described on (Leclercq and Lexcellent, 1996) and (Benzaoui et al., 1999). A constitutive model is presented by (Liang, 1990) and (Linag and Rogers, 1997). An improved model putting these basic works together is presented on (Elahinia and Ashrafiuon, 2002).

A key aspect of SMA modeling and simulation is how to define the heat convection coefficient. One possible way to define the heat convection coefficient is to consider it as a constant value, as presented on (Velazquez and Pissaloux, 2012). This approach, considering the coefficient as a constant value, is the most used case. However, simulation results can be strongly improved if the temperature's dependency of this coefficient is considered, as reported on (Elahinia and Ashrafiuon, 2002), (Jayender et al., 2008) and (Barbosa et al., 2016).

The current work presents a simulation framework that will be used to develop SMA control strategies. These control strategies will be used to apply SMA actuator in mechanical structures like robots or medical prosthesis and equipments. A physical model is adapt to the current situation. In order to improve simulation quality performance, the heat transfer coefficient is identified using an experimental setup built, considering temperature's dependency. Finally the simulation results are compared against real data collect from a SMA actuator.

2 SMA Model

A simplified approach for SMA dynamics modeling, based on physical laws, is presented on (Abdelaal and Nagib, 2014). The complete dynamic model consists of the three compartments:

A) SMA Thermal model to rely the applied electrical power to the wire's temperature using thermal balance;

B) SMA Phase Transformation to rely the temperature with Martensite fraction;

C) SMA Mechanical model to rely the Martensite fraction with the induced mechanical strain in the actuator.

The flowchart shown on Fig. (1) represent these three steps to model the SMA dynamics. The complete SMA model can be seen as a composition of three sub-models.

2.1 Thermal Model

SMA thermal behavior can be analyzed through an existing constitutive model, as detailed reported in (Velazquez and Pissaloux, 2012), and presented on this section. The classical differential equation of heat transfer can be obtained by analyzing the thermal balance of the SMA. The heat generated by an external source is labeled as Q_{source}, and the three different forms of heat dissipation are labeled as Q_{convec}, Q_{conduc} and Q_{radia}. Equation 1, as following, express this relationship:

$$\rho CV \frac{dT}{dt} = Q_{source} - Q_{convec} - Q_{conduc} - Q_{radia}, \quad (1)$$

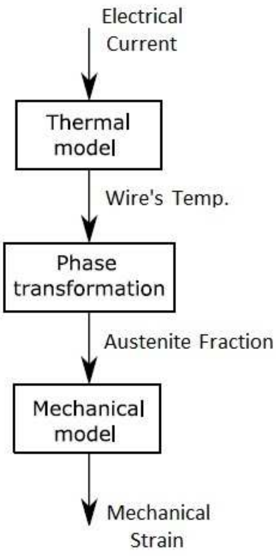

Figura 1: SMA Model Flowchart

where ρ is the density of the SMA wire, C is its specfic heat, V is the volume of SMA material, and T is the SMA temperature at a time t.

Considering SMA actuators driven by electrical power, the heat generated can be described by Lenz-Joule law, as following in Eq. (2):

$$Q_{source} = vi = i^2 R, \quad (2)$$

where i is the electrical current applied through the wire and R is the wire's electrical resistance.

The heat dissipate by convection can be estimated by the Eq. (3):

$$Q_{convec} = hA_s(T - T_e), \quad (3)$$

where h is the heat exchange coefficient, A_s is the wire surface area, and T_e is the environment's temperature.

In the order hand, the heat dissipate through conduction is usually neglected if it is assumed that the temperature is uniform in the material at all times due to its low internal resistance to heat conduction. And finally, considering applications within the atmosphere the Q_{radia} can also be neglected (Velazquez and Pissaloux, 2012).

After theses considerations, the heat transfer dynamics showed on Equation 1 can be conveniently represented by the Eq. (4):

$$\rho CV \frac{dT}{dt} = vi - hA_s(T - T_e). \quad (4)$$

This proposed SMA thermal model can be improved. The heat convection coefficient shows to be depended of the material temperature. In order to improve the heat transfer model, as reported on (Elahinia and Ashrafiuon, 2002) and (Jayender et al., 2008), h can be approximated by a second order polynomial, as in Eq. (5):

$$h = h_0 + h_1 T + h_2 T^2 \quad (5)$$

where the parameters h_0, h_1 and h_2 can be obtained through experimental procedure.

2.2 Phase Transformation

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 by the Equation 6 (Abdelaal and Nagib, 2014).

$$\xi(T) = \begin{cases} 0 & T > A_f \\ 0.5[cos(\pi \frac{T-A_s}{A_f-A_s}) + 1] & 0 \\ 1 & T < A_s \end{cases}, \quad (6)$$

where A_s is the Austenite Start temperature, and A_f is the Austenite Finish temperature. A similar equation can be easily obtained to describe the Austenite fraction.

2.3 Mechanical Model

Mechanical model depends on relationship between phase transformation and the actuator mechanical strain. The actuator stress is responsible move the correspondent structure, like a robotic arm, active orthosis, etc. The mechanical dynamics of the end-application structure is also considered on the mechanical model.

3 Simulation Framework

In order to implement a simulation model, first step is to build a framework. The framework used here is based on the three sub-models described on the previous section. The Simulink environment (Matlab) is used, and the model built can be seen on Figure 2.

The thermal sub-model is based on Equation 1, the classical differential equation of heat transfer, and is implemented as can be seen on Figure 3.

First group of the parameters are available as intrinsic characteristics of the SMA, and can be found on material datasheet (Dynalloy, 2009), like SMA density and specific heat capacity. Second group is related to the geometric characteristics of the actuator, like wire diameter, volume and surface area. This information can be found on Table 1.

A reasonable estimate of the heat convection coefficient is very important phase to have a satisfactory thermal model set of parameters. Unfortunately this parameter is variable with the temperature, as described previously.

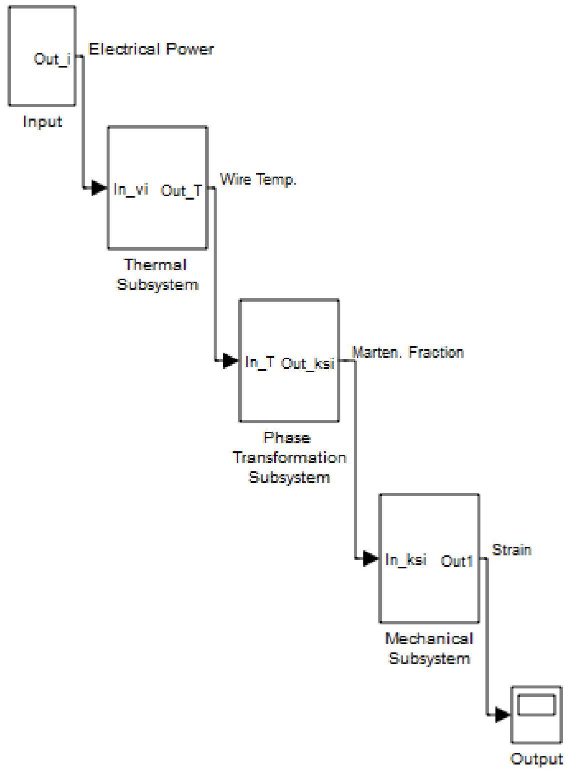

Figura 2: Simulink SMA Model

Parameter	Value	Unit
Density ρ	6450	$kg.m^{-3}$
Specific heat C	320	$J.kg^{-1}.^oC^{-1}$
Environm. temp.	38.5	^oC
Wire diameter	0.038	mm
Surface area	$3.26e^{-5}$	m^2
Volume	$3.10e^{-10}$	m^3

Tabela 1: Thermal and geometric properties of the SMA

An experimental procedure to estimate the parameter h is based on step response experiments, as reported in (Barbosa et al., 2016). The steady state conditions in the Equation 4 is considered. A set of four step response experiments were conducted, using different currents step amplitudes. Heat transfer coefficient obtained are presented at Table 2.

Voltage Step (Input)	$T_{ss}(^oC)$	h
1.0V	47.65	47.83
1.5V	57.50	53.07
2.0V	72.00	57.28
2.5V	87.00	64.55

Tabela 2: Heat transfer coefficient estimation

The temperature influence in this coefficient can be described through the Equation 5. Using the fitting curve tool available at Matlab it is possible to find the terms h_0, h_1 and h_2. The pa-

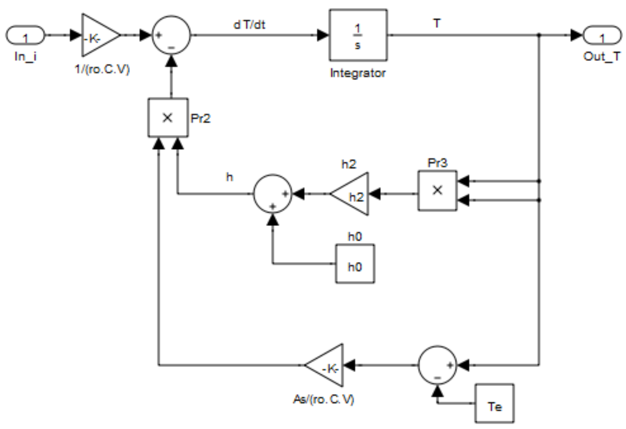

Figura 3: Simulink Thermal Model

rameters found were $h_0 = 42.53$, $h_1 = 0$ and $h_2 = 0.00294$. R-square found is equal to 0.9899, indicating a high quality fitting level.

4 Experimental Tests

4.1 Experimental Setup

The experimental setup used to conduct this investigation is composed by a mechanical structured responsible to support the SMA actuator, a pulley with an encoder attached and the mechanical load. Additionally there are two extra modules to data acquisition and actuator powering. A computer is also needed to interact with the data acquisition module. A schematic diagram is showed in the Figure 4.

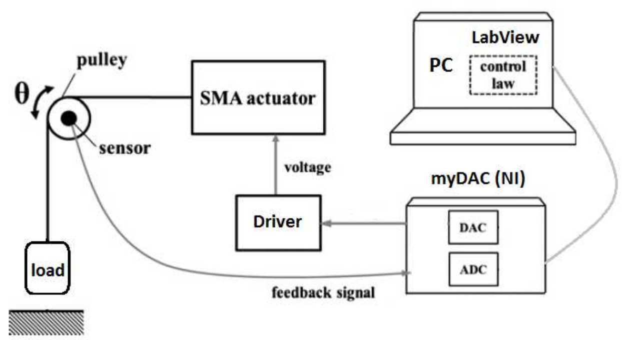

Figura 4: Test Bench Diagram

The SMA actuator used is a commercial type made by Miga Motors Company, available under the name MigaOne-15. 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 with $\sim 2.7\ \Omega$ resistance, as can be seen at Fig. (5), (MigaMotors, 2007).

The encoder is a 500 pulses, differential type, made by Cytron Technologies, part number 3806-

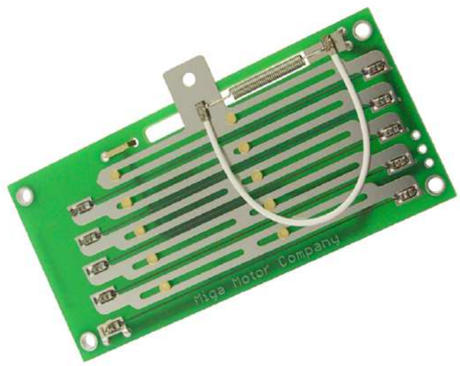

Figura 5: MigaOne-15 SMA actuator

500B-5-24F. Temperature is measured using a micro thermocouple type K. The mechanical load is a 400 grams piece of rubber. The data acquisition module is a myDAQ type made by National Instruments, and Labview software is used on a computer to manager the data storage. This test bench is presented on Figure 6.

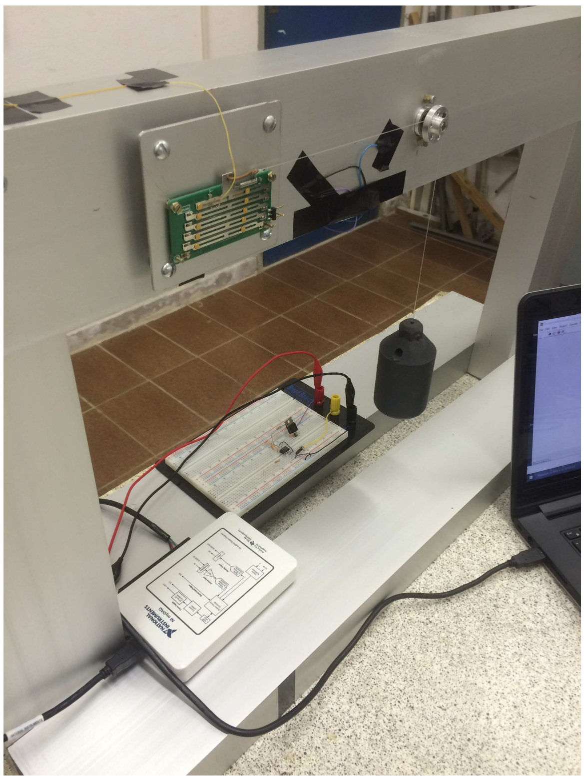

Figura 6: Test Bench

The power module consists of a dedicated voltage amplifier, based on power TIP transistors, and an ordinary 5V power source. The amplifier is set to have unitary gain, receiving the signal command from myDAQ and supplying power signal (up to 3 amperes) through the power transistor.

5 Results and Analisys

Simulation results are presented in this section. A sinusoidal voltage (power) signal is used as input, at a frequency of 0,005 Hz. Mechanical strain response of the SMA (in milimeters) is shown at Figure 7.

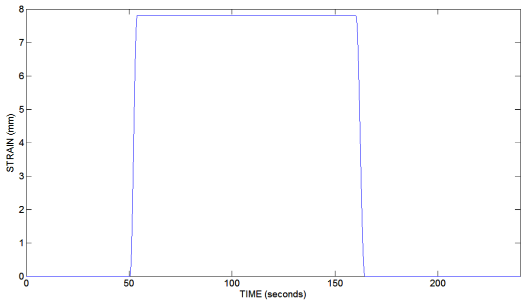

Figura 7: Strain x Time - Simulation

This result simulated can be compered with the mechanical strain response obtained from experimental test. Same signal input was used, and the SMA strain behavior is presented at Figure 8.

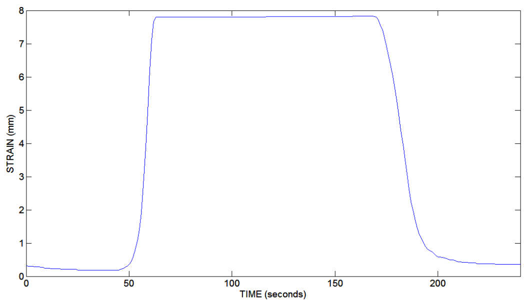

Figura 8: Strain x Time - Test Bench Results

Similarity between the two curves is satisfactory, specially when compared with simulation results using a constant heat transfer coefficient. Heating process has shown great coincidence. Although the cooling process start at a similar instant of time, the total time to cool the SMA doesn't match completely. Cooling process modeling need to be improved in a further work.

6 Conclusion

As it was commented during this text, SMA is still a subject of interest. However, its utilization as a practical actuator need to overcome some drawbacks. Modeling SMA dynamics is a basic task in order to better study and understand this great potential material. This can be used to simulation and also as part of control strategy. During this work a model was established and the appropriated parameters were defined or identified. A simulation framework was built on a frequently used simulation software and the simulation results where compered against experimental results. Final conclusion is that the model for simulation obtained will be suitable for SMA control developments.

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