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R. Cortez-Vega, I. Chairez, A. Luviano-Juárez, V. Feliu-Batlle

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A Hybrid Dynamic Model of Shape Memory Alloy Spring Actuators

R. Cortez-Vega[a,*], I. Chairez[b], A. Luviano-Juárez[a], V. Feliu-Batlle[c]

[a] *Instituto Politécnico Nacional - UPIITA. Av. IPN 2580 Col. Barrio la Laguna Ticomán, Ciudad de México, México, C.P. 07340. E-mail: rcortezv1500@alumno.ipn.mx, aluvianoj@ipn.mx*

[b] *Instituto Politécnico Nacional - UPIBI. Av. Acueducto de Guadalupe S/N, Col. Barrio la Laguna Ticomán, Ciudad de México, México, C.P. 07340. E-mail: ichairezo@gmail.com*

[c] *Department of Electrical, Electronic and Automatic Engineering, Higher Technical School of Industrial Engineering, University of Castilla-La Mancha, Av. Camilo José Cela s/n, 13071 Ciudad Real, Spain. E-mail: Vicente.Feliu@uclm.es*

Abstract

This paper presents the development of a hybrid model that describes the temperature, elongation and inner force relationships in a spring Shape Memory Alloy (SMA) actuator. The temperature-inner force relationship obeys a hybrid structure in which a sigmoid function correlates the variation of temperature for the SMA and the force executed by the spring actuator. The hybrid nature of the model describes the regular hysteresis behavior of the SMA. The switching law of the hybrid model depends on the time derivative of the temperature. A multivariable model depending on temperature, and inner and external forces was developed in order to characterize the Shape Memory Effect (SME). A set of experiments was carried out to obtain the parameters used to characterize the model. The application of the Levenberg-Marquardt method resulted in the parametric estimation procedure. An averaged correlation factor of 0.95 between the model response and experimental results justifies the proposed modeling approach.

Keywords: Shape Memory Alloy, Smart Actuator, Hysteretic Model, Hybrid model

1. Introduction

Shape Memory Alloys (SMA) are a special type of materials which have a property that eneables them to returning to a pre-established shape when their temperature is increased from a lower initial condition [1]. One of the commercial materials most frequantly used to produce SMA is a metallic alloy composed of nickel and titanium ($NiTi$) or nitinol, which is that used in this study. The usual relation in the composition of this alloy is around $50\% - 50\%$ [2], signifying that the behavior of the SMA is limited to NiTi alloys that have a near-equiatomic composition [3]. These materials behave with hysteresis when the load-deformation relationship is running on [4]. At low temperatures, the alloy behaves like a *plastic* object (first phase), but when the temperature increases, this behavior becomes *pseudo-elastic* (second phase), with a hysteresis loop between both phases.

A preformed sample of SMA has an initial deformation at low temperatures with an internal load beyond the yield limit. The heating of this sample introduces some inner forces into the material, leading to a deformation. The SMA consequently returns to its original configuration. This effect is the called *Shape Memory Effect* (SME)[5]. The SME characterizes the transient process between the two aforementioned phases, which are known as *martensite* (first phase) and *austenite* (second phase).

The SME occurs because each atom of nickel is surrounded by four atoms of titanium. This structure creates a three–dimensional symmetric crystalline grid. The crystal structure formed by the atomic forces allows the transition between both phases: martensite and austenite. The energy that enforces the transition is related to the corresponding temperature changes in the material. The reorganization of the crystalline structure is, therefore, responsible for the SME.

SMAs have several applications in diverse technological fields, such as the aeroespacial industry in which they are used as active actuators to regulate the shape of plane structures [6]; in biomedical applications for which they have several uses [7]; and in civil structures [8], seismic [9] and miniature applications in which traditional actuators such as motors cannot be set up [10]. The close relation between the mechanical force and the weight of the SMA makes it a reliable option for actuation purposes in small robotic systems (SRS) [11], [12], [13]. This is the main reason for selecting this actuator for the RS. However, there is still a major challenge that must be confronted before applying this device in a real RS: the behavior of the material has nonlinear (hysteresis) effects that must be modeled in order to establish an accurate control strategy.

Commercial SMAs have a very narrow SME with a predefined elongation (not greater than $3 - 5\%$ with regard to its initial size). This means that a long wire generates only a small movement when the temperature is varied around the austenite temperature. This effect makes it possible to modify the material in order to introduce a predefined different shape. This modification allows a larger movement of the SMA in a

*Corresponding author