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DEVELOPMENT OF A FUZZY CONTROLLER APPLIED TO FORCE AND DISPLACEMENT CONTROL IN A SHAPE MEMORY ALLOY ACTUATOR

André Fellipe Cavalcante Silva, af_andre.fellipe@hotmail.com
Alexsandro José Virgínio dos Santos, alexsandro@cear.ufpb.br
Simplício Arnaud da Silva, simplicioarnaud@gmail.com
Federal University of Paraíba, Department of Mechanical Engineering, Cidade Universitária, CEP: 58051-900, João Pessoa – PB, Brazil.

Cícero da Rocha Souto, cicerosouto@cear.ufpb.br
Federal University of Paraíba, Department of Electrical Engineering, Cidade Universitária, CEP: 58051-900, João Pessoa – PB, Brazil.

Carlos José de Araújo, carlos@dem.ufcg.edu.br
Federal University of Campina Grande, Department of Mechanical Engineering, Av. Aprígio Veloso, 882, Bairro Universitário, CEP: 58429-140, Campina Grande – PB, Brazil.

Abstract.*In the last decade, a new class of advanced materials, classified as smart materials, began to appear in the literature of materials science and engineering. Components manufactured with smart materials have unusual behaviors due to sensitivity to temperature, pressure, strain, magnetic and electrical fields, light, among others. A compact definition for smart materials is "materials that have functional properties of sensors and/or actuators". Main examples of smart materials are electro and magneto rheological fluids, piezoelectric ceramics and polymers, electroactive polymers and Shape Memory Alloys (SMA). The use of these materials with electromechanical responses coupled with the implementation of control techniques has allowed the creation of smart structures capable of solving various problems in the field of rehabilitation robotics and mechatronics in general. In this context, this paper presents the development of a controller, based on fuzzy logic, for control the mechanical effort generated by a shape memory wire actuator. For the study it was designed a linear actuator capable of generating force and large displacements when put under load. Experimental results on the performance of the controlled force and displacement are presented.*

Keywords: *Smart Materials, Shape Memory Alloy, Fuzzy Control.*

1. INTRODUCTION

In the last two decades, the development of smart materials capable of being used as compact, powerful and light actuators, have become the center of many research around the world. One of the smart materials that have been highlighted for scientific and technological researches are the Shape Memory Alloys (SMA).

SMA are metallic alloys that demonstrate the ability to recover its original shape after pseudo plastic strain or to develop considerable forces after the imposition of a temperature field through a phase transformation induced in the material (Otsuka & Wayman, 1998). These SMA possess the ability to develop relatively large strains, around 8%, without introducing irreversible plastic strain.

These materials present basically three thermomechanical behaviors: Shape Memory Effect (SME), Two Way Shape Memory Effect (TWSME) and Superelasticity (SE). The phenomena of SME or TWSME presented by these materials can generate intense recovery forces associated with significant displacement (mechanical work) making these materials become thermomechanical actuators. The range of possible application that these materials can be used has aroused interest for using them in very specific areas where it needs low noise and some kind of force or mechanical work (Lee et al, 2012). Some areas or applications that have benefited from research in SMA are position control (Silva et al, 2012a), shape changes (Song & Ma, 2007; Sofla et al, 2010), aerospace (Lagoudas, 2008), biomedicine (Machado & Savi, 2003) and robotics rehabilitation (Bundhoo et al, 2008; Farías et al, 2009 and Ko et al, 2011), among others.

An important feature for design with SMA is checking their transformation temperatures, force and displacement generated by the material. In order to measure the generated force and displacement produced by a Ni-Ti SMA wire with diameter of 0.305mm, in this work it was developed a winding system of SMA wires working against an elastic coil spring. This system is similar to that used recently by Silva et al (2012b) in a SMA robotic finger. Concurrently, a fuzzy logic based controller was developed to be used in testing the force of this SMA - elastic coil spring system.

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2. EXPERIMENTAL PROCEDURE

The work consists of designing and assembling a experimental test bench for verification of force and displacement of an SMA wire. It was initially prepared the physical structure of the test bench and subsequently developed an electrical interface for activation and control system based on fuzzy logic to control the strength of the SMA.

Figure (1) shows the bench designed in the CAD environment and an image of the bench constructed to accommodate the SMA wire.

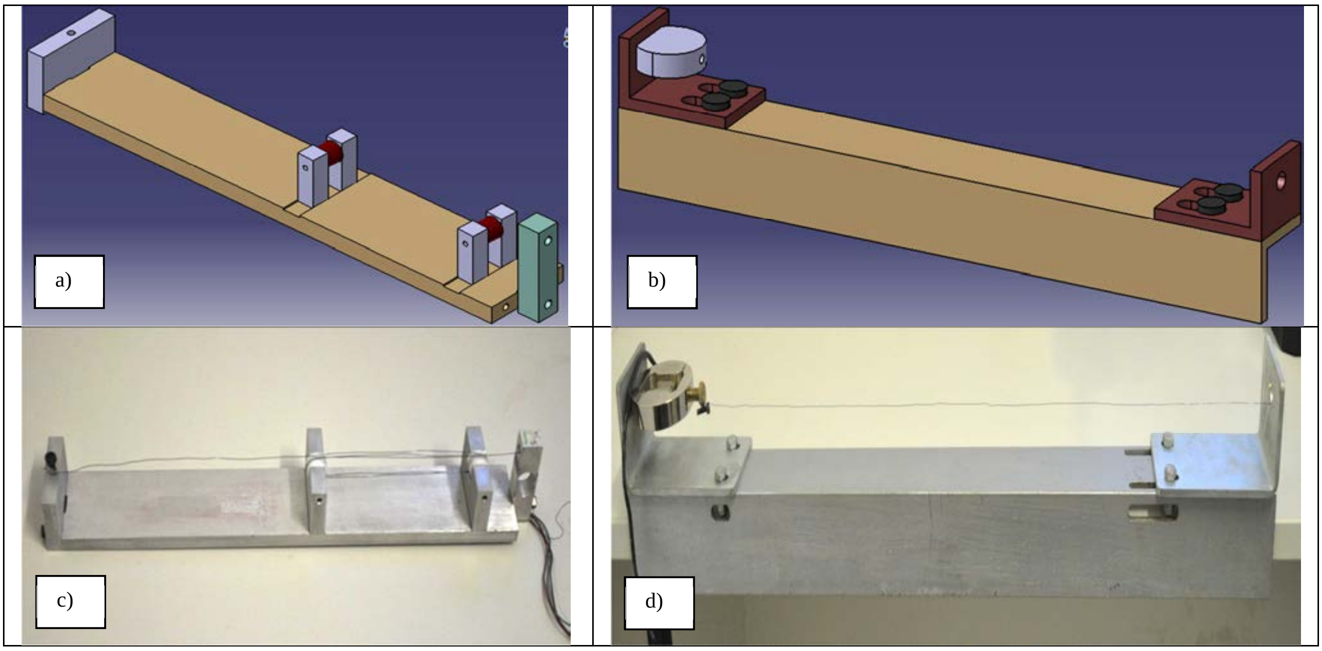

Figure 1. Frame of the experimental test bench. a) and c) system with pulleys, CAD design and photo of the fabricated bench respectively. b) and d)system without pulleys, CAD design and photo of the fabricated benchrespectively.

The mechanical structures of the test apparatus was manufactured in commercial aluminum. A load cell was placed at one end of the structure and an aluminum column in the opposite side for setting the SMA wire. To provide an electrical isolation, pulleys are manufactured in Teflon, given that the means adopted for heating the SMA wire actuator was through the passage of electrical current.

For this study, Ni-Ti SMA wires with 0.305 mm in diameter and 600 mm in length were supplied by Memory Metalle (Germany). This SMA Ni-Ti is named “alloy H”. Fig.(2) shows the phase transformation temperatures of the NiTi SMA wire measured by DSC (Differential Scanning Calorimetry). The M_f temperature is near 30 °C. Then, the transformation of Ni-Ti SMA wire can be only partial during the experiments, corresponding to the region between the R phase and austenite (Otsuka & Wayman, 1998; Lagoudas, 2008). Thus, the potential displacement by expansion and contraction of the Ni-Ti SMA wire actuator will be only partial.

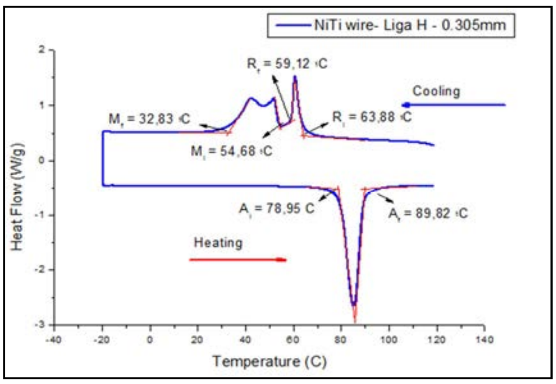

Figure 2. Phase transformation temperatures of the studied Ni-Ti SMA wire (alloy H).

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Figure (3) shows a schematic drawing of the complete experimental setup, which is composed by an analog-digital acquisition card made by National Instruments (1) (NI USB-6009), a printed circuit board (2, 7), a load cell (3), a mechanical frame to attach SMA wires under load (4) and a power supply (5) (Minipa 3303) for resistive heating and cooling of the SMA wire. A microcomputer (6) with Matlab® software in is used to drive the test system and store the measured data.

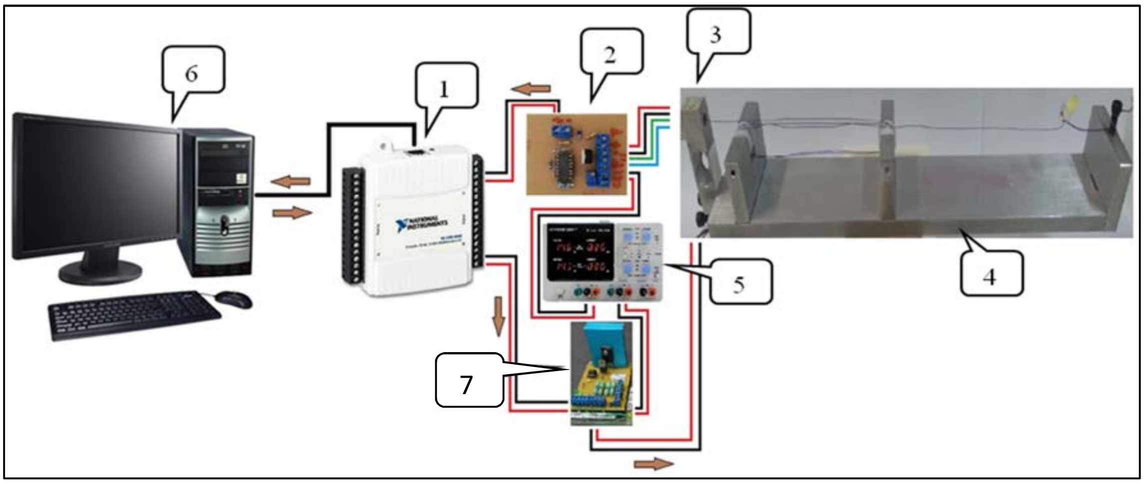

Figure 3. Experimental setup developed to determine the force response of SMA wires under load.

The acquisition card (1) receives the amplified signal (2) from the load cell (3), sending the signal to the computer (6). The computer sends back a signal to the acquisition card which forwards it to the amplifier circuit (7) and applies the necessary current to the SMA wire.

3. RESULTS AND DISCUSSIONS

The Ni-Ti SMA wire actuator was submitted to a training process for the apparition of the phenomenon of TWSME. The training consists of 1000 cycles of heating and cooling under a constant load corresponding to about 200 MPa. Figure (4) show the result of the tensile test performed on the Ni-Ti SMA wire to determine the maximum stress for training procedure. This stress level was chosen as one that leads to a strain of approximately 5%, corresponding toa region characterized by reorientation of martensite variants.

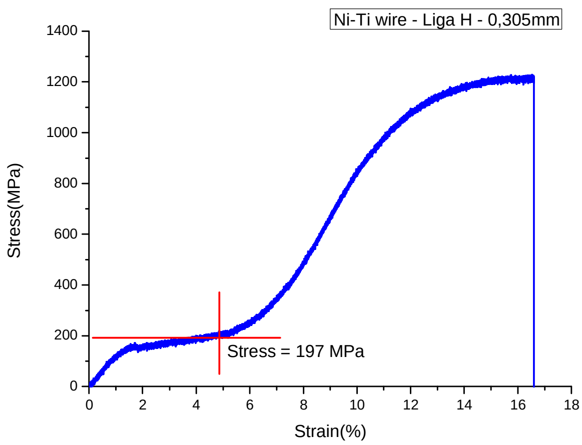

Figure 4. Stress vs strain behavior of the Ni-Ti SMA wire.

After training, the Ni-Ti SMA wire was installed in the experimental set up of Fig. (3) for force and displacement analysis. The tests were performed with the Ni-Ti wire and elastic coil spring fully stretched. For activation of the TWSME phenomenon, resistive heating was used by the passage of electric current through the SMA actuator.

The experiment was divided in two different configurations. The first one consists of coiling the SMA wire through pulleys, minimizing the setup size, as showed in Fig. (1a) and Fig. (1c); the other configuration consist of straining the SMA wire in line, as showed in Fig. (1b) and (1d).

3.1 System Without Pulleys

Figure 5 shows a step of current applied to the Ni-Ti SMA wire on the system without pulleys (Fig.1d), in order to verify the generated force. For this test, one end of the SMA wire was attached to a load cell and the other end was clamped. The aim of this first test was to determine the maximum load generated by the SMA wire actuator.

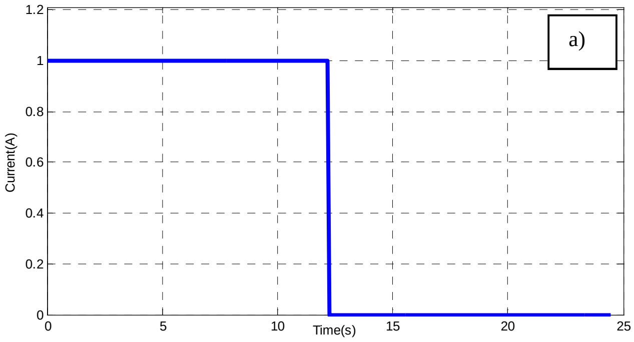

Figure 5. Current and force behavior of the SMA wire on the system without pulleys. a) Current vs. time. b) Force vs. time.

Figure 5(b) shows that the force generated when the SMA actuator wire has its extremities fixed, is about 17N. For verification of displacement, one end of the SMA actuator was fixed in the bench base and the other end was attached to an elastic spring. The spring used in this experiment has a stiffness of 46 N/m. To perform the measurement of displacement, a camera is used to monitor a certain point on the elastic spring; image processing is used to calculate the displacement from the starting point to the current point..

Figure 6shows the displacement produced by the Ni-Ti SMA wire working against the elastic coil spring.

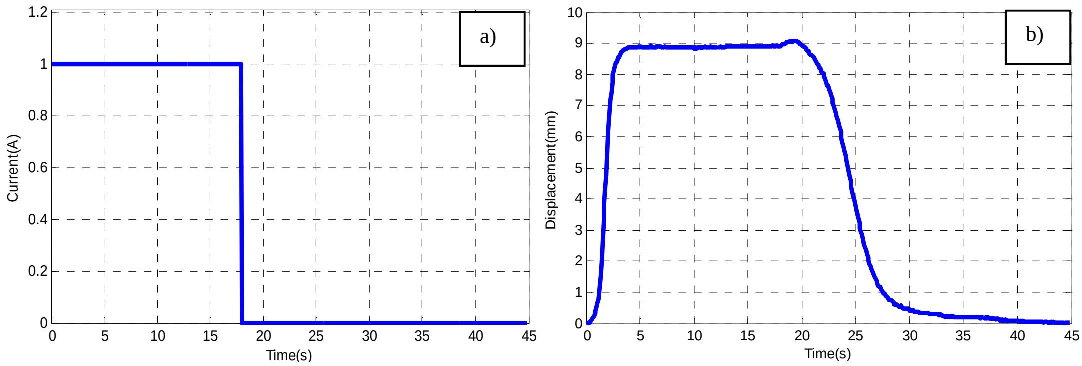

Figure 6. Current and displacement behavior of the SMA wire on the system without pulleys. a) Current vs. time. b) Force vs. time.

It was found that the SMA wire free system, or completely stretched, attains a displacement of 9 mm, corresponding to 1.5% of strain in relation to the initial length of the actuator wire.

3.2 System With Pulleys

Figure (7) shows a step of current applied to the Ni-Ti SMA wire on the system with pulleys Fig. (1c), with the objective of verifying the generated force in the coil configuration. For this test, one end of the SMA wire was attached to a load cell and the other end was fixed in the developed mechanics base, in order to have the maximum load of the SMA wire for this configuration.

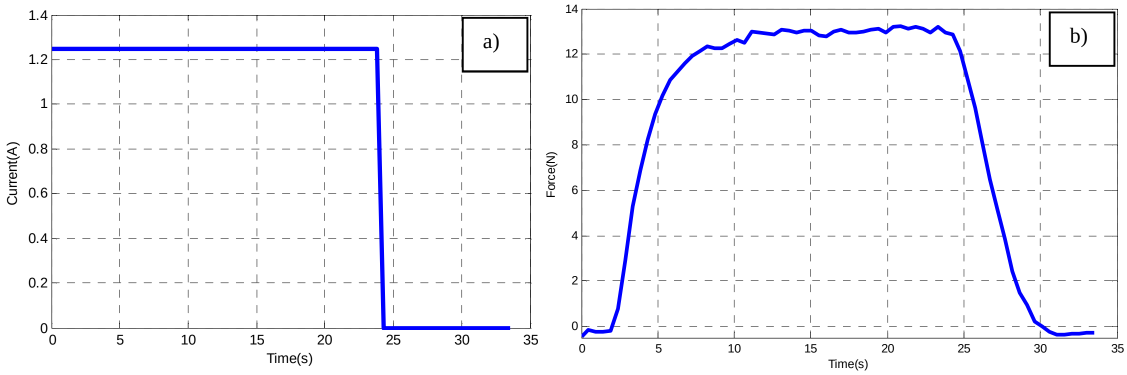

Figure 7. Current and force behavior of the SMA wire on the system with pulleys. a) Current vs. time. b) Force vs. time.

It is possible to observe from Fig.(7b) that the maximum force generated by the Ni-Ti actuator wire is about 13N.

For verification of the displacement, one end of SMA actuator was attached at the base of the bench and the other end fixed in an elastic spring. Figure (8) show the step current of 1 A and the corresponding displacement produced by the SMA wire.

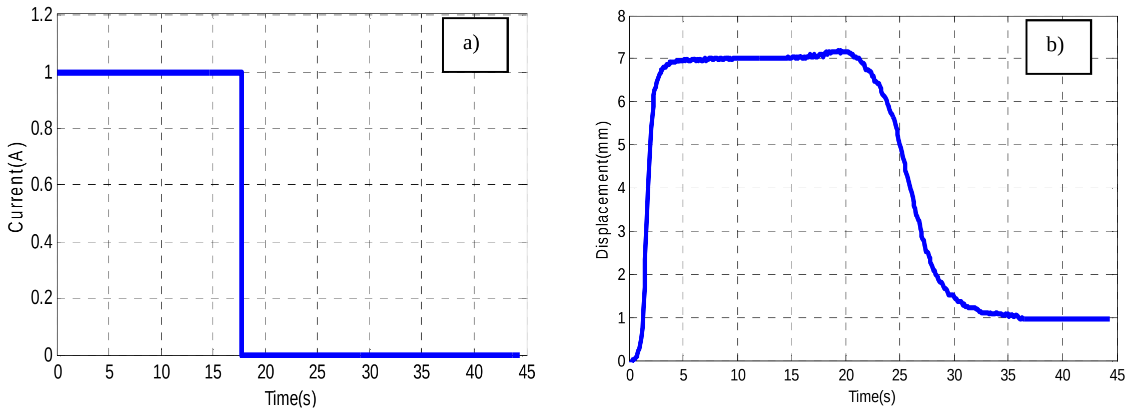

Figure 8. Current and displacement behavior of the SMA wire on the system with pulleys. a) Current vs. time. b) Force vs. time.

It was found that the SMA wire under conditions imposed by the system with pulleys, has achieved a displacement of the order of 7 mm. This displacement represents a contraction of 1.16% in relation of the initial length of the SMA wire. Based on the calculation of the spring stiffness, it was found that the force which would be acting on the spring system, of about 0.41 N.

In order to determine the magnitude of the friction generated by the system with pulleys, it was performed a test with one end attached to the spring and the other end attached to the load cell.

Figure (9) shows the measured force when an elastic spring is inserted. As in this test the system with pulleys was placed on one end of the elastic spring, the expected result that the load cell would receive the force of the spring. However, friction in the pulleys seems to be quite significant. The force exerted by the spring is approximately 0.41 N and load cell measured a force of 1.5 N. It can be concluded with this that system with pulleys generates a frictional force of about 1.1 N.

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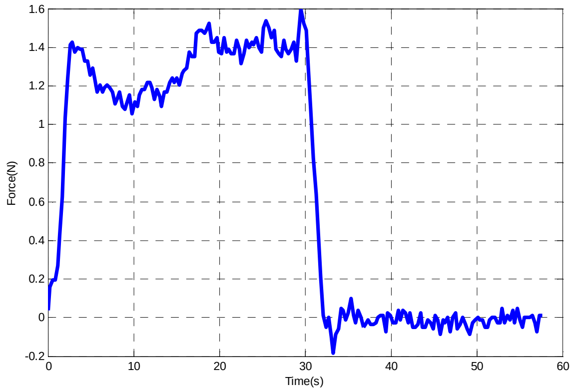

Figure 9. Force generated by the system with pulley.

3.3 Development of a Fuzzy Controller

In this section it was developed a fuzzy logic based controller to control only the force exerted by the SMA wire system with pulleys developed previously. The control applied to the SMA wire actuator was based on the theory of fuzzy controllers. Using this theory into controllers we can control a nonlinear plant without knowing its mathematical model.

For the design of the fuzzy controller is taken as input variables of the system the error between the reference force and the actual force assumed by the SMA wire (ER), and the rate of change of the error (ΔER). As output variable was adopted voltage that excites the current amplifier that makes heat the SMA wire (V). Furthermore, it was assumed that the fuzzy sets for these variables, ER and ΔER, are represented by seven linguistic qualifiers: NB - big negative, NM - average negative, NS - small negative, ZE - Zero, PS - positive small, PM - positive medium and PB - positive big. For the variable controller output (ΔV), it was assumed nine linguistic terms: NBG - very large negative, NB - negative big, NM - negative medium, NS - negative small, ZE - Zero, PS - positive small, PM - positive average PB - positive big and PVB - very large positive.

The method adopted was the Mamdani fuzzy. The choice of this method was given due to its large application and ease of use. To develop the rule base, it was taken as starting point a table found in the literature (Simões & Shaw, 2007) and some adjustments were made. The resulting rule base can be visualized in Table (1).

Table 1 - Base rules applied to the fuzzy control of forces in the SMA wire system with pulleys.

		Error						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
Change-in-Error	**NB**	NVB	NVB	NS	PS	NS	ZE	ZE
	NM	NVB	NVB	NS	PS	ZE	NS	ZE
	NS	NVB	NB	NS	ZE	PS	ZE	ZE
	ZE	NB	NM	NS	ZE	PS	NS	PS
	PS	NM	NS	NM	ZE	ZE	PVB	PVB
	PM	NS	NS	NS	ZE	ZE	PVB	PVB
	PB	ZE	NM	ZE	PS	PS	PS	PVB

The set of membership functions of the fuzzy control system represents the fundamental aspects of all theoretical and practical actions. A membership function is a, graphical or tabular function numerical, which assigns fuzzy membership values to discrete values of a variable in their universe (Simões &Shaw, 2007). It is necessary to define the shape of each membership function for each variable of the system, taking into account the context in which they are used in the representation of linguistic variables. In this sense, the format selected to the function should be chosen based on knowledge of the process to be studied. In the design of this controller, it were used for the input variables five triangular and two trapezoidal functions and for the output variable seven triangular and two trapezoidal functions, as can be observed in Fig.(10). These functions have been adopted because of a prior knowledge of the system.

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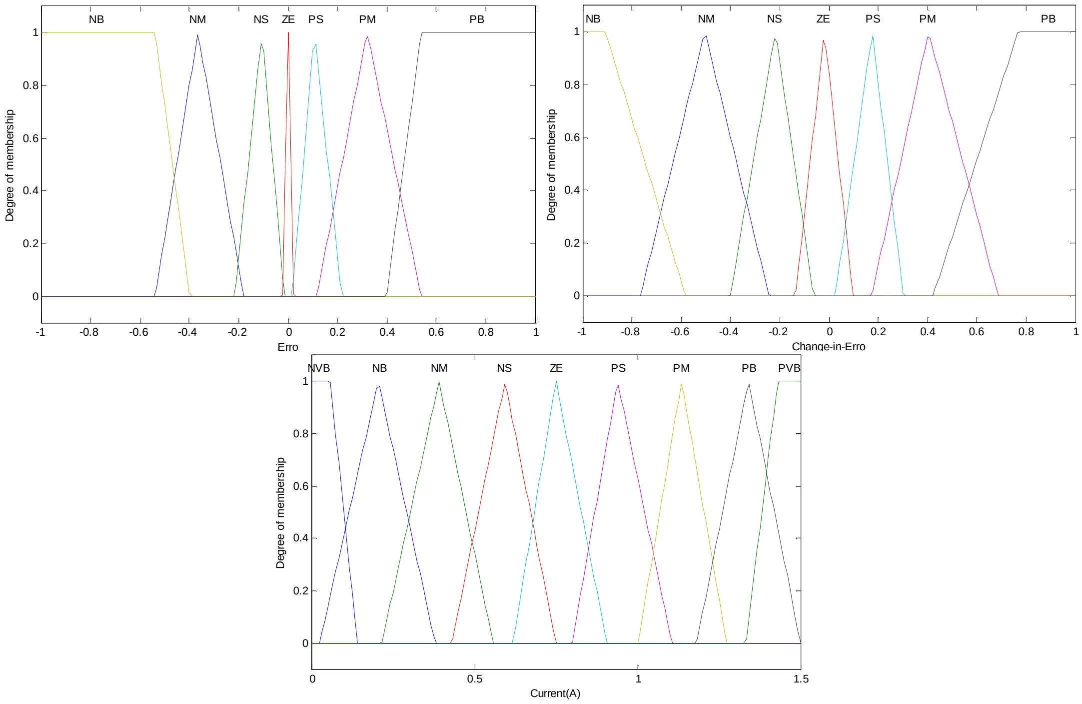

Figure 10. Fuzzy membership functions for each variable set.

Based on the result shown in Fig.(7), it can be checked the amplitude reached by the wire in this configuration, providing data for implementing the fuzzy controller. Figure (11) shows some results for the performance of the fuzzy control applied to the SMA wire pulley system.

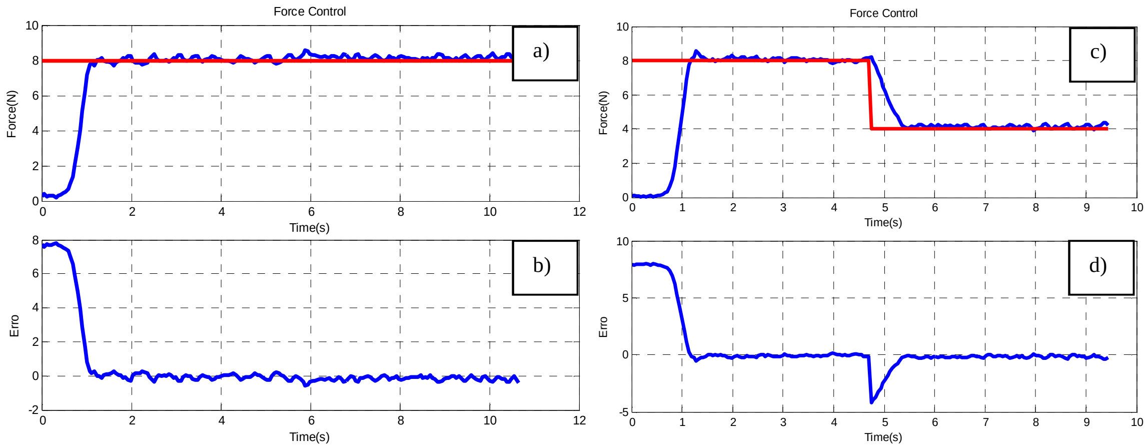

Figure 11. Force control closed loop. a) Desired force vs. measured force in the SMA wire. b) Percentage error of the fuzzy control. c) Two steps of desired force vs. measured force. d) Percentage error of the fuzzy control.

Figures (11a) and (11c) show that the rise time is approximately 1.2 s and the settling time is close to 2s. The error pointed out in Figs (11b) and (11d), for the steady state was of the order of 0.3 N in relation to the reference.

4. CONCLUSIONS

In this paper it was presented a comparison between two different setups with Ni-Ti SMA wire in order to investigate the force and displacement behavior. A pulley system to accommodate a relative amount of SMA wire was constructed and the comparative tests were performed with the same amount of SMA wire fully extended.

Based on the results presented, it can be concluded that the SMA pulley system has a lower performance on the displacement of approximately 22% with respect to strength, approximately 24%. Furthermore, the system with pulleysconfiguration causes a high frictional force on the pulley. However, even with these limitations, the pulleys system can be considered viable when it is necessary a lot of wire and there is just little space in the project. The presented results show that it possible apply the fuzzy control on some similar project where force control is need.

5. ACKNOWLEDGEMENTS

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