ANFIS Modeling and Feedforward Control of Shape Memory Alloy Actuators

Ayyoub Rezaeeian, Aghil Yousefi-Koma, Behrouz Shasti, and Alireza Doosthoseini

Abstract— This paper focuses on the application of ANFIS in the modeling of nonlinear behavior of the shape memory alloy actuators. Although, SMA actuators have attracted much attention for applications in several areas such as miniature robots they have not been widely employed for motion control applications due to their nonlinear behaviors and control difficulties. Because of their ability in the nonlinear learning and adaptation, ANFIS architectures are suitable tools in modeling and control of nonlinear systems. The experimental test bed includes a SMA wire, a force sensor, data acquisition system and a power amplifier. Results demonstrate the ability of ANFIS in modeling of shape memory alloy behavior and successful force control of the SMA wire.

Keywords— ANFIS, SMA, Force control, Inverse model, Feedforward control

I. Introduction

Nonlinear modeling based on fuzzy logic is an effective approach owing to its ability to model complexity and uncertainty. In shape memory alloys (SMAs), hysteresis is a nonlinear phenomenon that poses difficulties for controlling these alloys. In recent years, various researches have been designed to model and control these alloys. S. Tafazoli, M. Leduc, X. Sun [1] have used fuzzy subtractive clustering for hysteresis modeling. A.R. Mehrabian, S.V. Hashemi, E. Williams, M. Elahinia [2] have modeled shape memory alloy hysteresis using the two fuzzy partitioning algorithms, Gustafson-Kessel and Locally Linear Model Tree (LoLiMoT), and then controlled SMA by fuzzy feedforward algorithm. J. Jayender, R.V. Patel, S. Nikumb, M. Ostojic [3] proposed a robust H_∞ loop shaping control for SMA actuators. They made a formulation based on physical concepts to model the SMA [3]. K.K.Ahn, B.K.Nguyen [4] have used a self tuning fuzzy PID controller to control the position of SMA. M.H. Elahinia, H. Ashrafiuon [5] designed a nonlinear, robust control algorithm based on variable structure control. O.E. Ozbulut, C. Mir, M.O. Moroni, M. Sarrazin, P.N. Roschke [6] have applied a fuzzy model of SMA to vibration control. A. Kumagai, T. Liu, P. Hozian [7] used a neuro-fuzzy model and a feedback controller to control the motion of SMA actuator. H. J. Lee, J. J. Lee [8] derived a dynamics for SMA actuator using the modified Liang's model and this model can be used for the prediction of control performance and gain tuning of the time delay control (TDC) [8]. E. A. Khidir, N. A. Mohamed, M. J. M. Nor, M. M. Mustafa [9] used system identification techniques and extracted a model for SMA actuator. Finally they applied an ON/OFF controller to control their actuator. M. H. Elahinia, M. Ahmadian [10] used an extended Kalman filter (EKF) to control a shape memory alloy arm. They demonstrate that their method is also applicable for other SMA actuators [10]. E. shameli, A. Alasty, H. Salaarieh [11] have suggested a PID-P^3 controller and showed that the new method is more efficient than PID controller. E. P. Da Silva [12] used a shape memory alloy as an actuator to control beam shape and for this purpose he applied a proportional controller.

Hysteresis modeling is implemented in other fields such as ferromagnetic systems. M. Mordjaoui, M. Chabane, B. Boudjema, H. Zaier [13] used neuro-fuzzy dynamic hysteresis model. They showed that their model produced reliable outputs with relatively small errors [13].

Recently, considerable efforts are being made to use SMA wires as actuators, mainly because of the small size of SMA wires. For example, the use of SMA wires to employ force in grippers is an interesting issue in recent researches [14]-[17]. The most important problem in this instrument is the force control. J.H. Kyung, B.G. Ko, Y.H. Ha, G.J. Chung [14] proposed a PI controller to verify the performance of their designed gripper. O. Rohani, A. Yousefi-Koma, A. Rezaeeian, A. Doosthosseini [18] designed a fuzzy PID controller to control the force of SMA wire. They showed that their controller is efficient for different input.

In this paper, an adaptive neuro fuzzy inference system (ANFIS) model is developed for hysteresis modeling of SMA

Manuscript received January 23, 2008; Revised Received June 13, 2008.

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actuator. Data acquired from an experimental setup is used to measure the force induced in SMA wire. Eventually a feedforward controller is applied to control the SMA wire.

II. A Brief Summary of SMA Properties

Shape memory alloys are metallic alloys that are able to recover strain. A typical SMA wire of 300μm diameter produces a maximum strain of 5 to 8% of its length [3]. In addition, SMA has several advantages such as large reliability, and clean and silent actuation [2]. The disadvantages of SMA are nonlinear behavior and hysteresis phenomenon. These disadvantages make its modeling and control very difficult.

In fact properties of SMA depend on phase transformation that occurs between martensite phase (at low temperature) and austenite phase (at high temperature). This change in phase causes the crystal structure to take a different form. Fig. 1 demonstrates the hysteresis loop in length of SMA wire versus its temperature.

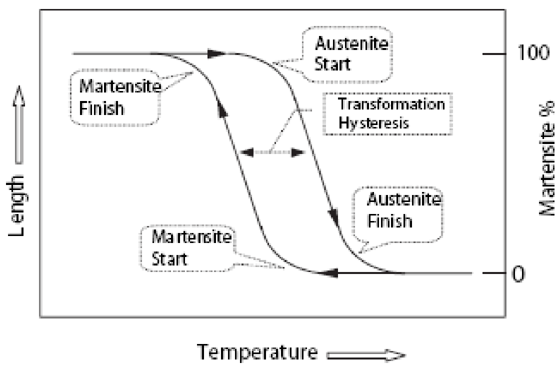

Fig.1. The hysteresis loop

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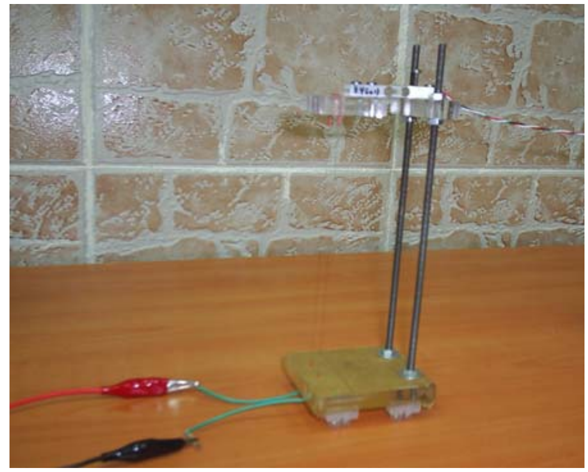
III. Experimental Setup

In this paper a load cell sensor is used to measure the force induced by SMA wire. The test bed that is implemented in this research is shown in Fig. 2. This setup includes a load cell sensor, data acquisition system, a power amplifier and a Nickel-Titanium wire. The specifications of SMA wire are 32cm length, 37.8Ω resistance and 0.1mm in diameter. The details of experimental setup are shown in Fig. 2, 3. In this paper two computers are used: one of them is the host computer and the other is the target computer, which are shown in Fig. 2.



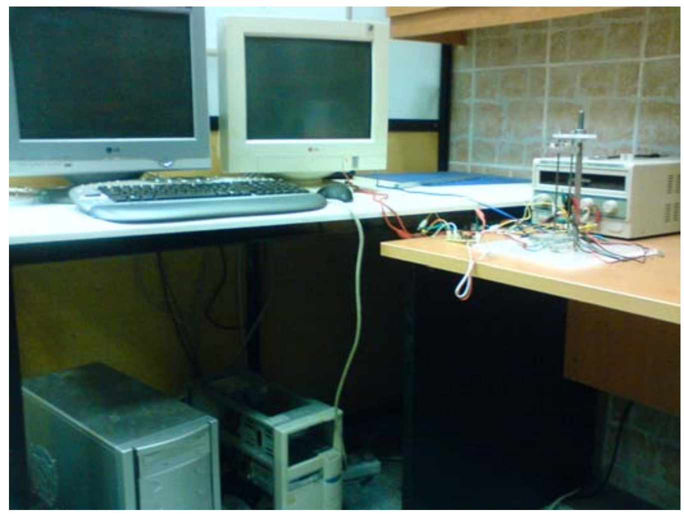
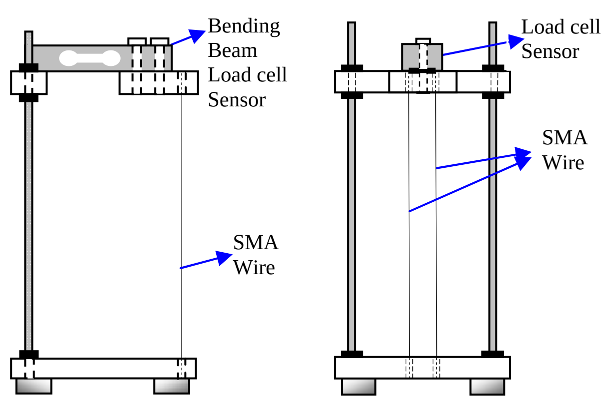


Fig.2. The experimental test bed



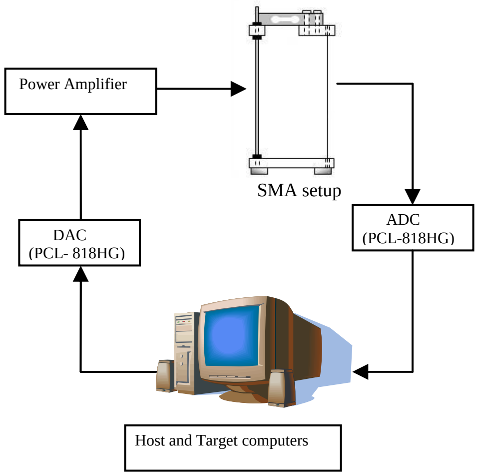


Fig.3. Schematic experimental setup

When the SMA wire is heated, it tends to be shortened. However it is impossible because the wire is clamped at two ends. As a result the wire produces a force and load cell senses it. When the SMA wire is cooled, this force will be vanished.

MATLAB XPC Target toolbox and D/A data acquisition system have been used to record this data.

Notice that the input of SMA wire is voltage and output is force measured by load cell. To use the load cell, the relationship between voltage and force is needed. This relationship is:

$$F = 6.966V + 0.0833 \tag{1}$$

IV. Overview of Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS is a class of adaptive networks that act as a fundamental framework for adaptive fuzzy inference systems [19]. Fig. 4 shows the ANFIS architecture. For sake of simplicity, we suppose our FIS has two inputs x and y and one output z; every input has two fuzzy sets A_1, A_2 and B_1, B_2. Notice that in Fig. 4, each circle shows a fixed node, whereas every square indicates an adaptive node. So the rule base system has two if-then rules of Takagi-Sugeno's type as:

$$\begin{aligned} &\text{Rule i : If } x \text{ is } A_i \text{ and } y \text{ is } B_i, \\ &\text{then } f_i = p_i x + q_i y + r_i \end{aligned} \tag{2}$$

i=1,2

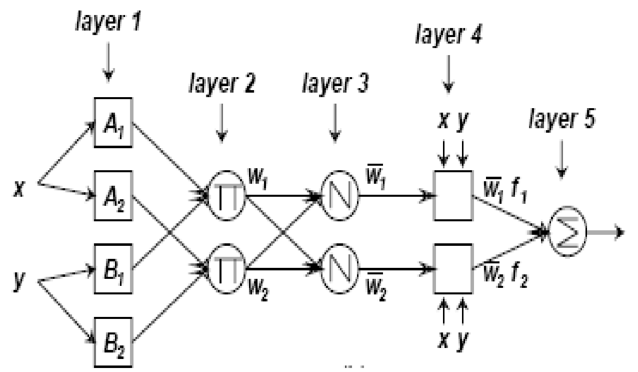


Fig.4. ANFIS architecture

Where f_i is output and p_i, q_i and r_i are the designed parameters that were assigned during the training algorithm of ANFIS.

Output of each node in every layer is denoted by O_i^l where *i* specifies the neuron number of next layer and *l* is the layer number. The performance of each layer is as follows:

A. Layer1

Each node in this layer is an adaptive node and outputs of these nodes are given by:

$$\begin{aligned} &O_i^1 = \mu_{A_i}(x) \\ &O_i^1 = \mu_{B_i}(x) \\ &\mathrm{i} = 1,2 \end{aligned} \tag{3}$$

Where $\mu_{A_i}(x)$ and $\mu_{B_i}(x)$ are membership functions that determine the degree to which the given x and y satisfy the quantifiers A_i and B_i.

B. Layer2

In this layer, each node is a fixed node that determines the firing strength of related rule.

$$O_i^2 = \omega_i = \mu_{A_i}(x)\mu_{B_i}(y) \tag{4}$$

C. Layer3

In this layer, every node is a circle node which computes the ratio of firing strength of each rule to the sum of all of them; the so-called normalized firing strength.

$$O_i^3 = \overline{\omega}_i = \frac{\omega_i}{\omega_1 + \omega_2} \tag{5}$$

D. Layer4

The output of each adaptive node in this layer is:

$$O_i^4 = \overline{\omega}_i f_i = \overline{\omega}_i(p_i x + q_i y + r_i) \tag{6}$$

Parameters p_i, q_i and r_i are called as consequence parameters.

E. Layer5

Final layer, presented with a circle node, computes the summation of all incoming signals.

$$O_i^5 = \frac{\sum_{i=1}^{2} \omega_i f_i}{\sum_{i=1}^{2} \omega_{ii}} \quad (7)$$

V. HYBRID LEARNING ALGORITHM

In order to improve the training efficiency, a hybrid learning algorithm is applied to justify the parameters of input and output membership functions. The antecedent parameters (the parameters related to input membership functions) and the consequent parameters (the parameters related to output membership functions) are two parameter sets in the ANFIS architecture which should be tuned. When we suppose that premise parameters are fixed, then the output of ANFIS will be a linear combination of the consequent parameters. So, the output can be written as:

$$f = \overline{\omega}_1 f_1 + \overline{\omega}_2 f_2 \quad (8)$$

With substituting Eq. (6) in Eq. (8), the output can be rearranged as:

$$f = (\overline{\omega}_1 x)p_1 + (\overline{\omega}_1 y)q_1 + (\overline{\omega}_1)r_1 + (\overline{\omega}_2 x)p_2 + (\overline{\omega}_2 y)q_2 + (\overline{\omega}_2)r_2 \quad (9)$$

So, the consequent parameters can be tuned by the least square method.

On the other hand, if consequent parameters are fixed, the premise parameters can be adjusted by the gradient descent method.

ANFIS utilizes hybrid learning algorithm in which the least square method is used to identify the consequent parameters in forward pass and the gradient descent method is applied to determine the premise parameters in backward pass.

VI. ANFIS MODELING OF SMA WIRE

The SMA wire has two completely separate paths. This property is shown in Fig. 1. For modeling these behaviors, an input is applied to SMA wire and the system response is achieved. Figs. 5, 6 depict the input and the corresponding output. Low pass digital filter is designed in order to remove the significant noise coming from the load cell sensor. The filter performance is showed in Fig. 5.

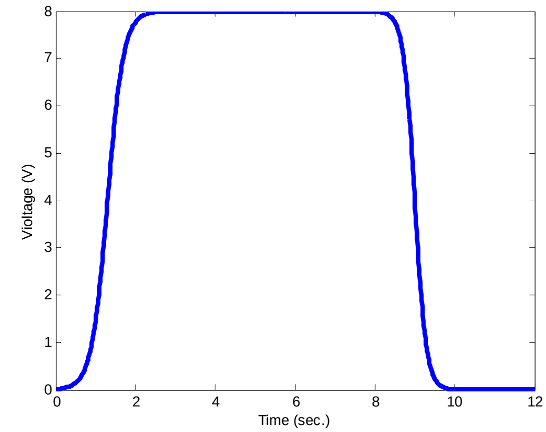


Fig.5. The input voltage

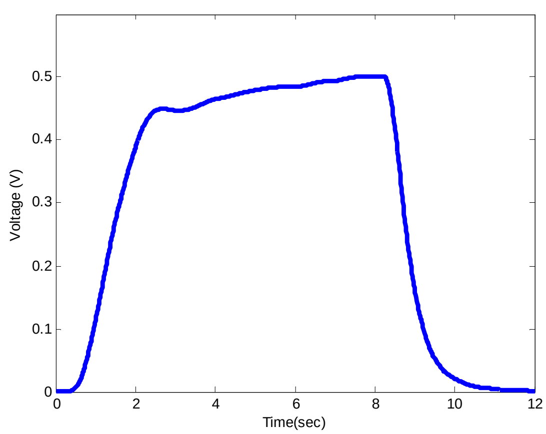


Fig.6. Response of SMA wire

Relationship between the input and output signals can be extracted by following steps:

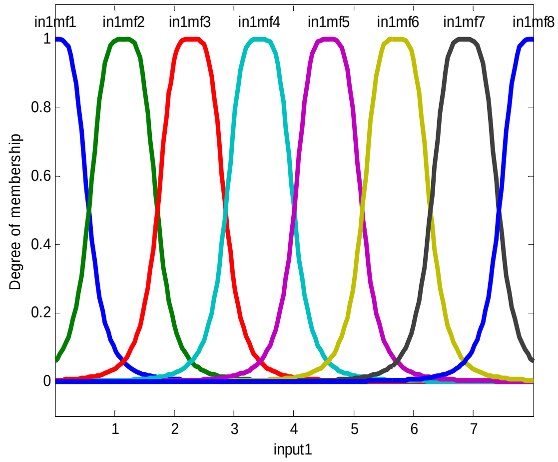
To sample input and output data as accurate as possible

To train the dynamical model

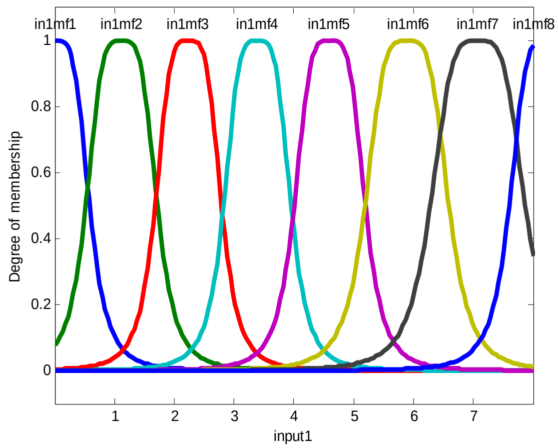
To validate the training model

Training data, checking data, and testing data are three different data sets necessary for training ANFIS. The training data is the input/output sets that are the expected input and output data of ANFIS but checking data is used to test the generalization ability of the fuzzy inference system established by the training data.

The ANFIS structure shown in Fig. 4 was simulated by using MATLAB software package that uses 600 training data, 200 checking data and 200 testing data and the step size parameter adaptation of ANFIS value is 0.1. In this model 8 bell-shaped membership functions are used. Fig. 7 displays membership functions before and after ANFIS modeling. Fig. 8 helps us to choose the enough number of epochs. In fact the epoch where the checking error goes away from the training error is sufficient, because afterward the training will be overflowed. So it is obvious that suitable number of epochs is less than 50.



(a)



(b)

Fig.7. Initial (a) and final (b) generalized bell shaped membership function

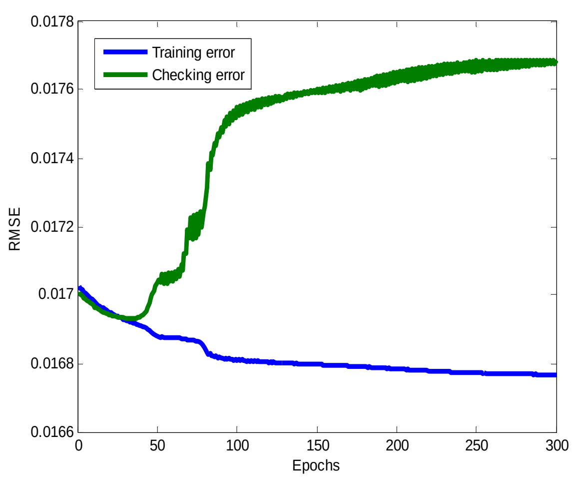


Fig.8. ANFIS performance (model of plant)

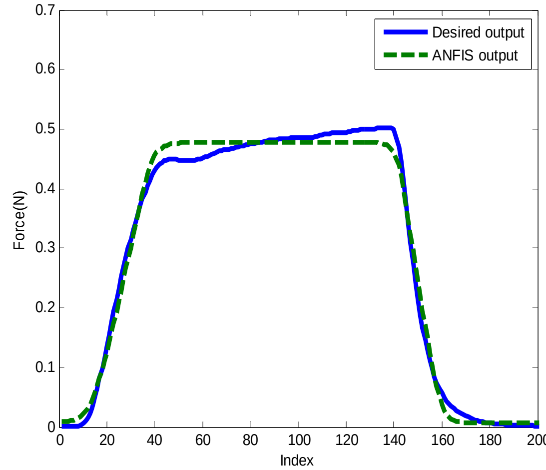
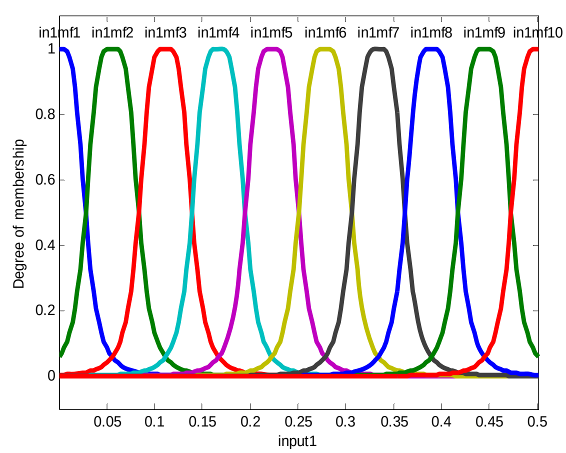


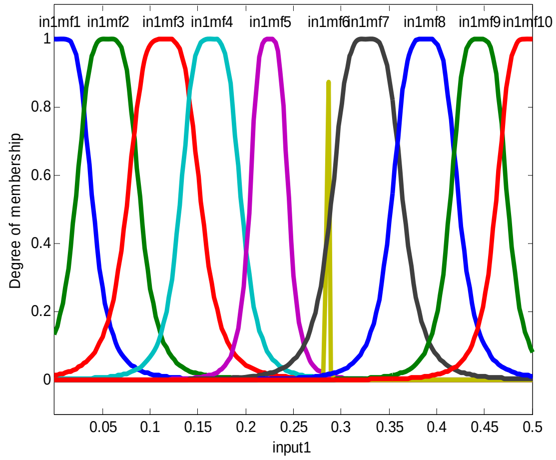
Fig.9. ANFIS output and desired curve (model of plant)

VII. Development of the ANFIS Inverse Model

In this section, we discuss the procedure by which the inverse model of the SMA wire is determined to develop an inverse controller. 600 training data, 200 checking data and 200 testing data are used for developing the ANFIS inverse model. The inverse modeling procedure is very similar to the SMA modeling procedure discussed in the previous section. The results for this part are shown in Fig. 10-12. The bell-shaped membership functions before and after training the inverse model are shown in Fig. 10. Fig. 11 depicts the suitable number of epochs selected similar to the previous section.



(a)



(b)

Fig.10. Initial (a) and final (b) generalized bell-shaped membership function

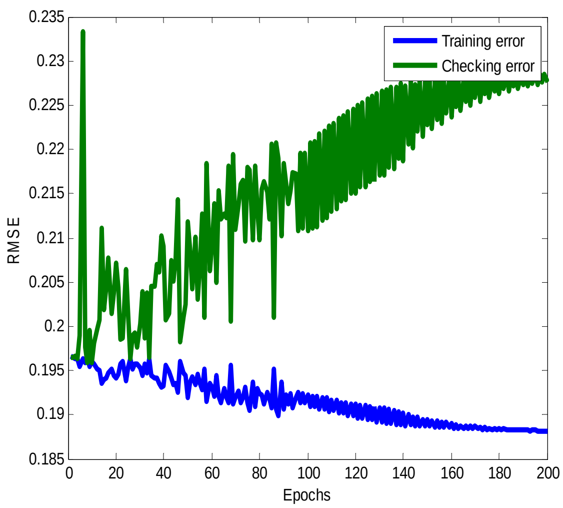


Fig.11. ANFIS performance (inverse model)

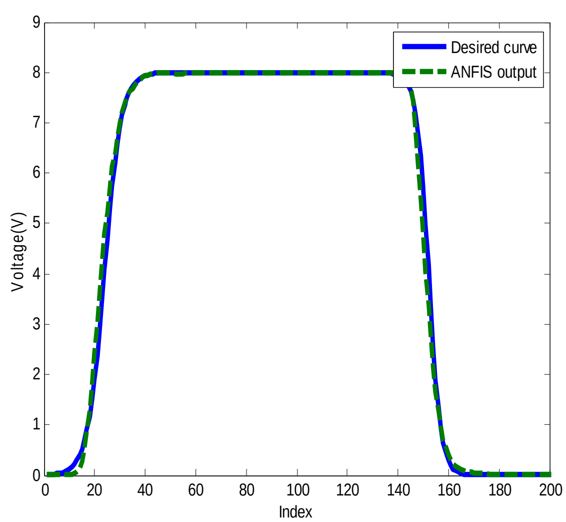


Fig.12. ANFIS output and desired curve (inverse model)

VIII. Results of Feedforward Control

The performances of the developed ANFIS forward and inverse models are tested in SIMULINK/MATLAB. In fact the inverse-model employed as a controller, is put in series before the ANFIS model of SMA wire. The desired force signal is sent into the inverse model and the resulting output is fed as voltage signal into the SMA wire.

The desired force is a sinusoidal signal, and its comparison with the actual force is shown in Fig. 13. It can be clearly seen that the inverse-ANFIS-model is able to control the behavior of the SMA wire although there are relatively small errors in maximums and minimums.

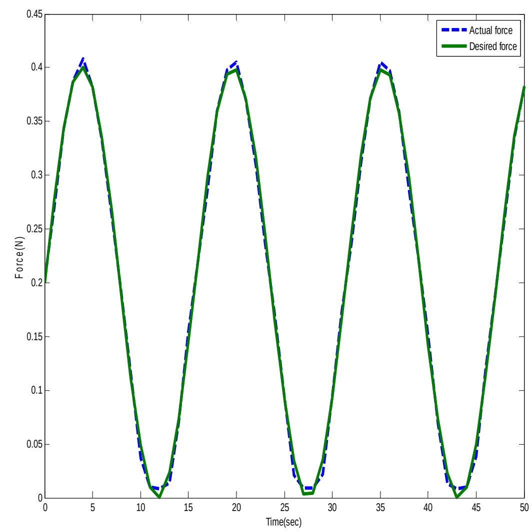


Fig13. Desired and actual force in simulations

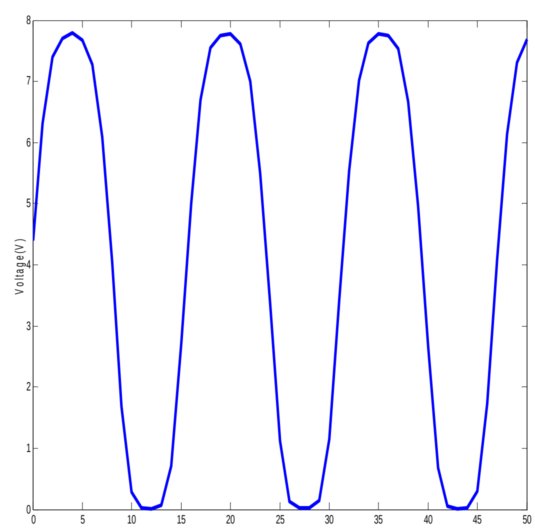


Fig.14. Applied voltage with ANFIS feedforward controller

IX. Conclusion

The nonlinear effect of SMAs makes their force control a challenging task. In this paper an experimental setup is developed to acquire the precise force data in a SMA wire. The experimental set up includes a SMA wire, a force sensor, a data acquisition board (PCL818HG) and XPC target Toolbox of MATLAB6, two computers (one of them is the host computer and the other is target computer). Hybrid learning algorithms of ANFIS, least squares method and gradient descent method, are employed in this study.

A neuro-fuzzy dynamic model is adopted as the controller and a feedforward ANFIS controller has been applied in this paper. Simulation results indicated that ANFIS was able to produce reliable outputs with relatively small errors. Consequently, the dynamic model can be easily used in systems with nonlinear behavior, particularly in force control.

Acknowledgment

The authors would like to thank Mr. S. Karbasi of the Electrical Engineering Department of the Tarbiat Moddares University for the design of the electrical circuits.

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