Chapter 8
Enhanced Adaptive Controller Applied to SMA Wire Control

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8.1 Introduction

Besides the mainly verified or validated properties of the modeling approaches of the SMA focusing to the modeling of the different observed effects, all these SMA models lack the applicability in different engineering applications and in the control of the SMA since they don't describe a general behaviour of any SMA type or shape; idealizing the material constants and thereby disallowing their application into different systems, and into different applications scenarios and also for model-based control design purposes. However, if an SMA wire within a control loop is replaced by another SMA wire with new properties, or with an SMA plate, etc. those mathematical models may be in detail weak to perform the control task as they lack generalization properties from an engineering point of view, and weak in understanding this actuator material behavior as an I/O-system with structured behavior. Model-based control approaches may allow in combination with suitable design approaches the design and the realization of robust control algorithms and therefore the general usage of the SMA not only to be used as actuator but also for application where the shape memory effect should not be used i.e. the actuation where the inverse model can cancel the expected behaviour of the SMA, therefore it is an open research topic as far as no SMA generalized behavioural based model exit (Ghanem 2010). Non-Model-based control systems are limited to the usage of the SMA as actuators in applications and need tuning for its procedures any time the material physical characteristics are changed. As a result, non-model-based adaptive control approaches in the position control of the SMA is of vital importance to be studied (Ghanem 2010; Ghanem et al. 2010).

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The adaptive approaches in control theory performs a redesign of the controller in accordance to the changing parameters of the plant. Adaptive control is a good choice in the shape memory alloy (SMA) wire actuator plant case. This is because control of SMA is a hard process due to the non-linearity exhibited by the SMA material. That is, the hysteretic behavior of the material causing the shape memory effect exhibited within it. However, methods used for controlling the position of the SMA lacks the simplicity and the adaptability to the SMA characteristics since environmental changes influence the characteristics of the SMA (Ghanem 2010; Reynolds 2003; Chirani et al. 2003; Bouvet et al. 2004; Dutta et al. 2005; Teh and Featherstone 2003; Song et al. 2003; Bizdoaca et al. 2006; Benzaoui et al. 1999; Silva 2007).

The proposed adaptive controller is derived through mathematical equations of the MRAC and STC adaptive control (Ghanem et al. 2010; Slontine and Li 1999). The concept of PID classical control functionality was used to let the PID proportional, integral, and derivative Kp, Ki, and Kd parameters respectively to be used as the estimator parameters or the adaptation parameters of the adaptive controller proposed.

The enhanced version of adaptive controllers that can be used to control linear or non-linear plants will be derived step by step, the robustness of this controller has been evaluated through a hard control problem which is the SMA wire, however, this adaptive controller can be used to tune the PID parameters giving more robust solutions; i.e. real time adaptive tuning, such that the parameters fit the plant in an easier way than using other well known tuning procedures in control.

The chapter will firstly introduce the basic two approaches of adaptive control used in the derivation of this adaptive controller, then it will discuss the shape memory alloy wire position control using the designed PID adaptive controller, a tuned PI controller, and the experimentally enhanced version of the adaptive controller. Finally, the experimental results of the enhanced adaptive controller and the tuned PI controller under different sets of actuation frequencies will be evaluated.

8.2 Adaptive Control Approaches

Since adaptive control performs a redesign of the controller in accordance to the changing parameters of the plant, adaptive control is a good choice in the application of SMA wire actuator plant control.

The next sections will introduce the basic two approaches of adaptive control that leads to the way how the PID adaptive controller is derived and tested on the SMA wire.

8.2.1 MRAC Control

Model reference adaptive controller basic principle is to build a reference model that specifies the desired output of the controller, and then the adaptation law adjusts the unknown parameters of the plant so that the tracking error converges to zero (Slontine and Li 1999).

8.2.2 STC Control

Self tuning adaptive controller basic principle of is to have a parameter estimator that estimates recursively the unknown parameters of the plant and feeds it to the controller. This recursive estimation based on the parameters that fit the past input-output criteria of the plant (Slontine and Li 1999).

8.3 Adaptive Control with Combined MRAC And STC

A combined approach that joins MRAC and STC will be introduced in building a PID adaptive controller. The reason for calling this approach a combined approach, is that the estimated parameters will be the controller parameters; which will adapt to the plant unknown parameters recursively like in STC, while the tuning will be according to the tracking error convergence to zero like in MRAC, since the reference model here is the plant itself, and that is the basis for calling the SMA actuator as the SMA actuator plant.

The equations corresponding to the MRAC controller for a first order plant are the following:

$$v(t) = [r \quad y]^T$$

where $v(t)$denotes the signal vector, r is the reference input signal, and y is the output signal.

$$\hat{a}(t) = \begin{bmatrix} \hat{a}_r \\ \hat{a}_y \end{bmatrix}.$$

where $\hat{a}(t)$ is the vector of the controller adaptive parameters; defined by their derivatives in terms of plant parameters to derive the adaptation law as follows:

$$\begin{aligned} \dot{\hat{a}}_r &= -sgn(\mathrm{b}_p)\gamma er \\ \dot{\hat{a}}_y &= -sgn(\mathrm{b}_p)\,\gamma ey \end{aligned} \tag{8.1}$$

where, $\dot{\hat{a}}_r$ is the derivative of the estimated parameter corresponding to the reference signal r and $\dot{\hat{a}}_y$ is the derivative of the estimated parameter corresponding to plant output signal y, e is the error signal, *sgn(bp)* determines the direction of search for the proper controller parameter, and γ is the adaptation coefficient.

8.3.1 Building an Adaptive Controller

Choose the position as the estimated parameter and the position error as the second estimated parameter. Let the signal vector be:

$$v(t) = \begin{bmatrix} e & y \end{bmatrix}^T$$

Here ***e*** is the position error, and ***y*** is the actual position.

Let the controller estimated parameters be:

$$\hat{a}(t) = \begin{bmatrix} \hat{a}_s \\ \hat{a}_y \end{bmatrix}$$

Where $\hat{a}_s$ is the estimated parameter corresponding to error signal, and $\hat{a}_y$ is the estimated parameter corresponding to actual position signal, then the adaptation law is the following:

$$\begin{aligned} \dot{\hat{a}}_s &= -sgn(\mathrm{b}_p)\gamma e^z \\ \dot{\hat{a}}_y &= -sgn(\mathrm{b}_p)\gamma ey \end{aligned} \tag{8.2}$$

Substitute b_p as 1 since there is no transfer function for the SMA wire dynamics to build the controller.

8.3.2 Building the PID Adaptive Controller

Using the error signal as one of the signals used for adaptation helps the controller to react. And since there is no equation expressing the plant dynamics, to build a PID adaptive controller the assumption will be to use the controller parameters as the estimated parameters of the plant; while this will help the PID controller to self-tune itself; which is a combined approach of MRAC and STC. Figure 8.1 shows a block diagram describing the idea.

In Fig. 8.1., $e(t)$ denotes the error signal; which equals the desired position subtracted from the actual position of the SMA to insure convergence of the error to zero, like in MRAC. The reference model of the MRAC is the plant itself; the adaptation coefficients are the estimator coefficients of the STC to let the PID adapt its controller coefficients to the plant. The block attached to the PID is a block to explain that the output of the controller is converted using blocks that derive the current into the SMA wire. Based on the formulas of regular PID controllers, the idea in Fig. 8.1 is that the $\dot{\hat{k}}_p$, $\dot{\hat{k}}_i$, and $\dot{\hat{k}}_d$ are the estimated parameters of the plant

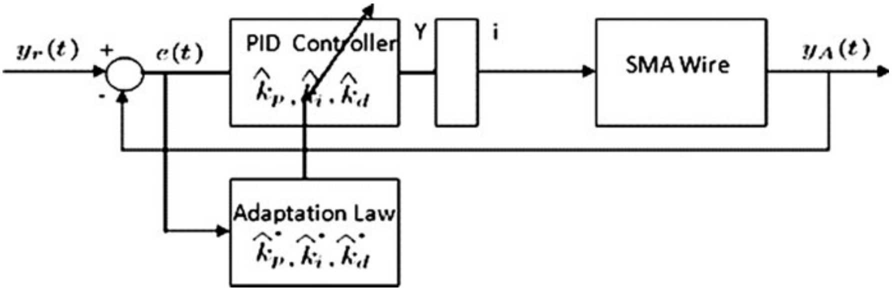


Fig. 8.1 The PID adaptive controller combined MRAC and STC

while they are recursively tuning their corresponding controller parameters as well with the following adaptation law, so that the PID controller coefficients are just the integral of the adaptation law.

$$\dot{\hat{k}}_p = -\gamma e^2 \qquad \Rightarrow \ \hat{k}_p = \int -\gamma e^2 dt.$$

$$\dot{\hat{k}}_i = -\gamma e \int edt \Rightarrow \hat{k}_i = \int -\gamma e \int edt \ dt.$$

$$\dot{\hat{k}}_d = -\gamma e \frac{de}{dt} \qquad \Rightarrow \ \hat{k}_d = \int -\gamma e \frac{de}{dt} dt. \tag{8.3}$$

$\hat{k}_p$ is the proportional gain, $\hat{k}_i$ is the integral gain, $\hat{k}_d$ is the derivative gain. While $\dot{\hat{k}}_p$ is the proportional estimated parameter, $\dot{\hat{k}}_i$ is the integral estimated parameter, and $\dot{\hat{k}}_d$ is the derivative estimated parameter. So the integral form of the estimated vector is:

$$\hat{a}(t) = \begin{bmatrix} \hat{k}_p \\ \hat{k}_i \\ \hat{k}_d \end{bmatrix}$$

And the signal vector corresponding to each of them like normal PID controller signals as follows:

$$v(t) = \begin{bmatrix} e(t) & \int e(t)dt & \frac{de(t)}{dt} \end{bmatrix}^T.$$

$$e(t) = y_A(t) - y_r(t)$$

where $y_A(t)$ is the actual position of the SMA wire and $y_r(t)$ is the desired position. The output of the PID Controller will be the following sum of the proportional, integral, and derivative outputs:

$$Y(t) = \sum \beta(i)$$

To simplify the representation of equations in time domain, the s-domain will be used. Where an integral is a division by s, and a derivative is a multiplication by s. And instead of using t as the time samples, i will be used as the iteration number, as follows:

$$\beta_P(i) = \gamma e^3(i)\frac{1}{S} = k_p e$$

$$\beta_I(i) = \gamma e^3(i)\frac{1}{S^2} = k_i \frac{e}{s}$$

$$\beta_D(i) = \gamma e^3(i)s = k_D es$$

Then the output of the controller can be expressed by the following stable system,

$$Y(i) = \sum\nolimits_{P,I,D} \beta(i) = \beta_p(i) + \beta_I(i) + \beta_D(i)$$

$$Y(i) = \gamma e^3 \frac{(s^4 + s^2 + 1)}{s^3}.$$

8.4 Position Control of The SMA

The Shape Memory Alloys (SMA) are smart materials that are difficult to control due to its hysteretic behavior and unpredictable changes to its characteristics under temperature, electrical excitation, or mechanical forces. Such type of behavior encourages the usage of adaptive control approaches in the control of the SMA wire. However, the SMA will be used to test the validity and robustness of the derived adaptive controller in controlling the position of the SMA wire. The SMA experimental setup includes all the hardware and software components required for the experiment: The NiTi SMA wire, a constant load connected to the wire, a slider or a removable block to enable the movement of the wire and the connected mass under negative and positive elongations. Software components mainly include the MATLAB/SIMULINK and the dSPACE data acquisition system for testing real time changes on the SMA wire. The SMA wire used in the experiments is a Nickel Titanium wire, with the parameters mentioned in Table 8.1.

Table 8.1 Parameters of the NiTi Shape Memory Alloy

Length (m)	Radius (m)	Density (Kg/m^3)	Area (m^2)	Volume (m^3)
0.55	0.0002	6,500	6.9115*10^{-4}	6.9115*10^{-8}

8.4.1 Adaptive Controller Test on SMA Position Control

To measure the output current from the SMA actuator wire, the values of voltages should be divided by the resistance R = 8Ω to approximate the current which is the square root of this value and saturated in the range 0 to 1.7A with $i(t) = \left\| \sqrt{Y(t)/8} \right\|_0^{1.7}$. Fig. 8.2 shows the block diagram for the PID adaptive controller in equation (3). A similar PID adaptive controller has been derived by Feng Lin, et al. (2000) using Fréchet derivative and SISO system formulas, while here simplified formulas and combination of adaptive approaches lead to this model.

8.4.1.1 Design of the PI Controller

The PID adaptive controller shows a single shot high performance results, in the experimental environment. However, the readings for the Kp, Ki, and Kd gains on real time allows the design of a classical tuned PI controller that is robust and consistent in the control of the position of the SMA wire in (Ghanem 2010; Ghanem et al. 2010).

8.4.1.2 Design of the Enhanced Adaptive Controller

Although simulation results are perfect for the PID adaptive controller, however, in the real world where no idealization exit, a set of recursive experiments on the PID adaptive controller proved inconsistency in the controller. This leads to the need improve the controller design and to test its behavior experimentally. The mathematical adaptation law in (3) will not change, while the adaptation mechanism will be modified. Such that the estimated parameters corresponding to $\mathrm{k_p}$, $\mathrm{k_i}$, and $\mathrm{k_d}$ will be the same, while the controller parameters already called $\mathrm{k_p}$, $\mathrm{k_i}$, and $\mathrm{k_d}$ will be changed so that it is not similar to proportional, integral, and derivative gains respectively. The error signal will be used as the signal vector such that:

$$v(t) = [e(t) \quad e(t) \quad e(t)]^T$$

for all controller parameters instead of using the proportional, integral, and derivative components of the error signal to get the corresponding controller parameters; which are not anymore PID parameters. In comparison with the previous PID adaptive controller parameters, the $\mathrm{k_p}$ is same as it was; dependent on the error signal, and the $\mathrm{k_i}$ and $\mathrm{k_d}$ are equally likely. This change indeed results in an enhanced version of a new adaptive controller, Fig. 8.3 shows the block diagram of the enhanced adaptive controller. The controller was tested in the control of the SMA wire and it gives a consistent robust control.

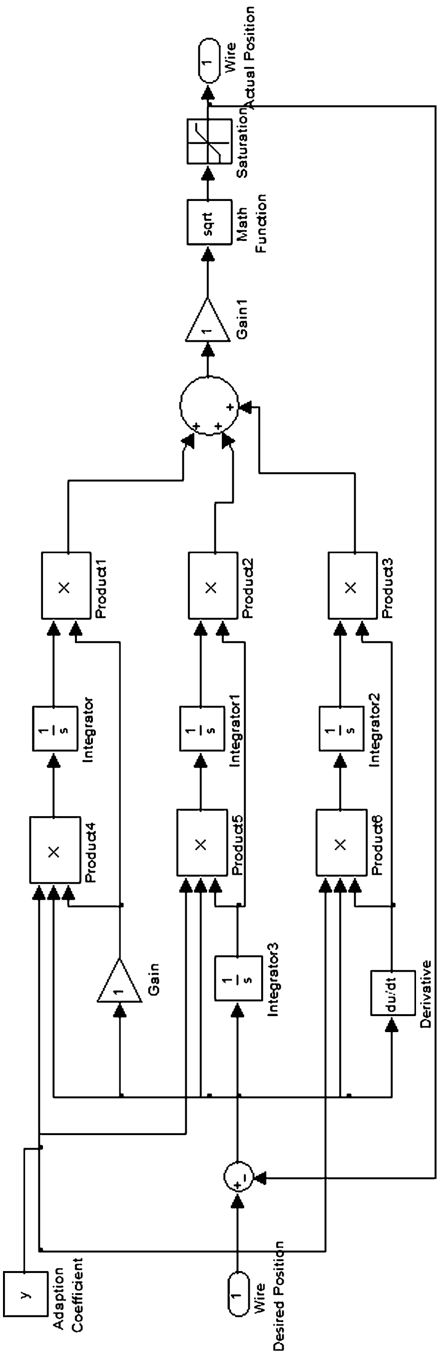


Fig. 8.2 PID adaptive controller for position control of the SMA

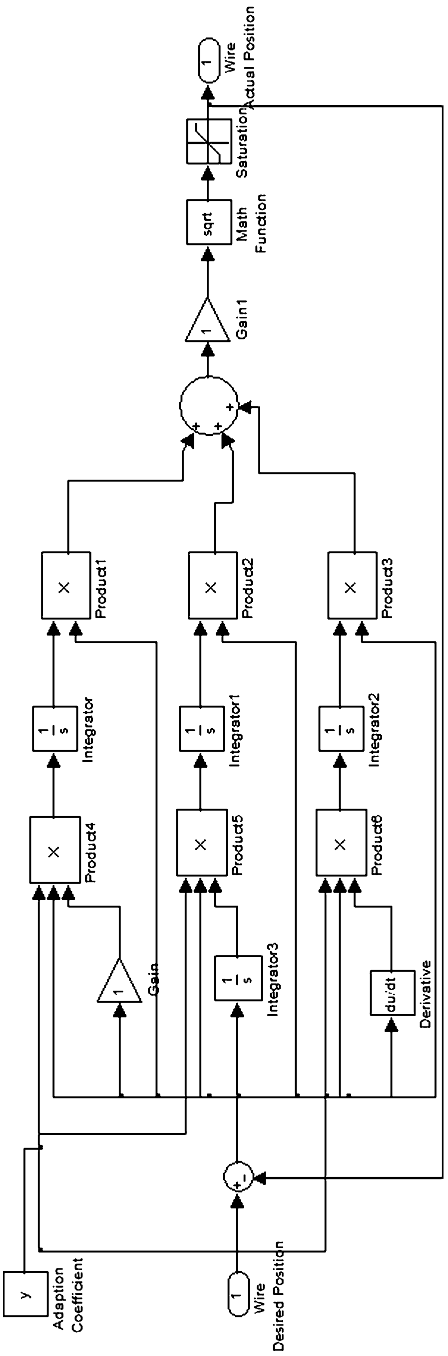


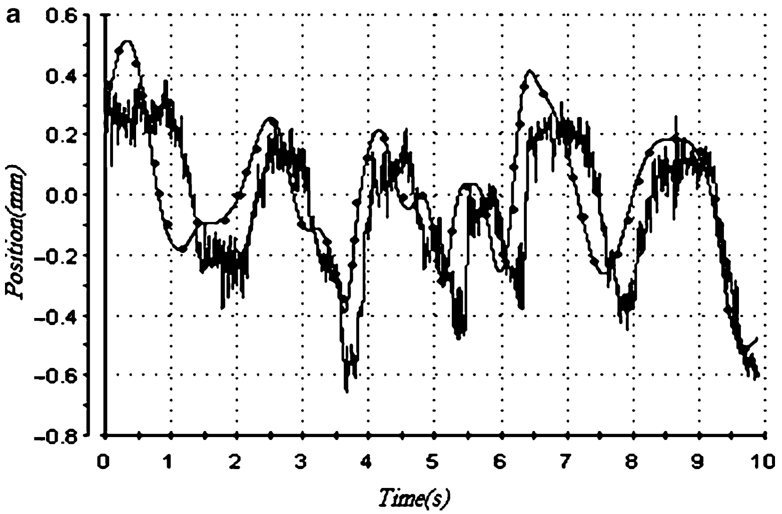
Fig. 8.3 Enhanced adaptive controller for position control of the SMA

8.4.2 Experimental Results

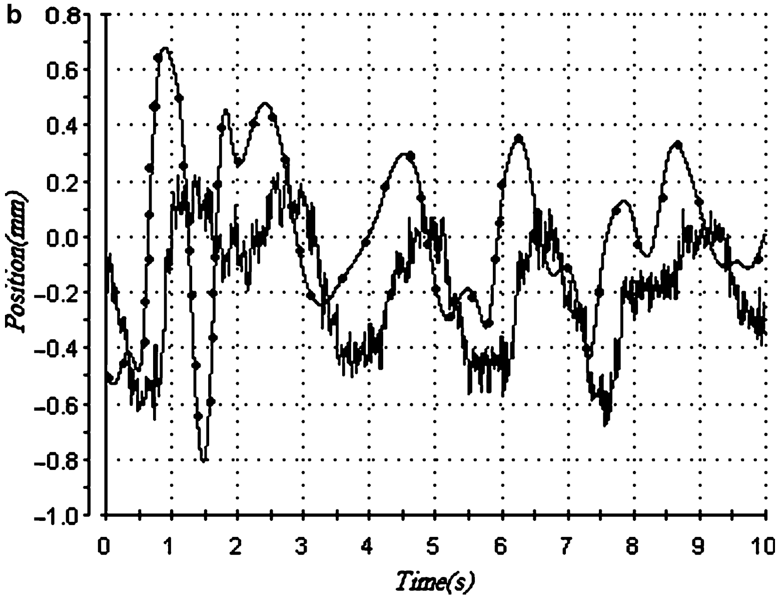
A detailed set of experimental results have been introduced in (Ghanem et al. 2010) using this controller setup, however, we sum up the following summarized points:

1. Equations of MRAC controller with adaptation law (1) do not respond experimentally and give no response to control the position of the SMA.
2. Refinement of equation (1) into (2) to make the parameter dependant on the error signal instead of the reference signal makes the controller starts to respond and control the position of the SMA, while the performance is low.
3. The PID adaptive controller with adaptation law in (3) was tested and it shows excellent results in controlling the position of the SMA. Note that there is a time interval needed for adaptation almost equal to 30 seconds. Multiple set of experiments show that the adaptive controller with error vector signal is an enhanced adaptive controller with more consistency and less adaptation time than the PID adaptive controller.
4. The enhanced adaptive controller was tested under different set of frequencies and gives high performance and robustness in the control of SMA under different sets of excitation frequencies (Ghanem 2010; Ghanem et al. 2010).
5. For this SMA actuator plant in Table 8.1, it is proved that chosing an adaptation coefficient $\gamma = 1$ under different sets of experiments gives the best performance, any increase or decrease of γ will affect the performance of the adaptive controller.
6. For this SMA in Table 8.1, the online Kp, Ki, and Kd parameters running the adaptive controller under different sets of adaptation coefficients gives the following values for the PID gains Kp = [13.2–13.9]; Ki = [0.3;1]; and for Kd = [0.33;0.39]. So, these values can be used for tuning a PID controller with coefficient's ratios [Kp: Ki: Kd] = [14:1:0.3], which are the tuned PI controller parameters. Hence, this adaptive controller can be used to tune the Kp, Ki and Kd coefficients for linear or non-linear plants with unknown dynamics.
7. Using a chaotic wave input signal, Fig. 8.4 shows the results of using an arbitrary chaotic signal as the desired position for both the PI controller and the enhanced adaptive controller. The chaotic signal is generated using the Chua's equations set (Yousef Al-Sweiti 2006). The performance of both controllers is very good with few delays in the actual position, but the overall performance of the PI controller is better. The adaptive controller shows that its adaptability is not mainly based on the input signal consistency, but it is dependent on the plant dynamics and the error signal as well.
8. Experimenting the tuned PI controller under different set of excitation frequencies. The PI controller tuned using the adaptive controller leads to better performance (Ghanem 2010; Ghanem et al. 2010).
9. Comparing the control error for both, the tuned PI controller and the enhanced adaptive controller under different set of excitation frequencies leads to better performance in the PI controller, Fig. 8.5 shows the comparison.

Note that the experimental results were taken in real time from the user interface of the dSPACE data acquisition system connected to the SMA test rig.



PI controller result using chaotic desired position.



Enhanced adaptive controller result using chaotic desired position, γ=3.

Fig. 8.4 PI and enhanced PID adaptive controller results using chaotic signal as the desired position. Time in (s) versus desired position (dotted) and actual position (solid) in (mm)

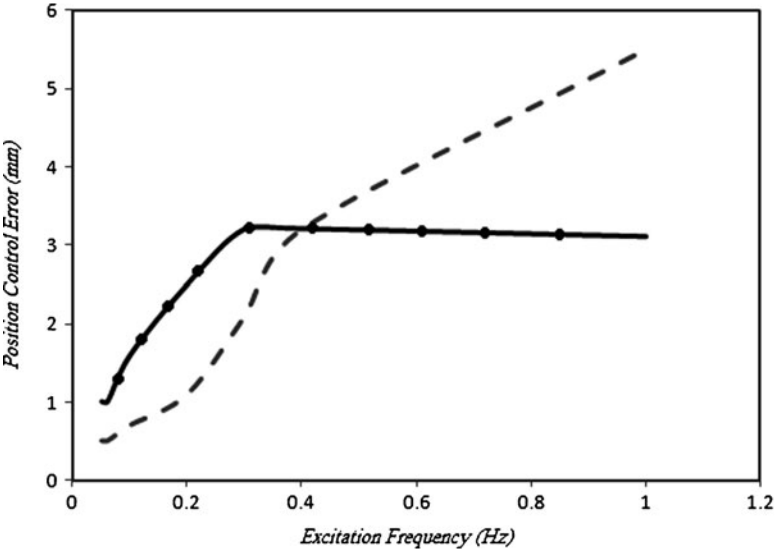


Fig. 8.5 Position control error (mm) for PI controller (dashed), and enhanced adaptive controller (dotted) under different excitation frequencies (Hz)

8.5 Conclusion and Future Work

In this chapter, we introduced the design of an adaptive controller using a combination of two basic adaptive approaches in control, the MRAC, and the STC. The PID adaptive version is used to derive a tuned PI controller. The PI controller and the enhanced adaptive controller are used to control the position of the SMA wire. The controller can be used to control different linear or non-linear plants with unknown dymanics, i.e. similar to the SMA. The adaptive control introduced as a smart alternative for the Non-model based approaches that lack the adaptability to such type of materials that change its behavior by changing its characteristics. While also adaptive control in such kind of difficult non-linear control problems stand as alternative for a model-based controller in their non-dependency on the temperature, i.e. the characteristic changes in the case of the SMA. However, it is still required to build model-based controllers that allows a general usage of the SMA not only to be used as actuator, but also for different engineering applications, where the application will not be only focused on the control of the position. Therefore, it is an open research topic as far as no SMA generalized behavioural based model exit.

References

Arbab Chirani S, Aleong D, Dumont C, McDowell D, Patoor E (2003) Superelastic behavior modeling in shape memory alloys. Journal de Physique 4(112):205–208

Benzaoui H, Chaillet N, Lexcellent C, Bourjault A (1999) A Non linear motion and force control of shape memory alloys actuators. Proceedings of SPIE - The International Society for Optical Engineering 3667:337–348

Bizdoaca N, Hamdan H, Selisteanu D (2006) Fuzzy Logic Controller for a Shape Memory Alloy Tentacle Robotic Structure. University of Craiova, Romania, IMRAC, France

Bouvet C, Calloch S, Lexcellent C (2004) A phenomenological model for pseudoelasticity of shape memory alloys under multiaxial proportional and nonproportional loading. European Journal of Mechanics, A/Solids 23(1):37–61

Dutta SM, Ghorbel FH, Dabney JB (2005) Modeling and control of a shape memory alloy actuator. In: Proceedings of the 20th IEEE International Symposium on Intelligent Control, ISIC ’05 and the 13th Mediterranean Conference on Control and Automation, MED, art. no. 1467151, pp 1007–1012, 2005

Teh YH, Featherstone R (2003) A new control system for fast motion control of SMA actutator wires. Department of Systems Engineering, Research School of Information Sciences and Engineering, The National University, 2003

Li F, Brandt RD, Saikalis G (2000) Self tuning of PID controllers by adaptive interaction. Proceedings of the American Control Conference, Chicago, IL

Reynolds DR (2003) A nonlinear thermodynamic model of phase transitions in shape memory alloy wires. P.h.D. Thesis. Rice University, Houston, TX, May, 2003

Ghanem SAM (2010) Position control of shape memory alloy (SMA) wire using model and behavioral-based and non-model-based controllers. ©2010, VDM Verlang Dr Müller

Ghanem SAM, Shibly H, Soeffker D (2010) Enhanced adaptive controller using combined MRAC and STC adaptive control approaches for the control of shape memory alloy wire. Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering and Computer Science 2010, WCECS 2010, 20–22 October, 2010, San Francisco, USA, vol 2187, pp 996–1001, Issue 1

Silva EPD (2007) Beam shape feedback control by means of a shape memory actuator. Materials and Design 28(5):1592–1596

Slontine JJ, Li WP (1991) Applied nonlinear control, pp 312–328, ©1991 by Prentice Hall International Inc.

Song G, Chaudhry V, Batur C (2003) Precision tracking control of shape memory alloy actuators using neural networks and a sliding-mode based robust controller. Institute of Physics Publishing, Smart Materials and Structures, vol 12, 2003

Yousef Al-Sweiti (2006) Modeling and control of an elastic ship-mounted crane using variable-gain model-based controller. Ph.D. Thesis. University of Duisburg-Essen, Germany, 2006