Proceedings of the World Congress on Engineering and Computer Science 2010 Vol II
WCECS 2010, October 20-22, 2010, San Francisco, USA

Enhanced Adaptive Controller using Combined MRAC and STC Adaptive Control Approaches for the Control of Shape Memory Alloy Wire

Samah A. M. Ghanem, Hassan Shibly, and Dirk Soeffker

***Abstract*—The paper introduces a contribution in the design of adaptive controllers. A PID adaptive controller derived using the mathematical formulas of model reference adaptive control (MRAC) combined with the self tuning adaptive control (STC). The controller tested in the position control of shape memory alloy (SMA) wire and enhanced by experiment to an Enhanced adaptive controller which is more robust and consistent than other classical adaptive controllers derived based on mathematical means. This controller is used to tune the parameters of a PI controller that could control the position of an SMA wire actuator. The performance of both the enhanced adaptive controller and the PI controller are compared under different sets of excitation frequencies of input current to the SMA wire showing robust control and low percentages of error rates.**

***Index Terms*— MRAC, PID, SMA, STC.**

I. Introduction

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 SMA wire actuator plant case. This is because control of shape memory alloy (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 the control methods used for SMA lacks the simplicity and the adaptability to SMA characteristics and environment influence in the characteristics of the SMA [1]-[7].

The proposed adaptive controller is derived through mathematical equations of the MRAC and STC adaptive control [10]-[12]. 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 in this paper.

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The primary goal of this paper is to present an enhanced version of adaptive controllers that can be used to control linear or non-linear plants, to present the robustness of this controller through a hard control problem which is the SMA wire, and to show the ability of this adaptive controller to tune the PID parameters giving more robust solutions tuned experimentally to fit the plant easier than other tuning procedures usually used. The paper organized as follows, section 2 will introduce the basic two approaches of adaptive control used in the derivation of this adaptive controller and steps of its development, section 3 will discuss a 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. Section 4 will show the experimental results of the enhanced adaptive controller and the tuned PI controller under different sets of actuation frequencies, and finally the conclusion.

II. Adaptive Control Approaches

A. *MRAC Control*

Model reference adaptive controller is shown in Fig. 1. The basic principle of this adaptive controller 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 [12].

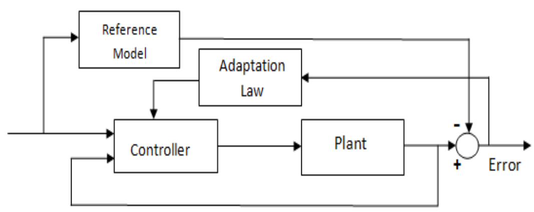

Fig. 1. MRAC adaptive control system [12]

B. *STC Control*

Self tuning adaptive controller is shown in Fig. 2 [12]. The basic principle of this adaptive controller 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.

ISBN: 978-988-18210-0-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

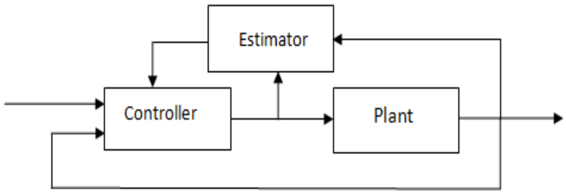

Fig. 2. STC adaptive control system [12]

C. Designing the PID adaptive controller

A combined approach that joins MRAC and STC will be used for building a PID adaptive controller. The reason for calling this approach a combined approach, since the estimated parameters will be the controller parameters that 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. Fig. 3 shows the MRAC adaptive controller with a first degree plant and two estimated parameters [12].

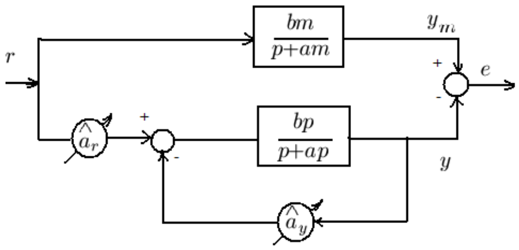

Fig. 3. MRAC system for a first order plant [12]

The equations corresponding to the MRAC controller in Fig. 3 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:

$$\begin{aligned} \dot{\hat{a}}_r &= -sgn(b_p)\gamma e r \\ \dot{\hat{a}}_y &= -sgn(b_p)\gamma e y \end{aligned} \qquad (1)$$

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(b_p)* determines the direction of search for the proper controller parameter, and γ is the adaptation coefficient.

Step1: 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:

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

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

Let the controller estimated parameters be:

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

Where $\hat{a}_e$ 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:

$$\begin{aligned} \dot{\hat{a}}_e &= -sgn(b_p)\gamma e^2 \\ \dot{\hat{a}}_y &= -sgn(b_p)\gamma e y \end{aligned}$$
(2)

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

Step 2: Building the PID adaptive controller

In step 1, using the error signal as one of the signals used for adaptation helps the controller to react. And as 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. Fig. 4 shows a block diagram describing the idea.

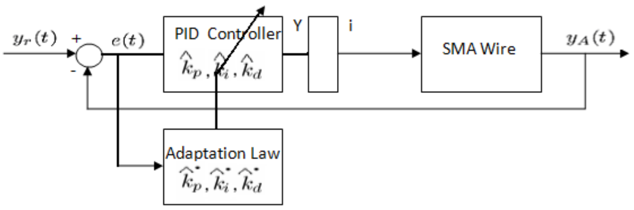

Fig. 4. The PID adaptive controller combined MRAC and STC.

In Fig. 4, *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. 4 is that the $\dot{\hat{k}}_p$, $\dot{\hat{k}}_i$, and $\dot{\hat{k}}_d$ are the estimated parameters of the plant 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 (1).

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

$$\dot{\hat{k}}_i = -\gamma e \int e\, dt \quad \Rightarrow \quad \hat{k}_i = \int -\gamma e \int e\, dt\; dt. \tag{3}$$

$$\dot{\hat{k}}_d = -\gamma e \frac{de}{dt} \quad \Rightarrow \quad \hat{k}_d = \int -\gamma e \frac{de}{dt}\; dt.$$

$\hat{k}_p$ 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:

$$v(t) = \left[e(t) \quad \int e(t)dt \quad \frac{de(t)}{dt}\right]^T.$$

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

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:

$$Y(t) = \sum_{P,I,D} \beta(i)$$

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 as the iteration number will be used as follows:

$$\beta_P(i) = \gamma e^3(i)\frac{1}{s} = k_P e$$

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

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

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

$$Y(i) = \sum_{P,I,D} \beta(i) = \beta_P(i) + \beta_I(i) + \beta_D(i)$$

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

III. 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 Test Rig will be used to test the validity and robustness of the derived adaptive controller in controlling the position of the SMA wire. The SMA test rig 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 I.

Table I. The 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	6500	$6.9115*10^{-4}$	$6.9115*10^{-8}$

A. *PID 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 1.7 A as follows:

$$i(t) = \left\| \sqrt{\frac{Y(t)}{8}} \right\|_0^{1.7}.$$

Fig. 5 shows the SIMULINK blocks for the PID adaptive controller in equation (3). A similar PID adaptive controller is derived by Feng Lin, et al. [13] using Frechet derivative and SISO system formulas, while here simplified formulas and combination of adaptive approaches lead to this model.

ISBN: 978-988-18210-0-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

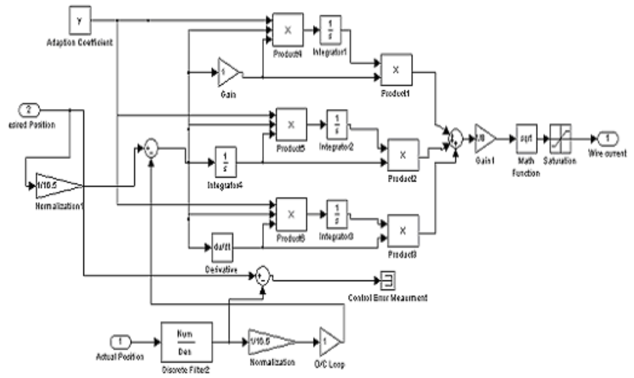

Fig. 5. PID adaptive controller for position control of the SMA.

B. Design of the PI controller

Running an experiment on the PID adaptive controller shows a single shot high performance results. 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 shown in Fig. 6. Experimental results of the PI controller will be shown in the last section.

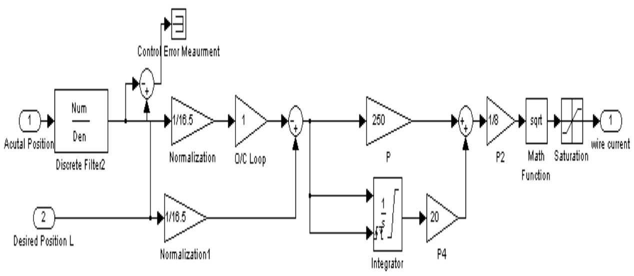

Fig. 6. Tuned PI controller

C. Design of the enhanced adaptive controller

A set of recursive experiments on the PID adaptive controller in Fig. 6 proved inconsistency in the controller. This leads the need to do some changes on the controller design and to test its influence experimentally, the mathematical adaptation law in (3) was not changes, while the adaptation mechanism will be modified so that the estimated parameters corresponding to kp, ki, and kd will be the same. While the controller parameters already called kp, ki, and kd 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 is not anymore PID parameters. Compared to the previous PID adaptive controller parameters, the kp is same as it was; dependent on the error signal, the ki and kd are equal likely. This change results in an enhanced version of a new adaptive controller, SIMULINK blocks of the enhanced adaptive controller are shown in Fig. 7. The controller was tested in the control of the SMA wire and it gives a consistent robust control.

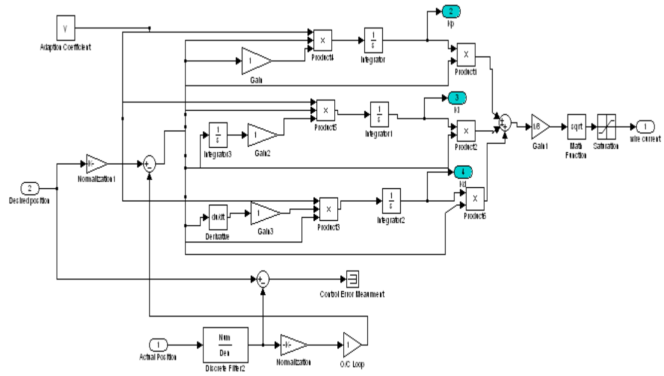

Fig. 7. Enhanced adaptive controller for position control of the SMA.

IV. Experimental Results

A. Equations of MRAC controller with adaptation law (1) are tested experimentally and fail to have any response to control the position.
B. Refinement of equation (1) into (2) in ***step1*** 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. Fig. 8 shows the result.

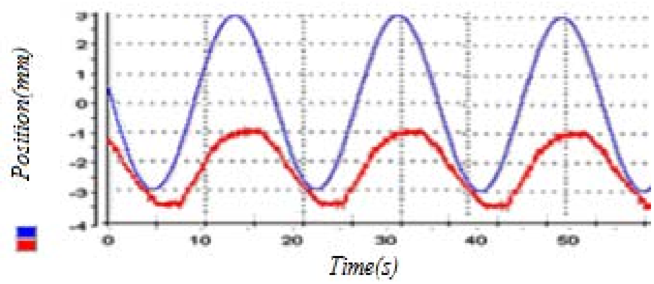

Fig. 8. Adaptive Controller in (2) with γ =1. Desired input position is a sinusoid with amplitude=3, and frequency=0.06Hz. Time in (s) versus actual position (red) and desired position (blue) in (mm).

C. The PID adaptive controller with adaptation law in (3) tested and shows excellent results in controlling the position of the SMA. Fig. 9 shows the position control results of the PID adaptive controller with excellent performance, 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.

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ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

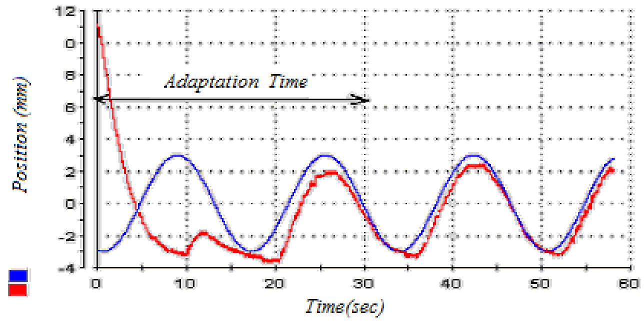
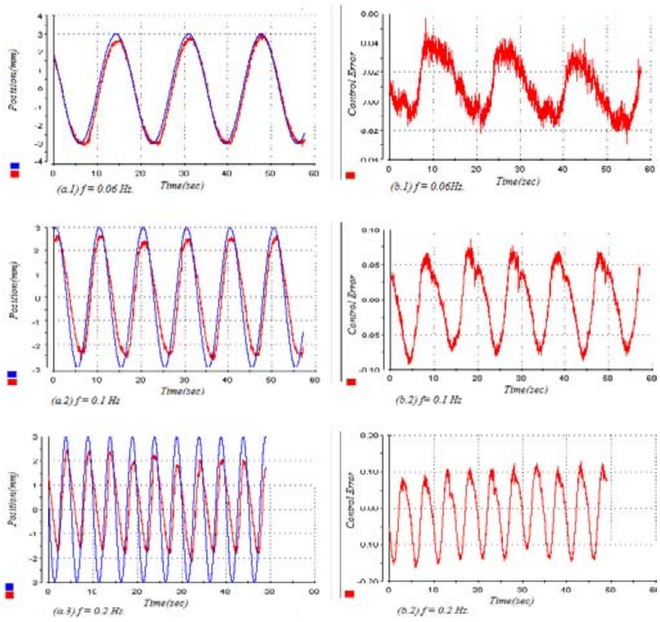


Fig. 9. PID Adaptive Controller, with γ =1. Desired input position is a sinusoid with amplitude=3, and frequency=0.06Hz. Time in (s) versus actual position (red) and desired position(blue) in (mm).

D. The enhanced adaptive controller was tested under different set of frequencies and gives high performance and robustness in the control of SMA. A set of experiments under different sets of excitation frequencies are done and results are shown in Fig. 10.

E. Enhanced adaptive controller was tested. Position control error under different sets of adaptation coefficients γ= (1, 0.5, and 0.3). For this SMA actuator plant, it is proved that γ=1 under different sets of experiments gives the best performance, any increase or decrease will affect the performance of the adaptive controller, this leads to the result that we can extract the γ from equations used to derive the controller replacing it by 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], that is the tuned PI controller parameters. Thus, this adaptive controller can be used to tune the Kp, Ki and Kd coefficients for linear or non-linear plants with unknown dynamics.



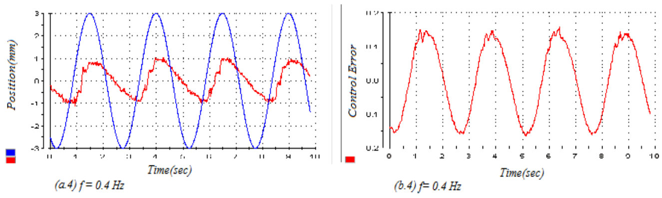


Fig. 10. Enhanced PID Adaptive Position Controller Results with γ =1. Desired input position is a sinusoid with amplitude =3. (a.1) to (a.4) Time in (s) versus actual position (red) and desired position (blue) in (mm). (b.1) to (b.4) Time in (s) versus control error under different frequencies of desired position.

F. Using chaotic wave input signal, Fig. 11 shows the results of using an arbitrary chaotic signal as the desired position for both the PI controller and the PID adaptive controller.
The chaotic signal is generated using the Chua's equations set [14]. 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.

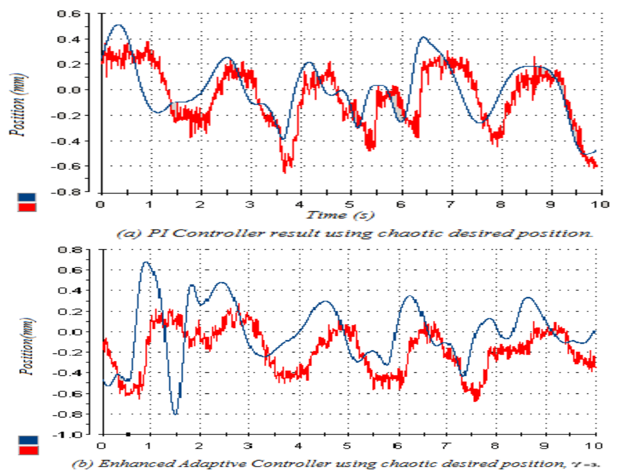


Fig. 11. PI and enhanced PID adaptive controller results using chaotic signal as the desired position. Time in (s) versus desired position (blue) and actual position (red) in (mm).

G. Experimenting the tuned PI controller as shown in Fig. 12 under different set of excitation frequencies. The PI controller tuned using the adaptive controller leads to better performance. Comparing 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, shown in Fig. 13.
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.

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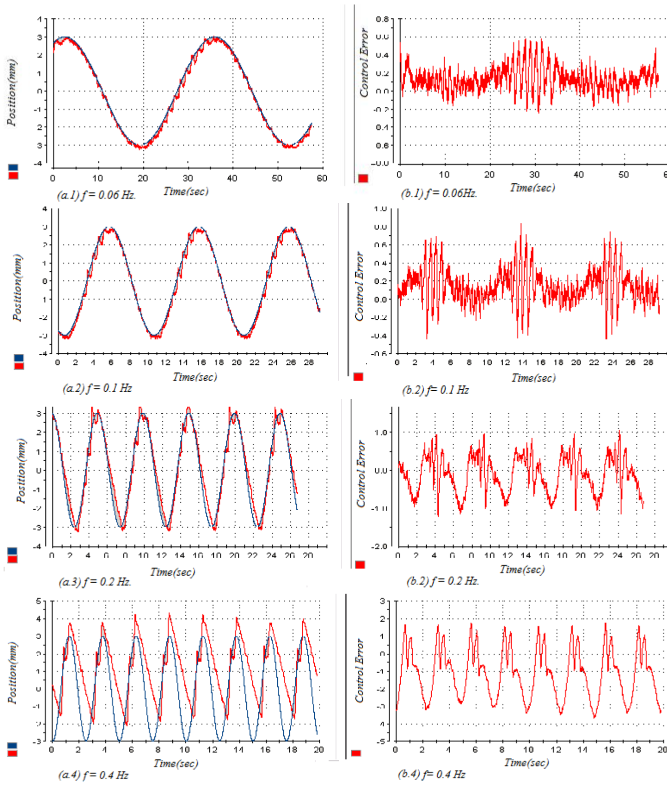

Fig. 12. PI Controller results. Desired input position is a sinusoid with amplitude =3. (a.1) to (a.4) Time in (s) versus actual position (red) and desired position (blue) in (mm). (b.1) to (b.4) Time in (s) versus control error under different frequencies of desired Position.

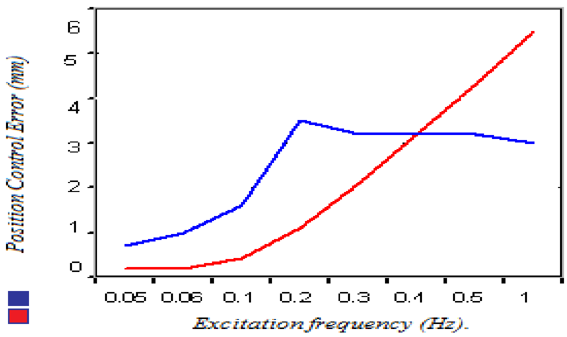

Fig. 13. Position control error (mm) for PI controller (red), and enhanced adaptive controller(blue) under different excitation frequencies (Hz).

V. Conclusion

The paper proposed a new design of adaptive controllers 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 experimentally enhanced adaptive controller are used to control the position of the SMA wire. The experimental results show the robustness and high performance of both controllers under a set of excitation frequencies.

Acknowledgments

This work has been supported by the government of North Rhein Westphalia, Germany, 2008.
The experiments has been conducted at the labs of the Chair of control and dynamics, SRS, at the University of Duisburg-Essen, Germany.

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ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)