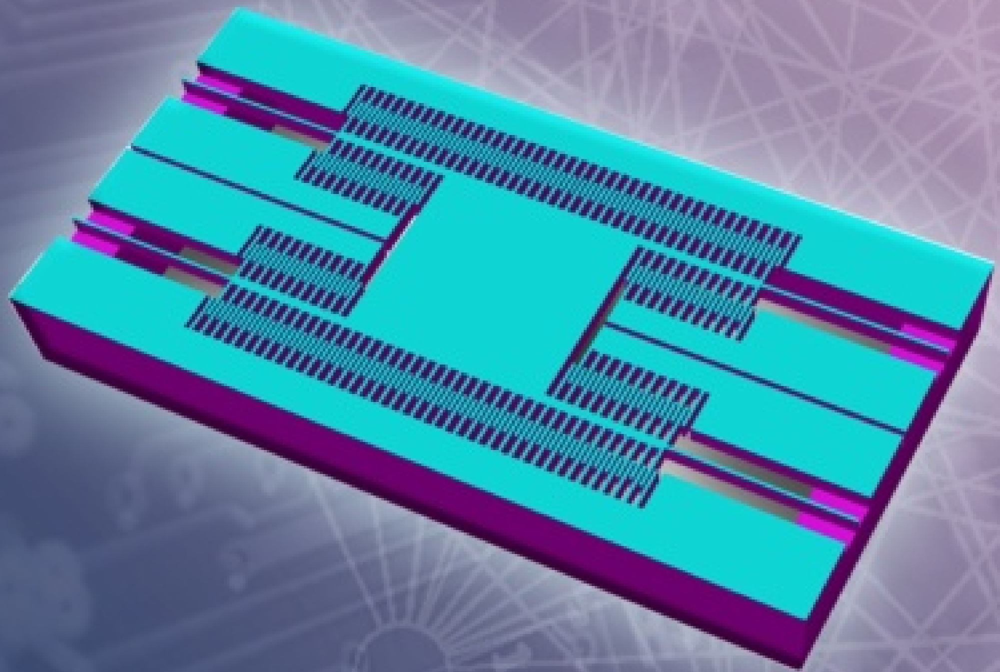
ISSN 1726-5479

SENSORS & TRANSDUCERS

12/12
vol. 17
Special



Sensors and Intelligent Systems

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 17, Special Issue
December 2012
www.sensorsportal.com
ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Contents

Volume 17
Special Issue
December 2012

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 17, Special Issue, December 2012, pp. 217-225

Sensors & Transducers
ISSN 1726-5479

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Optimal Feedforward Zero Phase Error Tracking Control for High Precision X-Y Table

[1] Hashimah ISMAIL, [2] Norlela ISHAK, [2] Mazidah TAJJUDIN,
[2] Mohd Hezri FAZALUL RAHIMAN, [2] Ramli ADNAN
[1] Faculty of Engineering, Universiti Selangor,
Bestari Jaya, 45600, Selangor, Malaysia
[2] Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM)
Shah Alam, Selangor, Malaysia
E-mail: hashimah@unisel.edu.my, ramli324@salam.uitm.edu.my

Received: 29 September 2012 /Accepted: 29 October 2012 /Published: 18 December 2012

Abstract: Tracking control is important for precise operations in manufacturing field. To achieve good performance for high speed XY table movements, adaptive feedforward using Zero Phase Error Tracking Control (ZPETC) is proposed. This technique uses ZPETC without factorization of zeroes. In this paper, the feedforward controller is improved by introducing Model Reference into the system. The reference model tells how the process output ideally should respond to the command signal. The system transfer functions of X and Y axis are obtained via system identification technique using Matlab Toolbox. The performance of the controller in reducing the tracking error using high frequency input is analyzed through simulation. The system is also tested by implementing the adaptive controller without model reference for benchmarking purposes. Both controller performances are compared and the result shows tremendous superior tracking performance. *Copyright © 2012 IFSA.*

Keywords: Position tracking, XY table, System identification, Feedforward ZPETC.

1. Introduction

The XY table application is useful especially in machining systems. This requires high speed and precision which contribute to great control challenge. The contour accuracy of the x-y plane is dominated by position and tracking error of each axis [1]. It is very important to satisfy the accuracy requirement especially for direct input used as reference for a servo motor. This high precision system usually represented by a non-minimum phase (NMP) system or in another words it has unstable zeros outside the unit circle for a discrete-time system.

The feedforward Zero Phase Error Tracking Control introduced by Tomizuka [2] is effective and has been used widely in solving unstable system as in [3-6]. This technique is suitable only for low frequency. Many researchers have modified this technique to achieve better control performance [7-10]. The main objective in feedforward ZPETC is to find the optimum gain filter so that the overall gain is close to unity. To avoid the unwanted phase error, Yeh and Hsu [11], Mustafa [12] and Adnan et al. [13] used ZPETC without factorization of zeros. In this method, gain filter is proposed as equation

$$F_g(z\ z^{-1}) = \sum_{k=0}^{n\alpha} \alpha_k \left(z^k + z^{-k}\right) \tag{1}$$

where n_α is the order of the filter. The value, α in equation 1 can be solved using comparing coefficient method as presented in [14] and Laurent series expansion method [12]. To find the optimum value of α, adaptive control technique proposed by Adnan et al. [13] is considered. Further improvement is presented in this paper by adding model reference as the excitation signal to find the value of α.

The plant transfer function was identified from ac servo XY table. To avoid the mechanical consideration complexity, System Identification technique is used to get the system plant transfer functions. Using this method, the model is derived based on input/output responses performed in time domain.

This paper is organized as follows: Section II describes the system plant and System Identification technique that are used to find the transfer function; Section III describes the controller design; Section IV is on results and discussion and Section V is the conclusions.

2. Plant & Model Identification

2.1. Plant Setup

The plant used in this research is X-Y table ac servo system. Basic hardware for XY table consists of servomotors, two servo drivers, two linear encoders, two linear precision sensors, motion card, data acquisition card, XY table and a host PC set. The linear sensor and encoder resolution is 1 µm. The minimum movement is 1 µm. The hardware setup is given in Fig. 1. For system control and interfacing, Microsoft Visual C++ 6.0 is used. Matlab software is used for model identification and results analysis.

2.2. Model Identification

Data collection for input-output open-loop test of the plant was done using developed Visual C++ console programming and data acquisition were done through Advantech PCI-1716 interface card and Advantech motion card. The input signal for both axes was generated using three different frequencies that based on equation (2).

$$u(k) = \sum_{i=1}^{p} a_i \cos \omega_i t_s k\ , \tag{2}$$

where a_i is the amplitude; ω_i is the frequency (rad); t_s is the sampling time (s); k is the integer.

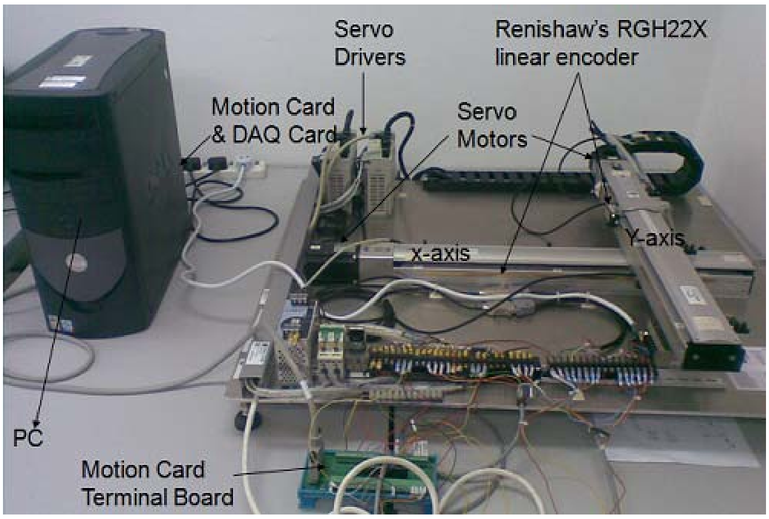
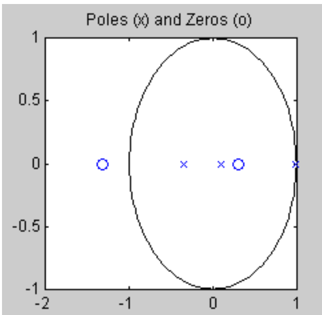


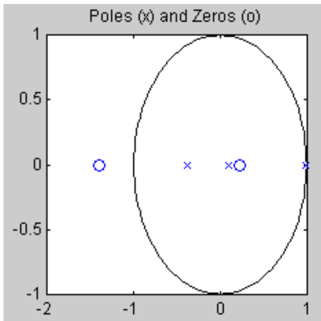
Fig. 1. Hardware Setup.

As the input signal comprises three different frequencies, the model that can be obtained is limited to second and third order only. Higher-orders model may produce unstable output. In these studies, the third-order ARX331 model is considered to represent the nearest model of true plant. The output signal is sampled at 45ms. To have perfect XY table system, data collection for both x and y axis is done simultaneously.

Matlab System Identification Toobox is used to get the system model. Using ARX331, the best fit model for x-axis is 94.83 % and for y-axis is 96.16 %. The pole and zero plots are shown in Fig. 2 below.



(a) X-Axis



(b) Y-Axis

Fig. 2. Zero-pole plot for x and y axis plant models.

The locations of zeros are at -1.3264 and 0.3008 for x-axis and at -1.3959 and 0.2212 for x-axis. This means that both models for x and y axis are non-minimum phase system with one zero located outside the unit circle.

3. Controller Design

This section presents the development and implementation of the controller design. Pole-placement feedback and adaptive feedforward ZPETC controllers are applied to the system. The general block diagram of the control system is given in Fig. 3.

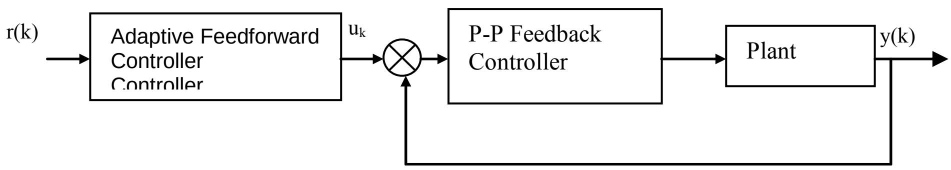


Fig. 3. Control System General Block Diagram.

For feedback controller, pole-placement method is used in the system. This method enables all poles of the closed-loop to be placed at desired location which produces stable output performance. For the adaptive feedforward ZPETC implementation, let the closed- loop transfer function of the system be presented by:

$$G_{cl}(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{z^{-d}B_c(z^{-1})}{A_c(z^{-1})}, \tag{3}$$

where

$A_c = 1 + a_1 z^{-1} + a_2 z^{-2} + ... + a_{n_a} z^{-n_a}$;

$B_c(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + ... + b_{n_a} z^{-n_b}$;

d = time delay.

The ZPETC structure without factorization of zeros based on [13] is utilized in this paper. The control structure is shown in Fig. 4.

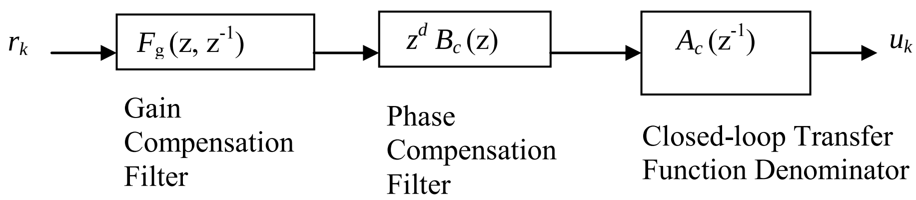


Fig. 4. ZPETC without factorization of zeros.

Same ZPETC approach with [11, 12 and 13] is followed to avoid phase error. They used the gain compensation filter so that it can be adapted with the input signal. For the gain compensator, Finite Impulse Response (FIR) symmetry filter is used. The filter can be represented by equation (1). The cost function to represent the error between desired and actual frequency response is given by eq. (4).

$$J(\alpha_i) = \left\| 1 - B_c\left(z^{-1}\right) B_c(z) \sum_{k=0}^{n_\alpha} \alpha_k \left(z^k + z^{-k}\right) \right\|_{l_2} \tag{4}$$

The objective is to find a set of α_k so that can minimized the cost function. By minimizing the cost function in equation (4) close to zero, the equation can be transformed to be:

$$B_c\left(z^{-1}\right) B_c(z) \sum_{k=0}^{n_\alpha} \alpha_k \left(z^k + z^{-k}\right) = 1 \tag{5}$$

The optimal set of α_k is estimated using the recursive least square (RLS) parameter estimation algorithm. This system can be represented by a block diagram in the Fig. 5.

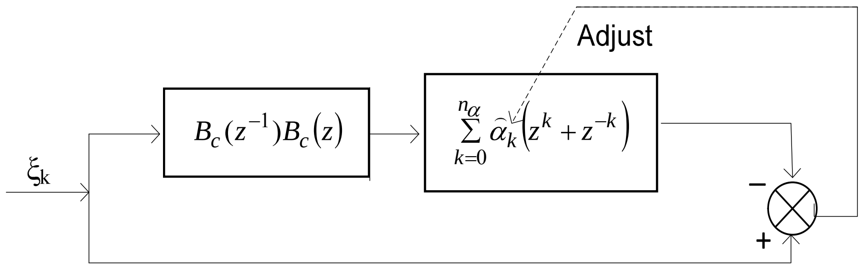


Fig. 5. Adaptive ZPETC without factorization of zeros.

Based on [13], in ensuring the generated signal ξ will always persistently exciting, a low level noise signal which its frequency spectrums close to the reference signal frequency spectrums is superimposed to the reference signal. The noise addition will not affect the system as it will not pass through the tracking system. It is only been used in the gain parameter estimation. To improve this parameter estimation part, this paper proposes model reference signal to be used instead of reference signal. The whole system block diagram utilizing this method is presented in Fig. 6. The plant model used in this paper is presented in part II.

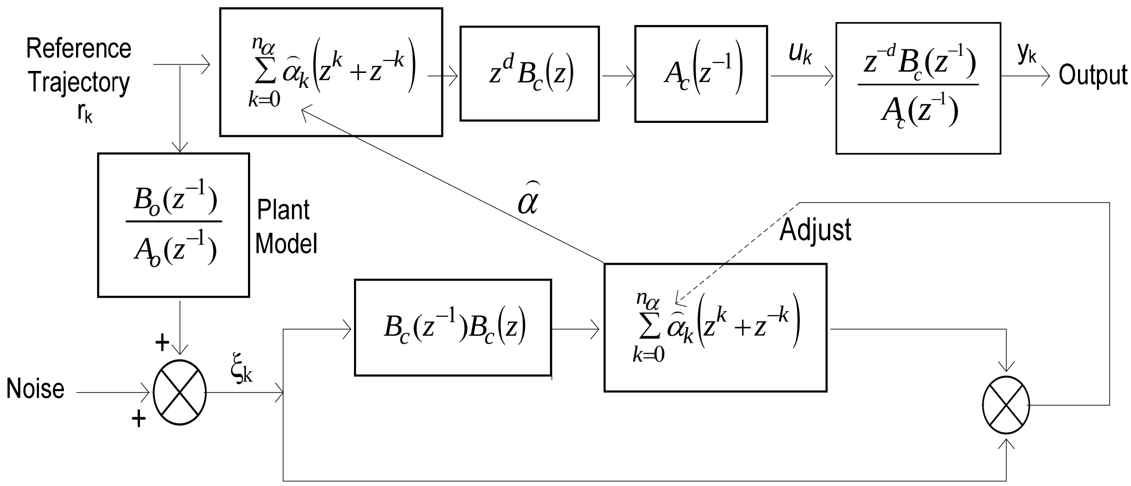


Fig. 6. ZPETC without factorization of zeros.

The implementation of the proposed structure was done by simulation using Visual C++ console programming. The forgetting factor used was 0.95.

4. Results & Discussions

In this section, the simulation results were analyzed to show the effectiveness of the proposed controller. High speed frequency sinusoidal inputs were applied to test the tracking capabilities. The x-axis used sine function and the y-axis used cosine function to produce circular contour in x-y plane. The equations of the input signal are given by equation (6) for x-axis and equation (7) for y-axis.

$$r_k = 40\sin(0.15t) \quad (6)$$

$$r_k = 40\cos(0.15t) \quad (7)$$

The gain filter order nα used in the experiments were varied to 5 and 10. This is to provide better performance comparison between the model reference structure and the structure without model reference (benchmarking). The results for all parameters are plotted and presented in Fig. 7 to Fig. 10. The displacement output for X and Y axis are then plotted in two dimensional to have circular contour. The simulation results of both techniques show superior tracking performance. However, by introducing the model reference to the adaptation structure, lower filter order is satisfied. Better tracking performance can also be achieved by raising the filter order such that the controller will have more degree of freedom to approximate the overall transfer function to unity.

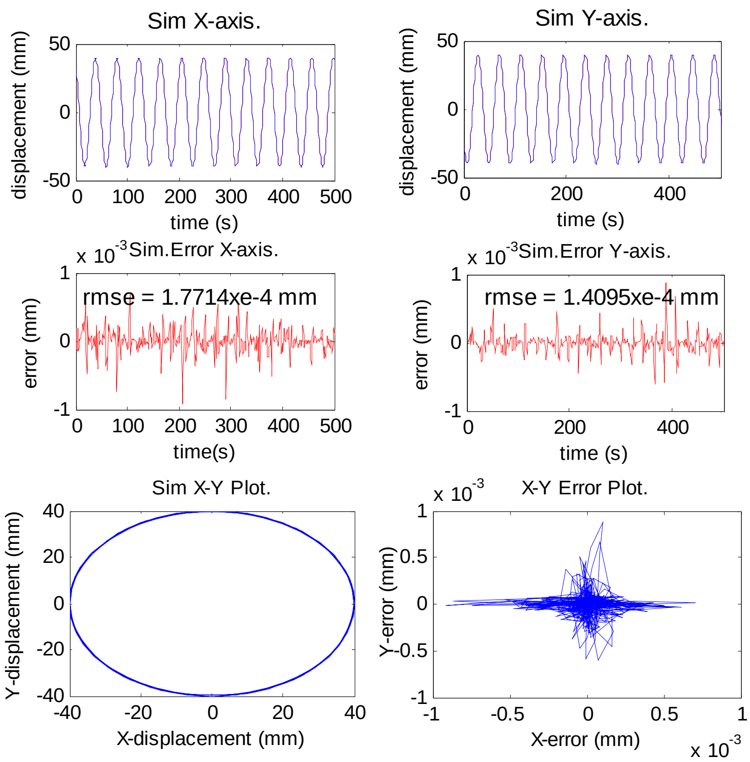


Fig. 7. Results from proposed technique 5th order filter.

The tracking performances in terms of root mean squared error (RMSE) for all results are summarized in Tables 1 and 2.

As it is observed from the results in Tables 1 and 2, by introducing the model reference input to the system, the performance has improved about 94 % for each case. Thus, the proposed technique is suitable for high speed input precision x-y table.

Table 1. RMSE Summary for Adaptive ZPETC with Model Reference Input Structure.

Axis	RMSE (mm)	
	5th order filter	10th order filter
X-Axis	1.7714×10^{-4}	5.2685×10^{-5}
Y-Axis	1.4095×10^{-4}	3.5769×10^{-5}

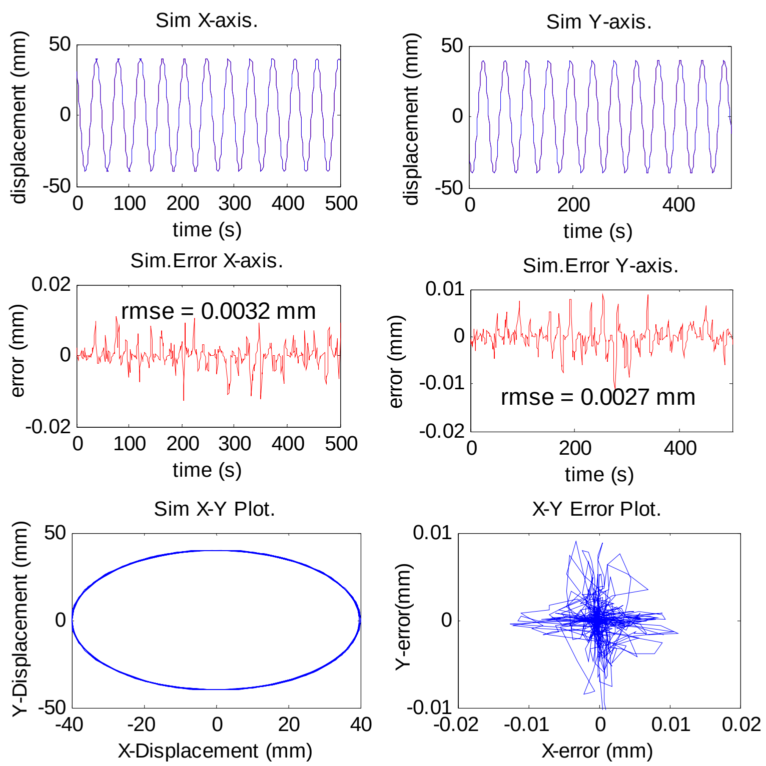


Fig. 8. Benchmarking technique using 5th order filter.

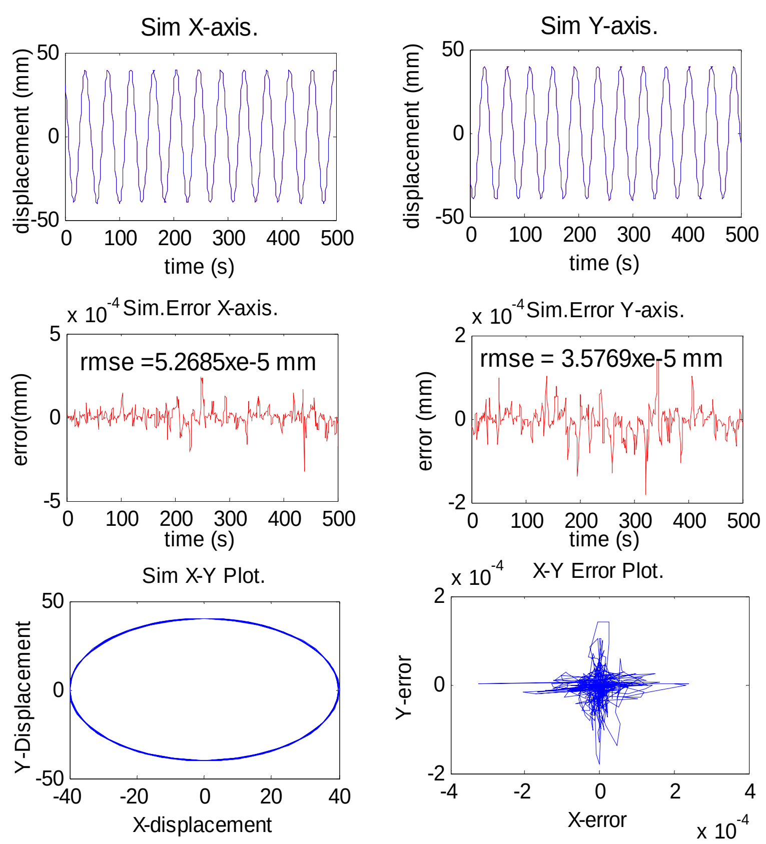


Fig. 9. Results from proposed technique using 10th order filter.

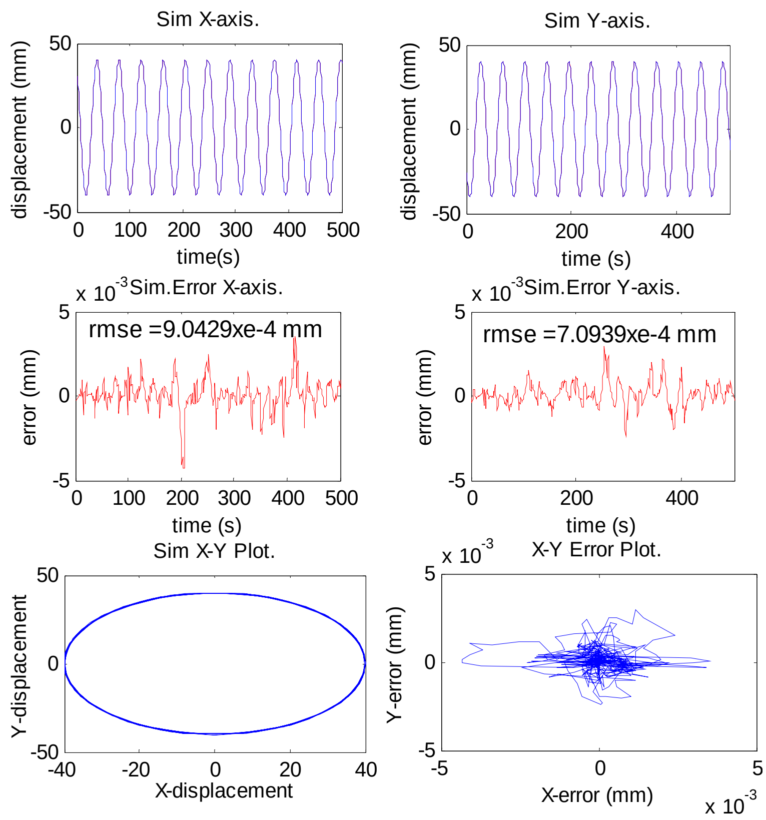


Fig. 10. Benchmarking technique 10^{th} order filter.

Table 2. RMSE summary for adaptive ZPETC without model reference input structure (benchmarking).

Axis	RMSE (mm)	
	5^{th} order filter	10^{th} order filter
X-Axis	0.0032	9.0429×10^{-4}
Y-Axis	0.0027	7.0939×10^{-4}

5. Conclusions

Trajectory adaptive ZPETC with model reference was successfully developed and applied to XY table by simulation. Sinusoidal high frequency input is applied to the system to the test the tracking performance. The displacement output for each axis and circular contour for XY table were plotted. The results have shown that the proposed adaptive ZPETC has improved the result tremendously compared to the benchmarking technique. The controller performances showed impressive results as model reference makes the adaptation mechanism converges faster by pre-introduced the plant system.

Acknowledgements

This work was conducted at Faculty of Electrical Engineering, UiTM facilities with financial support from UiTM Excellence Fund 600-RMI-ST-DANA-5/3/Dst(439/2011).

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