
# TRAJECTORY ADAPTIVE ZPET CONTROLLER WITHOUT FACTORIZATION OF ZEROS FOR NON-MINIMUM PHASE SYSTEM IN APPLICATION TO REAL-TIME DIGITAL TRACKING CONTROL OF ELECTRO-HYDRAULIC ACTUATOR

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***Abstract— Electro-hydraulic actuators are very important tools for industrial processes because they provide linear movement, fast response and accurate positioning of heavy load. Recently, with the research and development of mathematics, control theory and basic theory of hydraulic, hydraulic control technology has been developed and has been widely used in many applications such as industrial automation and machining processes. Due to its applications, the highest performance of the electro-hydraulic actuators on position, motion or tracking is needed. Therefore, a suitable controller is required to improve the performance of the electro-hydraulic actuator. Most researchers have used advanced control approach to improve the motion or tracking control. Based on these problems, we had done a real-time digital tracking control studies on electro-hydraulic actuator using trajectory adaptive zero phase error tracking control (ZPETC) without factorization of zero polynomial algorithm. The control strategy uses a recursive least square parameters estimation that***

***was done offline prior the actual control operation by taking advantage of the available known reference input. The experimental results obtained show significant tracking performance.***

**Keywords— Adaptive Control, feedforward control, tracking control, zero phase error tracking control**

## I. INTRODUCTION

Tracking control is very important, as the control device must follow the prescribed motion. Many studies on applications of digital tracking control using zero phase error tracking control (ZPETC) were done on electrical actuators [1] except hydraulic actuator [2]. Generally, hydraulic actuator has been widely used in industrial application due to its high force-mass ratio and faster response [3, 4]. These advantages have been utilized in hydraulic drive robot to enhance operation efficiency [5]. The natural non-linear property of hydraulic actuator had challenged researchers in designing suitable controller for positioning control [6] motion control and tracking control [7]

Generally, industrial hydraulic robot is using conventional PI (proportional-integral) controller in velocity command mode. With attention to improve the motion or tracking performance effectively, many researches have used advanced control strategies to control hydraulic actuator [2, 8]. Based on these scenarios, this study discusses the implementation of real-time digital tracking control of electro-hydraulic actuator using trajectory adaptive zero phase error tracking control (ZPETC) without factorization of zeros polynomial. The model treated was a non-minimum phase system since using faster sampling time rate to sustain optimum information will always introduces non-minimum phase zeros in discrete-time transfer function [9].

## II. DIGITAL TRACKING CONTROL

In tracking control system, perfect tracking control is an object control strategy with zero-tracking error [10]. Perfect tracking control can be achieved using feedforward controller, which is the inverse transfer function of the closed-loop system [11]. This feedforward controller is capable of cancelling all poles and zeros of the closed-loop system. This results an overall transfer function of unity from the reference input to actual output. However, if there is a non-minimum phase zero outside the circle, then the inverse transfer function of the closed-loop system, which is the resulting feedforward controller, will not be stable. Thus, the internal stability will not be guaranteed [12]. The ZPETC method that was proposed by

Tomizuka [13] had attracted many researchers as one of the effective and easiest solutions to the non-minimum phase zeros problems. Even though, the zeros of the non-minimum phase system cannot be cancelled, by eliminating the phase error, ZPETC has shown impressive tracking performance [14]. However, the gain error that cannot be cancelled by ZPETC will increase for high-speed tracking that cause undesired effect to tracking performance. To overcome these problems, many studies have been done and published to improve tracking performance.

## III. ZPETC WITHOUT FACTORIZATION OF ZEROS

The tracking control system with two-degrees-of-freedom that is consisting of feedback and feedforward controllers is given in figure 1 [15]. In tracking control system without feedforward controller, the reference signal continuously varying and mixed with the closed-loop system dynamics, which make tracking error always remains. Note that the major function of feedback controller is regulation against disturbance inputs. The feedforward controller is required such that the reference signal can be pre-shaped by the feedforward controller, so that more emphasis to the frequency components that were not sufficiently handled by the feedback system can be provided [16]

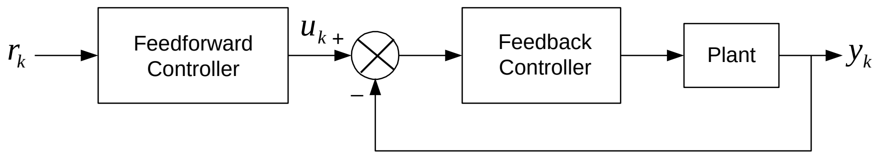



Figure 1. Two-degree-of-freedom controller

Referring to figure 1, the closed-loop transfer function of the system (without feedforward control) can be represented by the following discrete time model:

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

where

$$A_c = 1 + a_1 z^{-1} + a_2 z^{-2} + \dots\dots\dots\dots + a_{n_a} z^{-n_a}$$

$$B_c(z^{-1}) = b_o + b_1 z^{-1} + b_2 z^{-2} + \dots\dots + b_{n_a} z^{-n_b}$$

$d$ = time delay

The function $B_c\,(z^{-1})$ can be factorized into minimum phase and non-minimum phase factors:

$$B_c(z^{-1}) = B_c^{+}(z^{-1})B_c^{-}(z^{-1}) \tag{2}$$

where $B_c^{+}(z^{-1})$ denotes the minimum phase factor and $B_c^{-}(z^{-1})$ denotes the non-minimum phase factor. The conventional ZPETC reported in the literature [15] can be divided into three blocks as shown in figure 2. The block diagram of feedforward ZPETC consists of the gain compensation filter, phase compensation filter and stable inverse. Figure 3 shows the structure of the ZPETC feedforward controller without zeros factorization. The block diagram of feedforward ZPETC without factorization of zeros consists of the gain compensation filter, phase compensation filter and closed-loop transfer function denominator.

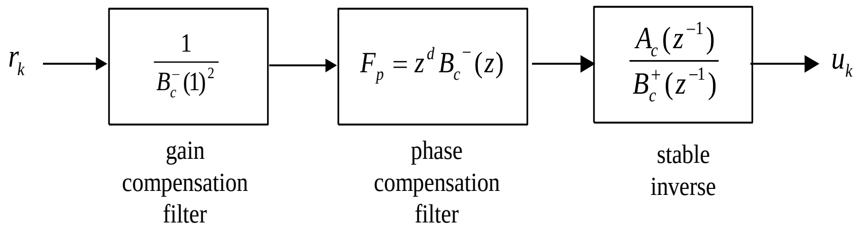



Figure 2. Conventional ZPETC structure block diagram

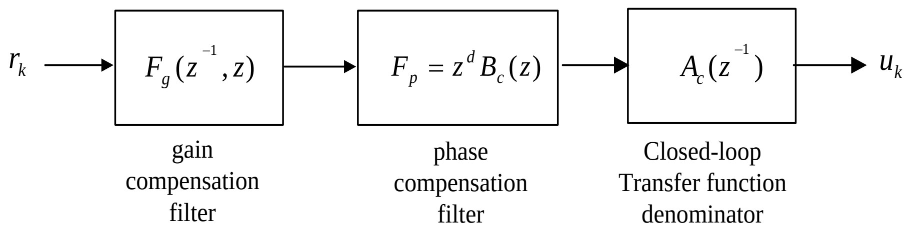



Figure 3. ZPETC without factorization of zeros structure block diagram

Similar to all others ZPETC, the design mainly focused on the selection of appropriate gains compensation filter to ensure the overall gain is unity within the frequency spectrum of reference trajectory. To ensure the gain compensation filter, $F_g$ does not introduces any phase error, the same approach done by [17] and [18] will be followed. The FIR symmetric filter was used. The filter is represented by equation:

$$F_g(z, z^{-1}) = \sum_{k=0}^{n_\alpha} \alpha_k (z^k + z^{-k}) \tag{3}$$

where $n_\alpha$ is the order of the filter. A suitable cost function to represent the error between the desired and actual frequency response is given by Eq. (4).

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

The design objective here is to find a set of $\alpha_k$ such that the cost function given by Eq. (4) is minimized. For finite $\alpha_k$, Eq.(4) cannot be made zero for all frequencies. By minimizing the cost function of Eq. (4),

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

The coefficients $\alpha_k$ can be estimated using the recursive least square parameters estimation algorithm and the implementation is done as in figure 4. $r_k$ is the reference trajectory signal and $n_k$ is white noise. We have developed a C++ program to approximate the set of $\alpha_k$ using U-D factorization algorithm [19, 20]

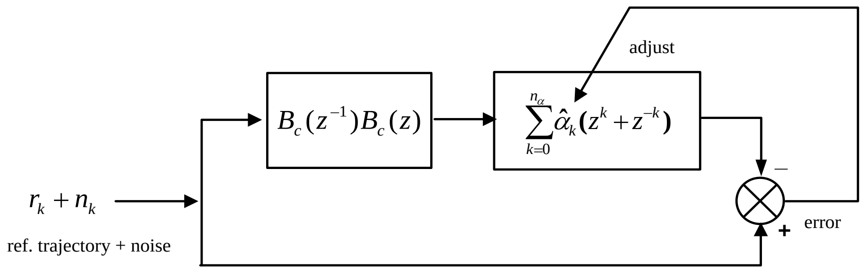



Figure 4. Computing gain compensation filter coefficients

## IV. TRAJECTORY ADAPTIVE ZPETC SCHEME

The proposed trajectory adaptive ZPETC is given in figure 5. In order to ensure the generated signal will always persistently exciting, a low level noise signal, which has its frequency spectrum close to the trajectory signal frequency spectrum is superimposed to the reference trajectory. The additions of noise to this reference trajectory will not adding extra disturbance to the system, as the noisy reference trajectory will pass through the tracking system. In these real-time studies, the controller parameters are first adaptively computed offline before the actual control, which means the use of fixed controller parameters throughout the whole operation.

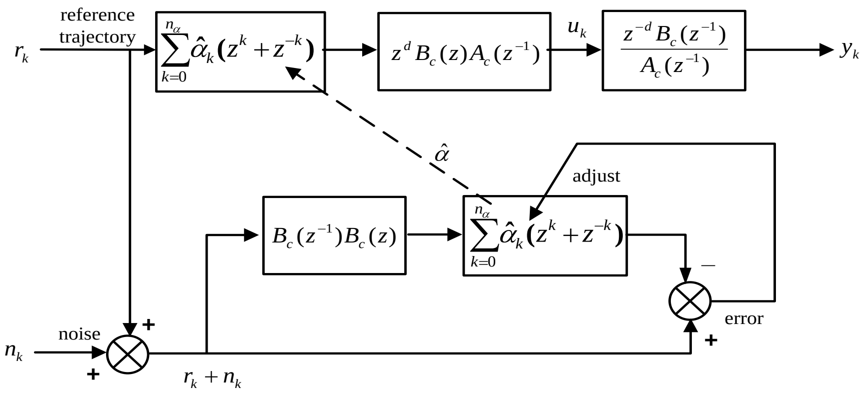



Figure 5. Trajectory adaptive ZPETC structure

## V. EXPERIMENTAL SET-UP

The experimental equipment that used in these real-time studies is an electro-hydraulic system that is shown in figure 4. The hydraulic cylinder was held in vertical position. This is a very challenging problem as effect of gravity is trivial. The electro-hydraulic system consists of single-ended cylinder type of actuator. The bidirectional cylinder has 150 mm stroke length; 40 mm bore size and 25 mm rod size. The wire displacement sensor is mounted at the top of cylinder rod. The pressurized fluid flow is control by electronic control valve.

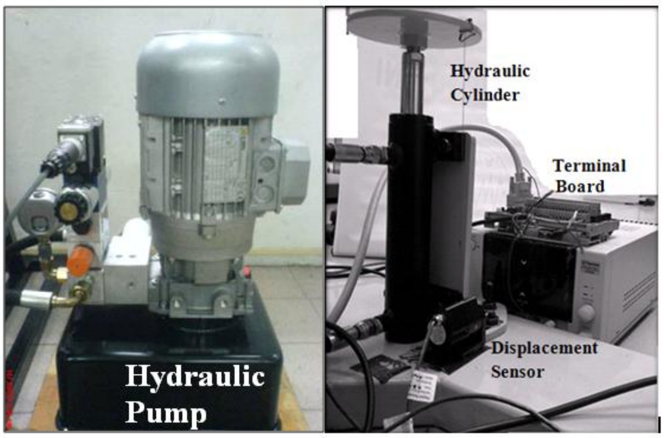



Figure 6. Electro Hydraulic Actuator

The schematic diagram of complete experimental set-up is given in Figure 7. The interfacing between the computer and plant was done using Matlab Real-Time Workshop via Advantech PCI-1716 interface card.

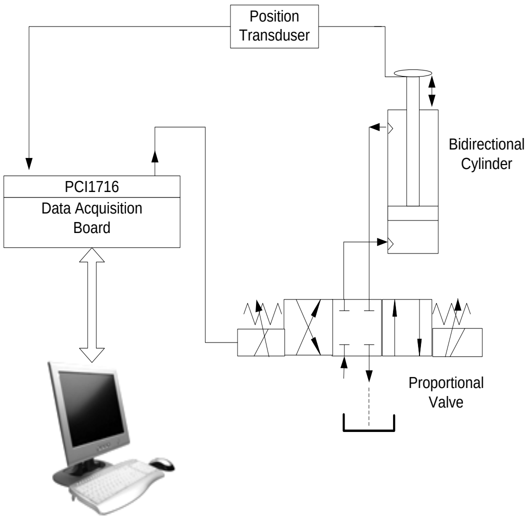



Figure 7. Experimental setup for electro-hydraulic system

## VI. PLANT MODEL

The plant model that used in these studies was obtained through open-loop experiment on the Electro-hydraulic system of figure 6. The open-loop transfer function of the plant was approximated using Matlab System Identification Toolbox. The signal given in figure 8 was used as an input signal to the plant for model identification. The signal was generated using three different frequencies based on Eq. (6) and represented by Eq. (7).

$$u(k) = \sum_{i=1}^{p} a_i \cos \omega_i t_s k \tag{6}$$

$$V_{in}\,(k) = 2\,Cos\;0.3\;t_s k + 2\,Cos\;4\;t_s k + Cos\;6\;t_s k \tag{7}$$

where $a_i$ is the amplitude, $\omega_i$ is the frequency (rad/sec), $t_s$ is the sampling time (sec) and $k$ is integer. From Eq. (7), when using three different frequencies for input signal, 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 with input-output signals sampled at 50ms was selected to represent the nearest model of true plant.

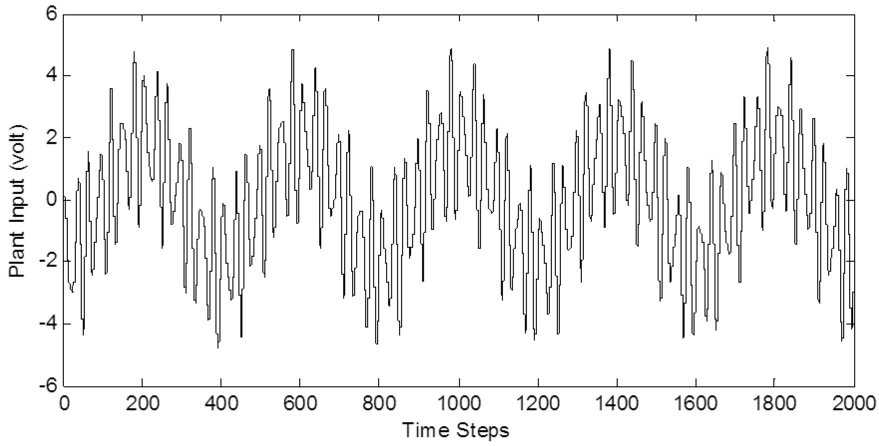



Figure 8. Input signals for model identification

The output signal of the plant obtained using the input signal of figure 5 and sampled at 50 ms, is given in figure 9. The input and output signals of Figure 8 and Figure 9 were divided into two parts, i.e. (500-1000) samples and (1001-1500) samples. The first part of the input – output signals was used to obtain the plant model and the second part of the input-output signals was used to validate the obtained model.

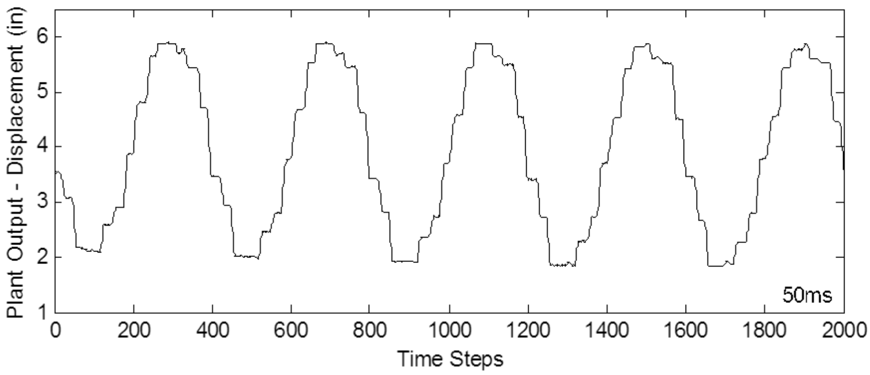



Figure 9. Output signal of the plant using 50 ms sampling time

Using Matlab System Identification Toolbox, the first part of the input-output signal produces a plant model, ARX331 in the form of discrete-time open-loop transfer function as follows:

$$\frac{B_o(z^{-1})}{A_o(z^{-1})} = \frac{0.0087z^{-1} + 0.0037z^{-2} - 0.0088z^{-3}}{1 - 1.5800z^{-1} + 0.3938z^{-2} + 0.1861z^{-3}} \quad (8)$$

From Eq. (8), its can be simplified as

$$\frac{B_o(z^{-1})}{A_o(z^{-1})} = \frac{0.0087z^{-1}(1+0.4232z^{-1}-1.0148z^{-2})}{1-1.5800z^{-1}+0.3938z^{-2}-0.1861z^{-3}} \quad (9)$$

From Eq. (9), the zeros polynomial is given by

$$B_c(z^{-1}) = 1+0.4232z^{-1}-1.0148z^{-2} \quad (10)$$

$$B_c(z) = 1+0.4232z-1.0148z^2$$

When Eq. (10) is factorized, the locations of zero are at z = 0.8178 and z = -1.2410. This means that the model obtained is a non-minimum phase model with a zero situated outside the unity circle. A non-minimum phase model can be obtained using small sampling time whereas minimum phase model can be obtained using larger values of sampling time [17]. The pole-zero plot of Eq. (10) is given in figure 10.

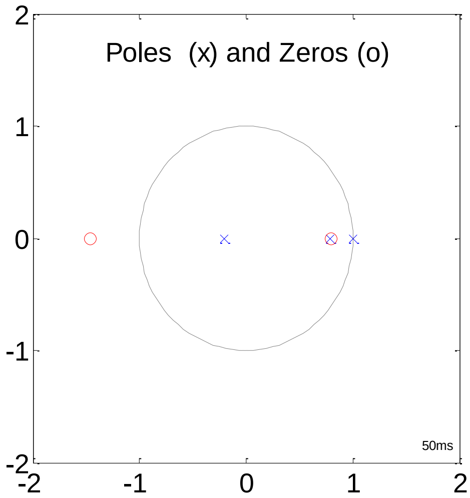



Figure 10. Pole-zero plot of Eq. (10)

The second part of input-output signals was used to validate the obtained model of Eq. (8). The second part of the input signal was used as an input to the model and the output from the model was compared with the second part of the output signal. The result can be seen from figure 11. Using model selection criterions, the following information were obtained:

| | |
|---|---|
| Best Fit : | 89 % |
| Loss Function : | 3.292 $e^{-005}$ |
| Akaike's Final Prediction Error, FPE: | 3.371 $e^{-005}$ |

Based on the smallest values criteria of FPE and Best Fit of 89 %, this model can be accepted.

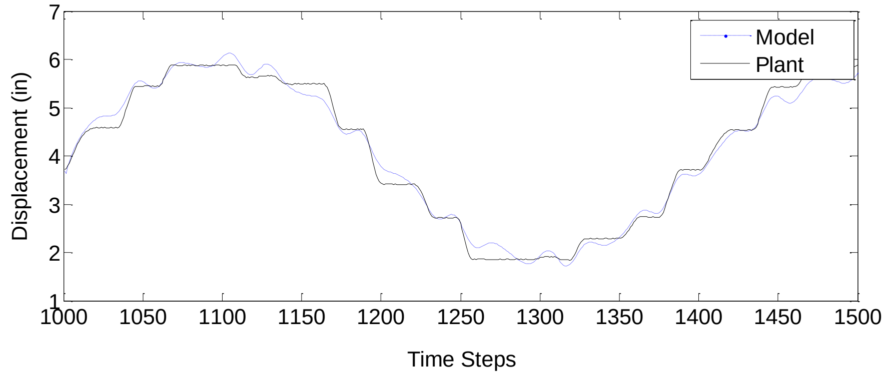



Figure 11. Comparison between the model and plant output signal

## VII. REAL TIME STUDIES

The tracking control structure that used for real-time studies is shown in figure 12. The structure is divided into two parts: feed-forward control; and feedback control. The feed-forward control block is using the trajectory ZPETC where the optimum controller parameters are obtained offline using recursive least square (RLS) method. The feedback control block is using pole-placement method to determine its controller parameters.

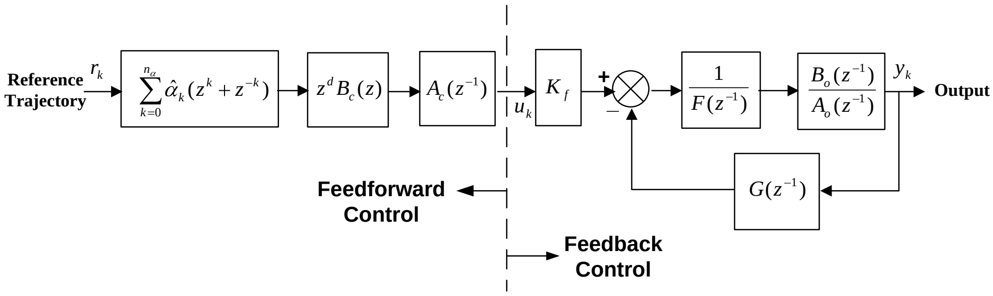



Figure 12. Tracking structure for real-time studies

## VIII. FEEDBACK CONTROL SYSTEM

The feedback control system for the proposed trajectory ZPETC system is given in figure 13. The controller was designed using pole-placement method.

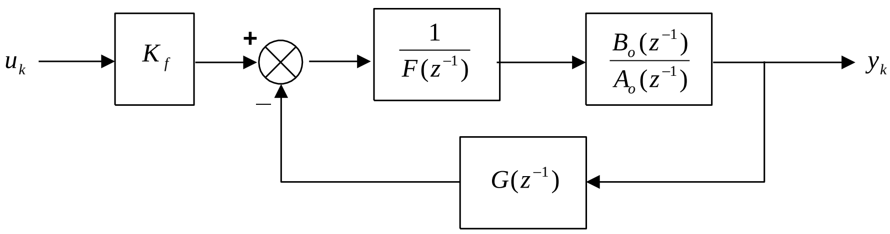


Figure 13. Feedback controller using pole-placement method.

This method enables all poles of the closed-loop to be placed at desired location and providing satisfactory and stable output performance. All controller parameters were obtained by solving the following Diophantine equation to solve for $F(z^{-1})$ and $G(z^{-1})$.

The closed-loop transfer function of the system is given by:

$$\frac{Y(z^{-1})}{U(z^{-1})} = \frac{K_f B_o(z^{-1})}{A_o(z^{-1})F(z^{-1}) + B_o(z^{-1})G(z^{-1})} \tag{13}$$

where

$$A_o(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + \cdots + a_n z^{-n}$$
$$B_o(z^{-1}) = b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} + \cdots + b_m z^{-m}$$
$$F(z^{-1}) = 1 + f_1 z^{-1} + f_2 z^{-2} + f_3 z^{-3} + \cdots + f_m z^{-m-1}$$
$$G(z^{-1}) = g_0 + g_1 z^{-1} + g_2 z^{-2} + g_3 z^{-3} + \cdots + g_{n-1} z^{-n-1}$$

Using Diophantine equation to solve for $F(z^{-1})$ and $G(z^{-1})$,

$$A_o(z^{-1})F(z^{-1}) + B_o(z^{-1})G(z^{-1}) = T(z^{-1}) \tag{14}$$

with $T(z^{-1}) = 1 + t_1 z^{-1}$ and $t_1$ is the location of a pole in a unit circle. The range of $t_1$ is $0 < t_1 < 1$. For slow response, $t_1$ is set large and for fast response, $t_1$ is set small. The forward gain $K_f = \frac{Sum(T)}{Sum(B_o)}$.

In this paper, we used $t_1 = 0.82$ since the tracking required slow response. Attempts have been made to use small values of $t_1$, but the responses are very fast and producing large tracking errors. Using developed Visual C++ console programming and Matlab/Simulink, the following parameters were computed:

$$T = 1 - 0.82z^{-1}$$
$$K_f = 50$$
$$F(z^{-1}) = 1 + 0.2189z^{-1} - 0.2165z^{-2}$$
$$G(z^{-1}) = 62.1614 - 6.9397z^{-1} - 4.5606z^{-2}$$

## IX. RESULTS AND DISCUSSION

In this section, the real-time results were analyzed to show the effectiveness of the designed controller. The reference trajectory signal of figure 14 was used in the real-time studies of non-minimum phase model. As we can observe from that figure, for time steps of 0-350, low frequencies are used. But, for the 350-600 time steps, higher frequencies are used. The shape of this signal was purposely chosen to demonstrate the ability of the controller to track the trajectory with changing frequency components.

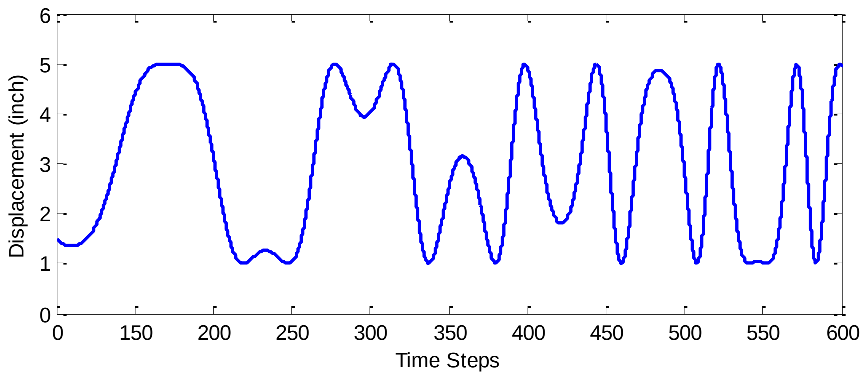
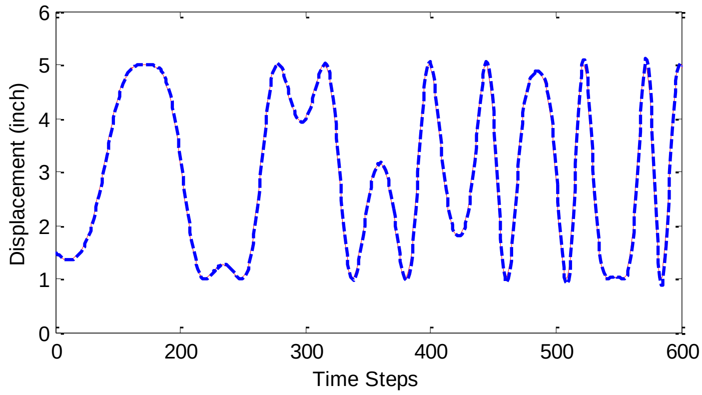


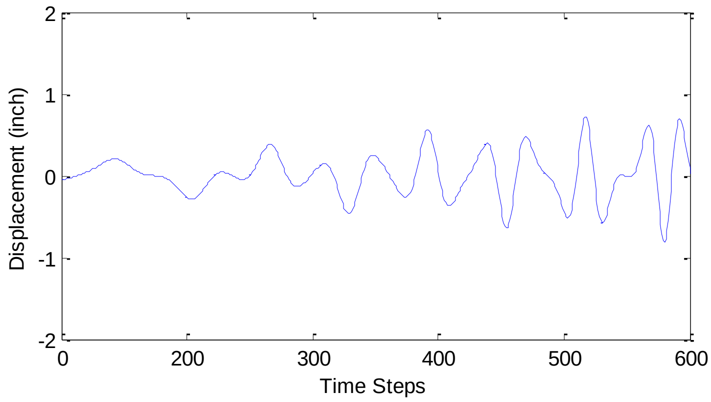

Figure 14. Reference trajectory signals, $r_k$

Firstly, a feedback control system using pole-placement method without feedforward, ZPETC controller was applied to observe its tracking performance. A high root mean square tracking error of 0.0907 inch was obtained. We can observe in figure 15(a), that the plant tracking is almost perfect as the overlapping between the two signals is difficult to been seen. Their different can only be seen when the view of 350-600 time steps is enlarge as given in figure 15(d). From figure 15(b), we can observe that for 300-600 time steps, high tracking error occurred when there are changes in dominant frequencies of reference trajectory. Therefore, feedforward controller is required to pre-shape the reference signal so that more emphasis to the frequency components that were not sufficiently handle by the feedback system can be provided.

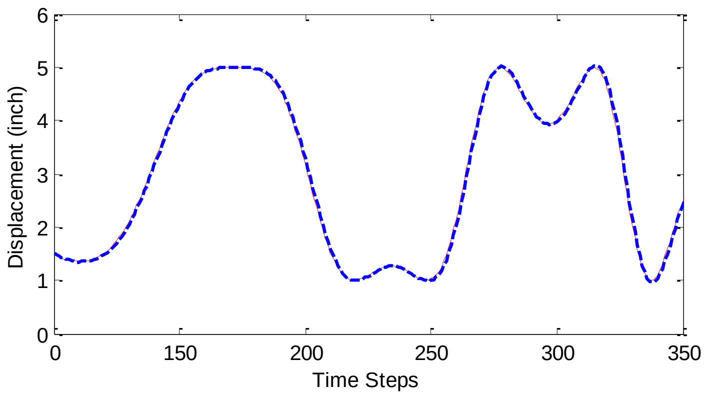



(a) Tracking

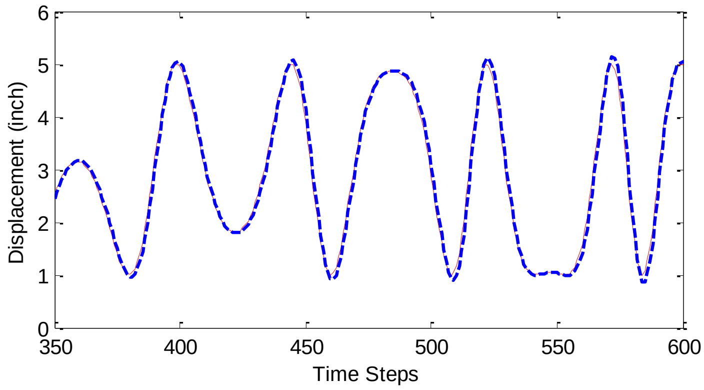
Ref  Output




(b) Tracking Error



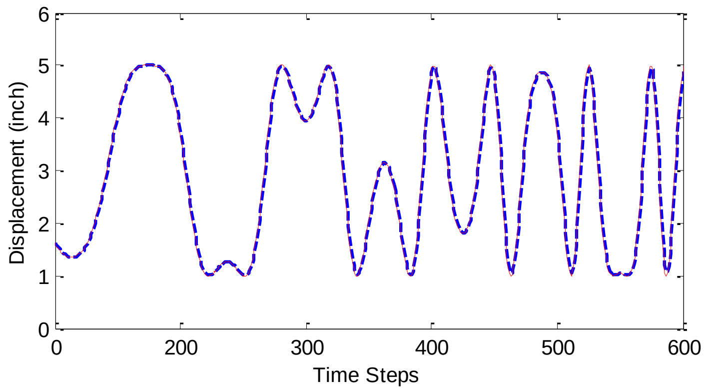

(c) Enlargement view




(d) Enlargement View

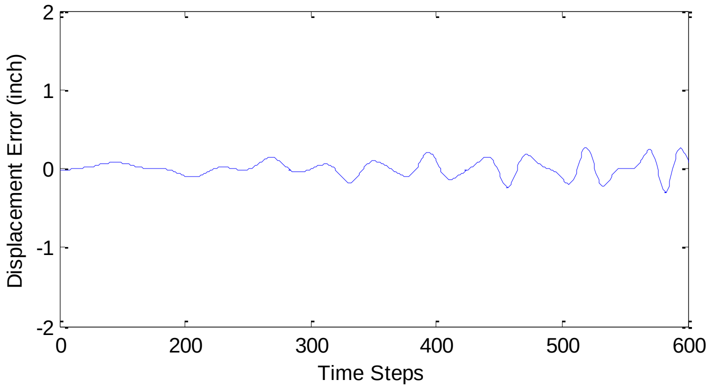
Figure 15. Experimental results using feedback control system with RMSE 0.0907 inch.

Next, we apply feedforward, ZPETC controller proposed by Tomizuka [13] . The obtained experimental result is given in figure 16 with r.m.s tracking error of 0.0812 inch. If we compare this tracking performance with the one given in figure 15, it is obvious that the tracking error has been reduced. From figure 16(a), the plant tracking is almost perfect as the overlapping between the two signals is difficult to be seen. From 16(b), and figure 16(c, d) that have been enlarge, tracking error improved compare with the one given in figure 15(b) and 15(d). This is because the controller was able to approximate the overall system transfer function close to unity for all frequencies. Therefore for accurate position tracking, it requires feedforward control. However, the gain error that cannot be cancelled by ZPETC will increase for high-speed tracking that cause undesired effect to tracking performance.

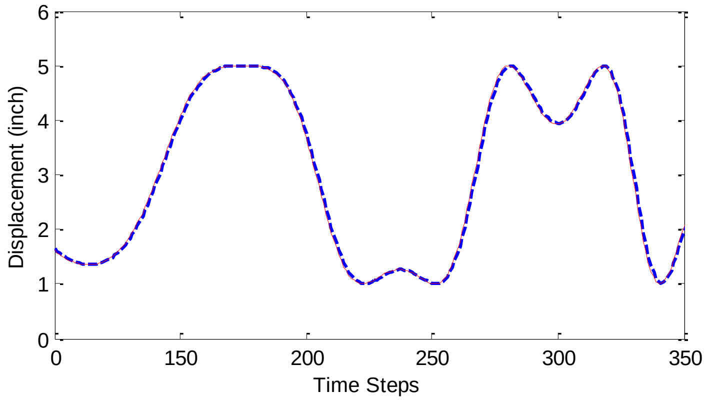



(a) Tracking

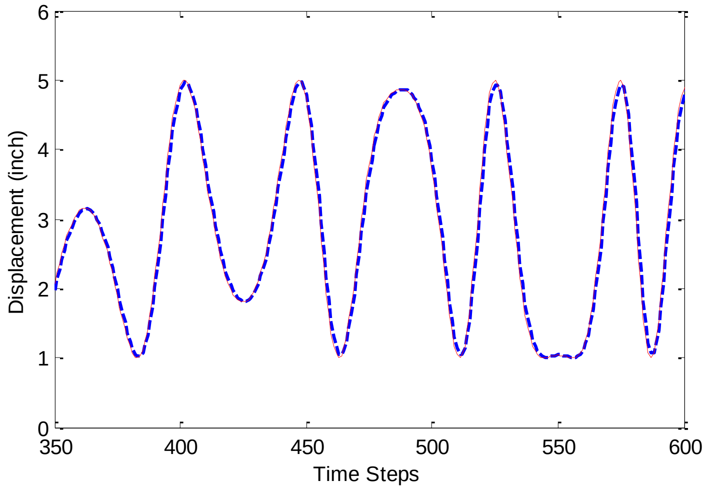
Ref — Output - - -




(b) Tracking Error




(c) Enlargement View




(d) Enlargement View

Figure 16. Experimental results using Tomizuka method with RMSE 0.0812 inch

With objective to reduce tracking error further, we apply the propose ZPETC with fixed controller parameters obtained by adaptive method given in figure 4. In order to determine the correct filter order to be used in the trajectory ZPETC, the frequency response of the ZPETC given in figure 3 are plotted using the transfer functions of plant model. The resulting frequency response is given in figure 17. From figure 17, it can be observed that an approximate overall unity gain can be achieved when using filter order, N≥20.

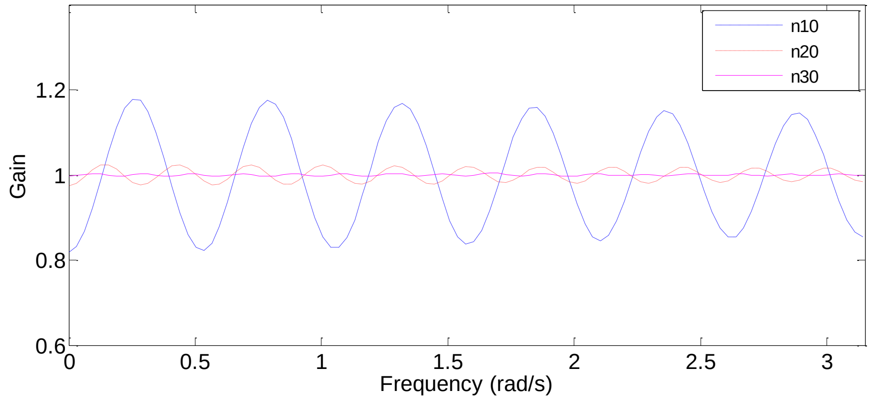



Figure 17. Frequency response of 10th,20th and 30th order of proposed ZPETC

The real-time experimental results are shown in figure 18, figure 19 and figure 20. From the graph, it is observed that the tracking error is very flat for N≥20. The root mean square (RMS) of tracking error for N=10 is 0.2106 inch, for N=20 is 0.0282 inch and for N=30 is 0.0030 inch. It can be deduced that the higher the N, the better will be the root mean square of tracking error. From figure 18, we can observe that high tracking error had occured. These are due to the approximate controller parameters are still in the process of adaptation and not yet converged. The problem of longer converging time can be shorten when using higher filter order, N. The effect can be observed from the real-time result given in figure 19 dan 20, when the filter order is increase. The resulting rms tracking error is much better than the tracking error when using conventional ZPETC that the one given in figure 16. This is because higher controller order can produce an overall transfer function very much closer to unity due to larger degree of freedom.

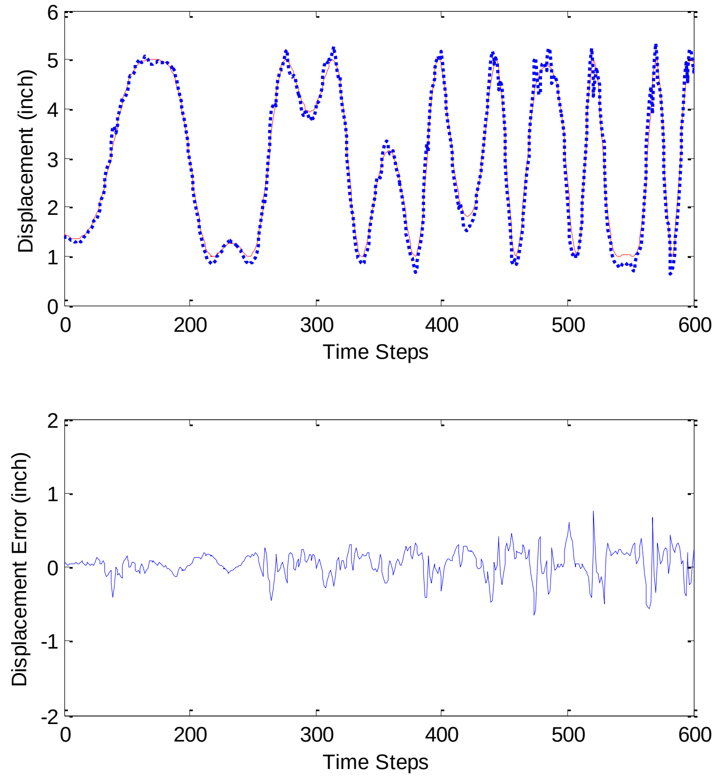



Figure 18. Experimental result using 10th order proposed ZPETC with RMSE 0.2106 inch

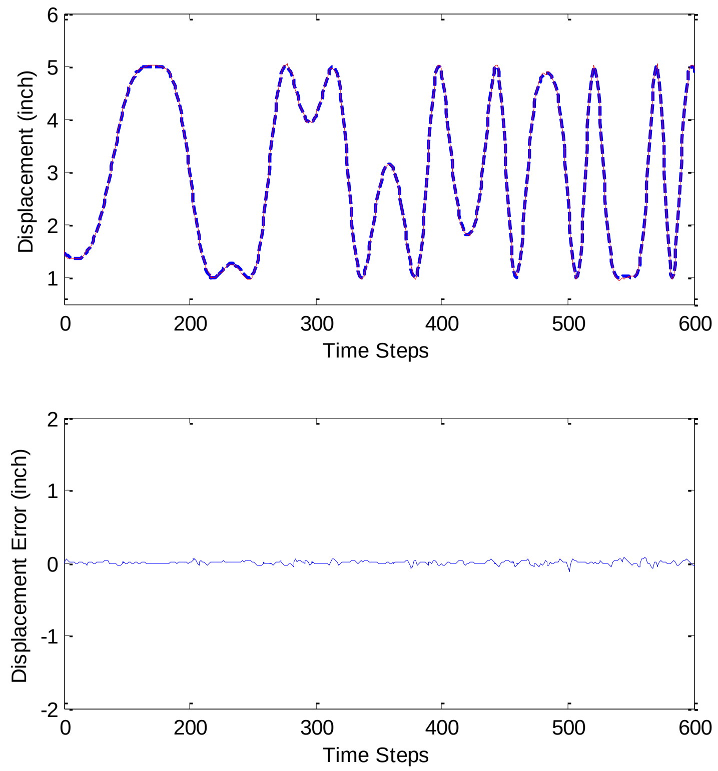



Figure 19. Experimental result using 20th order proposed ZPETC with RMSE 0.0282 inch

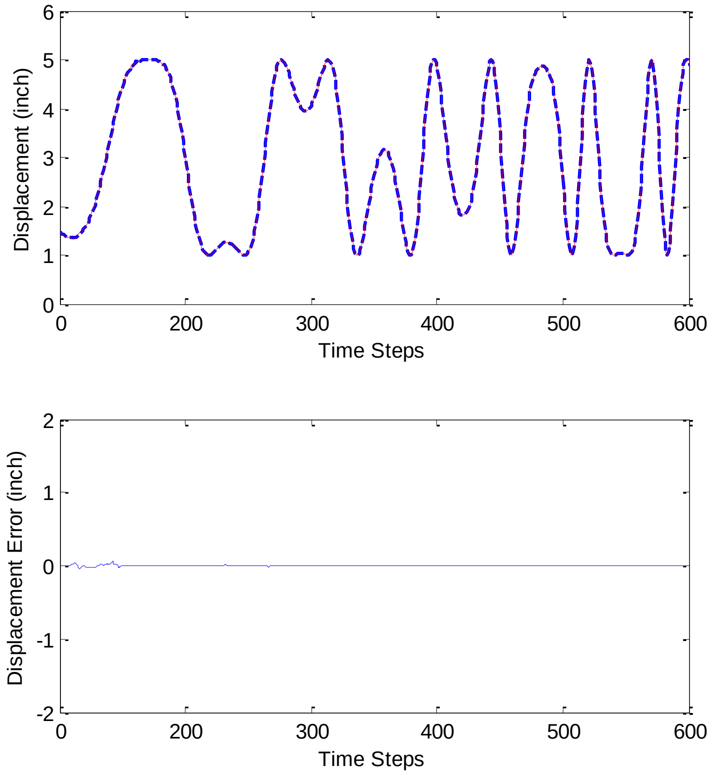



Figure 20. Experimental result using 30$^{th}$ order proposed ZPETC with RMSE 0.0030 inch

## X. CONCLUSIONS

The implementation and experimental results of real-time digital tracking control of hydraulic actuator using the proposed controller design based on trajectory ZPETC without factorization of zeros polynomial has been presented. Experimental results show that the proposed method can provide satisfactory tracking performances to a non-minimum phase hydraulic actuator system. Experimental results show good tracking performances when higher order filter was used in the design. A much smaller tracking error cannot be achieved due to plant-model mismatch and electronic valve open-close capability. Hence, the implementation of the proposed controller on the electro-hydraulic actuator system can offer a significant improvement in modern equipment positioning applications.


## ACKNOWLEDGMENT

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