Abstract—Hydraulic actuator has been widely used in industrial applications because it exhibits linear movements, fast response and accurate positioning of heavy load. In automotive technology, it is used to develop active suspension systems, which are applied as road profile generator and actuator. Reducing the position tracking error of the hydraulic system is a challenging task. This paper presents the development and implementation of feedforward Zero Phase Error Tracking Control (ZPETC) in controlling the position variation of electro-hydraulic actuator. The electro-hydraulic system mathematical model is approximated using system identification technique with non-minimum phase system being considered. The performance of the controller is analysed through simulation and real-time experiment using Matlab Simulink environment. The system is further improved by introducing an error filter to the feedforward controller to increase frequency bandwidth. Both controller performances are compared and the result shows significant improvement.

Keywords—Feedforward Control, ZPETC, Error Filter, Real-time Control, System Identification

I. INTRODUCTION

HYDRAULIC actuator system has gained popularity in many applications such as paper mills, aircrafts and automotive industries where linear movement, fast response and accurate positioning with heavy loads are required. However, the nonlinear properties of hydraulic cylinder become the challenge in designing a perfect controller for this actuator. Difficulties in identifying an accurate model of inherently nonlinear and time-varying dynamics make controller design more complicated. The natural nonlinear property of hydraulic cylinder had challenge researchers in designing suitable controller for motion control or tracking control [1]. With intention to improve the motion or tracking performance, many researchers have used advanced control strategies to control hydraulic cylinder [2]. In this paper, feedforward zero phase error tracking controller proposed by Tomizuka [3] for non-minimum phase plant was designed and implemented. The plant transfer function was identified from the electro-hydraulic actuator. The non-minimum phase zeros cannot be fully compensated by feedback controller. For accurate position tracking, it requires feedforward controller.

However, non-minimum phase zeros are difficult to be compensated perfectly by classical feedforward control because the direct inverse of zeros become unstable poles [3]. Fortunately, zero phase error tracking control provides a strategy to control non-minimum phase system by eliminating phase error caused by non-minimum phase zeros. In order to improve the tracking performance, several strategies have been proposed in [4-7]. In this paper, by cascading an error filter to ZPETC, it can achieve a significantly improved bandwidth in the gain frequency response.

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

II. PLANT AND MODEL IDENTIFICATION

A. Plant

Hardware set-up in these real-time studies is an electro-hydraulic system that is shown in Fig. 1. 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. This control valve is of proportional and directional type. The valve input voltage is ±10V dc with current range 4-20 mA.

Fig. 1 Electro-Hydraulic System

B. Model Identification

The data collection for input-output open-loop test of the plants was done using MATLAB Real-time workshop via Advantech PCI-1716 interface card. The input signal used

N.Ishak, M.Tajjudin, M.H.F.Rahiman, R.Adnan, is with Faculty of Electrical Engineering, University Teknologi MARA (UiTM) Shah Alam, Selangor, Malaysia (email: norlelaishak@salam.uitm.edu.my).

H.Ismail, with Faculty of Engineering, University Selangor Bestari Jaya, Selangor, Malaysia (email: hashimah@unisel.edu.my).

Y.M. Sam, with Faculty of Electrical Engineering, University Teknologi Malaysia (UTM) Skudai, Johor, Malaysia (email: yahaya@fke.utm.my).
for model identification was generated using three different frequencies as represented by Eq. (1)

\[ u(k) = \sum a_i \cos \omega t_i k \]  

(1)

where \( a_i \) is the amplitude, \( \omega_i \) is the frequency (rad), \( t_i \) is the sampling time (sec) and \( k \) is integer. When the system was perturbed by a signal up to third harmonics, the model that can be obtained is limited to second and third order only. Higher orders model may produce unstable output [11].

III. CONTROLLER DESIGN

A. Feed-forward Controller Design

This section presents a two-degrees-of-freedom controller consisting of feedback and feed-forward controllers. The overall block diagram is given in Fig.2. The feed-forward controller is required in addition to the closed-loop feedback system to achieve superior tracking.

Let the closed-loop system be represented by the following discrete time model:

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

(2)

Where

\[ A_c = 1 + \alpha_1 z^{-1} + \alpha_2 z^{-2} + \ldots + \alpha_n z^{-n} \]

\[ B_c(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots + b_n z^{-n} \]

\( d \) = time delay

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

\[ B_c(z^{-1}) = B_c^+(z^{-1})B_c^-(z^{-1}) \]  

(3)

where \( B_c^+(z^{-1}) \) denotes the minimum phase factor and \( B_c^-(z^{-1}) \) denotes the non-minimum phase factor.

The ZPETC reported in the literature [8] can be divided into three blocks as shown in Fig. 3.

B. Error Filter Design

In order to improve the performance of feedforward ZPETC, an error filter which proposed by Haack and Tomizuka [5] is added to the system. The original ZP ET C is modified by adding an error cancellation filter to widen the frequency bandwidth. The modified controller is given in Fig. 4. The overall block diagram of tracking control with ZPETC Haack and Tomizuka is given in Fig. 5, with transfer function:

\[ \frac{y(k)}{r(k)} = \frac{B_c^-(z)B_c^+(z^{-1})}{[B_c^-(1)]^2 (1 - b)(z - b)} \]  

(4)

Fig. 2 Two-degree-of-freedom controller

Fig. 3 Tomizuka ZPETC structure block diagram

Fig. 4 ZPETC Haack and Tomizuka structure block diagram

Fig. 5 Overall block diagram with ZPETC Haack and Tomizuka structure

The frequency responses of the overall system with ZPETC controller and ZPETC controller with error filter (EFILTER) are given in Fig. 6. The frequency response gain remains close to 1 in a low frequency range as compared to the desired response of unity gain for all frequencies. Moreover, as shown in Fig. 6, the bandwidth of ZPETC system with error filter is significantly improved.

Fig. 6 Frequency response using ZPETC compare with ZPETC plus EFILTER

C. Feedback Controller Design

The feedback controller was designed using pole-placement method [9, 10] as given in Fig. 7. This method enables all poles of the closed-loop to be placed at desired location to produce stable output performance.

Fig. 7 Feedback controller using pole-placement method
In this system, the location of poles $T(z^{-1})$ were required. Using $T(z^{-1})=1+tz^{-1}$, only one pole position is considered at $t=-p$ which is inside the unity circle. Other poles cancelled each others. The range of $p$ is $0<p<1$. For slow response, $p$ is set large and for fast response, $p$ is set small. The forward gain is given as $K_f=\text{Sum}(T)/\text{Sum}(B_o)$. Detailed literature and solution to find vector $F$ and $G$ can be obtained from [11]. The computed controller parameters are as follows:

$$T = 1 - 0.88 z^{-1}$$

$$K_f = 92$$

$$F(z^{-1}) = 1 - 3.3459 z^{-1} + 4.4449 z^{-2}$$

$$G(z^{-1}) = -594.557 - 712.341 z^{-1} - 26.828 z^{-2}$$

IV. RESULT AND DISCUSSIONS

In this section, the simulation and real-time results were analyzed to show the effectiveness of the designed controller. The reference signal with time-varying frequency is given in Fig. 8. The shape is chosen such that to demonstrate the ability of the controller to track the reference signal with changing frequency components.

Firstly, a feedback control system using pole-placement method without feedforward, ZPETC controller was applied to observe its tracking performance. This can be observed from the RMSE index given in Table I. A high root means square (RMSE) tracking error of simulation and real-time results were obtained. Therefore, feedforward controller is required to pre-shape the reference signal so that more emphasis to the frequency components that were not sufficiently handled by the feedback system can be provided.

Next, a feedforward, ZPETC controller as proposed by Tomizuka [3] was applied. The obtained real-time experimental results are given in Fig. 9, Fig. 10 and Fig. 11. Comparing this tracking performance as given in Table I with the pole-placement, it is obvious that the tracking error has been greatly reduced. This is because of its improved bandwidth, as given shown in Fig. 6.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Pole-Placement</th>
<th>ZPETC</th>
<th>Adding Error Filter</th>
<th>Pole-Placement</th>
<th>ZPETC</th>
<th>Adding Error Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>0.0392</td>
<td>0.0348</td>
<td>0.0291</td>
<td>0.0471</td>
<td>0.0434</td>
<td>0.0405</td>
</tr>
</tbody>
</table>

In order to reduce tracking error further, an error filter is applied by cascading it with feedforward, ZPETC controller. The obtained real-time experimental results are given in Fig. 12 and Fig. 13. Comparing this tracking performance with the previous feedforward, ZPETC, it is obvious that the tracking error has been greatly reduced. This is because of its improved bandwidth, as shown given in Fig. 6.

Fig. 8 Reference signal with time-varying frequency

Fig. 9 Experimental Result using pole placement

Fig. 10 Experimental Result using ZPETC

Fig. 11 Tracking Error using ZPETC

Fig. 12 Experimental Result with Error Filter
The performance between the simulation studies shows good response compare with real-time result. This is due to the ability of electronic valve to open and close at its capability rate.

V. CONCLUSIONS

In this study, a real-time tracking control using feed-forward ZPETC and also with feed-forward ZPETC cascaded to error filter has been successfully developed and applied to electro-hydraulic actuator for quarter car system. The error filter (E-Filter) is a simple enhancement to reduce the error of the electro-hydraulic actuator for quarter car system. The error filter had achieved better tracking performance with time. The simulation analysis showed that the ZPETC with error filter had achieved better tracking performance with variation to reference input signal as compared to by experiment due to plant-model mismatch and plant limitation.

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REFERENCES


Norlela Ishak was born in Perak, Malaysia on February 12, 1968. She received the Bachelor of Engineering (Hons) in Electronic and System Engineering from Leeds Metropolitan University UK, in 1997 and Master of Engineering in Electrical-Mechatronics and Automatic Control from University Teknologi Malaysia (UTM) in 2006. She is now doing Ph.D degree in Electrical Engineering in Universiti Teknologi MARA (UiTM). She works with Universiti Teknologi MARA (UiTM) as a lecturer in faculty of electrical engineering since August 2002 till now. Her current research interests are on system identification, tracking control and adaptive control.

Mazidah Tajjudin was born in Kedah, Malaysia on 16th November 1978. She received the B.Eng. degree in Electrical (Control and Instrumentation) and the M.Eng. degree in Mechatronic and Automatic Control, both from Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia, in 2000 and 2002, respectively. She received her PhD degree in System Identification from Universiti Teknologi Malaysia in 2009. He is currently a senior lecturer at Universiti Teknologi MARA (UiTM), Malaysia. His major research interests include essential oil extraction process automation, process control and optimization algorithms.

Mohd Hezri Fazalul Rahman was born in Perak, Malaysia on 22nd February 1978. He received the B.Eng. degree in Electrical (Control and Instrumentation) and the M.Eng. degree in Electrical Engineering from Universiti Teknologi Malaysia (UTM), Skudai, Malaysia, in 2000 and 2002, respectively. He received his PhD degree in System Identification from Universiti Teknologi Malaysia in 2009. He is currently a senior lecturer at Universiti Teknologi MARA (UiTM), Malaysia. His major research interests include essential oil extraction process automation, process control, and system identification.

Ramli Adnan was born in Perak, Malaysia on 8 September 1962. He received his B. Sc. in Electrical Engineering from SDSU, South Dakota, USA in 1985 and M.Sc. in Electrical Engineering from Drexel University, Philadelphia, USA in 1993. He was then pursue his PhD in Electrical, Electronic and System Engineering from Universiti Kebangsaan Malaysia (UKM) in 2007. Currently, he is an Associate Professor at Universiti Teknologi MARA, Malaysia. His research interests include tracking control, adaptive control and system identification.

Hashimah Ismail was born in Kelantan, Malaysia, on April 17, 1977. She received the Bachelor of Engineering (Hons.) in Mechatronics from International Islamic University Malaysia, in 2002 and Master of Engineering in Electrical-Mechatronics and Automatic Control from Universiti Teknologi Malaysia in 2006. She is now doing Ph.D degree in Electrical Engineering in Universiti Teknologi MARA (UiTM). She works with Universiti Selangor (UNISEL) as a lecturer in faculty of engineering since June 2003 till now. Her current research interests are on system identification, adaptive control and mechatronics.

Yahaya Md Sam received the B.E. degree in electrical engineering from University Technology of Malaysia in 1986, M.Sc. degree in control systems engineering from Sheffield University, United Kingdom, in 1988, and the Ph.D. degree in control engineering from University Technology of Malaysia in 2004. He is currently an Associate Professor with the Faculty of Electrical Engineering, University Technology of Malaysia. His research interests include optimal control, robust control, composite nonlinear feedback and sliding mode control and application of these ideas to the automotive systems.