www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

FEED FORWARD LINEAR QUADRATIC CONTROLLER DESIGN FOR AN INDUSTRIAL ELECTRO HYDRAULIC ACTUATOR SYSTEM WITH SERVO VALVE

J. Micheal, M.F. Rahmat*, N. Abdul Wahab and W.K. Lai
Department of Control and Instrumentation Engineering, Faculty of Electrical Engineering
Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
Emails: jason_maivia@hotmail.com, fuaad@fke.utm.my, aliza@fke.utm.my,
wklai1988@gmail.com

*Correspondent author: M.F. Rahmat, fuaad@fke.utm.my

Submitted: Sep. 25, 2012 ***Accepted: Dec. 15, 2012*** ***Published: Feb. 20, 2013***

Abstract- Electro-hydraulic servo actuator (EHA) system consists of several dynamic parts which are widely used in motion control application. These dynamic parts need to be controlled to determine direction of the motion. In this research paper, system identification technique is used for system modeling and the model of the system is estimated by using parameter estimation technique. This process started with collection of input and output data from experimental procedure. The data collected is used for model estimation and Auto Regressive with eXogeneous input (ARX) model is chosen as model structure of the system. Based on the input and output data of the system, best fit criterion and correlation analysis of the residual is analyzed to determine the adequate model to represent the EHA system. Once the model is obtained, discrete PID and feed forward plus Linear

Quadratic Regulator (LQR) controller is developed to improve the performance and position tracking performance of EHA system. In order to verify these controllers, it is applied to the real time system and the performance of the system is monitored. The result obtained shows that the output of the system in simulation mode and experimental works is almost similar for both controllers. The output of the system also tracked the input given successfully. Finally, by comparing the best tuning output from these two different controllers, feed forward plus LQR controller proved to give a better output performance than the classical discrete PID controller by minimize the phase lag and reduce disturbance effect in the system.

Index terms*: Electro-hydraulic system, System identification, ARX model, PID controller, LQR controller*

I. INTRODUCTION

It is often necessary to design fast and accurate controllers for plants in which system parameters substantially change, or for plants which operate under large external disturbances. To name a few among such plants, there are robot manipulators picking and playing payloads, indexing systems of flexible forging machine which rotate inertia changing work pieces and flight control systems under large wind resistance. In order to satisfactorily control such plants, it is necessary to have an actuator that can supply sufficient instantaneous torque demanded for fast control actions and a control law which enables fast and accurate control under two factors which are internal parameter variations and external disturbances. For an actuator required for control actions, an Electro-hydraulic actuator (EHA) system appears a reasonable choice. Figure 1 shows the actual model of an EHA system.

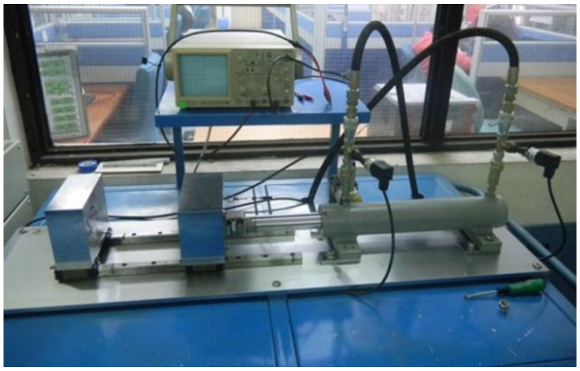

Figure 1. Model of EHA System

EHA system converts electrical signal to hydraulic power[1]. It has become one of the most important actuators in the recent decades. It offers many advantages such as good capability in positioning, fast and smooth response characteristics and high power density. Due to its capability in positioning, it has given a significant impact in modern equipment for position control applications. Its applications in position control can be found in production assembly lines, robotics, aircraft equipment and in industrial process.

However, EHA system is a complicated system which suffers from uncertainties, nonlinearities and disturbances. These inconveniences may lead to degradation of control performance in force, pressure or position tracking of EHA system[2]. Position tracking performance of EHA can be assured when its robustness and tracking accuracy are guaranteed. The robustness and tracking accuracy can be ensured when nonlinear behaviours, uncertainties and disturbances in the EHA system are compensated.

Therefore, this project is important in that it will use two different controllers which are PID and LQR in order to improve the position tracking of EHA system. Hence the accuracy and best fittings between the two controllers will be compared. It expects to contribute a significant impact in the control of modern equipment positioning applications.

II. BACKGROUND STUDY

a. Typical positioned EHA system

Hydraulic motion drives are widely used in several areas of industry, especially in application that require high forces and torque. Figure 2 shows the block diagram of a typical position controlled hydraulic system consist of a power supply, flow control valve, linear actuator, displacement transducer, and electronic servo-controller. The servo controller compares the signal from the feedback displacement to drive the flow control valve. The control valve adjusts the flow of pressurized oil to move the actuator until the desired position is attained; a condition indicate by the error signal falling to zero. A force controlled hydraulic system operates in similar way, except the oil flow is adjusted to achieve output force measured by a suitable transducer. While typical hydraulic system has relatively simple mechanical components, they are characterized by nonlinear dynamics, specifically, a square root relationship between the differential pressures that drives the flow of the hydraulic fluid and flow rate.

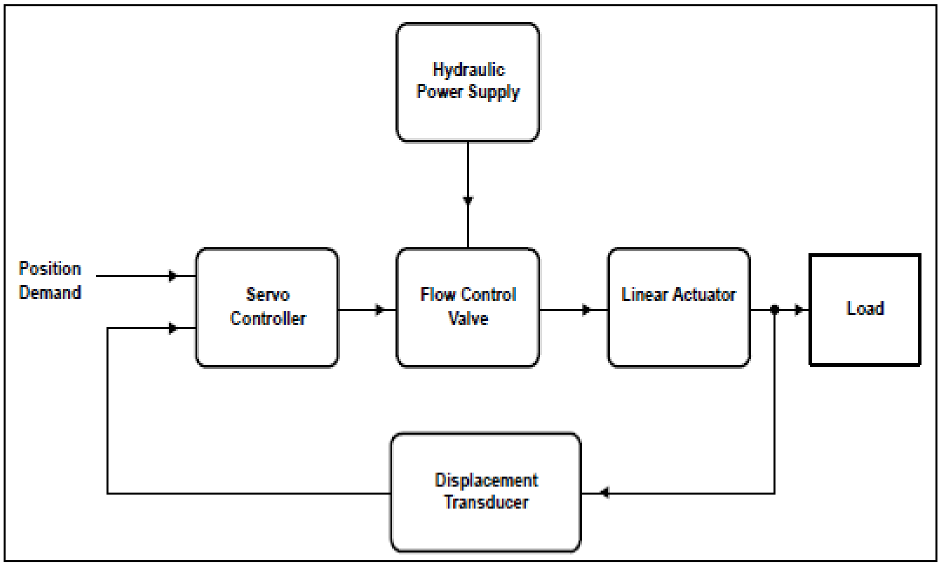

Figure 2: Block Diagram of Typical Positioned Controlled Hydraulic Actuator

b. Previous research on EHA system

A model identification method of electro-hydraulic position servo system based on system identification toolbox in MATLAB and hardware-in-the-loop simulation environment of Real-Time Workshop (RTW) has been proposed[3, 4].A new nonlinear hybrid controller composed of a proportional controller, a fuzzy controller and a classical PID controller for the model has been introduced. A similar work to identify the model of electro-hydraulic actuator also had been done (Zulfatman and Rahmat, 2009). However, the proposed PID controller for the model can only be applied in simulation mode and limited access to real time implementation.

Regarding to the existing controller design for position tracking control of the EHA system, indirect adaptive controller scheme using pole placement controller was designed in robust mode (Yu, 1996). It was followed by a simple pole placement design and applied to a linearized model of the system (Lim, 1997), and robust controller for a variable displacement hydraulic motor (Plahuta, *et. al.*, 1998). These all aforementioned controllers were designed with the consideration of linear model of the EHA system.

However, the linear controllers contain some limitations to ensure the tracking accuracy and robustness of the controller, especially for highly nonlinear problems. Therefore, nonlinear robust controllers which ensure the stability and robustness of the system were developed due to their main advantage in manipulating nonlinearities in the system (Sohl and Bobrow, 1999), combined with adaptive features for double-rod actuator (Yao, *et. al*., 2001) and single-rod actuator (Yao, *et. al*., 2001), trajectory-based (Loukianov, *et. al*., 2009). These control designs were completing with two powerful robust controllers based-Lyapunov function. They were Backstepping Mcontroller and Variable Structure Control (VSC). They commonly present in their combination with adaptive, fuzzy logic or neural networks. Backstepping controllers which constitute a powerful control strategy for handling the nonlinearities of EHA system were introduced by (Sirouspour and Salcudean, 2001), (Kadissi, *et. al*., 2007), (Zeng and Sepehri, 2008), and (Guan and Pan, 2008).

Also, there were number of efforts which employed by using artificial intelligent techniques such as ANN (Jianjun, *et. al*., 2008), and fuzzy control (Kalyoncu and Haydim, 2009). Other efforts were carried out by combining the merits of fuzzy and conventional controllers in (Shao, *et. al*., 2005) and (Kyoung, *et. al*., 2007).

c. Modeling of EHA system

A mathematical modeling model of EHA consists of the dynamics of the system disturbed by an external load and the dynamic of a servo valve. The linear differential equations that describe the actuator valve dynamics are given by,

$$\dot{\nu}(t) = \frac{1}{m}\left[AP_L(t) - b\,\nu_p(t) - F_L(t)\right] ----------(1)$$

$$\dot{P}_L = \frac{4\beta}{V}\left[K_f x_v(t) - K_f P_L(t) - A\,\nu_p(t)\right] ----------(2)$$

where,

v_p = piston velocity

P_L = hydraulic pressure

F_L = external load disturbance

x_v = spool valve displacement

A = piston surface area

m = mass of the load

β = effective bulk modulus
b = viscous damping coefficient
V = total volume of hydraulic oil in the piston chamber and the connecting lines

For zero initial conditions, the Laplace Transform of the equation (1) and (2) produced the following input-output relation,

$$U_P(s) = H(s)X_v + H_L(s)F_L(s) ----------- (3)$$

where,

$$H(s) = \frac{4\beta AK_f}{(ms+b)(Vs+4\beta K_f) - 4bA^2} ----------- (4)$$

$$H_L(s) = \frac{-4\beta AK_f - Vs}{(ms+b)(Vs+4\beta K_f) + 4bA^2} ----------- (5)$$

The transfer function of solenoid can be approximated by the servo valve spool position gain denoted by k_V. Thus, input- output relation (3) can be written as

$$U_p = H(s)k_v V_{in}(s) + H_L(s)F_L(s) ----------- (6)$$

where,
$V_{in}(s)$ = Laplace transform of the control voltage $v_{in}(t)$
Using the equation (1) and (2), linear system with uncertain structure is derived in state space form as,

$$\frac{d}{dt}x(t) = A_o(q)x(t) - B_o(q)v_{in}(t) + D_oF_L(t) ----------- (7)$$

$$y(t) = C_o x(t)$$

where,

$$x(t) = \begin{bmatrix} \upsilon_p(t) \\ P_L(t) \end{bmatrix}$$

$$A_o(q) = \begin{bmatrix} -\dfrac{b}{m} & \dfrac{A}{m} \\ -\dfrac{4q_1 A}{V} & -\dfrac{4q_1 q_2}{V} \end{bmatrix}$$

$$B_o(q) = \begin{bmatrix} 0 \\ \dfrac{4q_1 q_2 k_v}{V} \end{bmatrix}$$

$$C_o(q) = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$$D_o(q) = \begin{bmatrix} -\dfrac{1}{m} \\ 0 \end{bmatrix}$$

Thus, the mathematical model of EHA system is fully cleared and established.

III. METHODOLOGY

System identification is a process of formulating mathematical model of systems using measurement data [5].The term identification was first introduced by Zadeh [6], referring to the problem of determining the input-output relationships of a black box or modeling based on experimental data sets. Model of the system is needed as the prediction of system's behavior and aid in controller design. Stimulus signal is the signal used to excite the system so that the characteristics of system can be realised. Thus, the signal has to be rich in frequency and amplitude which excite every operation region of the system.

Good stimulus signal can assure a more accurate model. Linearization process during data taking process is Important, as EHA system is nonlinear. Without linearization, the linear estimation of the model is hard to achieve. The linearization process is done be adding an offset to the stimulus signal. After the input and output data is linearized, linear model estimation method can be applied. A linear model is used to estimate a nonlinear model as the EHA system. Linear model is used as it is the simplest, discrete time model that can represent the relationship between u(t) and y(t). Linear model is chosen over nonlinear model as linear model is much simpler than nonlinear model, while at the same time, can represent the behaviour of the real system with high precision. Thus, ARX model which is the simplest and most popular model is chosen to estimate the EHA system.

IV. EXPERIMENTAL SETUP

The experiment setup of the EHA system contains of a few main parts: hydraulic pump, piston, position sensor, servo valve, and hydraulic motor, as shown in Figure 3.

Stimulus signal is generated by a computer, using MATLAB platform, and sent to servo valve through NI-PCI-6221 card. The servo valve is the part to control the flow of hydraulic fluid and move the piston accordingly. The position of piston, which is connected to a load, is captured by wire sensor, WDS 300 p60 attached to the load. The wire sensor is able to measure up to 300mm, corresponding to the piston length, which is 300mm as well. Experiment is start by setting the piston to middle position, to enable it to perform response when stimulus signal is provided.

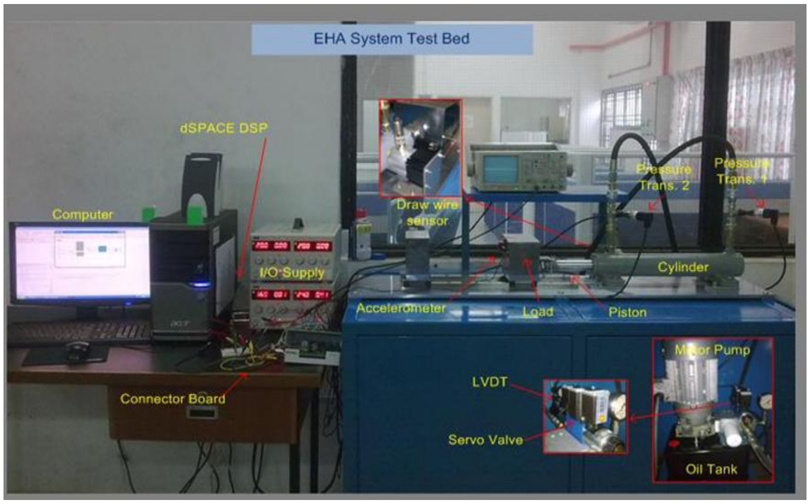

Figure 3: Experimental Setup

V. RESULTS AND DISCUSSION

Figure 4 illustrates the complete Simulink block of the system for with PID controller. The input signal excited to the signal will be in the form of step and sine input which will be act as displacement in millimeter (mm).The gain of 1/15 will be given so that the displacement (±150) will be converted to voltage (±10) for the signal to enter the system. The feedback loop will loop back and compensate the error signal and PID controller will be compensated so that system will produce the best performance. Block diagram of LQR plus feed forward controller is shown in Figure 5. Based on the figure, the LQR controller acts as a feedback control which permits the system's output to follow the desired trajectory while feed forward controller is introduced to reduce the phase lag due to feedback control problem.

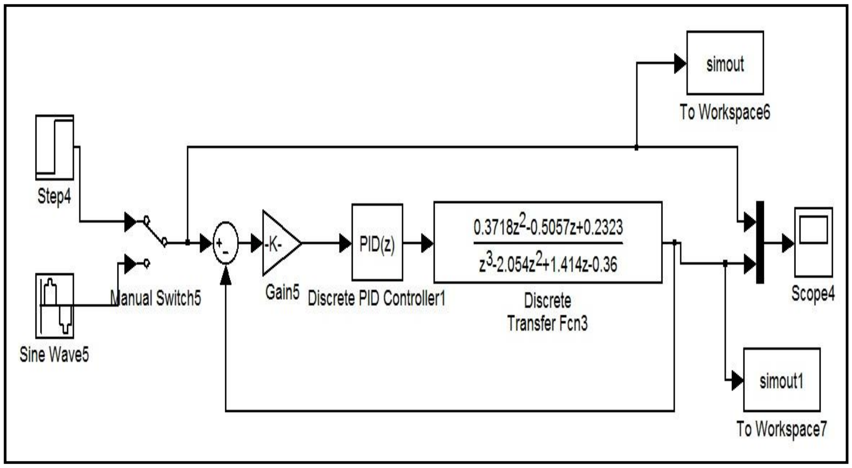

Figure 4: PID Controller Simulation Block

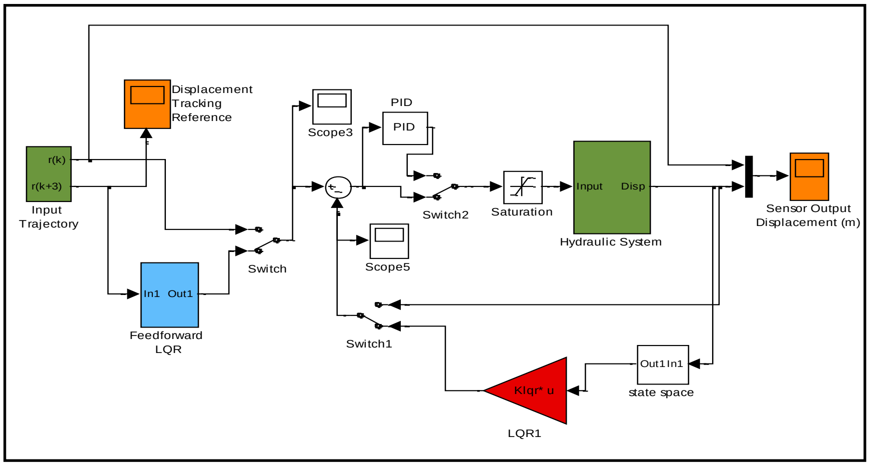

Figure 5: LQR plus Feed Forward Controller Simulation Block

a. PID controller via simulation

Response of PID controller with step and sine input in simulation are shown in Figure 7 and 8. . The critical gain for the model attained is K_c = 10.35 with critical period, T_c = 3.632. From calculation based on Ziegler Nichols tuning method and trial and error method, the PID controller's tuning parameters are obtained. The parameters are $K_p = 6.20968$, $K_i = 3.4198$ and $K_d = 2.19014$. The simulation is simulated in discrete form with 0.05second sampling time and the input reference is set to 50mm as the desired position.

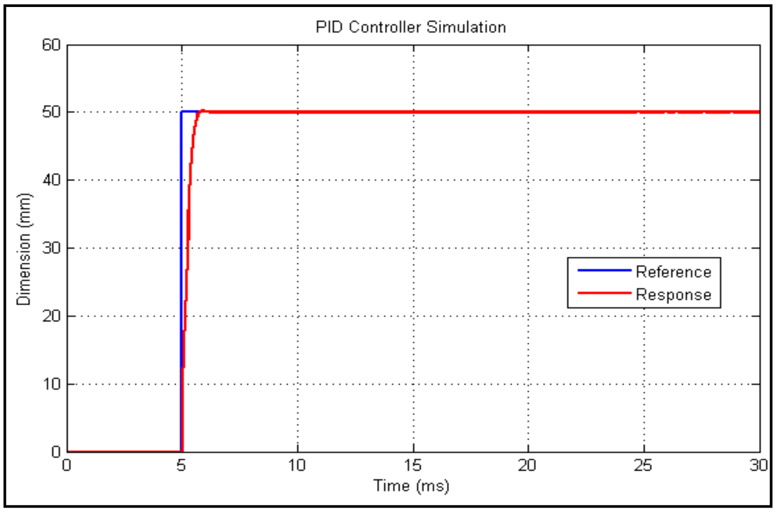

Figure 6: Response of PID Controller with Step Input (Simulation)

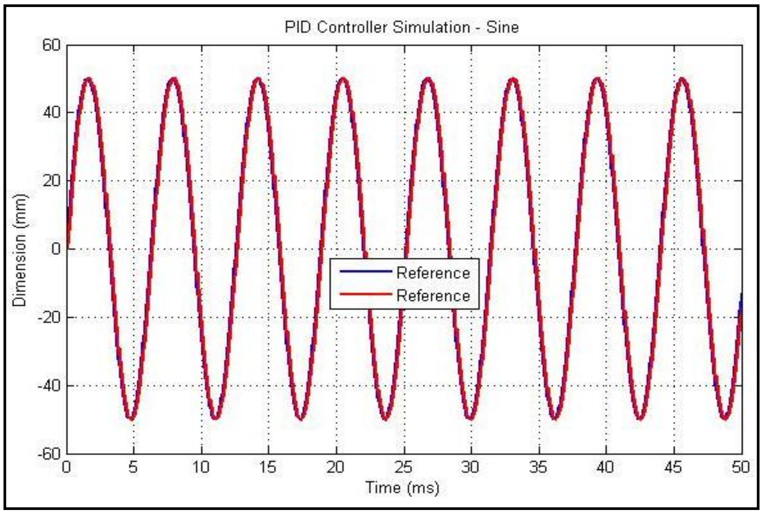

Figure 7: Response of PID Controller with Sine Input (Simulation)

Based on Figures 6 and 7, by adding PID controller in the forward path of the system, the output response of the system with step and sine input are improved. The output of the system has successfully tracked the input given with very small steady state error.

b. PID controller via experiment

The similar PID controller is then inserted in the forward path of the system in real time mode and the response is observed. The response of the system with step and sine input are revealed in Figure 8 and Figure 9 respectively. Based on the figures, the response from real time experiment is almost similar with the response attained from simulation which produces fast response time and very small steady state error. Besides, the setting value of K_p, K_i and K_d of the PID controller is acceptable and improved the performance of the system. However, a slight difference between input and output occurred especially in the step response because the EHA system which is nonlinear modelled in linear model and some nonlinearity and uncertainties characteristics are ignored.

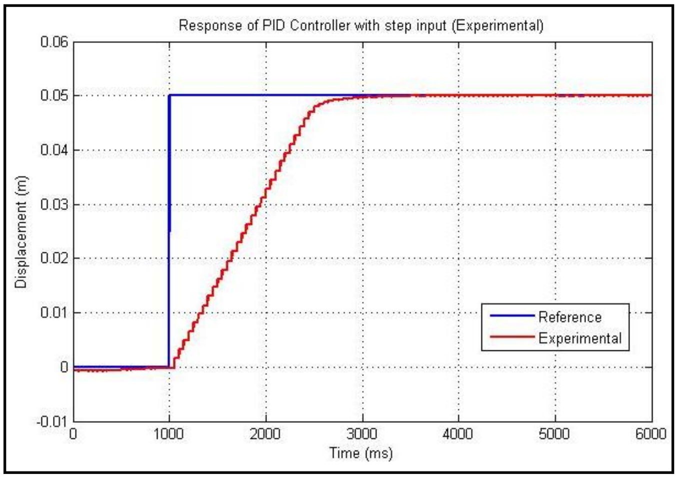

Figure 8: Response of Real-Time PID Controller with Step Input (Experiment)

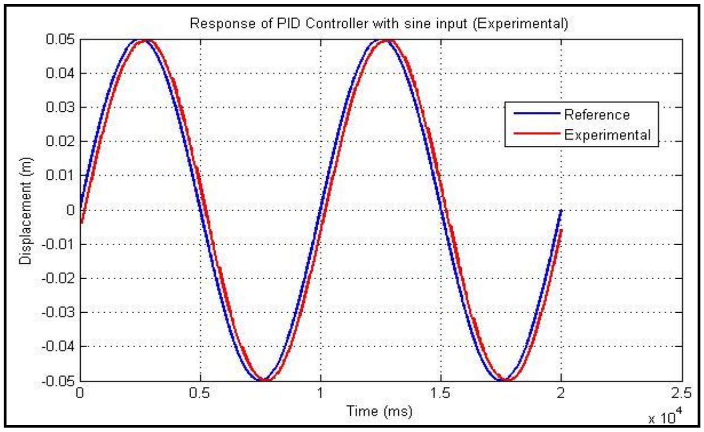

Figure 9: Response of Real-Time PID Controller with Sine Input (Experiment)

c. LQR plus feed-forward controller via simulation

LQR controller acts as a feedback control which permits the system's output to follow the desired trajectory while feed forward controller is introduced to reduce the phase lag due to feedback control problem. Figure 10 and Figure 11 shows the response of the system with LQR plus feed forward controller with step and sine input respectively. Based on the figures, it clearly shows that the proposed controller achieved good accuracy in 10mm reference trajectory and thus its shows that the linear model is capable to represent the EHA system.

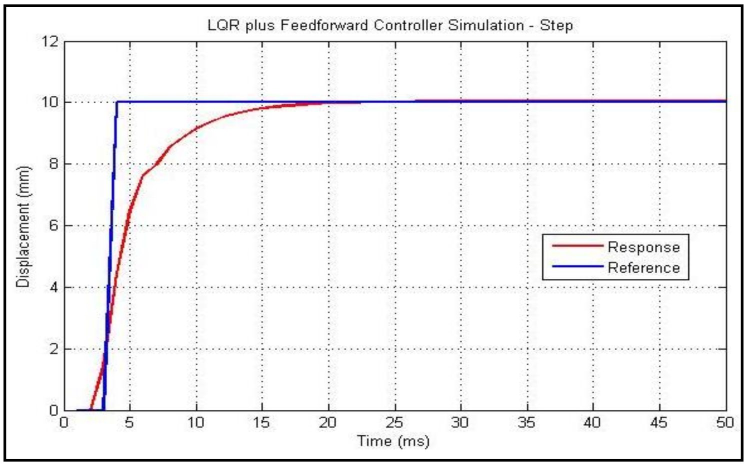

Figure 10: Response of LQR plus Feed Forward Controller with Step Input (Simulation)

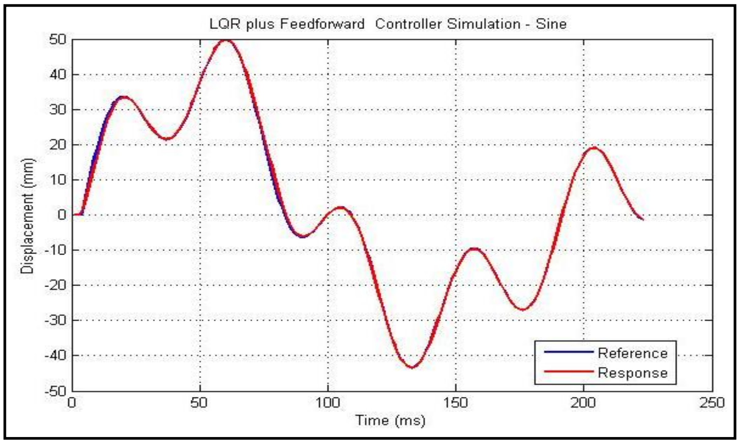

Figure 11: Response of LQR plus Feed Forward Controller with Sine Input (Simulation)

d. LQR plus feed-forward controller via experiment

After obtained the simulation results, the LQR plus fed forward controller is then fed into real plant and the response of the system is observed as shown in Figure 12 and Figure 13. Based on both figures, it's clearly shows that the output of the system has successfully tracked the desired input. Besides, the experiment results also show that the tracking output is following slightly the performance of the simulation result. Thus, the proposed controller has been fine tuned in simulation study before implementation with real system.

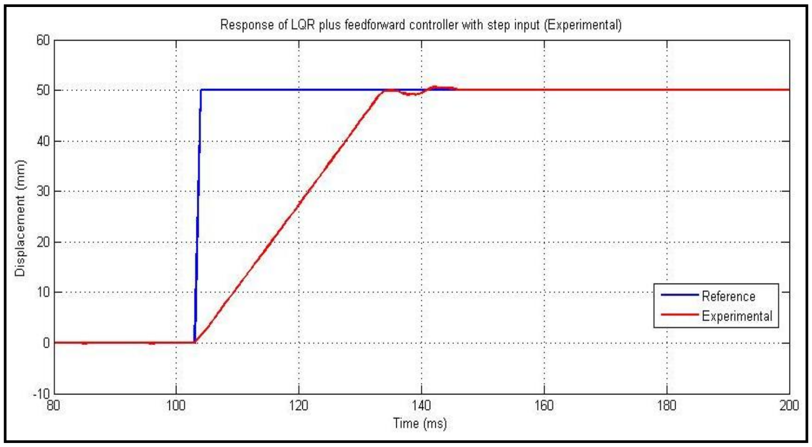

Figure 12: Response of Real-Time LQR plus Feed Forward Controller with Sine Input (Experiment)

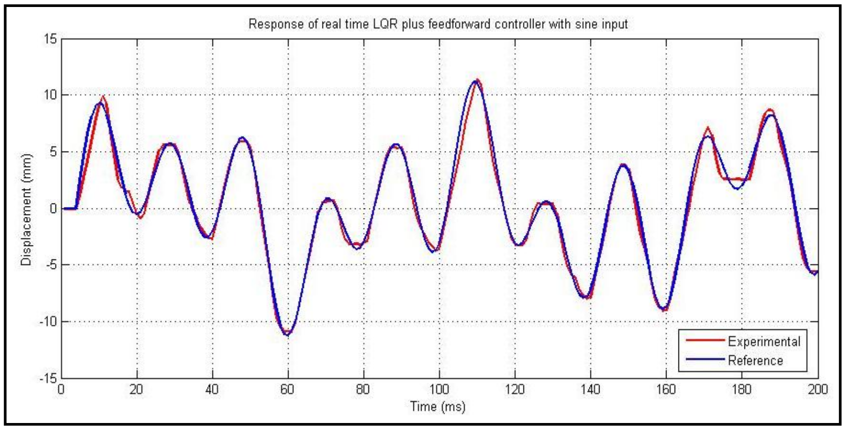

Figure 13: Response of Real-Time LQR plus Feed Forward Controller with Sine Input (Experiment)

e. Comparison between PID and LQR plus feed-forward controller

The experimental results of PID and LQR controller is compared and discussed. Figure 14 shows the comparison between these controllers in step input. Based on the figure, it clearly shows that both controllers output successfully tracked the input given. The LQR plus feed forward controller has better settling time compared to PID controller.

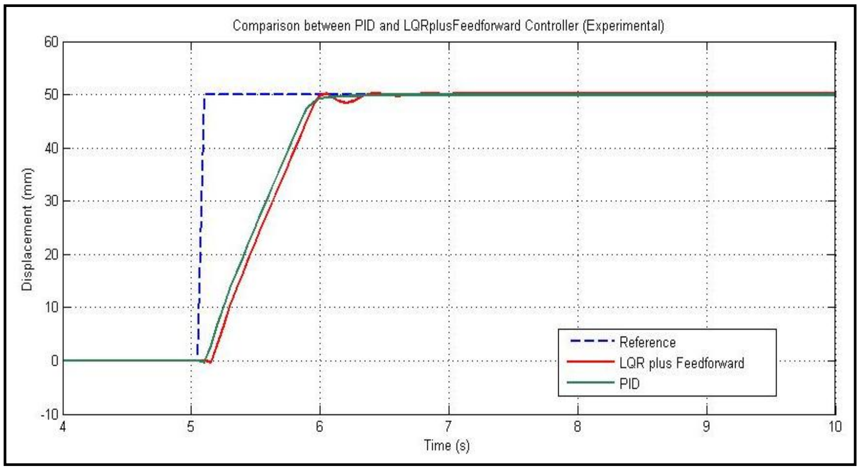

Figure 14: Comparison between PID and LQR plus Feed Forward Controller with Step Input

Significant findings can be shown in Figure 15 which shows the comparison between PID and LQR controller when sine input is given. A random sinusoidal signal is used as a reference trajectory to show the capability in reducing phase error using LQR with feed forward controller. Based on the figure, it clearly shows that the LQR plus feed forward controller tracked down the input given better than PID controller in the form of phase lag. The phase lag is significantly reduced in the LQR plus feed forward controller and thus giving a better performance to the EHA system

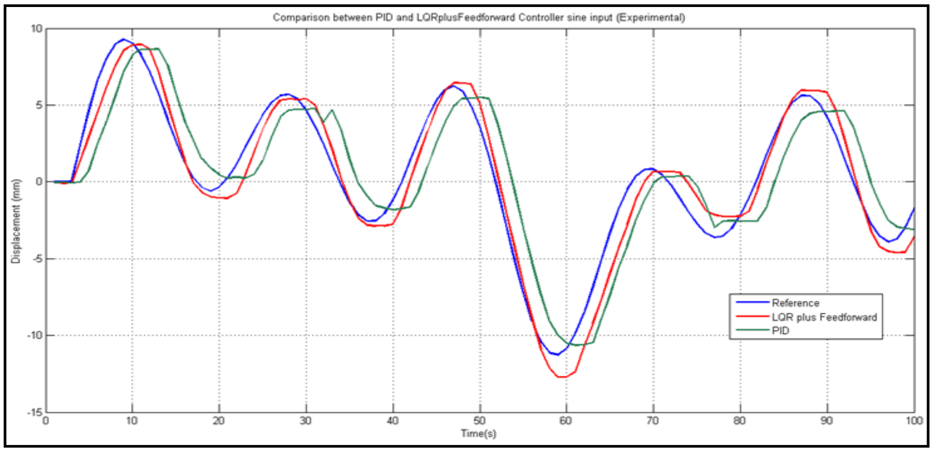

Figure 15: Comparison between PID and LQR plus Feed Forward Controller with Sine Input

VI. CONCLUSIONS

As a conclusion, the objective of this paper were achieved and fulfilled. System identification technique has been applied to EHA system in order to obtain the best linear discrete model and thus it can be used successfully in designing a controller to improve the overall system performance. Two controllers which are PID controller based on Ziegler Nichols method and Feed forward plus LQR controller has been designed effectively for the system and applied in both simulation and experimental mode. Step and sine input are injected to the EHA system and the simulation result clearly shows that the output of the system has successfully tracked the input given. Furthermore, this is also proved from the real-time experiment where the output obtained is almost similar with the output response from the simulation mode. When compared the performance of both controllers, the feed forward plus LQR controller has better performance compared to PID controller by minimising the phase lag and reduce disturbance effect in the system.

REFERENCES

[1] M. A. Avila, A. G. Loukianov, et al., “Electro-hydraulic actuator trajectory tracking”, American Control Conference Proceedings, 2004.

[2] R. Ghazali, Y. Md Sam, et al., “Position tracking control of an electro-hydraulic servo system using sliding mode control”, IEEE Student Conference on Research and Development (SCOReD), 2010.

[3] C. Guan and S. Pan, “Nonlinear adaptive robust control of single rod electro-hydraulic actuator with unknown nonlinear parameters”, IEEE Transaction on Control Systems Technology, Volume 16, Issue 3, page 434-445, 2008.

[4] Y. Jianjun , W. Liquan, W. Caidong, Z. Zhonglin, J. Peng, “ANN-based PID controller for an electro-hydraulic servo system”, Proceedings of the IEEE International Conference on Automation and Logistics, Qingdao, China, page 18-22, 2008.

[5] S. Junpeng, C. Lihua, et al., “The application of fuzzy control strategy in electro-hydraulic servo system”, IEEE International Symposium on Communications and Information Technology, (ISCIT), 2005.

[6] C. Kaddissi, J. P. Kenne and M. Saad, ”Identification and real-time control of an electrohydraulic servo system based on nonlinear back-stepping”, IEEE Transaction on Mechatronics, Volume 12, Issue 1, page 12-21.

[7] M. Kalyoncu and M. Haydim, “Mathematical modelling and fuzzy logic based position control of an electro-hydraulic servo system with internal leakage”, Mechatronics, Volume 19, page 847-858, 2009.

[8] K. A. Kyoung, K. N. Bao and H.S. Yoon, “Self Tuning Fuzzy PID control for hydraulic load simulator”, Proceedings of International Conference on Control, Automation and Systems, Seoul Korea, page 345-349, 2007.

[9] T. J. Lim, “Pole placement control of an electro-hydraulic servo motor”, Proceedings of the 2nd International Conference on Power Electronic Drive System, Singapore, Part 1(1), page 350-356, 1997.

[10] T. G. Ling, M. F. Rahmat, et al., “System identification of electro-hydraulic actuator servo system”, 4th International Conference on Mechatronics (ICOM), 2011.

[11] M. F. Rahmat, T. G. Ling, A. R. Husain, K. Jusoff, Accuracy Comparison of ARX and ANFIS Model of an Electro-Hydraulic Actuator System, *International Journal of Smart Sensing and Intelligent System*, 2011, Scopus Index Journal, Volume 4, Number 3, September 2011, page 440 – 453.

[12] A. G. Loukianov, J. Rivera, Y. V. Orlov and E. Y. M. Teraoka, “Robust trajectory tracking for an electro-hydraulic actuator”, IEEE Transaction on Industrial Electronics, Volume 56 , Issue 9, page 3523-3531, 2009.

[13] R. Ghazali, Y. M. Sam, M. F. Rahmat, K. Jusoff, Zulfatman and A. W. I. M. Hashim, Perfect Tracking Control with Discrete-Time LQR for a Non-Minimum Phase Electro-Hydraulic Actuator System, *International Journal of Smart Sensing and Intelligent System*, 2011, Scopus Index Journal, Volume 4, Number 3, September 2011, page 424-439.

[14] M. F. Rahmat, S. Md Rozali, et al., “Modeling and Controller Design of an Electro-Hydraulic Actuator System”, American Journal of Applied Sciences, Volume 7, Issue 8, page 1100-1108, 2010.

[15] J. Shao, L. Chen and Z. Sun, “The application of fuzzy control strategy in electro-hydraulic servo system”, Proceedings of the IEEE International Conference on Mechatronics and Automation, Niagara Falls, Canada, page 2010-2016, 2005.

[16] M. R. Sirouspour and S. E. Salcudean, ”Nonlinear control of hydraulic robots”, IEEE Transaction on Robotics and Automation, Volume 17, Issue 2, page 173-182, 2001.

[17] G. A. Sohl and J. E. Bobrow, “Experiments and simulations on the nonlinear control of a hydraulic servo system”, IEEE Transaction on Control Systems Technology, Volume 7, Issue 2, page 238-247, 1999.

[18] Zulfatman and M. F. Rahmat, “Application of Self-Tuning Fuzzy PID Controller on Industrial Hydraulic Actuator using System Identification Approach”, International Journal of Smart Sensing and Intelligent System, Vol. 2 No. 2, June 2009, page 246-261.

[19] M. F. Rahmat, S. Md Rozali, N. Abdul Wahab and Zulfatman, “Application of Draw Wire Sensor in Position Tracking of Electro-Hydraulic Actuator System”, International Journal of Smart Sensing and Intelligent System, Volume 3 Number 4, December 2010, page 736-755.