APPLICATION OF DRAW WIRE SENSOR IN POSITION TRACKING OF ELECTRO HYDRAULIC ACTUATOR SYSTEM

MF Rahmat[1], S Md Rozali[2], N Abdul Wahab[1] and Zulfatman[1]

[1]Faculty of Electrical Engineering,

Universiti Teknologi Malaysia,

UTM Skudai 81310,

Johor,Malaysia;

E-mail : fuaad@fke.utm.my,aliza@fke.utm.my, joe_has@yahoo.com

[2]Faculty of Electrical Engineering,

Universiti Technical Malaysia Melaka,

76109 Durian Tunggal,

Melaka,Malaysia;

E-mail : sahazati@utem.edu.my

Abstract - Draw-wire sensor is classified as a contact measurement method. This sensor is ideal for applications with large measuring ranges, small sensor dimensions and when a low cost solution is required. The objective of this research is to explain the application of a draw-wire sensor in position tracking of electro-hydraulic actuator system. The work started with the modeling of the electro hydraulic actuator system. Draw wire sensor is attached to the load of electro hydraulic system to measure its motion when an input signal is injected to the system. The sensor output is the displacement in millimeter and converted to the voltage based on the input signal given. These input and output readings are collected and applied to a system identification procedure in order to obtain the best mathematical model of the system. The modeling process is followed by designed a proportional integral and derivative controller (PID) for the system to assure the output is tracking the input given. The designed controller is applied to the system in both simulation and real time mode. The output performance of the system for these two modes is compared and it can be seen that the simulation and real-time output are almost similar. The overall process of this work shows the important role of draw wire sensor in capturing the output data of the electro hydraulic actuator system precisely either with or without controller. Other displacement transducer might be used in future work of position tracking of electro-hydraulic actuator system.

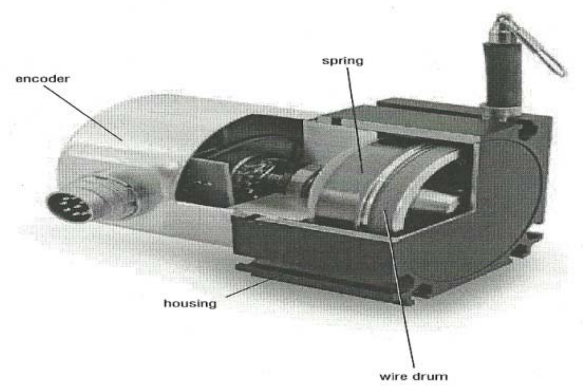
Keywords: Electro-hydraulic actuator, draw wire sensor, system identification, ARX model, PID controller

I. INTRODUCTION

a. DRAW-WIRE SENSOR

Draw-wire displacement measurement is classified as a contact measurement method. Every draw-wire sensor consists of the basic wire elements, drum and spring motor (combined as mechanics) and a potentiometer or encoder for the measurement signal generation. This sensor is ideal for applications with large measuring ranges, small sensor dimensions and when a low cost solution is required. Depending on the sensor design, the wire is normally an extremely thin steel wire, which is sheathed with polyamide. The wire is around 0.8mm thick on average, depending on the type of stress forces involved. Figure 1 illustrates component of draw-wire sensor.

Figure 1 : Components of draw-wire sensor



Draw-wire linear position sensors measure the linear movement of a component via a highly flexible steel wire which is wound onto a drum by a durable spring-driven motor. The winding drum is linked axially to a multi-turn potentiometer, incremental encoder or absolute encoder. The free end of the wire is attached to the moveable body. A linear movement is transformed into a rotation by the draw-wire principle and converted into an electrical signal using a rotary encoder to a proportional analog signal or to countable increments. A spring motor provides sufficient pre-tension of the wire. The spring motor is a coil spring with torque load, similar to those used in mechanical watch mechanisms. The further the wire is drawn out, the higher the tensioning force of the spring.

This sensor has certain features which can provide benefits to the user. It allows a short to long range capability from a minimal sensor footprint with 100 to 5000mm measuring range. It also suitable for a wide range of industrial applications since it is rugged, robust and has very compact design. The choice of interface signals for this sensor can be either analogue or digital outputs. Analogue connection is chosen for high volume production applications while digital connection is used where the relative position displacement should be measured. Besides, the sensor suited to hostile conditions since it is protected to IP65. Other additional feature is the measuring wire can be deflected using deflection pulleys. Because of its benefits, draw-wire sensor is widely used in medical engineering applications such as position measurement on X-ray machines, monitoring of training exercises on rehabilitation and therapy machines, angle measurement in SoloAssist, position measurement in computer tomography and positioning of operating tables. In logistics applications, the sensor is used in displacement measurement on slag transporter, positioning of catering trucks at Airbus A380 and lift-height measurement in fork-lift trucks. The sensor also widely used in other variety applications such as automotive, aerospace, power plant engineering and etc.

b. ELECTRO-HYDRAULIC ACTUATOR SYSTEM

Electro-hydraulic actuators (EHA) are highly non-linear system with uncertain dynamics in which the mathematical representation of the system cannot sufficiently represent the practical system [2]. The actuator plays a vital role in manoeuvring industrial processes and manufacturing line. The electro-hydraulic actuator can use either proportional valve or servo valve. It converts electrical signal to hydraulic power [3]. Important specifications for electro-hydraulic valve actuators include actuation time, hydraulic fluid supply pressure range and acting type. Other features for these actuators include over torque protection, local position indication and integral pushbuttons and controls. The applications of electro-hydraulic actuators are important in the field of robotics, suspension systems and industrial process. This is because it can provide precise movement, high power capability, fast response characteristics and good positioning capability. In order to acquire the highest performance of the electro-hydraulic actuator, a suitable controller has to be designed. As the controller design require mathematical model of the system under control, a method of identifying the actuator need to be chosen so that the best accuracy of the model can be obtained.

Though this research focused on the role of draw-wire sensor in positioning tracking of electro-hydraulic system, there are many previous research on positing applications on other system by using variety types of sensor. Salil Shukla and Colin Bradley [4] outline a new approach utilizes lasers, cameras and image sensor for positioning a patient on the treatment table for radiation therapy sessions. A new technological approaches and improvements to existing methods of measuring position in automation, sports and general applications is described by Christine Connolly [5] in his research. Another research on positioning sensor is done by Gary Pepka [6]. The research is designed to encourage electronic device designers to take a new look at a recent technology, Hall-effect sensing that has seen exceptional growth in certain areas but could find much wider application and acceptance due to new supporting technologies.

The correct feeding of the textile material defines a challenge to be solved. Joerg Stephen [7] describes a low-cost infrared sensor system for contour tracking and detection of edge defects. Another research by Don Braggins [8] describes the development and fabrication of an inductive position sensing system based on low cost printed circuit technology. Robert J. Stone [9] looks at changes in the human-computer interface, particularly in the field of using computers for applications which require an accurate registration from an input device in six degrees of freedom. The research proposed several techniques for positioning sensor such as electromechanical techniques, electromagnetic techniques, acoustic techniques and optical techniques.

The research by Lee Danisch, Kevin Englehart and Andrew Trivett [10] describes shape tape, a thin array of fiber optic curvature sensors laminated on a ribbon substrate, arrange to sense bend and twist. Wireless proximity switches that incorporates a communication module for the power supply, signal transmission and man-machine communication is introduced by Christoffer Apneseth et.all [11]. Gojko Nikolic and Goran Cubric [12] pursue the research of different types of sensors suitable of positioning edge accuracy of textile material since the problem of accurate product positioning on machines for clothing production is more complex than similar problems in other fields of production and installation because of the type of material that is used. Industrial robots are not accurate enough to be used without heavy investment in fixtures and manual programming to correct for positional variations. This situation could be corrected with the introduction of a new position determination system which is called as PosEye elaborated by Monica Schofield [13].

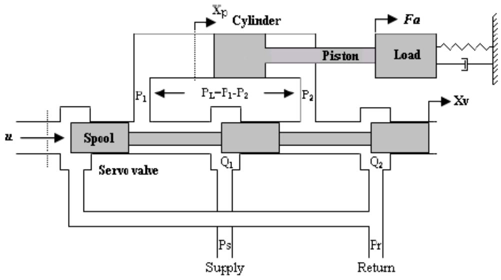
Rama Chellappa, Gang Qian and Qinfen Zheng [14] present a fusion framework using both video and acoustic sensors for vehicle detection and tracking. Markoc Chain Monte Carlo techniques are then used for joint audio-visual tracking based on different characteristics of audio and visual trackers. Robert J. Barsanti and Murali Tummala [15] investigate the application of batch oriented MAP estimation scheme to the problem of tracking a moving acoustic target from sensors of uncertain position. A research where a real-time optical sensor has been integrated into a robot end effector is done by Moshe Shoham et.all [16]. The sensor consists of a four-element position sensing spot detector and can control a robot motion in two dimensions.

The research done by Vultchan Gueorgiev [17] optimized differential sensor for linear displacement in terms of linearity and sensitivity which is carried out with respect to its characteristic displacement-output voltage. Yu-He Gau et.all [18] present a two-phase localization algorithm for WSNs. Each sensor node obtains its initial position by DV-hop method in the first phase while in the second phase, each sensor node gathers the locations and distances to its neighbors, updates and exchanges these location information periodically and then operates the multilateration with different weight values. Another research by John Golby [19] outlines the basic principles of inductive position sensors and then goes on to explain these advances in more detail together with some of the applications suitable for this sensor.

c. MODELLING OF ELECTRO-HYDRAULIC ACTUATOR SYSTEM

The output device of the hydraulic control system is called *actuator*. It is the mechanism that is responsible for delivering force and motion to the external load system of a given application [20]. The primary advantage of using a hydraulic control system over other control systems is the high effort-to-inertia ratio that is exhibited by hydraulics. The hydraulic actuator consists of a proportional valve and a hydraulic cylinder. This is illustrates in Figure 2.

Figure 2 : Electro-hydraulic actuator



Referring to the above figure, P_s is the pressure of hydraulic supply, P_r is the return pressure, x_v is the spool valve displacement, P_2 and P_1 are the fluid pressure in the upper and lower cylinder chambers of the actuator. The hydraulic cylinder extends or compresses depend on the pressure differences between P_2 and P_1. The mathematical model of an electro-hydraulic actuator describes the dynamic behaviour of the system. It considers the dynamics of the hydraulic actuator and the dynamics of the servo valve [21]. The dynamics of the hydraulic actuator is modelled as a spring and a damper element that are paralleled to the piston.

The dynamic equation is given by

$$\dot{x}_p = v_p \quad (1)$$

$$\dot{v}_p = \frac{1}{m}\left(-kx_p - bv_p + AP_L - F_r - D\right) \quad (2)$$

where x_p is the piston displacement, v_p is the velocity of the piston, P_L is the load pressure, A is the piston area, F_r is the cylinder friction, b is the viscous damping of the load and external disturbance is defined by D. Since the load pressure is defined as the pressure across the actuator piston, its derivative given by the total load flow through the actuator divided by the fluid capacitance

$$\frac{V_t}{4\beta_e}\dot{P}_L = Q_L - A_c\dot{x}_p - C_T P_L \quad (3)$$

where A_p is the cross section area of a hydraulic cylinder, V_t is the total actuator volume, β_e is the effective bulk modulus, C_T is the coefficient of total leakage due to pressure and Q_L is the turbulent hydraulic fluid flow through an orifice. By using this equation, spool valve displacement x_v and load flow Q_L is related through equation (4) as follow

$$Q_L = C_d w x_v \sqrt{\frac{P_s - \mathrm{sgn}(x_v)P_L}{\rho}} \quad (4)$$

In this equation, C_d is the valve discharge coefficient, w is the valve spool area gradient, P_s is the supply pressure and ρ is hydraulic fluid density. Thus, equation (4) and (5) give the load pressure state equation as

$$\dot{P}_L = \frac{4\beta_e}{V_t}\left(-A_c v_p - C_T P_L + C_d w x_v \sqrt{\frac{P_s - \mathrm{sgn}(x_v)P_L}{\rho}}\right) \quad (5)$$

The dynamic equation for servo valve subsystem is controlled by an input servo valve, u. Thus, the corresponding relation can be state as

$$\dot{x}_v = \frac{1}{\tau_v}\left(-x_v + k_a u\right) \quad (6)$$

where k_a and τ_v are constant value based on data sheet. Based on equation (1) to equation (6), the state variable are defined as

$$x_1 = x_p$$
$$x_2 = v_p$$
$$x_3 = P_L$$
$$x_4 = x_v$$

The state equations of the servo valve hydraulic systems may be written as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{1}{m}\left(-k_s x_1 - bx_2 + Ax_3 - F_r\right) \\ \dot{x}_3 &= -\alpha x_2 - \beta x_3 + \left(\gamma\sqrt{P_s} - x_3 sign(x_4)\right)x_4 \\ \dot{x}_4 &= -\frac{1}{\tau_v}x_4 - \frac{k_a}{\tau_v}u \end{aligned} \quad (7)$$

The output of the system is given by

$$y = Ax_3 - F_r \quad (8)$$

The objective of this paper is to provide alternative sensor for position tracking of electro-hydraulic actuator system. This paper focused on draw wire sensor used in electro-hydraulic system to measure the position of the load.

II. EXPERIMENTAL SETUP

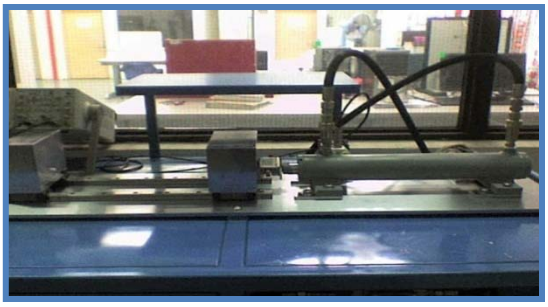
The experiment starts with collecting input and output data for model estimation and validation. Multi sine input is injected to the EHA system through simulink to capture the position of the load recorded by draw-wire sensor. The collected input and output data that has been stored in workspace Matlab then is used for model estimation and validation part. The suitable model is chosen from that data based on the best fit and residuals analysis. The response of the model obtained is tested using step and sine input without any controller so that a suitable controller can be designed to improve the performance of the system.

PID controller is designed based on Ziegler-Nichols tuning method. The calculated parameters are inserted in PID block in simulink and the output result is examined. The PID controller for the system is tested in two different ways. Firstly, it is operated in simulation mode which the PID controller is connected to the model represented by discrete transfer function in simulink block only. The output response is observed and recorded. Then, the next step is inserted the similar PID in real-time system. In this step, the PID controller designed in simulink block with same parameters as simulation PID is located in the forward path of real-system. The different between this mode and the previous mode is the latter used the electro-hydraulic actuator system itself instead of model transfer function in the previous one. The output response is also recorded and compared with the output response attained from the simulation mode. All the experimental process involved the important role of draw-wire sensor in position tracking of the output of EHA system so that the best input and output data can be collected.

a. ESTIMATION OF THE MODEL

Figure 3 shows the electro-hydraulic actuator system that is used in this work.

Figure 3 : Electro-hydraulic actuator system



Referring to the figure, the system is open-loop system that used draw-wire sensor as position sensor in order to track the location of the load when certain input is given to the system. Draw-wire sensor that is used in this system and the way it is attached to the system can be seen in Figures 4 and 5 respectively. The model of draw-wire sensor used in this work is WDS-300-P60-SR-U. From this serial number, the information about the specification of the model can be obtained. 300 means the measuring range of the sensor is 300mm while P60 revealed that 60mm square housing. SR tells the user that the sensor used radial plug including female connecter and the letter U notify that the output of the sensor is voltage.

Figure 4 : Draw-wire sensor series P60

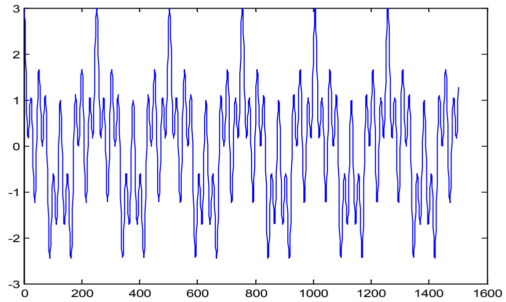
Figure 5 : The sensor attached to the output of the system

System Identification technique is applied to the electro-hydraulic actuator system in order to attain the model and parameters of the system. The procedures begin with experimental studies where the input is injected to the system to collect the input and output data. Here, draw-wire sensor plays important role to track the position of the load of the system to ensure the input and output data collected is precise. This is significant to obtain the best model of the system. Secondly, a suitable model structure is selected for the system. It is followed by model estimation then validation. Validation process is done to compare the estimated model output with the real output from the experiments [22]. The validated model can be accepted based on the best fit criterion and other related specifications.

The input to the system is multi sine signal with three different frequencies [23]. This signal is preferable compared to original sinusoidal signal in order to capture the dynamic characteristic of EHA system. The signal is represented as follow and illustrated in Figure 6.

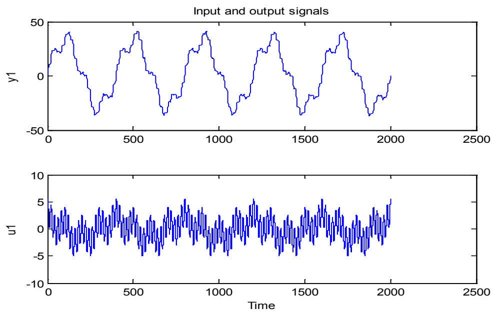
$$multi\sin e = \cos(0.5t_s) + \cos(2t_s) + \cos(5t_s) \qquad (9)$$

Figure 6 : Multi sine signal with three different frequencies



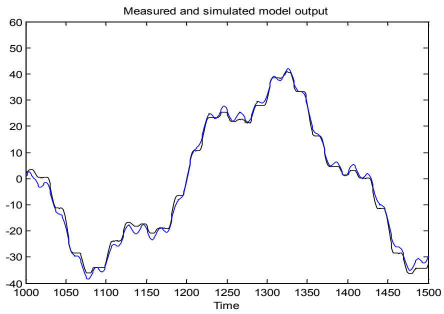
The signal is injected to the EHA system and the input and output of the system at respective time is recorded. This can be done from the good position tracking of the system by draw-wire sensor. Several input output data from the experiments are collected for model estimation and validation. 1500 number of data are collected with sampling time 50ms. The input and related output data is shown in Figure 7.

Figure 7 : The input-output data of EHA system



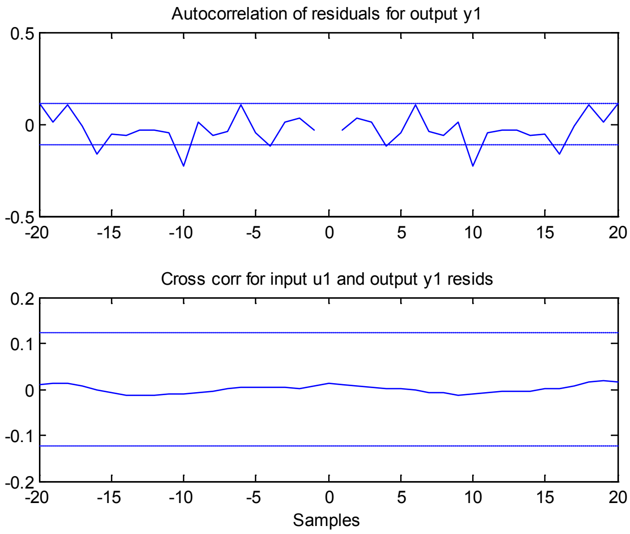
The estimation process of the model is completed by the System Identification toolbox in Matlab. The data is separated into two parts; the first part for model estimation and the second part for model validation. Auto-regressive Exogenous (ARX) model is selected as the model structure of the system. The model can be accepted when the best fit percentage is more than 90% [22]. Besides, from the residuals analysis, the auto correlation and cross correlation of input and output data should be in the range of confidence interval. Validation of the data obtained shows that 92.8% best fit meaning that the estimated model is almost tracking the real output data from the experiments. It can be seen in Figure 8 below.

Figure 8 : The best fit graph of the estimated model



The residuals graph of auto correlation and cross correlation of the input and output data also revealed that the data are within range of confidence interval. This is shown in Figure 9.

Figure 9 : The residuals graph



The transfer function for ARX model is given by [23] $G(q) = \frac{B(q)}{A(q)}$

From SI toolbox, the polynomial model attained is in the form of discrete time equation represented as follow

$A(q) = 1 - 2.056z^{-1} + 1.186z^{-2} + 0.177z^{-3} - 0.3061z^{-4}$ and $B(q) = 0.01944z^{-1} + 0.6005z^{-2} - 1.014z^{-3} + 0.5188z^{-4}$

Thus, the transfer function for the system can be represented by

$$G(q) = \frac{0.01944z^{-1} + 0.6005z^{-2} - 1.014z^{-3} + 0.5188z^{-4}}{1 - 2.056z^{-1} + 1.186z^{-2} + 0.177z^{-3} - 0.3061z^{-4}}$$

Figures 10 and 11 demonstrate the frequency response and step response of the model.

Figure 10 : Frequency response of the system

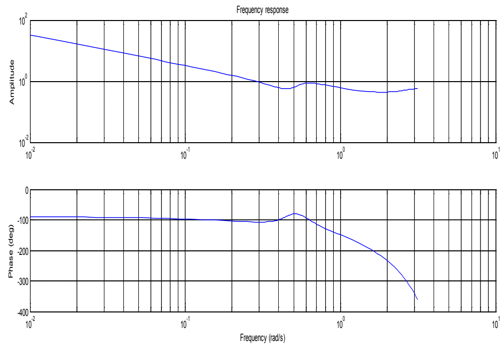
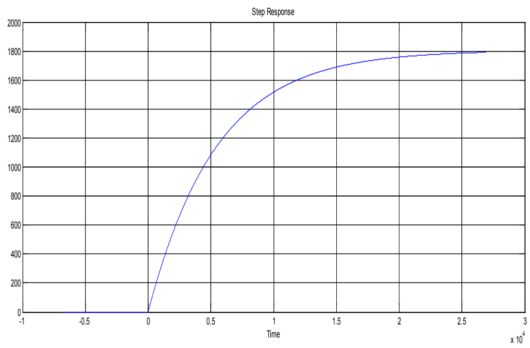


Figure 11 : Step response of the system



Although the model is accepted as the best model for the system by looking at short rise time, fast response and settling time of the step response, the stability of the model need to be improved. This is because based on the frequency response analysis; the phase plot does not give 180 degree when amplitude is in zero magnitude.

b. CONTROLLER DESIGN

PID (proportional integral derivative) controller is chosen for the system in order to help the draw-wire sensor attached to the output part of EHA system track the input injected to it. PID is one of the earliest control strategies and has wide range of applications in industrial control.

The performance of the system such as rise time, overshoot, settling time and steady state error can be improved by tuning the value of K_p, K_i and K_d of the PID controller. K_p or proportional controller is used to assure the output reach the reference input. However, the output of the system with this controller will never reach zero steady state error. In order to obtain zero or very small steady state error, K_i or integral controller is given to the system. Derivative controller or K_d will improve the speed performance of the system. However, sometimes derivative action may not be required since the proportional and integral action already produce good output response [24].

The tuning value of K_p, K_i and K_d are determined by using Ziegler-Nichols tuning method [23-24]. The tuning method begin with finding the critical gain,K_{cr} and critical period of oscillation,T_{cr}. The value of K_p, K_i and K_d is adjusted from this two parameters based on Table 1 below. These calculated values are only the reference value. K_p, K_i and K_d might be adjusted manually around this value to produce the best output response.

Table 1: The value of K_p,K_i and K_d based on Ziegler-Nichols tuning method

Controller Type	Calculation of characteristic values				
	Kp	Ti	Td	Ki	Kd
P	0.5Kcr	-	-	-	-
PD	0.8Kcr	-	0.12Tcr	-	KpxTd
PI	0.45Kcr	0.85Tcr	-	Kp/Ti	-
PID	0.6Kcr	0.5Tcr	0.12Tcr	Kp/Ti	KpxTd

The critical gain for the model obtained is K_c = 0.46 with critical period, T_c = 7.1481. From calculation based on Table 1 and manual adjustment, the parameters of PID controller with different input are shown in Table 2.

Table 2 : The calculated value of K_p,K_i and K_d based on Ziegler-Nichols tuning method

Input	Kp	Ki	Kd
Step	0.276	0.028	0.09
Sine	1.8	0.03	0.01

III. RESULTS AND DISCUSSION

Figures 12 and 13 show the block diagram of the model without controller with step and sine input respectively. Figures 14 and 15 represent the output response with each input. The red line is the reference input while the blue line is the actual output.

Figure 12 : The model with step input

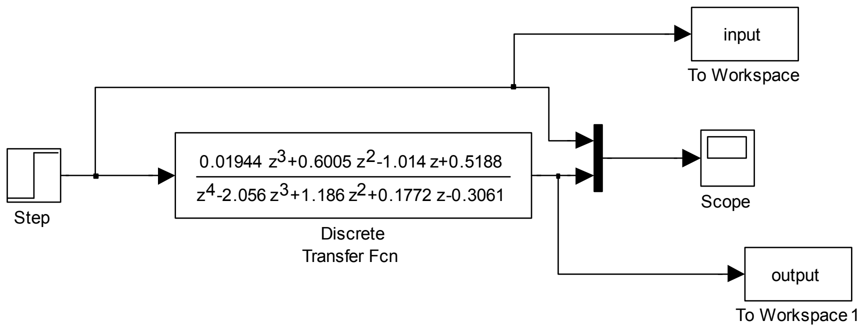


Figure 13 : The model with sine input

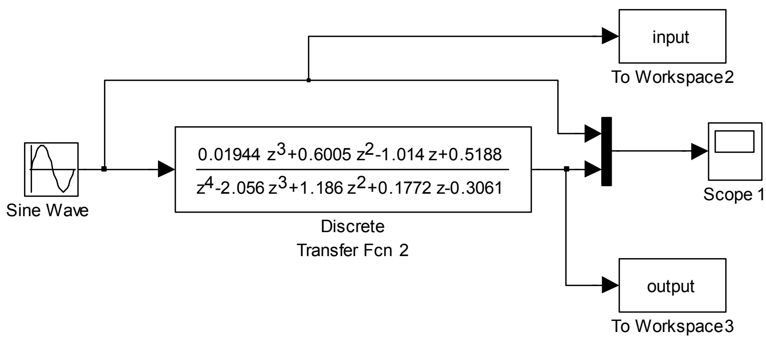


Figure 14 : Response of the model with step input

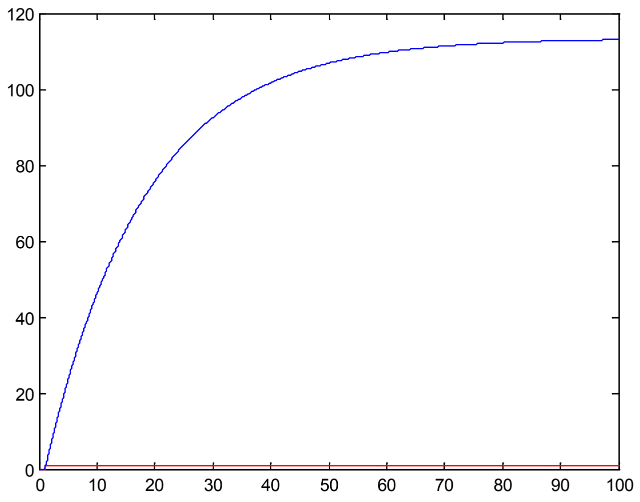
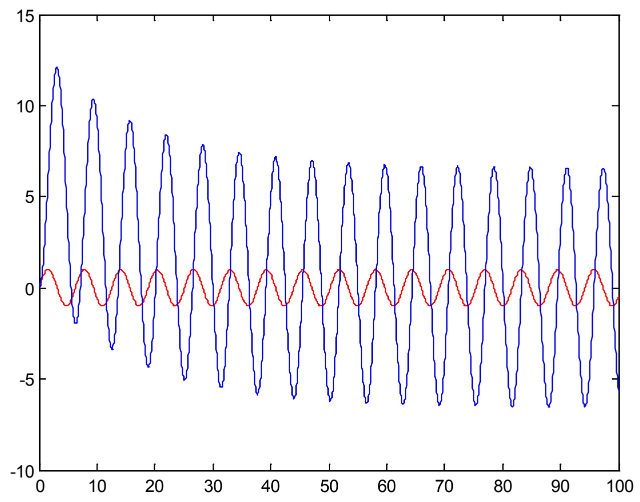


Figure 15 : Response of the model with sine input



The block diagram of the system with PID controller can be seen in Figures 16 and 17 and the output response is illustrated by Figures 18 and 19.

Figure 16 : System with PID controller with step input

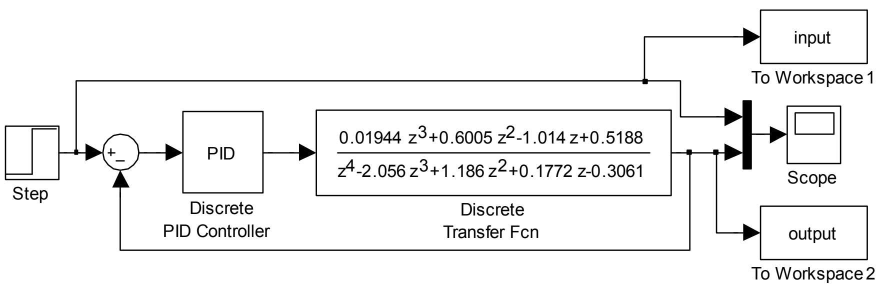


Figure 17 : System with PID controller with sine input

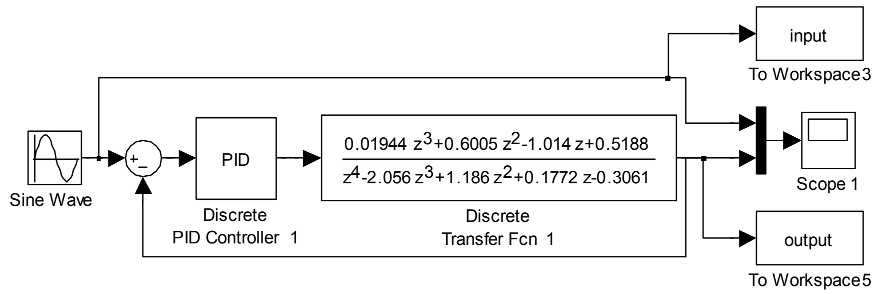


Figure 18 : Response of the system with PID controller with step input (simulation)

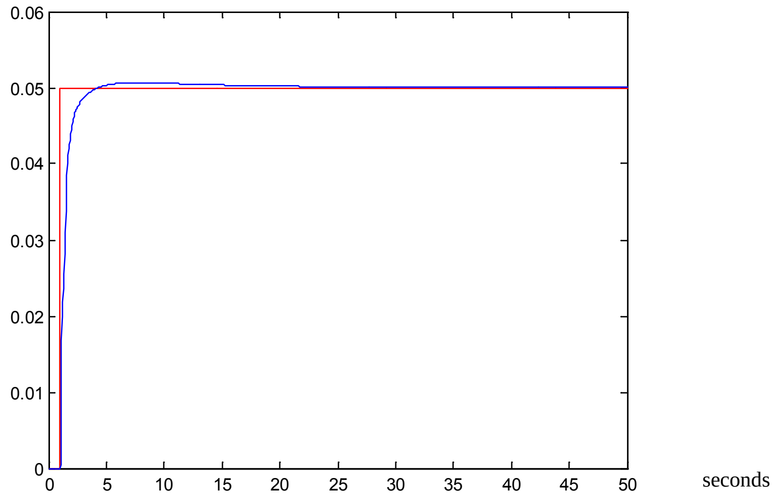
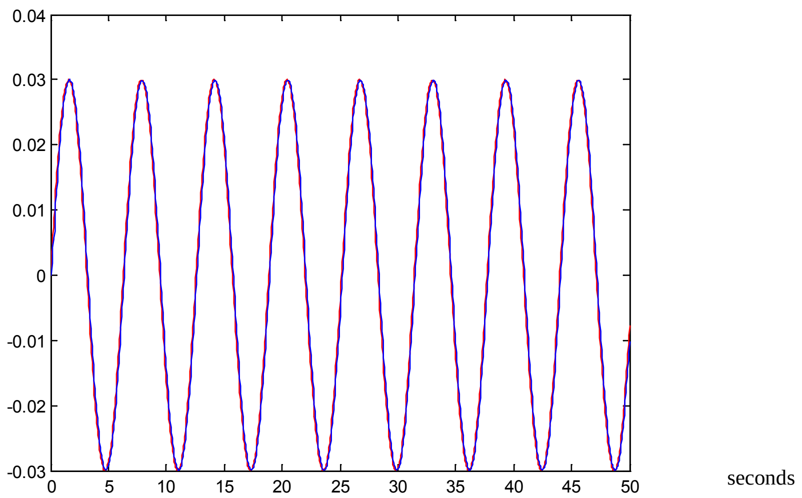
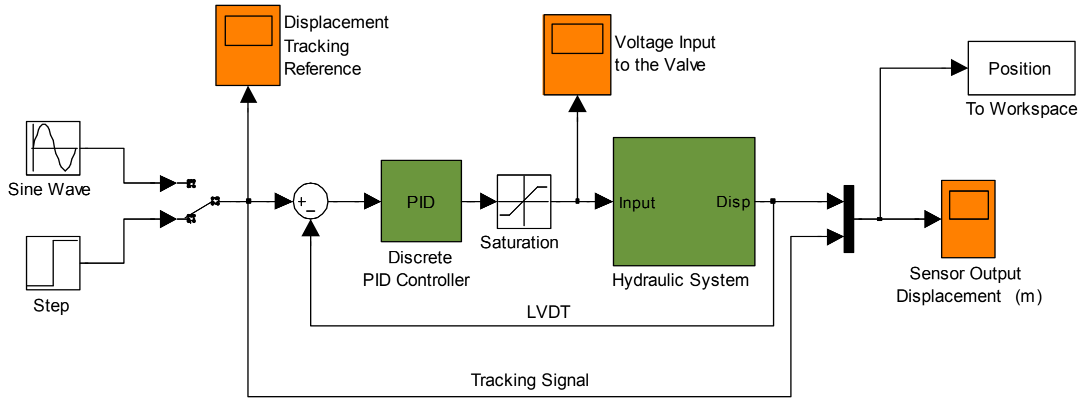


Figure 19 : Response of the system with PID controller with sine input (simulation)



Based on Figures 18 and 19, the output response of the system with step and sine input is improved by adding PID controller in the forward path of system. These responses are obtained through simulation mode. Figure 20 shows the similar PID is inserted in the forward path of the system in real-time mode.

Figure 20 : Real-time PID controller



Based on this figure the response of the system with step and sine input are revealed by Figures 21 and 22 respectively. The green line is the reference input while the actual output is indicated by the blue line.

Figure 21 : Response of real-time PID controller with step input (experiment)

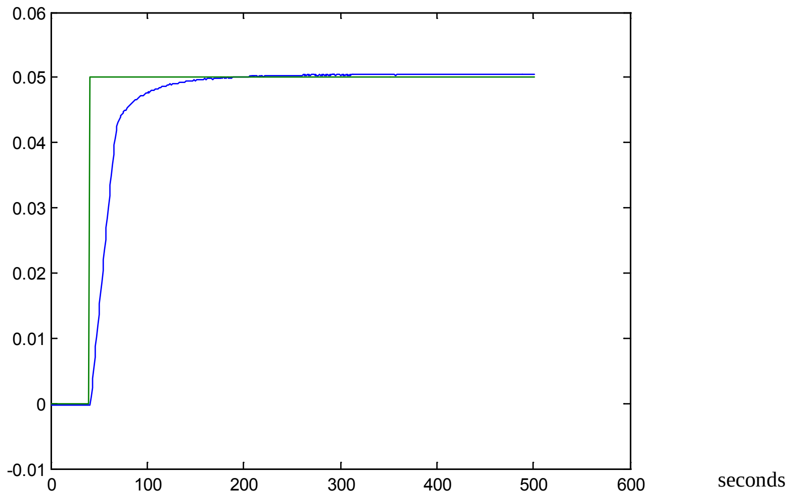
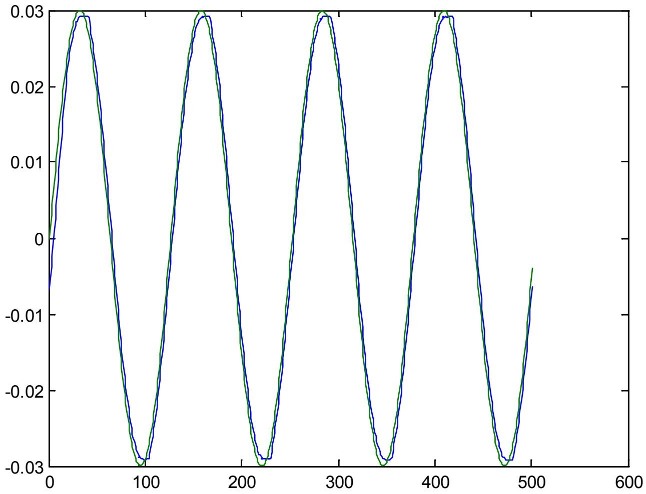


Figure 22 : Response of real-time PID controller with sine input (experiment)



Both the above Figure 21 and Figure 22 show that the outputs from real-time experiments are almost similar with the output attained from simulation. It also can be seen that the output tracking the input with very small correction. The best fit of the model also has been proved to increase from 92% to 98%. It indicates that the setting value of K_p, K_i and K_d of the PID controller is acceptable and improve the performance of EHA system. A slight different between input and output happened because the system is modeled in linear model and some nonlinearity and uncertainties characteristic are ignored.

IV. CONCLUSION

A proper system identification technique has been applied to electro-hydraulic system to produce the best linear discrete model of the system. PID controller has been designed for the system and applied in simulation and real-time experiments with successfully. Ziegler-Nichols method is chosen as a tuning method to determine the value of K_p, K_i and K_d since this tuning method is used widely. Step and sine input are injected to the system and the simulation result shows that the output follow the input. This is also proved from the real-time experiments where the output obtained is almost similar with the output response from simulation mode. All experimental processes involved the important role of draw-wire sensor in order to collect the output data of electro-hydraulic system.

REFERENCES

[1] Thomas E.Kissell, *Industrial Electronics*, Prentice Hall Upper Sadle River, New Jersey,1997; pp 345 - 441 .

[2] Zhongwen Wang, Junpeng Shao, Jianying Lin and Guihua Han, *Research on Controller Design and Simulation of Electro-hydraulic Servo System,* International Conference on Mechatronic and Automation, Changchun China, August 9 – 12 2009.

[3] Zulfatman, M.F.Rahmat and R.Adnan, *Modeling and Controller Design of Electrohydraulic Actuator*, The Second International Conference on Control, Instrumentation and Mechatronic Engineering, Malacca,Malaysia, June 2-3 2009.

[4] Salil Shukla , Colin Bradley, Wayne Beckham and Derek Wells, *A Vision System for Patient Positioning in Radiation Therapy,* Sensor Review, Vol 25 No 1, 2005, 261-270.

[5] Christine Connolly, *Technological Improvements in Position Sensing,* Sensor Review, Vol 27 No 1, 2007 , 17-23.

[6] Gary Pepka, *Position and Level Sensing Using Hall-effect Sensing Technology*, Sensor Review, Vol 27 No 1, 2007, 29-34.

[7] Joerg Stephan, *Efficient Sensor System for Online Contour Tracking in Textile Machinery,* Sensor Review, Vol 22 No 4, 2002, 328-333.

[8] Don Braggins, *"Spiral" Sensors Provide Low Cost Position Sensing*, Sensor Review, Vol 18, No 4, 1998, 242-244.

[9] Robert J. Stone, *Position and Orientation Sensing in Virtual Environments*, Sensor Review, Vol 16 No 1, 1996, 40-46.

[10] Lee Danisch, Kevin Englehart and Andrew Trivett, *Spatially Continuous Six Degree Of Freedom Position And Orientation Sensor,* Sensor Review, Vol 19 No 2, 1999, 106-112.

[11] Christoffer Apneseth, Dacfey Dzung, Snorre Kjesbu, Guntram Scheible and Wolfgang Zimmermann, *Wireless-Introducing Wireless Proximity Switches*, Sensor Review, Vol 23 No 2, 2003, 116-122.

[12] Gojko Nikolic and Goran Cubric, *Investigating The Positioning Edge Accuracy of Sensors in Textile and Clothing Manufacture*,International Journal of Clothing science and Technology, Vol 19 No ¾, 2007, 178-185.

[13] Monica Schofield, *Does Your Robot Really Know Where It Is?*, International Journal on Industrial Robot, Vol 29 No 5, 2002, 407-411.

[14] Rama Chellappa, Gang Qian and Qinfen Zheng, *Vehicle Detection And Tracking Using Acoustic And Video Sensors*,University of Maryland,Arizona State University, 2004.

[15] Robert J.Barsanti and Murali Tummala, *Passive Target Tracking With Uncertain Sensor Positions*,Naval Postgraduate School Monterey, 2000.

[16] Moshe Shoham, Yeshayahu Fainman and Ehud Lenz, *An Optical Sensor For Real-Time Positioning, Tracking And Teaching Of Industrial Robots*,IEEE Transactions on Industrial Electronics, Vol IE-31 No 2, May 1984.

[17] Vultchan Gueorgiec, Zaharin Gergova and Ivan Yatchev, *Optimization Of A Linear Displacement Sensor Using Fem And Secondary Model*, International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol 28 No 5, 2009, 1266-1275.

[18] Yu-He Gau, Hung-Chi Chu and Rong-Hong Jan, *A Weighted Multilateration Positioning Method For Wireless Sensor Networks*,International Journal of Pervasive Computing and Communications, Vol 3 No 3, 2007, 289-303.

[19] John Golby, *Advances In Inductive Position Sensor Technology*,Sensor Review, Vol 30 No 2, 142-147, 2010.

[20] Noah D.Manring, *Hydraulic Control Systems*, John Wiley & Sons, Inc., 2005; pp 305.

[21] Manuel A.Avila, Alexander G.Loukianov and Edgar N.Sanchez, *Electro-hydraulic Actuator Trajectory Tracking*, Proceeding of the 2004 American Control Conference Boston, Massachusetts, June 30 – July 2, 2004.

[22] L.Ljung, *System Identification:Theory for The User*, Upper Saddle River Prentice-Hall, PTR, New Jersey, 1999; pp 491.

[23] M.N.Taib, R.Adnan, M.H.F.Rahiman, *Practical System Identification*, University of Technology Mara, Shah Alam, Malaysia, 2007; pp 3.1–3.32.

[24] Aidan O'Dwyer, *Handbook of PI and PID Controller Tuning Rules*,Dublin Institute of Technology, Ireland, 2003;pp 169.