

Self-Tuning Fuzzy PID Controllers Application on Industrial Hydraulic Actuator using Unique System Identification Approach

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Abstract- In this paper, Self Tuning Fuzzy PID controller is developed to improve the performance of the electro-hydraulic actuator. The controller is designed based on the mathematical model of the system which is estimated by using System Identification technique. The model is performed in linear discrete model to obtain a discrete transfer function for the system. Model estimation procedures are done by using System Identification Toolbox in Matlab. Data for model estimation is taken from an experimental works. Fuzzy logic is used to tune each parameter of PID controller. Through simulation in Matlab by selecting appropriate fuzzy rules are designed to tune the parameters K_p , K_i and K_d of the PID controller, the performance of the hydraulic system has improved significantly compare to conventional PID controller.

Keywords: Identification, Hydraulic Actuator, Position Control, Self-Tuning, Fuzzy PID

I. INTRODUCTION

Hydraulic actuators are important equipment in modern applications and widely used in industry, because of their high power capability, fast and smooth response characteristics and good positioning capability. The range of applications for electro-hydraulic actuators is diverse, and includes manufacturing systems, materials test machines, active suspension systems, mining machinery, fatigue testing, flight simulation, paper machines, ships and electromagnetic marine engineering, injection molding machines, robotics, and steel and aluminium mill equipment. In all those applications the highest performance of the electrohydraulic actuators on position, force or pressure is needed. In improving the performance of the electro-hydraulic actuator, a suitable controller is required. Therefore, during last two decades thousands investigation and development on the control of position, force or pressure outputs of electro-hydraulic actuators have been done and become a great interest in the industrial fields and academic.

An important step in designing a control strategy is proper modelling of the system to be controlled. An exact system model should produce output responses similar to the actual system. The complexity of most physical systems, however, meets any difficulties in developing the exact models. In case the model and parameters are unknown, appropriate techniques that called System Identification can be applied to overcome those limitations.

Currently, a number of techniques of system identification have been applied to estimate the hydraulic actuator model in form linear models, non-linear models and intelligent models. Linear model such as Auto-regressive

Exogenous (ARX) model with PRBS signal as input signal [1]. Nonlinear model has proposed in observer canonical form using a modified Recursive Instrument Variable [2], and Hammerstein model which makes the assumption that the nonlinearities of the systems can be separated from the system dynamics [3]. Since neural networks have been successfully used in various fields, back propagation neural networks were applied in identification of electro-hydraulic actuator model [4]. In the last few years, neural networks have been developed in form online identification using Recurrent High Order Neural Networks (RHONN) method [5]. Another online identification of the systems parameters is based on recursive least square algorithm, with constant trace [6]. Regarding to control design, starting with linear control, which applied a simple poles placement to a linearized model of an electro-hydraulic system [7] and following by classic cascaded loops and proportional-integral-derivative (PID) controllers were employed respectively for the position control of a hydraulic actuator [8], [9]. The next control design is an indirect adaptive controller, based on pole placement for the speed and position feedback of electro-hydraulic systems [10], [11].

However, the controllers which are based on a linear model of the plant, imposes certain limitations on the efficiency and robustness of the controller. Sliding Mode Control (SMC) was used to investigate the position tracking problem and combine with fuzzy inference and PI to improve the tracking accuracy [12]. Then, force tracking control was performed using PI controller to reject the effects of disturbance [13] and recurrent neural networks to eliminate the undesired chattering effect [14]. Moreover, the Lyapunov-based nonlinear controllers are widely used, with their main advantage being the lack of restrictions in manipulating system nonlinearities, where an electro-hydraulic actuator is provided with good tracking force [15]. Back stepping is a particular component of Lyapunov-based controllers. It constitutes a powerful control strategy for handling the nonlinearities which was employed in electro-hydraulic systems [16]. The algorithm was developed to employ in a real-time nonlinear back stepping control [5].

Intelligent control for electro-hydraulic actuator such as neural networks was proposed for adaptive control which consists of two BP networks [4] and SMC using recurrent high order sliding mode neural networks [5]. Meanwhile, ANN-based PID control was developed to reach high precision of tracking control of an electro-hydraulic actuator [17].

Recently, fuzzy logic control has been actively researched and utilized such as fuzzy-PID controller by combining the merits of fuzzy and conventional, self-tuning fuzzy linear control to improve the robustness and hybrid control of fuzzy and PID [18], Fuzzy-PD control with stability equation which makes the systems being stable and robust [19], and Fuzzy Internal Mode Control (FIMC) where the two-degree-of freedom internal model control strategy whose feedback controller is designed as a special fuzzy subsystem [20].

This paper presents a development of position control of electro-hydraulic actuator by using a self-tuning fuzzy PID controller to overcome the appearance of nonlinearities and uncertainties in the systems. The self-tuning fuzzy PID controller is the combination of a classical PID and fuzzy controller. The mathematical model of the hydraulic actuator is estimated by using System Identification technique.

The rest of this paper is organized as follows. The hydraulic actuator modeling is presented in section II. System Identification procedures are described in section III. Section IV performs the controller design. Section V presents the simulation results and discussion. Finally, conclusion is drawn in section VI.

II. ELECTRO-HYDRAULIC ACTUATOR MODEL

The electro-hydraulic actuator model consists of a servo valve and a hydraulic cylinder as shown in Fig. 1. The linear actuator is a single-rod, single ended piston, double-acting hydraulic cylinder. In the Fig. 1, P_s is the hydraulic supply pressure and P_r is the return pressure. X_v is the spool valve displacement, and P_2 and P_1 are the fluid pressure in the upper and lower cylinder chambers of the actuator. When differences between P_2 and P_1 exist, the hydraulic cylinder expands or compresses.

The complete mathematical model of the system, which describes characteristics and behaviours of the electro hydraulic system, consists of the hydraulic actuator dynamics including the load and the servo-valve dynamics [14], [24].

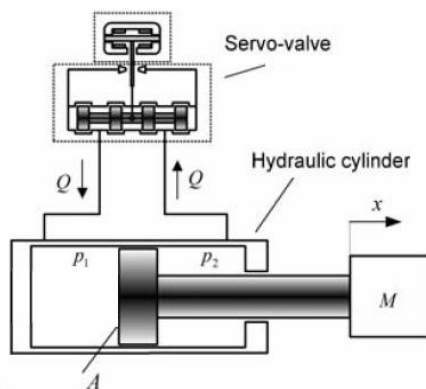


Fig. 1. Electro-Hydraulic Actuator.

The mechanical subsystem dynamics of the piston is depending on the damper and spring component that are

placed in parallel to the piston as part of load environment.

Where, x_p is the displacement of the piston, v_p is the piston velocity and d_u is an external disturbance.

There are two forces can be derived from the dynamics of servo hydraulic system. The forces are the hydraulic actuating force F_a and the hydraulic friction force F_f . The hydraulic actuating force F_a is a nonlinear function of the control input voltage, load environment, cylinder pressure, etc.

The differential equation govern the dynamics of the actuator are given. Defining the load pressure to be the pressure across the actuator piston, the derivative of the load pressure P_L , is given by the total load flow through the actuator divided by the fluid capacitance using the equation for hydraulic fluid flow through an orifice, the relationship between spool valve displacement x_v , and the load flow Q_L , is given where, A_p is the cross section area of a hydraulic cylinder, P_L is the cylinder differential pressure, V_t is the total actuator volume, β_e is the bulk modulus of hydraulic oil, C_T is the total leakage coefficient, C_d is discharge coefficient, w is the spool valve area gradient, and ρ is the oil density.

The dynamic equation for spool displacement of the servo valve x_v , is controlled by an input servo valve u . The corresponding relation can be simplified as where, k_a and τ_v are constant value based on data sheet. if the state variable are selected as $x_1=x_p$, $x_2=v_p$, $x_3=P_L$, and $x_4=x_v$, the state equations of the servo hydraulic systems may be written as suppose the variable ranges of the parameters K_p , K_i and K_d of PID controller are respectively parameter was determined based on the simulation on PID controller to obtain a feasible rule bases with high inference efficiency.

III. MODEL ESTIMATION

Model estimation of the hydraulic actuator is done in general procedure of system identification such as data examination, model structure selection, parameter estimation and model validation [21]. Data examination is done to obtain a good data. Model structure is selected to choose which model we want to produce. It can be in form linear, non-linear or intelligent model. Validation is done to validate the estimated model output compare to the real output from the experiments. The model validation can be accepted if it satisfies the percentage of fit and other criterions [22], [23]. Data for model estimation is taken from an experimental works on the hydraulic actuator with multi-frequency sine wave input. Number of data is 1500 and time sampling 55ms. The input and output signals as shown in Fig. 2 below. In order to estimate the model, the data divided into two parts. The first part is used to determine the model of the systems and the second one is applied to validate the model. All procedures to estimate the model is done by using System Identification Toolbox in Matlab.

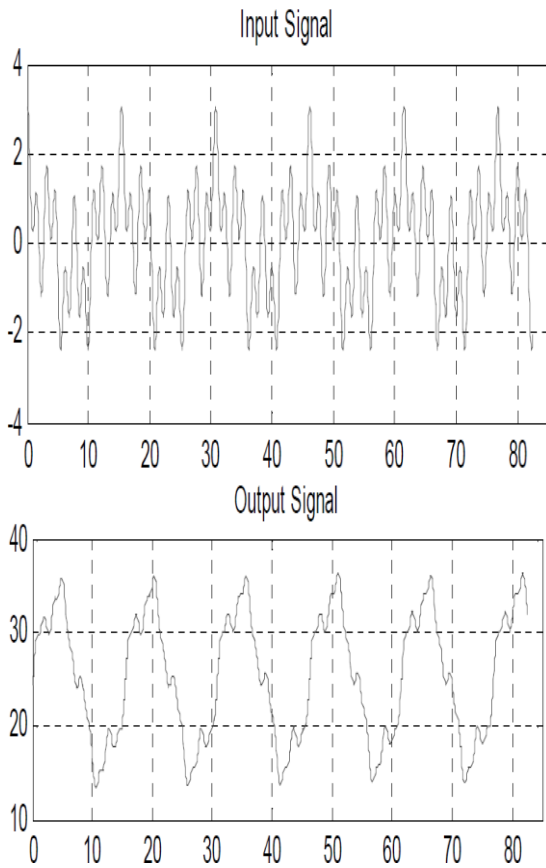


Fig. 2. Input and Output Signal.

ARX model is selected as model structure to estimate the model of the system. The model can be accepted when the validation of the model is successful by comparing measured output and simulated model output in form of the model output curve. Refer to the fit percentage; the selection of the best model is made here. As a rule of thumb, models can be accepted when the fit percentage higher than 90%.

Based on the output model curve as shown in Fig. 3, the polynomials of the model ARX331 can be reached. From the polynomials, the transfer function is derived and the rest of the response curves are analyzed. The output model curve shows the fit percentage is 93.22%.

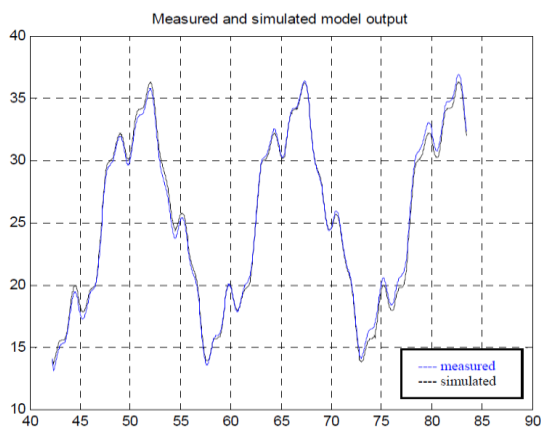


Fig. 3. Validation Curve.

The polynomials for this model output curve are also generated by the toolbox. The discrete time polynomial model obtained is a discrete polynomial model

$$A(q)y(t) = B(q)u(t)+e(t)$$

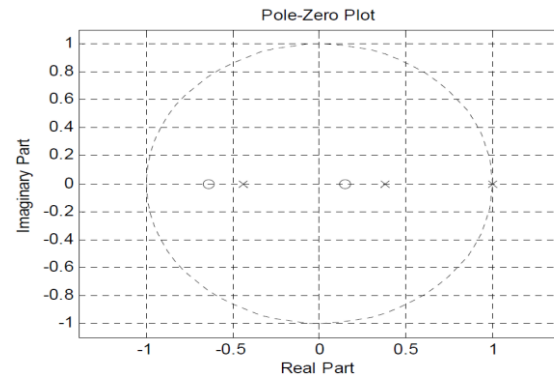


Fig. 4. Pole-Zero Plot for the Model.

The plot in Fig. 4 shows that all poles and zeros are within the unit circle. This is called a minimum phase model. This model address to the rule of causality and stability and it would be used for further analysis and to derive a relation between the input and output.

From this, analysis on the transient response and frequency response are done.

The transient response as represented in Fig. 5, shows that the systems response show the characteristic such including quite slow rise time, no overshoot, fast settling time and small error steady state.

By looking at the frequency response of the model, the Bode plot can be seen as below in Fig. 6 Frequency response of the model shows that when the amplitude in zero magnitude, the phase is around 100 deg. It indicates the desire bandwidth have not met yet.

Hence, the system should be examined to obtain the cross-over frequency in 180 deg and to meet the stability.

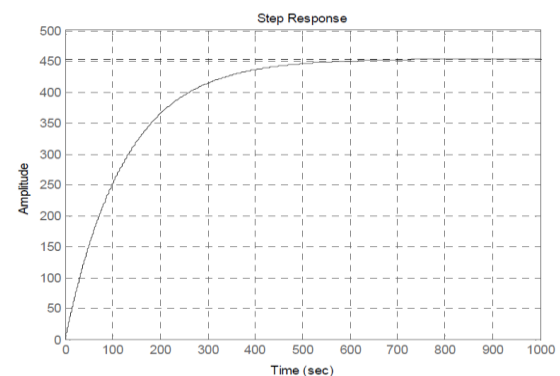


Fig. 5. Transient response of the Hydraulic Model.

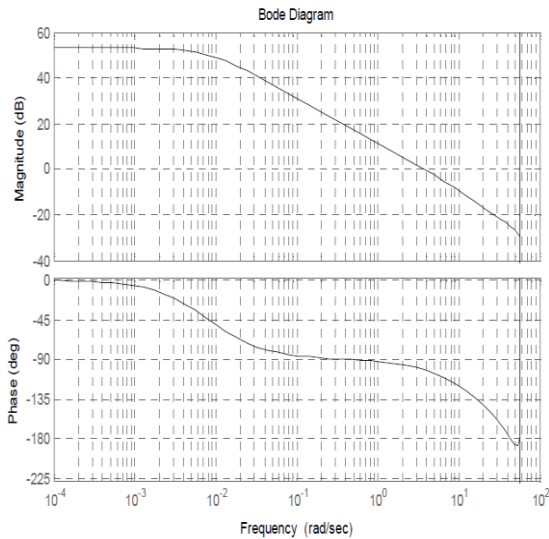


Fig. 6. Frequency Response of the Model.

IV. SELF-TUNING FUZZY PID CONTROLLER DESIGN

A. Proportional Integral Derivative (PID) Controller

PID controller is still the most popular controller which is widely used to improve the performance of the hydraulic actuator in industry, because it's easy to operate and very robust. Latest PID controller's structure is quite different from the original one and the implementation is based on a digital design. These digital PID include many algorithms to improve their performance, such as anti wind-up, auto-tuning, adaptive, fuzzy fine-tuning and Neural Networks. However, the basic operations still remain the same. The performance specifications of the systems such as rise time, overshoot, settling time and error steady state can be improved by tuning value of parameters K_p , K_i and K_d of the PID controller, because each component has its own special purposes. Mathematically it is represented as $K_i = K_p/T_i$ and $K_d = K_p.T_d$.

B. Structure of Fuzzy Controller

Fuzzy logic controller as shown in Fig. 7 consists of main four parts fuzzification, rule base, inference engine and defuzzification.

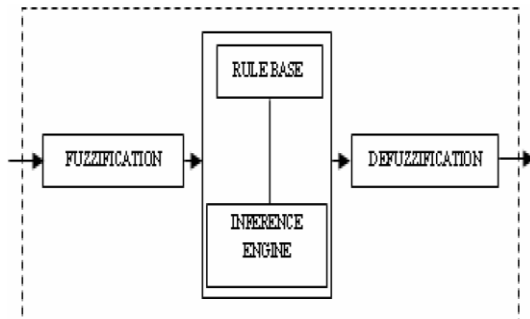


Fig. 7. Fuzzy Logic Controller Block.

C. Structure of Self-Tuning Fuzzy PID Controller

Self-tuning fuzzy PID controller means that the three parameters K_p , K_i and K_d of PID controller are tuned by using fuzzy tuner [25], [26]. The coefficients of the

conventional PID controller are not often properly tuned for the nonlinear plant with unpredictable parameter variations. Hence, it is necessary to automatically tune the PID parameters. The structure of the self-tuning fuzzy PID controller is shown in Fig. 8.

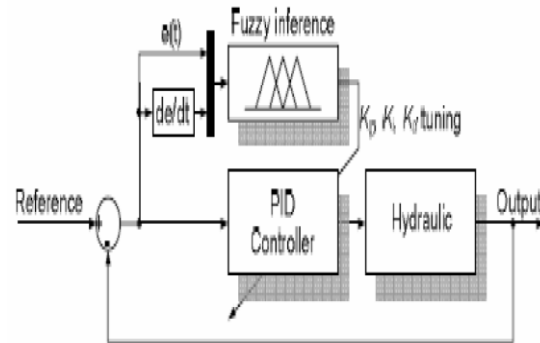


Fig. 8. Structure of Self-Tuning Fuzzy PID Controller.

D. Design of Self-Tuning Fuzzy PID Controller

The rules designed are based on the characteristic of the electro-hydraulic actuator and properties of the PID controller. Therefore, the fuzzy reasoning of fuzzy sets of outputs is gained by aggregation operation of fuzzy sets inputs and the designed fuzzy rules. The aggregation and defuzzification method are used respectively max-min and centroid method. Regarding to the fuzzy structure, there are two inputs to fuzzy inference: error $e(t)$ and derivative of error $de(t)$, and three outputs for each PID controller parameters respectively K'_p , K'_i and K'_d . Mamdani model is applied as structure of fuzzy inference with some modification to obtain the best value for K_p , K_i and K_d . Fuzzy inference block of the controller design is shown in Fig. 9 below.

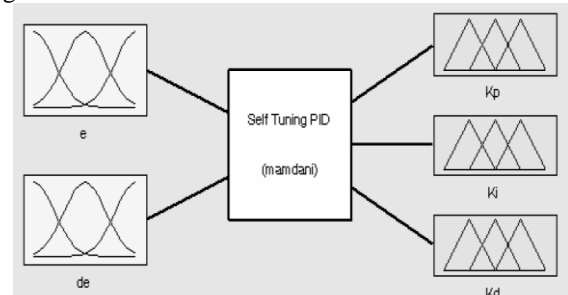


Fig. 9. Fuzzy Inference Block.

Suppose the variable ranges of the parameters K_p , K_i and K_d of PID controller are respectively $[K_{pmin}, K_{pmax}]$, $[K_{imin}, K_{imax}]$, and $[K_{dmin}, K_{dmax}]$. The range of each parameter was determined based on the simulation on PID controller to obtain a feasible rule bases with high inference efficiency. The range of each parameters are, $K_p \in [10, 100]$, $K_i \in [0.1, 1]$ and $K_d \in [0.001, 0.01]$. Therefore, they can be calibrated over the interval $[0, 1]$.

The membership functions of these inputs fuzzy sets are shown in Fig. 10 and 11. The linguistic variable levels are assigned as NB: negative big; NS: negative small; ZE: zero; PS: positive small; PB: positive big. These levels are

chosen from the characteristics and specification of the electro-hydraulic actuator. The ranges of these inputs are from -0.1 to 0.1, which are obtained from the absolute value of the system error and its derivative through the gains.

Whereas the membership functions of outputs K'_p , K'_i and K'_d are shown in Fig. 12. The linguistic levels of these outputs are assigned as S: small; MS: medium small; M: medium; MB: medium big; B: big, where the ranges from 0 to 1.

Generally, the fuzzy rules are depended on the plant to be controlled and the type of the controller and from practical experience. Regarding to the above fuzzy sets of the inputs and outputs variables, the fuzzy rules are perform in rules table as shown in Fig. 13 and composed as follows:

Rule i : If $e(t)$ is A_{1i} and $de(t)$ is A_{2i} then $K'_p = B_i$ and $K'_i = C_i$ and $K'_d = D_i$. Where $i = 1, 2, 3, \dots, n$, and n is number of rules. Since we have 5 variables as input and 5 variables as output, hence, in the design we have 25 fuzzy rules.

V. RESULTS AND DISCUSSION

Self-tuning fuzzy PID regulator subsystem block as shown in Fig. 14 consists of Fuzzy and PID block with some modification refers to the formula which is applied to calibrate the value of K'_p , K'_i and K'_d from fuzzy block to obtain the value of K_p , K_i and K_d . Each parameter has its own calibration. While, the complete Simulink Block for whole system including the control design and the plant is shown in Fig. 15.

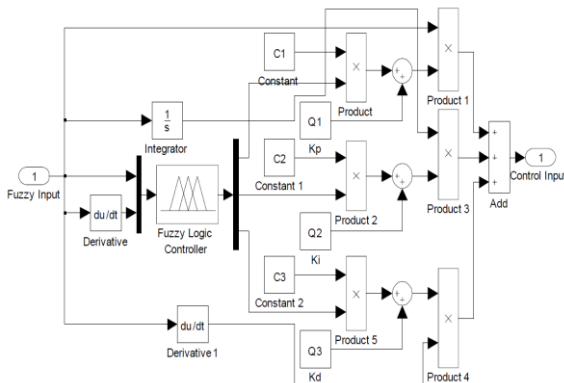


Fig. 14. Simulink Block of Fuzzy PID regulation.

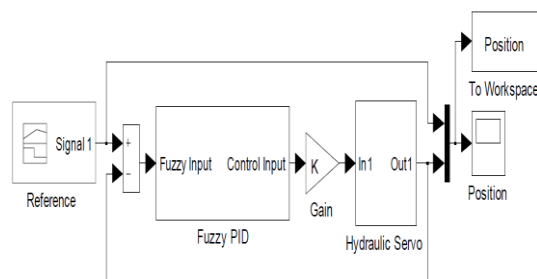


Fig. 15. Simulink Block of the System and Controller.

The value of parameter K_p , K_i and K_d are tuned by using signals from fuzzy logic block based on the changes in the error between reference signals and output signals. In order to perform the output of the system, two types of

input signal are applied respectively step input and square wave input. The outputs of the simulation for both inputs are represented in Figure 16 and 17 below.

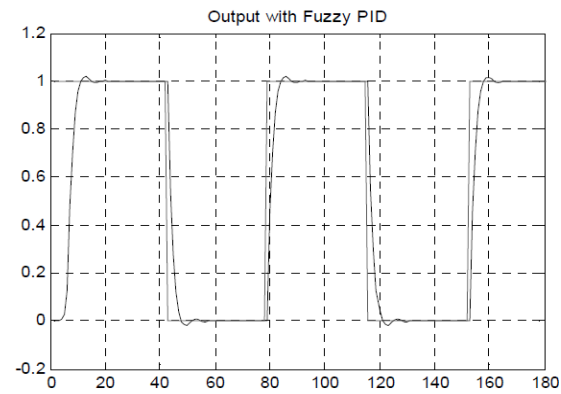
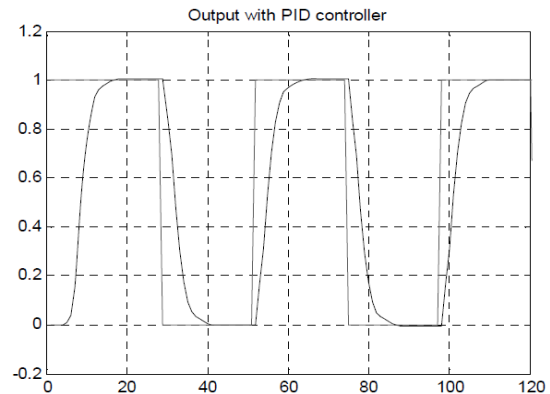


Fig. 16. Depict the performance of the proposed control design with square wave reference input.

The response is still slow when the conventional PID controller is applied on the system. In the other hand, when the self-tuning fuzzy PID controller is implied into the system, the response become significantly faster.

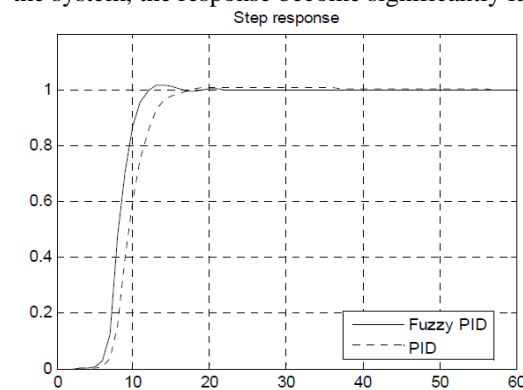


Fig. 17. Shows the performance of the control system with respect to step reference input signal.

The system response to step reference input compared with conventional PID controller and self-tuning fuzzy PID controller. The self-tuning fuzzy PID controller achieves better tracking response than conventional PID controller. It is indicated from faster rise time, faster settling time, less overshoot and without steady state error. The responses of the proposed control design look

satisfied. However, the proposed control needs to develop by including disturbance and any others nonlinearity and uncertainties in the design with various frequencies in reference input signals.

VI. CONCLUSION

Modelling was done on the electro-hydraulic actuator and self-tuning fuzzy PID controller was proposed successfully. System Identification technique was employed to obtain a linear discrete model of the hydraulic system. Self-tuning fuzzy controller was applied to tune the value of K_p , K_i and K_d of the PID controller. Through some tests on the system by using square wave signals and step input signals. The system responses indicate the performance of the hydraulic system was improved and satisfied compare to conventional PID controller.

REFERENCES

- [1] Huang S. H, Chen Y. H. C. 2006. Adaptive Sliding Control with Self-Tuning Fuzzy Compensation for Vehicle Suspension Control. *Mechatronics*, Vol. 16: 607-622.
- [2] Jelali M., Schwarz H. 2005. Nonlinear Identification of Hydraulic Servo-drive Systems. *IEEE Control Systems*: 17-22.
- [3] KwakByung-Jae, Andrew E. Yagle, Joel A. Levitt. 1998. Nonlinear System Identification of Hydraulic Actuator Friction Dynamics using a Hammerstein Model. *IEEE*: 1933-1936.
- [4] Anyi H., Yiming R., Zhongfu Z., and Jianjun Hu. 1997. Identification and Adaptive Control for Electro-hydraulic Servo Systems Using Neural Networks, In *Proceeding of the 1997 IEEE International Conference on Intelligent Processing Systems*, 688-692. Beijing, China.
- [5] Lizarde C., Loukianov A., Sanchez E. 2005. Force Tracking Neural control for an Electrohydraulic Actuator via Second Order Sliding Mode. In *Proceeding of the 2005 IEEE International Symposium on Intelligent Control*, 292-297, Limassol, Cyprus.
- [6] Kaddissi C., Kenne J-P., Saad M. 2007. Identification and Real-time Control of an Electrohydraulic Servo System Based on Nonlinear Backstepping. *IEEE Transaction on Mechatronics*, Vol. 12 No.1:12-21.
- [7] Lim, T. J. 1997. Pole Placement Control of an Electro-hydraulic Servo Motor. In *Proc. of 1997 2nd Int. Conf. Power Electronic Drive System*, Part 1, Vol. 1, 350-356. Singapore.
- [8] Plahuta M. J., Franchek M. A., Stern H. 1997. Robust Controller Design for a Variable Displacement Hydraulic Motor. *Proc. of ASME Int. Mech. Eng. Congr. Expo.* Vol. 4, 169-176.
- [9] Zeng W., Hu J. 1999. Application of Intelligent PDF Control Algorithm to an Electro hydraulic Position Servo System. In *Proc. of IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, 233-238. Atlanta, GA.
- [10] Yu W.-S., Kuo T.-S. 1996. Robust Indirect Adaptive Control of the Electro-hydraulic Velocity Control Systems, In *Proc. of Inst. Elect. Eng.: J. Control Theory Appl.*, Vol. 143 (5):448-454.
- [11] Yu W.-S., Kuo T.-S. 1997. Continuous-time Indirect Adaptive Control of the Electro-hydraulic Servo Systems. *IEEE Transactions Control System Technology*, Vol. 5, No. 2 : 163-177.
- [12] Mihajlov M., Nikolic V., Antic D. 2002. Position Control of Electro Hydraulic Servo System Using Sliding Mode Control Enhanced By Fuzzy PI Controller, *FactaUniversitaties Series: Mechanical Engineering* , Vol. 1 No. 9 : 1217-1230.
- [13] Sam Y. M., Huda K. 2006. Modeling and Force Tracking Control of Hydraulic Actuator for an Active Suspension System, In *Proceeding of the 2006 IEEE ICIEA*.
- [14] Loukianov A. G., Sanchez E., Lizarde C. 2007. Force Tracking Neural Block Control for an Electro-Hydraulic Actuator via Second-Order Sliding Mode. *Int. Journal of Robust and Nonlinear Control*, Wiley InterScience, 20 June : 319-332.
- [15] Liu R. and Alleyne A. 2000. Nonlinear Force/pressure Tracking of an Electrohydraulic Actuator. *Journal Dynamic System Measurement Control-Trans. ASME*, Vol. 122 : 232-237.
- [16] Kaddissi C., Kenn'e J.-P., Saad M. 2004. Position Control of an Electro-hydraulic Servo System - a Non-linear Backstepping Approach. *Int. Conf. Informatics in Control, Automation and Robotics-ICINCO*, Setubal, Portugal.
- [17] Jianjun Y., Liquan W., Caidong W., Zhonglin Z. and Peng J. 2008. ANN-based PID Controller for an Electro-hydraulic Servo System. In *Proceedings of the IEEE International Conference on Automation and Logistics*, 18-22. Qingdao, China.
- [18] Shao J., Chen L., Sun Z. 2005. The Application of Fuzzy Control Strategy in Electro-hydraulic Servo System. In *Proceedings of the IEEE International Conference on Mechatronics & Automation*, 2010-2016. Niagara Falls, Canada.
- [19] Huang Y. J., Kuo T. C., Lee H. K. 2007. Fuzzy-PD Controller Design with Stability Equations for Electro-hydraulic Servo Systems. In *Proceeding of International Conference on Control, Automation and Systems 2007*, 2407-2410. COEX, Seoul, Korea.
- [20] Hong Li, Shibo X. 2008. Fuzzy Internal Mode Control for Electro-hydraulic Servo Systems, In *Proceedings of the 27th Chinese Control Conference*, 372-376. Kunming, Yunnan, China.
- [21] Ljung. 1999. *System Identification: Theory for the User*, Upper Saddle River Prentice-Hall, PTR New Jersey.
- [22] Soderstrom T. and Stoica P. 1989. *System Identification*. Prentice-Hall Int., London.
- [23] Ljung. 2002. *System Identification: Theory for the User*, Prentice-Hall.
- [24] Avila M. A., Loukianov A. G., and Sanchez E. N. 2004. Electro-Hydraulic Trajectory Tracking. In *Proceedings of the 2004 American Control Conference*, 2603-2608. Boston, Massachusetts.
- [25] Kyoung K. A., Bao K. N., Yoon H. S. 2007. Self Tuning Fuzzy PID Control for Hydraulic Load Simulator. *Int. Conference on Control, Automation, and Systems 2007*, 345-349. Ceox, Seoul, Korea.
- [26] Kyoung K. A., Bao K. N. 2006. Position Control of Shape Memory Alloy Actuators Using Self Tuning Fuzzy PID Controller. *Int. J. of Control, Automation, and Systems*, Vol.4 (6): 756-762.