APPLICATION OF SELF-TUNING FUZZY PID CONTROLLER ON INDUSTRIAL HYDRAULIC ACTUATOR USING 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.***

Index terms: 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 aluminum mill equipment. In all those applications the highest performance of the electro-hydraulic 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 modeling 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 Figure 1. The linear actuator is a single-rod, single ended piston, double-acting hydraulic cylinder. In the Figure 1, P_s is the hydraulic supply pressure and P_{τ} is the return pressure. x_v is the spool valve displacement, and P_2 and P_l are the fluid pressure in the upper and lower cylinder chambers of the actuator. When differences between P_2 and P_l exist, the hydraulic cylinder extends or compresses.

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

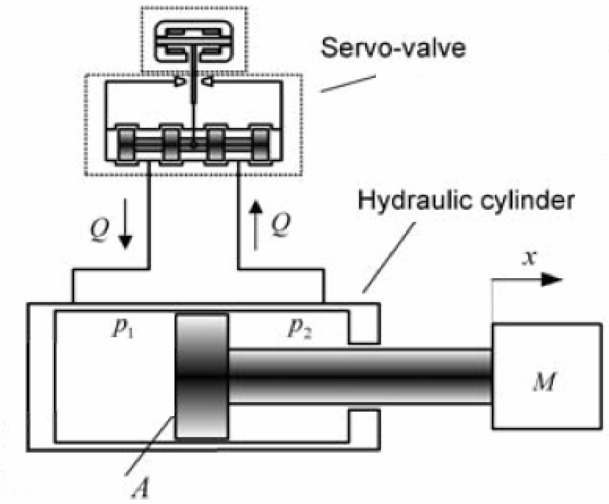

Figure 1. Electro-hydraulic actuator

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. The dynamic equations is given by

$$\dot{x}_p = v_p \tag{1}$$

$$m\dot{v}_p = -k_s x_p - b_s v_p + A_L P_L - F_f - d_u \tag{2}$$

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, and it can be represented as

$$F_a = A_P P_L \qquad (3)$$

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

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

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

$$Q_L = C_d w x_v \sqrt{\frac{P_s - sigm(x_v)P_L}{\rho}} \qquad (5)$$

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.

Therefore, from equation (3) to (5), the hydraulic dynamics of the actuating force of the cylinder is given by

$$\dot{P}_L = -\alpha v_P - \beta P_L + \left(\gamma\sqrt{P_s - sigm(x_v)P_L}\right)x_v \qquad (6)$$

where, $\alpha = \frac{4A_P\beta_e}{V_t}, \quad \beta = \frac{4C_T\beta_e}{V_t}, \quad \gamma = \frac{4C_d w\beta_e}{V_t\sqrt{\rho}}$

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

$$\dot{x}_v = \frac{1}{\tau_v}(-x_v + k_a u) \qquad (7)$$

where, k_a and τ_v are constant value based on data sheet. From equation (1) to (7), 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

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{1}{M_s}(-k_s x_1 - b_s x_2 + A_P x_3 - F_f)$$

$$\dot{x}_3 = -\alpha x_2 - \beta x_3 + (\gamma\sqrt{P_s - x_3 sigm(x_4)})x_4$$

$$\dot{x}_4 = -\frac{1}{\tau_v}x_4 - \frac{k_a}{\tau_v}u \qquad (8)$$

And output of the system is

$$y = A_P x_3 - F_f \qquad (9)$$

Such that the mathematical model of the servo hydraulic system has fully cleared and established.

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 Figure 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.

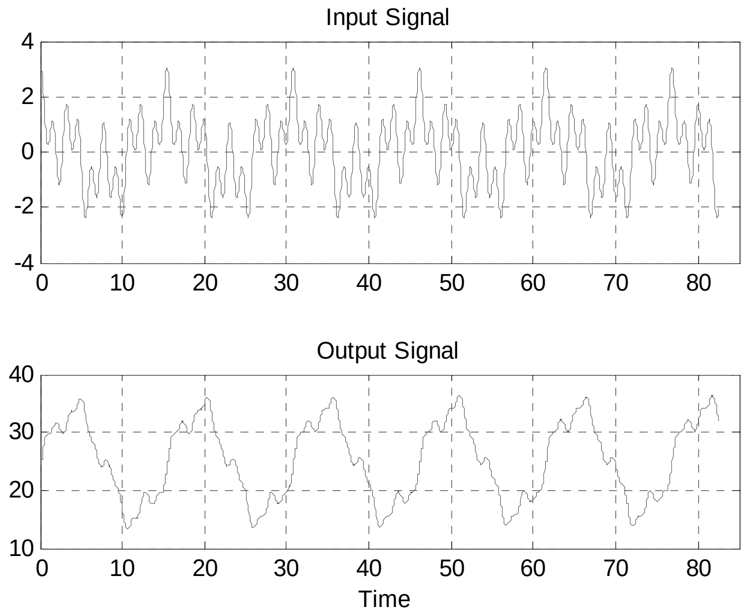

Figure 2. Input and output signals

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 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 Figure 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%.

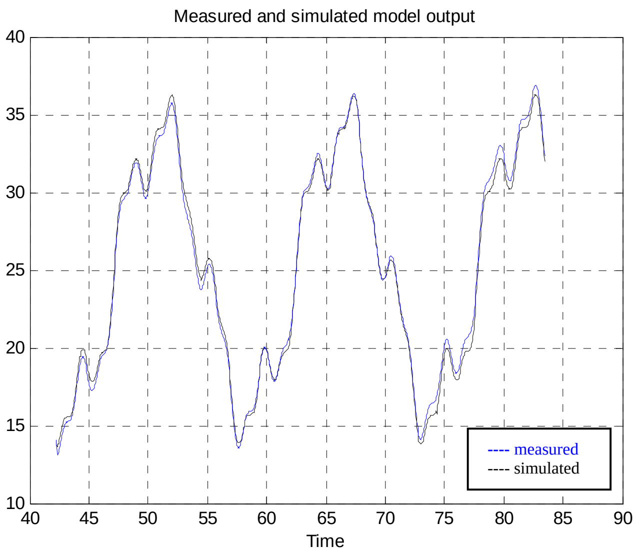

Figure 3. Validation curve

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

$$A(q)y(t) = B(q)u(t) + e(t) \tag{10}$$

$$A(q) = 1 - 0.9357q^{-1} - 0.2315q^{-2} + 0.1676q^{-3}$$

$$B(q) = 0.1292q^{-1} + 0.06435q^{-2} - 0.01196q^{-3}$$

Hence, Loss function = 0.001836 and Akaike's Final Prediction Error (FPE) = 0.00186572.

Now let's derive the discrete polynomial transfer function for the model by starting with the general expression below

$$H(s) = \frac{L\{(x(t)\}}{L\{(y(t)\}} = \frac{b_m s^m + b_{m-1}s^{m-1} + .. + b_1 s + b_0}{s^n + a_{n-1}s^{n-1} + .. + a_1 s + a_0} \tag{11}$$

Similarly the discrete LTI transfer function shows that

$$H(s) = \frac{Y(q)}{U(q)} = \frac{c_0 + c_1 q^{-1} + .. + c_{m-1}q^{-m-1} + c_m q^{-m}}{q^{-1} + d_1 q^{-2} + .. + d_{n-1}q^{-n-1} + d_n q^{-n}}$$

Since the general equation to describe ARX model is

$$A(z^{-1})y(k) = B(z^{-1})u(k-d) + C(z^{-1})e(k) \qquad (12)$$

Hence, the transfer function is performed as

$$H_{arx} = \frac{B(q)}{A(q)} = \frac{0.129q^{-1} + 0.064q^{-2} - 0.012q^{-3}}{1 - 0.936q^{-1} - 0.232q^{-2} + 0.168q^{-3}}$$

To narrow down on the model, the pole and zero plot for each model is observed. The best model will have all its poles and zeros within the unit circle to show the stability.

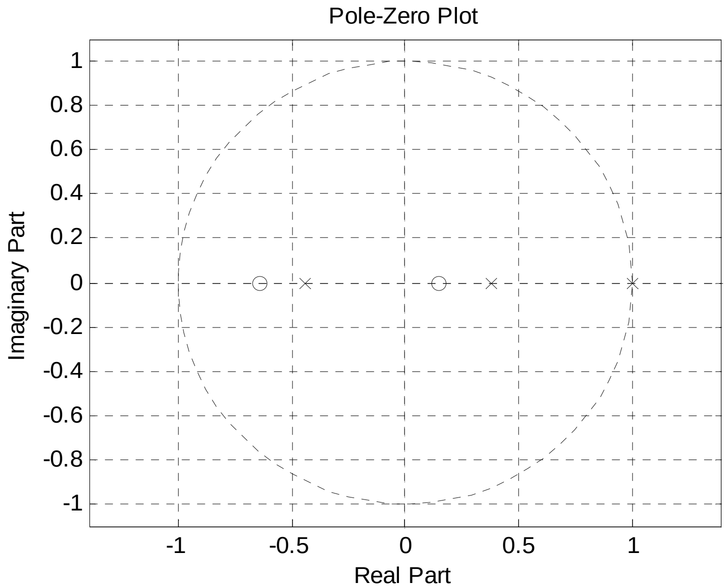

Figure 4. Pole Zero plot for the model

The plot in Figure 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 Figure 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 Figure 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.

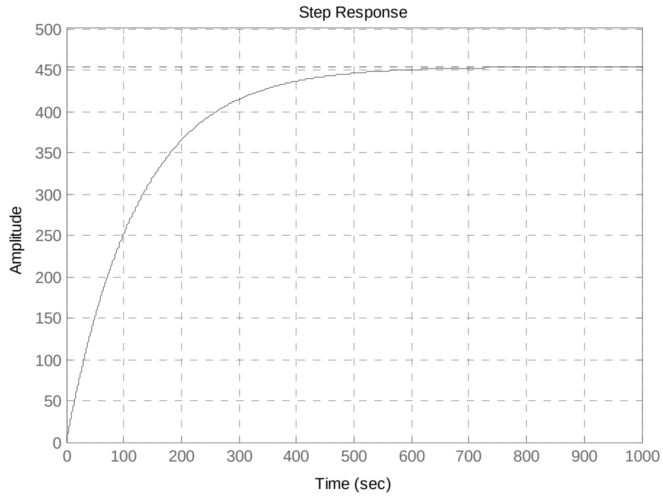

Figure 5. Transient response of the hydraulic model

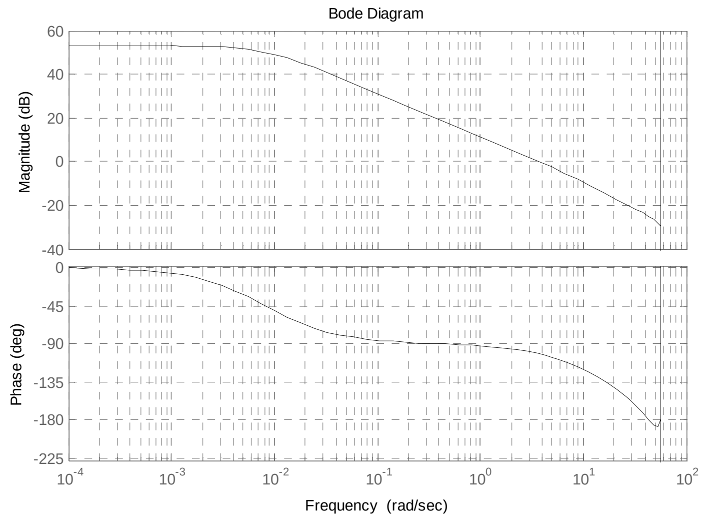

Figure 6. Frequency response of the model

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_p of the

PID controller, because each component has it's own special purposes. Mathematically it is represented as

$$y(t) = K_p \left[e(t) + T_d \frac{d(e)}{d(t)} + \frac{1}{T} \int_0^t e(t) d(t) \right]$$

$$y(t) = \left[K_p e(t) + K_d \frac{d(e)}{d(t)} + K_i \int_0^t e(t) d(t) \right] \qquad (13)$$

Where: $K_i = K_p / T_i$ and $K_d = K_p . T_d$.

b. Structure of Fuzzy Controller

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

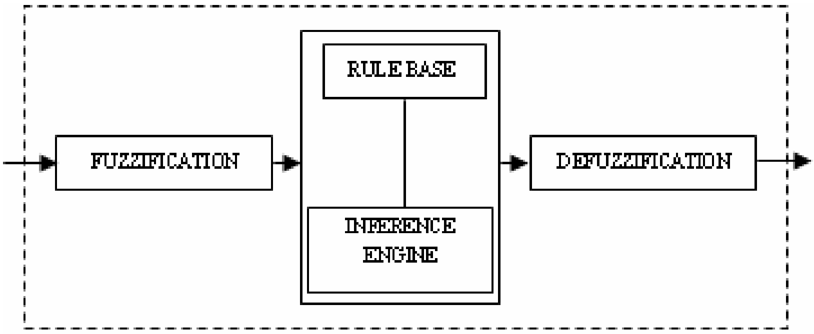

Figure 7. Fuzzy Logic Controller block

c. Structure of Self-Tuning Fuzzy PID Controller

Self-tuning fuzzy PID controller means that the three parameters K_p, K_i and K_p 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 Figure 8.

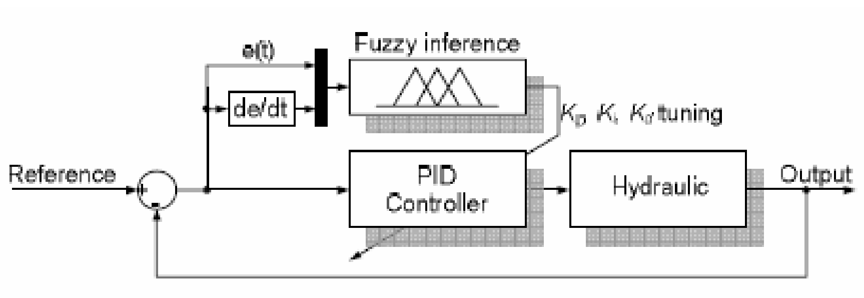

Figure 8. Structure of self tuning fuzzy PID controller

Where e(t) is the error between desired position set point and the output, de(t) is the derivation of error. The PID parameters are tuned by using fuzzy inference, which provide a nonlinear mapping from the error and derivation of error to PID parameters.

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 Figure 9 below.

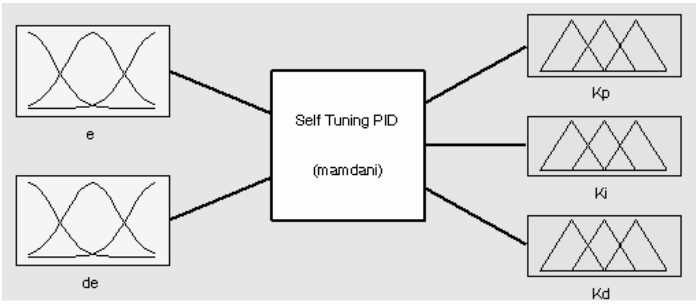

Figure 9. Fuzzy inference block

Suppose the variable ranges of the parameters K_p, K_i and K_p of PID controller are respectively $\left[K_{p\min}, K_{p\max}\right]$, $\left[K_{i\min}, K_{i\max}\right]$, and $\left[K_{d\min}, K_{d\max}\right]$. 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] as follows:

$$K_p^{'} = \frac{K_p - K_{i\min}}{K_{p\max} - K_{p\min}} = \frac{K_p - 10}{100 - 10}$$

$$K_i^{'} = \frac{K_i - K_{i\min}}{K_{i\max} - K_{i\min}} = \frac{K_i - 0.1}{1 - 0.1}$$

$$K_d^{'} = \frac{K_d - K_{d\min}}{K_{d\max} - K_{d\min}} = \frac{K_d - 0.001}{0.01 - 0.001}$$

Hence, we obtain:, $K_p = 90K_p^{'} + 10$ $K_i = 0.9K_i^{'} + 0.1$, and $K_d = 0.009K_d^{'} + 0.001$.

The membership functions of these inputs fuzzy sets are shown in Figure 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,

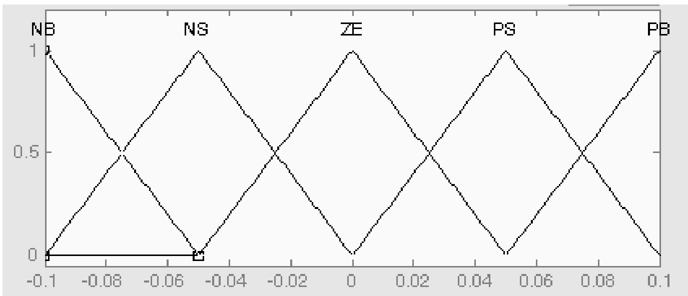

Figure 10. Membership functions of e(t)

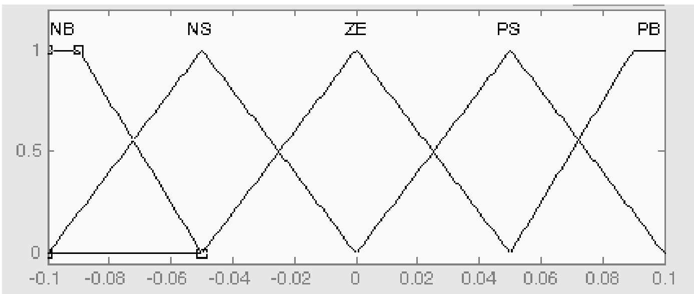

Figure 11. Membership functions of de(t)

Whereas the membership functions of outputs K'_p, K'_i and K'_d, are shown in Figure 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.

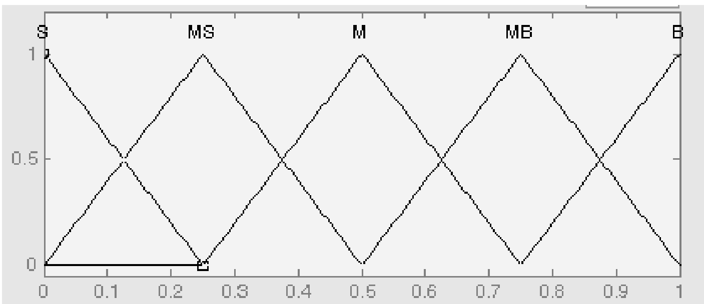

Figure 12. Membership functions of K'_p, K'_i and K'_d

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 Figure 13 and composed as follows:

Rule *i*: If *e(t)* is A_{1i} and *de(t)* A_{2i} then $K'_p = B_i$ and $K'_i = C_i$ and $K'_d = D_i$.

Where i= 1, 2, 3,..., n, and n is number of rules. From the table, since we have 5 variables as input and 5 variables as output, hence, in the design we have 25 fuzzy rules.

De\e	NB	NS	ZE	PS	PB
NB	S	S	MS	MS	M
NS	S	MS	MS	M	MB
ZE	MS	MS	M	MB	MB
PS	MS	M	MB	MB	B
PB	M	MB	MB	B	B

Figure 13. Rules of the fuzzy inference

V. RESULTS AND DISCUSSION

Self-tuning fuzzy PID regulator subsystem block as shown in Figure 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 it's own calibration. While, the complete Simulink block for whole system including the control design and the plant is shown in Figure 15.

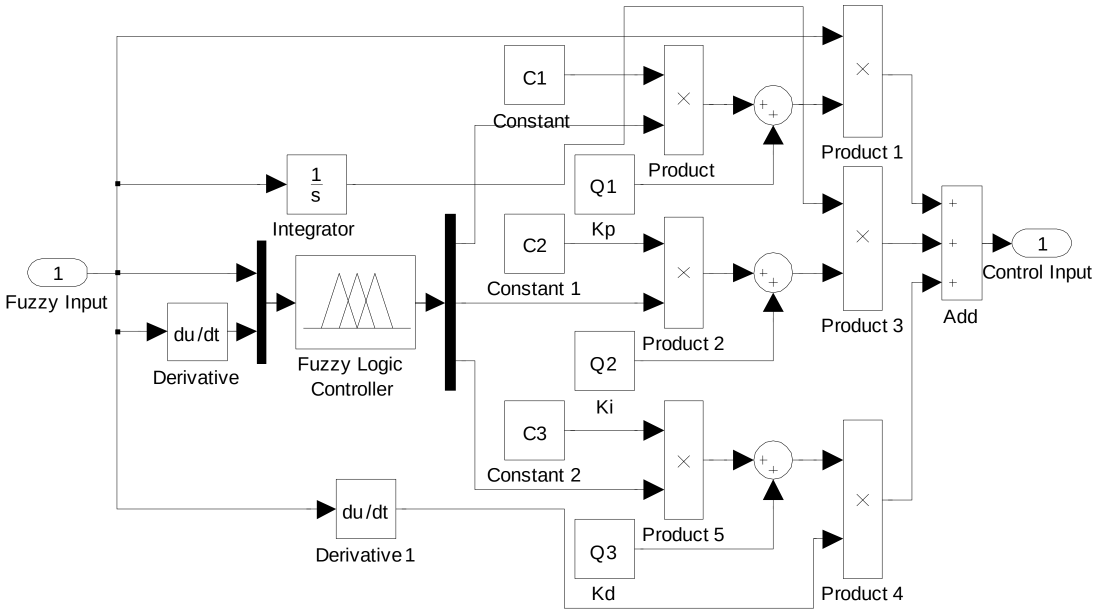

Figure 14. Simulink Block of Fuzzy PID regulator

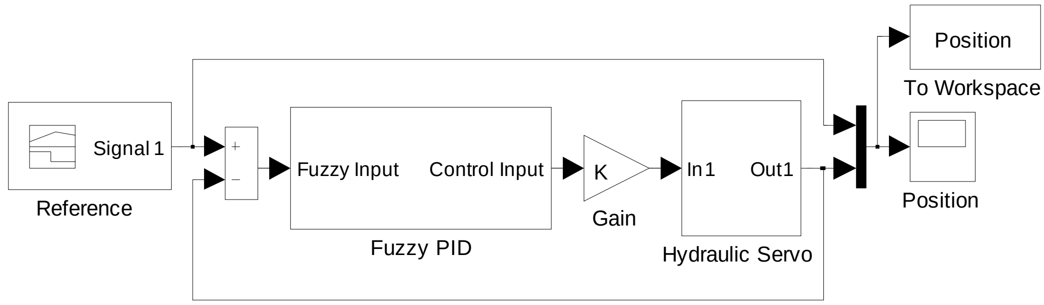

Figure 15. Simulink Block of the system and controller

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.

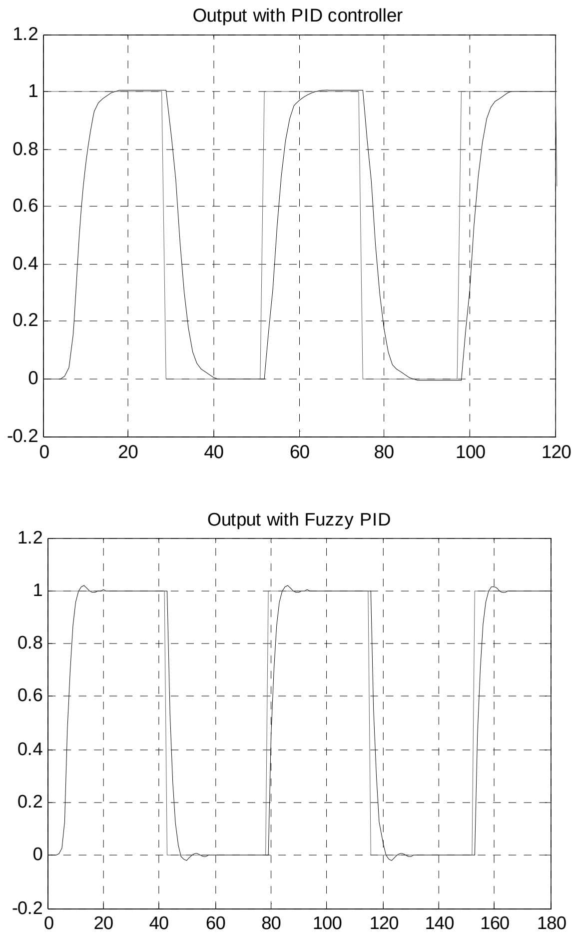

Figure 16. Output signal with square input

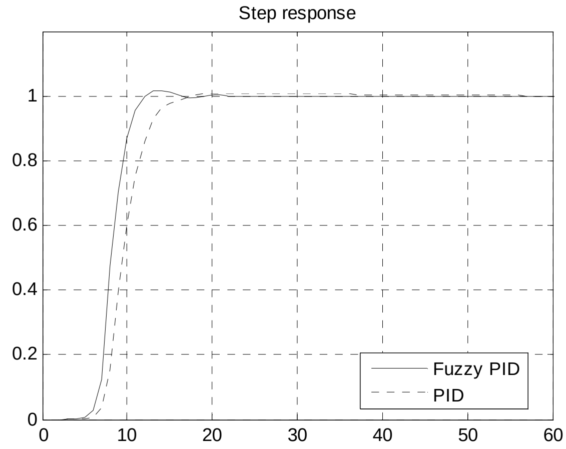

Figure 17. Output signal with step input

Figure 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.

Figure 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

Modeling 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.

ACKNOWLEDGMENTS

This research is supported by Ministry of Science, Technology and Innovation (MOSTI) Malaysia and Universiti Teknologi Malaysia (UTM) through Science Fund Grant vote number 79345 which is led by Assoc. Prof. Dr. Mohd. Fua'ad bin Hj. Rahmat. Authors are grateful to the Ministry and UTM for supporting the present work.

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