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A Hybrid of Fuzzy and Proportional-Integral-Derivative Controller for Electro-Hydraulic Position Servo System

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Abstract: Problem statement: While classical PID controllers are sensitive to variations in the system parameters, Fuzzy controllers do not need precise information about the system variables in order to be effective. However, PID controllers are better able to control and minimize the steady state error of the system. To enhance the controller performance, hybridization of these two controller structures comes to one mind immediately to exploit the beneficial sides of both categories. **Approach:** A hybrid fuzzy PID controller for the Electro-Hydraulic Position Servo System (EHPSS) was proposed in this study. The proposed control scheme was separated into two parts, fuzzy controller and PID controller. Fuzzy controller was used to control the piston when the piston locates far away from the target position. PID controller is applied when the piston is near the desired position. **Results:** We demonstrated the performance of control scheme via experiments performed on the EHPSS. **Conclusion:** The results from the experiments showed that the proposed hybrid fuzzy PID controller has superior performance compared to individual PID controller and fuzzy controller.

Key words: PID controller, fuzzy controller, hybrid fuzzy PID controller, electro-hydraulic position servo system

INTRODUCTION

The application of hydraulic actuation to heavy duty equipment reflects the ability of the hydraulic circuit to transmit larger forces and to be easily controlled. It has many distinct advantages such as the fast response speed, very high system stiffness and a higher force to weight ratio (Zhao and Virvalo, 1993; Li *et al*., 2006). The electro-hydraulic servo system, among others, is perhaps the most important system for position servo applications because it takes the advantages of both the large output power of traditional hydraulic systems and the rapid response of electric systems. Typical applications of Electro-Hydraulic Position Servo Systems (EHPSS) include injection molding machines, different kinds of machine tools and construction machinery, etc. However, there are also many challenges in the design of electro-hydraulic control system (Zhao and Virvalo, 1993; Li *et al*., 2006; Chuang and Shiu, 2004). For example, they are the highly nonlinear phenomena such as fluid compressibility, the flow/pressure relationship and deadband due to the internal leakage and hysteresis and the many uncertainties of hydraulic systems due to linearization. Therefore, it seems to be quite difficult to perform a high precision servo control by using linear control method.

Classical PID controller is the most popular control tool in many industrial applications because they can improve both the transient response and steady state error of the system at the same time. Moreover, it has simple architecture and conceivable physical intuition of its parameter (Parnichkun and Ngaecharoenkul, 2000; Erenoglu *et al*., 2006). Traditionally, the parameters of a classical PID controller, i.e., K_P, K_I and K_D, are usually fixed during operation. Consequently, such a controller is inefficient for control a system while the system is disturbed by unknown facts, or the surrounding environment of the system is changed.

Fuzzy control is robust to the system with variation of system dynamics and the system of model free or the system which precise information is not required. It has been successfully used in the complex ill-defined process with better performance than that of a PID controller. Another important advance of fuzzy controller is a short rise time and a small overshoot. However, there are still difficulties in the design of fuzzy controller. One of the important problems

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involved with the design of fuzzy logic controller is the complexity of fuzzy controller. The complexity of fuzzy controller increases exponentially when the number of input variables increases. The hybrid of fuzzy and PID controllers takes advances of the nonlinear characteristics of the fuzzy controller and the accuracy near a set point which is guaranteed by the classical PID controller (Parnichkun and Ngaecharoenkul, 2000).

MATERIALS AND METHODS

Dynamic model of electro-hydraulic position servo systems: The block diagram of the hydraulic position servo system (Chuang and Shiu, 2004) is shown in Fig. 1. The valve displacement and the flow rate are governed by the orifice law that is:

$$Q_L = X_v K_j \sqrt{P_s - \mathrm{sgn}(X_v) P_L} = X_v K_s \tag{1}$$

Where:

K_j = A constant depended on the specific hydraulic component

P_s and P_L = The supply pressure and the load pressure

Hence, the valve flow gain K_s will be depended on the working conditions. The volume and continuity expressions can be combined to yield:

$$Q_L = D\omega + C_{tp} P_L + \frac{4\beta}{V_t}\dot{P}_L \tag{2}$$

This is the usual form of the continuity equation:

D = Volumetric displacement

C_{tp} = The total leakage coefficient

β = The bulk modulus of the oil and

V_t = The total volume of the oil

ω = The velocity of the hydraulic cylinder

The resulting torque equation is:

$$T = DP_L = J\dot{\omega} + B\omega + T_L \tag{3}$$

Where:

J = The total inertia coefficient of the hydraulic cylinder

B = The viscous damping constant

The spring load T_L will vary depended on the Hook's law, that is:

$$T_L = K_H \theta$$

where, K_H is the Hook's constant. The hydraulic cylinder position θ is obtained by:

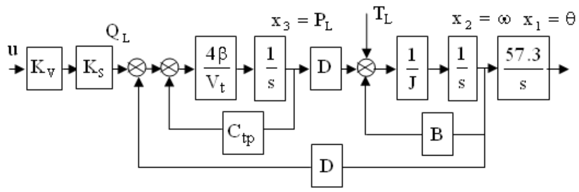

Fig. 1: Dynamic model of the EHPSS

$$\dot{\theta} = 57.3\omega \tag{4}$$

where the constant 57.3 cm/rad is the transforming gain from radius to centimeters. The variables of position θ, velocity ω and load pressure P_L, are all measurable.

Therefore, the electro-hydraulic position servo system call be described as:

$$\dot{x}_1 = -a_{11}x_1 - a_{12}x_2 - a_{13}x_3 - f_1 \tag{5a}$$

$$\dot{x}_2 = -a_{21}x_1 - a_{22}x_2 - a_{23}x_3 - f_2 \tag{5b}$$

$$\dot{x}_3 = -a_{31}x_1 - a_{32}x_2 - a_{33}x_3 - f_3 + bu \tag{5c}$$

$$y = c_1x_1 + c_2x_2 + c_3x_3 \tag{5d}$$

where, y = θ means the hydraulic position and:

$$a_{11} = a_{13} = a_{23} = a_{31} = f_1 = f_3 = 0, a_{12} = 57.3$$
$$a_{21} = \frac{B}{J}, a_{22} = \frac{D}{J}, a_{32} = \frac{4\beta}{V_t}D, a_{33} = \frac{4\beta}{V_t}C_{tp},$$
$$b = \frac{4\beta}{V_t}K_vK_s \text{ , and } f_2 = \frac{1}{J}T_L$$

Using the forward difference transformation, that is:

$$\dot{x} = \frac{x(k+1) - x(k)}{T}$$

where, T is the sampling time period, one has the discretized system equations as:

$$x_1(k+1) = x_1(k) - Ta_{11}x_1(k) - Ta_{12}x_2(k) - Ta_{13}x_3(k) - Tf_1(k) \tag{6a}$$

$$x_2(k+1) = x_2(k) - Ta_{21}x_1(k) - Ta_{22}x_2(k) - Ta_{23}x_3(k) - Tf_2(k) \tag{6b}$$

$$x_3(k+1) = x_3(k) - Ta_{31}x_1(k) - Ta_{32}x_2(k) - Ta_{33}x_3(k) - Tf_3(k) + Tbu(k) \tag{6c}$$

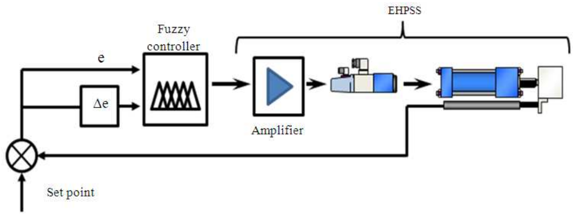

Fig. 2: Diagram of a fuzzy control system

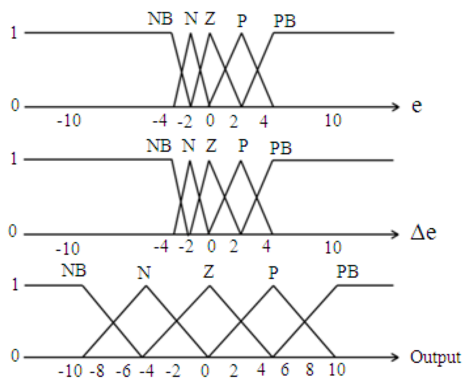

Fig. 3: Fuzzy sets of a usual fuzzy PD controller

$$y(k) = c_1x_1(k) + c_2x_2(k) + c_3x_3(k) \tag{6d}$$

Control systems: There are various types of control system logic used in classical control, modern control and intelligent control systems, each having been studied and implemented in many industrial applications. Every control system method has its advantages and disadvantages. Therefore, the trend is to implement hybrid systems consisting of more than one type of control technique.

PID control: The PID control method has been widely used in industry during last several decades because of its simplicity. The implementation of PID control logic, as shown in Eq. 7, requires finding suitable values for the gain parameters K_P, K_I and K_D. To tune these parameters, the model is linearized around different equilibrium points:

$$u(k) = K_p e(k) + K_I \sum_{i=0}^{k} e(i) + K_D \left[e(k) - e(k-1)\right] \tag{7}$$

where, e(k) is the error signal. However, the PID method is not suitable for controlling a system with a large amount of lag, parameter variations and uncertainty in the model. Thus, PID control logic cannot accurately control position in a hydraulic system.

Fuzzy control: Fuzzy control has found many applications in a variety of fields since Zadeh (1965) introduced fuzzy set theory in 1965. Among the most successful applications of this theory has been the area of Fuzzy Logic Control (FLC) initiated by the research of Mandani and Assilian (1975).

FLC has the advantage that it does not require an accurate mathematical model of the process. It uses a set of artificial rules in a decision-making table and calculates an output based on the table. Figure 2 shows a schematic diagram of a fuzzy control system. Input variables go through the fuzzification interface and are converted to linguistic variables. Then, a database and rule base holding the decision-making logic are used to infer the fuzzy output. Finally, a defuzzification method converts the fuzzy output into a signal to be sent out.

When used in a control system, FLC is robust since it provides a fast rise time and a small amount of overshoot. However, some difficulties can occur when designing the FLC.

One problem is that the complexity of fuzzy controllers increases exponentially with respect to the number of input variables. Furthermore, fuzzy controllers are similar to that of standard PD controllers in that the steady state error of the controlled variable is difficult to eliminate (Kim *et al*., 1994).

The control parameters and set of terms that describe each linguistic variable must be determined when designing a FLC. Obviously, the position in the electro-hydraulic is the parameter to be controlled in the system. A two-dimension structure will be used to product fast calculations. The two input linguistic variables are the error of the position “e” and the error change of the position “Δe” The output is the voltage signal to control amplifier and servo valve. Thus, the FLC has two antecedences and one consequence.

First, the two input variables must be defined in terms of linguistics. The error (e) in position is expressed by a number in the interval from -10 to 10. There are five linguistic terms of the error in position: Negative Big (NB), Negative (N), Zero (Z), Positive (P) and Positive Big (PB). Similarly, the fuzzy set of the error change of the position (Δe) is presented as {NB, N, Z, P, PB} over the interval from -10 to 10. Finally, the fuzzy set of the output signal is presented as {NB, N, Z, P, PB} over the interval from -10 to 10.

The knowledge base for a fuzzy controller consists of a rule base and membership functions. It is reasonable to present these linguistic terms by triangular-shape membership functions, as shown in Fig. 3. A fuzzy control knowledge base must be developed that uses the linguistic description of the input variable. In this study, an expert’s experience and knowledge method is used to build a rule base (Liu *et al*., 2007). The rule base consists of a set of linguistic IF-THEN rules containing two antecedences and one consequence, as expressed in the following form:

$$R_{i,j,k}: \text{ IF } e = A_i \text{ and } \Delta e = B_j \text{ THEN } u = C_k$$

where, $1 \le i \le 5$, $1 \le j \le 5$ and $1 \le k \le 5$. The total number of IF-THEN rules is 25 and is represented in matrix form, called a fuzzy rule matrix (Liu *et al*., 2007), as shown in Table 1.

The decision-making output can be obtained using a max-min fuzzy inference where the crisp output is calculated by the Center Of Area (COA) method.

Since the dynamics of cylinder is not symmetric, due to the difference in the effective area of the rod side and the head side of the piston. The designed fuzzy set of the fuzzy controller accounts for this asymmetry.

A set of fuzzy rules is shown in the Table1. The fuzzy rules in the center of the table are related to the steady state behavior of the process. When both the position error (e) and the change of position error (Δe) are negative, the position is high the set point and is moving further away. In response the control action should be negative such that it will reduce the position error. While the "Δe" is positive and the "e" is negative , the piston is moving toward, then the control action should be low enough to slow down the approach to the set point. Other fuzzy rules are obtained in Table 1 consider from Fig. 2.

Hybrid of fuzzy and PID control: While conventional PID controllers are sensitive to variations in the system parameters, fuzzy controllers do not need precise information about the system variables in order to be effective. However, PID controllers are better able to control and minimize the steady state error of the system. Hence, a hybrid system, as shown in Fig. 4, was developed to utilize the advantages of both PID controller and fuzzy controller.

Figure 4 shows a switch between the fuzzy controller and the PID controller, where the position of the switch depend son the error between the actual value and set point value.

If the error in position reaches a value higher than that of the threshold e_0, the hybrid system applies the fuzzy controller, which has a fast rise time and a small amount of overshoot, to the system in order to correct the position with respect to the set point. When the position is below the threshold e_0 or close to the set point, the hybrid system shifts control to the PID, which has better accuracy near the set position.

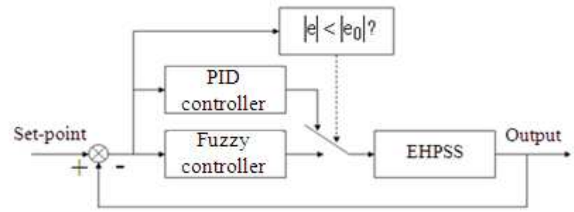

Fig. 4: Block diagram of a hybrid fuzzy PID controller

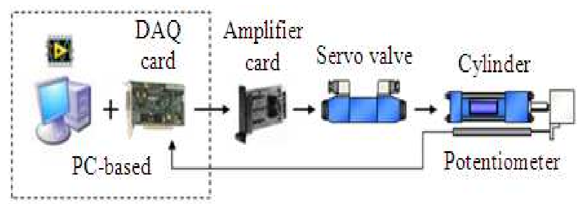

Fig. 5: PC-based position control of the EHPSS

Table 1: Fuzzy rules of a fuzzy controller

	Δe				
e	NB	N	Z	P	PB
NB	NB	NB	N	N	Z
N	NB	N	N	Z	P
Z	N	N	Z	P	P
P	N	Z	P	P	PB
PB	Z	P	P	PB	PB

Description of experiment equipment: The specifications of the EHPSS are depicted in Fig. 5 and Table 2 respectively. Figure 5 shows a diagram of the tested system. The position control of the EHPSS procedure is described as follows: Upon the intended initial and ending position of the piston (stroke) are given, the computer receives the feedback signal through DAQ card (A/D) from linear potentiometer, realizes various control algorithm and transmits a control signal through DAQ card (D/A) and amplifier card to servo valve. The piston displacement of cylinder is proportional to the input signal.

RESULTS

The experimental results: The control algorithms of PID, fuzzy and hybrid fuzzy PID were applied to the EHPSS shown in Fig. 5 using LabVIEW by Nation Instruments as the development platform. In our experiments we compare the performance of individual PID and fuzzy controllers to the proposed hybrid fuzzy PID controller. A testing of response of the system was performed using a step input signal.

Table 2: Specifications of the EHPSS

Elements	Descriptions
Cylinder	Piston diameter 16 mm, piston rod diameter 10 mm, stroke 200 mm
Servo valve (linear motor type)	Directly actuated spool valve, grade of filtration 10 µm, nominal flow rate 1.5 l min^{-1} (at Δp_N = 5 bar/control edge), leakage oil flow <0.01 l min^{-1} (at 60 bar), nominal current 680 mA, resolution <1 mA, setting time of signal jump 0…100% = 60 ms, repetition accuracy <1%
Supply pressure	60 bar
Linear potentiometer	Output voltage 0…10 V, measuring stroke 200 mm, linearity tolerance 0.5%
Amplifier card	Set point values ± 10 VDC, solenoid outputs (PWM signal) 24 V, dither frequency 200 Hz, max current 800 mA,
DAQ Card NI 6221 PCI	Analog input resolutions 16 bits (input range ±10V), output resolutions 16 bits (output range ±10V), 833 kS s^{-1} (6 µs full-scale settling)
Operating systems and program	Windows XP and Lab VIEW 8.2

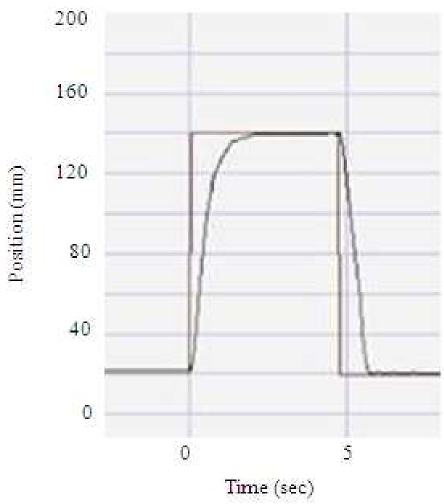

Fig. 6: Output responses of a PID controller

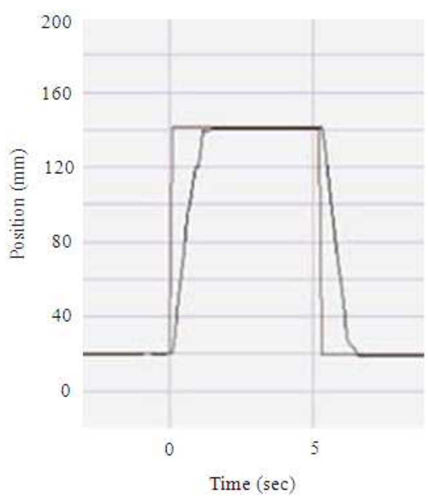

Fig. 7: Output responses of a fuzzy controller

Figure 6-8 shows the step response for the PID, fuzzy and hybrid fuzzy PID controllers, respectively. The PID control method was applied to a system with many difference positions of the EHPSS.

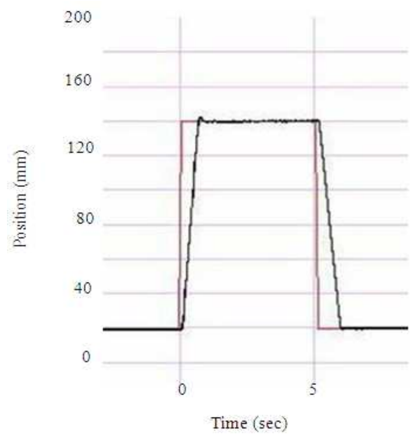

Fig. 8: Output responses of a hybrid fuzzy PID controller

The results from experiments find that the control parameters need to be adjusted to different values. Figure 6 shows the optimum dynamic response which adjusted the gain K_P = 5.6. Moreover, the PID controller also led to overshoot in the system. A large value of overshoot leads to vibrations and noise that could harm the hydraulic components and shorten their life cycles. Figure 7 shows the dynamic response (rise time) of the system using a fuzzy controller was faster than that of the PID controller. The parameter values of a hybrid fuzzy PID were experimentally determined to be: K_P = 5.6 and e_0 = 0.92, Figure 8 shows the dynamic response of system. From Fig. 6-8, the hybrid fuzzy PID gives the most satisfying results of rise time, overshoot and steady state error.

DISCUSSION

The experimental results using a step input signal revealed that the PID controller accurately controlled the steady-state position but did not robustly handle parameter variations in the system while the fuzzy controller provided a fast rise time of the position in the system. In the order to attain the advantages of both the fuzzy and PID controllers, a hybrid control scheme was developed. The experimental results show that the hybrid fuzzy PID controller proposed in this study was indeed possess the advantages of both PID and fuzzy controllers. According to their researches of (Parnichkun and Ngaecharoenkul, 2000; Erenoglu *et al*., 2006; Liu *et al*., 2007). Therefore, it can be concluded that the hybrid fuzzy PID controller is suited for the EHPSS.

CONCLUSION

The objective of this study was to develop a control scheme for the EHPSS. First, a PID controller and a fuzzy controller were individually applied to the EHPSS. The PID controller accurately controlled the steady state error but did not robustly handle parameter variations in the system while the fuzzy controller provided a fast rise time and low overshoot of the dynamic response output of the system. Then, the hybrid fuzzy PID controller proposed in this study was tested experimentally and the results were compared with that of individually applied PID and fuzzy controllers. The results from the experiments show that the proposed controller has superior performance compared to individual PID controller and fuzzy controller. Hence, it can be concluded that the hybrid fuzzy PID controller is suited for the EHPSS.

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