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Intelligent PI Fuzzy Control of An Electro-Hydraulic Manipulator

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Abstract**—** The development of a fuzzy-logic controller for a class of industrial hydraulic manipulator is described. The main element of the controller is a PI-type fuzzy control technique which utilizes a simple set of membership functions and rules to meet the basic control requirements of such robots. Using the triangle shaped membership function, the position of the servocylinder was successfully controlled. When the system parameter is altered, the control algorithm is shown to be robust and more faster compared to the traditional PID controller. The robustness and tracking ability of the controller were demonstrated through simulations.

Index Terms**—**Manipulator Position Control, Fuzzy Logic Control, PID, Electrohydraulic Servodrives.

I. Introduction

In the last few years research devoted to fuzzy logic and its application to manipulators has significantly increased. There are many articles on the successful application of fuzzy control to electrically actuated manipulator, ranging from the application of a fuzzy control matrix (similar to a look-up table) to the direct implementation of fuzzy rules and membership functions. General issues in tuning and validation of fuzzy systems have also been addressed in many papers[1, 2, 3, 4].

The application of fuzzy control to hydraulically actuated manipulators, on the other hand, is sparse and can only be found in a few research papers. Zhao and Virvalo [5] combined a linear state controller with fuzzy rule evaluation to produce what they named a fuzzy state controller. The method indirectly detects the presence of a load, based on fuzzy rule evaluation of actuator velocity, and decides on the gains of a state controller accordingly in order to make the controller insensitive to load variations. Chou and Lu [6] developed a fuzzy controller for a class of hydraulic servo systems. The tracking ability of the controller were demonstrated through experimental studies. No report has been found stating problems with steady-state errors or flow deadband nonlinearities.

Hydraulically actuated robots are, in general, different from electrically actuated robots [7, 8]. In a hydraulic robot given a zero spool displacement (i.e. valve closed), the arm can be kept in place due to the oil trapped on both sides of the cylinder. This means that the hydraulic robot can come to rest quickly when the valve spool returns to its neutral position. In a low friction electric robot the link can still move and may pass the target point with a zero motor voltage. The amount of overshoot depends on the inertia and the velocity. Negative motor voltage may be needed before the arm reaches the desired position to prevent excessive overshoot.

Also, a constant motor voltage is required in electric robots, in order to keep the arm in place in the presence of gravity. Since the control requirements and characteristics of each class of actuation differ, thus similar fuzzy rules and strategies do not work equally well on both electric and hydraulic robots.

The dynamic characteristics of the servo-hydraulic system are always complex and highly nonlinear. Moreover, there are too many uncertainties in it ; for example, the viscosity of oil, the bulk modulus, the oil volume, the system pressure, the wear and the cavitation [9]. The loading conditions are usually rather unsteady, and the loading forces change in a wide rang during operation.

When the process is complex and nonlinear with variable parameters, the conventional control theory can not be applied. The modern control theory and adaptive control techniques have been used to control that plant. However, the adaptive control requires accurate mathematical control model or lot of computational effort to estimate and adapt the controller parameters [10].

The non-mathematical approach called "Fuzzy Set Theory" [11], [12] is suitable for developing reliable logic controller for plants with wide parameters variations. In this paper, an intelligent Fuzzy controller (IFC) is presented for position control of an electrohydraulic servo.

The paper has been organized as follows: Section 2 describes the system dynamic model of the electrohydraulic manipulator. Section 3 reviews the PI FLC tuning method. Section 4 illustrates the simulation results of the proposed controller. Finally, a conclusion of the proposed PI FLC technique is presented in Section 5.

II. System Dynamic Model

The main reasons to use positioning servos in industry are the demands on the accuracy, the stiffness and good dynamic responses to the changes in the command signal or the load. The electrohydraulic system shown in Fig. 1 is comprised of a cylinder, and 4/3 way proportional valve. A complete mathematical model of such an electrohydraulic system, for example, has been given by [13]. However, these equations are highly complex and difficult to utilize in control design. A more practical model may be obtained through the linearization of the non-linear functions.

A mathematical model of the plant can be derived from the flow equation of the valve, the continuity equation and balance of forces at the piston. The valve flow-rate equation is highly non-linear and dependent on the valve displacement from neutral, which is proportional to the input current *I*- and the pressure drop across the load P_L.

From Moog Technical bulletin, a convenient form for the servo valve transfer function, [9] is:

$$\frac{Q_v(s)}{I(s)}=\frac{C_v}{\left(1+\tau_v s\right)\left(\frac{s^2}{\omega_v^2}+\frac{2\zeta_v}{\omega_v}s+1\right)} \tag{1}$$

where Q_v is the valve main stage flow rate, I is the valve input, C_v is the total valve flow gain, τ_v is the valve time constant and ω_v, ζ_v are the undamped natural frequency and damping ratio of the valve respectively.

The equations of the servovalve flow to and from the actuator (assuming symmetric valve port, zero lap design and zero return pressure) are as follows,

For $X_v \geq 0$

$$Q_f = C_d W X_v \operatorname{sgn}(P_s - P_f)\sqrt{\frac{2}{\rho}\left|P_s - P_f\right|},$$

$$Q_n = C_d W X_v \operatorname{sgn}(P_n)\sqrt{\frac{2}{\rho}\left|P_n\right|} \tag{2}$$

For $X_v \leq 0$

$$Q_f = C_d W X_v \operatorname{sgn}(P_f)\sqrt{\frac{2}{\rho}\left|P_f\right|},$$

$$Q_n = C_d W X_v \operatorname{sgn}(P_s - P_n)\sqrt{\frac{2}{\rho}\left|P_s - P_n\right|} \tag{3}$$

where X_v is the spool displacement, P_s is the supply pressure, ρ is the mass density of the oil, C_d is the discharge coefficient of the orifice, W is the width of the orifice, suffix n denotes the annular side and suffix f denotes the full side.

The linearized flow equation of the actuator is given by [6]:

$$q_{le}=K_l\frac{A_e}{A_f}\left[\frac{1+\left(\frac{A_n}{A_f}\right)^2}{1+\left(\frac{A_n}{A_f}\right)^3}\right]p_{le}+A_e\dot{X}_p+\frac{2A_e}{A_f}\frac{\dot{P}_{le}}{4B}\left[\frac{V_f+\left(\frac{A_n}{A_f}\right)^2 V_n}{1+\left(\frac{A_n}{A_f}\right)^3}\right] \tag{4}$$

where

$$P_{le}=\frac{p_f A_f - p_n A_n}{A_e},\quad q_{le}=\frac{q_f+q_n}{2},\ A_e=\frac{A_f+A_n}{2}$$

, P_{le} is the effective load pressure, q_{le} is the effective load flow rate, A_e is the effective piston area, B is the oil bulk modulus, k_1 is the leakage coefficient of the piston, X_p is the piston displacement, V_n is the oil volume under compression in the annular side of the cylinder, V_f is the oil volume under compression in the full side of the cylinder, A_n is the annular area of the cylinder, A_f is the full area of the cylinder.

It is assumed that the loading point may be treated as a mass-damper system. The linearized equation for the force developed by the actuator on the loading point, after eliminating the steady state terms, can be written as

$$f_a = M\ddot{X}_p + B_l\dot{X}_p \tag{5}$$

where M is the mass of the load concentrated at the loading point and B_l is the viscous damping coefficient of the structure at that loading point.

Equations (9), (10),(11) and (12) may be manipulated and Laplace transformed to give the actuator displacement:

$$X_p(s) = \frac{\frac{K_v}{A_e} X_v(s)}{\frac{MV_t}{4BA_e^2} s^3 + (\frac{K_c M}{A_e^2} + \frac{B_p V_t}{4BA_e^2}) s^2 + (1 + \frac{K_c B_p}{A_e^2} + \frac{K_s V_t}{4BA_e^2}) s}$$

$$, \quad V_t = \frac{2A_e}{A_f} \left[\frac{V_f + \left(\frac{A_n}{A_f}\right)^2 V_n}{1 + \left(\frac{A_n}{A_f}\right)^3} \right] \qquad (6)$$

where $B_p = B_1 + K_{vf}$, K_{vf} is the viscous friction coefficient of the piston, K_v is the flow/displacement gain for the main stage of the valve, K_c is the total flow-pressure coefficient and V_t is the effective trapped oil volume.

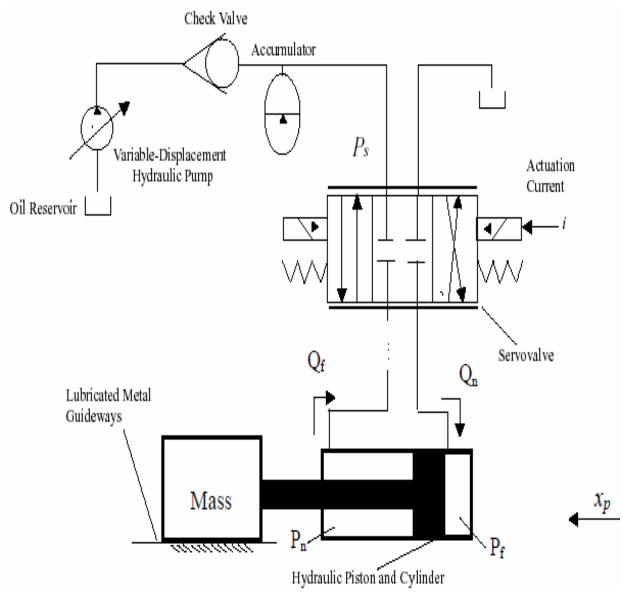


Fig.1 Schematic diagram of the manipulator hydraulic circuit

It can be presented in standard form so as to reveal equivalent values of natural frequency and damping ratio may be written for the asymmetric actuators as

$$\omega_0 = \sqrt{\frac{4BA_e^2}{V_t M}} \text{ and}$$

$$\delta = \frac{K_c}{A_e} \sqrt{\frac{BM}{V_{te}}} + \frac{B_p}{4A_e} \sqrt{\frac{V_t}{BM}}$$

$$X_p(s) = \frac{\frac{K_v}{A_f} X_v}{s(\frac{s^2}{\omega_0^2} + \frac{2\delta}{\omega_0} s + 1)} \qquad (7)$$

where X_p is the piston position, δ is the load damping ratio and ω_0 is the load natural frequency.

A. Closed Loop Transfer Function For The System

The equations may be manipulated to obtain the closed-loop transfer function relating the error voltage $V_e(s)$ and the output voltage $V_0(s)$ representing the position signal. The specifications of the system are indicated in Appendix 1 and Fig. 1.

The transfer function for the single-actuator system is

$$\frac{V_o(s)}{V_e(s)} = \frac{K_o}{(\tau_v s+1)(\frac{s^2}{\omega_v^2} + \frac{2\zeta_v}{\omega_v} s+1) s (\frac{s^2}{\omega_o^2} + \frac{2\delta}{\omega_o} s + 1)} \qquad (8)$$

where $K_o = \frac{K_{tr}.C_v.A_f}{K_v}$, V_o is the output voltage according to the piston position, V_e is the error signal voltage, K_o is the overall system gain and K_{tr} is the position transducer gain.

III. PI Fuzzy Logic Controller

Fuzzy sets were first introduced by Zadeh [14] . Later Zadeh [15] defined the terms; linguistic variable as a variable whose values are sentences in natural language. He introduced fuzzy conditional statements as expressions of the form ''IF A THEN B'', where A and B have fuzzy meaning; e.g., IF x is small THEN y is large, where small and large are viewed as labels of fuzzy sets. A fuzzy algorithm is an ordered sequence of instructions which may contain fuzzy assignments and conditional statements; e.g., x is very small, IF x is small THEN y is large. The execution of such algorithms is governed by the compositional rule of inference [14]. Based on Zadeh's work, Mamdani developed a new control strategy based on fuzzy logic, [15]. He converted heuristic control rules stated by a human operator into an automatic control strategy. Based on his pioneering work on fuzzy logic control, he implemented the technique in the context of practical applications. Since then there have been numerous applications of fuzzy logic controllers in industry. The inference method for a controller based on the compositional rule of inference of Zadeh [15], is called ''composition-based inference''.

The block diagram of the structure of fuzzy control system is shown in the Fig. 2. The fuzzy logic controller designed include three important steps: Fuzzification, fuzzy reasoning and defuzzification. The error and step change in error will be fuzzified with the membership function. The used membership functions of error and integration of the error are triangles shaped, which is shown in Fig. 3.

The basic fuzzy controller used in this paper is a simple two-input controller. The gains (scaling factors) K_e and $K_{\Delta e}$ are that put the resulting e and Δe values within the controller universe of discourse. The fuzzy controller fuzzifies these input quantities through algorithms that work with a set of membership functions. The fuzzified quantities are then passed through a series of decision rules; the current status of the system is assessed and a set of control actions are determined based on the degree of truth for all rules.

Because overlap between the fuzzy variables exists, more than one rule can fire simultaneously. Defuzzification is then applied using all the output variables, and a crisp control action is determined. Rules are normally written based on experience, observations and understanding of how the system responds and the attributes it must contain.

The basic structure of the self-tuning fuzzy PI controller [13] is identical to the conventional fuzzy PI controller except the self-tuning operation, which is shown in Fig. 2. The controller is tuned dynamically by adjusting its output scaling factor $K_{\Delta u}$ in each sampling time by an updating factor α_F . The value of α_F is determined by fuzzy rules defined on the error K_e and change of error $K_{\Delta}e$. The focus is on tuning of the output scaling factor due to its strong influence on the performance and stability of the system.

The output scaling factor of the controller is modified by a self-tuning mechanism, which is shown by the dotted line in Fig.2. The membership functions (MF) for the controller inputs, e and Δe and for the incremental change in the controller output $K_{\Delta u}$ are defined in the common normalized domain [-1,1], whereas the MF for α_F is defined on the normalized domain [0,1], as shown in Fig. 3b. All the MF for both normalized inputs e_n, Δe_n and the output Δu_n of the controller have been defined on the normalized domain [-1, 1].

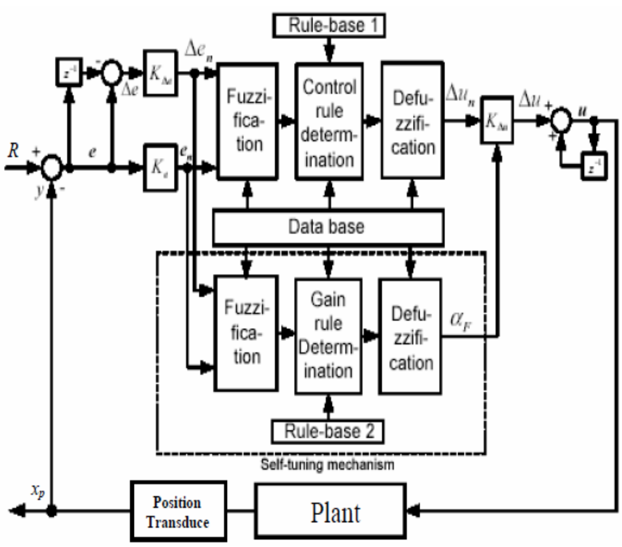


Fig. 2 diagram of the self-tuning PI fuzzy controller.

The relationships between the scaling factors K_e, $K_{\Delta e}$ $K_{\Delta}u$, and the input and output variables of the self-tuning fuzzy PI controller are as follows:

$$e_n = Ke \cdot e, \tag{9}$$

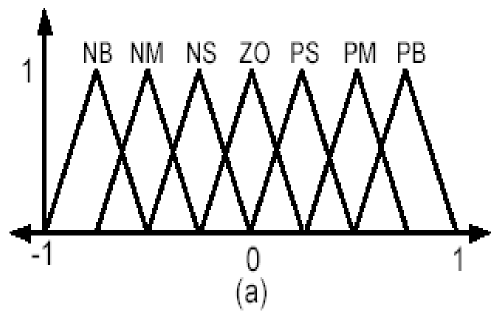
$$\Delta e_n = K_{\Delta e} \cdot \Delta e, \tag{10}$$

$$\Delta u = (\alpha_F \cdot K_{\Delta u}) \cdot \Delta u_n, \tag{11}$$

$$u(k) = u(k-1) + \Delta u(k). \tag{12}$$

The rules and the membership functions of the implemented self-tuning fuzzy PI controller are shown in Fig. 3.a

Δe\e	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZO
NM	NB	NM	NM	NM	NS	ZO	PS
NS	NB	NM	NS	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PS	PM	PB
PM	NS	ZO	PS	PM	PM	PM	PB
PB	ZO	PS	PS	PM	PB	PB	PB



Δe\e	NB	NM	NS	ZO	PS	PM	PB
NB	VB	VB	VB	B	SB	S	ZO
NM	VB	VB	B	B	MB	S	VS
NS	VB	MB	B	VB	VS	S	VS
ZO	S	SB	MB	ZO	MB	SB	S
PS	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
PB	ZO	S	SB	B	VB	VB	VB

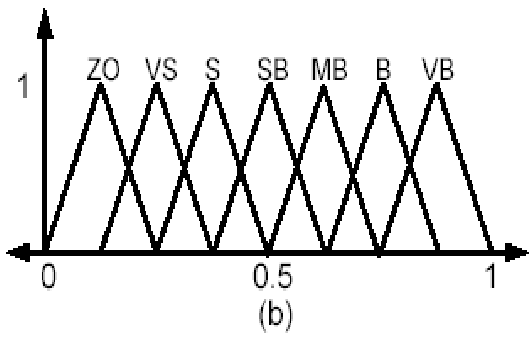


Fig. 3.(a) Fuzzy rules for computation of u and MFs of e , e and u . (b) Fuzzy rules for computation of α_F and MFs of gain updating factor (α_F).

A. Rules of thumb for tuning the fuzzy PI controller

Step 1: Tune the scaling factors $K_{e,}$ $K_{\Delta e}$ $K_{\Delta}u$, assuming α_F = 1 (i.e., assume a normal PI-type fuzzy logic controller). The scaling factor K_e is chosen such that the expected error e_n is normalized to the domain [-1,1] to make efficient use of the rule-bases. Then $K_{e,}$ and $K_{\Delta e}$ are tuned to make the transient response of the system reasonably. At the end of this step, we get a controller without self-tuning. This controller is the starting point for Step 2.

Step 2: Set the output scaling factor $K_{\Delta}u$ of the self-tuning fuzzy PI controller greater than the value of the controller resulting from Step 1, while keeping the values of K_e and $K_{\Delta e}$ at the same level as in Step 1. Then, adjust $K_{\Delta}u$, if necessary, to get again almost the same rise time as in Step 1.

Step 3. Fine-tuning the rules for α_F depending on the desired response [13] according to performance measures such as the peak overshoot, the settling time, the rise time or the integral absolute error.

The magnitude of this control is, however, small to prevent overshoot or sustained oscillations at the set point. The membership functions representing the input and output values' degree of truth for each set of linguistic variables are simple symmetric triangular functions. They have sufficient overlap to produce a smooth control output [16].

Note that during the simulation, the control output membership functions contain narrow large (PB or NB) regions. This allowed large control voltages (i.e. full spool travel) to be mostly applied in the presence of absolutely large errors; they are less effective when the position error has membership in both small and large error zones. This modification helped to suppress overshoot.

The fuzzy reasoning method used in this paper is based on Mamdani's "Minimum Operation Rule (MOR)" and "Center Of Area (COA)" defuzzification technique (see [12]). In this study the gains were incrementally adjusted by repeatedly performing the step response. The program evaluated the performance error, altered the gains and repeated the step response test until the best performing gains were determined.

Step response was easy to apply and the minimization of error for the entire step response ensured both low rise time and low overshoot. The technique was in principle similar to the ones suggested by Passino et al. [17], in which the gains were tuned to get acceptable response given a performance measure on overshoot and response time.

IV. Simulation Results

The tuned PID controller is designed by using of MATLAB software package under the conditions of the overshoot do not exceed than 10% and no steady state error, (K_P= *1.2*, K_I=*1*, K_D=*0.75*). However if we try to improve the response conditions to be zero overshoot and no steady state error, (K_P= *0.8*, K_I=*.55*, K_D=*0.5*) the response will give larger rise and settling time. The simulation results to step response are shown in Figure 4 based on the tuned PID and the self tuning FL controllers policies under the same loading conditions. It can be observed that the proposed controller has smaller settling time without overshoot and less rise time.

The corresponding control signals for each controller are illustrated in Figure 5, it is interesting to notice that the amplitude of the self tuning FLC is smaller compared with both of the PID control signals, which is important index in designing and choosing the hydraulic system components.

Figures 6 represent the self tuning mechanism output (α_F) during the simulated test. It arrived to fixed value as the desired response achieved. Figure 7 shows the response of FLC without tuning mechanism, it gave larger settling time. For illustrating the robustness of the proposed controller, in Fig. 8 the response of the system under proposed control system strategy offered robust response even with system which is characterized by delay time.

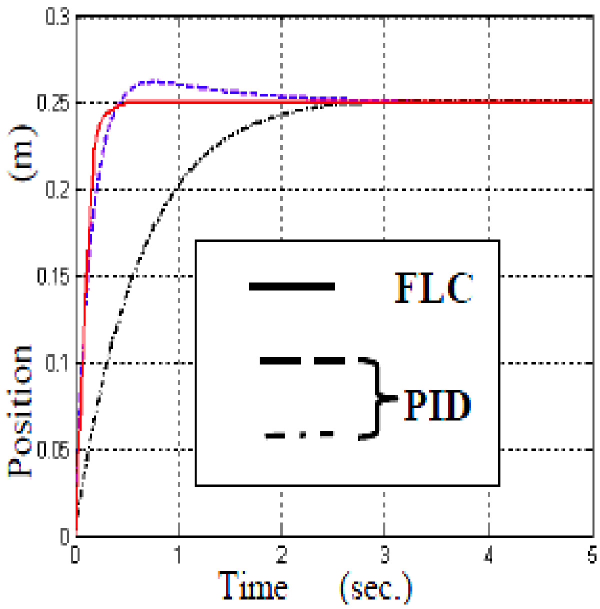


Fig. 4 System Step Response Based on PID and self tuning FL Controllers

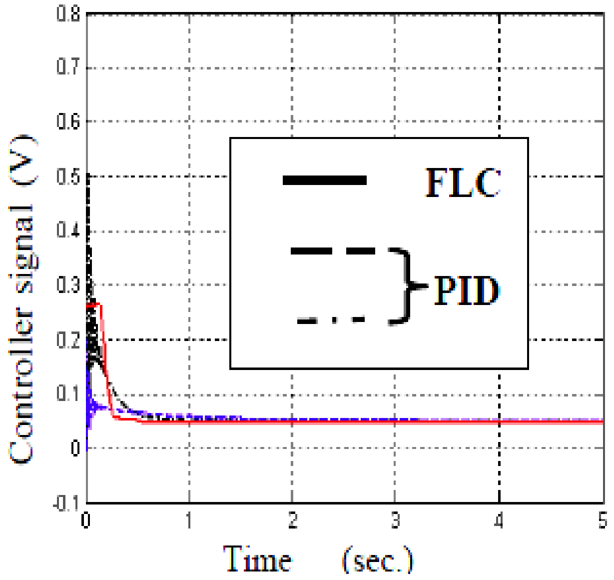


Fig. 5 Controllers signals of PID and self-tuning FLC.

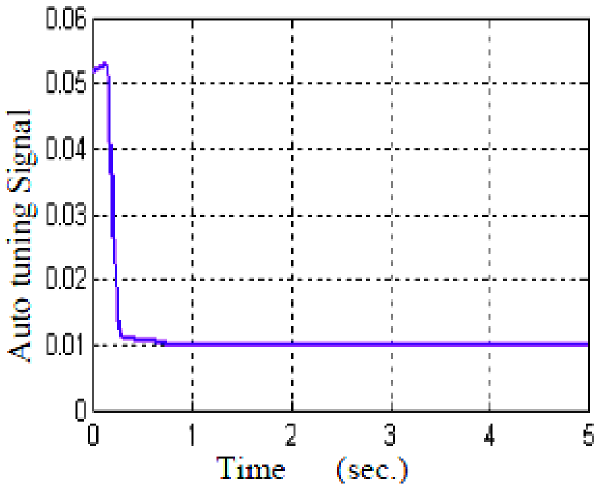


Fig. 6 Auto tuning mechanism output.

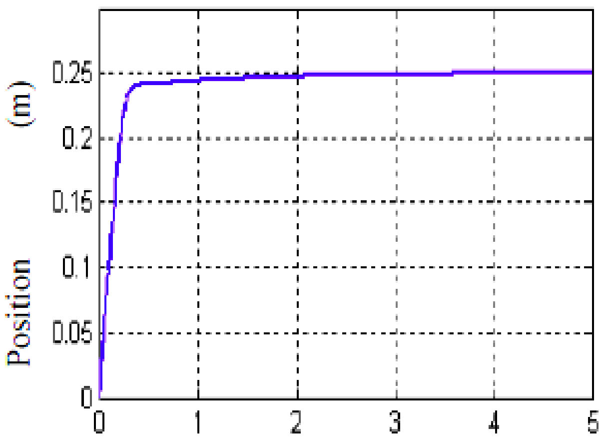


Fig. 7 System Step Response Based on FL Controllers without tuning mechanism

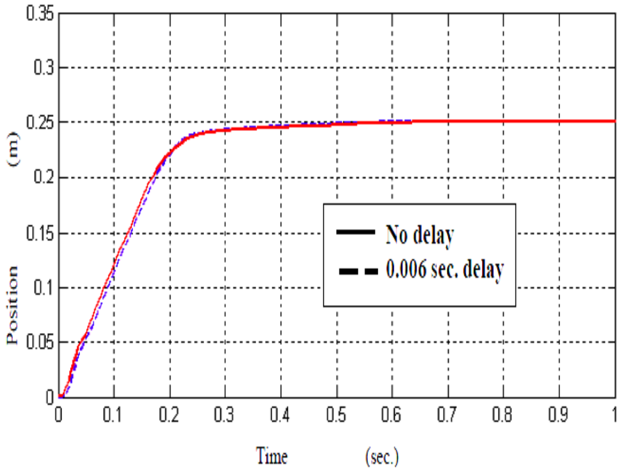


Fig. 8 System step response with and without delay time base on FLC

V. Conclusion

The position control problem of a class of hydraulic manipulators with model of delay time has been addressed in this paper. The rules of the fuzzy controller were designed in order to suit the requirements of the hydraulic actuation system under investigation.

It is shown that the proposed fuzzy controller has a good effect and robust control performance.

The main advantage of the proposed controller:

- The control algorithm is simple and does not need a precise model.
- It clear the effect of the self tuning mechanism for improving the dynamic characteristics of controlled system
- When the system is examined by adding a delay time function, the control algorithm kept robust. This results is a significant enhancement of the control performance of the hydraulic system with long hoses.

References

[1] Lee C. C., "Fuzzy logic in control systems: fuzzy logic controller-Parts I & II", 1EEE Trans. Syst., Man Cybern. 20, 404-433 (1990).

[2] Daugherity W. C., "Performance evaluation of a self-tuning fuzzy controller", Proc. IEEE 1st International Conference on Fuzzy Systems, pp. 389-397, San Diego, CA (1992).

[3] Boscolo A., "Computer aided tuning validation of fuzzy systems", Proc. IEEE 1st International Conference on Fuzzy Systems, pp. 605-614, San Diego, CA (1992).

[4] Smith S. M. and Comer D. J., "An algorithm for automated fuzzy-logic controller tuning", Proc. 1EEE 1st International Conference on Fuzzy Systems, pp. 615-622, San Diego, CA (1992).

[5] Zhao T. and Virvalo T., "Fuzzy control of a hydraulic position servo with unknown load", Proc. IEEE 2nd International Conference on Fuzzy Systems, pp. 785-788, San Francisco, CA (1993).
[6] Chou C. H. and Lu H. C., "Design of a real-time fuzzy controller for hydraulic servo systems", Comput. Ind. 15, 129-142 (1993).
[7] Sepehri N., Dumont G. A. M., Lawrence P. D. and Sassani F., "Cascade control of hydraulically actuated manipulators", Robotica 8,207-216 (1990).
[8] Kotzev A., Cherchas D. B., Lawrence P. D. and Sepehri N., "Generalized predictive control of a robotic manipulator with hydraulic actuators", Robotica 10,447-459 (1992).
[9] P. M. Fitz and J. J. Palazzolo, "Modelling of a One Degree-of-Freedom Active Hydraulic Mount", Journal of dynamic Systems, Measurement and control, Vol. 118 Page 439, (1996).
[10] Zhao,T. and Virvalo,T., "Fuzzy State Controller and Its Application in Hydraulic Position Servo", Fluid power, Page 417, (1993).
[11] Rajani K. Mudi and Nikhil R. Pal, "A self-tuning fuzzy PI controller", Fuzzy Sets and Systems 115 (2000) 327-338.
[12] Wang and Felow, "Generating Fuzzy Rules By Learning From Examples", IEEE, Vol. 22, No. 6, Nov.(1992).
[13] Merrit HE. "Hydraulic control system", New York: Wiley, 1967.
[14] L.A. Zadeh, "Fuzzy sets", Journal of Information and Control, Vol.8 Page 338-353, (1965).
[15] Z.-X. Cai, "Intelligent Control", Electronics Industry press, Beijing, China, (1996).
[16] Kumbla K., Moya J., Baird R., Rajagopalan S. and Jamshidi M., "Fuzzy control of three links of a robotic manipulator", Robotics and Manufacturing; Proc. 1SRAM '92 (Edited by M. Jamshidi et al.), pp. 687-694. ASME Press, New York (1992).
[17] Kevin M. Passino and Stephen Yurkovich, "Fuzzy Control", Wasely Longman, Inc., California, USA, (1998).

Appendix -A

Tabel A.1 Specifications of the system

Diameter of piston	112.7 mm
Diameter of piston rod	70.4mm
Stroke	1000mm
Load natural frequency	19.6 rad/s
Load damping ratio	0.1
Total flow pressure coefficient	4.425×10^{-11} $(m^3/s)/(N/m^2)$
Valve flow gain, no load	2.613×10^{-3} $m^3/s/mA$
Natural frequency of servo valve	688.7 rad/s.
Damping factor of servo valve	0.3572
Supply pressure	70 MPa ±500kPa
House - delay time	0.006 s

Biographical notes: Ayman A. Aly holds a BSc with excellent honour degree (top student) in 1991, MSc in Sliding Mode Control from Mechanical Engineering Department, Assiut University, Egypt in 1996 and PhD in Adaptive Fuzzy Control from Yamanashi University, Japan in 2003. He was an Assistant Professor at Assiut University from 2003–2008. Currently, he is an Associate Professor and the Head of Mechatronics Engineering Section at Taif University, Saudi Arabia.

In additions to 5 text books, Ayman A. Aly is the author and coauthor of more than 55 scientific papers in Refereed Journals and International Conferences. He supervised some of MSc. and PhD. Degree Students. His main areas of research interests are Intelligent Control of Mechatronics systems, Automotive control systems, Thermofluid systems modeling and simulation.

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