TELKOMNIKA, Vol. 11, No. 6, June 2013, pp. 3374 ~ 3382
e-ISSN: 2087-278X

Direct Drive Electro-hydraulic Servo Control System Design with Self-Tuning Fuzzy PID Controller

Wang Yeqin
Huaiyin Institute of Technology, Huai'an 223001
e-mail: yeqin-wang@163.com

Abstract

According to the nonlinear and time-varying uncertainty characteristics of direct drive electro-hydraulic servo control system, a self-tuning fuzzy PID control method with speed change integral and differential ahead optimizing operator is put forward by combining fuzzy inference and traditional PID control in this paper. The rule of fuzzy logic is designed, the membership function of the fuzzy subsets is determined and lookup table method is used to correcte the PID parameters in real-time. Finally the simulation is conducted with the typical input signal, such as tracking step, sine etc. The simulation results show that, the self-tuning fuzzy PID control system can effectively improve the dynamic characteristic when the system is out of the range of the operating point compared with the traditional PID control system, there is obvious improvement in the indexes of rapidity, stability and accuracy, and fuzzy self-tuning PID Control is more robust, and more suitable for direct drive electro-hydraulic servo system.

Keywords: *direct drive, electro-hydraulic servo system, self-tuning fuzzy PID, PID controller*

1. Introduction

In last decade, with the development of volumetric speed control technology and AC servo motor control technology in hydraulic field, a direct driving electro-hydraulic servo system (DDVC) appeared. Pump output flow is changed by controlling the servo motor speed, it can regulate the flow to achieve energy saving. The main advantages of the system are high efficiency, small volume and low cost, but the low dynamic characteristic compared with the valve control electro-hydraulic servo system causes its application restrictions in some area. Therefore, studying direct drive electro-hydraulic servo system's dynamic performance, expanding its application scope and improving the system's practical value have an important significance. The study of direct drive electro-hydraulic servo system is more early, and the related technology has tend to be mature in foreign country especially in USA and Japan, and its application has been successfully applied to many developing fields, the good economic benefit has been got [1-3]. Domestic research starts relatively late, and it mainly focused on some universities, such as Harbin Institute of Technology [4] Taiyuan University of Technology [5-6] Zhejiang University [7] Beijing University of Aeronautics and Astronautics [8] Guangdong University of Technology etc [9]. Some enterprises try to cooperate with college's to develop direct drive electro-hydraulic servo system product, which have made some achievements. But there is still great gap between the world advanced level, so the theoretical analysis and experimental research on direct drive electro-hydraulic servo system has important economic and social benefit.

2. Nonlinear and Time Variation Analysis of Direct Drive Electro-hydraulic Servo System

There are many factors that go against performance improvement of direct drive electro-hydraulic servo system, which mainly includes nonlinear and time-varying uncertainty.

2.1. Nonlinear factors

2.1.1. Friction

Friction is one of the important factors influencing the system performance, it mainly include seal friction in servo cylinder and mechanical friction caused by gear transmission.

Received January 9, 2013; Revised April 18, 2013; Accepted April 26, 2013

2.1.2. Transmission Chain Gap

There are gaps between gear and rack, it include lateral backlash and bearing clearance.

2.1.3. Hysteretic Characteristic

Hysteretic characteristic is caused by the magnetic hysteresis characteristics of ferromagnetic, it affects the sensitivity and static error of system, and its effect on dynamic performance is phase delay.

2.1.4. Saturation Characteristic

When input signal exceed the linear range, The output signal no longer change with the input signal but maintain at a certain value. Servo motor torque cannot increase indefinitely, it will be in saturated state. At the same time servo amplifier also has a saturation characteristic.

2.1.5. Dead Zone Characteristics

Pump have specific demand in lowest stable speed, dead zone characteristics has great influence on the the static error of system, and the system exhibit the phenomenon of delayed-stagnant phenomena.

2.2. Time Variation Uncertainty Factors

1) Vary of the liquid parameters
   There are some soft quantities in direct drive electro-hydraulic servo system, such as the bulk modulus of the oil β_e, viscosities μ ect. There are many influencing factors that influence β_e which mainly include air contents in fluid and working pressure. β_e will decrease with the air contents increases, but increase with the pressure increases. μ change with the oil pressure and temperature, and the temperature effect is the main. Changes of β_e and μ make the system parameters is variable.
2) Vary of the load moment
   Direct drive electro-hydraulic servo actuator researched in this paper is mainly used for controlling the opening of the valve, the force moment suffered during the screwing up and closing process, includes driving force moment, static moment and friction moment, among them, driving force moment play key roles.
3) The high temperature of device running environment and temperature variation causes the parameters variation of the motor servo amplifier power device, feedback detection device and controller.
4) There are serious disturbance include static interference and noise disturbance because of the adverse operation circumstances. The disturbance are introduced to the system by electromechanical coupling which cause the precision decrease of system and even cause instability.

Direct drive electro-hydraulic servo system has the characteristic of nonlinear and time-varying uncertainty, the influence factor of system is complex, it is difficult to obtain the accurate mathematical model. During the system modeling, system inevitably had the presence of unmodeled dynamics because of the series of hypothesis and simplification, which have important effect on the dynamic and steady performance of system. In order to improve the robustness of the system, it is necessary to consider the unmodeled dynamics.

3. Fuzzy Self-tuning PID Controller Design of Electro Hydraulic Servo System

3.1. Fuzzy Self-tuning PID Controller

PID control algorithm with speed change integral and differential ahead optimizing operator is realized by computer, its discrete control law as follows:

$$u(k) = K_P e(k) + K_I T_S \sum_{i=0}^{k} e(i) + (K_D / T_S)[e(k) - e(k-1)]$$

Incremental algorithm:

$$\Delta u(k) = K_P \Delta e(k) + K_I T_S e(k) + (K_D / K_S)\Delta^2 e(k)$$
$$u(k) = u(k-1) + \Delta u(k)$$

Error variable is defined as follows:

$$\Delta u(k) = K_P \Delta e(k) + K_I T_S e(k) + (T_D / T_S)\Delta^2 e(k)$$
$$\Delta e(k) = e(k) - e(k-1)$$
$$\Delta^2 e(k) = \Delta e(k) - \Delta e(k-1)$$

where *u* (*k*) is the output at sampling time k, *e* (*k*) is the error at sampling time k, K_P、K_I、K_D is the PID Proportion, integral, differential parameters, T_S is the sampling period.

The conventional PID without on-line tuning parameter function does not meet the the parameter self-tuning requirements of system in different cases, thus affect the further improvement of its control effect. The error and the error varying are input signals in fuzzy self-tuning PID controller, to meet the parameter self-tuning requirements of error E and error varying EC in different time [10]. Fuzzy theory correct the parameters of PID controller on-line, that is fuzzy self-tuning PID controller,Which are shown in Figure 1.

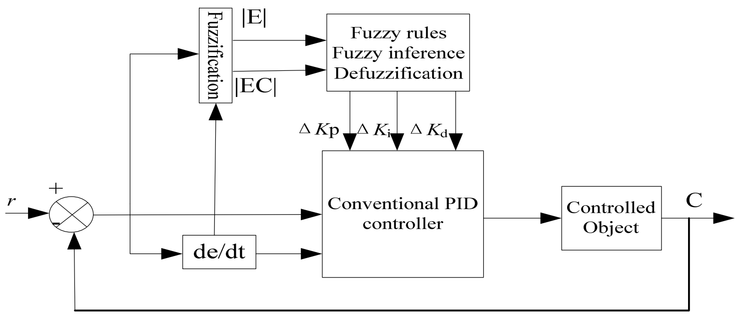


Figure 1. The Structure of Fuzzy Self-tuning PID Controller

3.2. Design of Fuzzy-PID Controller

According to the actual situation of system, and reference to PID controller design experience [11]. In the fuzzy-PID controller, its inputs are the absolute value of error |E| and the absolute value of error varying |EC|, both of them are divided into 7 linguistic values as negative big (NB), negative middle(NM), negative small(NS), zero(ZO), positive smal(PS), positive middle (PM), positive large(PB) [12-13]. The fuzzy quantizing domains of e is [-6,-6], the domains of KP is [-3,3], KI is [-0.3,0.3],and KD is [-0.6,0.6].

Gaussian membership function is employed to fuzzify the variables include the two input variables error |E|, error varying |EC|, and three output variables KP , KI , KD are shown in figure 2-6, NB、PB present gaussian distribution, and others present linear distribution.

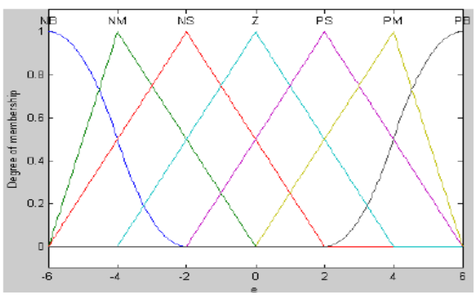


Figure 2. The Membership Functions for E

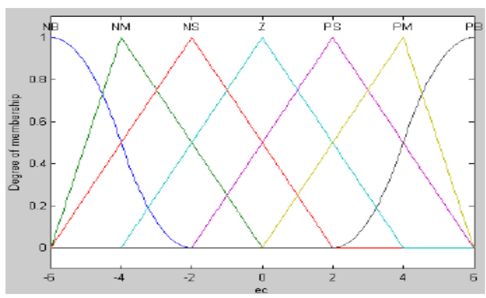


Figure 3. The Membership Functions for EC

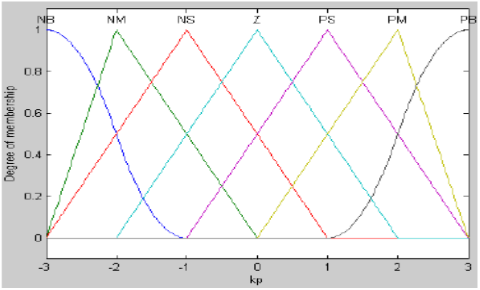


Figure 4. The membership functions for K_P

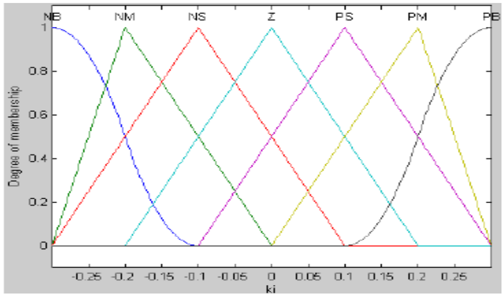


Figure 5. The membership functions for K_I

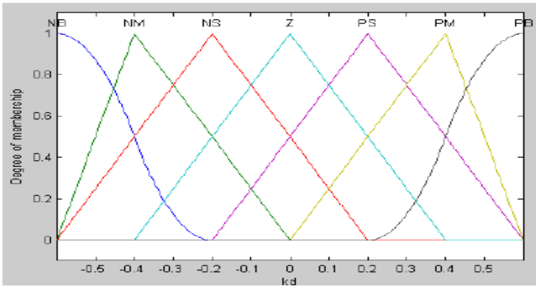


Figure 6. The membership functions for K_D

The rule of fuzzy control rule design: While error is large, control variable should try to reduce error quickly. While error is small, the stability of system should be considered, besides eliminating the static error. Fuzzy rules are based on experience and related technical knowledge [14-15], the fuzzy control rule table for ΔK_P、ΔK_I、ΔK_D shown in Table 1-3.

Table 1.The Fuzzy Control Rule Table for ΔK_P

ΔK_P		E						
		NB	NM	NS	ZO	PS	PM	PB
	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PS	PS	ZO	NS
	NS	PM	PM	PM	PS	ZO	NS	NS
EC	ZO	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NM	NM	NM	NB
	PB	ZO	ZO	NM	NM	NM	NB	NB

Table 2. The Fuzzy Control Rule Table for ΔK_I

ΔK_i		E						
		NB	NM	NS	ZO	PS	PM	PB
	NB	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
EC	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PM	PM	PB	PB

Three parameters of PID controller can be modified online by the follow formula:

$$K_P = K_P` + \{E_i, EC_i\} = K_P` + \Delta K_P$$

$$K_I = K_I` + \{E_i, EC_i\} = K_I` + \Delta K_I$$

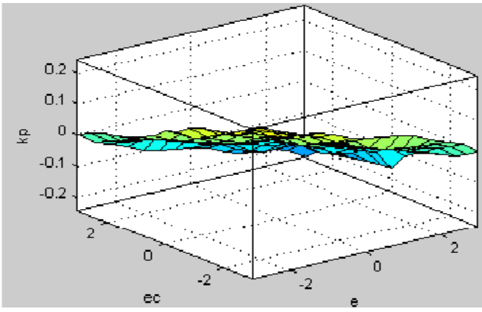
$$K_D = K_D` + \{E_i, EC_i\} = K_D` + \Delta K_D$$

Where $\{E_i, EC_i\}$ is the value of error and error varying.

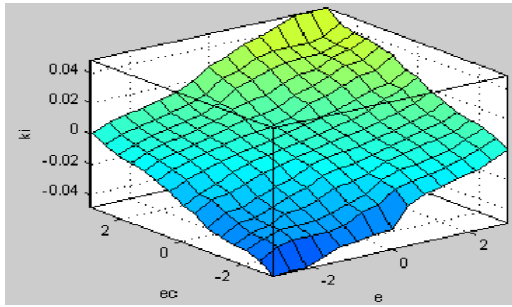
Table 3. The Fuzzy Control Rule Table for ΔK_D

ΔK_D		E NB	NM	NS	ZO	PS	PM	PB
EC	NB	PS	NS	NB	NB	NB	NM	PS
	NM	PS	NS	NB	NM	NM	NS	ZO
	NS	ZO	NS	NM	NM	NS	NS	ZO
	ZO	ZO	NS	NS	NS	NS	NS	ZO
	PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PM	PB	NS	PS	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB

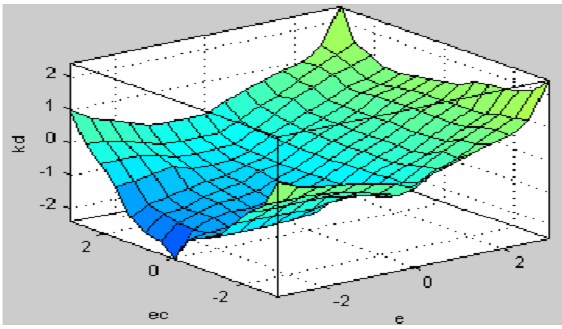
Figure 7 is the fuzzy—rule graph of $\triangle K_P$、$\triangle K_I$、$\triangle K_D$, the result demonstrates the relation between $\triangle K_P$、$\triangle K_I$、$\triangle K_D$ and the two inputs vividly.



(a) The Fuzzy—Rule Graph of $\triangle K_P$



(b) The Fuzzy—Rule Graph of ΔK_I



(c) The Fuzzy—Rule Graph of ΔK_D

Figure 7. The Fuzzy—Rule Graph of ΔK_P、ΔK_I、ΔK_D

The main idea of fuzzy self-tuning PID control system is to establish fuzzy rule table according to the the fuzzy quantizing domains of the input signals and their membership function. Lookup table method can be used to gain the modified parameter, and then update the last sampling parameters of PID controller. During running, the control system deal with fuzzy rules, lookup the rule table and correct the PID parameters in real-time adjustment.

4. Experiment result

A two-dimensional fuzzy controller was designed in this paper, its inputs are angle deviation E, and the change of angle deviation EC[16], its outputs are the variable quantity of the PID controller parameters denoted as ΔKp , ΔK i , ΔK d. The software structure of fuzzy self-tuning PID controller is shown in Figure 8.

And the system structure of fuzzy self-tuning PID controller is shown in Figure 9.

The simulation model of PID controller and fuzzy controller are established respectively in MATLAB/Simulink, and then fuzzy PID controller is formed through putting them together, which are shown in Figure 10-12.

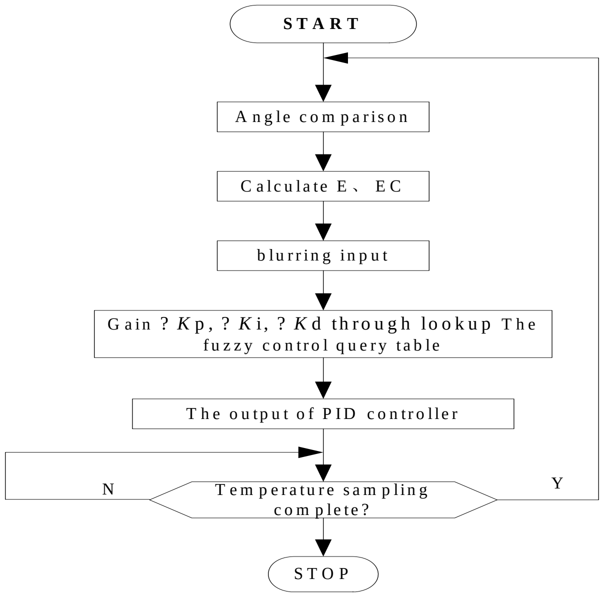


Figure 8. The Software Structure of Fuzzy Self-Tuning PID Controller

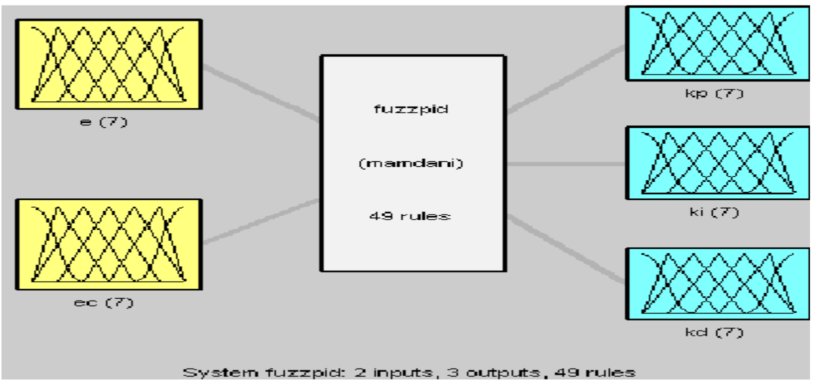


Figure 9. The System Structure of Fuzzy Self-Tuning PID Controller

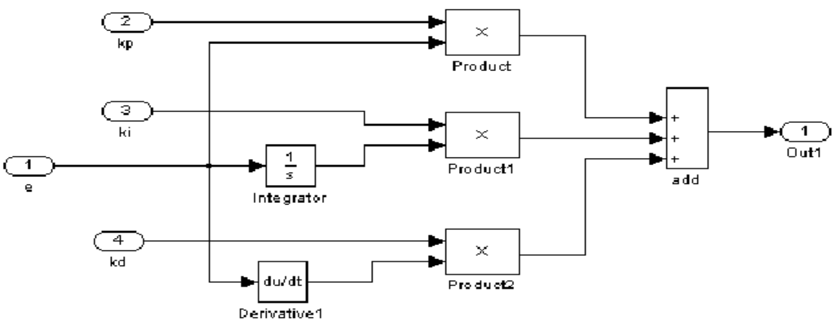


Figure 10. The Simulation Model of PID Controller in Simulink

The simulation model of control system based on fuzzy PID controller is shown in Figure 13, and the simulation result is shown in Figure 14-15. The comparison analyses between the self-tuning fuzzy PID controller and the traditional PID controller are made through a simulation experiment.

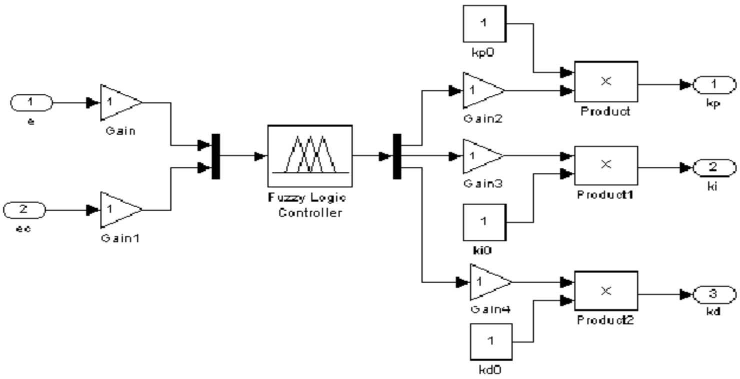


Figure 11. The Simulation Model of Fuzzy Controller in Simulink

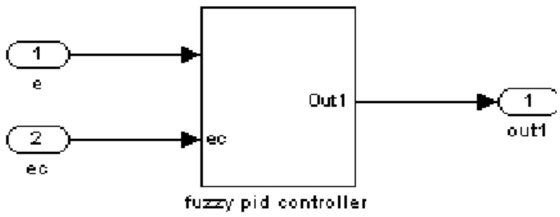


Figure 12. The Simulation Model of Fuzzy PID Controller in Simulink

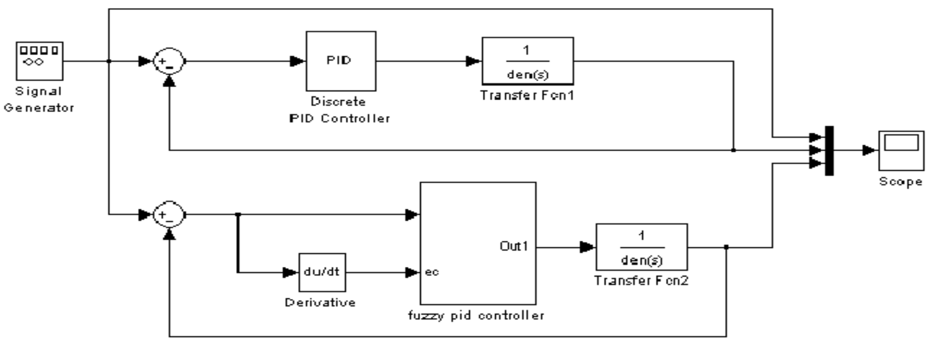


Figure 13. The Simulation Model of Control System

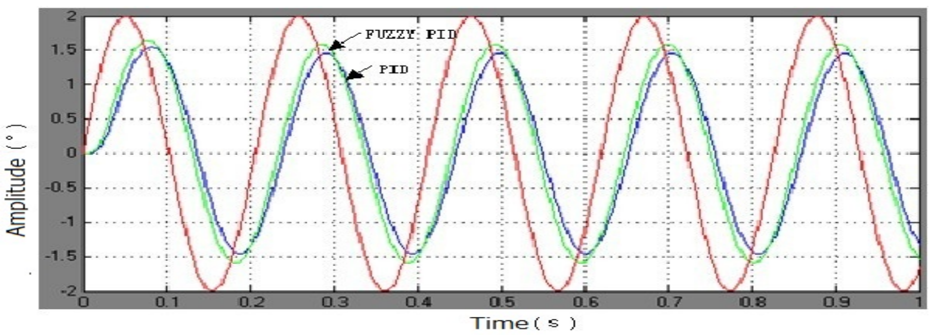


Figure 14. Unit Step Response Curve

Figure 14 show the experimental result of unit step response curve, simulation results show that unit step response time need 0.13s in fuzzy self-tuning PID control

t (s)

system, which is faster than the 0.16s that is needed in traditional PID control system, and overshooting is hardly observed in the experiments, and the system has well stability.

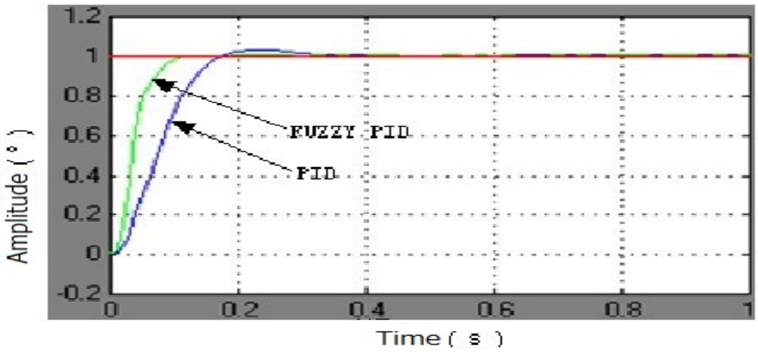


Figure 15. Sine Response Curve

Figure 15 show the experimental result of sine response curve, in the conditions of frequency 5Hz, voltage 2V, the results show that the two controllers both can realize the effective tracking of input signal, but the output signal amplitude value decay and phase lag is smaller compared with traditional PID control system.

5. Conclusion

The factors that affect the control performance of direct drive electro-hydraulic servo system was analyzed, which is include nonlinear and time-varying uncertainty. According to the characteristics of nonlinear and time-varying uncertainty in direct drive electro-hydraulic servo system, the self-tuning fuzzy PID control is designed combining fuzzy reason and traditional PID control. Comparison analyses between the self-tuning fuzzy PID controller and the traditional PID controller are made through a simulation experiment in Matlab/Simulink, Simulation results show that its performance is superior to that of traditional PID controller, and it is more suitable for Direct Drive Electro-hydraulic Servo System.

References

[1] Zavala, Eddie, Fiber. Ptic Experience with the Smart Actuation System on F-18 Systems Research Aircraft. *NASA TM-97-206224*. 7: 39-25.
[2] XP OuYang, HY Yang, B Xu. Research on the Hydraulic Transformer with New Distribution Pairs. *Science in China Series E: Technological Sciences*. 2008; 51(4): 435-442.
[3] PAJ Achten. *Volumetric Losses of a Multi Piston Floating Cup Pump.* Proceedings of the 50th National Conference on Fluid Power. 2005; 1-7.
[4] Su Wen-hai, Jiang Ji-hai. Quantitative feedback robust control for direct drive electro-hydraulic servo rotary vane steering gear. *Journal of Jilin University (Engineering and Technology Edition)*. 2011; 41(3): 670-675.
[5] Long Quan. Research on the Performance of the New Type of Proportional Pressure and Flow Control Valve. *Chinese Journal of Mechanical Engineering.* 2003; 16(3): 281-284.
[6] Long Quan. Principle to Closed Loop Control Differential Cylinder with Double Speed Variable Pumps and Single Loop Control Signal. *Chinese Journal of Mechanical Engineering.* 2004; 17(1): 85-88.
[7] HY Yang, J Yang, B XU. Computational Simulation and Experimental Research on Speed Control of VVVF Hydraulic Elevator. *Control Engineering Practice*. 2004; 12: 563-568.
[8] B Gao, YL Fu ZC. Research on Dual-Variable Integrated Electro-Hydrostatic Actuator. *Chinese Journal of Aeronautics.* 2006; 19(1): 77-82.
[9] Chen Guiyin. Design and Implementation of Fuzzy PID Vector Control Speed Adjusting System. *JDCTA: Iternational Journal of Digital Content Technology and its Applications*. 2012; 6(21); 517-523.
[10] Song Shuran, Ruan Yaocan, Hong Tiansheng, et al. Self-adjustable fuzzy PID control for solution pressure of pipeline spray system in orchard. *Transactions of the CSAE.* 2011; 27(6): 157-161.
[11] DU Mingfang, FANG Jianjun, LIANG Lanzhen. Design of a parameter self-tuning fuzzy-PID controller of a library robot manipulator. *CAAI Transactions on Intelligent Systems*. 2012; 7(2): 161-166.

[12] Liu Zhizhuang, Hong Tiansheng, Zhang Wenzhao, et al. Fuzzy control implementing and testing on electromechanical flow valve. *Transactions of the CASE*. 2010; 26(1): 22-26.
[13] Ji Jiangtao, Wang Rongxian, Fu Lijun. Grey prediction fuzzy PID control of the feeding quantity in combine. *Transactions of the CASE.* 2008; 39(3): 63-66.
[14] Ahmed Rubaai, Marcel J Castro-Sitiriche, Abdul R Ofoli. Design and implementation of parallel fuzzy PID controller for high-Performance brushless motor drives: an integrated environment for rapid control prototyping. *IEEE transactions on industry applications*. 2008; 1090-1098.
[15] Servet Soyguder, Mehmet Karakose, Hasan Alli. Design and simulation of self-tuning PID-type fuzzy adaptive control for an expert HVAC system. *Expert Systems with Applications*. 2008; 4566-4573.
[16] Yi Jiangang, Lin Zan. An Improved Digital PID Algorithm for Angle Position Electric-hydraulic Servo System. *JDCTA: International Journal of Digital Content Technology and its Applications*. 2011; 5(4): 74-81.