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FUZZY ADAPTIVE PID CONTROL OF LARGE ERECTING SYSTEM

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ABSTRACT

In considering nonlinearity and uncertainty in the large erecting system, a fuzzy adaptive PID controller is introduced to improve the control performance. The mathematic model is constructed at first based on the physical laws. Then, the fuzzy logic algorithm which can regulate PID parameters on-line is designed and fuzzy inference rules are established between the PID parameters and the error and change in error. Step response and position tracking are implemented on this large erecting system. Simulation and experiment results demonstrate that the fuzzy adaptive PID controller has effectively improved the performance as compared with the conventional PID controller and fixed fuzzy controller. Further, the fuzzy adaptive PID controller is simple, easy to understand and realize.

Keywords: *Fuzzy PID, Adaptive Control, Erecting System, Electro-Hydraulics*

1. INTRODUCTION

Electro-hydraulic proportional systems have been frequently used in large erecting mechanism of many machineries and equipment, for example, the crane and some armaments. Because they provide many advantages compared to electric motors, including high power capability and mechanical efficiency, good positioning capability, and fast response characteristics. However, the hydraulic systems have many uncertainties, time varying and highly nonlinear characteristics due to the flow-pressure relationship, oil leakage, dead zone of valve, volume flow unbalance of asymmetrical cylinder, oil temperature variation and so on [1]. Furthermore, the large erecting systems are always subjected to large inertia variation, substantial external loads and various working environments. So using conventional control methods cannot guarantee our request for the large erecting system.

In order to solve such hydraulic erecting control problems some research efforts have been made in recent years. For example, C. L. Ma proposed intelligent integration controller in article [2], and C. Q. Yu applied non-linear predictive controller in reference [3]. These control methods provide satisfactory results from their simulation. However, all of them have not been down experiments. Further, when parameters of the plants or environments change, they cannot adaptively compensate these changes and always lead to instability. Fuzzy logic-based controller is an intelligent control method based on the fuzzy set theory which proposed by L. A. Zadeh in 1965. The fuzzy controller imitates the humans thinking and needn't to know the accurate mathematical model of the controlled object. It shows good results when applying to control the nonlinear systems. So in recent years, more and more research efforts about using fuzzy controller in hydraulic systems control have appeared [4-7]. But the design of fuzzy rules which is the centre of fuzzy control depends largely on the experience and knowledge of experts. There is no systematic method to design the number of rules and membership functions by now, and only the fuzzy logic control method may not guarantee satisfactory request. PID controller is a most widely used control method in industrial control, but it cannot regulate PID parameters under different conditions. Combining the two control methods that using fuzzy logic algorithm to regulate the PID parameters has proved to be a good solution, and many researchers have down contributory research. For example, Y. L. Sang proposed a fuzzy controller for an electro-hydraulic fin actuator using phase plane method [8], J. M. Zheng applied self-tuning fuzzy PID controller for a SRM direct drive volume control hydraulic press [9], and D. Edvard used fuzzy PID controller to electro-hydraulic servo control [10].

In this paper, a fuzzy adaptive PID controller which can adaptively adjust PID parameters on-line is designed to compensate nonlinearity of the system. To demonstrate the effectiveness of this controller, a series of simulations and experiments are performed on the erecting system. The simulation and experimental results show that it can improve the performance and robustness of the system in response to the nonlinearity. And the fuzzy adaptive PID control scheme performs more accurate response and better stability, as compared with the conventional PID control and fixed fuzzy control.

2. MATHEMATIC MODEL OF ERECTING SYSTEM

Fig.1 shows the schematic diagram of the erecting system, which is composed of a hydraulic pump, an electro-hydraulic proportional valve, an asymmetrical cylinder, large erect arm and angle sensor. One end of the cylinder O_1 linked to the frame and the other end O_2 linked to the erect arm. The cylinder can rotate around the two points O_1 and O_2. At the same time, the erect arm can rotate around the point O which is the integration point of the erect arm and the frame. The angle of the erect arm is controlled as follows: Once the voltage input corresponding to the desired angle θ_d is transmitted to the controller, the input current is generated in proportion to the error e between the input and the output from the angle sensor which is applied to measure the erect angle θ of the erect arm. Then, the valve spool position and direction are controlled according to the input current. Depending on the spool position, the flows as well as the direction supplied to each cylinder chamber is determined. The motion of the erect arm actuated by the cylinder is then controlled by these flows.

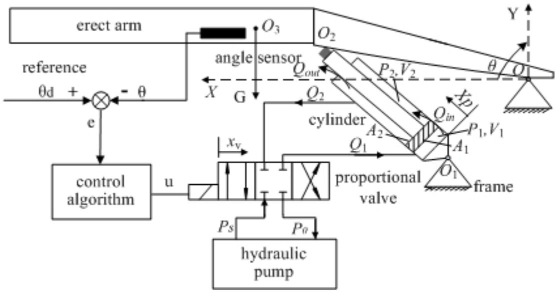


Figure 1: The Schematic Diagram Of Erecting System

2.1 Kinematic and Dynamic of Erecting System

In Fig.1 P_S is the hydraulic supply pressure and P_0 is the reservoir pressure, P_1 and P_2 are the fluid pressure on the two cylinder sides. x_v is the spool valve displacement, θ is the erect angle, X_P is the piston displacement, O_3 is the erect arm center of gravity. Let $OO_1=l_1$, $OO_2=l_2$, $O_1O_2=l_3$, $OO_3=l_4$, $\angle O_1OO_2=\theta_0$, $\angle OO_2O_1=\alpha$, $\angle XOO_3=\gamma$. Kinematic model of the erect system can be written as

$$X_P=\sqrt{l_1^2+l_2^2-2l_1l_2\cos(\theta+\theta_0)}-l_3 \qquad (1)$$

And based on the rotation differential equation of the erect arm, the dynamics model can be derived.

$$J\ddot{\theta}=Fl_1\sin\alpha-Gl_4\cos(\gamma+\theta) \qquad (2)$$

where F represents the output force from the cylinder, J is the erect arm moment of inertia and G is its gravity. In the triangle OO_1O_2, applying law of sines we can receive the equation

$$\frac{l_1}{\sin\alpha}=\frac{l_3+X_P}{\sin(\theta+\theta_0)} \qquad (3)$$

So from the equations (2) and (3), we have

$$F=\frac{J\ddot{\theta}+Gl_4\cos(\gamma+\theta)}{l_1\sin(\theta+\theta_0)/(l_3+X_P)} \qquad (4)$$

2.2 Mathematic Model of Hydraulic System

We assume that the flow areas to the supply and return port of the valve be proportional to the spool displacement x_v. Then the flow of oil across the spool valve can be given as:

$$Q_1=\begin{cases} C_dwx_v\,\mathrm{sgn}(P_S-P_1)\sqrt{\frac{2}{\rho}\left|P_S-P_1\right|} & x_v\ge 0 \\ C_dwx_v\sqrt{\frac{2}{\rho}P_1} & x_v<0 \end{cases} \qquad (5)$$

$$Q_2=\begin{cases} C_dwx_v\sqrt{\frac{2}{\rho}P_2} & x_v\ge 0 \\ -C_dwx_v\,\mathrm{sgn}(P_S-P_2)\sqrt{\frac{2}{\rho}\left|P_S-P_2\right|} & x_v<0 \end{cases} \qquad (6)$$

where C_d is the discharge coefficient, w is the spool valve area gradient, ρ is the oil mass density, and the following function sgn(x) is used

$$\mathrm{sgn}(x)=\begin{cases} 1 & x>0 \\ 0 & x=0 \\ -1 & x<0 \end{cases} \qquad (7)$$

Applying the continuity equation to the fluid flowing in each chamber of the cylinder, the following two expressions can be derived.

$$Q_1=A_1\frac{dX_P}{dt}+C_{in}(P_1-P_2)+\frac{V_1}{\beta}\frac{dP_1}{dt} \qquad (8)$$

$$Q_2=A_2\frac{dX_P}{dt}+C_{in}(P_1-P_2)-C_{out}P_2-\frac{V_2}{\beta}\frac{dP_2}{dt} \qquad (9)$$

where C_{in} is the inwards leakage coefficient of cylinder, C_{out} is the outwards leakage coefficient of cylinder, β is the fluid bulk modulus, $V_1=V_{10}+A_1X_P$ and $V_2=V_{20}+A_2(l-X_P)$ are the total fluid volumes in the two sides of the cylinder, l is the cylinder stroke, V_{10} and V_{20} are the dead volumes of the two sides.

Based on the Newton's law of motion, the force balance equation of the cylinder can be obtained as follows:

$$m\frac{d^2X_P}{dt^2} = (P_1A_1 - P_2A_2) - B\frac{dX_P}{dt} - F_L \qquad (10)$$

where m represents the equivalent mass of the cylinder, B is the equivalent viscous damping coefficient, F_L is the external force come from the erect arm and it is equal to the F in the equation (4).

The spool valve dynamics is always approximate to a linear second order differential equation:

$$\frac{d^2x_v(t)}{dt^2} + 2w_nB_d\frac{dx_v(t)}{dt} + w_n{}^2x_v = w_n{}^2u(t) \qquad (11)$$

where w_n represents the natural frequency and B_d is the damping factor.

3. FUZZY ADAPTIVE PID CONTROLLER DESIGN

3.1 Structure and Principle of Fuzzy Adaptive PID Controller

The erecting system is a complicated nonlinear system as introduced in section 1. Applying the conventional PID controller is difficult to achieve high control precision and good performance due to the influences of the nonlinear and uncertain factors existed in the erecting system. Meanwhile, it is poor in turning parameters in different conditions. For these reasons, the fuzzy adaptive PID control technique is introduced to overcome the above problems in this paper.

The fuzzy adaptive PID controller is combined the conventional PID with the fuzzy logic algorithm to improve the performance of the erecting system. Its principle is shown in Fig.2. The fuzzy logic algorithm has two inputs error e and change in error ec, and three outputs ΔK_p, ΔK_i and ΔK_d which are the change in parameters K_p, K_i and K_d of the PID controller. And it composed of three main elements: fuzzification, fuzzy inference and defuzzification.

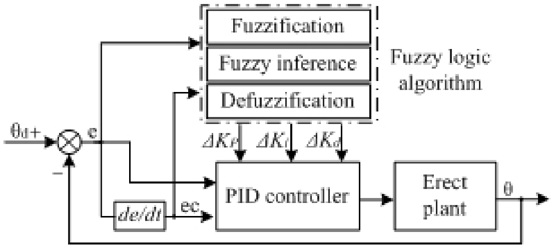


Figure 2: Structure Of The Fuzzy Adaptive PID Controller

3.2 Fuzzification of Input and Output Variables

The first step is fuzzification of the input and output variables, which transforms the input and output data into semantic value. In this paper, the fuzzy range of the variables are $e,ec \in [-3, 3]$, $\Delta K_p \in [-1, 1]$ $\Delta K_i \in [-0.2, 0.2]$and $\Delta K_d \in [-0.05, 0.05]$. And they all transformed into uniform fuzzy range [-1 1]. Then, the fuzzy range is separated into 7 semantic variables, and the corresponding fuzzy subsets are e, ec, ΔK_p, ΔK_i , ΔK_d=[*NB*, *NM*, *NS*, *ZO*, *PS*, *PM*, *PB*], where *NB* is negative big; *NM* is negative middle; *NS* is negative small; *ZO* is zero; *PS* is positive small; *PM* is positive middle; *PB* is positive big. Let *NB* be Z-shaped membership function 'zmf', *PB* is Sigmiod membership function 'smf' and others are triangular membership function 'trimf'. From the membership function, the degree of membership of all the fuzzy subsets can be derived. All the fuzzy member functions are shown in Fig.3 and Fig.4.

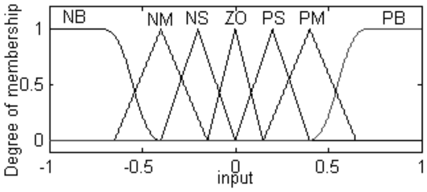


Figure 3: Fuzzy Membership Function Of E And Ec

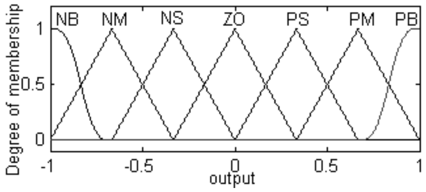


Figure 4: Fuzzy Membership Function Of ΔK_p, ΔK_i And ΔK_d

3.3 Fuzzy Inference and Defuzzification

The most important step is establishment of fuzzy inference rule between the input variables e,ec and the output variables ΔK_p, ΔK_i , ΔK_d based on the experience of experts or input-output data. In this paper, the laws of the PID parameters act on the erecting system are studied through simulations and experiments. All the fuzzy inference rules are summarized in Table 1.

Table 1: Fuzzy Rule

ΔK_p/ ΔK_i/ ΔK_d — e \ ec	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/NM/NB	PS/NS/NB	ZO/ZO/NM	ZO/ZO/PS
NM	PB/NB/PS	PB/NB/NS	PM/NM/NB	PS/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/ZO/ZO
NS	PM/NB/ZO	PM/NM/NS	PM/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/PS/NS	NS/PS/ZO
ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NM/PM/NS	NM/PM/ZO
PS	PS/NM/ZO	PS/NS/ZO	ZO/ZO/ZO	NS/PS/ZO	NS/PS/ZO	NM/PM/ZO	NM/PB/ZO
PM	PS/ZO/PB	ZO/ZO/NS	NS/PS/PS	NM/PS/PS	NM/PM/PS	NM/PB/PS	NB/PB/PB
PB	ZO/ZO/PB	ZO/ZO/PM	NM/PM/PM	NM/PM/PM	NM/PM/PS	NB/PB/PS	NB/PB/PB

There are 49 rules in Table 1, and the implication used in the rules is as follows:

If e is A_i and ec is B_j, then $\Delta K_p/\Delta K_i/\Delta K_d$ is $C_{ij}/D_{ij}/E_{ij}$ where A_i, B_j, C_{ij}, D_{ij}, E_{ij} are corresponding to the fuzzy subsets of e, ec, ΔK_p, ΔK_i, ΔK_d. The Mamdani's Min-Max operator is adopted to carry out fuzzy inference. For example, the degree of membership of the fuzzy subsets C_{ij} for the parameter ΔK_p can be derived.

$$u_{C'}(\Delta K_p) = \bigvee_{i,j=1}^{7} \{[u_i(e) \wedge u_j(ec)] \wedge u_{Cij}(\Delta K_p)\} \quad (12)$$

where $u(x)$ is the degree of membership.

Defuzzification is the process of converting fuzzy variables to crisp values. The center of gravity method is applied to obtain the crisp values. The parameter ΔK_p (ΔK_i and ΔK_d.are similar) can be calculated from the following equation.

$$\Delta K_p(e, ec) = \frac{\sum_{k=1}^{7} \Delta K_p u_{C'}(\Delta K_p)}{\sum_{k=1}^{7} u_{C'}(\Delta K_p)} \quad (13)$$

After defuzzification, the three parameters K_p, K_i and K_d can be obtained as follows:

$$K_p = K_{p0} + \Delta K_p$$

$$K_i = K_{i0} + \Delta K_i$$

$$K_d = K_{d0} + \Delta K_d$$

where K_{p0}, K_{i0} and K_{d0} are the original parameters of the PID controller.

4. SIMULATION AND EXPERIMENTAL RESULTS

In order to demonstrate the performance of the fuzzy adaptive PID controller, some of simulations and experiments are implemented on the erecting system under different conditions. The simulation model is built in versatile software Matlab/Simulink using the derived equations in section 2. It composed of four parts: controller, spool valve, cylinder and erect arm. Fig.5 shows this simulation model, and Table 2 shows the characteristic parameters of the erecting system.

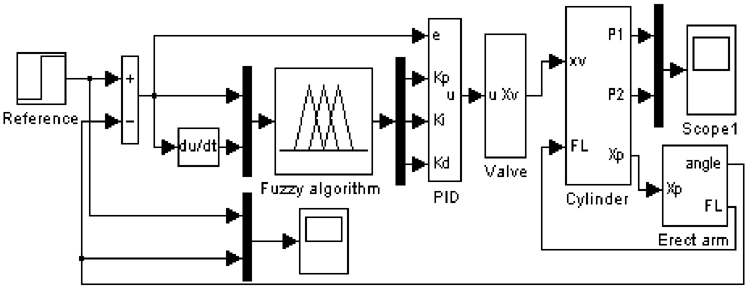


Figure 5: Simulink Block Diagram Of The Erecting System Model

Table 2: The Characteristic Values Of The Erecting System

Parameters	Symbols	Values	Units
Supply pressure	P_S	18	*MPa*
Discharge coefficient of the spool valve	C_d	0.62	—
Area gradient of the spool valve	w	2.51×10^{-2}	*m*
Bulk modulus of oil	β	7.5×10^{8}	*Pa*
Length of piston head	l	1.5935	*m*
Equivalent viscous damping coefficient	B	800	*N/m/s*
Mass density of oil	ρ	868	Kg/m^3
Equivalent mass of the piston	m	178.31	*Kg*
Inwards leakage coefficient of cylinder	C_{in}	2.41×10^{-11}	$m^3/s*Pa$
Outwards leakage coefficient of cylinder	C_{out}	7.1×10^{-13}	$m^3/s*Pa$
Equivalent mass of the erect arm	M	1155.98	*Kg*
Moment of inertia of the erect arm	J	10023	$Kg*m^2$
Section area of piston-side/rod-side	A_1/A_2	0.0175/0.0133	m^2
Dead volume of piston-side/rod-side	V_{10}/V_{20}	$1.7\times10^{-5}/1.3\times10^{-5}$	m^3
Length of $OO_1/OO_2/O_1O_2/OO_3$	$l_1/l_2/l_3/l_4$	1.132/1.62/1.032/3.5	*m*
Angle of $\angle O_1OO_2/\angle XOO_3$	θ_0/γ	0.6816/0.1047	*rad*

The step response simulation results of PID, fixed fuzzy and fuzzy adaptive PID are shown in Fig.6, and the step value is 5 degree. It can be seen that the step response speed of fixed fuzzy controller is slow, and it has vibration when reach the step value. The PID controller has higher response speed as increase of the K_p, K_i and decrease of K_d, but overshoot and more adjusting time will happen. However, the fuzzy adaptive PID controller shows fast response speed, accurate steady-state precision and short adjusting time. Because this method can regulate the PID controller parameters adaptively according to the error e and change in error ce.

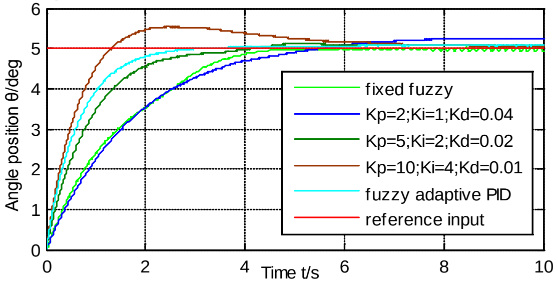


Figure 6: Simulation Results Of PID, Fixed Fuzzy, And Fuzzy Adaptive PID Step Response

Fig.7 shows the step response experimental results of the three controllers under same condition. We can see that the experimental results are similar to the simulation results in general and the fuzzy adaptive PID controller is also the best controller among the three controllers. Compared to the simulation, the curves are not smooth and much straighter. And it has about 1.23s lag time in real erecting system, for example, the steady-state response time is 4.62s for fuzzy adaptive PID controller in experiment, but just 3.37s in simulation.

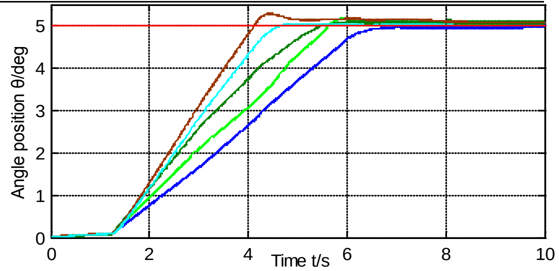
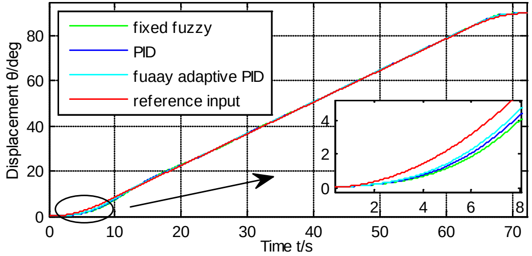


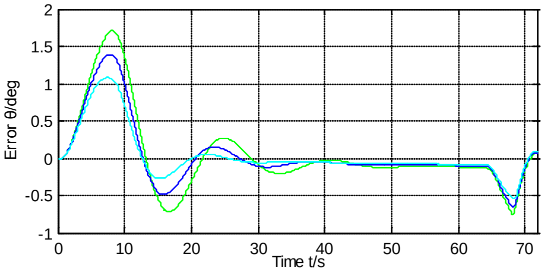
Figure 7: Experiment Results Of PID, Fixed Fuzzy, And Fuzzy Adaptive PID Step Response

In order to demonstrate the tracking ability of fuzzy adaptive PID controller, the tracking simulation and experiment are designed. The tracking objective is an angular displacement curve from 0° to 90° as shown in Fig.8 (a) (the red), and its angular velocity obey to the curve shown in Fig.8 (c) (the red). Applying the PID, fixed fuzzy and fuzzy adaptive PID to track the angular displacement curve, the simulation and experiment results are shown in Fig.8 and Fig.9, respectively.

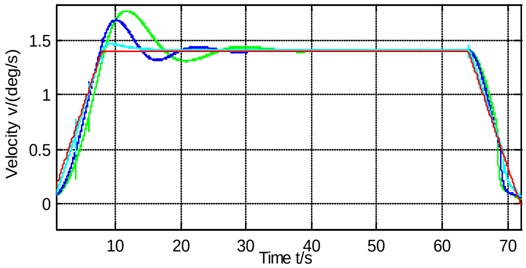
Fig.8 (a) and Fig.9 (a) exhibit the tracking curves of the three controllers, and also present some details of the curves. It can be seen that the experimental results are similar to the simulation, but the lag time 1.23s exists in the experiment. Fig.8 (b) and Fig.9 (b) present the tracking error. We can see that the fuzzy adaptive PID controller has the best tracking precision, and the max error is 1.06° in simulation and 1.14° in experiment, but for PID is 1.38°/1.53° (simulation/experiment) and for fix fuzzy is 1.71°/1.98°. Meanwhile, there are vibration and noise in the experiment, especially in the process of after about 16s. Because the valve has nonlinearity and the real erecting system also need a response time to the control signal. The angular velocity curves of the three controllers are shown in Fig.8 (c) and Fig.9 (c). The angular velocity curve of fuzzy adaptive PID controller is steadier than conventional PID controller and fixed fuzzy controller. For example, the max error is 1.54deg/s in the experiment, but 1.84deg/s for PID and 1.97deg/s for fixed fuzzy.



(A) Angular Displacement

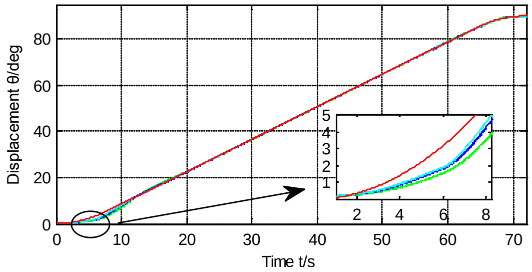


(B) Tracking Error

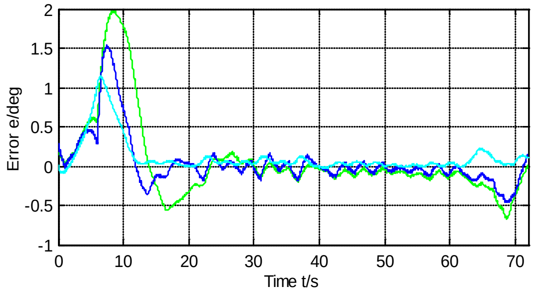


(C) Angular Velocity

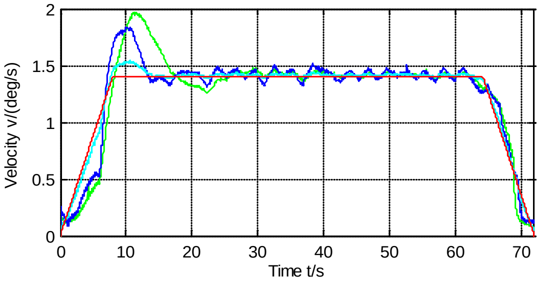
Figure 8: Simulation Results Of PID, Fixed Fuzzy, And Fuzzy Adaptive PID Tracking Control



(A) Angular Displacement



(B) Tracking Error



(C) Angular Velocity

Figure 9: Experiment Results Of PID, Fixed Fuzzy, And Fuzzy Adaptive PID Tracking Control

All the simulations and experiments demonstrate that the fuzzy adaptive PID controller can obviously improve the response speed and control precision, and it presents satisfactory performance for the large erecting system.

5. CONCLUSION

In this paper, a fuzzy adaptive PID controller is applied to the erecting system to realize nonlinear control. A series of simulations and experiments are performed to test the effectiveness of this controller. The step response simulation and experiment show that the fuzzy adaptive PID controller solves contradiction between response speed and steady-state, and realizes fast response and high accurate. The tracking simulation and experiment results demonstrate that the fuzzy adaptive PID controller presents faster and more accurate performance compared with the conventional PID controller and the fixed fuzzy controller. And the max tracking error is 1.14°, and error of the end point (90°) is 0.1°. So this satisfies our requests and it is clear that the fuzzy adaptive PID controller is effective for the large erecting system control.

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