

Research on the Speed Synchronization Control System of The Rotary Blowout Preventer Hydraulic Motor

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Abstract: Aiming at the problem of unsynchronised rotational speed of the new drilling rotary blowout prevention type hydraulic rotary motor, the rotary hydraulic control system was designed. Using the method of mathematical analysis, a mathematical model was constructed for analysis, and a fuzzy PID controller was designed according to the analysis results, and the hydraulic motor speed control system was simulated and analysed using Matlab/Simulink software. Simulation results show that: in the motor speed control system, the designed controller control effect is obvious, the stability of the system is significantly improved, and for the complex external load environment of the turntable, the adaptability is good and robust.

Keywords: Hydraulic motor; Simulink; Fuzzy Logic Control.

1. Introduction

The hydraulic rotary table is one of the key pieces of equipment in drilling engineering, used to transfer hydraulic power and torque to achieve rotation of the drill bit. Currently, various hydraulic rotary tables from multiple manufacturers, such as NOV, WIRTH (Germany), and Baoshi Machinery (China), have been widely applied in petroleum drilling operations[1]. However, these systems only meet general rotational power requirements and struggle to control the blowout prevention sealing in the annulus during rotation operations[2]. The new type of rotary blowout preventer hydraulic rotary table can be used as a standard hydraulic rotary table without installing a sealing rubber sleeve, and, when the sealing sleeve is installed, it serves as a blowout preventer for both rotation and pipe handling operations. This rotary table features a complete range of functions, a compact structure, high torque transmission capacity, stable operation, stepless speed regulation, and controllable anti-torque release[3].

In operations such as active drilling tools and various downhole logging tasks, the motor speed output is easily disturbed by external load conditions due to the complex external load environment of the rotary table. This presents a

high requirement for the motor speed control system[4]. Therefore, this study addresses the external load interference issue in the new rotary blowout preventer hydraulic motor speed control system by designing a self-tuning fuzzy PID controller. The system adjusts the motor speed by electrically controlling the tilt angle of the variable displacement pump's swashplate to mitigate the load interference[5].

2. Hydraulic System Principles and Mathematical Modeling

2.1. Hydraulic System Working Principle

The new rotary blowout preventer hydraulic motor speed control system mainly consists of a controller, electro-hydraulic proportional valve, hydraulic cylinder, variable displacement pump, and hydraulic motor. The electro-hydraulic proportional valve receives adjustment signals from the controller, which controls the displacement of the valve core[6]. This, in turn, alters the flow entering the hydraulic cylinder, causing displacement that drives the swashplate mechanism of the variable displacement pump to adjust the tilt angle of the swashplate, thus controlling the hydraulic motor's speed[7].

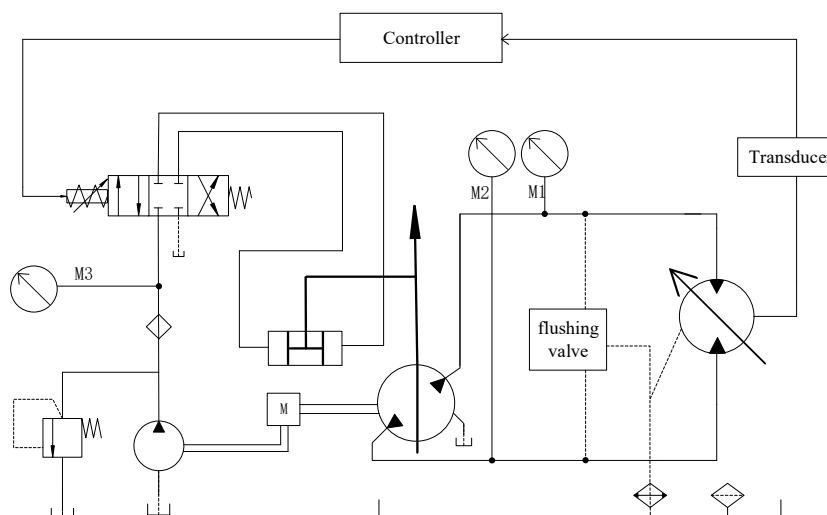


Figure 1. Schematic Diagram of the Rotary Blowout Preventer Hydraulic Motor Speed Control System

2.2. Hydraulic System Mathematical Modeling

2.2.1. Valve-Controlled Cylinder System Transfer Function

1) Electro-hydraulic proportional valve flow equation:

$$q_L = K_x x_v - K_c p_L \quad (1)$$

Meaning of the Symbols:

q_L -the flow output of the proportional valve,;
 X_v -the valve core displacement;
 K_x -the valve flow gain;
 P_L -the load pressure drop;
 K_c -the flow pressure coefficient.

2) Hydraulic Cylinder Flow Equation:

$$Q_L = C_{tc} P_L + A_p \frac{dx_p}{dt} + \frac{V_t}{\beta_e} \times \frac{dp_L}{dt} \quad (2)$$

Meaning of the Symbols:

C_{tc} -the total leakage coefficient of the variable hydraulic cylinder;

X_p -the piston displacement;

V_t -the total volume of the cylinder's two chambers;

β_e -the oil elasticity modulus of the hydraulic cylinder;

A_p -the effective area of the hydraulic cylinder piston.

By performing Laplace transforms and solving:

$$Q_L(s) = K_x X_v(s) - K_c P_L(s) \quad (3)$$

$$Q_L(s) = C_{tc} P_L(s) + A_p s x_p(s) + \frac{V_t}{\beta_e} s p_L(s) \quad (4)$$

The transfer function of the valve-controlled hydraulic cylinder system is obtained.

$$x_p(s) = \frac{\frac{K_x}{A_p} x_v(s)}{s \left(\frac{s^2}{\omega_n^2} + \frac{2\varepsilon_n}{\omega_n} s + 1 \right)} \quad (5)$$

ω_n is the hydraulic natural frequency, ε_n is the hydraulic damping ratio.

$$\omega_n = \sqrt{\frac{4\beta_e D_m^2}{V_t J_m}} = 2D_m \sqrt{\frac{\beta_e}{V_t J_m}}$$

$$\varepsilon_n = \frac{k_{ce}}{D_m} \sqrt{\frac{\beta_e J_m}{V_t}} + \frac{B_m}{4D_{md}} \sqrt{\frac{V_t}{\beta_e J_m}}$$

2.2.2. Pump-Controlled Motor System Transfer Function

1) Pump Flow Equation:

$$Q_p = D_p n_p - C_{ip} (p_h - p_s) - C_{ep} p_h \quad (6)$$

$$D_p = k_p r \quad (7)$$

Meaning of the Symbols:

Q_p -the variable pump flow;

D_p -the pump displacement

N_p -the pump speed

C_{ip} -the internal leakage coefficient

C_{ep} -external leakage coefficient

p_h, p_s -high-pressure and low-pressure side pressure

k_p -pump displacement gradient

γ -pump swashplate tilt angle

2) Motor Flow Equation:

$$Q_m = C_{im} (p_h - p_s) + C_{em} p_h + D_m \frac{d\theta_m}{dt} + \frac{V_0}{\beta_e} \frac{dp_h}{dt} \quad (8)$$

Meaning of the Symbols:

C_{im} -motor internal leakage coefficient;

C_{em} -motor external leakage coefficient;

θ_m -motor output rotational angle;

D_m -motor displacement;

ω_m -motor angular velocity;

V_0 -total volume of the working chamber.

3) The transfer function of the valve-controlled cylinder System:

$$\frac{x_p(s)}{x_v(s)} = \frac{\frac{k_x}{A_p}}{s \left(\frac{s^2}{\omega_n^2} + \frac{2\varepsilon_n}{\omega_n} s + 1 \right)} \quad (9)$$

The transfer function of the pump-controlled motor system:

$$\frac{\theta_m(s)}{r(s)} = \frac{\frac{k_{qp}}{D_m}}{s \left(\frac{s^2}{\omega_r^2} + \frac{2\varepsilon_r}{\omega_r} s + 1 \right)} \quad (10)$$

2.3. System Transfer Function

The principle of the motor electro-hydraulic proportional control system is shown in the[8].

The main parameters of the mathematical model are shown in[9]. The open-loop transfer function of the system is obtained.

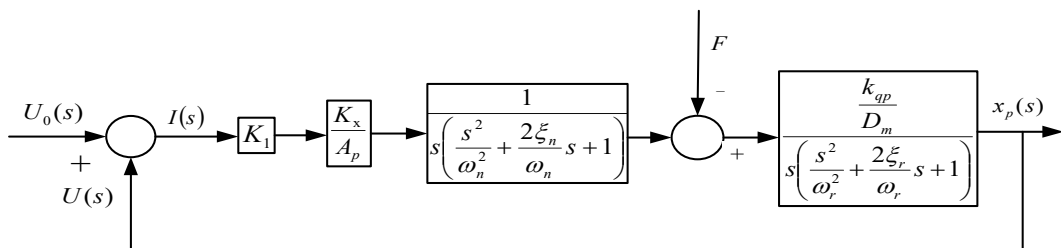


Figure 2 The principle of the motor electro-hydraulic proportional control system

Table 1. The main parameters of the mathematical model

Symbol	Symbol Meaning	Parameter
D_m	Hydraulic Motor Volume Displacement per Radian	$1.5 \times 10^{-4} \text{ m}^3/\text{rad}$
ω_n	Hydraulic Natural Frequency of Valve-Controlled Cylinder System	231.9 rad/s
ε_n	Hydraulic Damping Ratio of Valve-Controlled Cylinder System	0.126
β_e	Comprehensive Oil Elasticity Modulus of Hydraulic Cylinder	$6.8 \times 10^8 \text{ N/m}^2$
V_0	Total Volume of the Working Chamber	$2.8 \times 10^{-4} \text{ m}^3$
k_x	Steady-State Flow Gain of Electro-Hydraulic Proportional Valve	$2.5 \times 10^{-3} \text{ m}^3(\text{A}\cdot\text{s})$
ω_v	Frequency of Electro-Hydraulic Proportional Valve	377rad/s
ε_v	Equivalent Damping Coefficient of Electro-Hydraulic Proportional Valve	0.6
A_p	Effective Area of Hydraulic Cylinder Piston	$3.14 \times 10^{-4} \text{ m}^2$

3. Fuzzy PID Controller Design

3.1. Control Principle

Fuzzy PID control based on the traditional PID algorithm works by using the deviation E between the desired signal and the actual measured signal, as well as the rate of change of the deviation EC, as inputs. Fuzzy rules are matched to determine the adjustment quantities for tuning the PID parameters (i.e., K_p , K_d , and K_i) for real-time correction. The corrected parameters are obtained through a defuzzification process. This controller adapts to internal parameter changes and has strong capabilities in overcoming external disturbances, allowing the controlled system to have good dynamic and static characteristics[10]. The principle of fuzzy PID control is shown in the diagram. The adjustment formula for K_p , K_d , and K_i is as follows:

$$\begin{cases} k_p = k_p' + \Delta k_p \\ k_i = k_i' + \Delta k_i \\ k_d = k_d' + \Delta k_d \end{cases} \quad (11)$$

3.2. Fuzzy Controller Design

Define the input variables E and EC, and the fuzzy subsets and meanings of the output variables K_p , K_d , and K_i as {NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big)}. The domain of these variables is defined in the range of [-6, 6]. In the fuzzy logic toolbox's membership function editor, the membership functions for the input variables E and EC are chosen to be Gaussian, while the membership functions for the output variables K_p , K_d , and K_i are triangular[11]. The specific related parameters are shown in the Figure 3.

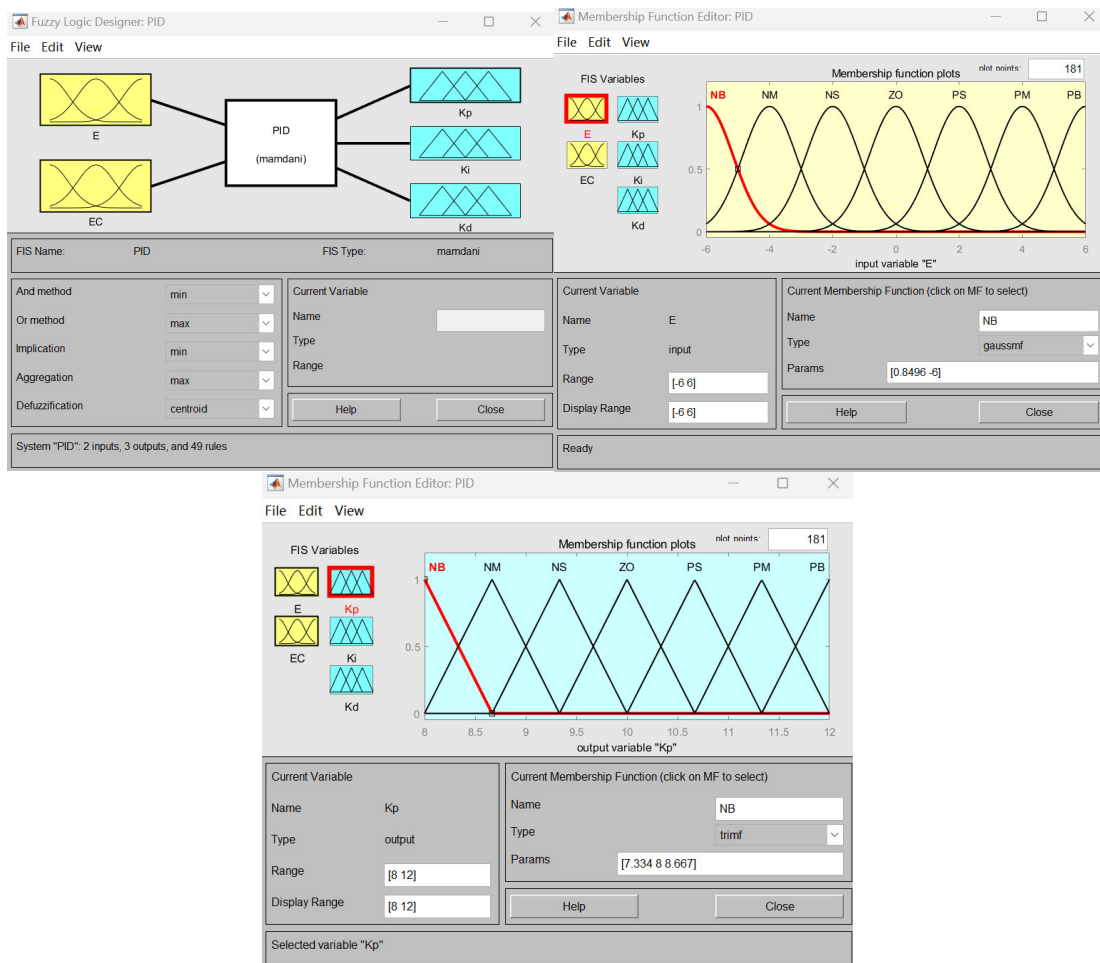


Figure 3. Fuzzy controller parameter settings

3.3. Fuzzy Control Rules

Inducing the relationship between the input variables E, EC,

and the output variables K_p , K_d , and K_i [12]. The fuzzy rules for the PID controller parameters K_p , K_d , and K_i are established as shown in Figure 4.

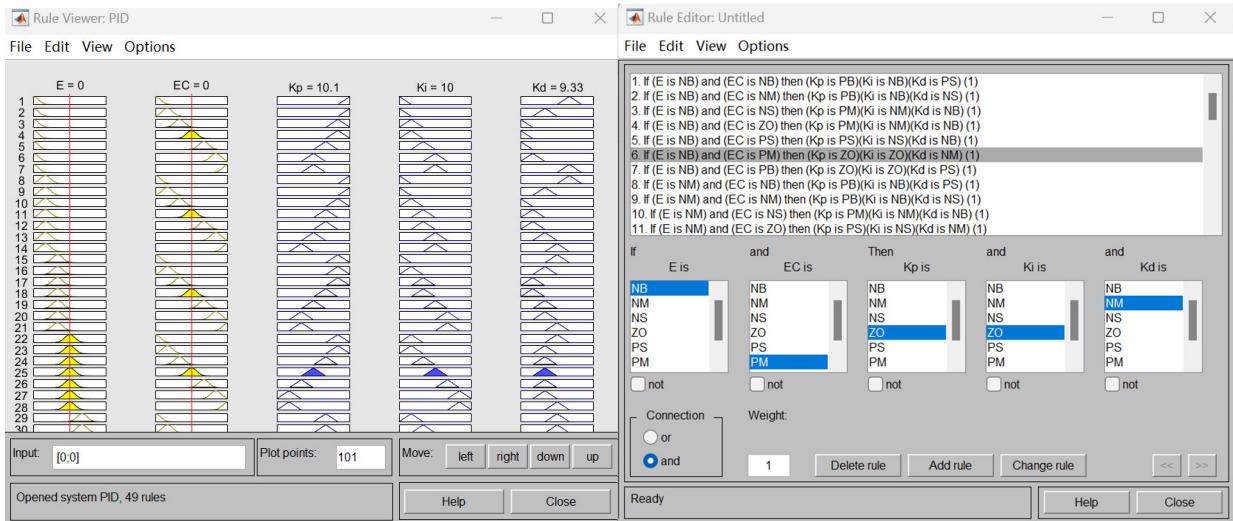


Figure 4. Fuzzy Rules for K_p K_i K_d

4. System Modeling and Simulation Analysis

Using MATLAB/Simulink, a simulation model of the

control system based on the derived transfer functions is built. Both PID control and self-tuning fuzzy PID control algorithms are simulated to verify their effectiveness[13].

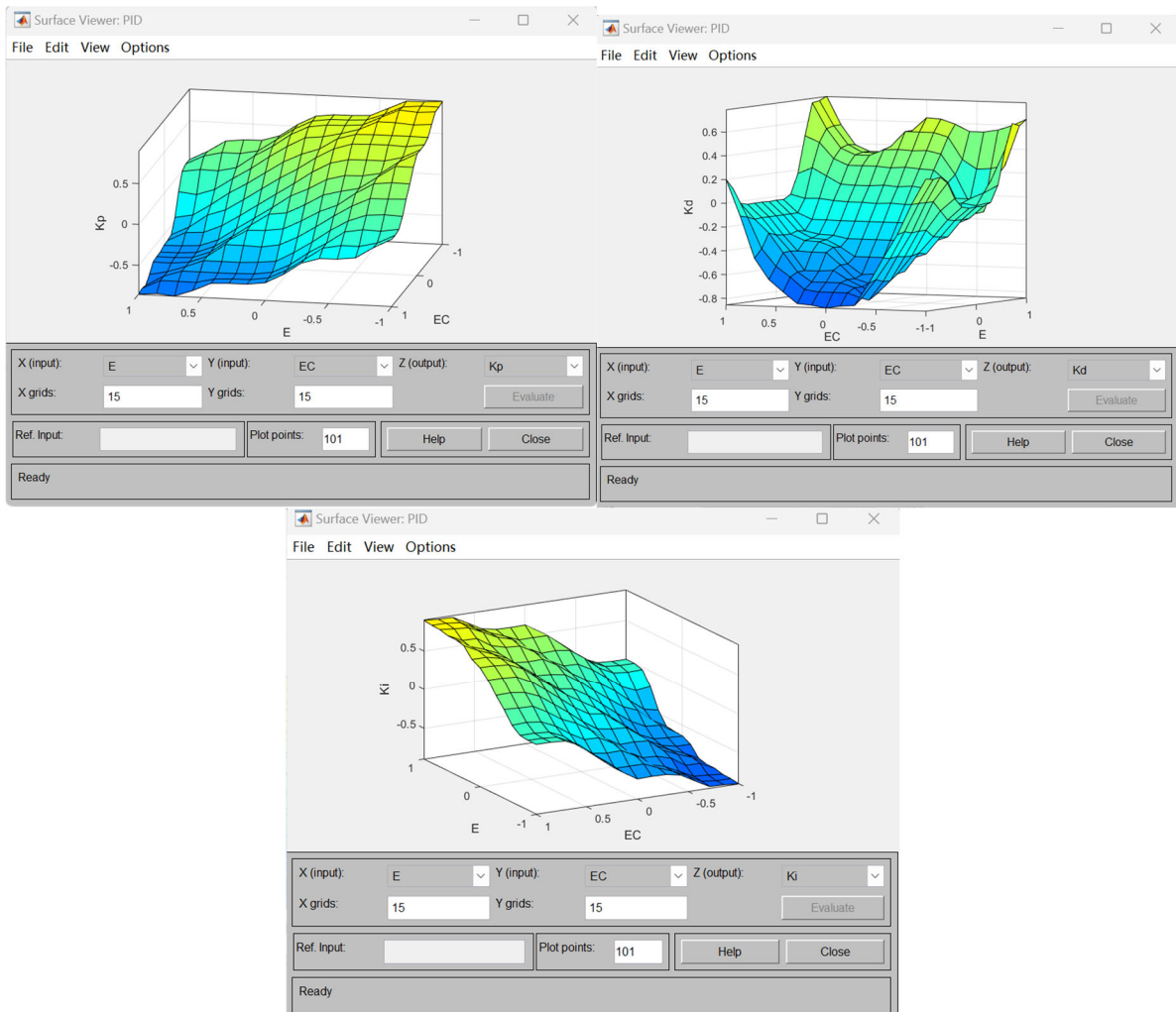


Figure 5. Fuzzy Rules for K_p K_i K_d

4.1. PID Control System Model and Fuzzy PID Control System Model

Based on the transfer function, the Simulink control model

of the PID control system and the fuzzy PID control system is obtained as shown in Figure 6[14].

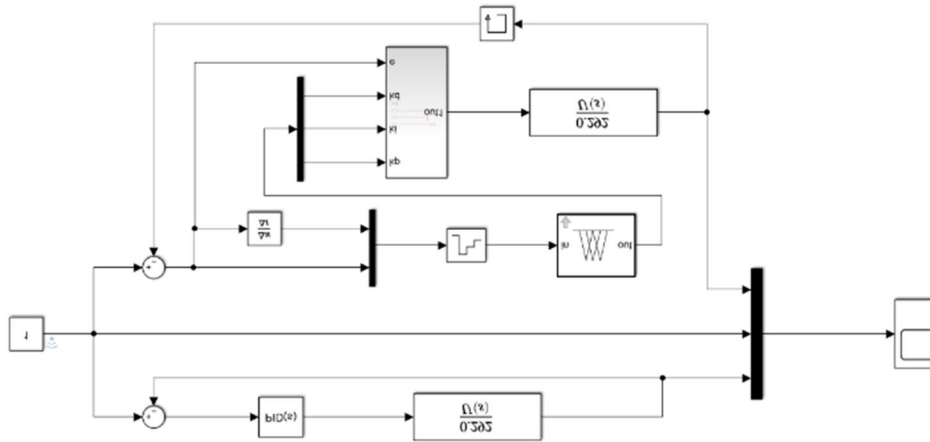


Figure 6. PID control system and the fuzzy PID control system model

4.2. Simulation

Set the system simulation sampling time to 10 second. Tune the three PID parameters, ultimately obtaining $K_p = 0.25$, $K_i = 0.24$, $K_d = 0.02$. Substitute the three parameters into the controller.

Based on the above steps, simulation analysis of the

hydraulic turntable motor speed synchronization control system is conducted using both the PID controller and the fuzzy PID controller[15].

4.2.1. Simulation results

The simulation results of the hydraulic motor speed under PID control and the fuzzy PID control are presented.

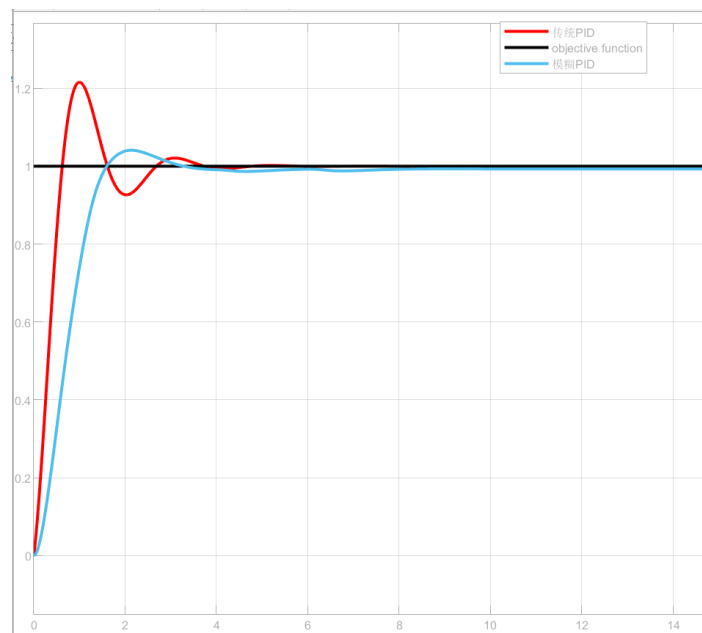


Figure 7. Speed curves of hydraulic motors under two types of control

From the simulation results, it can be seen that: when the target speed signal is input, the two kinds of control reach the steady state after going through the adjustment, and the steady state error is basically zero. In the rotational speed response stage, the traditional PID control showed overshooting, with an overshooting amount of 1.25, and a response time of 4.5s, while the fuzzy PID control did not show overshooting and had a response time of 3.2s, which was substantially improved compared to the traditional PID control[16].

5. Conclusion

The study focuses on the development of a speed synchronization control system for a rotary blowout preventer hydraulic motor, addressing the external load interference that affects motor speed stability in drilling operations. To mitigate these disturbances, a fuzzy PID controller was designed to adjust the hydraulic motor speed by controlling the tilt angle of the variable displacement pump's swashplate[17].

Key conclusions from the study include:

1) The hydraulic system's working principle and mathematical models were established, including the valve-controlled cylinder and pump-controlled motor systems.

2) A fuzzy PID controller was designed, which helps in overcoming load disturbances and enhancing dynamic and static performance.

3) Simulation results indicated that the fuzzy PID controller significantly outperforms traditional PID control in terms of system stability and tracking performance.

In conclusion, the proposed speed synchronization control system using a fuzzy PID controller effectively improves the stability and responsiveness of the rotary blowout preventer hydraulic motor under varying operational conditions.

References

- [1] Luo K, Luo YL. Simulation study on speed control of closed-loop pump-controlled motor hydraulic system[J]. *Computer and Digital Engineering*, 2024, 52(09): 2819-2823.
- [2] Zhang JR, Ge L, Hao YX, et al. Discrete PID control of closed-loop pump-controlled hydraulic-mechanical linear actuator[J]. *Hydraulics and Pneumatics*, 2024, 48(09): 54-60.
- [3] Zhang YH. Comparison and optimization of response characteristics of hydraulic pump-controlled motor systems[J]. *Equipment Manufacturing Technology*, 2024, (08): 45-49.
- [4] Wang DW, Wang SM, Ding HG, et al. Study on feedforward-feedback combined control strategy of valve-controlled cylinder electro-hydraulic system[J]. *Machine Tool & Hydraulics*, 2024, 52(13): 7-14.
- [5] Zheng LT. Nonlinear characteristics analysis and control method study of valve-controlled cylinder system[D]. Harbin University of Science and Technology, 2024.
- [6] Gao P, Zheng MD, Li Y, et al. Influence of oil elastic modulus on the characteristics of closed-loop pump-controlled motor system[J]. *Mechanical Design and Manufacturing*, 2024, (12): 314-317.
- [7] Zhang YS. Dynamic response and stability study of electro-hydraulic proportional valve-controlled motor system[D]. Qilu University of Technology, 2024.
- [8] Xiao PF. Proportional pressure reducing valve valve-controlled cylinder system based on fuzzy PID control[J]. *Construction Machinery*, 2024, 55(02): 126-131+11.
- [9] Cheng YH, Huang XF. Electro-hydraulic proportional pump-controlled motor speed compound control[J]. *Hydraulics and Pneumatics*, 2023, 47(12): 133-140.
- [10] Guo ZY. Study on electro-hydraulic proportional variable mechanism of closed-loop system based on pressure difference control[D]. Yanshan University, 2023.
- [11] Dong MX. Study on dynamic characteristics of electro-hydraulic proportional valve-controlled cylinder system based on fuzzy PID control[D]. Shandong University of Transport, 2023.
- [12] Dong MX, Kong XZ. Study on leakage compensation of electro-hydraulic proportional valve-controlled cylinder system based on fuzzy PID control[J]. *Machine Tool & Hydraulics*, 2022, 50(16): 143-149.
- [13] Chen C. Study on supercharging and speed regulation system based on synchronous motor[D]. Central South University, 2022.
- [14] Xu KP, Ding HG. Development of pump-controlled motor electro-hydraulic proportional speed regulation experimental system based on virtual instrument[J]. *Machine Tool & Hydraulics*, 2019, 47(22): 118-121.
- [15] Lou TX, Ding HG, Dong J, et al. Design and simulation analysis of coal mine hydraulic winch electro-hydraulic proportional closed-loop drive system[J]. *Hydraulics and Pneumatics*, 2019, (06): 63-68.
- [16] Guan G, Xing HL, Zhou BL. Fuzzy parameter self-tuning PID control of electro-hydraulic proportional pump-controlled motor system[J]. *Construction Machinery Technology and Management*, 2016, 29(05): 83-87.
- [17] Xu Q. Study on electro-hydraulic proportional pump-controlled motor speed control system based on PID strategy[D]. Chang'an University, 2008.