Application of fuzzy PID controller for valveless hydraulic system driven by PMSM

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Abstract. For the disadvantages of low efficiency, slow speed response and unsteady speed regulation performance in the application of traditional motor drive in valveless hydraulic system, a vector controlled permanent magnet synchronous motor (PMSM) is proposed to replace the conventional motor to drive the quantitative pump in the valveless system, and a mathematical model of the valveless hydraulic system is established. In view of the non-linear and time-varying problems in the control process of the valveless hydraulic system designed, the traditional PID is difficult to solve. So the fuzzy PID position controller based on the system designed is designed. The joint simulation of the hydraulic system is carried out by using AMESim and Matlab software, and the simulation results are compared with the simulation results with traditional PID. The joint simulation results show that the fuzzy PID control method has a good effect on response speed, anti-interference and position tracking accuracy.

1. Introduction

Hydraulic transmission technology is widely used in the industrial field and develops rapidly. Recently, the combination of hydraulic and microelectronics technology has brought its development into a new stage-electro-hydraulic servo technology. The traditional hydraulic servo system has the advantages of fast frequency response, large output power and high tracking accuracy, but its disadvantages are obvious, such as big volume, high consuming of energy, low total efficiency. In addition, its servo valve is sensitive to oil pollution and has complex structure. In the interest of saving energy and improving efficiency, valveless system has gradually been beginning to replace servo valve control system [1]. Compared with the traditional hydraulic system, the valveless hydraulic system also has the features of energy saving, miniaturization of integration, easy operation, economy and environmental protection [2]. In view of the advantages mentioned above, the valveless hydraulic servo system is bound to have good prospects for development.

In valveless hydraulic system, the control of cylinder displacement is to control the cylinder hydraulic oil and response speed to ensure the accuracy and speed of load displacement [3]. Zheng Jianming and others proposes to use the switched reluctance motor to drive the pump to control the valveless hydraulic system [4]. Wang Luyang chooses AC asynchronous motor to drive valveless
electro-hydraulic servo system for low-speed control research, and this paper puts forward permanent magnet synchronous motor as the drive device of the system [5]. Compared with the quantitative pump system driven by the variable frequency asynchronous motor, it has the characteristics of accurate speed regulation, high motor efficiency, fast response and good robustness. Combined with vector control technology, the position control system is designed to reduce the control link of the system. In recent years, many scholars have done a lot of research on the algorithm of hydraulic servo position control system for better control effect. The application of sliding mode control and neural network control greatly reduces the instability of the hydraulic system and speeds up the response speed [6]. Chen Lifu and others have greatly improved the maneuverability and smoothness of the vehicle through fuzzy PID. Based on it, the author chooses fuzzy PID as the control algorithm of the system, and designs the fuzzy control rule which is suitable for the system [7,8]. Then we use AMESim and Simulink to carry out joint simulation in order to verify whether the fuzzy PID can effectively improve the control performance of the valveless hydraulic system.

2. Working principle of valveless hydraulic

The working principle of valveless hydraulic system is illustrated in Fig. 1. The valveless hydraulic system is composed of two-way quantitative pump, hydraulic control one-way valve, motor and cylinder. Permanent magnet synchronous motor (PMSM) is used as power source to drive bidirectional quantitative pump, which adjusts the direction, displacement and pressure of hydraulic cylinder. By changing the speed of permanent magnet synchronous motor to control the pump flow output, thereby adjusting the load displacement. From the working principle of the system, the control of motor speed plays a vital role in the performance of valveless hydraulic system.

![Fig.1 Schematic diagram of valveless hydraulic system](image)

3. Mathematic model of system

3.1. Mathematical model of PMSM module

For convenience of analysis, when the magnetic saturation, space harmonics, iron loss, eddy current and hysteresis loss are neglected, the space magnetic field is sinusoidal. When the rotor of PMSM is cylindrical and the equivalent inductance is symmetrical in d-q coordinate system ($L_d = L_q = L$), if the rotor flux is directional control, the mathematical model of PMSM in d-q coordinate system is:

$$
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} =
\begin{bmatrix}
\frac{R_d}{L} & -\frac{L}{L} \\
-\frac{L}{L} & \frac{R_q}{L}
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
+ \frac{1}{L}
\begin{bmatrix}
0 \\
\frac{1}{L}
\end{bmatrix}
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix}
- \frac{1}{L}
\begin{bmatrix}
0 \\
\frac{1}{L}
\end{bmatrix}
\begin{bmatrix}
\psi_d \\
\psi_q
\end{bmatrix}
$$

$$\omega_t = \frac{E_d - E_q - B_0 \omega_t}{J}$$

$$T_e = \frac{3}{2} P \psi_f \omega_t$$

Where, $U_d$ and $U_q$ are stator-voltage in d-q coordinate system; $i_d$ and $i_q$ are stator-current in d-q coordinate system; $L_d$ and $L_q$ are equivalent inductors of stator in d-q coordinate system; $R$ and $L$ are stator resistance and inductance; $\omega_t$ is angular speed of motor rotor; $\psi_f$ is flux linkage; $T_e$ is electromagnetic torque; $T_L$ is load torque; $P$ is polar logarithm; $B_0$ is viscous friction coefficient; $J$ is moment of inertia.
3.2. Mathematical model of the hydraulic system module

2.3.1. Flow continuity equation

When the piston rod moves forward, because there is a container difference between the rod cavity and the non-rod cavity, the oil recharge is completed by hydraulic check valve. At this time, hydraulic check valve is equivalent to ordinary check valve. The system continuity equation is:

\[ V_P \dot{p}_p + p_D \dot{D}_P \dot{V}_p = n_P \dot{D}_P - \dot{A}_P \dot{P}_H + V \beta \lambda \]

Where, \( n \) is the speed of pump; \( D_P \) is displacement; \( \lambda \) is leakage coefficient of cylinder and pump; \( P_H \) is pressure of high pressure chamber; \( V \) is volume of high pressure chamber; \( \beta \) is effective bulk elastic modulus of oil.

The volume of the rodless cavity:

\[ V = V_0 + A_X \]

Where, \( V_0 \) is the volume of the balance point of the rod less cavity; \( A \) is the effective working area of the rod-free cavity; \( X \) is the displacement of the piston. Then:

\[ \dot{V} = \dot{A}_P \dot{P}_H + \dot{V} \beta \lambda \]

2.3.2. The force equilibrium equation of system

Ignoring the influence of non-linear load, such as static friction on the system, the force balance equation of the valveless hydraulic servo system is as follows:

\[ F = A_P \dot{P}_H + M \ddot{X} + B_S \dot{X} + K_J \dot{X} + F_e \]

Where, \( F \) represents the theoretical output force of hydraulic cylinder; \( M \) is the equivalent mass of the piston; \( B_S \) is viscous damping coefficient of load and piston; \( K_J \) is the elastic stiffness of load; \( F_e \) is the external disturbance force.

Laplace transform (6) and (7) whose the initial value is zero, we can get equations as follow:

\[ \dot{P}_H \dot{X} = \dot{A}_P \dot{P}_H + \dot{A}_P \dot{V}_0 + \dot{A}_P \dot{X} \]

\[ \dot{X} = A_P \dot{P}_H - (K_J + \frac{F_e}{B_S}) \dot{X} + \frac{K_J}{B_S} \dot{X} \]

Then, combining (8) and (9), we can get the equation as follow:

\[ \ddot{X} = \frac{A_P \dot{P}_H - (K_J + \frac{F_e}{B_S}) \dot{X} + \frac{K_J}{B_S} \dot{X}}{\frac{K_J}{B_S} \dot{X}} \]

The system block diagram can be gotten according to equation (8) and equation (9):

![Forward motion block diagram of hydraulic subsystem](image)

4. Design of fuzzy PID controller

Because of the influence of nonlinear and time-varying factors in valveless hydraulic system, the traditional PID controller is difficult to achieve ideal results. In addition, it is difficult for traditional PID controllers to adjust parameters in response to various operating mode. To solve these problems, the adaptive fuzzy PID controller is used to replace the traditional PID controller.

In this paper, a fuzzy PID controller is used to solve the problems of control precision, frequency response and load robustness of valveless hydraulic system driven by PMSM. Its structure is shown in Figure 3. The fuzzy inference module is added to the conventional PID controller to adjust the gain parameters Kp, Ki and KD adaptively based on the error and error changes. The structure of the fuzzy inference module includes two inputs and three outputs, in which the input is the variation of error E.
and error EC, and the output is the gain parameters Kp, Ki and Kd of the PID controller. Fuzzy reasoning module is based on experience knowledge and fuzzy set theory, and the PID parameters are adjusted by nonlinear mapping between input and output.

4.1. Structure of fuzzy PID controller

Fuzzy PID controller adjusts the PID control parameters through the deviation e and the deviation rate of change ec, so as to constantly correct the motor speed, thus obtaining higher position accuracy. The formula of fuzzy PID is as follows:

\[ U = (k_e + \Delta k_e)e + (k_i + \Delta k_i)e \int e dt + (k_d + \Delta k_d)e \frac{de}{dt} \]  \hspace{1cm} (11)

Where, Kp is initial scaling coefficient, Ki is initial integral coefficient, Kd is initial differential coefficient; \( \Delta k_e, \Delta k_i, \Delta k_d \) are parameter setting of proportion, integral and differential; e is position deviation.

![Fig.3 Structure of adaptive fuzzy PID controller](image)

4.2. Determination of linguistic variables and membership functions

This paper sets the fuzzy subsets of the input variables values of e and ec for \{NB, NM, NS, ZO, PS, PM, PB\}; e, ec = {-1, -0.2, -0.1, 0, 0.1, 0.2, 1}; It sets the fuzzy subsets of the input variables values of \( \Delta k_e, \Delta k_i, \Delta k_d \) for \{SS, MS, MM, BM, BB\}; \( \Delta k_e, \Delta k_i, \Delta k_d = \{0, 0.2, 0.4, 0.6, 0.8, 1\} \); The membership function of each input and output are shown in fig 4 and fig 5.

![Fig.4 Membership function of e and ec](image)

![Fig.5 Membership function of Kp, Ki and Kd](image)

4.3. Establishment of fuzzy inference rule

According to the adjustment function of PID parameters to the output of the system, the tuning law of 3 parameters is summed up. \( \Delta k_e \) has the function of reducing system deviation and accelerating system response speed. When the position deviation e is large, it should be large. When e is small, it should be smaller. \( \Delta k_i \) can eliminate the steady-state error of the system and speed up the elimination of the steady-state error of the system. However, excessive \( \Delta k_i \) will lead to system overshoot. \( \Delta k_d \) can predict the direction of deviation and restrain the deviation. Therefore, fuzzy control rules are established, as shown in table 1.
Table 1 Fuzzy control rule table

| e | e | c | c |
|---|---|---|---|
| NB | NB | BB/SS/ | BB/SS/ |
| NM | NM | MM/MM/ | MM/MM/ |
| NS | NS | MS/MM/ | MS/MM/ |
| ZO | ZO | SS/MS/ | SS/MS/ |
| PS | PS | SS/MM/ | SS/MM/ |
| PM | PM | MS/MM | MS/MM |
| PB | PB | MM/MM | MM/MM |
| Kp | Kp | Kp | Kp |
| Ki | Ki | Ki | Ki |
| Kd | Kd | Kd | Kd |

5. Simulation and analysis

5.1. Model establishment
The valveless hydraulic system driven by permanent magnet synchronous motor is modified by an ordinary hydraulic system. According to figure 1, the hydraulic system simulation module is built using AMESim software, as shown in Figure 6. The simulation model is built using Simulink, as shown in figure 7. In figure 7, the main circuit is composed of vector control system and permanent magnet synchronous motor. The stator current, electromagnetic torque, rotor angle and rotor speed are observed using Scope space. Through the joint simulation, the hydraulic load is imported as the load torque of the motor, and the difference between the displacement feedback signal and the set displacement is used as the current reference value of the motor speed regulator output in the direction q to change the motor speed, thereby changing the flow of the pump, and setting the current reference value in the D direction to be zero.

5.2. Co-simulation settings
The s-function interface is set and the AMESim hydraulic model and the simulink control model are
jointly simulated. The simulation type adopts the fixed step, and the solver is ode3, all other properties are default value. Table 2 is the main parameter of the AMESim hydraulic model.

| Parameters                          | Symbols | Values | Units |
|-------------------------------------|---------|--------|-------|
| The length of the stroke            | L       | 500    | mm    |
| Damping ratio of hydraulic system   | Bc      | 50     | N/(m/s) |
| Piston diameter                     | R       | 100    | mm    |
| Rod diameter                        | r       | 20     | mm    |
| Every revolution flow of the pump   | Dp      | $6 \times 10^{-5}$ | m$^3$/rev |
| Leakage coefficient of cylinder and pump | $\lambda_{cp}$ | $7 \times 10^{-11}$ | m$^3$/s Pa |
| Effective bulk elastic modulus of oil | Be     | $7 \times 10^{8}$ | Pa |
| The dead zone volume of port        | V       | 0.05   | L     |
| The mass of the piston and the load | M       | 100    | Kg    |

5.3. Simulation and analysis of step response

The step response simulation results of the position closed loop system by using PID and fuzzy PID control are shown in Fig. 8 for valveless hydraulic system. It can be seen that the step response speed of the closed-loop control system with PID position gradually increases with the increase of KP, Ki and the decrease of Kd, and the steady-state error gradually decreases. However, the phenomenon of over harmonic vibration will be generated, thus extending the adjustment time. Therefore, it is difficult to solve the contradiction between response speed and regulation time using PID control. However, fuzzy PID can be used to optimize the response speed, steady-state accuracy and adjustment time.

![Fig.8. Simulation results of PID and fuzzy PID step response](image)

As shown in Fig. 8, the steady-state error of 0.1mm is achieved within the shortest time (0.76s) using the fuzzy PID controller. In order to study the anti-interference capability of the system, a 350N external interference was added between 2s and 2.5s. The simulation results showed that the response curves of conventional PID and fuzzy PID were stable again after a short period of fluctuation, but the fuzzy PID was faster than the traditional one. Therefore, fuzzy PID is superior to traditional PID in terms of comprehensive response speed and anti-interference ability.

5.4. Simulation and analysis of position tracking response

The simulation results of curve tracking control using traditional PID and fuzzy PID respectively are shown in Fig. 9 and Fig. 10. The tracking target is a sinusoid with a amplitude of 75mm and a frequency of 2Hz.
According to Fig. 9 and Fig. 10, the hydraulic system has a lag between the displacement output and the tracking target using the traditional PID system and the fuzzy PID system. In order to compare the advantages and disadvantages of the two methods, the phase of the tracking target is idealized. The traditional PID should delay 0.09s to reach the best position of the tracking curve, while the fuzzy PID delay only needs 0.05s to reach the best position of the tracking curve. It shows that the fuzzy PID has a good effect in eliminating the time delay of the system.

According to Fig. 11 and Fig. 12, the error amplitude of conventional PID is 20mm, while that of fuzzy PID is 10mm. After the phenomenon of time delay is eliminated, the maximum error of conventional PID is 8 mm, while that of fuzzy PID is only 5 mm. The results show that the fuzzy PID is superior to the traditional PID in curve tracking accuracy and reducing the time-delay phenomenon in hydraulic system.

6. Conclusion
This paper introduces a valveless hydraulic system driven directly by permanent magnet synchronous motor. In combination with the application of vector control technology in the control of permanent magnet synchronous motor, an adaptive fuzzy PID controller is designed and successfully applied to valveless hydraulic system. The fuzzy PID control method and the traditional PID control method are simulated respectively, and the effectiveness of the fuzzy PID control is verified.

The results show that the delay in the hydraulic system has a great influence on the characteristics of the position closed loop control system. Fuzzy PID controller can solve the contradiction between the response frequency and overshoot, improve the control accuracy and the ability to suppress external interference. It also has a good effect on eliminating the tracking delay in the system. In the simulation, the maximum positioning error of 0.1mm and the maximum tracking error of 5mm are achieved. It can be found that the fuzzy PID control method is effective for the valveless hydraulic system driven by permanent magnet synchronous motor.

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