

Design of the Driving and Clamp Rotation Hydraulic Control System for the Heavy Load Forging Manipulator

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Abstract. The manipulator was equipped with full hydraulic drive. We designed the hydraulic systems for the driving and clamping rotation. We used a fuzzy PID control strategy to design the electro-hydraulic proportional control system. We built a united simulation model based on the co-simulation of MATLAB/Simulink and AMESim. A mathematical model of the system was also established. We did separate simulations of the system's dynamic characteristics for fast forging and normal forging working conditions. The parameters were optimized. The field test shows that the steady-state error of the hydraulic system is small and the system response is fast. The system's rapid response speed, high precision, and stability under heavy load were realized.

1 Introduction

The forging manipulator is a complex piece of equipment, because the mechanism, electronic, and hydraulic system designs are integrated. Due to the heavy load, large inertia, and impact, it is difficult to design the transmission system. Therefore, a study on the forging manipulator's hydraulic circuit and control technology has great significance for the development of China's forging manipulator and forging industry 1-6.. To meet the needs of large load, frequent impact load, 20T hydraulic forging manipulator's driving and clamp rotation systems were designed. A theoretical analysis and an experiment were conducted; stable, accurate, and rapid control during the forging operation .was verified through the simulation and the test.

2 Design of the Forging Manipulator's Hydraulic Driving and Clamp Rotation Systems

2.1 Driving System

The driving system is divided into two symmetrical electro-hydraulic proportional control systems. The manipulator walking is driven by 4 hydraulic motors; the control circuit can achieve control of the manipulator position by using 4 groups of a cartridge valve and a proportional directional valve. The proportional directional valve's diameter is 25 mm; its maximum flow is 390 L/min when the pressure drop is 1 MPa. The displace-

ment of the hydraulic motor is 107 mL/r. Due to the manipulator and the forging's large inertia, the accumulator, one-way valve, and relief valve are used to reduce the impact of starting and stopping. The accumulator's charging pressure is 20 MPa, and the capacity is 10 L. The setting pressure of the relief valve is 22 MPa, and the one-way valve's opening pressure is 0.05 MPa. To buffer the forging operation's passive force, the system is equipped with a relief valve and an accumulator. The accumulator absorbs vibration and shock in the manipulator's traveling process, and the relief valve provides an overload protection. A schematic diagram of the manipulator's right hand side is shown in figure 1.

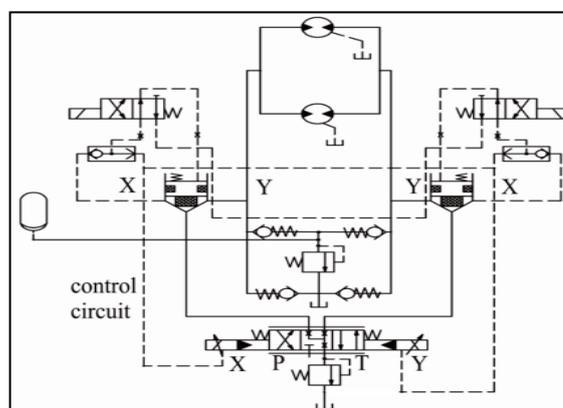


figure 1. Driving hydraulic system schematic

2.2 Clamp Rotation System

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Gripped by the clamp, the forging pieces and the clamp's rotation can be driven by the hydraulic motor. The rotating direction and the speed of the hydraulic motor in the system are controlled by regulating the opening of the electro-hydraulic proportional directional valve. To ensure that the clamp can drive a large load and reduce the hydraulic shock while the motor is breaking the system adopts two groups of parallel drive hydraulic motors; the accumulator and overflow valve are used in combination. The schematic diagram is shown in figure 2. The accumulator's capacity is 4 L and the inflation pressure is 20 MPa. Selection of the other element parameters is the same as with the manipulator's driving system.

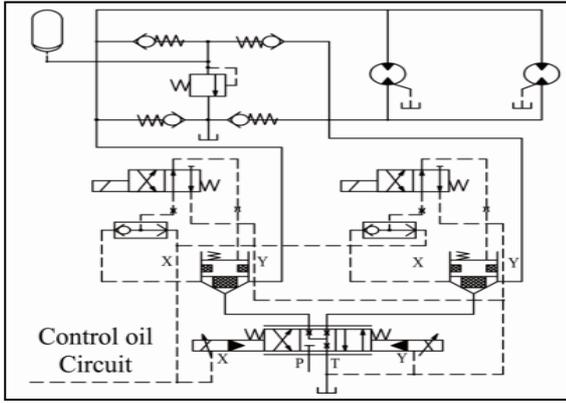


Fig 2 .Clamp rotation hydraulic system schematic

3 Mathematical Model and Control Strategy of the Driving and Clamp Rotation System

The driving and clamp rotation are the two main movements of a forging manipulator; the position controlling accuracy and the reliability of the hydraulic control system are the premises that ensure the normal work of the operation and the quality of forgings. Therefore, we simulate the controlling performance of the system.

3.1 System Modeling

The manipulator driving system and the clamp rotation system are composed of the electro-hydraulic proportional valve, hydraulic motor, and the load. Together they form the hydraulic servo system. The dynamic characteristics of the hydraulic components (namely the valve controlled hydraulic motor) determine the performance of the whole system. Therefore obtaining the mathematical model of the valve controlled hydraulic motor is the premise for an analysis of the whole drive system.

To get the mathematical model of the hydraulic power components, we start with the flow equations of the electro-hydraulic proportional valve and the continuous flow equations of the hydraulic motor. Also, the torque balance equation between the hydraulic motor and the load is established. After the Laplace transform is given, the results are shown as follows:

$$Q_L = K_q X_V - K_c p_L \quad (1)$$

$$Q_L = D_m s \theta_m + C_m p_L + V_t s p_L / (4\beta_e) \quad (2)$$

$$p_L D_m = J_t s^2 \theta_m + B_m s \theta_m + G \theta_m + T_L \quad (3)$$

where K_q is the flow gain coefficient of the proportional valve, K_c is the flow-pressure coefficient of the proportional valve, p_L is the load pressure drop, Q_L is the load-flow, X_V is the spool displacement of the proportional valve, D_m is the displacement of the hydraulic motor, θ_m is the rotation angle of the hydraulic motor, T_L is the load torque acting on the motor shaft, B_m is the viscous damping coefficient of the hydraulic motor and the load, G is the torsion spring stiffness of the load, J_t is the total inertia of the hydraulic motor shaft, V_t is the total volume of the hydraulic motor's cavities and the connecting pipes, e is the effective elastic modulus of the hydraulic oil, C_m is the leakage coefficient of the hydraulic motor.

The spool displacement and external load are acting on the motor at the same time. The motor's angular displacement expression is deduced as follows:

$$\theta_m = \frac{\frac{K_q}{D_m} X_V - \frac{1}{D_m^2} \left(K_c + C_m + \frac{V_m}{4\beta_e} s \right) T_L}{\frac{V_t J_t}{4\beta_e D_m^2} s^3 + \left(\frac{J_t K_{ce}}{D_m^2} + \frac{B_m V_t}{4\beta_e D_m^2} \right) s^2 + \left(1 + \frac{B_m K_{ce}}{D_m^2} + \frac{G V_t}{4\beta_e D_m^2} \right) s + \frac{G K_{ce}}{D_m^2}} \quad (4)$$

where the K_{ce} is the total flow-pressure coefficient of the proportional valve.

In this valve controlled motor system the motor and load are rigidly connected through the final gear, so the elastic load could be neglected, that is $G=0$. Since , the expression can be simplified, and the transfer function of the spool displacement corresponding to the hydraulic motor shaft's angle is given as follows:

$$\frac{\theta_m}{X_V} = \frac{\frac{K_q}{D_m}}{s \left(\frac{s^2}{\omega_h^2} + \frac{2\xi_h}{\omega_h} s + 1 \right)} \quad (5)$$

where

$$\omega_h = \sqrt{\frac{4\beta_e D_m^2}{V_t J_t}} \quad (6)$$

$$\xi_h = \frac{K_{ce}}{D_m} \sqrt{\frac{\beta_e J_t}{V_t}} \quad (7)$$

3.2 Control strategy

The accurate and stable position of the manipulator driving and clamp rotation directly influence the efficiency of the forging and the quality of the workpiece, so it is necessary to adopt an appropriate control method. The traditional PID control algorithm used in engineering is simple and has a strong real-time performance, but the PID parameter setting cannot achieve an online adjustment in real-time. It is often used in linear systems. The driving system and the clamp rotation system of the manipulator have the characteristics of a time-varying, strongly nonlinear, and interfering large load. So a fuzzy PID control strategy combined with fuzzy logic and PID control is used, which achieves the online adjustment of the nonlinear control parameters. This algorithm has strong real-time control and is robust. Furthermore, it is easy to implement and is able to meet the system requirements in the theory⁷⁻⁹.

The fuzzy controller included the error ‘e’ and error changing rate ‘ė’ of cart walking displacement (or clamp rotation angle), and the incremental PID coefficients of ΔK_p , ΔK_i and ΔK_d . In the PID controller, the rules for change of the three parameters can be written as follows:

$$K_p = K_{p0} + \Delta K_p; \quad (8)$$

$$K_i = K_{i0} + \Delta K_i; \quad (9)$$

$$K_d = K_{d0} + \Delta K_d; \quad (10)$$

where K_{p0} , K_{i0} , K_{d0} are three initial parameters of the PID controller and K_p , K_i , K_d are output parameters of the PID controller. Define the fuzzy set range of the e and ė as $\{-1,1\}$, the ΔK_p , ΔK_i , ΔK_d is also defined as $\{-1,1\}$.

3.3 Model building

The clamp rotation control system simulation model is built by using the hydraulic element module in the A-MESim components library¹⁰. We establish the simulation model of the fuzzy PID control algorithm based on the MATLAB / Simulink. The simulation of the manipulator driving system and the clamp rotation control system are combined with the motion control algorithm simulation through co-simulation technology, and thus the actual working condition of the mechanism is simulated. The joint simulation system model is shown in Figure 3, and the principal parameters of the simulation are shown in Table 1.

Tab.1 The main parameters of the simulation

Parameter	Value	Unit
Load m1	20	T
Manipulator mass m2	120	T
System pressure p	10	MPa
System flow Q	556	L·min ⁻¹
Motor displacement V	107	mL·r ⁻¹
Gear ratio I	4.6	
Diameter of the chain wheel D	0.656	m

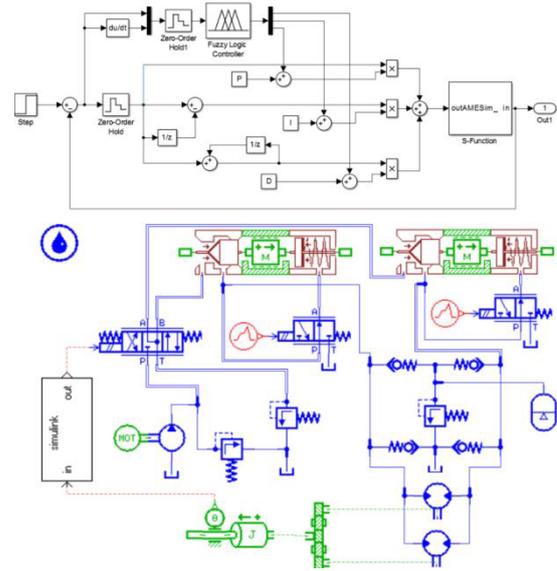


Fig. 3 Combined simulation model

4 Simulation and test

Based on the manipulator’s hydraulic control principle above, a 20T forging manipulator was made by Anyang Forging Machinery Industry Co. Ltd. It is shown in Figure 4. Since the forging manipulator, forgings, and forging press are costly, the correctness of the simulation results and the reliability of the hydraulic system should be verified through tests.



Fig. 4 The 20T forging manipulator

4.1 Simulation and test of the manipulator driving

According to the design requirements, the manipulator driving error is ± 10 mm. The simulation studies were completed so that the manipulator axial feed was 0.06 m and 0.12 m in fast forging conditions. In normal forging conditions there is a 0.1-m feed in axial direction. Japan’s Koyo rotary encoder is adopted for the test. When the displacement input is given to the system, the displacements at the different sampling time are obtained through the test. The test curve is drawn using the point method. Under the control of the two kinds of PID, the test

dynamic characteristics and the test results of the system of manipulator driving are shown in Figure 5.

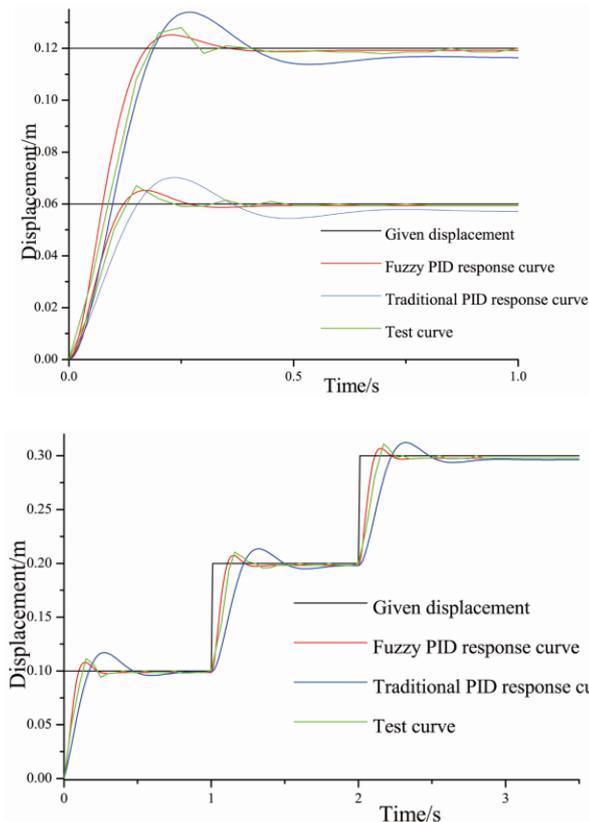


Fig. 5 Simulation and trial curve of driving system in fast and normal forging

As can be seen from the simulation curves of the two control strategies in Fig. 10, when the fuzzy PID control is used, the stability of manipulator driving system obviously improves and satisfies the requirement that the steady-state error is ± 10 mm. In different working conditions the system can reach the steady state in about 0.6 s, and the work cycle of the forging press is 1 s. Thus the manipulator can realize the linkage with the forging press. The test results are consistent with the simulation results, and therefore verify the accuracy of the design and simulation models.

4.2 simulation and test of the clamp rotation

The design requirement of the maximum clamp rotation speed is 18 r/min and the rotation accuracy is $\pm 1^\circ$. The test method and experimental process are similar to the manipulator driving system's experiment. When the rotation angle is set to 15° , 30° , and 60° , the fuzzy and traditional PID are given for each rotation angle separately. The dynamic characteristic curve and the test results of the clamp rotation system are shown in Figure 6.

As can be seen from the simulation curves of the two control strategies in Fig. 12, the clamp system's dynamic performance and steady-state accuracy is improved by using fuzzy PID control.

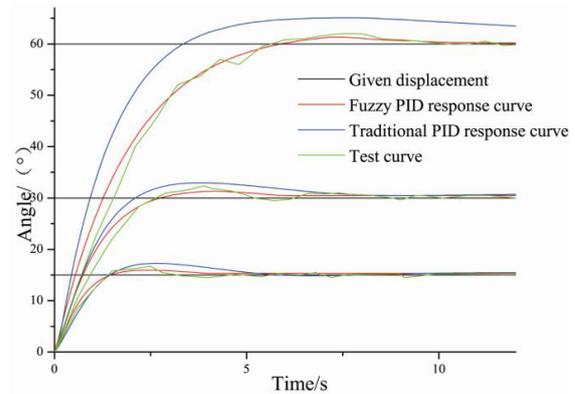


Fig. 6 Simulation and trial curve of clamp rotation system

And the system's overshoot and the deviation are relatively large when the traditional PID control is used, moreover, the system steady-state error would grow with the increasing input angle. As a result of that, the number of recycled forgings increased, and also the forging cycle extended. The test results and the simulation results are almost the same, thus verifying the accuracy of the system design and physical models.

5 Discussion and conclusions

(1) According to the technical requirements, we designed driving and clamp rotation hydraulic control system for the forging manipulator and established the mathematical and simulation model of the manipulator driving and clamp rotating mechanism.

(2) The fuzzy PID control algorithm was used in the control system. Based on the MATLAB / Simulink joint simulation technology, the simulations of the system were combined with the motion control algorithm simulation. And the actual working condition of the mechanism was simulated. The simulation results showed that the clamp rotation and the manipulator walking's accuracy improved, and the robustness and adaptability of the system appeared to improve as well. Linkage with the forging press was implemented, and the production efficiency was improved. However the energy consumption of the system was reduced.

(3) Through product testing, we verified the correctness of the design scheme and the simulation model, and the stability, accuracy and rapid control of the forging manipulator is realized.

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