Simulation Research on Cutterhead Hydraulic Drive System of Shield Machine

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Abstract. The core of the cutter head drive system of shield machine is the hydraulic system. Combined with a certain type of shield machine, the structure and working principle of 1.8 m hydraulic driving system for cutterhead of shield machine are studied, and the closed loop control mode of variable pump variable motor is adopted to design the 1.8 m hydraulic driving system for cutterhead of shield machine, the simulation model of the cutter head drive system is established in the hydraulic simulation environment, and the parameters of the sub-model are designed according to the actual situation.

1. Introduction
The shield machine is a technology-intensive super large engineering equipment that integrates mechanical, electrical, hydraulic, measurement, control and other multi-disciplinary technologies and is dedicated to the excavation of underground tunnels. With its high-efficiency, fast and safe characteristics, shield tunneling machines have a wide range of applications in the field of tunnels all over the world. The hydraulic drive system is the power source of the cutter head of the shield machine, which drives the cutter head to rotate and provides cutting force for the tunnel excavation of the shield machine [1].

During the tunneling process of the shield cutter head, although the working speed is not high, the geological structure is complicated and the cutter head has a large working diameter. Therefore, the cutter head drive system is required to have: high power, large torque output, impact resistance, two-way continuous adjustable speed, reduced installed power, energy saving and consumption reduction under the premise of meeting the requirements of use [2]-[4]. The drive system of the cutter head must have high reliability and good operating performance, and the use of a global power adaptive pump-controlled motor system can greatly reduce the overflow loss and throttling loss during the loop process, and the heat dissipation effect is also good [5]-[ 6].

2. The principle of shield cutter head hydraulic drive system
The hydraulic drive system of the cutter head uses a variable pump and two fixed motors to form a closed control loop to drive the cutter head to rotate. The hydraulic system adopts a proximity switch to detect the speed of the cutter head in real time, control the displacement of the variable cylinder according to a suitable strategy, and then control the displacement of the variable pump, forming a continuous and real-time controllable cutter head drive hydraulic control system according to load conditions. The complex working conditions in tunnelling, the system has good energy-saving effect.
The whole system can realize two working conditions, namely, low speed and large torque in soft rock conditions and high speed and small torque in hard rock conditions. The conversion of the two conditions can be achieved by controlling the electromagnetic directional valve. When the electromagnet is powered off, the overflow valve determines the maximum pressure of the system. At this time, the system pressure is set to 10MPa, the output torque is small, but the flow rate is large (the maximum is 300 L/min), and the output speed is high; when the electromagnet is energized at this time, the overflow valve determines the maximum pressure of the system. At this time, the system pressure is set to 25MPa, the output torque is large, but the flow is small, and the output speed is low.

During the entire tunnelling process, the cutter head speed is continuously adjustable in real time, and the speed can be adjusted by adjusting the displacement of the variable pump. The pressure sensor measures the oil inlet pressure of the hydraulic motor, and the signal of the pressure signal can be fed back to the proportional valve of the main pump in real time to form a speed closed-loop control system.

The forward and reverse rotation of the hydraulic motor can be controlled by the electro-hydraulic directional valve. The electromagnet B1 is energized, the motor rotates forward, the electromagnet B2 is energized, and the motor reverses. It can be seen that the output power of the system is always compatible with the power required by the load. When the system pressure exceeds the pressure set by the safety valve, after the pilot safety valve is turned on, the main spool of the cartridge valve opens and the system overflows.

The pressure line filter is equipped with a differential pressure signalling device. When the filter element is contaminated and the oil inlet and outlet pressure difference is 0.35MPa, an alarm (switch) signal will be issued. At this time, the filter element should be replaced in time. When a person comes to replace the filter element, the bypass valve located in the filter cover will automatically open to achieve the purpose of protecting the safety of the system.

The schematic diagram of the shield cutter head hydraulic drive system is shown in Figure 1.

![Figure 1. Schematic diagram of the shield cutter head hydraulic drive system](image-url)
3. Establishment of simulation model of shield driving hydraulic system of cutter head

The simulation model established according to the hydraulic control schematic diagram is shown in Figure 2. Figure 2 is a simulation model created on a hydraulic simulation platform based on the simplified schematic diagram of the cutter head drive hydraulic pressure of the shield machine shown in Figure 1.

Figure 2. Constant power variable piston pump control variable hydraulic motor hydraulic schematic diagram model

3.1. Simulation parameter table

The main model parameter table of the system is shown in Table 1.

| Element          | Simulation parameters | Value   |
|------------------|-----------------------|---------|
| Motor            | Rotating speed        | r/min   | 1500    |
| Hydraulic pump   | Displacement          | ml/min  | 260     |
| Relief valve     | Pressure              | MPa     | 31.5    |
| Relief valve     | Flow pressure gradient| L/min/bar| 180    |
| Hydraulic motor  | Displacement          | ml/r    | 45.6    |
| Cutter           | Moment of inertia     | kg\cdot m^2 | 256000 |
| Cutter           | Maximum static friction torque | N\cdot m | 3000000 |
| Cutter           | Coulomb friction torque | N\cdot m | 10000  |
| Cutter           | Coefficient of Viscous Friction | N\cdot m/(r/min) | 10000  |
| Reducer          | Reduction ratio       |         | 80.4    |
4. Simulation Analysis of Cutterhead in Low Speed and High Torque Gear

From the simulation curve shown in Figure 3, it can be seen that the hydraulic motor reaches a stable working pressure of 243 bar within 0.5s. The theoretical calculation result shows that the output pressure of the hydraulic motor when the output torque is 154.3 N\(\cdot\)m is 240 bar, which is 3 bar more than the calculation result. The error is 0.5\%, which is less than 1\%, so the error can be ignored.

Figure 3. Hydraulic motor output pressure simulation curve

From the simulation curve shown in Figure 4, it can be seen that the hydraulic motor reaches a stable working pressure of 243 bar within 0.5s. At this time, the rotational speed of the hydraulic motor is 715 \(\text{r/min}\), which is consistent with the theoretical calculation.

Figure 4. Hydraulic motor output speed simulation curve

From the simulation curve shown in Figure 5, it can be seen that the hydraulic motor reaches a stable working pressure of 243 bar within 0.5s. At this time, the rotational speed of the hydraulic motor is 715 \(\text{r/min}\), which is consistent with the theoretical calculation.

Figure 5. Simulation curve of hydraulic motor output torque
From the simulation curve shown in Figure 5, it can be seen that the hydraulic motor reaches a stable output torque of 175Nꞏm in about 0.5s. At this time, the output pressure of the hydraulic motor is stable at 243bar, and the hydraulic motor speed is at 715r/min. At this time, the shield sweeping speed is 1.5r/min, which meets the simulation requirements of hydraulic motors. Therefore, the hydraulic motor meets the requirements of the hydraulic system.

In the same way, the simulation curve of the hydraulic pump is analysed. The stable pressure of the variable plunger pump is 241bar. The stable flow of the variable plunger pump is 390L/min, and the rated speed of the variable plunger pump is 1500r/min the output torque of the variable plunger pump is 1000.1Nꞏm. The simulation results fully satisfy the shield The drive requirements of the machine cutter head. Therefore, the hydraulic motor meets the requirements of the hydraulic system.

When the load torque is 38.141kNꞏm, 76.283kNꞏm, 117kNꞏm, the pressure of the system corresponds to 76.5bar, 153bar, and 243bar. When the motor is at low speed and high torque, the higher the load torque, the higher the system pressure.

During the shield construction process, due to the different underground geological conditions, the working conditions of the cutter head are complex, and the load on the cutter head often fluctuates irregularly. In order to study the impact of this working characteristic of the cutter head load on the entire hydraulic system, it is necessary to The system pressure, flow rate and cutter speed are simulated and analyse when the load fluctuates. Now give the variable pump a speed control signal to make the variable pump work at the maximum displacement. The load signal is changed from a linear signal to a random signal. The simulation results of the pressure of the hydraulic system and the speed of the cutter head are shown in the figure below.
When the random signal fluctuates, the pump is always at the maximum displacement, the output flow of a single pump remains unchanged, and the system pressure will change with the change of the load. At this time, the cutter head speed will also fluctuate slightly. It can be seen from Figure 7 that the system pressure fluctuates up and down 130bar.

5. Conclusion
With the continuous expansion of the application scope of shield machine technology in the field of underground space in my country and the complication of construction conditions. The cutter head drive hydraulic system is used as the key control system of the shield. Whether the actual situation can meet the expected requirements has a more direct impact on the quality of shield construction. This paper analyses the complex working conditions of shield construction, and completes the design of the drive hydraulic system for the cutterhead of the 1.8m simulated shield machine. The simulation analysis of the cutterhead hydraulic drive system for the 1.8m simulated shield machine is carried out by hydraulic simulation software. Meet the construction requirements of shield machine.

References
[1] Hu, S. L., Qiao, S. S. (1999) Introduction to shield machine[J]. Construction Machinery.
[2] Cui, G.H., Wang, G. Q., He, E. G., et al. (2006) Research status and development prospects of shield machine[J]. Mining Machinery., 06: 24-27.
[3] Xie, Q., Yang, J. Q., Gao, W. X. (2009) Design of the hydraulic system of the cutter head drive of the shield machine[J]. Hydraulics and Pneumatics. 000,004: 74-76.
[4] Zhang, J. Y. (2015) Design and Exploration of Cutterhead. Drive Hydraulic System of Shield Machine[J]. Technological Innovation and Application, 32: 137-137.
[5] Jiang, R. Q. (2015) Design and simulation analysis of cutter head drive hydraulic system of shield machine[D].
[6] Shen, X. F. (2013) Analysis of Cutterhead. Drive Hydraulic System of Herrenknecht S673 Shield Machine[J]. Architectural Knowledge: Academic Journal, 000,012: 427-427.