Analysis of Synchronous Loop of Hydraulic Multi-cylinder Load of 60 MN Super Large Tonnage Compression shear tester

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Abstract. In order to meet the mechanical properties testing requirements of super large tonnage bridge bearings, the 60 MN super large tonnage compression shear test equipment is specially developed. This article systematically carries out load analysis and machine working principle analysis, designs a four-cylinder synchronous control schematic diagram, adopts “master-slave control” position closed-loop feedback, adds force closed-loop feedback to improve system pressure stability, and uses AMESim simulation software to model and simulate actual operating conditions. Optimized control by using PID, the system obtains better displacement accuracy.

1. Introduction

The compression and shear tester machine is used for mechanical properties testing of bridge rubber bearings. In order to meet the detection needs of large tonnage bridge bearings, the 60 MN tonnage compression shear tester is designed. In this super large tonnage machine, four-cylinder synchronous loading is used at the first time. The hydraulic cylinder movement, which is due to factors such as manufacturing errors, pressure loss, and leakage of hydraulic components, is not synchronized [1]. In recent years, many scholars have immersed themselves research on synchronization control and achieved good results. Yuan Zheng [2] uses PLC control program to control the proportional flow control valve synchronization loop to improve the synchronization accuracy of the system and has good real-time performance. Ailing Liu [3] bases on the fuzzy control theory to establish the symmetric double-cylinder fuzzy feed forward controller to verify the feasibility of fuzzy control theory in synchronous control system, but there are still large errors.

This article uses PID to optimize the “master-slave control” [4], and AMESim software to perform modeling and simulating calculation to improve the synchronization position accuracy of the system. At the same time, the upper oil tank + filling valve is used to fill fluid to the hydraulic cylinder when it is falling with no load, the circuit is connected in series with the balance valve to achieve smooth and fast movement. To avoid large hydraulic shock during the return stroke of the hydraulic cylinder, the unloading valve unloads before the stroke returning to ensure the smooth operation of the machine.
2. Load analysis
The bridge rubber bearing is a flexible connection between the bridge pier and deck. While bearing the weight of bridge, the bearing must bear the usual vibration and load. Therefore, the bridge bearings must have sufficient vertical stiffness to withstand vertical load, and the pressure on the upper bridge surface must be reliably transmitted to the pier [5]. In the bearing analysis, the bridge bearing is simplified as a spring-damping model, which is shown in Figure 1.

Balance equation of output force and load of hydraulic cylinder.

\[ p_1 A_h - p_2 A_t = m_t \frac{d^2 x_p}{dt^2} + B_p \frac{dx_p}{dt} + Kx_p + F_L \]  

In the formula: \( m_t \) - the total mass of the piston and the load converted to the piston, Kg; \( K \) - the load spring stiffness, N/m; \( F_L \) - any external load force acting on the piston, N; \( B_p \) - Damping coefficient.

![Figure 1. Loading model](image)

3. Working principle of 60 MN compression shear tester machine
The device is a super large tonnage static loading device. The vertical actuator uses 4 large hydraulic cylinders, which are symmetrically distributed at four corners and driven synchronously. In order to make the loading system run smoothly and achieve higher accuracy requirements, an electro-hydraulic proportional position closed-loop control system is used. As shown in Figure 2, the movement of the machine is divided into five stages: idling down, loading, holding pressure, unloading and idling up.

![Figure 2. Step by step loading diagram](image)

In the working principle diagram of the compression shear tester in Figure 3, because of too large load, which the foundation can’t support, the reflexive framework turns up. The output force of the actuator acts between in reflexive framework to avoid damage to the foundation. According to JB / T 11528-2013, the vertical force holding time should not be less than 2 minutes, and the allowable value
variation of the force is ±2% of the maximum force [6]. That the sensor detects the change of the actuator output force in real time forms closed-loop control to achieve a stable output of the force.

Figure 3. Schematic diagram of vertical loading equipment for 60 MN compression shear tester machine

4. Four-cylinder synchronous hydraulic sub-circuit principle
The schematic diagram of electro-hydraulic proportional closed-loop control system of four-cylinder synchronous is shown in Figure 4.

Figure 4. Schematic diagram of electro-hydraulic proportional closed-loop control system

The system adopts “master-slave control” comparative feedback for synchronous movement. The leftmost hydraulic cylinder is set as the reference hydraulic cylinder. The displacement sensors detect the displacement of remaining three hydraulic cylinders and compare them with the displacement of
the reference cylinder. The difference is processed and passed to electro-hydraulic proportional directional valve after being processed by the PID controller and the opening flow of the proportional directional valve is changed. Thereby, the displacement of remaining three hydraulic cylinders is as consistent as possible with the reference cylinder to achieve synchronous control [7]. The working conditions of the electro-hydraulic proportional directional valves in the hydraulic system are shown in Tab 1. “+” indicates that the electromagnet is on, and “−” indicates that the electromagnet is off.

| Table 1. Electromagnet working condition |
|-----------------------------------------|
| Working state                           | Electromagnet |
|                                        | 1YA | 2YA | 3YA | 4YA | 5YA | 6YA | 7YA | 8YA |
| Idling down                             | +   | -   | +   | -   | +   | -   | +   | -   |
| Loading                                 | -   | +   | -   | +   | -   | +   | -   | -   |
| Holding pressure                        | -   | -   | -   | -   | -   | -   | -   | -   |
| Hydraulic cylinder unloading            | -   | -   | -   | -   | -   | -   | -   | -   |
| Idling up                               | -   | -   | -   | +   | -   | +   | -   | +   |

Sub-loop working principle details.
1) During the idling down period, the electromagnets 1YA, 3YA, 5YA and 7YA are turned on, and the rest of the electromagnets are turned off. The piston of the hydraulic cylinder descends by its own weight and the weight of the load. The top-mounted tank fills the rodless cavity of the hydraulic cylinder through the filling valve. The descending speed is controlled by the speed control valve on the reference oil return path, and the rest hydraulic cylinders track the displacement of the reference cylinder to realize the synchronous output.
2) During the loading period, the electromagnets 1YA, 3YA, 5YA and 7YA are turned on, and the rest of the electromagnets are turned off. The hydraulic oil enters the rodless cavity of the hydraulic cylinder through the electro-hydraulic proportional directional valve. The force sensor detects the changes of output force in real time.
3) In the holding pressure phase, when the hydraulic cylinder rodless cavity pressure drops due to leakage of hydraulic cylinder or the support of plastic deformation. An electrical signal is issued when the force sensor detects a change to a certain threshold valve, and the electro-hydraulic proportional directional valve operates again to pressurize hydraulic cylinder.
4) After the experiment is completed, the pressure of the rodless cavity should be released to a safe range, otherwise there is excessive hydraulic shock when proportional valve is reversed.
5) During the idling up period, the electromagnets 2YA, 4YA, 6YA and 8YA are turned on, and the rest of the electromagnets are turned off. The hydraulic oil, which passes through the electro-hydraulic proportional valve and balancing valve, enters the rod cavity of hydraulic cylinder. The hydraulic cylinder piston rises, and the remaining three hydraulic cylinders track the displacement of the reference cylinder to achieve synchronous retraction.

5. Four-cylinder synchronous hydraulic sub-circuit simulation analysis
The simulation model, built with AMESim software, is shown in Figure 5. The filling valve is modelled with HCD library, and the remaining hydraulic components are modelled with the hydraulic library. With the relatively simple synchronous control method, the displacement deviation will be very large, and the PID control is introduced in this system. The left to right hydraulic cylinders are
defined as 1#, 2#, 3# and 4#, the 1# hydraulic is defined as the reference cylinder. Parameters of synchronous system loading are shown in Table 2.

**Figure 5. System AMESim simulation model**

**Table 2. Hydraulic system simulation parameters**

| Module name                          | Value   | unit |
|--------------------------------------|---------|------|
| Hydraulic resource $Q$               | 110     | L/min|
| Rated pressure of hydraulic source $p$| 28      | MPa  |
| Proportion P                         | 25      |      |
| Integration I                        | 0.1     |      |
| Differentiation D                    | 0       |      |
| Gain $K$                             | 13333   |      |
| Hydraulic cylinder diameter $D$      | 900     | mm   |
| Load quality $m_t$                   | 4*50000 | Kg   |
| Rated flow of proportional valve $q_n$| 43      | L/min|

The distance from the origin of the actuator to the surface of the workpiece (idling down) is 100 mm, which makes it easy to place workpiece. Rated pressure of hydraulic source is 28 MPa. Installing force sensor and using the gap function establish force closed-loop control to form a pressure-holding circuit. The simulation step is 0.01s and the simulation time is 500s. The displacement results of the hydraulic cylinder are shown in Figure 6.

**Figure 6. Hydraulic cylinder displacement**
In the Figure 6, it takes about 56s to complete the filling liquid for hydraulic cylinder, and the largest deviation occurred after 403s. The main reason is the sudden start of the hydraulic cylinder. Meanwhile, there are factors such as uneven load, different pipeline lengths and manufacturing errors of the hydraulic components. The 1 # hydraulic cylinder is defined as the reference cylinder, the displacement is $s_1$, and the remaining 2 #, 3 #, and 4 # hydraulic cylinders track the reference hydraulic cylinder. The synchronous displacement deviation is $\text{error} = s_1 - s_i (i=2,3,4)$, which is shown in Figure 7.

![Figure 7. Hydraulic cylinder synchronization circuit deviation](image)

It can be seen from the Figure 7, there are some minor fluctuation during the holding pressure and idling down stage. The obvious error occurs after 402s (the piston rod starts to leave the workpiece in idling up period). Hydraulic shock caused by sudden start of hydraulic cylinder and pressure difference between two chambers of hydraulic cylinder. Meanwhile, the 4# cylinder, which is the farthest from the hydraulic resource to cause maximum pressure loss, produces the largest displacement error 1.5 mm. However, the system can quickly adjust to a stable state after error occurs.

6. Conclusion
In the above study, the loading system adopts 4-cylinder synchronous loading and the closed-loop feedback of the force forms a pressure-holding circuit, which ensures the pressure stability. Using PID control to get good system adjustment response characteristics. During the idling down phase, the flow rate of each filling valve reaches 73 L/min, which achieves the purpose of energy saving.

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