Dynamic Simulation and Experimental Study of Hydraulic Shift System for Deep Hybrid Transmission

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Abstract. The hydraulic shift system of a deep hybrid transmission in a certain model was simulated and tested. First, the basic configuration of the gearbox was introduced. Then, the working principle of the hydraulic source, main oil circuit control system, shifting and parking control system, cooling lubrication system and shifting execution system were explained according to the schematic diagram of the hydraulic shifting system. The dynamic simulation model of hydraulic shift system was established via AMESim. Based on the comparison between the experimental data and the simulation results, the correctness of the model was verified. The dynamic characteristics of the main oil circuit and the shifting element were simulated. The results show that the hydraulic shift system meets the design requirements. The bench test results of powertrain verified the correctness and rationality of the hydraulic shifting system.

1. Introduction

The internal combustion engine is used as the only driving source of the traditional automobile gearbox, while the hybrid electric vehicle special gearbox is driven by the combination of internal combustion engine and motor. The use of motor can not only optimize the working state of the engine and improve the working efficiency, but also convert part of the energy into electric energy to realize braking energy regeneration. The hydraulic system is important for the motor cooling and lubrication of hybrid power gearbox. At the same time, because it contains a complex shift element system, it is necessary to realize the function of clutch and brake through a specific oil circuit. Therefore, for the shift system of deep hybrid power gearbox, it is essential to develop a multifunctional hydraulic scheme integrating cooling lubrication and high pressure braking. Bravo R R S \cite{1} set up a hydraulic hybrid power system to realize the function of combining high efficiency and high energy regeneration braking. Han Bing \cite{2} et al studied the hydraulic system design method of power shunt deep hybrid gearbox, and analyzed the dynamic characteristics of hydraulic system by simulation, and optimized the design of hydraulic system combined with experimental analysis. Compared with the development of hydraulic system technology of hybrid gearbox in foreign countries, the research in this field in our country is still in a backward state, on account of a lack of the development of hydraulic system integration scheme and related technology \cite{3}. In this paper, the hydraulic shift system of a deep hybrid power gearbox is taken as the object. The configuration of the gearbox and the working principle of the hydraulic shift system are introduced, and the simulation analysis and experimental research of the hydraulic shift system are carried out.
2. Hybrid gearbox configuration

Fig. 1 shows the schematic diagram of a hybrid gearbox configuration, which integrates the motor with large motor E2 and small motor E1, planet row PGS1 and PGS2, clutch C0 and C1, and brakes B1 and B2. The system can realize the various modes of pure electric power, hybrid drive and idle power generation, which can recover most of the braking energy, and improve the power and fuel economy of the gearbox. In the working process of the motor, the power consumption will lead to the temperature rise, which needs cooling treatment. The power shunt system adopts double planet arrangement mechanism, which also needs enough lubrication flow at work. This system contains complex shift elements and it is need to design a high pressure oil circuit for providing closed pressure. Therefore, the transmission hydraulic system shall have both cooling and high pressure braking functions.

![Fig 1. Schematic diagram of hybrid gearbox configuration](image)

3. The principle of hydraulic shift system

The schematic diagram of hydraulic shift system is shown in figure 2, which includes hydraulic source and main oil circuit control system, shift and parking control system, cooling lubrication system and shift execution system. This main oil circuit control system can realize the real-time adjustment of the pressure in the main oil circuit, and avoid the hydraulic system from working in the state of high oil pressure all the time, and can reduce the leakage and power consumption of the hydraulic system. Cooling lubrication system mainly lubricates the large and small motors, planet gears and bearings.

![Fig 2. Schematic diagram of the hydraulic shift system](image)

3.1. Shift control system

The schematic diagram and characteristic curve of shift solenoid valve are shown in Fig. 3. When the shift element needs to be closed, the controller will give the corresponding current signal to cause the
solenoid valve to form the corresponding driving force, and then the force promote the movement of the valve core. At this time, the high pressure oil flows through the electromagnetic directional valve to the shift element and drives the shift element to close [4].

Fig 3. C0/C1/B2 solenoid reversing valve

3.2. Shift execution system
The research objects of this paper include C0 clutch, C1 clutch, B1 brake and B2 brake. Table 1 shows the locking state of shift elements in different working modes. B1 brake can lock the planet frame by hydraulic drive. B2 brake can lock the small motor E1. C0 clutch connects the engine to the planet row. C1 clutch connects the engine to the large motor E2. Different working states of clutch and brake can form a variety of pure electric and hybrid driving modes, and different driving modes can be selected in different road conditions, which reduces the power loss and improves the economy and power performance and ride comfort of the whole vehicle [5].

Table 1. Locking status of shift elements in different working modes

| Working mode | B1 | B2 | C0 | C1 |
|--------------|----|----|----|----|
| EV-1         | ●  | ○  | ○  | ○  |
| EV-2         | ○  | ●  | ○  | ○  |
| EV-3         | ○  | ○  | ○  | ○  |
| HEV-1        | ●  | ○  | ○  | ●  |
| HEV-2        | ○  | ●  | ○  | ●  |
| HEV-3        | ○  | ●  | ●  | ○  |
| HEV-4        | ○  | ○  | ●  | ●  |
| HEV-5        | ○  | ○  | ●  | ○  |
| EV-1RD       | ●  | ○  | ○  | ○  |

4. Simulation of hydraulic shift system

4.1. Simulation model
Compared with bench test and vehicle test, simulation analysis can not only shorten the cycle of research and development, but also reduce the cost of research and development [6]. In this paper, the simulation model of hydraulic shift system is established based on AMESim software as shown in Fig. 5, in which all the components are packaged by supercomponents, and the actual situation of oil circuit is fully taken into account. The simulation model of shift actuator is shown in Fig. 4, and the actual leakage factor is not taken into account in the model. The main parameters of the shift element are shown in Table 2.
4.2. Verification of Simulation Model

In order to verify the correctness of the simulation model of hydraulic shift system, the simulated pressure curve of the main oil road is compared with the pressure curve of the test. The powertrain test bench is shown in Fig. 6. The basic principle is as follows: the driving equipment is connected at the spindle input end to simulate the engine speed and two load motors are separately connected at the gearbox outputs, and the load motor simulates the wheel speed in the speed control mode. Under specific working conditions, the computer transmits the shift signal to the controller, then the controller responds to the signal and gives instructions, and at the same time the sensor passes the main oil pressure signal to the computer by the controller.

It’s shown in Fig. 7 that the control current of solenoid valve in HEV-5 and EV-2 shift test. In the simulation, the control current is used as the simulation input, and the speed of the oil pump is set to 1200 rev/min, and the simulation time is 11 s, and the step size is 0.005 s. The pilot solenoid valve is an inverse proportional solenoid valve, so the output pilot pressure decreases when the pilot current increases in Fig. 7, so the main oil circuit pressure decreases in Fig. 8 accordingly. In Fig. 8, the simulation pressure of the main oil circuit is slightly higher than the experimental value at 0 ~ 2 s. When the control current changes sharply during the shift period, the overshoot of the simulation is slightly higher than the experimental value, which is caused by leakage in the test process.

The results show that the simulation results of the main oil pressure curve coincide well with the test results, so the accuracy of the hydraulic system model is proved, and the feasibility of establishing the hydraulic system physical model based on AMESim is guaranteed to some extent.

![Simulation model of C0 and C1 clutch](image1)

![Simulation model of B2 brake](image2)

Fig 4. Simulation model of shift elements

![Simulation model of hydraulic system](image3)

Fig 5. Simulation model of hydraulic system

Table 2. Main parameters of the shift element

| Parameter                      | B1      | C0      | C1      |
|--------------------------------|---------|---------|---------|
| Piston outer diameter (mm)     | 75      | 48      | 54      |
| Piston inner diameter (mm)     | 65      | 23      | 26      |
| Piston stroke (mm)             | 1.8     | 1.8     | 1.7     |
| Piston mass (kg)               | 0.436   | 0.296   | 0.304   |
| Number of friction pairs       | 6       | 4       | 4       |

Fig 6. Bench test of hybrid gearbox powertrain
4.3. Simulation Analysis

Fig. 9 shows the set value of solenoid valve control current during simulation. Fig. 10 shows the simulated main oil circuit pressure, C0 and B2 flow rate, C0 and B2 pressure and C0 and B2 piston displacement characteristic curve. In Fig. 9, the current of C0 and B2 solenoid control valves is 0 A at 0~3s, and the main oil circuit is disconnected from the oil circuit of gearshift element. The control current of the pilot solenoid valve is 0 A, and the maximum pilot pressure is output. Therefore, the main oil pressure in Fig. 10 can reach the maximum pressure of about 20 bar after over-regulation. When the current of C0 solenoid control valve is 1 A, the main oil circuit flows with the brake oil circuit of C0 clutch to realize the process of oil filling joint. When the flow rate of C0 clutch increases, the pressure increases and the displacement of piston decreases to 1.8 mm, and the C0 piston is reset due to the action of spring force, which accords with the design characteristics of C0 clutch. At 5~7s, the current of B2 solenoid control valve is 1 A, and the main oil circuit and B2 brake oil circuit flows to realize the process of oil charging brake. In Fig. 10, the flow of B2 brake increases, and the pressure rises, and the piston displacement is about 1.8 mm, when the current drops to 0 A, the B2 piston is reset under the action of spring force, meeting the design characteristics of B2 brake. When the C0 clutch and B2 brake operate, the pressure of the main oil circuit fluctuates instantly, but the amplitude of the pressure fluctuation is small, so it will not have an effective effect on the system, and it can be ignored. At 7.5s, the control current of the pilot valve is 1 A, and the output pressure of the pilot is 0 bar, and the pressure of the main oil circuit is reduced to about 4.5 bar, which meets the design requirements of the hydraulic system.
5. Experimental Study on Hydraulic Shift System

The function test of hydraulic shift system of hybrid power gearbox is mainly to verify the correctness of the principle scheme and the rationality of the parameters [7]. In this paper, the experimental study on the switching between HEV-5 and EV-2 gear is carried out. It is actually the process of opening the C0 clutch, and then opening the B2 brake after the oil filling joint, and refilling the C0 clutch. Fig. 11 (a) shows the control current curve of B2 and C0 solenoid valve and pilot regulating valve. Fig. 11 (b) is the pressure curve of main oil circuit. Fig. 11 (c) and (d) is the C0 and B2 pressure curve and C0 and B2 joint state curve, respectively. Coordinate 1 in the Fig. 11 (d) indicates that the gearshift element is in the open state. Coordinate 2 indicates that the gearshift element is in the sliding state, and Coordinate 4 represents the gearshift element is locked successfully. Fig. 11(a) and (c) show that the pressure of C0 and B2 is in good response to the change in the control current, and the working pressure of C0 and B2 can be accurately controlled. Fig. 11(b) shows that with the increase of the current of the pilot regulating valve, the pressure of the main oil circuit decreases, and when the current decreases, the pressure of the main oil circuit increases, which accords with the current and pressure characteristics of the reverse proportional pressure regulating valve. When the control current of C0 and B2 solenoid valve changes, the pressure of C0 and B2 will change with it, and the pressure of main oil circuit will fluctuate, but the fluctuation is small, and its effect on the system can be ignored. Fig. 11(d) can be observed that when the control current of C0 solenoid valve changes from 0.82 A to 0 A, the C0 clutch changes from joint state to open state, and when the control current of C0 solenoid valve changes from 0 A to 0.82 A, the C0 clutch changes from open state to joint state, but in the process of engagement, the C0 clutch has an oil filling stage and the engagement time is about 0.35 s. When the current is controlled by B2 solenoid valve, the joint state of B2 brake will also change with it, but there is also oil filling stage in the process of joint, so B2 brake becomes locked state after applying current. The test results show that the principle scheme of the hydraulic shift system is correct and meets the design requirements.
6. Conclusion

(1) The performance of a strong hybrid hydraulic shift system is studied by means of dynamic simulation and experimental analysis. The working principles of hydraulic source and main oil circuit control system, shift and parking control system, cooling and lubrication system and shift execution system are described.

(2) The simulation model of hydraulic shift system is established. On the basis of verifying the correctness of the simulation model, the hydraulic shift system is simulated based on AMESim. The results show that the pressure performance of the hydraulic system and the working characteristics of the shift elements meet the functional requirements of the system.

(3) Based on the bench test of hybrid gearbox powertrain, the working characteristics of hydraulic shift system are analyzed. The test results show that the principle scheme of the hydraulic shift system is correct and meets the design requirements. The research content of this paper has been applied to the hydraulic shift system of a hybrid gearbox, which is of practical significance to the optimization of the system.

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