Research on a new type of buffering valve for vehicle shifting

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Abstract: The traditional buffering valve for vehicle shifting mainly relies on the throttle hole and spring to control the pressure in the clutch. However, its accommodative facility and adaption are inferior. Therefore, two-dimensional (2D) digital technology is proposed to be applied to the vehicle shift buffering area, and the 2D digital buffering valve is designed. This study introduces the structure and working principle of the 2D digital buffering valve and establishes the mathematical model of the 2D digital buffering valve. The classical proportional-integral-differential control algorithm is adopted and Matlab/Simulink is used to simulate its control model. Finally, an experimental study is carried out. The study results show that when the frequency is 50 Hz, the amplitude of the valve output pressure decays to ~3 dB, and when the frequency is 60 Hz, the phase of the valve output pressure lags by 90°. The output of the 2D digital buffering valve meets the requirement of the change of the oil pressure in the clutch during the vehicle shifting process. The control precision of its buffering pressure characteristic reaches 15%. The simulation and test results of the buffering valve are consistent, which verifies the correctness of the simulation model.

1 Introduction

The hydraulic buffering valve for vehicle shifting is usually used in the shifting hydraulic system of the vehicle. Its function is to control the change of oil pressure in the clutch to realise the smooth transition of speed. In China, early studies mainly aimed at the impact of the structural parameters of the traditional buffering valve on the gear-shifting buffering [1–3], and recent research studies aim to optimise the structure of the buffering valve [4, 5]. However, the traditional buffering valve has the shortcomings of slow response and poor adaptability. With the improvement of vehicle technology, the buffering valve that can rapidly and precisely control the pressure in the clutch oil cylinder are in urgent need.

With the development of electronic technology, hydraulics and control theory, electronic control technology has also been applied to the buffering valve. The electro-hydraulic buffering valve has evolved to the electro-hydraulic proportional valve from the high-speed switching valve. Li et al. [6] of the National University of Singapore and Wang et al. [7] of Zhejiang University designed different high-speed switching buffering valves. However, since their control modes adopted the pulse width modulation signals, which belongs to discrete control, it is hard to realise precise control [8] although it can increase the response time of the valve. The EPRV-16 type of electro-hydraulic proportional valve of Vickers was used by Lin et al. [9] as the buffering valve to realise buffering control during the shifting process. Meng et al. [10] took the proportional valve as the pilot valve. It combines with the flow valve and forms a valve block which plays the role of buffering during the shifting process. The flow valve plays the role of amplifying power. The valve block consisting of electro-hydraulic proportional pressure valve and the solenoid-controlled directional valve is adopted in the reliable and widely used D65 automatic transmission, and the buffering control is realised during shifting [11]. The principle of the valves studied in these literature is to take the electro-hydraulic valve as the pilot valve, which forms a valve block together with the hydraulic valve to realise the clutch buffering control. Its shortcomings are as follows: the volume of the valve is too large and the magnetic circuit of the proportion electro-magnet is generally monolithic magnetic materials. If high-frequency signals are adopted to control, the iron loss will cause severe temperature rise.

At present, the wide application of digital technology in hydraulics makes the digitisation of the hydraulic components become a trend, especially with the invention of the 2D digital valve [12] by Professor Ruan Jian of Zhejiang University of Technology. The 2D digital valve is famous for the free revolving and sliding of the spool and features by strong anti-pollution ability, fast response speed, high control accuracy, and low production cost. It has been widely used in the aviation and aerospace fields [13]. Two-dimensional digital technology is not only applied in the servo valves, but also in the proportional valve [14, 15], high-speed switching valve, vibration valve [16], and high-speed pump.

This paper put forward a brand new buffering valve structure, i.e. applying the 2D digital technology to the vehicle shifting to precisely control the change of the oil pressure in the clutch. Based on expounding on its structure principle, the mathematical model of the buffering valve is established according to the hydrodynamic theory, and its basic features are studied through simulation and experiment. The feasibility of the application of 2D digital technology to the buffering valve is also proved.

2 2D digital buffering valve

2.1 Structure and working principle of 2D digital buffering valve

To follow the change rule of oil pressure in the clutch and improve the control precision of the output pressure to improve the vehicle shifting quality, a digital buffering valve is designed in this paper. Therefore, a new structure of the buffering valve is presented. The current mature 2D digital technique is used in the pressure control of clutches, and the 2D digital buffering valve is designed. Its structural sketch is shown in Fig. 1.
The 2D digital buffering valve consists of an electro-mechanical transducer, transmission mechanism and main valve body. The main valve body is composed by the 2D digital pilot valve and main pressure reducing valve. There are high and low-pressure holes in the spool of the 2D digital pilot valve. The high-pressure hole is interlinked with the oil inlet and the high-pressure hole is interlinked with the oil outlet. There is a spiral groove in the valve sleeve of the pilot valve. The high and low-pressure holes and the spiral groove form an arch overlapping area. The two arch overlapping areas formed high-pressure throttling holes and low pressure throttling holes between the oil inlet and the oil outlet.

2.2 Working principle of 2D digital buffering valve

Its working principle is shown in Fig. 2. The main valve of the 2D digital buffering valve is normally closed, and the zero position of the pilot valve is to make the pilot spool in a stress equilibrium state. When certain electrical signals are input, the electro-mechanical converter rotates counterclockwise by a corresponding angle. The rotatory movements are passed to the valve spool through the transmission mechanism, which makes the overlapping area formed by the high-pressure hole and the spiral chute dwindle and the area formed by the low-pressure hole and the spiral chute increase. At this time, the pressure in the sensitive cavity drops and the balance of the spool is broken. The spool moves leftward to impose pressure on the spring, and then it pushes the main spool to move leftward as well. When the main valve is open, the oil liquid moves towards the outlet and enters the clutch, so that the clutch is filled with oil.

3 Mathematical model of 2D digital buffering valve and proportional–integral–differential (PID) algorithm

3.1 Mathematical model of pilot valve

Before establishing the model, this paper assumes that the system works in a stable state and ignores the inertia of each part in the buffering valve. The mechanical friction of each part is ignored and the leakage is also ignored.

According to the flow continuity equation, the flow-equation of the flow that enters into the sensitive cavity is:

$$Q_c - Q_l = A \frac{dx}{dt} + V_c \frac{dp}{\beta_s} \frac{dt}{dr}$$

where \(V_c\) is the capacity of the sensitive cavity, \(m^3\); \(x\) is the spool displacement, \(m\); \(\beta_s\) is the elasticity modulus of the oil volume, \(Pa\); \(A\) is the action area of the pilot spool in the sensitive cavity, \(m^2\).

According to Newton's principle of mechanical equilibrium, the kinetic equation of the digital pilot valve is:

$$P_r A - P_l A_l = m \frac{d^2 x}{dt^2} + B \frac{dx}{dt} + K x$$

where \(A_l\) is the action area of the fuel inlet chamber, \(m^2\); \(B\) is the total viscosity coefficient and \(K\) is the spring stiffness, \(N/m\).

3.2 Mathematical model of the main valve

Since the main spool is a bilateral slide valve and the throttle window is matched and symmetric, the upper equation can be linearised, and then the following flow equation is obtained:

$$\Delta Q = Q_l - Q_c = K_m \Delta v_c - K_p \Delta P_l$$

The following equation can be obtained according to the movement of the main spool and the flow continuity:

$$Q = Q_l - Q_c = -A_s \frac{dx}{dr} + V_l \frac{dp}{\beta_s} \frac{dt}{dr}$$

where \(A_s\) is the cross-sectional area of the main spool, \(m^2\); \(\beta_s\) is the volumetric modulus of elasticity of the oil liquid, \(Pa\); \(x\) is the spool displacement and \(V_l\) is the volume of the load cavity.

The main spool is subjected to the inertia force, viscous force and spring force. The main spool is in equilibrium in the interaction of these forces. The kinetic equation of the main spool can be obtained according to the principle of dynamics:

$$k(x - x_s) - p_l A_s = m_v \frac{d^2 x}{dt^2} + B_v \frac{dx}{dt} + K_s x_v$$

where \(m_v\) is the total quality of the spool, \(B_v\) is the viscosity coefficient, \(K_s\) is the hydrodynamic spring stiffness.

3.3 PID algorithm of 2D digital buffering valve

The system chart of the 2D digital buffering valve can be obtained using the mathematic model in Sections 2.1 and 2.2 and it is shown in Fig. 3.

It can be seen from the system chart in Fig. 3 that the output pressure of the system and the input angular displacement of the spool are open-loop. Therefore, it is necessary to give feedback to the output pressure of the 2D digital buffering valve. The PID algorithm is adopted to make adjustment. The system chart after the algorithm is added is shown in Fig. 4.
The transfer function after PID algorithm is introduced can be induced from Fig. 4:

\[ G(s) = \frac{K_c (1 + \frac{1}{T_i s} + T_d s)}{1 + K_c (1 + \frac{1}{T_i s} + T_d s) G(s)} \]  

(6)

where \( G(s) \) is the transfer function of the 2D digital buffering valve. Its block diagram is as shown in Fig. 3.

Simulink is one of MATLAB’s most important components. It uses graphical tools for modelling and simulation, and can provide an integrated environment for dynamic system modelling, simulation, and comprehensive analysis. The mathematical model of the valve can be solved using Matlab/Simulink, and the simulation model established in Matlab/Simulink is shown in Figs. 5–7.

Fig. 5 is the simulation model of the 2D digital buffering valve. Fig. 6 is the pilot valve model, which is the ‘TDvalve’ module in Fig. 5. Fig. 7 is the main valve model, which is the ‘MainValve’ module in Fig. 5. Set the simulation step size to 0.001 s when using Matlab/Simulink to solve the model.

4 Buffering characteristics test

4.1 Test platform

In order to verify the correctness of the simulation model and test the performance of the 2D digital buffering valve, the test platform of the valve needs to be established. In the test, the pressure of the system is 2 MPa. The test platform is shown in Fig. 8.

The hydraulic pump station provides the oil and pressure as the system pressure. The 2D digital buffering valve (4) is connected to the hydraulic system through the valve block (3). A pressure sensor installation interface is opened on the side of the valve. The signal is fed back to the electronic control part for closed-loop control of the valve, and the interface of the pressure gauge is also set at the valve block (3) to observe the pressure change.

4.2 Study of the dynamic property of the 2D digital buffering valve

The dynamic characteristics of 2D digital buffering valves can be reflected by the step characteristics and frequency characteristics. It is one of the important indexes to determine the performance of the buffering valve. The response time of the step characteristics is one of the important parameters to measure the dynamic characteristics of the 2D digital buffering valve. The shorter the response time is, the faster the response of the 2D digital buffering valve is. The step response curve obtained in the test is shown in Fig. 9. The horizontal coordinate represents time, and the vertical coordinate is the outlet pressure of the valve. The solid line is the input step signal, and the hidden line is the step response curve of the spool.

It can be seen from Fig. 9 that the step response time of the valve is about 55 ms, and the peak time is about 65 ms. The maximum overshoot is about 18.62%. Further experimental study on the influence of the frequency characteristics of the valve is...
carried out. Frequency characteristic is another important dynamic performance index of the 2D digital buffering valve. It mainly tests the response of the output pressure of the 2D digital buffering valve when the bowstring wave signals with the same amplitude and different frequencies were input. Fig. 10 shows the response curves of the output pressure of the valve port when the frequency of the input signal is 0.1, 10, 50 and 90 Hz, respectively. The solid line in Fig. 10 is the input signal and the imaginary line represents the pressure output. The horizontal axis in Fig. 10 is the timer shaft t/s and the vertical coordinate represents the pressure of the valve oil liquid p/MPa.

It can be seen from Fig. 10 that when the signal with the frequency of 0.1 Hz is input, the outlet pressure of the 2D digital buffering valve has sound following the performance. With the gradual rise of the frequency of the input signal, the output oil pressure of the valve also changes gradually. The output amplitude decreases constantly, and the phase also lags.

The amplitude decay of the valve output pressure is rather slow within the frequency range of 0.1 to 20 Hz and its phase also lags gradually. From the frequency of 30 Hz, the amplitude of the valve output pressure declines sharply. However, the phase lag is slow, and its value is approaching π/2.

The following characteristics of the 2D digital buffering valve have been clearly demonstrated through the above analysis. To further study the dynamic performance of the 2D digital buffering valve, calculated analysis is carried out to the above data obtained from the experiment and the magnitude-frequency characteristic and phase frequency response curve of the 2D digital buffering valve are obtained, which are shown in Fig. 11.

It can be seen from Fig. 11 that the gradual rise of the frequency of the input signal makes the amplitude of the valve output pressure decrease gradually and the phase is also lagging. When the amplitude of the valve delivery pressure decays to −3 dB, the frequency of the corresponding input signal is around 50 Hz. When the phase position of the input–output lags by 90°, the corresponding input frequency is around 60 Hz. As the 2D digital valve is taken as the electro-hydraulic buffering valve, it is required to control the change of the oil pressure in the clutch within 1.5 s. It can be seen from the above test that the frequency characteristic of the 2D digital buffering valve can meet the requirement of use.

### 4.3 Study on the buffering characteristics of the 2D digital buffering valve

The buffering characteristic of the 2D digital buffering valve is its main dynamic characteristic, which is one of the indexes determining the performance of the buffering valve. The buffering characteristic curve of the 2D digital buffering valve can be obtained through simulation and test, which is shown in Figs. 12–14.
It can be seen from Fig. 13 that the buffering features of the valve can be better realised through adopting the 2D digital buffering valve designed with the 2D digital technology and under the PID algorithm. The impact of different control signals on the output of the valve is further studied and the result is shown in Fig. 14.

The pressure output result curve of the valve is shown in Fig. 14 when different control signals are input. It can be seen from Fig. 14 that the result can better reproduce the input control signal of the buffering valve and fairly sound buffering valve pressure can be obtained, which greatly improves the adaptability of the digital buffering valve. In different working conditions, the appropriate control signal is obtained according to the driving condition of the vehicle and the environment to make the valve output different buffering oil pressure.

5 Conclusions

The traditional hydraulic buffering valve is passive. The shifting buffering control feature is single. Its adaptability is poor. Therefore, this paper first applies the 2D digital technology to the vehicle shift buffering and the 2D digital buffering valve is put forward. The PID algorithm is adopted to conduct closed-loop control over its output pressure. It can be learned from theoretical analysis and experimental study that:

(i) The 2D digital buffering valve is mainly composed of 2D digital pilot valve spool and the main reducing valve. The main reducing valve is opened by the thrust generated by the 2D digital pilot valve, thus the output pressure of the valve changes with the input signal.

(ii) When the frequency is 50 Hz, the amplitude of the valve output pressure decays to −3 dB. When the frequency is 60 Hz, the phase of the valve output pressure lags by 90°, the frequency characteristics of the 2D digital buffering valve satisfies the actual operation requirements. The simulation result of the buffering valve is consistent with the test result, and the test result verifies the accuracy of the simulation model.

(iii) In terms of the adaptability, 2D digital buffering valve changes with the input signal. Therefore, it is only necessary to revise the input signal. On the other hand, the gear-shifting quality of different working conditions can be further studied. The self-adaptation control strategy of the 2D digital buffering valve can be applied.

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7 References

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