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Research on Buffer Characteristics of a New 2D Digital Buffer Valve for Vehicle Shift

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Abstract: The clutch is currently developing towards high power, high stability, and intelligent operation. The traditional hydraulic buffering valve mostly uses a passive hydraulic buffer valve or a high speed on-off valve and a proportion valve. It has a single buffering characteristic and poor adaptability. It is difficult to meet the requirements. Therefore, a new theory and a new method are proposed. In the field of clutch oil pressure control, the 2D digital buffer valve is designed using 2D digital technology. The structure of the 2D digital buffering valve is described. Based on the working principle of the valve, a mathematical model is set up. MATLAB/Simulink is used to solve the model. The results are analyzed in this paper. Finally, a valve test platform is built and an experimental study carried out. The research indicates that the 2D digital buffering valve has a good static characteristic. The linearity is 9.25%, and the hysteresis is 0.106. The response time of the 2D digital buffer valve is about 55 ms, and the valve overshoot is only 18.62%. During shifting, the maximum deviation is 0.165 MPa, and the steady-state error is 0.056 MPa. Different buffer control signals as the input and the output of the valve can follow the input change. The experimental and simulation results are consistent. The rationality of the mathematical model has been verified.

Keywords: shift; buffer valve; 2D digital valve; buffer characteristic

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1. Introduction

With the development of hydraulic technology and control theory, fluid transmission and control technology is presenting new, vigorous development in the field of vehicles [1–3]. During the shifting of the vehicle, the friction elements in the shifting clutch undergo a slipping process during separation and engagement, which is inevitably accompanied by a torque disturbance, generating a corresponding shifting impact and affecting the stability of the shifting. If the oil pressure in the clutch slowly rises or falls within a certain period of time, the friction elements in the shift clutch are smoothly combined or separated [4]. This can reduce the torque disturbance and improve the shift quality. At present, a shift buffer valve is usually connected in series with the hydraulic circuit of the vehicle shift clutch [5–7].

Early buffer valves mainly relied on the orifice and the buffer spring to control the pressure within the clutch. However, this structure has the disadvantages of high processing difficulty and poor dirt resistance and is easy to damage. Over the years, with the wide application of electro-hydraulic control theory in the hydraulic field, electro-hydraulic buffer valves have gradually emerged in automatic transmissions, and many companies and scholars in many countries have carried out research in this field. In the Mitsubishi

F4A41 transmission [8], a valve block structure with high-speed on-off valve as the pilot and a pressure regulating valve as the main valve appears, and the internal hydraulic pressure of the clutch in the transmission is controlled by the corresponding control algorithm. In the HD4070PR transmission [9], Allison, in the United States, uses a solenoid valve, a pressure regulating valve, and a counterbalance valve to form a cushioning component. PWM is used to control the solenoid valve and then to control the output of the pressure regulating valve, in order to adjust the pressure within the clutch. Riccardo Morselli of the University of Modena in Italy [10] studied the cushioning components of the solenoid valve and control regulator combination. Balau [11] studied an electro-hydraulic drive clutch for a vehicle shift and designed an effective predictive control strategy for the clutch. Walker [12], from the University of Technology in Sydney, conducted various studies on similar electro-hydraulic buffer valves. In China, Professor Chen Huiyan from the Beijing Institute of Technology [13] began to design and study electro-hydraulic components as buffer components at the beginning of this century. Via the application of high-speed on-off valves to proportional valves, Yang Shujun of Yanshan University [14] and Zhang Yingfeng of the Military Transportation College [15] also carried out simulations and experimental research on electro-hydraulic buffer valves. Most of the solenoid valves used in these documents use high-speed on-off valves. Because the control mode adopts a PWM signal, it is a discrete control method. Although the method can improve the response time of the valve, the control signal of the high-speed on-off valve is noisy, easily causing pressure pulsation in the hydraulic pipeline, which is difficult to accurately control.

As a new digital technology, 2D digital technology was invented by Professor Ruan Jian, working at Zhejiang University of Technology. It has been successfully applied to various hydraulic valve components [16–18] in his research for more than 30 years. The 2D digital valve has the advantages of high control precision, stable output, and quick response. Therefore, in this paper, we apply 2D digital technology to the shifting buffer valve of the vehicle and design a 2D digital buffer valve with stable output oil pressure and high control precision. Based on its structural principle, we establish a digital model by applying fluid dynamics theory and study its basic characteristics using simulation and experimental methods. It is feasible to apply 2D digital technology to the buffer valve.

2. 2D Digital Buffer Valve's Structure and Working Principle

The structure of the 2D digital buffer valve is mainly introduced into the pressure regulating screw mechanism in 2D digital technology. This mechanism is used as the guiding and controlling stage of the buffer valve, and its structure is shown in Figure 1.

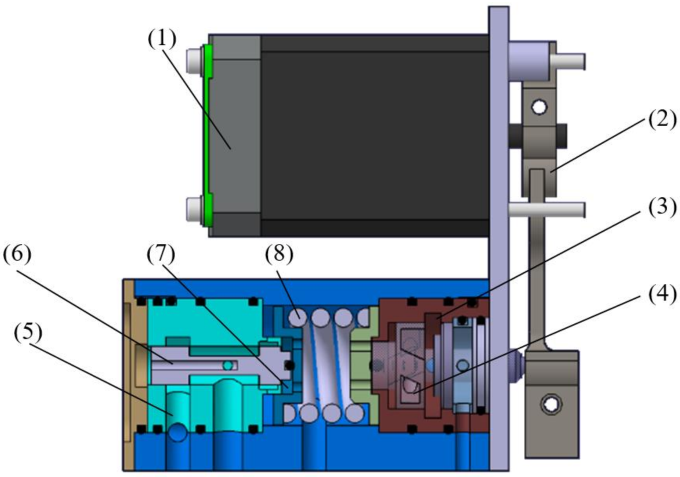

Figure 1. Diagram of 2D digital buffer valve structure. (1) Electromechanical converter; (2) transmission mechanism; (3) pilot valve sleeve; (4) pilot main spool; (5) main valve sleeve; (6) main spool; (7) spring seat; (8) spring.

In Figure 1, the electromechanical converter, transmission mechanism, and main valve make up the 2D digital buffer valve. The main valve is composed of a 2D valve and a pressure reducing valve. The working principle is shown in Figure 2.

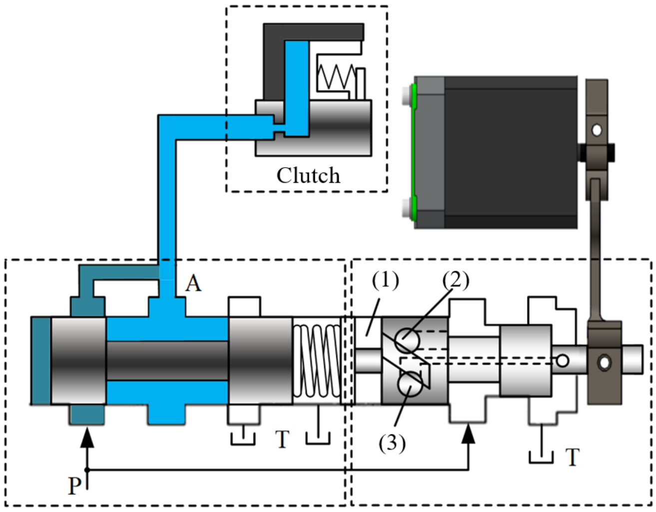

Figure 2. Diagram of 2D digital buffer valve working principle. (1) Sensitive cavity; (2) high-pressure hole; (3) low-pressure hole.

When the electromechanical converter starts to rotate, the rotation of the motor is proportionally reduced and transmitted to the rotation of the digital spool. The rotation of the digital spool will cause the spiral groove of the pilot valve sleeve and the overlapping area of the high- and low-pressure holes on the pilot spool to change, and the oil pressure in the sensitive cavity will also change. The change in pressure in the sensitive cavity causes the pilot spool to become unbalanced, thereby driving the axial movement of the pilot spool, compressing the spring and pushing the main spool to move via the spring force, so that the area of the inlet and outlet ports changes, and finally the pressure is adjusted. Here, the compressive force of the spring is generated due to the inconsistent oil pressure acting on the pilot spool. Therefore, the hydraulic pressure is used to compress the spring. The electromechanical converter uses a stepping motor, and a pressure measuring point on the oil outlet is opened on one side of the valve body to install a pressure sensor to monitor the output pressure of the valve and feed the signal back to the controller, to achieve closed-loop control of the oil pressure.

3. Analysis of Buffer Characteristics of 2D Digital Buffer Valve

3.1. Model Assumption

We assume that the system works in a steady state, the fluid is an incompressible ideal liquid, and the oil temperature and bulk modulus of elasticity are constant. The inner and outer leakage in the valve is ignored.

3.2. Mathematical Model of 2D Digital Valve

(1) Flow equation

The flow Q_1 flows into the sensitive cavity:

$$Q_1 = C_{\mathrm{d}} A_1 \sqrt{\frac{2(p_{\mathrm{s}} - p_{\mathrm{c}})}{\rho}} \tag{1}$$

where C_{d} is the flow coefficient, A_1 is the overlapping area of the high-pressure hole and the chute in m^2, ρ is the oil density in $\mathrm{kg/m}^3$, p_{s} is the oil pressure at the inlet in MPa, and p_{c} is the oil pressure in the sensitive cavity in MPa.

The flow Q_2 flows out of the sensitive cavity:

$$Q_2 = C_d A_2 \sqrt{\frac{2p_c}{\rho}} \tag{2}$$

where A_2 is the overlapping area of the low-pressure hole and the chute in m^2.

(2) Overlapping area calculation

During the rotation of the digital spool, the overlapping area between the high- and low-pressure holes on the valve core and the chute on the valve sleeve will change with the rotation angle. The area change is shown in Figure 3.

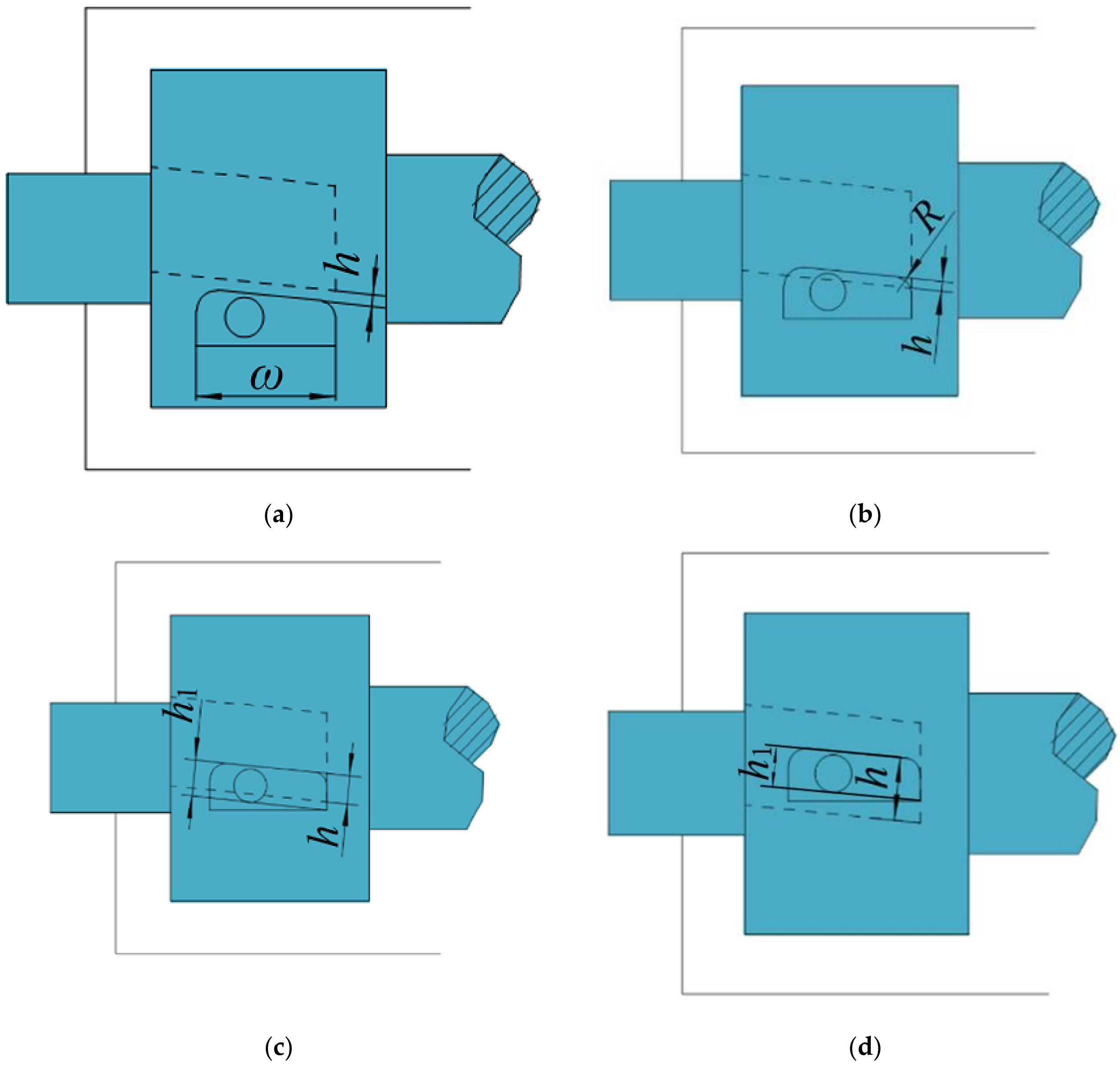

Figure 3. Change in overlap area between high- and low-pressure holes and chute: (**a**) $h \leq 0$; (**b**) $0 < h \leq R$; (**c**) $R < h \leq h_1$; (**d**) $h_1 < h$.

From Figure 3, we can calculate the overlap area A (h,R) in each case, based on the geometric relationship.

$$A(h,R) = \begin{cases} 0 & (h \le 0) \\ h\sqrt{2Rh-h^2} + R^2 \arcsin\frac{\sqrt{2Rh-h^2}}{R} - R\sqrt{2Rh-h^2} + \frac{\omega h - 2Rh}{\sin\beta} & (0 < h \le R) \\ \frac{\pi R^2}{2} + \frac{\omega h - 2R^2}{\sin\beta} & (R < h \le h_1) \\ \frac{\pi R^2}{2} + \frac{\omega h - 2R^2}{\sin\beta} - \frac{(h_1-h_0)^2}{\sin 2\beta} & (h_1 < h) \end{cases} \quad (3)$$

where h is the overlap height of the low-pressure hole and the chute in m and h_1 is the vertical height between the oblique side of the low-pressure hole and the apex of the groove in m. R is the radius of the low-pressure hole fillet in m, β is the inclined angle of the inclined groove in rad, and ω is the width of the low-pressure hole along the axial direction in m.

(3) Fluid continuity equation

$$Q_1 - Q_2 = A\frac{dx}{dt} + \frac{V_c}{\beta_e}\frac{dp_c}{dt} \quad (4)$$

where V_c is the capacity of the sensitive cavity in m^3, x is the displacement of the spool in m, and β_e is the elastic modulus of the volume of the oil in MPa. A is the area of the pilot spool in the sensitive cavity in m^2.

(4) Digital spool dynamics equation

$$P_c A - P_s A_1 = m\frac{d^2x}{dt^2} + B\frac{dx}{dt} + kx \quad (5)$$

where, A_1 is the area of action of the oil inlet chamber and B is the total viscosity coefficient.

3.3. Main Valve Mathematical Model

(1) Flow equation

The flow to the valve body is:

$$Q_1 = C_d w_1 (U + x_v)\sqrt{\frac{2(p_S - p_L)}{\rho}} \quad (6)$$

The outlet flow is:

$$Q_2 = C_d w_2 (U - x_v)\sqrt{\frac{2p_L}{\rho}} \quad (7)$$

where C_d is the flow coefficient of main valve port in m. U is the positive opening of the valve port in m, w_1 is the area gradient of the high-pressure side valve port in m, w_2 is the area gradient of the low-pressure side valve port in m, p_s is the inlet pressure in MPa, and p_L is the pressure of the control chamber in MPa.

(2) Continuity equation

The equation of motion of the main spool is based on the principle of flow continuity:

$$Q = Q_1 - Q_2 = -A_C\frac{dx_v}{dt} + \frac{V_L}{\beta_e}\frac{dp_L}{dt} \quad (8)$$

where A_C is the cross-sectional area of the main spool in m^2, β_e is the elastic modulus of the oil volume in MPa, x_v is the spool displacement in m, and V_L is the volume of the load chamber in m^3.

(3) Main spool dynamic equation

$$K(x - x_v) - p_L A_C = m_v \frac{d^2 x_v}{dt^2} + B_v \frac{dx_v}{dt} + K_S x_v \tag{9}$$

where m_v is the total mass of the valve core in kg, B_v is the viscosity coefficient, K_s is the spring stiffness of the hydraulic power in N/m, and K is the spring stiffness in N/m.

Equations (1)–(9) form the mathematical model, which reveals the buffer pressure law of the 2D digital buffer valve. After linearization and pulling, the transfer function block diagram is established, as shown in Figure 4.

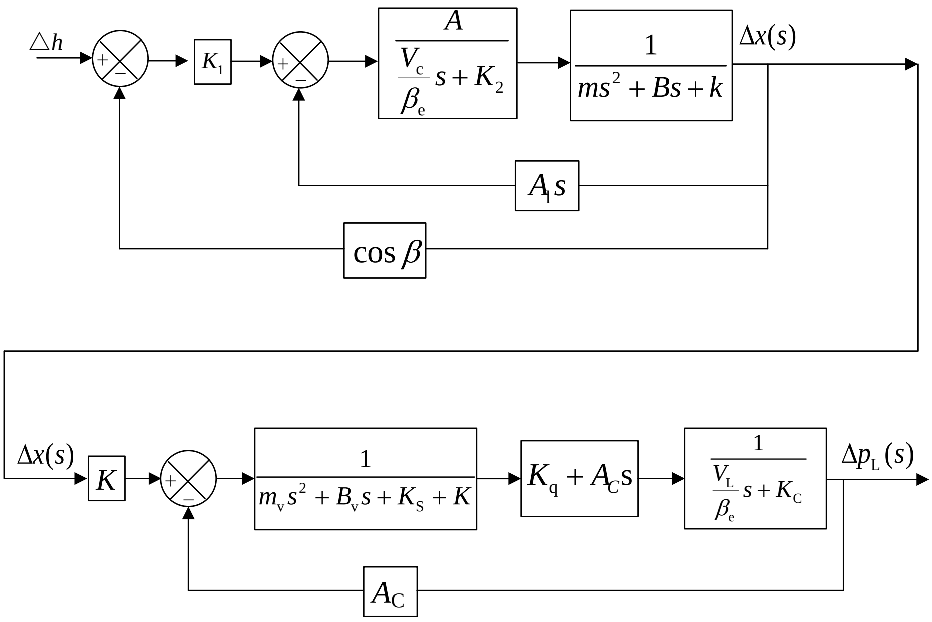

Figure 4. The 2D digital buffer valve transfer function block diagram.

3.4. Simulation and Results

The mathematical model of the valve can be simulated in MATLAB/Simulink. The simulation parameters are shown in Table 1.

Table 1. The 2D digital buffer valve simulation parameters.

Parameter	Value
System pressure p_s/MPa	2
Density ρ/(kg/m^3)	860
Flow coefficient C_d	0.62
Viscous damping B	23.83
Volumetric modulus of elasticity of oil β_e/MPa	700
Pilot digital spool quality m/g	15.5
Pilot spool radius R/mm	9
Main spool radius R_m/mm	4
Oblique groove inclination β/rad	1.13
Spring stiffness K/(N/mm)	115
Small hole diameter r/mm	3
Small hole initial bow height h_0/mm	0.1
System pressure p_s/MPa	2
Density ρ/(kg/m^3)	860
Flow coefficient C_d	0.62

Generally, the performance indicators required by the system are given in the form of the time-domain magnitude, that is, according to the response of the system to the step input. Therefore, the step characteristic curve, which is drawn from the simulation results of the valve, is shown in Figure 5.

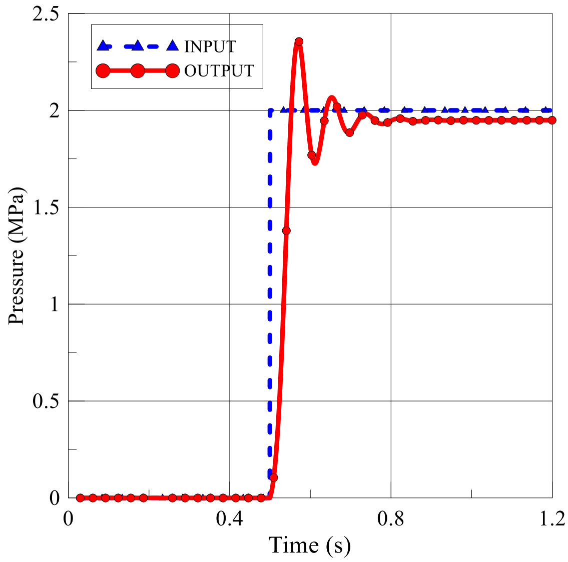

Figure 5. The 2D digital buffer valve's step characteristic curve.

In Figure 5, the response time of the system is about 50 ms, the peak time is about 60 ms, and the overshoot is about 20.6%. During the adjustment time of the transition process, the system underwent 3.5 oscillations, and it can be seen from the overshoot that the damping ratio is between 0.4 and 0.8. For the general case, the system is required to work in the underdamped state, that is, the damping ratio is required to be in the range of 0~1, so that the system meets the working requirements.

There is a further need to study the buffer oil pressure characteristics of 2D digital buffer valves. The buffer pressure characteristic of the buffer valve should achieve reasonable control of the pressure in the clutch. To achieve a target curve, the input signal of the 2D buffer valve needs to be obtained according to the load oil pressure curve. According to this, the buffer oil pressure characteristic input and the output characteristic curve of the buffer valve can be simulated, as shown in Figure 6.

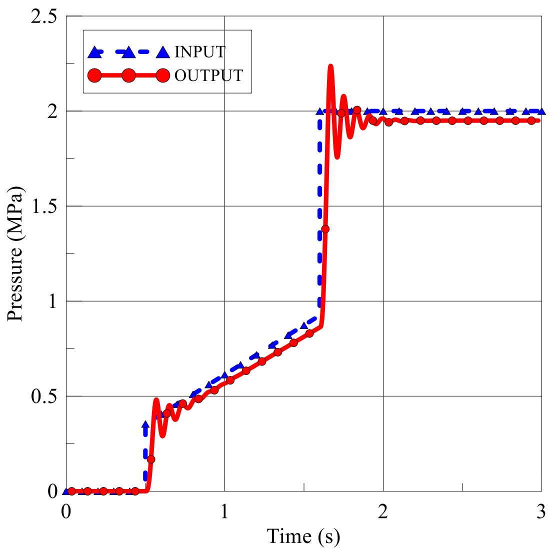

Figure 6. The 2D digital buffer valve cushioning characteristic curve.

Figure 6 shows that the 2D buffer valve can realize buffer control of the clutch pressure. It is opened at 0.5 s and the buffering time is 1.1 s. In the buffering phase, the pressure output of the 2D digital buffer valve has no impact at the initial moment. After 4.5 oscillations, the pressure output tends to be stable; the steady state error is 0.059 MPa and the maximum deviation is 0.1.5 MPa. After the step, that is, at 1.6 s, the output overshoot of the 2D digital buffer valve is 17.9%. During the adjustment time of the transition process, the output tends to be stable after 5 oscillations, and the steady state error is 0.05 MPa.

4. Buffer Characteristic Test of 2D Digital Buffer Valve

4.1. Test Platform of 2D Buffer Valve

A test bench was designed for testing the buffering characteristic of the 2D digital buffer valve. The test platform is shown in Figure 7.

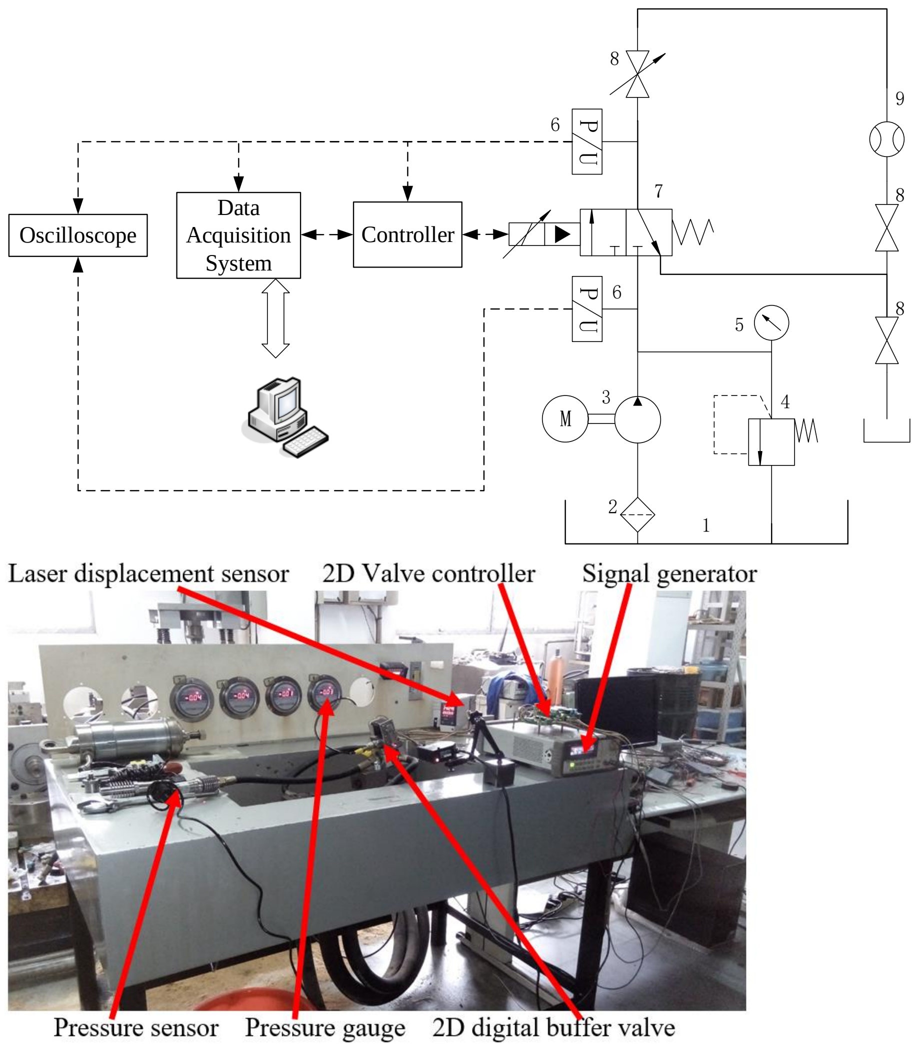

Figure 7. The 2D digital buffer valve buffer characteristics test platform. 1: tank; 2: filter; 3: pump; 4: relief valve; 5: pressure gauge; 6: pressure sensor; 7: 2D digital buffer valve; 8: globe valve; 9: flowmeter.

The hydraulic pump station provides the oil pressure. The 2D digital buffer valve is connected to the hydraulic system through the valve block. The side of the valve opens an installation interface for installing the pressure sensor. The valve outlet pressure signal is fed back to the controller, in order to carry out closed-loop pressure control. The hydraulic gauge can display the pressure values of the valve.

4.2. Static Characteristics of 2D Buffer Valve

The static characteristics of the 2D buffer valve refer to the relationship between the input voltage signal and the output oil pressure. It is the main characteristic of the valve, from which the linearity and hysteresis of the valve can be obtained. The test and simulation results are shown in Figure 8.

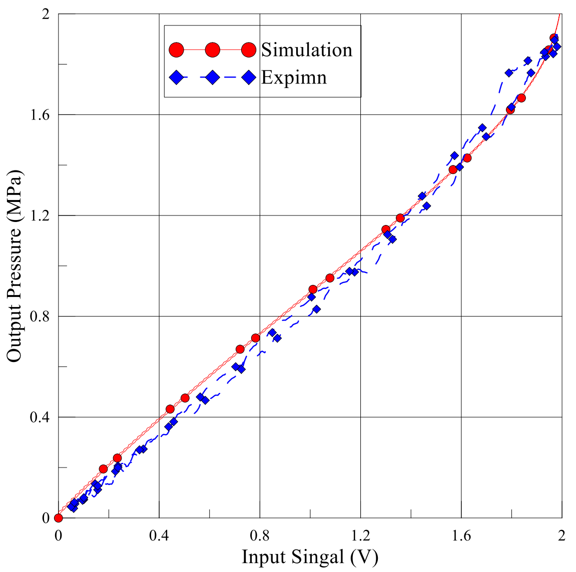

Figure 8. Simulation and test static characteristic results.

Figure 8 shows that the trends of the simulation and test curves are consistent. They all show an approximately linear trend. The linearity of the valve is 9.25% and the hysteresis is 0.106 throughout the data analysis test.

4.3. Step Characteristics of 2D Buffer Valve

The simulation study of the step characteristics of the buffer valve was described in Section 3.4. The response time is one of the important parameters which can measure the dynamic characteristics of the valve. The step response characteristic curve of the valve can be obtained through experiments.

Figure 9 shows that the simulation results and test results of the buffer valve have the same trend. Important data relating to the results are shown in Table 2.

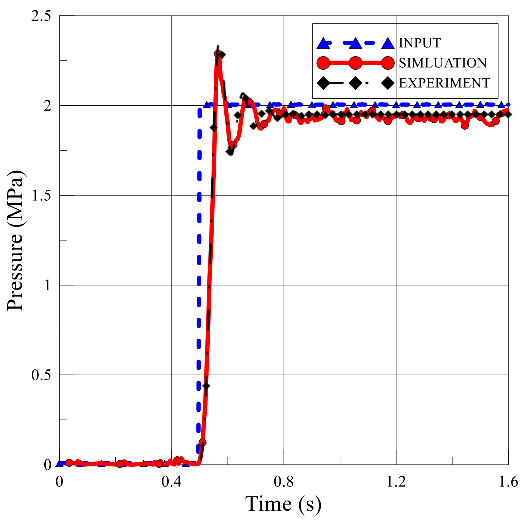

Figure 9. Step response characteristics of 2D digital buffer valve.

Table 2. Important data relating to results.

Parameter	Value
Step response time	55 ms
Peak time	65 ms
Maximum overshoot	18.62%

During the adjustment time of the transition process, the system underwent 3 oscillations, and these results are basically consistent with the simulation analysis in Section 3.4. The 2D digital buffer valve is mainly used to achieve a certain curve change of the pressure in the clutch within 1.5 s, and therefore the step performance of the valve measured from the test is sufficient to meet the application requirements.

4.4. Experimental Study of Buffer Characteristics of 2D Buffer Valve

The above-mentioned dynamic characteristics test was carried out on the 2D digital buffer valve. To further research the buffer pressure characteristics of the buffer valve, an experimental study of the buffer pressure characteristics was carried out. The results for the buffer characteristics from the experiment and the simulation were compared, as shown in Figure 10.

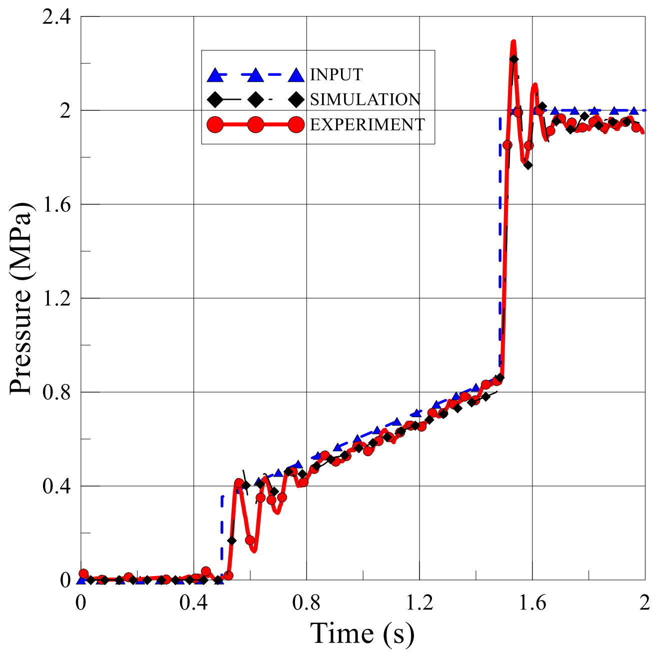

Figure 10. Buffer characteristics experiment and simulation comparison curve.

Figure 10 shows that the simulation and test results of the buffer valve have the same trend. The valve opening time was 0.5 s and the buffer phase of the valve was 1.1 s. The comparison results from the simulation and experimental data are summarized in Table 3.

From Table 3, the data for the simulation results and the relevant indicators of the test results are almost consistent; only the maximum deviation is large and the curve measured in the buffer stage is more fluctuating, as shown in Figure 9. However, the curve from the simulation is smoother. The impact of the valve's transient characteristics is related to the volume of the cavity in the model. In practice, the machining error and assembly error of the valve may cause certain errors in the simulation results and test results. It can also be seen from Figure 9 that in both the simulation and the test, the 2D digital buffer valve can realize the buffering characteristics of the valve well. The results of further studies of the influence of different control signals on the output pressure of the valve are shown in Figure 11.

Table 3. Test and simulation comparison for 2D digital buffer valve.

Contrast Stage	Contrast Phase	Experiment	Simulation
Buffer stage	Maximum deviation (MPa)	0.165	0.105
	Peak time (ms)	60	68
	Steady-state error (MPa)	0.056	0.059
	Number of oscillations	4	4.5
Step stage	Overshoot	18.5%	17.9%
	Peak time (ms)	65	69
	Steady-state error (MPa)	0.055	0.05
	Number of oscillations	3.5	5

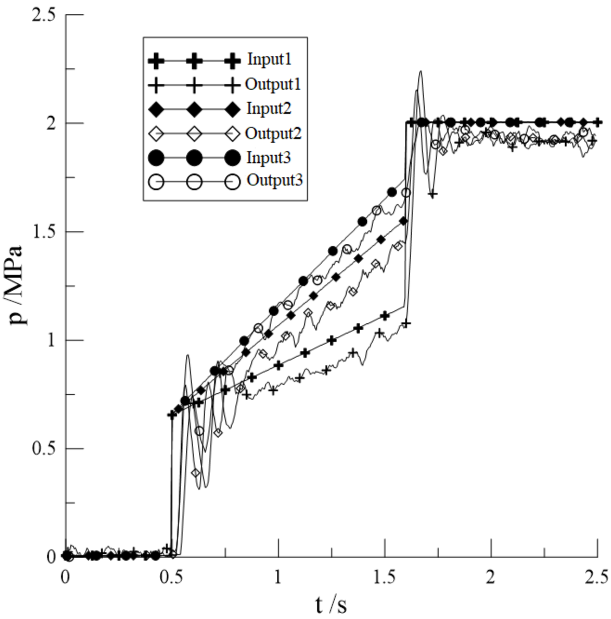

Figure 11. The 2D digital buffer valve's buffer following the characteristic curve.

The pressure output results curves of the 2D digital buffer valve with different input control signals are shown in Figure 11. It can be seen from the figure that the valve results can reproduce the input control signal of the buffer valve well and can obtain a better buffer pressure, so that the adaptability of the digital buffer valve is improved. Under different working conditions, according to the driving conditions and environment of the vehicle, a suitable control signal is obtained, so that the valve outputs a different buffer oil pressure and the pressure in the clutch is better controlled.

5. Conclusions

The characteristic of the digital valve is that it can be directly controlled by digital technology. In this paper, a series of experiments have been carried out on the 2D digital buffer valve, including theoretical analysis and experimental research. The simulation is solved by MATLAB/Simulink, and the test shows that:

(1) The 2D buffer valve can be designed using digital technology. During shifting, it can directly control the output pressure through digital technology to meet the pressure change within the clutch.
(2) The step response time is about 55 ms, and the maximum overshoot is about 18.62%. The step performance of the valve is sufficient for the application.
(3) In the buffering stage, the output pressure of the valve tends to be stable after 4 oscillations. The maximum deviation is 0.165 MPa, and the steady-state error is 0.056 MPa. In the step stage, the overshoot is 18.5%, and after 3.5 oscillations, it tends to be stable.

(4) Different input signals can produce different buffering characteristics; the 2D digital buffer valve has better buffer following characteristics, and the output can reproduce the input, so that the vehicle can change the control signal to adapt to different operating conditions.

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