Research on comprehensive performance test system for proportional relay valve of commercial vehicle EBS

Yi Lu, Jinhao Zhou, Jie Lu and Bin Guo

1. College of Metrology and Measurement Engineering, China Jiliang University, Hangzhou, Zhejiang, China
2. Hangzhou Wolei Intelligent Technology Co., Ltd, Hangzhou, 310018, China
3. E-mail: luyi9798papaer@163.com

Abstract. The proportional relay valve is one of the core components of EBS. In this regard, high-speed data acquisition system and computer-based control technology were used to design the EBS proportional relay valve comprehensive performance test system. The test items mainly included hysteresis characteristic test, dynamic characteristic test, and sealing test. The open current/pneumatic test was introduced in the hysteresis characteristic. In order to verify the accuracy of the system, a proportional relay valve simulation model based on MATLAB/Simulink was designed. Combined with the measured data, the influences of different control methods on the performance of the proportional relay valve were tested and analysed. The results showed that the dynamic response time under the condition of electronic control was shorter than that under the condition of air control, and the decompression stability was worse under the condition of electronic control. The maximum hysteresis current was 0.23A. The maximum hysteresis pressure was 56.64kPa.

1. Introduction

The Electronic Control Brake System (EBS) is the next generation of commercial vehicle brake systems that has emerged in recent years [1]. It combines the traditional anti-lock braking system with the conventional braking system. It implements braking through electronic control, eliminating the problems of slow mechanical response time and poor braking comfort, greatly improving the braking performance of commercial vehicles.

At present, EBS has become the mainstream brake system for commercial vehicles in Europe and the United States, and research on EBS tends to be perfect [2-4]. EBS proportional relay valve adopts the combination of electronic control and air control. It differs greatly from conventional relay valves that employ gas control. Domestic study mainly focused on the integral brake system [5]. The study of the proportional relay valve for EBS was rare. Han Zhengtie and others of Jilin University analyzed and proposed a hysteresis compensation method combining PID control and feedforward compensation for the hysteresis characteristic of EBS proportional relay valve electronic control mode [6]. Yu Mujie and others of Tsinghua University established the mathematical model of proportional valve of EBS, focusing on the influence of main physical and geometric parameters on the valve characteristics [7]. Some well-known auto parts manufacturers in China, such as VIE and SORL, had only assembled EBS valve production lines for R&D purposes. Above all, the study is important for China to put forward EBS regulations and standards, and it plays an important role in the formation of EBS proportional relay valve test methods and test items.
The EBS proportional relay valve has a complex structure and a wide variety of performance parameters. Traditionally, tests and studies on only one of its parameters obviously cannot meet the requirements for evaluating the overall performance of the valve. Therefore, it is necessary to develop a set of EBS proportional relay valve comprehensive performance testing system that can be used in the laboratory and industrial field. In order to verify the accuracy of the test system, the MATLAB/Simulink simulation software was used to design the EBS proportional relay valve simulation model which added the proportional valve equation.

2. Proportional relay valve test system design

2.1. Proportional relay valve test requirements

The main function of the proportional relay valve is to output the brake pressure of the front axle of the commercial vehicle. It is divided into two modes: electronic control and air control. It consists of proportional solenoid valve, relay valve and pressure sensor. The proportional relay valve structure principle is shown in figure 1.

![Figure 1. The proportional relay valve structure principle.](image)

In the comprehensive performance of EBS proportional relay valve, the parameters to be tested were divided into three items: (1) Hysteresis characteristic detection: Hysteresis current/pressure and startup current/pressure were tested. The same output pressure value would correspond to two control signal values in the process of pressurizing and depressurizing. The absolute value of the maximum difference was hysteresis current/pressure. When the output pressure value began to rise significantly, the corresponding control signal value was the startup current/pressure. (2) Dynamic characteristic test: It was the time required for the test valve to complete the action after receiving the control signal. The time required for the output pressure value that rose from 0 to 75% of the rated output pressure value was the response time. The time required for the rated output air pressure that dropped to 15% of this value was the release time. (3) Sealing test: The amount of pressure leakage at the valve port was tested when the valve was fully closed.

2.2. Test system design

Based on the above test requirements, referring to National Compulsory Standard GB 12676-2014 and Automotive Industry Standard QC/T 37-2011, EBS proportional relay valve comprehensive performance test system and test piping were designed. The test piping design is shown in figure 2. The system adopted industrial computers, high-speed data acquisition cards, and programmable power supplies as the core of control and processing. The data acquisition card controlled the action of the relevant valve in the air circuit and collected the value of the pressure sensor. The rate of the data acquisition card was up to 100K to meet the test requirements. The programmable current source provided the necessary drive current for the valve, and its current accuracy was 0.1%. The pressure adjustment of the control port in the pneumatic system was regulated by the electric proportional valve. The control signal was 0~10V, corresponding to the pressure adjustment of 0~1MPa. Differential pressure sensors 11 and 17 had an accuracy of 0.1%. The pressure sensors 22, 23 and 24 were piezoresistive pressure sensors with a precision of 0.05% and their response time was less than 2ms.
The hysteresis characteristics of the relay valve with proportional EBS were measured and divided into two cases: electronic control and gas control. The industrial control computer opened the air control valve 13 to supply gas to the input port. Under the electronic control mode, the control current was slowly increased or decreased according to the instruction through the serial port communication. Under the air control mode, the upper computer controlled the electrical proportional valve 7. It opened the solenoid valves 8, 9, 9', 12, 14, 14', 15, 15', 18, and closed the solenoid valve 8'. The control port pressure slowly increased or decreased to control the change of the output pressure. Finally, the IPC processed the hysteresis current/atmospheric pressure and the open current/atmospheric pressure during the test process, and obtained the relationship between the output pressure and the control signal.

Measuring the dynamic characteristics of the proportional relay valve was also divided into two conditions: electronic control and air control. The upper computer opened the air control valve 13. Under the electric control mode, the electronic control port of the proportional relay valve was directly controlled by the serial port communication to quickly switch on and off. Under the air control mode, the gas control valves 5, 6 were rapidly opened and closed through the data acquisition card, and then the control port of the control valve was rapidly charged and deflated. Finally, the IPC obtained the response time and release time of the valve.

The method of measuring the seal of a proportional relay valve was differential pressure method and was divided into four processes: intake process, balance process, test process, and exhaust process. The corresponding solenoid valve was opened during measurement. At the same time, the valve port and the reference chamber were inflated for a certain period of time and then the solenoid valve was closed to stop the inflation. The balance valve was opened to balance the air pressure at the valve port and the air pressure in the reference chamber. After a certain period of time, the balance valve was closed and measurement was started. According to the differential pressure sensor, the valve outlet pressure leakage was measured.

3. EBS proportional relay valve simulation model
In order to verify the accuracy of the system test, the mathematical model of the proportional relay valve of EBS was established firstly. The model consisted of magnetic circuit equation, motion equation and gas path equation. Then its simulation model was established.

3.1. Mathematical model establishment

3.1.1. Magnetic circuit equation. According to Maxwell’s electromagnetic force formula and Kirchhoff’s law, the electromagnet’s electromagnetic force dynamic process was expressed by the following equation:
\[ F_e = \frac{B'^2 S}{2u_0} = \frac{1}{2} (NI)^2 \frac{u_0 S}{\delta} \]  

(1)

Among them: \( F_e \) was the electromagnet suction; \( B \) was the air gap flux density; \( \delta \) was the maximum air gap; \( u_0 \) was the permeability in vacuum, \( u_0 = 4\pi \times 10^{-7} \text{H/m} \); \( S \) was the cross-sectional area; \( N \) was the number of coil turns; \( S \) was the input current.

3.1.2. Equation of motion. When the proportional relay valve worked, the spool was subjected to spring force, electromagnetic force, and air pressure resistance. Spool motion was not exactly the same in electronically controlled and pneumatically controlled modes.

In the electronic control mode, the motion equation included the proportional valve spool movement equation (2) and the relay valve spool movement equation (3). In the air-controlled mode, the proportional valve spool did not work, and the movement side only had the spool movement equation of the relay valve (3). \( P_c \) was the pressure of the control port at this time.

Proportional valve motion equation:

\[
\begin{align*}
& m_1 \ddot{x} = F_e + m_1 g - P S_b \cdot k_1 (x + x_{10}) - \beta_1 \dot{x}_1 \\
& (0 \leq x < \delta_{11})
\end{align*}
\]

\[
\begin{align*}
& (m_1 + m_2) \ddot{x} = F_e + (m_1 + m_2) g - P S_b \\
& -k_1 (x + x_{10}) - k_2 (x + x_{20} - \delta_{12}) - (\beta_1 + \beta_2) \dot{x} \\
& (\delta_{12} \leq x \leq x_{\text{max}})
\end{align*}
\]  

(2)

Among them: \( m_1 \) was the quality of the solenoid valve and the ball valve; \( m_2 \) was the mass of the proportional valve; \( k_1 \) was the stiffness of the spring 3; \( k_2 \) was the stiffness of the spring 5; \( x_{10} \) was the preload of the spring 3; \( x_{20} \) was the preload of the spring 5; \( \beta_1 \) was the equivalent viscous damping coefficient of spring 3; \( \beta_2 \) was the equivalent viscous damping coefficient of spring 5; \( P_c \) was the air pressure of chamber C; \( S_b \) was the effective pressure area acting on the ball valve; \( \delta_{12} \) was the initial clearance between the ball valve and the proportional valve spool.

Relay valve motion equation:

\[
\begin{align*}
& m_4 \ddot{y} = P S_b + m_4 g - P S_b \cdot k_4 (y + y_{10}) - \beta_4 \dot{y}_1 \\
& - \text{sign} (\dot{y}) F_f \\
& (0 \leq y < \delta_{44})
\end{align*}
\]

\[
\begin{align*}
& (m_4 + m_5) \ddot{y} = P S_b + (m_4 + m_5) g - P S_b \\
& -k_4 (y + y_{10}) - k_5 (y + y_{20} - \delta_{44}) - (\beta_4 + \beta_5) \dot{y} \\
& - \text{sign} (\dot{y}) F_f \\
& (\delta_{44} \leq y \leq y_{\text{max}})
\end{align*}
\]  

(3)

Among them: \( m_3 \) was the mass of the relay valve piston; \( m_4 \) was the valve seat mass of the relay valve; \( k_4 \) was the stiffness of the spring 7; \( k_5 \) was the stiffness of the spring 9; \( x_{10} \) was the preload of the spring 7; \( x_{20} \) was the preload of the spring 9; \( \beta_4 \) was the equivalent viscous damping coefficient of the spring 7; \( \beta_5 \) was the equivalent viscous damping coefficient of the spring 9; \( P_a \) was the air pressure of the chamber; \( S_b \) was the effective pressure area acting on the piston of the relay valve; \( S_3 \) was the effective pressure area under the piston of the relay valve; \( \delta_{44} \) was the initial clearance between the ball valve and the proportional valve spool; \( F_f \) was the friction between the relay valve piston and the valve body.

3.1.3. Pneumatic equation. It was assumed that there was no gas leakage during the movement of the spool. Because the charging and discharging process was short and fast, the entire process could be considered as an adiabatic process. The dynamic change equation of the plenum filling and deflation process:

Among them: \( A(t) \) was the effective diameter of the valve port; \( P_1 \) was the pressure before the chamber; \( P_2 \) was the pressure after the chamber; \( R_0 \) was the gas constant, air: \( R_0 = 287 J/(\text{kg} \cdot \text{K}) \); \( T_1 \)
was the absolute temperature of the gas in the chamber, $T_1 = 313K$; $k$ was the adiabatic index, $k = 1.4$; $V$ was the volume of the chamber.

\[
\frac{dp}{dt} = \begin{cases} 
\frac{kA(t)p_i}{V} \left( \frac{2^{k-1}}{k+1} \right) \sqrt{\frac{2kRT_1}{k+1}} \\
\left(0 \leq p_i \leq 0.528\right) \\
\frac{kA(t)p_i}{V} \sqrt{\frac{2kRT_1}{k-1} \left[ \left( \frac{p_2}{p_1} \right)^{\frac{3}{k-1}} - \left( \frac{p_2}{p_1} \right)^{\frac{2}{k-1}} \right]} \\
\left(0.528 \leq p_i \leq 1\right)
\end{cases}
\]  

(4)

3.2. Simulation model establishment

According to the above magnetic circuit equation, motion equation and gas path equation, a simulation model of proportional relay valve was established based on MATLAB/Simulink software. It was divided into two models: electronic control and air control. The models are shown in figure 3.

a. The simulation model of electric control  
b. The simulation model of gas control

**Figure 3.** The proportional relay valve simulation model.

4. Test, simulation results and analysis

4.1. Hysteresis characteristics experiment results

The source pressure was set to a typical value of 0.8MPa. The control current was slowly loaded from 0 to the rated maximum current of 1.4A and then decreased to 0. The control air pressure slowly increases from 0 to the maximum pressure of 0.8MPa and then decreased to 0. Experiments were performed on the simulation model and the test system. The results are shown in figure 4.

a. Hysteresis characteristics of electrical control mode.  
b. Hysteresis characteristics of gas control mode.

**Figure 4.** Hysteresis characteristics of different control modes.
Combined with the analysis of (a.) and (b.) in figure 4, the simulation curve and the test curve were similar in the electronic control or air control mode. Among them: (1) under the electric control condition, the control current rose to the opening current value of 0.5A, and the output air pressure started to rise obviously. During the pressurization process, the control current and the output pressure were basically linear and had good stability. In the decompression process, when the current was reduced to a certain degree, the output air pressure would decrease, and the stability would be poor. At the initial stage of decompression, the pressure fluctuation in area A in figure (a.) was significant. This was due to the fact that when the decompression was started, the static friction force was greater than the sliding friction force and the valve port was not stable. Among them, the measured maximum hysteresis current was 0.23A. (2) In the air control mode, the measured opening pressure was 58.98kPa. In the process of pressurizing and depressurizing the output air pressure, the control current and the output air pressure were in a good linear relationship and the stability was good. In the early stage of decompression, there was no significant vibration in the air pressure. This was because there was no effect of the pilot stage proportional valve spool and no magnetic hysteresis of the electromagnet core under the pneumatic control mode. The valve body structure was simplified. Among them, the measured maximum hysteresis pressure was 43.92kPa. (3) The main reasons for the formation of hysteresis characteristics were the opposite movement direction of the various friction forces in the process of pressurization and decompression of the valve core, the compressibility of the gas, the hysteresis effect of the electromagnetic core, and the like.

4.2. Hysteresis characteristics experiment results
The air supply pressure was set to a typical value of 0.8MPa, the control current was given to the maximum rated current of 1.4A. The control air pressure was given to the maximum supply pressure of 0.8MPa. The control signal was given at time 0, and the control signal was removed after the output pressure stabilized for 4 seconds. The experimental results are shown in figure 5.

Combined with the analysis of (a.) and (b.) in figure 5, the simulation curve and the test curve were basically the same in the electronic control or air control mode. Among them: (1) under the electric control mode, the valve response time was 0.19s and the release time was 0.17s. In the simulation results, the air pressure of the air chamber C was rapidly increased or decreased without any delay before the air pressure response of the air chamber E. It could be seen from Equation (4) that the gas chamber C had a much smaller volume in the gas chamber than the gas chamber E whose load was connected. Therefore the response and release time become shorter. (2) Under the air control mode, the valve response time was 0.31s and the release time was 0.3s. The pressure in the chamber A was the control port pressure. In the test result, the chamber A was increased from 0.1s to 0.8MPa. As in the case of the electronic control mode, the response and release time of the air chamber E were longer than the response and release time of the air chamber A. (3) Comparing the slopes of the rising and falling pressures of the output pressure under the two control modes, it could be seen that both the response time and the release time were shorter than the air control mode under the electronic control mode. This was because throttle aperture was narrow and there were gas resistance factors in
controlling the air path. In the electronic control mode, the current control was used, and there were no air resistance and other factors in the control circuit.

4.3. Sealing test results
Good airtightness was the basic requirement of the valve. According to the design of the gas circuit, the valve was tested using the differential pressure method under the condition of the maximum rated input pressure of 1MPa. The results are shown in figure 6. It could be seen that in the test results, the valve outlet leakage was less than 0.2kPa, which was in line with the enterprise standard.

5. Conclusions
The proportional relay valve simulation model was built through the way which was based on MATLAB/Simulink. An EBS proportional relay valve comprehensive performance testing instrument was designed and developed. Several parameters were tested such as its hysteresis current/pressure, open current/pressure, response time, valve port leakage, etc. The experimental results showed that the system could well evaluate the comprehensive performance of EBS proportional relay valve, which had important significance for the research of EBS technology of commercial vehicles, the formulation of product testing standards and the localization of production and manufacturing.

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