AUTOMATIC TESTING METHOD FOR STATIC PRESSURE DRIVE PERFORMANCE OF ELECTRONIC HYDRAULIC BRAKE SYSTEM

by

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To solve the problem of static pressure transmission performance of electronic hydraulic brake system, the mathematical models of main cylinder, solenoid valve, accumulator, and motor hydraulic pump of electronic hydraulic brake system are established. Based on the mathematical model, the static pressure transmission performance of electronic hydraulic brake system is analyzed. Then the standard normal state model of static pressure transmission performance of electronic hydraulic brake system is established by statistical method. The threshold correlation degree between the vibration signal of the static pressure drive and the normal state mode obtained by the vibration acceleration sensor are calculated. If the threshold correlation degree is greater than or equal to 0.5, the precision pressure transmission state of the electronic hydraulic brake system to be tested belongs to the standard normal state, and the threshold correlation degree is less than 0.5, indicating that the precision pressure transmission state of the electronic hydraulic brake system to be tested does not belong to the standard normal state. The test results show that the proposed method can effectively detect the boost response of the static pressure transmission of the electronic hydraulic brake system under high and low strength conditions under normal conditions and accumulator failure conditions. The method can effectively detect the static pressure transmission state of the electronic hydraulic brake system belongs to the fault state according to the threshold correlation degree, which is consistent with the simulation results.

Key words: *electronic hydraulic, braking, static pressure, transmission performance, detection, threshold correlation degree*

Introduction

Electronic hydraulic braking (EHB) system is developed on the basis of traditional hydraulic brakes. The control mechanism replaces the traditional hydraulic brake pedal with an electronic brake pedal and cancels the huge vacuum booster. As a new braking system, EHB has a short development time, but has a broad application prospect [1]. Compared with the electronic mechanical braking (EMB) system, the EHB system is simple and easy to implement [2]. It does not need to provide a separate 42 V power supply, so it has a good prospect in the short term. Traditional hydraulic braking system realizes vehicle braking function directly through hydraulic devices, while line-controlled braking system uses physical signals to transmit braking information and electronic control unit to control mechatronics device to implement braking [3]. Therefore, in essence, the EHB system is not a real line-controlled braking system.

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Although EHB can brake completely independent of the brake pedal [4], its physical circuit does not extend to the wheel brake, the electronic hydraulic brake system still needs brake fluid to transfer brake energy from the accumulator to the brake wheel cylinder. However, compared with other line control braking systems, this structure also has the advantages of high braking efficiency, good portability, easy to control braking force of four wheels independently and easy to realize braking energy recovery, besides basic braking and ABS functions. Because the original hydraulic brake system structure can be retained, manpower can be used as a standby brake option [5] when the energy supply device fails.

With the continuous increase of car ownership in China [6], traffic accidents are also gradually increasing, and vehicle driving safety has become the focus of attention of the industry [7]. The static pressure transmission performance of EHB system plays an important role in vehicle driving safety. It is found that 67% of the safety problems in EHB system are static pressure transmission problems. This paper first establishes the mathematical model of the main cylinder, solenoid valve, accumulator and motor hydraulic pump of the electronic hydraulic brake system, and analyses the static pressure transmission performance of the electronic hydraulic brake system. Then, through the static pressure transmission performance test method of the EHB system based on threshold correlation degree, the static pressure transmission status of the EHB system is detected, and the all-round automation of the static pressure transmission performance of the electronic hydraulic brake system is realized.

Materials and methods

Structure and working principle of electronic hydraulic brake system

The EHB system is mainly composed of brake pedal unit, hydraulic regulating unit and electronic control unit. Brake pedal unit includes brake pedal, brake fluid tank, brake main cylinder, pedal travel sensor and brake pedal sensory simulator. Hydraulic regulating unit includes hydraulic regulator, brake pipeline, wheel brake and pressure sensor installed in accumulator and wheel brake. Electronic control unit is integrated with hydraulic regulator [8], mainly receives signals from sensors and sends control instructions to hydraulic regulators through the controller area network bus. Under normal braking conditions, the brake pedal unit in the EHB system no longer provides braking energy to the wheel brake. It is mainly used to collect the driver's braking intention by using pedal travel sensor and to simulate the driver's braking feeling by using the pedal sense simulator.

The hydraulic regulating unit of electronic hydraulic brake system mainly includes intake valve, outlet valve, balance valve, isolation valve, air bag accumulator and motor pump. Compared with the hydraulic control unit of the electronic stability program, EHB adds isolation valves at the connection between the main cylinder and the hydraulic regulator to isolate the physical connection between the brake pedal unit and the hydraulic control unit [9], it uses a high pressure accumulator to store the high pressure brake fluid from the motor pump to the wheel brake, which provides braking energy to achieve active braking under ordinary braking. The motor pump only drives the motor to make the hydraulic pump work when the accumulator pressure is reduced to the prescribed limit. When the electronic hydraulic brake system works normally, open the oil inlet valve and close the oil outlet valve, the brake fluid enters the brake cylinder from the accumulator through the oil inlet valve to achieve pressurization, it opens the oil outlet valve and close the oil inlet valve, and the brake fluid returns to the brake tank from the brake wheel cylinder through the oil outlet valve to achieve decompression [10], while both the oil inlet valve and the oil outlet valve are closed, the pressure is maintained. When the pressure of brake wheel cylinder on one side needs to be controlled separately, the balance valve should be closed, and the corresponding inlet and outlet valves should work. The isolation valve is closed under normal working condition, and when the EHB power supply device fails, the isolation valve opens without flow. The driver can still send the brake fluid in the main brake cylinder to the brake wheel cylinder through the isolation valve and the brake pipeline through the brake pedal to achieve a certain intensity of braking [11-13].

Mathematical model of electronic hydraulic brake system

The EHB system is a complex non-linear system. In order to effectively realize the static pressure transmission performance of the automatic testing system, the static pressure transmission performance of the system is analyzed based on the hydraulic characteristics of the key parts of the system, including the main brake cylinder, solenoid valve and accumulator. According to the working principle of the electronic hydraulic brake system, during the boosting process, the hydraulic oil passes from the high pressure accumulator to the brake wheel cylinder through the oil pipe and the oil inlet valve and during the decompression process, the hydraulic oil returns to the oil cup from the brake wheel cylinder through the oil pipe and the oil outlet valve. Regardless of the pressure loss of the tubing, the hydraulic characteristics of the main brake cylinder, solenoid valve and accumulator of EHB system are modeled separately.

The isolation valves, balance valves and inlet/outlet valves can be regarded as throttle holes when they are modeled for static pressure transmission characteristics. The flow state of brake fluid in brake pipeline is generally laminar, but the flow state at throttle orifice varies with different working conditions [14, 15]. Compared with the inlet and outlet valves (which are high-speed solenoid valves), the natural frequencies of isolation valves and balance valves are lower, and the flow velocity of brake fluid through isolation valves and balance valves is also lower. When the flow of brake fluid at the throttle orifice is turbulent, the flow continuity equation of the throttle orifice is:

$$q_V = C_d A \sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

where q_V is the flow rate of transmission fluid, C_d – the flow coefficient, ρ – the density of brake fluid, Δp – the pressure difference at both ends of throttle hole, and A – the cross section area of throttle hole.

When the flow of transmission fluid at the throttle orifice is laminar, the flow continuity equation of the throttle orifice is:

$$q_V = \frac{8C_d^2 A^2 \Delta p}{\nu \rho x \mathrm{R_e}} \tag{2}$$

where Re is the critical Reynolds number, ν – the motion viscosity of the transmission fluid, and x – the wet circumference length of the transmission pipeline.

In the transmission process, the piston displacement of the transmission wheel cylinder is very small. In fact, the friction lining has been in close contact with the transmission disk or drum [16, 17]. Therefore, in the process of establishing the static mathematical model of the transmission wheel cylinder, the influence of the displacement of the piston of the transmission wheel cylinder can be directly neglected, and the compressibility of the transmission fluid and the elastic deformation of the transmission disc and friction lining can be mainly considered. Then the flow continuity equation of the transmission wheel cylinder can be expressed:

$$Q_C = \frac{V_C}{K_E}\frac{\mathrm{d}P_C}{\mathrm{d}t} \tag{3}$$

where Q_C is the flow rate of the driving wheel cylinder, V_C – the volume of the driving wheel cylinder, K_E – the equivalent bulk modulus of elasticity of the driving wheel cylinder, and P_C – the pressure of the driving wheel cylinder.

After considering the stiffness of the transmission, the K_E equation is:

$$\frac{1}{K_E} = \frac{1}{K_0} + \frac{A_C^2}{K_C V_C} \tag{4}$$

where K_0 is the volume elastic modulus of transmission fluid, K_C – the equivalent spring stiffness of transmission disk, and A_C – the piston cross-section area of transmission wheel cylinder, among them, the volume elastic modulus of transmission fluid, the equivalent spring stiffness of transmission disk and the piston cross-section area of transmission wheel cylinder are obtained from the parts manufacturer.

Testing method for static pressure transmission performance of EHB system based on threshold correlation degree

Aiming at the automatic detection of static pressure transmission performance of EHB system, if the vibration signal of static pressure transmission performance D of EHB system is obtained by vibration acceleration sensor, *n* characteristic parameters have been determined, and the state mode vector of the characteristic parameters is:

$$f^{(i)} = \left[f_1^{(i)}, f_2^{(i)}, \cdots, f_j^{(i)}, \cdots, f_n^{(i)} \right]^T \tag{5}$$

Among them, *n* is the number of characteristic parameters.

The state mode vectors of the normal state characteristic parameters of the static pressure transmission performance of standard EHB system are:

$$f^{(0)} = \left[f_1^{(0)}, f_2^{(0)}, \cdots, f_j^{(0)}, \cdots, f_n^{(0)} \right]^T \tag{6}$$

Let $f_j^{(0)}$ obey the normal distribution of mean $f_j^{(0b)}$ and variance σ_j^2, $(j = 1, 2, \cdots, n)$.

The smaller $| f_j^{(i)} - f_j^{(0)} |$ is, the greater the possibility of $F_i \in F_0$ is. When $| f_j^{(i)} - f_j^{(0)} | \le K\sigma$, it is judged as $F_i \in F_0$, when $| f_j^{(i)} - f_j^{(0)} | > K\sigma$, it is judged as $F_i \notin F_0$. The $K\sigma$ is actually the confidence interval of characteristic parameters.

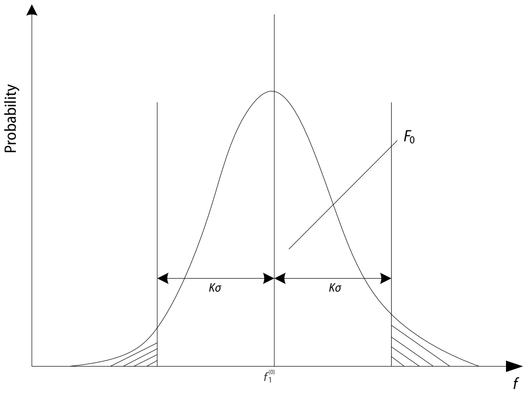

Figure 1. Prevalence diagram of error despite truancy

As shown in fig. 1 when the static pressure transmission performance F_i of EHB system falls within $K\sigma$, the $F_i \in F_0$ is judged, when the static pressure transmission performance F_i of EHB system falls outside $K\sigma$, the $F_i \notin F_0$ is judged. When the test state F_i of EHB system static pressure transmission performance falls into the shadow of the figure, a false rejection error occurs, that is, the test state belonging to the normal state of EHB system static pressure transmission performance standard is misjudged as not belonging to the normal state of standard. The probability of false rejection P_1 is the area of shadow under the curve, and the bigger K, the smaller P_1. The probability density function obeying the Gauss distribution can be obtained by integral operation.

There is a contradiction between rejection of truth and acceptance of falsehood. Only by choosing the appropriate K value according to the specific situation, the probability of rejection of truth and acceptance of falsehood can be tolerated.

From $| f_j^{(i)} - f_j^{(0)} | \le K\sigma$, it can be inferred that:

$$\frac{1}{2} \le \frac{K\sigma}{\left| f_j^{(i)} - f_j^{(0)} \right| + K\sigma} \le 1 \tag{7}$$

Therefore, it shows that the static pressure transmission performance of EHB system is in normal state.

Let the threshold correlation coefficients on the j eigenvalue:

$$r_j^{(i)} = \frac{K\sigma_j}{| f_j^{(i)} - f_f^{(0)} | + K\sigma_j} \tag{8}$$

where $K \in (0,3]$ is a real number. When the threshold correlation coefficient of the j characteristic parameter is greater than 0.5, it can be considered that the j characteristic parameter belongs to the normal state range. For all the characteristic parameters, their functions should be considered comprehensively. Threshold correlation can be used to represent:

$$r^{(i)} = \frac{1}{\sum\limits_{j=1}^{n} a_j} \sum_{j=1}^{n} a_j r_j^{(i)} \tag{9}$$

where a_j is the weighted coefficient. Different feature parameters have different weights, and the weights should be analyzed in detail. Through the previous analysis of static pressure transmission performance, the following conclusions are drawn:

- $r^{(i)} < 0.5$, EHB system static pressure transmission performance to be tested state does not belong to the standard normal state.
- $r^{(i)} \ge 0.5$, EHB system static pressure transmission performance to be tested state does not belong to the standard normal state.

In practical application, because the total mean and variance of the characteristic parameters of EHB static transmission performance standard cannot be obtained, the sample mean $\hat{f}_f^0$ is used instead of the total mean f_f^0, and the sample variance $\hat{\sigma}_j^2$ is used instead of the total variance σ_j^2.

Results

Characteristic detection of supercharging response of static pressure drive

The static pressure transmission performance of EHB system under normal conditions is tested by this method. Figure 2 shows the curve of the static pressure transmission performance of EHB system under ordinary braking. Figure 2 shows the anti-lock control curve of static pressure transmission performance of EHB system under emergency braking.

From the data of fig. 2, it can be seen that the response time of this method is about 20 ms at low strength and 40 ms at high strength. With the increase of strength, the pressure gap between front axle and rear axle wheel cylinder of EHB system decreases.

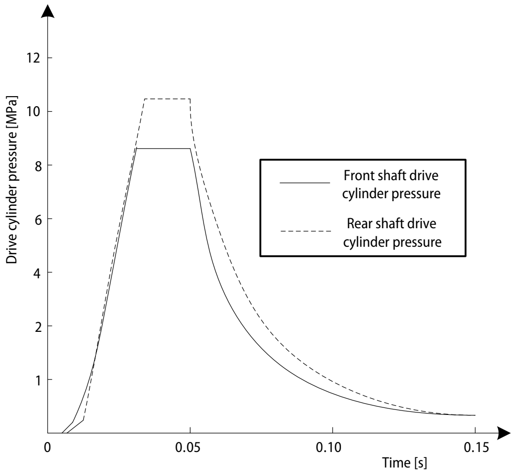

Figure 2. Increase and decompression curve of wheel cylinder with front and rear shaft under different transmission strength

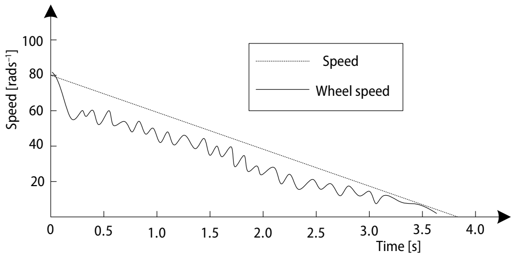

Figure 3. Anti-lock braking curve of road

It can also be seen from fig. 3 that the response time of static pressure drive in EHB system is about 3-5 times that of boosting response time. It can also be concluded that the EHB system controlled by this method can control the slip rate of wheels well on high and low adhesion pavement.

Detection of static pressure drive state of electronic hydraulic brake system

The static pressure transmission performance of the electronic hydraulic brake system of the experimental vehicle is tested by this method. The vibration acceleration signal of five points on the electronic hydraulic brake system is used as the original signal. The state mode vector is composed of skewness index fp, kurtosis index fq, peak index ff and power spectrum center of gravity index fg of the original signal. There are 20 characteristic parameters. When calculating threshold correlation degree, each threshold coefficient is set to equal weight.

The static transmission fault is simulated in EHB system. The static transmission performance of EHB system fault is tested again, and the vibration signal data of 2 and 3 points are recorded. The skewness index fp, kurtosis index fq, peak index ff and power spectrum center of gravity index fg of two-point vibration signal are calculated by the recorded data. The threshold coefficients of each index relative to the normal state of EHB system static pressure transmission performance standard are calculated by eq. (14). The threshold of two measuring points vibration signal relative to the normal state of EHB system static pressure transmission performance standard is calculated by eq. (15). The threshold coefficients are shown in tab. 1.

The threshold correlation in tab. 1 is weighted by equal weight. When the threshold coefficient $K = 2$, the threshold correlation degree of EHB static pressure transmission performance is $r = (0.4702 + 0.469)/2 = 0.4701 < 0.5$, which indicates that the static pressure transmission state of the system is judged as a fault state, and the judgment is correct. It shows that this method can effectively detect the static pressure transmission state of the EHB system and reflect the static pressure transmission performance of the electronic hydraulic brake system based on the threshold correlation degree.

Table 1. Relevance of threshold for two points

		Offset index threshold coefficient	Trigonal index threshold coefficient	Peak peak index threshold coefficient	Power spectrum center of gravity threshold coefficient	Threshold correlation
The threshold coefficient is 2	2#Measurement point	0.433	0.468	0.504	0.476	0.47
	3#Measurement point	0.412	0.446	0.512	0.507	0.469

Conclusion

Based on the mathematical model of the main cylinder, solenoid valve, accumulator and motor hydraulic pump of the electronic hydraulic brake system, the static pressure transmission performance of the electronic hydraulic brake system is analyzed, and then the static pressure transmission performance of the EHB system is tested by the static pressure transmission performance detection method based on threshold correlation degree. The transmission performance of EHB under common braking and hardware failure is studied based on the mathematical model. It is concluded that this method can effectively detect the boost response of static pressure transmission of EHB system under high strength and low strength under normal conditions and accumulator failure. With the increase of strength, the front and rear axle wheels of EHB system can be detected. This method can effectively detect the static pressure transmission state of EHB system, and comprehensive experimental results show that this method can detect the static pressure transmission performance of EHB system in all aspects.

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