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Pneumatic Regulating Module of Regenerative Braking System in Electric Bus

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Abstract

The Regenerative Braking System (RBS), as an important energy-saving technology, can effectively improve the energy economy of the electric vehicle [1]. The introduction of the regenerative braking force requiring the pneumatic regulating module to control the friction braking force more precisely and quickly. Solenoid on/off valve (SV) is controlled discontinuously with long response time as well as frequent pressure fluctuation, so consider using proportional relay valve (PPV) instead of it. A typical braking and Anti-lock Brake System (ABS) control Hardware-In-Loop (HIL) test was conducted with two kinds of pneumatic regulating modules. The test results shown that the PPV has more advantages in application of RBS.

Key Words: Electric Vehicle, Regenerative Braking Systems, Solenoid On/off Valve, Proportional Relay Valve, Hardware-In-Loop

1. Introduction

Related research shows that 30% to 50% of the energy used to drive the vehicle is consumed in the braking process under urban conditions, if this part of the energy regenerated and stored can greatly improve the car's fuel economy. The RBS, as an important energy-saving technology, can effectively improve the energy economy of the electric vehicle, which is a great significance for relieving energy crisis and environmental pressure. For electric vehicles, the RBS technology can use the motor to convert part of the vehicle kinetic energy into electrical energy and stored in the battery, which making a significant contribution to extending the mileage [2].

However, the introduction of the regenerative braking force makes the pneumatic regulating module to adjust friction braking force according to the intervention degree of the motor regenerative braking force in real time. The friction braking force is not only determined by the brake pedal, but also affected by the battery status and motor load. In order to meet the demand of the total braking force, requiring the pneumatic regulating module to control the friction braking force more precisely and quickly. The SV, which was widely used for pneumatic regulating module, is controlled discontinuously with long response time as well as frequent pressure fluctuation, which makes it unable to realize accurate control. Additionally, the repeated switch action of the valve block limits the working life and causes noise which affects the driving comfort. While the PPV with continuous control, no work-noise, long life, and high precision control, so consider using PPV instead of SV as pneumatic regulating module to adjust the friction braking force.

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2. The Scheme Design of Pneumatic Regulating Module for RBS

The scheme of pneumatic regulating module with SV and PPV are shown in Figure 1 and 2. The motor control unit (MCU) controls the motor in the power generation state and stores the electric energy in the battery, during the braking or deceleration of the vehicle. The brake control unit (BCU) controls the pneumatic regulating module to adjust the friction braking force according to the intervention degree of the motor regenerative braking force in real time. Vehicle control unit (VCU) monitor the vehicle running status. VCU, MCU, BCU as well as Battery Management System (BMS) through the Controller Area Network (CAN) to communicate [3,4].

The scheme of pneumatic regulating module with SV for RBS is based on the mature pneumatic ABS. Each wheel were installed a SV for pneumatic adjustment, and the front and rear axle installed a relay valve to rapidly reduce pressure and shorten the pressure adjustment time. BCU using ABS/RBS integrated control unit, which all worked by the SV to adjust pressure in the RBS and ABS state.

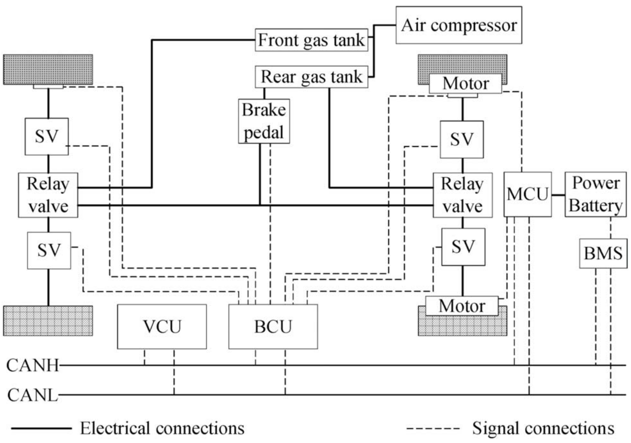

Figure 1. The scheme of pneumatic regulating module with SV for RBS.

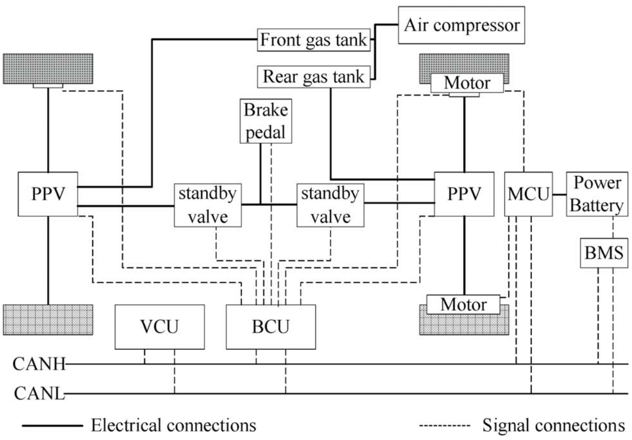

Figure 2. The scheme of pneumatic regulating module with PPV for RBS.

The RBS with the PPV is also based on pneumatic ABS. The front and rear axles are fitted with a PPV. The standby port is connected to the gas tank through the standby switch valve, and the connection is shown in Figure 3. The PPV is connected with the atmosphere under normal working condition. When the electronic control part is failure, the standby switch valve is also powered off, normally open valve open, normally closed valve closed, so that the standby port directly connected with the gas tank, ensure that the vehicle has a conventional braking capacity to protect the safety of vehicle braking.

3. HIL Test

3.1 Introduction to HIL Test System

HIL, also known as semi-physical simulation, is a substitute for some virtual objects to simulate, the requirements of the site and equipment more relaxed relating to the actual system testing and have better aspect relating to pure virtual system simulation [5].

HIL test system platform structure and physical connection shown in Figure 4, 5, which including xPC realtime simulation system, data collection – control unit system and pneumatic test bench [6,7].

Vehicle models and control algorithms run in the xPC target environment in real time. xPC targetis an add-on product based on the RTW system that Math Works

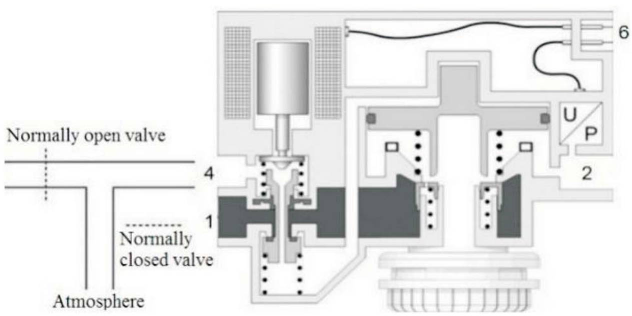

Figure 3. The connection between standby switch valve and PPV.

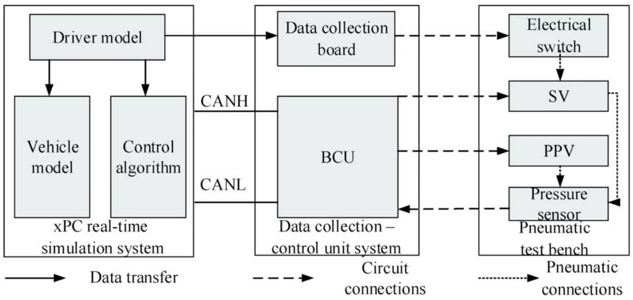

Figure 4. HIL test system platform structure.

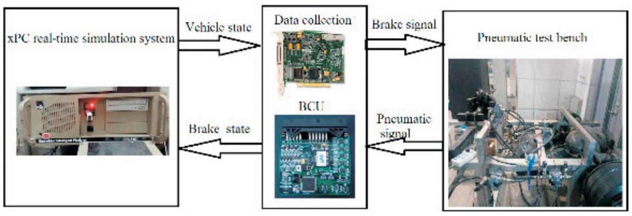

Figure 5. HIL test system physical connection.

distributes and offers. xPC target uses the host-target machine to run and the target is responsible for running the host-generated code in realtime, which through the serial port connection or Ethernet connection to communication.

The data collection – control unit system includes a data collection board and a brake control unit. Data collection board using NI's PCI 6221 data collection board and brake control unit using ABS/RBS integrated controller.

Pneumatic test bench transform from electric vehicle pneumatic braking system, which including air compressor, gas tank, brake pipe and so on. Using the electrical switch simulation brake pedal to achieve automatic control to automatically track the driving cycle conditions on the bench. BCU and xPC target through the CAN for real-time communication.

3.2 Typical Braking HIL Test

In order to test the effectiveness and safety of the control algorithm and key components, the typical braking test was carried out based on the HIL test system. The control effect of two kinds of pneumatic regulating modules is analyzed and compared from the aspects of pressure fluctuation, braking smoothness and regenerative braking efficiency under different braking intensity.

During the regenerative braking process, the coupling and switching of the regenerative brake and the friction brake directly affects the braking smoothness of the vehicle, so the impact rate J is used to evaluate the braking smoothness. The impact rate is the rate of change in vehicle acceleration.

From the vehicle theory related knowledge that:

$$J = \frac{d^2 u_0}{dt^2} \tag{1}$$

where u_0 is the longitudinal velocity of the vehicle body.

Related research shows that in the comfortable range of people can withstand the maximum impact rate is 10 m/s^3. The higher the comfort requirement, the smaller the impact rate should be controlled during the braking process.

The typical braking HIL test's condition is on the high surface (the adhesion coefficient is 0.8), the initial speed is 60 km/h.

For the SV, take moderate brake for example, the parameter of speed, deceleration, impact rate are shown in Figure 6. Speed curve is relatively smooth, which shown that the vehicle can achieve a smooth braking. The fluctuation of deceleration due to the fluctuations of pressure, which will be reduced when the coupling and switching of the regenerative braking and the friction brake, yet the overall deceleration is basically maintained near the target value. The impact rate is mainly appear at the initial braking and braking coupling, but the absolute value is maintained at an acceptable range of 10 m/s^3. The aspect of pressure following in the steady state process is favorable, yet there is pressure fluctuations in the dynamic process, which is determined by the control algorithm's characteristics. The overall aspect of pressure following can meet the needs.

For the PPV, take moderate brake for example, the parameter of speed, deceleration, impact rate, front and

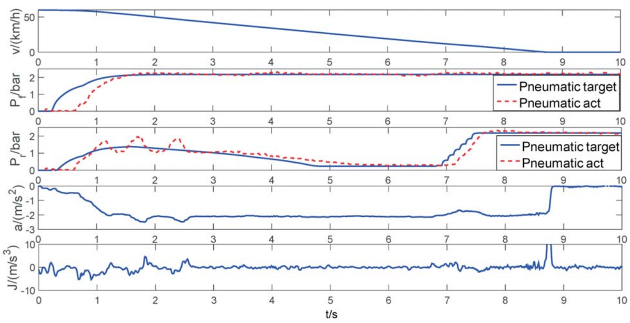

Figure 6. The HIL test results of moderate brake with SV.

rear axis pressure are shown in Figure 7. Speed curve is shown that the vehicle can achieve a smooth braking too. The deceleration curve is relatively smooth and only exist slightly fluctuates during the brake switching process. The fluctuation of the impact rate is still appear at the initial braking and braking coupling, but vehicle braking smoothness have been greatly improved. PPV can be very good to achieve the target pressure following, especially in the initial stage of the brake.

Compared from the aspects of pressure fluctuation, braking smoothness and regenerative braking efficiency to further quantify the control effect of two kinds of pneumatic regulating modules.

The Root Mean Square Error (RMSE) of the actual pressure and the target pressure is taken as the evaluation criterion of the pressure following effect. The formula is as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(e(k))^2} \tag{2}$$

where n is the total number of samples; k is the k-th sample.

The braking smoothness is expressed by impact rate. Because the impact rate has positive and negative, the impact rate is evaluated by the Root Mean Square Jerk (RMSJ). The formula is as follows:

$$RMSJ = \sqrt{\frac{1}{n}\sum_{k=1}^{n}J^2} \tag{3}$$

The regenerative braking efficiency is used to measure the regenerative energy capacity of the system. It is defined as the percentage of regenerative energy by the motor to the recoverable energy of the vehicle, denoted by η_{reg}, as follows:

$$\eta_{reg} = \frac{E_{regen}}{E_{recoverable}} \times 100\% \tag{4}$$

where E_{regen} is the regenerative energy actually; $E_{recoverable}$ is the recoverable energy of the vehicle.

$$E_{regen} = \sum_{i=1}^{n}\left(\int_{t_{i0}}^{t_{ik}} T_{mot\_ij}\,\omega_{ij}\,dt\right)(T_{mot\_ij} < 0) \tag{5}$$

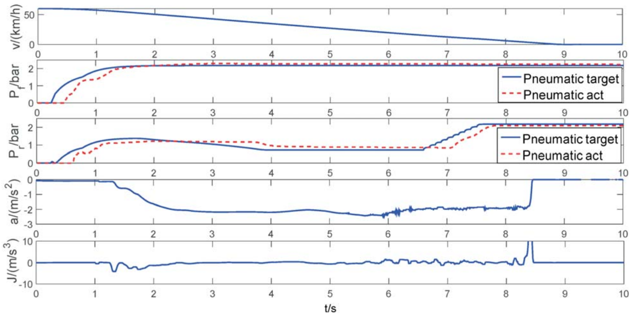

Figure 7. The HIL test results of moderate brake with PPV.

where t_{i0} is the braking or deceleration start time; t_{ik} is the braking or deceleration end time; T_{mot_ij} is the regenerative braking torque at the time of the i-th j-th; ω_{ij} is the motor rotating speed at the time of the i-th j-th.

In the whole case, all the recoverable vehicle kinetic energy at the generator input port is:

$$\begin{aligned} E_{recoverable} = &\left(\sum_{i=1}^{n}\left(\frac{1}{2}m(v_{i0}^2 - v_{ik}^2)\right) - \int_{t_{i0}}^{t_{ik}} fmgv_{ij}\,dt \right.\\ &\left. - \int_{t_{i0}}^{t_{ik}} \frac{C_D A}{21.15}(3.6v_{ij})^2 v_{ij}\,dt\right)\eta_d \end{aligned} \tag{6}$$

where v_{i0} is the initial speed of the i-th braking or deceleration process; v_{ik} is the vehicle speed at the end of the i-th braking or deceleration process; v_{ij} is the vehicle speed at the time of the i-th j-th; m is the vehicle mass; f is the rolling resistance coefficient; g is the acceleration of gravity, take 9.8 m/s^2; C_D is the drag coefficient; A is the windward area; η_d is the transmission efficiency.

The HIL test results of pneumatic regulating module with SV and PPV for RBS is shown in Table 1.

From the parameters of the table can be seen that the RMSE under the control of PPV is smaller relative to the SV, which indicating the PPV have a higher control accuracy. When the maximum impact rate occurs at the end of the braking, the deceleration is reduced to zero in a very short time, so there is a peak in the impact rate. This is difficult to avoid, only through the control algorithm to improve. The RMSJ value is more valuable. The RMSJ under the control of two kinds of pneumatic regulating modules are below the 10 m/s^3, and have good braking smoothness. Under the control of PPV, J_{max} improvement rate more than 40%, RMSJ also has a great improvement relative to the SV. The lower the severity of braking, the greater the degree of regenerative braking torque, the

Table 1. Comparison of typical braking HIL test results

Severity of braking	Modules	RMSE (Mpa)	J_{max} (m/s^3)	The improvement range of J_{max}(%)	RMSJ (m/s^3)	The improvement range of RMSJ(%)	η_{reg}
Mild braking	SV	0.158	15.75	42.04%	1.016	33.71%	47.97%
	PPV	0.150	9.16		0.670		49.10%
Moderate braking	SV	0.352	30.82	41.86%	2.031	19.95%	24.71%
	PPV	0.313	17.79		1.628		25.65%
Severe braking	SV	0.586	47.62	45.62%	3.385	11.56%	21.56%
	PPV	0.549	25.89		2.996		22.51%

higher the efficiency of the regenerative braking. The regenerative braking efficiency under the control of the PPV is higher than SV. In addition, the environmental noise is also one of the factors that affect the comfort of the vehicle brake. There is no quantitative analysis on the work noise problem, but the subjective feeling is not in the order of magnitude when doing experiments. From this point of view, the PPV have a better braking smoothness.

In summary, the PPV can achieve the precise adjustment of pneumatic, which have the advantage of high precision and largely improve the vehicle braking smoothness and comfort relative to the SV.

3.3 ABS Control HIL Test

The control strategy is the core of the ABS control unit. The logic threshold control, which is based on the large number of test calibration results, has strong robustness and is the widely used technology [8].

The ABS system on the impact of vehicle stability need to be considered. It will produce additional steering torque that led to vehicle out of control, if two sides of the instantaneous braking torque largely different. Front and rear wheels are based on the most obvious side of the lockout trend to adjust the braking torque, that is low-selection control strategy, as shown in Figure 8 [9−11].

Where $\dot{\omega}_f$ is the deceleration of the left side wheel; $\dot{\omega}_r$ is the deceleration of the right side wheel; S_f is the reference speed of the left side wheel; S_r is the reference speed of the right side wheel; Phase is the stage of the control cycle. S_1 is the small slip rate logic threshold; S_2 is the large slip rate logic threshold; $-a_1$ is the deceleration logic threshold; a_2 is the small acceleration logic threshold; a_3 is the large acceleration logic threshold. Eight phases can be divided into "increase", "keep", "decrease" three states, respectively, that the trend of changes in pneumatic braking force.

Phase 1 is the "keep" stage, which is entered when both sides of the wheel deceleration have less than $-a_1$. On both sides of the reference slip rate there is a greater than S_1, then the control logic goes into the "decrease" phase 2. Phase 3 and phase 4 are twin logic. The control logic goes into the "decrease" phase 3 when both sides of the wheel deceleration are greater than $-a_1$ and the reference slip rate is greater than S_2, otherwise enter the "keep" phase 4. Phase 3 is to decrease the pneumatic braking force at the lower adhesion coefficient, so that the wheel speed rapidly increasing. The controllogic goes into the "keep" phase 5 when both sides of the wheel decelera-

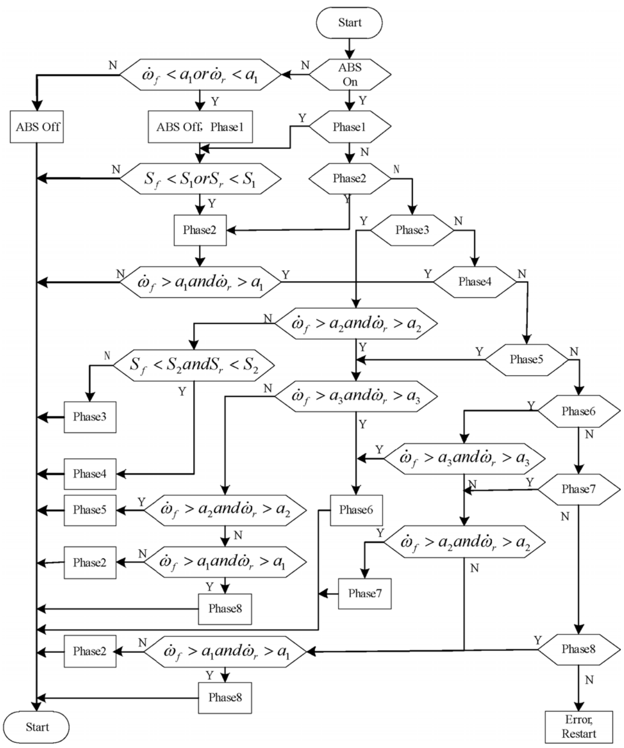

Figure 8. The ABS two - wheel low - election control strategy.

tion is greater than a_2, which can be seen as the extension of phase 4 at the high adhesion coefficient of the road. Phase 6 is the "increase" stage, which is entered when both sides of the wheel deceleration are greater than a_3. The control logic from the "increase" phase 6 goes into the "keep" phase 7 when the two sides of the wheel deceleration is less than a_3. The control logic goes into the "increase" phase 8 when both sides of the wheel deceleration is less than a_2, and goes into the "decrease" phase 2 when both sides of the wheel deceleration has a less than $-a_1$.

The basic principle of ABS two-wheel low-election control strategy is that when both sides of the wheels appeared to lockout trend, then decrease the pneumatic braking force; when both sides of the wheels are out of danger, then increase the pneumatic braking force. Although the low-selection control strategy may make the adhesion coefficient utilization of the better side is low, but can ensure that both sides of the brake force is basically same which ensure vehicle stability. In the control strategy, there is no pneumatic adjustment when the vehicle speed is reduced to below 8 km/h to prevent the malfunction.

The two kinds of pneumatic regulating modules were tested under the low adhesion coefficient based on the HIL test system to test the control effect in the ABS state under the emergency braking. The control effect of two kinds of valves is analyzed and compared from the parameters of the change of the wheel speed, braking distance, slip rate, adhesion coefficient utilization [12].

According to the "anti-lock braking test method", the test conditions is 80 km/h for the initial speed in the low adhesion coefficient (adhesion coefficient is 0.2). The ABS control effect with the SV is shown in Figure 9.

The front wheel are not locked under the effective regulation of the ABS control strategy. The pneumatic pressure and the wheel speed show periodic changes. The slip rate is kept at 20% near the best slip rate. When the slip rate in the near of 20%, the longitudinal adhesion coefficient and the lateral adhesion coefficient are larger, and the vehicle is in a stable state.

The ABS control effect with the PPV is shown in Figure 10. The front wheel are not locked under the effective regulation of the ABS control strategy. The pneumatic pressure and the wheel speed show periodic changes. The slip rate is kept at 20% near the best slip rate.

Compared from the parameters of slip ratio, impact rate, brake pressure, braking distance and adhesion coefficient utilization to further quantify the ABS control effect of two kinds of pneumatic regulating modules.

The adhesion coefficient utilization is defined as:

$$\varepsilon = \frac{z_{AL}}{k_M} \tag{7}$$

where ε is the adhesion coefficient utilization; z_{AL} is the maximum braking strength when ABS system is working; k_M is the measured road surface adhesion coefficient.

The maximum braking strength when ABS system working is:

$$z = \frac{0.849}{t_M} \tag{8}$$

where t_M is the time that the vehicle decelerates from 45 km/h to 15 km/h.

The ABS control effect of two kinds of pneumatic regulating modules is shown in Table 2.

The test results show that the average braking pressure under the control of the PPV is higher relative to the

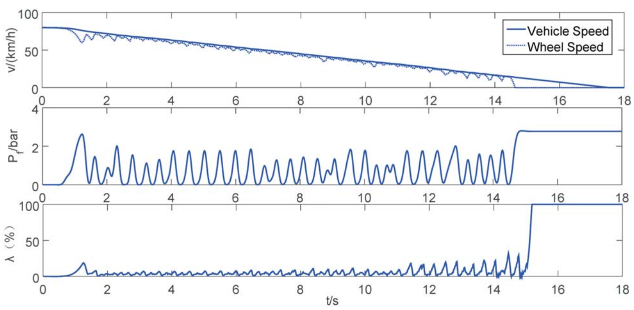

Figure 9. The ABS control effect in the low adhesion coefficient with SV (left front wheel).

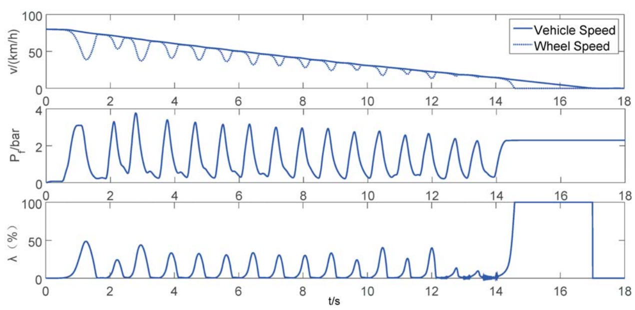

Figure 10. The ABS control effect in the low adhesion coefficient with PPV (left front wheel).

Table 2. Comparison of ABS control HIL test results

Project	SV	PPV
Braking strength (m/s^2)	1.30	1.33
Impact rate (m/s^3)	3.61	2.45
Braking pressure (Mpa)	0.154/0.169	0.158/0.171
80 km/h~0 braking distance (m)	191.6	186.0
Adhesion coefficient utilization (%)	80.43	84.10

SV, which resulting in a higher average braking strength, a shorter braking distance and a higher adhesion coefficient utilization. And the average impact rate is smaller, which significantly improved the braking smoothness. In summary, the two valve blocks can meet the application requirements in braking pressure and braking strength, but the PPV has greatly improved the braking distance and impact rate, greatly improving the ride comfort of the vehicle.

4. Conclusion

The pneumatic regulating module of RBS of electric vehicle were investigated in this paper. Based on the mature pneumatic ABS, the RBS with SV and PPV is designed.

A HIL test system, which including xPC real-time simulation system, data collection – control unit system and pneumatic test bench, was built. The typical braking HIL test results shown that the RMSE under the control of PPV is smaller relative to the SV, and the impact rate significantly improved, the maximum impact rate of improvement more than 40%, regenerative braking efficiency increased about 1%. The ABS control HIL test results shown that the braking pressure under the control of PPV is higher relative to the SV, and braking distance reduced 5.6 meters, the average impact rate is smaller which significantly improved the braking smoothness. The test results shown that the PPV has more advantages in application of regenerative brake systems.

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