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Development of Integrated Electro-Hydraulic Braking System and Its ABS Application

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This paper presented a new type of integrated EHB system. The EHB consisted of a compact three-chamber structure of master cylinder and mode switching valves. This allowed for the easy implementation of three different modes: normal mode, failsafe mode and ABS mode. In normal mode, a PWM control method was proposed for pressure regulation that took into account overshoot and hysteresis. To provide a favorable pedal feeling, a pedal stroke simulator was designed and integrated with the master cylinder. The failsafe and ABS modes were verified and the performance of the EHB in the three modes was evaluated using co-simulation and a bench test.

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1. Introduction

With the development of electric vehicles (EVs), hybrid electric vehicles (HEVs) and intelligent vehicles, the Brake-By-Wire (BBW) system now plays a more important role than before. Since BBW is independent of engine vacuum structurally, the system would have no impact on drive's braking intent. Moreover, it was more flexible to meet the requirement of other upper controller, such as applied to regenerative braking system.[1] As the two main categories of BBW systems, the electro-hydraulic braking (EHB) system and electro-mechanical braking (EMB) system are not compact enough and their fail-safe function has been a worrying aspect. Considering that EMB braking torque is difficult to estimate precisely,[2,3] the EHB seems to be a better solution for current application situation in terms of complexity, reliability and cost.

BOSCH developed a brake-by-wire system on a hydraulic basis, called Electro-hydraulic Brake (EHB) in the early 1990s.[4] It became a template for the subsequent EHBs.[4-6] Its hydraulic control unit (HCU) was similar to typical structure of Vehicle Dynamic Control (VDC). Brake pressure buildup was supplied by a high pressure accumulator. Generation of the high pressure was done by an electric motor driven pump. Additionally, the pressure between master cylinder and wheel cylinder was tactfully decoupled by a new design of pedal stroke simulator. On the basis of that, Nakamura et al. improved performance of wheel cylinder pressure through linear solenoid valves other than high-speed on-off valves.[7]

However, the usage life of hydraulic accumulator limited the reliability of EHB. An electrically-driven intelligent braking system was developed by Nissan Motor and Hitachi Automotive Systems.[8] There were two pressure sources providing redundancy feature. The braking pressure in the master cylinder was regulated by two parallel pistons. The primary piston was driven by the motor and ball screw, while secondary piston was linked directly to the pedal. Two pistons were connected by springs for a good pedal feeling. For fail-safe and ABS design, VDC HCU could be as the second pressure source in the downstream. Wang et al. proposed a distributed EHB system.[9] Each disc brake was controlled by an independent closed-loop actuator. In this scheme, EHB was hard to install and control. Considering the machining precision, the estimation of braking torque was difficult to realize. Yong et al. introduced a new integrated modular brake system (IBS) from LSP Innovative Automotive Systems.[10] The pressure was controlled by piston motion which was driven by a BLDC motor. And a transmission mechanism was adopted to change rotary motion of motor to translational motion of piston. Since master cylinder piston was controlled according to pressure-volume characteristic, an accurate pressure regulation was feasible. Although ABS function was integrated in IBS, the pressure regulation of wheel cylinders couldn't be implemented individually in ABS mode. Jin et al. designed an active pedal stroke simulator to regulate pedal feeling.[11] However, the coupled pressure between master cylinder and wheel cylinder was overlooked. D'alfio et al. suggested the main design specifications of EHB and made it clear the advantages over conventional brake systems.[12]

The application of ABS based on EHB structure should be focused on. However, there were few researches about ABS application on EHB system. Generally, ABS was installed as an independent HCU module, and could provide superior performance in hard braking. In terms of installation, cost and control structure, it was difficult to execute ABS function for existing EHB configuration. Therefore, a new type of integrated EHB was introduced in this paper.

This paper was organized as follow. Firstly, the integrated structure of EHB and its three working modes were presented. The proposed EHB was quite different from the above configurations. The high pressure accumulator was removed, while ABS and failsafe braking could be well implemented through valves and motor control. In addition, mathematical models of key components in EHB were built. To ensure a good pedal feeling, a passive pedal stroke simulator was designed. Moreover, a pressure following algorithm in normal mode and a logic threshold method in ABS mode were proposed. Finally, the co-simulation based on AMEsim/Simulink /CarSim and the bench tests were implemented to analyze the EHB characteristic.

2. EHB Configurations

The integrated EHB architecture was illustrated in Fig. 1 and 2. The EHB system was mainly composed of three parts including the mode-switch module, the integrated master cylinder module and the wheel cylinder module. The mode-switch module was composed of three on-off solenoid valves for three typical modes, the normal mode, failsafe mode and ABS mode. The operation condition of solenoid valves in three typical modes was described in Table 1. The integrated master cylinder consisted of master cylinder and pedal stroke simulator. The master cylinder which contains three chambers was developed from the traditional structure. While the pedal stroke simulator was designed using composite springs 2 and accumulator 18. Between the two components, an oil-catch piston 22 was adopted for connection. A significant advantage of the structure lied in decoupling between brake pressure generation and driver's pedal feeling. In addition, EHB system provided a backup mode in which brake pressure was built up via pedal force directly when control unit failed. Simultaneously, the proposed EHB system could save nearly 50% spaces for installation compared to traditional brake system. All actuators including master cylinder, twelve solenoid valves, sensors, motor and simulator were integrated as a whole block which was shown in Fig. 1.

Fig. 3 presented the flow of brake fluid in normal mode. When EHB was working in normal mode, the pressure in the third chamber 23 was higher than the simulator and the oil-catch piston 22 was pressed at the bottom of the chamber, which decoupled the connection between master cylinder and the pedal stroke simulator. The decoupled relationship avoided pressure ripple from delivering to the pedal. During the pressure increasing stage, the pressure difference made the piston 14 and 17 move left. The fluid in the first and the second chamber was compressed, and the pressure in the wheel cylinder could be built immediately. During the pressure decreasing stage, the pressure decreased firstly in the third chamber 23. With the piston 14 and 17

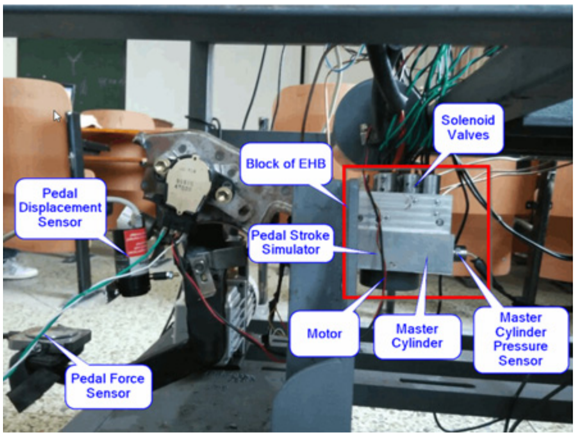
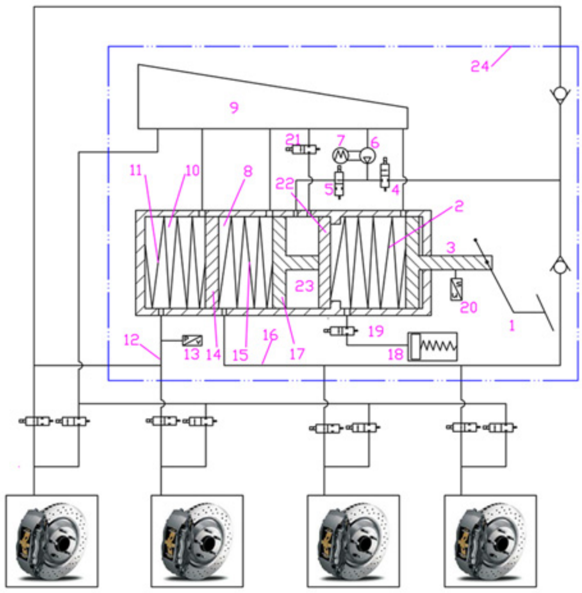


Fig. 1 Composition of EHB system



1. Brake Pedal; 2. Composite Springs; 3. Pedal Push Rod; 4. Control Valve for ABS Mode; 5. Control Valve for Normal Mode; 6. Pump; 7. DC Motor; 8. The Second Chamber; 9. Oil Tank; 10. The First Chamber; 11. Return Spring; 12. Circuit Ⅰ 13. Pressure Sensor; 14. Intermediate Piston; 15. Return Spring; 16. Circuit Ⅱ 17. Push-Rod Piston; 18. Spring Loaded Accumulator; 19. Control Valve for Failsafe Mode; 20. Displacement Transducer; 21. Release Valve; 22. Oil-Catch Piston; 23. The Third Chamber; 24. Integrated Master Cylinder Valve Block;

Fig. 2 Structure of EHB system

Table 1 Operation condition of mode-switch module

Modes	ABS Valve	Normal Valve	Failsafe Valve
Normal Mode	CLOSED	OPEN	OPEN
Failsafe Mode	CLOSED	CLOSED	CLOSED
ABS Mode	OPEN	CLOSED	OPEN

moved right, the pressure of wheel cylinder declined. In this method, the pressure regulation was in accordance with pressure-volume characteristic of traditional master cylinder.

If there was a breakdown for electronic control unit, all actuators including valves and motor were in its default state. In this case, the built-up pressure totally relied on pedal force exerted by foot. Fig. 4 illustrated the flow of brake fluid in failsafe mode. The failsafe valve 19 was closed, and the fluid couldn't flow into accumulator 18. So the pressure in the simulator became higher than the third chamber 23 and the oil-catch piston 22 was able to push the push-rod piston 17. In failsafe mode, the brake pressure was generated through a conventional hydraulic way.

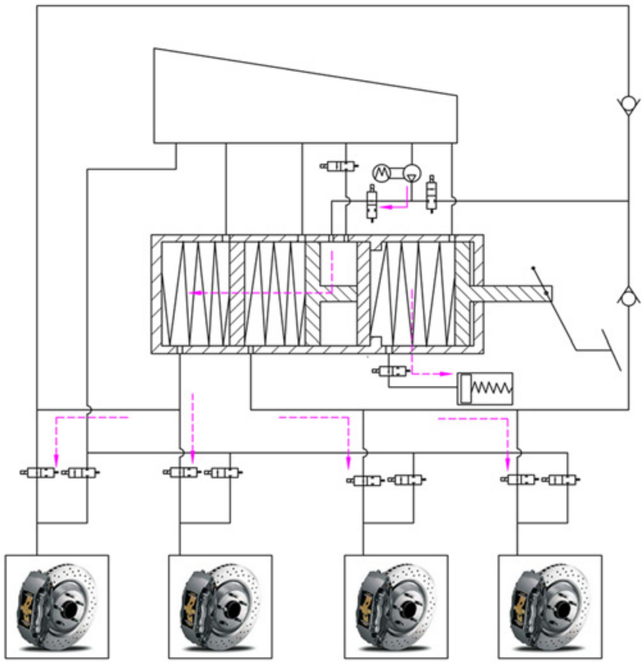


Fig. 3 Flow of fluid in normal mode

Unlike conventional ABS structure, the low pressure accumulator and specific ABS motor were removed in the EHB system. It meant that the motor operated to generate pressure both in normal mode and ABS mode. The main function of eight solenoid valves was responsible for independent pressure regulation of wheel cylinder in ABS mode. The flow of brake fluid in ABS mode was shown in Fig. 5. When in ABS increasing stage, the plunger pump 6 made fluid flow into wheel cylinders via ABS valve 4 and corresponding normally open valves. In ABS decreasing stage, the fluid directly flowed back to oil tank via normally closed valves. In ABS mode, the piston 14 and 17 hardly moved since pressure was maintained in the third chamber 23. In other words, the total oil volume in master cylinder could be seen as a constant. Therefore, the pressure regulation was achieved through the fluid flow increasing or releasing in wheel cylinder, similar to the principle of VDC system.

3. Hydraulic System Model

3.1 Master cylinder model

The pistons and springs in the traditional master cylinder could be used in the EHB system, so the mathematical model was similar to the tradition structure. As seen in Fig. 1, after the pressure was built in the third chamber 23, the push-rod piston 17 squeezed the brake fluid into brake circuit II. The compression of the spring and the pressure in brake circuit II actuated the intermediate piston 14, which built up pressure in brake circuit II. When the push-rod piston 17 had not touched the intermediate piston 14, the two pistons could be considered as two independent rigid bodies. The state function could be concluded as below:

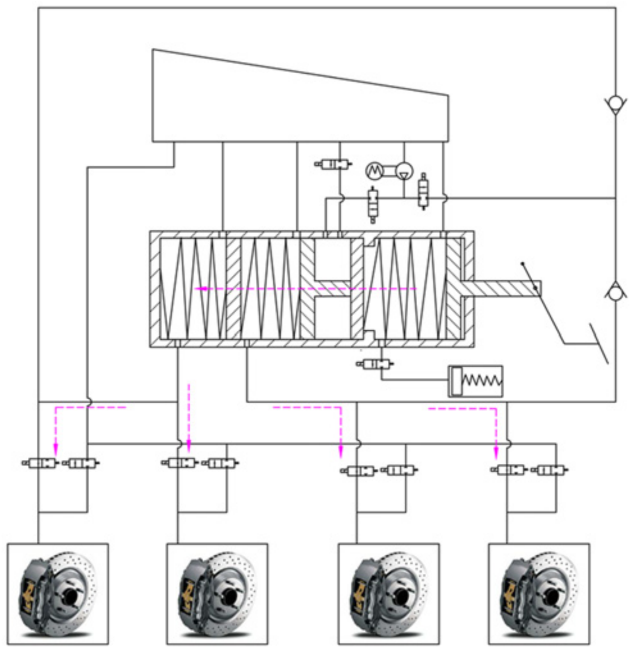


Fig. 4 Flow of fluid in failsafe mode

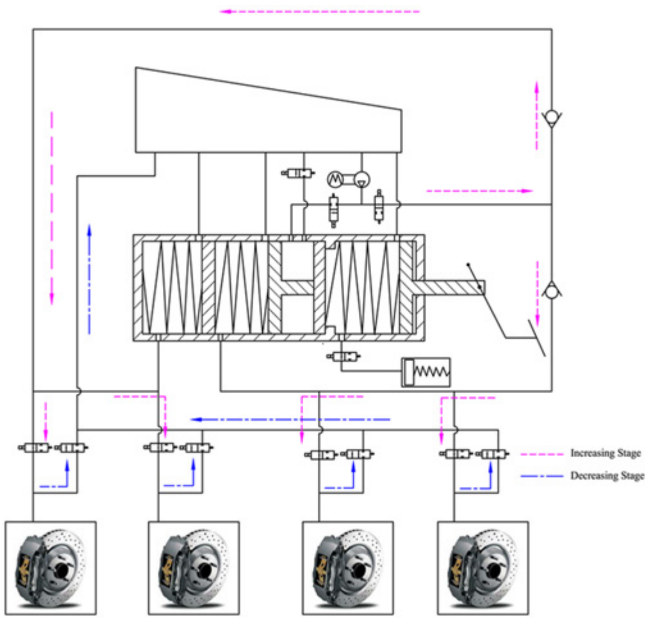


Fig. 5 Flow of fluid in ABS mode

$$\begin{cases} m_1\dfrac{d^2x_1}{dt^2} = F_b - p_1A_1 - F_{s1} - F_{d1} \\ m_2\dfrac{d^2x_2}{dt^2} = p_1A_1 + F_{s1} + F_{d1} - p_2A_2 - F_{s2} - F_{d2} \end{cases} \tag{1}$$

Here, m_1 was the mass of the push-rod piston; m_2 was the mass of the intermediate piston; x_1 was the displacement of the push-rod piston; x_2 was the displacement of the intermediate piston; F_b was the push-rod piston force; F_{s1} was the spring force on the push-rod piston; F_{s2} was the spring force on the intermediate piston; F_{d1} was the damping force on push-rod piston; F_{d2} was the damping force on intermediate piston; p_1 was the pressure in circuit II; p_2 was the pressure in circuit II;

The flow continuity equation in the master cylinder could be described in Eq. (2).

$$\begin{cases} q_1 = A_1\dfrac{dx_1}{dt} \\ q_2 = A_2\dfrac{dx_2}{dt} \end{cases} \tag{2}$$

Here, q_1 was the rate of flow in circuit II; q_2 was the rate of flow in circuit II;

3.2 hydraulic pump model

As seen in the Fig. 2, the plunger pump 6 was mounted to cooperate with DC motor 7 for brake pressure generation in the EHB system. As an eccentric mechanism, the characteristic of pump could be expressed as follows,

$$\begin{aligned} Q_b &= V_b S_m \\ &= \frac{1}{2}\pi S_m D_b^2 \int_0^T \left(e\theta sin\theta - \frac{e^2\theta sin\theta cos\theta}{\sqrt{e^2cos^2\theta + r^2 - e^2}} \right) \end{aligned} \tag{3}$$

Here, Q_b was the flow rate of the pump, S_m was the mean speed of the motor, V_b was the pump displacement, D_b was the diameter of the plunger and r, e and θ were the radius, offset and deflection angle of the eccentric.

3.3 Wheel cylinder model

In the ABS mode, the pressure of wheel cylinder was under control independently. The key components were eight solenoid valves for wheel cylinder. Ding et al. introduced a hydraulic model to describe the pressure regulation by solenoid valves.[13] On that basis, the brake pressure in the wheel cylinder could be controlled by the Eqs. (4) and (5) for EHB system.

Pressure increase:

$$P_w(t) = P_m - [(P_m - P_{w0})^{\phi_{inc}} - K_{inc}\phi_{inc}(t-t_0)]^{1/\phi_{inc}} \tag{4}$$

Pressure release:

$$P_w(t) = [P_{w0}{}^{\phi_{inc}} - K_{inc}\phi_{inc}(t-t_0)]^{1/\phi_{inc}} \tag{5}$$

Here, P_{w0} was the pressure of wheel cylinder at time t_0; P_m was the pressure of wheel cylinder; K_{inc} and ϕ_{inc} were coefficients which were determined by the system characteristic.

To define pressure change rate of wheel cylinder, the following equation proposed by Peng et al. was used.[14]

$$\frac{dp_w}{dt} = \begin{cases} 35.7418(P_m - P_{w0})^{0.58} & increase \\ 0 & hold \\ -36.3714P_w^{0.92} & decrease \end{cases} \tag{6}$$

4. Pedal Stroke Simulator

For EHB system, brake pedal feeling totally depended on performance of simulator. For pedal stroke simulator, the stroke-force curve similar to the traditional vacuum boosted system was given. As shown in Fig. 6, Phase OA stood for the process of overcoming preload force of seating spring, while phase AB represented the pressurization process. When the pedal force reached to point B, it was the maximum force that vacuum booster could offer. The brake force beyond point B totally came from pedal force, so phase BC was not sharply increasing compared with AB.

The pedal stroke simulator was designed as a relatively independent module in the EHB system. Considering the complexity, practicability and cost, the composite springs are adopted as a passive simulator. As seen in Fig. 1, the composite springs 2 were installed in the integrated master cylinder. It was directly linked to the pedal push rod. Liu et al. suggested that three springs could be implemented to simulate the pedal feeling.[15] The displacement of the pedal stroke simulator x_r could be obtained from the following equation,

$$x_s = \frac{x_r A_r}{A_s} \tag{7}$$

Here, A_s was the cross sectional area of the piston in pedal stroke simulator, A_r was the cross sectional area of pedal push rod piston.

Dynamic equation of the pedal stroke simulator piston could be analyzed as follows,

$$m_s = \frac{d^2x_s}{dt^2} = p_sA_s - c_s\frac{dx_s}{dt} - k_ix_s \tag{8}$$

Here, i was the stage of spring compression ($i = 1, 2, 3$), k_i was the equivalent stiffness of the three compression stages and c_s was the damping between the cylinder and the piston.

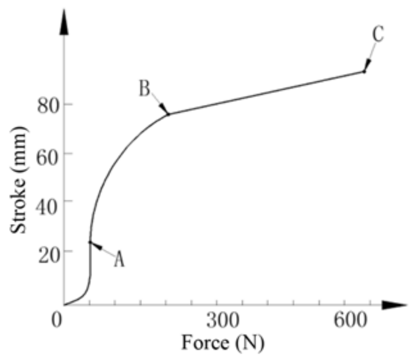


Fig. 6 Ideal stroke-force curve

$$k_i = \begin{cases} \dfrac{k_1 k_2}{k_1 + k_2} & x_s \in [0, L_1] \\ k_2 & x_s \in [L_1, L_2] \\ k_2 + k_3 & x_s \in [L_2, L_3] \end{cases} \tag{9}$$

Here, k_1, k_2 and k_3 were the stiffness of the three springs, respectively.

5. Pressure Following Algorithm

In normal mode, the main function of EHB system was realized by brake pressure following in wheel cylinder. As seen in the Fig. 1, the target pressure was estimated from pedal stroke sensor 20, and actual pressure was measured by pressure sensor 12. Two sensor signals should be filtered through 1-D Kalman filter. The Fig. 7 gave pressure-volume relationship based on vehicle test. According to the pressure difference, motor 7 and release valve 21 were under control to increase or decrease pressure respectively. With pressure change in the third chamber, zero difference for wheel cylinder pressure could be implemented.

During the pressure following, overshoot and delay were inevitable because of nonlinearity and hysteresis for mechanical hydraulic system. According to literature proposed by Wu et al, pressure variation was result from flow rate of brake fluid, and it was mainly influenced by motor power and cross-section area of valves.[16] Therefore, a PWM control method was adopted to accomplish continuous change of fluid flow. Fig. 8(a) and 8(b) illustrated the increasing and decreasing rate of pressure with different duty cycle of motor and release valve.

To ensure a rapid and accurate pressure following, a suitable duty cycle should be determined according to pressure difference. In addition, Fabio et al. suggested the pedal velocity should be taken into consideration in pressure following control.[17] According to his study, driver's braking intention could be estimated through pedal input. When slamming on the brake pedal, considering a required rapid response, a little overshoot of pressure could be accepted. On the other hand, when pedal was pressed down slowly, the pressure hysteresis might be permissible to some extent. Based on the above situations, the compromising values should be selected in the Table 2 when PWM control parameters were calibrated.

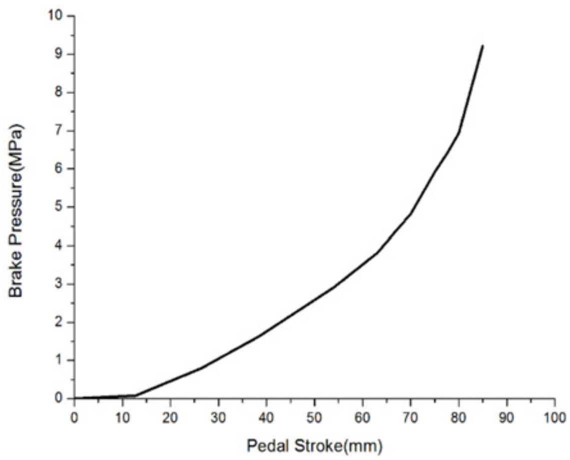


Fig. 7 Displacement-pressure relationships

6. Simulation of EHB System

Brake performance and pedal feeling were regarded as two important performance indexes for EHB system. In this section, the brake performance of the normal mode and the fail mode would be presented. The content about the ABS mode in EHB system would be discussed in the following section. Beyond that, simulations on stroke-force characteristic of the pedal would also be illustrated in this section.

Fig. 9 was the hydraulic model of the proposed EHB system in AMEsim. The pressure following algorithm in the previous section was realized by Simulink. Eventually, the simulation result of pressure

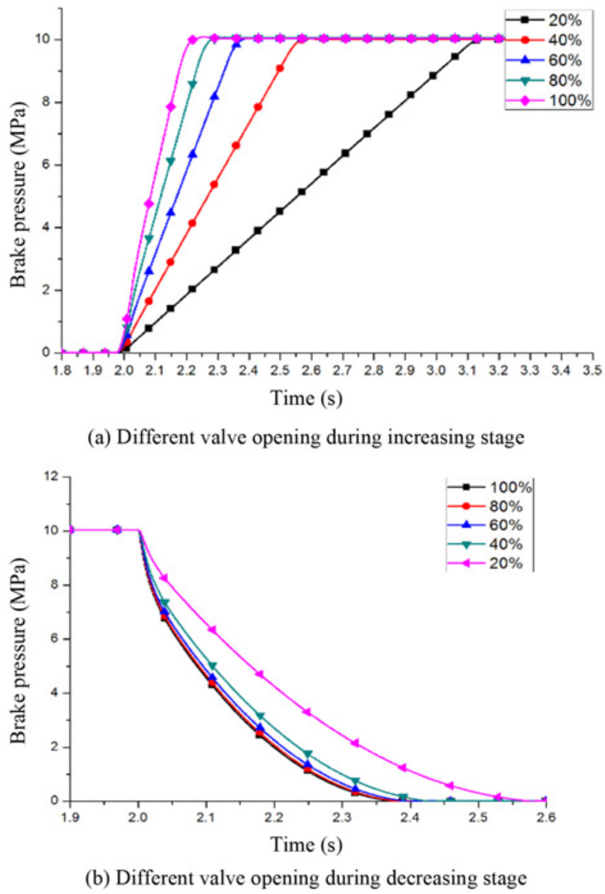


Fig. 8 Pressure variation with different duty cycle

Table 2 PWM control parameters of motor and valves (P_t is the target pressure and P_a is the actual pressure)

$\Delta P = P_t - P_a$ (MPa)	Fast Press Pedal (dx/dtv)		Slow Press pedal (dx/dtv)	
	Motor	Valve	Motor	Valve
a_1	p_1%	0	p_3 %	0
a_2~a_1	p_2%	0	p_4%	0
$-a_3$~a_2	0	0	0	0
$-a_3$~a_4	0	p_5%	0	p_7%
$-a_4$	0	p_6%	0	p_8%

following control was shown in Fig. 10(a) and 10(b) illustrated pedal stroke under given force. As seen from the figures, actual pressure had a quick response with the proposed PWM control method. However, Fig. 10 also showed that actual pressure did not coincide with the target pressure during the increasing stage. It was because the motor had a delay at the beginning of pressure generation.

In order to guarantee brake pedal feeling which was analogous to existed vacuum boosted system, the passive stroke simulator needed to satisfy the stroke-force curve according to pressure-volume characteristic. From Eq. (9), three different stiffness springs were adopted to simulate pedal characteristics. The simulation result was shown in Fig. 11. The stroke-force curves of depressing stage and releasing stage were not completely overlapped due to "hysteresis loss", especially in the first stage, but it was similar to traditional pedal feeling.

In order to provide EHB with high level of safety and reliability, a superior failsafe performance was required. If the system switched to failsafe mode, a mechanical - hydraulic connection between brake pedal and master cylinder was established. The brake fluid in the master cylinder was pushed by oil-catch piston to flow into the wheel cylinder, generatingan emergency brake. Therefore, the brake performance totally

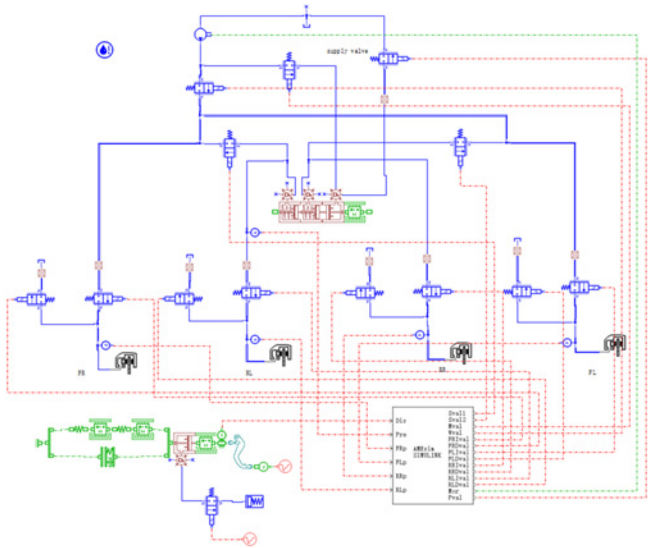
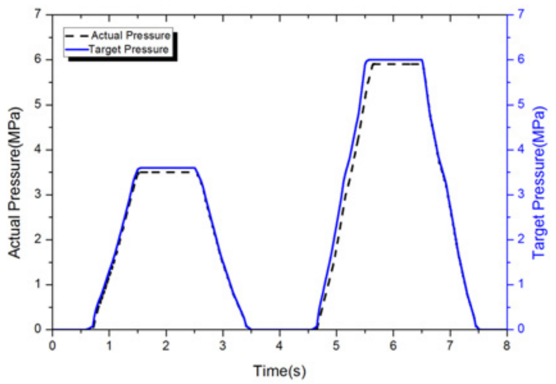
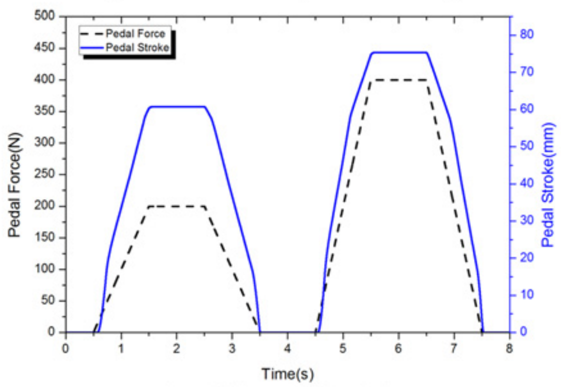


Fig. 9 Hydraulic model of EHB in AMEsim



(a) Simulation result of pressure following



(b) Pedal inputs of simulation

Fig. 10 Simulation of pressure following control

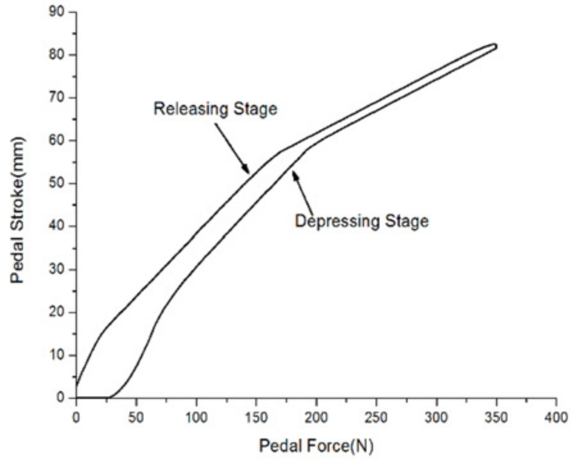


Fig. 11 Simulation of pedal characteristics

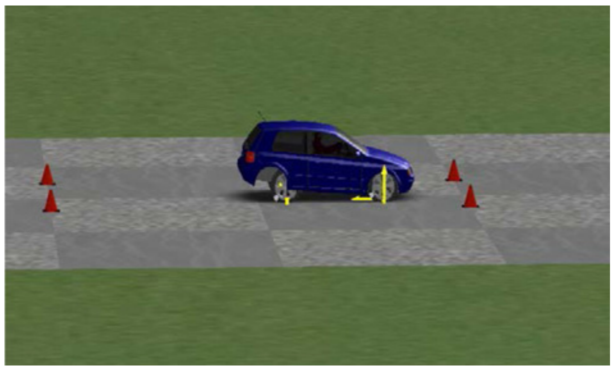


Fig. 12 Vehicle model in CarSim

Table 3 Parameters of the vehicle model

Vehicle parameters	Setting value
Vehicle mass	1231 kg
Wheelbase	2600 mm
Track width	1560 mm
Distance between vehicle center of gravity and front axle	1040 mm
Distance between vehicle center of gravity and rear axle	1560 mm
Height of mass center above ground	540 mm

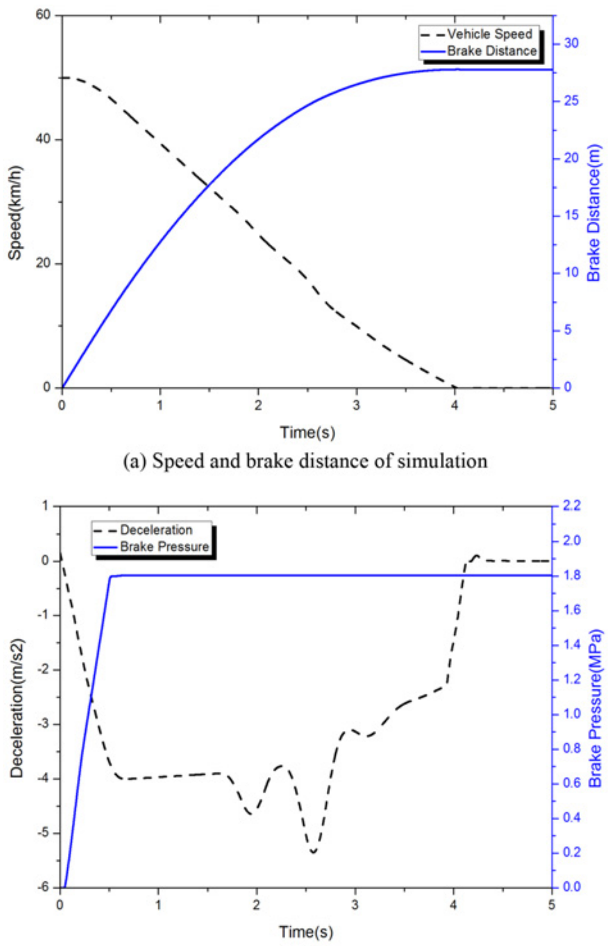
depended on structural design of the integrated master cylinder. The failsafe mode of EHB was examined through AMEsim and CarSim co-simulations. Vehicle parameters and model were shown in Table 3 and Fig. 12. Referring to the literature written by Reuter, for a typical hydraulic braking system of a passenger car, 500N brake pedal force input without boost could generate a deceleration of about 0.3g.[18] Fig. 13(a) and 13(b) exhibited the results of the co-simulation in failsafe mode. With the simulation conducted in the co-simulation, the car created a non-boosted pressure of about 2.4 MPa and generated a deceleration of about 4 m/s^2. The results in the simulation were quite satisfactory.

7. ABS Control and Simulation in EHB

Once the wheel was approaching to lock due to excess braking pressure, the control valves of EHB would switch from normal mode into ABS mode immediately. In ABS mode, the actual pressure inthe wheel cylinder was relatively independent from the master cylinder. Because pressure regulation no longer relied on the displacement pressure relationships shown in the Fig. 7. The proposed EHB system could be able to support the pressure separation between master cylinder and wheel cylinder through flow regulation, and additional device was not necessary.

Logic threshold control had been used widely in ABS algorithm. This control method was simple for no mathematical model. Wheel deceleration and slip rate were selected as the control parameters, in which deceleration was taken as the main parameter. Fig. 14(a) illustrated the control flow for ABS logic threshold, and this algorithm could be achieved in Stateflow as seen in Fig. 14(b). Fig. 15 presented a Four-Phase control cycle, in which, A1 and A2 represented the wheel deceleration threshold while S1 and S2 were the wheel slip rate threshold. However, these threshold values should be calibrated based on lots of vehicle tests.

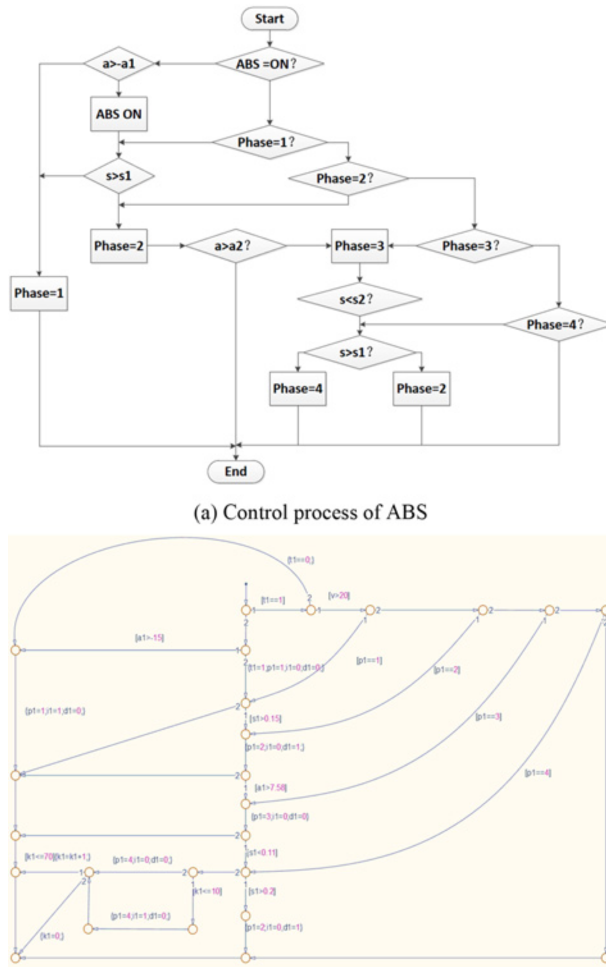
Ji et al. used vehicle model in CarSim to test the brake performance.[19] In the vehicle simulation, AMEsim was responsible for the hydraulic model while SIMULINK was for the control model. And the vehicle model used in simulations was built in CarSim. Fig. 16 showed the control model in SIMULINK. The system controller in SIMULINK received the pressure signal and pedal displacement signal from AMEsim. Then it calculated the command outputs for motorand valves. Meanwhile, SIMULINK and CarSim exchanged information with each other. The pressuresignals of wheel cylinders were transmitted to the vehicle model in CarSim for a brake event, and the vehicle speed and wheel speed were fed back to SIMULINK for the calculation of



(a) Speed and brake distance of simulation

(b) Deceleration and brake pressure of simulation

Fig. 13 Simulation of failsafe mode



(a) Control process of ABS

(b) Control algorithm in Stateflow

Fig. 14 ABS control algorithm

slip rate and wheel deceleration. So it was the typical closed-loop control.

Simulations were conducted to verify the feasibility of the proposed EHB system by offering an ABS brake event. The test vehicle was B-class and the test was carried out on a high-adhesion road. The road frictioncoefficient was set at 0.85 and the initial braking speed was 120 km/h. Fig. 17(a) illustrated the wheel speed and vehicle speed during ABS. As was indicated in Fig. 17(a), in order to prevent wheel lock, the rear wheel had a faster regulation cycle than the front wheels. When the vehicle speed reached to 20 km/h, ABS stopped working and the wheels were locked rapidly. The braking pressure in the wheel cylinder was presented in Fig. 17(b). During the brake, the rear wheel pressure

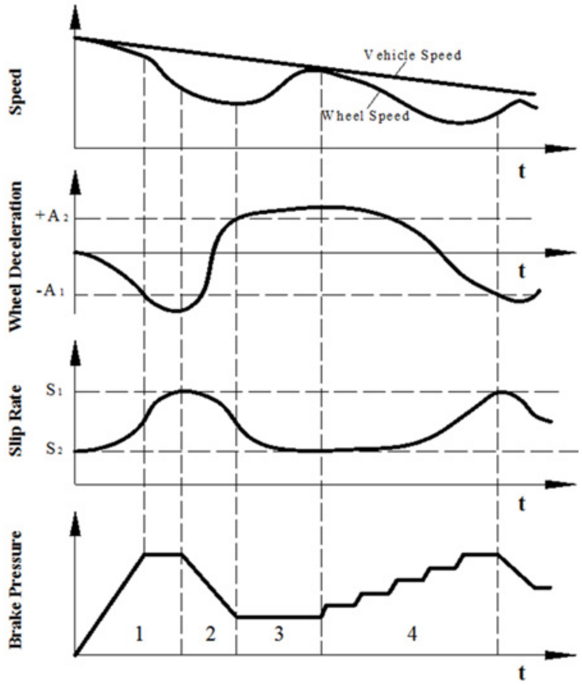


Fig. 15 ABS Four-Phase control cycle

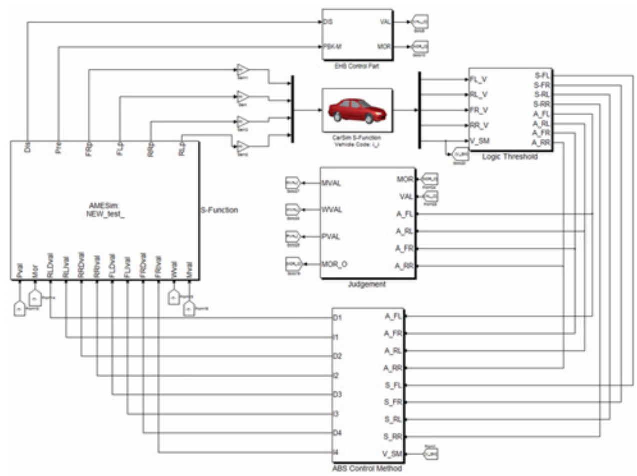
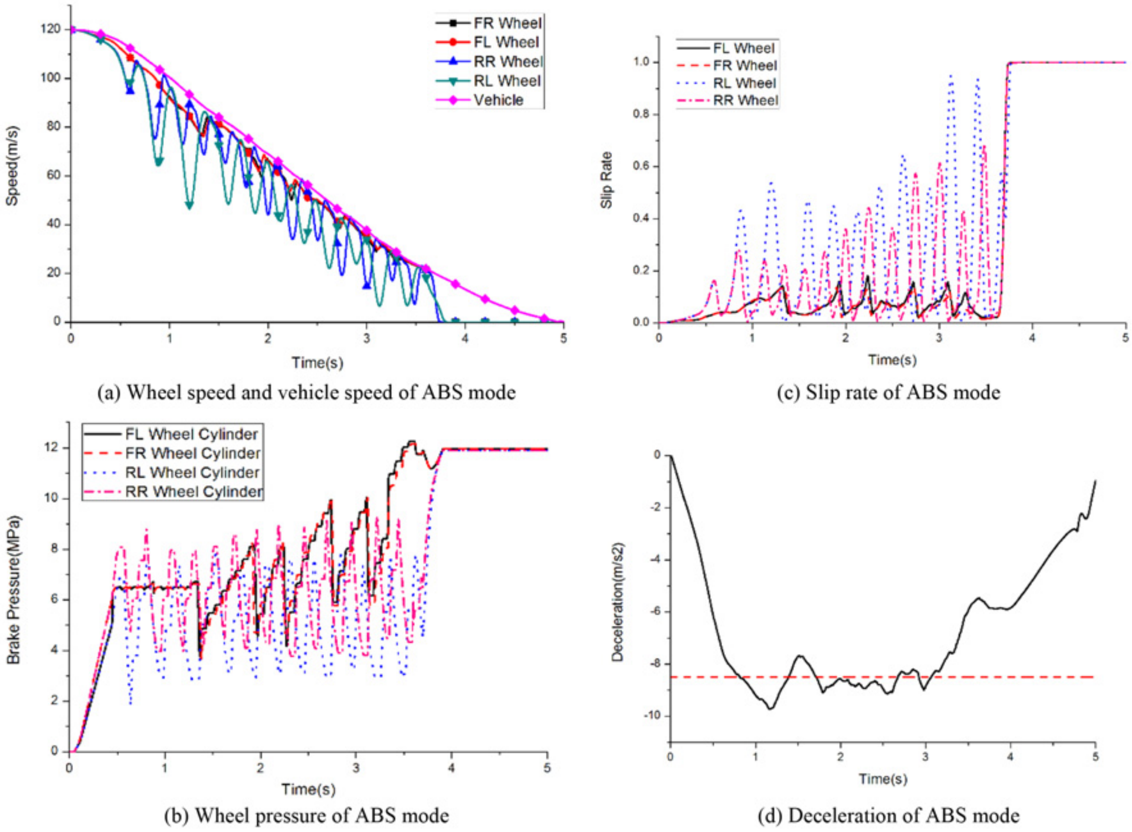


Fig. 16 Control algorithms in SIMULINK



(a) Wheel speed and vehicle speed of ABS mode

(c) Slip rate of ABS mode

(b) Wheel pressure of ABS mode

(d) Deceleration of ABS mode

Fig. 17 Simulation of ABS mode

was lower and more frequent than the front wheel pressure. Fig. 17(c) and 17(d) showed the slip rate and vehicle deceleration in the brake event. The braking deceleration was about 8.5 m/s^2. Therefore,the ABS mode could take full advantage of the braking force providing by the road. On the basis of the results, the embedded ABS function had a good compatibility and feasibility with the proposed EHB system.

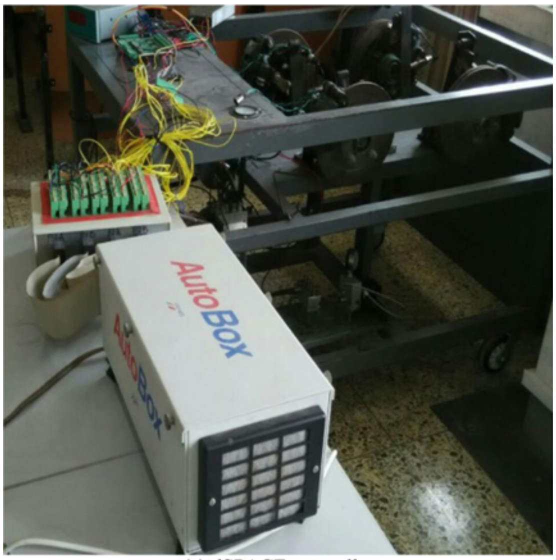
8. EHB Bench Test

The main target of EHB test was the response of EHB system and the performance of pressure following control. Since integrated pedal simulator was based on springs, a good and repeatable pedal feeling could be assured, and the test of pedal simulator was not presented here.

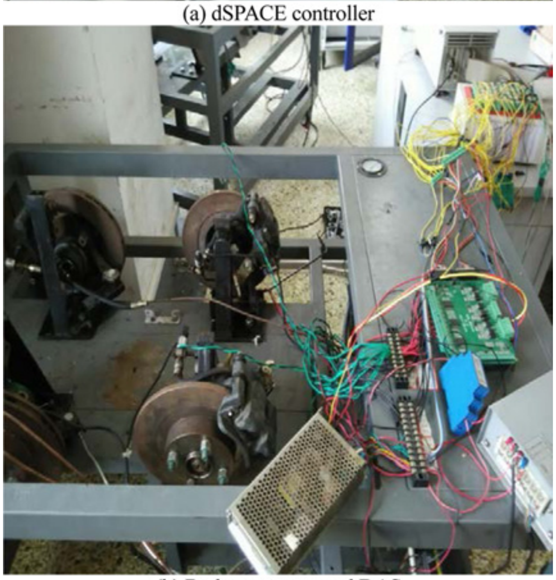
An EHB test bench was illustrated in Fig. 18. As a central part, the control algorithm was downloaded in dSPACE. In addition, sensor signal input, actuator output instruction and HMI were easy to be implemented in dSPACE. The hardware included EHB block, disc brakes, pedal and sensors. Besides the required sensors for closed-loop control, additional sensors were used to monitor pedal force and wheel cylinder pressure. Eventually, open-loop control and brake pressure following control was experimented in the bench respectively.

The result of open-loop control was illustrated in Fig. 19. As shown, the actuator of EHB had a fast response both for pressure rise and drop. The maximum pressure exceeded 15 MPa, which was considered adequate for brake system. The rising time from 0 to 14 MPa was about 200 ms, while pressure dropping rate was faster and reached up to 200 Mpa/s. Therefore, the EHB system was capable of tracking target pressure.

The test result of pressure following control was shown in Fig. 19(b). According to pedal displacement, the target pressure had a random and rapid changed from 0 to 6.5 Mpa. Compared with actual hydraulic pressure, the motor and solenoid valves of EHB were controlled by proposed PWM control method. As shown in Fig. 19(b), with rapid change of target pressure, the actual pressure was capable of tracking quickly but in early rising stage. At the same time, there was no obvious pressurefluctuation, and maximum error was less than 0.2 Mpa. Taking the hydraulic hysteresis into consideration, the pressure following characteristic of the EHB system was acceptable.

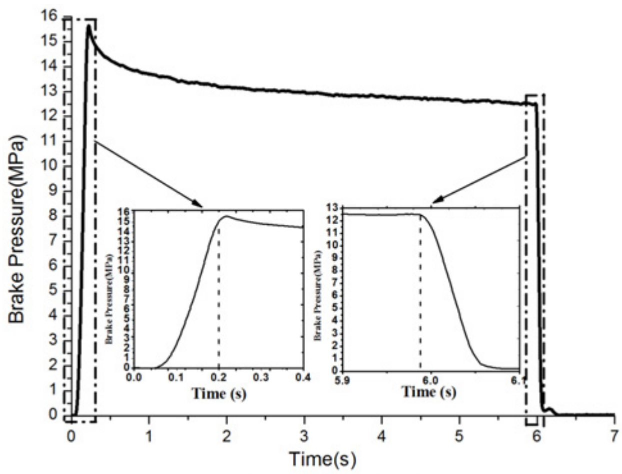


(a) dSPACE controller

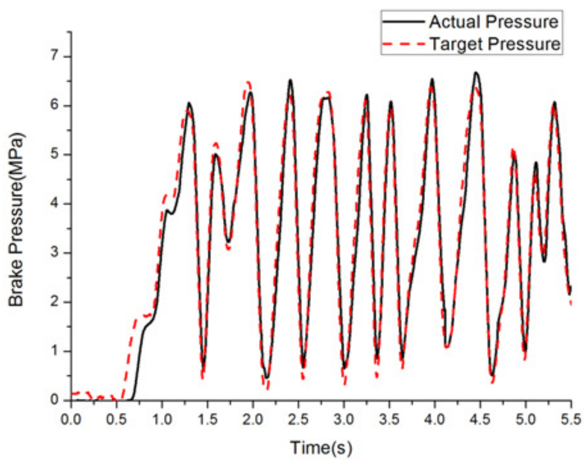


(b) Brake actuators and DAS

Fig. 18 Scenario of test bench



(a) Open-loop control in bench test



(b) Pressure following in bench test

Fig. 19 Results of bench test

9. Conclusion

In this research, a novel integrated Electro-Hydraulic Braking system with three modes was developed. A compact and decoupling structure of three-chamber master cylinder was designed. By using passive pedal simulator composed of springs, a good and repeatable braking feeling could be guaranteed. Furthermore, a PWM control method according to pressure difference and pedal velocity was proposed for braking pressure following. While in ABS mode of the EHB, Four-Phase logic threshold method was adopted. The co-simulation and bench test were implemented. The result showed that the EHB not only had a rapid and accurate response for braking pressure following in normal mode, but also had capable braking performance in failsafe mode and ABS mode. On the basis of integrated EHB structure, further research on ABS performance would continue through Hardware-in-Loop simulation.

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