Research on Electro Hydraulic Composite Brake System

Qinghe Liu, Lan Zhan and Ti He

Abstract This paper describes a proposal of electro hydraulic composite brake system, which is based on the high-speed switching valve, and sets up a algorithm of the composite braking resistance distribution, according to the law of ECE and motor's external characteristic. By using the simulator ADVISOR, the algorithm is analyzed. The result shows that this algorithm can realize the braking safety primly, at the same time, recuperates energy of 220 kJ, leading to a 0.75 % increase of battery status.

Keywords Composite brake system · Brake resistance distribution · Braking energy regeneration · Braking safety · ECE law

1 Technical Paper: Introduction

Since the 21st century, faced with the much more serious problems of energy exhaustion and environmental pollution, many car-producing countries have been controlling the polluting emissions and fuel economy of their vehicles by setting

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more strict standards. Therefore, it brings the new energy vehicle, which can regenerate energy while braking, to public focus.

Regenerative braking system reserves part of the braking energy for driving the vehicles, which can increase vehicle economy effectively. But the effect of regenerating energy is decided by the certain algorithm of the composite braking force distribution. Because the traditional braking system cannot realize independent and variable control of the hydraulic braking force, many complex algorithms, which have strict requirements for the control of the hydraulic braking force, can not be applied to real cars. This traditional system limits the regenerative efficiency of braking energy and the improvement of braking safety. However, the electro hydraulic composite brake system provides a practical way to solve this problem.

In this study, we aim to research on the electro hydraulic composite brake system. Based on the high-speed switching valve, a proposal of this system, which provides a foundation for the following study, is raised. According to the law of ECE and motor's external characteristic, we set up an algorithm of the composite braking force distribution. Finally, by using the simulator ADVISOR, this algorithm is analyzed, from the perspectives of energy regeneration and braking safety. The ultimate result shows that this algorithm of the composite braking force distribution is superior in both of the aspects.

2 Structural Concept of the Composite Electro Hydraulic Brake System

During the composite braking process, in order to realize active control of the hydraulic braking force, the electro hydraulic brake system should contain the following basic functions.

1. The electro hydraulic composite brake system should have similar pedal feeling with the traditional ones.
2. According to the master controller's requirements of the composite brake system, this system should have the active ability to increase and decrease the pressure of the hydraulic brake system. Hydraulic brake should be separated with pedal operation.

After the functional analyses of the composite brake system and the electro hydraulic brake system, we raise a proposal of the electro hydraulic composite brake system (Fig. 1), which is based on the high-speed switching valve. The most obvious attribute of this proposal is that it can satisfy the requirements of varies algorithms of the composite braking force distribution toward exact control of the hydraulic braking force [1].

Attributes of the proposal:

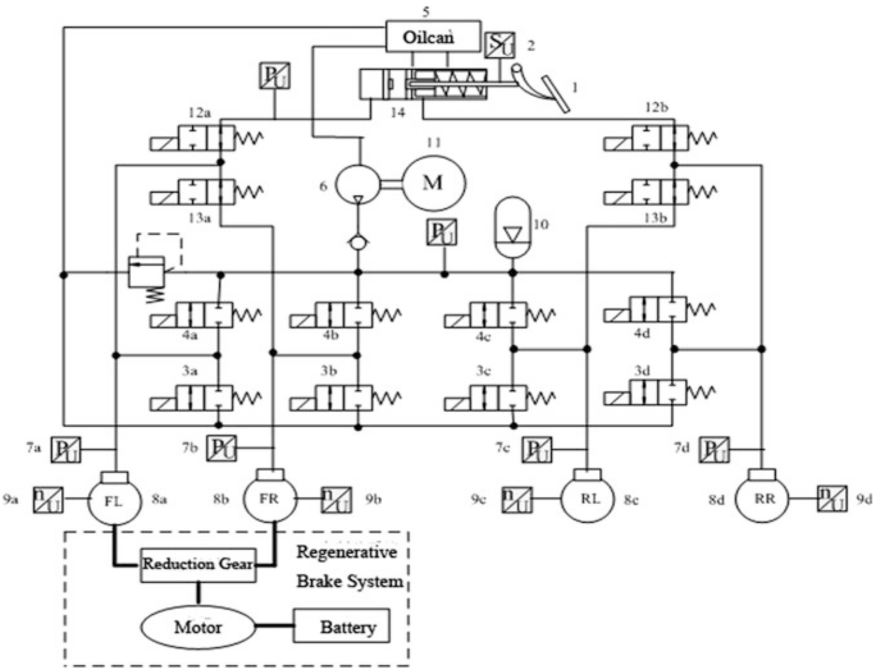


Fig. 1 The structure of the electro hydraulic composite brake system. *1* braking pedal, *2* braking pedal position sensor; *3a, 3b, 3c, 3d* high-speed switching valve for oil circulation; *4a, 4b, 4c, 4d* high-speed switching valve for feeding, *5* braking oilcan, *6* wheel pump, *7a, 7b, 7c, 7d* pressure sensor, *8a, 8b, 8c, 8d* wheel braking cylinder; *9a, 9b, 9c, 9d* wheel speed sensor; *10* accumulator; *11* motor; *12a, 12b* spare high-speed switching valve for brake; *13a, 13b* equilibrium valve; *14* brake master cylinder

1. Electro hydraulic brake system can independently control the hydraulic braking force of every wheel, providing the foundation for those much more complex and efficient algorithms of the composite braking force distribution.
2. In this proposal, the electro hydraulic system cut down the mechanical connection between braking pedal and braking pipe. To ensure the driver's pedal feeling while braking, this system adds a pedal feeling simulator, which is used to simulate the braking force reaction to the pedal.
3. In the braking process, once the electro hydraulic brake system suddenly broke down or the braking control system failed, the spare braking system would begin to work [2].

Figure 2 shows the control logic of the electro hydraulic composite brake system. According to the signals sent by the position sensor of braking pedal, the electro hydraulic braking control unit gets the driver's braking intention and sends the intention to the electro hydraulic composite braking control unit via a bus. At the same time, via the bus network, the composite braking control unit receives the signals of car speed and battery's state of charge from VMS (Vehicle Manage

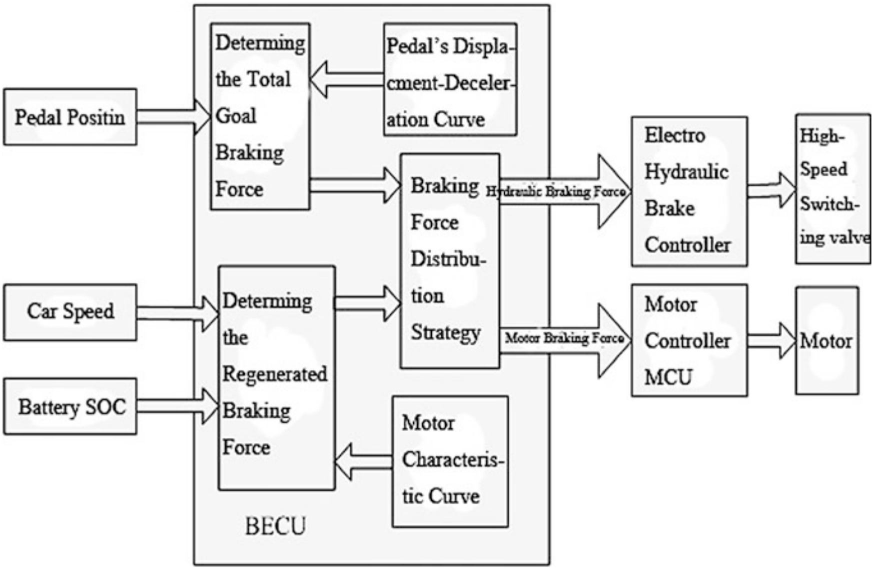


Fig. 2 Control logic of the electro hydraulic composite brake system

System). In accordance with the algorithm of composite braking control, it calculates the regenerative braking force, which should be provided by the regeneration brake system, and the hydraulic braking force supplied by the electro hydraulic brake system. Based on the results, signals are sent to the hydraulic control unit, by controlling the hydraulic actuator, the pressure of every wheel cylinder is controlled, thus the hydraulic braking forces are controlled. Simultaneously, signals are sent to the motor controller, controlling the braking force generated by it to satisfy the total requirement of the severity of braking [3].

3 Performance Test of Electro Hydraulic Brake System

As the electronic control of the hydraulic brake system is the premise of realizing electro hydraulic brake, performance test of the new proposal's electro hydraulic is conducted.

The performance test is divided to two work conditions: the step-input and sinusoidal-input.

1. The wheel baking cylinder's pressure response under step pressure

Set the objective pressure of increasing pressure to 2.5, 5, 7, 8.5 MPa respectively in the controller, the control effect is showed in Fig. 3. The Initial pressure is 9 MPa, set the objective pressure of decreasing pressure to 6, 4, 2, 1 MPa respectively, the control effect is showed in Fig. 4. As the figures show, the control

Fig. 3 Step increasing of wheel

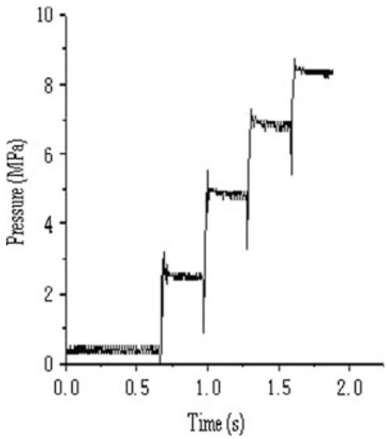
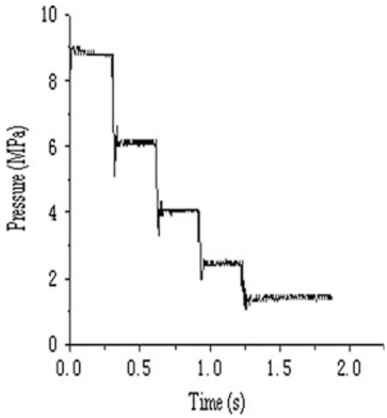


Fig. 4 Step decreasing of wheel



system can effectively follow the step-input pressure, the steady-state error is minor, the time of reaction is within 100 ms, and can satisfy the brake system's requirement towards the pressure reaction speed.

2. The wheel baking cylinder's pressure response under sinusoidal pressure

The (a) in Fig. 5 shows the performance curve of the wheel baking cylinder's pressure response under sinusoidal pressure of $3\sin(3t) + 4$, when the switching valve is in the zone of linearity. (b) shows the performance curve of the wheel baking cylinder's pressure response under sinusoidal pressure of $3\sin(3t) + 4$, when permitted to work in the nonlinear region. (c) shows the performance curve of the wheel baking cylinder's pressure response under sinusoidal pressure of $3\sin(4t) + 4$. (d) shows the performance curve of the wheel baking cylinder's pressure response under sinusoidal pressure of $3\sin(4t) + 4$, when permitted to work in the nonlinear region.

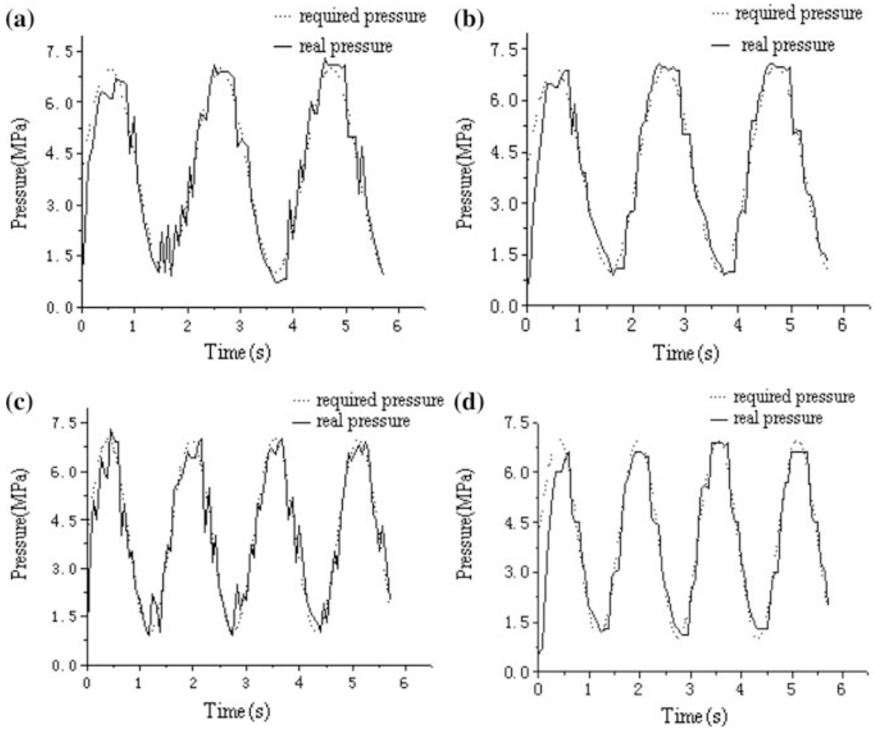


Fig. 5 The performance curve of the wheel baking cylinder's pressure

The experiment result shows that under inputting sinusoidal required pressure, the real pressure can effectively follow the objective pressure. When keeping the switching valves working in the zone of linearity, the pressure fluctuates markedly. This is largely due to the high dutyfactor (minimum value is 0.05) of the PWM signal inputted by the controller. Therefore, markedly fluctuation of pressure would happen once the switching valves are regulated. When the switching valves are allowed to work in the nonlinear region, the pressure of the wheel cylinder can follow the objective pressure much more exactly. This is because when the difference between the required pressure and objective pressure is small, the pressure can be fine-tuned by using the space of dutyfactor between 0.03 and 0.05.

4 The Composite Braking Control Algorithm, Based on the Law of ECE and Motor's External Characteristic

According to the law of ECE and motor's external characteristic, we set up a composite braking control algorithm. On the premise of satisfying braking safety and braking severity, we set our primary goal as recovering the maximum energy.

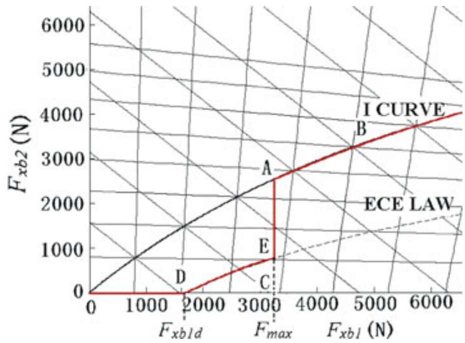


Fig. 6 Composite braking force distribution curve

Therefore, the recovered energy should be used as more as possible while braking, to increase the efficiency of recovering. When braking severity is low, only the motor provides regenerated braking force for the front wheels. When the braking severity is medium or high, the hydraulic system and regenerated braking system provide the force corporately. Before reaching the ideal distributive severity of braking force, the braking force of front wheels is only provided by the motor. The electro hydraulic brake system does not provide any braking force. The braking force of the rear wheels is provided by the hydraulic system. When the ideal distributive severity is reached, every wheel's braking force is distributed according to the ideal braking force distribution curve. The motor provides its maximum regenerative braking force for the front wheels, if it is not enough, hydraulic braking system would be added, while the rear's is solely provided by the hydraulic brake system [4].

Before braking force is distributed, the electro hydraulic composite control unit, according to the received signal from the braking pedal, calculates the car's objective braking severity z and total required braking force F_r, at the same time, according to the motor's rev and the transmission agent's transmission ratio, calculates the largest regenerative braking force $F_{\max}$ that can be provided by the motor.

First, calculating the front wheel's braking force on the curve of ECE law, while the braking force of the rear wheel is zero.

$$\begin{cases} F_{\mathrm{xb1}} = \dfrac{z + 0.07}{0.85}(b + zh_{\mathrm{g}})G/L \\ 0 = Gz - F_{\mathrm{xb1}} \end{cases} \tag{1}$$

$$F_{\mathrm{xb1}} = F_{\mathrm{xb1d}} \tag{2}$$

In the equation, F_{xb1d}—abscissa of the point that ECE curve cross with the horizontal axe

Judging from the magnitude comparison between F_{xb1d} and the maximum braking force $F_{\max}$ provided by the motor, there are two kinds of braking force distribution methods:

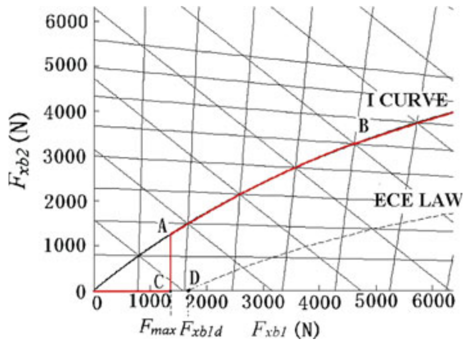


Fig. 7 Composite braking force distribution curve

When $F_{\max} > F_{\mathrm{xb1d}}$, the braking force distribution is the ODEAB curve (Fig. 6, [5])

(1) $z \leq z_D$, total regenerative braking section.

$$F_m = F_r, \quad F_{\mathrm{hf}} = 0, \quad F_{\mathrm{hr}} = 0$$

In the equation,

F_m motor's regenerative braking force (N);
F_{hf} front wheels' hydraulic braking force (N);
F_{hr} rear wheels' hydraulic braking force (N).

(2) $z_D < z \leq z_E$, braking force distribution changes along the curve of ECE law

$$F_m = \frac{z + 0.07}{0.85}(b + zh_{\mathrm{g}})G/L, F_{\mathrm{hf}} = 0, F_{\mathrm{hr}} = F_r - F_m$$

(3) $z_E < z \leq z_A$, motor provides the maximum braking force

$$F_m = F_{\max}, F_{\mathrm{hf}} = 0, F_{\mathrm{hr}} = F_r - F_{\max}$$

(4) $z > z_A$, braking force distribution changes along curve I

$$F_m = F_{\max}, F_{\mathrm{hf}} = F_r \frac{b + h_{\mathrm{g}} F_r/G}{L} - F_m, F_{\mathrm{hr}} = F_r \frac{a - h_{\mathrm{g}} F_r/G}{L}$$

When $F_{\max} \leq F_{\mathrm{xb1d}}$, the braking force distribution changes along curve OCAB (Fig. 7).

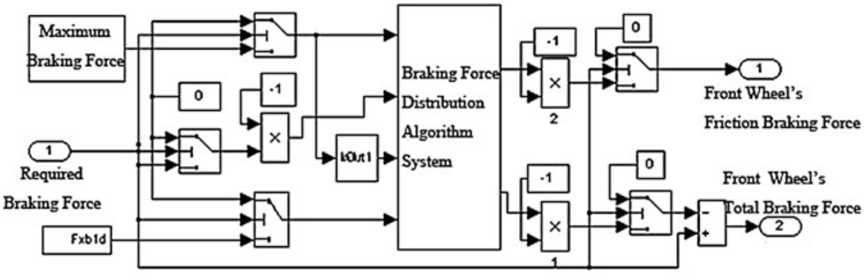


Fig. 8 The model of braking force distribution strategy

(1) $z \leq z_C$, total regenerative braking section, braking force only provided by the motor.

$$F_m = F_r, \quad F_{\text{hf}} = 0, \quad F_{\text{hr}} = 0$$

(2) $z_C < z \leq z_A$, motor provides the maximum braking force

$$F_m = F_{\max}, F_{\text{hf}} = o, F_{\text{hr}} = F_r - F_{\max}$$

(3) $z > z_A$, braking force distribution changes along curve I

$$F_m = F_{\max}, F_{\text{hf}} = F_r \frac{b + h_g F_r / G}{L} - F_m, F_{\text{hr}} = F_r \frac{a - h_g F_r / G}{L}$$

5 Simulation of the Electro Hydraulic Composite Braking Strategy

5.1 Building of the Simulative Model

By using the ADVISOR simulator, we conduct simulative analysis toward the algorithm of the composite braking force distribution. Primarily, we inset the law of ECE and motor's external characteristic into the policy module of ADVISOR (Fig. 8), the module's input signal is the car's total required braking force, and the output signals are the front wheels' total required braking force and their frictional braking force [6].

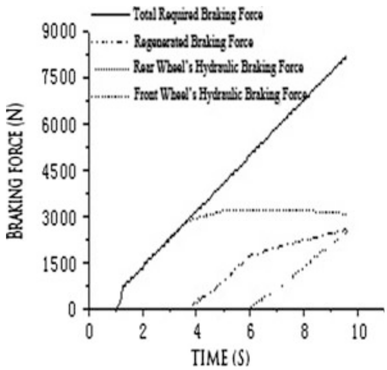


Fig. 9 Braking force distribution curve

Using the models of every assembled vehicle element in ADVISOR, some assembled m documents are modified necessarily. For example, it happens when selecting transmission ratio of driving chain, we try to make the motor work in the zone of high efficiency and high torquemoment, however, we also have to make sure that transmission is fixed in the certain gear when braking.

5.2 Analysis of the Simulation Result

In a process of slow braking, to test the rationality and validity of the braking force distribution algorithm, we simulate the distribution of the car's braking force, the situation of the wheel's motion and energy regeneration, to test the rationality and validity of the braking force distribution algorithm.

From the analysis of Figs. 9 and 10, we can know that in the beginning period of braking, the car is in the total regenerative braking situation, in which the hydraulic braking system doesn't provide braking force. As the total braking force reaches 3000 N, the hydraulic braking system begins to provide braking force for the rear wheel. At this time, the braking force provided by the motor hasn't reached the maximum, to satisfy the braking severity requirement, and avoid the front wheels, using the attachment coefficient, breakthrough the limitation of ECE law, hydraulic braking force is added to the rear wheels, sharing some of the braking force. After the braking force reaches 5000 N, hydraulic braking force is also provided to the front wheels, and the motor works in the zone of constant-torsion, which is under the basic speed, providing the largest braking force under this rev. At this time, all the wheels' braking force is distributed according to the ideal braking force distribution. The slip ratios of front and rear wheels are equal, and equal to the braking severity [7].

As the Figs. 11 and 12 shows, in the beginning period of braking, the battery situation increases slightly, which is due to the reasons that the regenerative braking force is comparatively small, the recovered braking energy is less and some of the equipments in the car consumes certain amount of electricity.

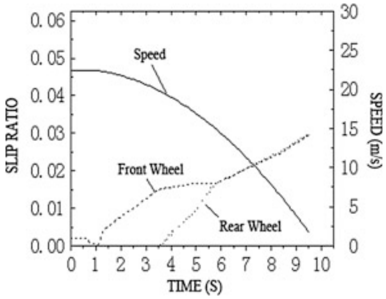


Fig. 10 Car speed and slip ratio curve

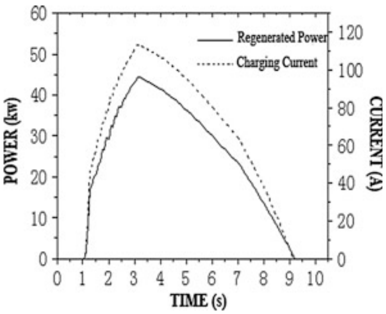


Fig. 11 Motor's regenerative power and charging electric current

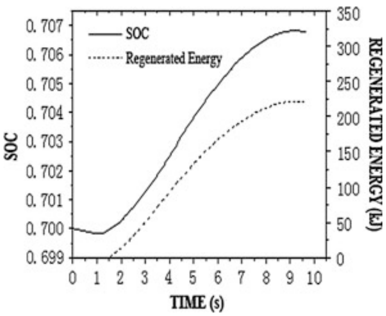


Fig. 12 The battery's regenerative energy and SOC

However, as the braking severity increases, the regenerative braking force increases and the motor's generated output increases and reaches the maximum. Subsequently, the car's speed decreases, the motor's rev decreases, the motor begins to work in the zone of constant-torsion, and the motor's regenerative power decreases to 0.

In the whole process of braking, the motor's maximum regenerative power is 42 kW, the maximum charging electric current is 110 A, the battery situation increases 0.75 %, from 70 to 70.75 %, total regenerative energy is 220 kJ. From all these data, we can know that the algorithm of braking force distribution mentioned in this paper can realize the braking safety and regenerate comparatively large amount of braking energy.

6 Conclusion

1. We raise a proposal of electro hydraulic composite brake system, which is based on the high-speed switching valve, and verify the feasibility of the electro hydraulic braking system through tests.
2. An algorithm of the composite braking force distribution is set up, according to the law of ECE and motor's external characteristic.
3. Based on the ADVISOR simulator, the electro hydraulic composite brake system's braking strategy is simulated, and according to the simulation result, the braking safety and the amount of regenerative braking energy are analyzed.

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