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ADVANCEMENTS IN THE DEVELOPMENT OF ELECTRO-HYDRAULIC COMPOSITE BRAKING SYSTEMS FOR ELECTRIC VEHICLES

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Abstract: This paper meticulously categorizes, hones, and summarizes pertinent technical matterspertinent technical matters both domestically and internationally, focusing on the optimal design, system control, and testing platform of the electro-hydraulic composite braking system. It also presents a comprehensive review of the advancement of electro-hydraulic composite braking systems for electric vehicles, offering a future perspective. Research indicates that the integration, reliability, and robustness of electro-hydraulic composite braking systems are crucial areas for further improvement, as they emerge as a significant development trajectory for braking systems in electric vehicles.

Keywords: Electro-hydraulic composite braking; Optimized design; System control; Test platform

1 OPTIMIZED DESIGN

As people pay more and more attention to energy and environmental protection issues, the regenerative braking technology of electric vehicles has become a hot research issue and has been implemented in engineering applications. The regenerative braking force of the motor can be divided into three types: front axle compound braking, front and rear axle compound braking, and rear axle compound braking according to the location of the braking force. form. The regenerative braking torque and hydraulic braking torque on each wheel can be adjusted in real time. When the car is braking, the electric drive system is used to convert kinetic energy into electrical energy and is stored in the battery energy storage system. The sensor detects the driver's braking signal and transmits it to the controller, which distributes the braking force to meet the vehicle's braking requirements and achieve energy recovery at the same time. Regenerative braking has become a key technology for electric vehicles to save energy and improve their cruising range. The system should meet the following points: comply with braking safety regulations, meet braking safety and robustness requirements, effectively recover braking energy, provide driver braking comfort, and have effective fault tolerance mode.

In order to study the issues of electric vehicle electro-hydraulic composite braking system more deeply, based on the development of related technologies, the existing related research and technological progress will be studied and reviewed focusing on optimization design, system control and test platform.

Domestic and foreign scholars have achieved rich research results in the optimization design of electro-hydraulic composite braking systems. Literature [1] based on the constraints of braking regulations, motor characteristics, braking stability and braking comfort, ideally designs the electric vehicle motor braking/electronic hydraulic brake (EHB) composite braking system. For power distribution control optimization, a multi-boundary condition optimization design method for the electro-hydraulic composite braking system control algorithm is proposed, and the front and rear axle braking force distribution coefficients are determined based on factors such as braking intensity requirements and the frequency of use of roads with different adhesion coefficients. Yu Zhuoping [2] studied the matching method of the electro-hydraulic composite braking system of wheel-driven electric vehicles, and optimized the electro-hydraulic composite braking parameters of an electric vehicle. Liu Qinghe et al. [3] proposed an electro-hydraulic parallel braking system structure suitable for electric vehicles and designed a parallel braking force distribution scheme. Literature [4] simulates and analyzes the impact of the main parameters of the solenoid valve and accumulator on the dynamic characteristics of EHB, which provides a basis for the optimal design of the EHB system. Song Shigang et al. [5] determined the safe operating range of series electro-hydraulic composite regenerative braking of electric vehicles, established a mathematical model for the regenerative braking optimization problem, and improved the recovery rate of vehicle braking energy.

The ideal relationship curve between front and rear wheel ground braking force distribution is expressed by the formula:

$$Fxb_2 = \frac{1}{2}\left[\frac{G}{h_g}' \sqrt{b^2 + \frac{4h_g L}{G} F_{xb1}} --2Fxb1 \frac{Gb}{h_g}\right], (1)$$

In the formula: Fxb_1 and Fxb_2 are the ground braking forces of the front and rear wheels, N; G is the gravity of the car, N; b is the distance from the center of mass of the car to the center line of the rear axle, m; hg is the height of the center of mass of the car, m; L is the axle of the car. Distance, m.

On the basis of the above, Lan Fengchong et al. [6] used a hierarchical control method to control the stability of dual-motor four-wheel drive electric vehicles, and obtained the optimal control through coordinated control of the output torque of the front and rear axle motors and the hydraulic braking torque of the wheels. It optimizes the yaw moment and increases the vehicle speed while ensuring the stability of the vehicle. The control objective is in the form of standard quadratic programming:

$$f(x) = \frac{1}{2} xTHx + CTx, (2)$$

satisfies biTx=vci, i = 1, 2,...; ci is a vector; F1, F2, F3, and F4 are the braking forces of the left front wheel, right front wheel, left rear wheel, and right rear wheel respectively.

Yang Pengfei et al. [7] designed a joint control strategy for the wheel hub motor and hydraulic braking system of a four-wheel hub-driven electric vehicle. The upper layer of the controller uses a sliding mode variable structure to obtain the generalized force, and the lower layer uses the quadratic programming method for optimal torque distribution. Taking the overall road load status of the vehicle as the optimization goal:

$$\min J=\sum_{i=1}^{4} \frac{F_{xi}^2 + F_{yi}^2}{(\mu F_{zi})^2}, i = fl, fr, rl, rr, (3)$$

In the formula: μ is the road adhesion coefficient, which can be obtained through identification; Fxi and Fyi are the longitudinal and lateral forces of each wheel respectively; Fzi is the vertical load of each wheel; fl, fr, rl, rr are the left front wheel, Right front wheel, left rear wheel, right rear wheel.

Zhou Lei et al.[8] ensured braking performance while taking into account energy recovery and reducing brake pad wear. Literature [9] established mathematical models of brake wheel cylinders, solenoid valves, DC motors, hydraulic pumps, etc. based on AMEsim, and carried out optimized designs. Gao et al. [10] optimized the braking force distribution control model and energy feedback system, and realized the anti-locking function of electric vehicles by setting the threshold value of the motor's regenerative braking force. Lee et al. [11-12] designed an EMB approximate time-optimal tracking controller and designed a high-bandwidth controller based on the time-optimal switching surface. Han et al. [13] designed a constraint function to ensure the optimal distribution of regenerative braking torque and improve vehicle lateral stability and braking energy recovery.

2 SYSTEM CONTROL

2.1 Braking Dynamics Control

In view of the shortcoming of poor braking feeling in the research on braking dynamics control, some scholars have conducted in-depth research on this issue. Li Shoutao et al. [14] analyzed the pedal force transmission path, pedal feel and its influencing factors under normal working conditions and oil leakage conditions in the front and rear chambers respectively, and used fuzzy adaptive PID control solenoid valve to establish a good simulated braking feeling. . EHB electro-hydraulic coordinated control includes regenerative braking and hydraulic pressure
move.

Pan Ning et al. [15] proposed a braking intention classification method and online identification method for the purpose of improving comfort, and controlled the hydraulic actuator based on the classification results; using multi-sensor data fusion, using neural networks to identify braking intentions , improve braking comfort and safety. Solenoid valve control is essentially flow control. Literature [16] analyzed the transmission path of pedal force in the normal and failure modes of the electro-hydraulic composite braking system, and studied the pedal feel and its influencing factors in different modes. Literature [17] proposed a wheel slip rate control method based on EHB. The superimposed braking energy feedback system directly superimposes the motor feedback braking force on the friction braking force. This control strategy has poor braking feeling and low feedback efficiency [18-20]. Ko et al. [21] pointed out that the performance of regenerative braking control can be improved by improving the accuracy of hydraulic control of electric vehicles. Amodeo et al. [22] used a high-order sliding mode controller to suppress chatter during the control process. Ivanov et al. [23] verified through experiments the coordinated control algorithm of electro-hydraulic composite braking and ABS on low-adhesion road surfaces, which improved braking comfort.

Compared with traditional braking systems, active control in EHB systems appears more and more frequently in braking conditions. The quality of the braking dynamics control algorithm has become a key factor in whether the EHB system can achieve real-time and accurate pressure control. It is also the key to achieving a good match with the entire vehicle.

2.2 Vehicle Control Strategy

In terms of research on vehicle control strategies, Liu Shunan et al. [24] proposed using a digital high-speed switching valve and a single-chip microcomputer to form a braking force electro-hydraulic proportional distribution device to achieve proportional distribution of the pressure of the front and rear brake cylinders to meet different working conditions and road surfaces. requirements. Literature [25] conducts anti-lock control considering comfort for the electro-hydraulic composite braking system of distributed electric vehicles. On the basis of the above research, in order to improve the control accuracy of hydraulic brake pressure in electro-hydraulic composite braking of electric vehicles, literature [26] designed an electro-hydraulic composite braking ABS control method based on wheel speed error. Jin Liqiang et al. [27] proposed a new configuration of electromechanical composite regenerative braking system and control strategy suitable for electric vehicles. Considering the impact of battery SOC value and braking intensity on the motor regenerative braking torque, a dual-input single-output fuzzy control was designed. The device realizes the recovery of regenerative braking energy while ensuring braking efficiency. Yuan Xiwen et al. [28] aimed to achieve vehicle active safety and braking energy recovery, and proposed a control strategy integrating AFS and electro-hydraulic composite braking of distributed electric drive vehicles. Jo et al. [29-30] considered static friction and

Stribeck effect, established an EMB planetary gear model, developed two coordinated control strategies of friction braking force and feedback braking force suitable for electric cars, and achieved good control effects. Literature [31] proposed a hierarchical control strategy for electro-hydraulic composite braking direction stability of electric wheel vehicles. Literature [32] designed a series electro-hydraulic composite braking structure that can realize electro-hydraulic braking.

In addition to the above control strategies, some scholars also study the control issues of electro-hydraulic composite braking systems from other perspectives. The driver's braking feeling and vehicle braking comfort are improved through the braking force distribution correction module and motor force compensation module [33]. Xie Shaobo et al. [34] analyzed the relationship between the front and rear axle braking forces during the braking process of an electric car and its impact on stability. Liu Yang et al. [35] defined feedback energy efficiency and driver driving interpretation consistency as quantitative evaluation indicators for different solutions. The coordinated braking energy feedback system has good braking feeling and high feedback efficiency [36-37]. Cikanek et al. [38] rationally distribute the motor braking torque and mechanical braking torque, and perform as much regenerative braking as possible to improve energy utilization under the premise of meeting braking regulations and safety. Ko et al. [39] considered factors such as system response, wheel speed, road adhesion coefficient, and motor rotation angle, and proposed a collaborative control strategy for motor braking and mechanical braking. Novellis et al. [40] adjusted the yaw moment of the vehicle through coordinated control of the electric motor braking force and the mechanical braking force, thereby improving the active safety of the vehicle under extreme working conditions.

A large number of studies have shown that there are many control methods for the existing electric vehicle electro-hydraulic composite braking system, but a systematic system has not yet been formed, and the evaluation method is not perfect enough. Although a mathematical model has been established, the definition of the input quantity is not clear enough. These issues remain to be further resolved.

2.3 Wheel Cylinder Pressure Control

Many scholars have conducted research on wheel cylinder pressure control, which has greatly improved the accuracy of pressure control, as shown in Table 1.

Table 1 Wheel cylinder pressure control

Method	Research Content	In Conclusion
Number table interpolation algorithm [41]	Build a hydraulic brake system model and analyze the braking force adjustment characteristics	Achieve fast and fine adjustment
Dynamic coordinated control [42]	Summarizes the key technologies of electromechanical composite braking coordination control	Coordinated control and parameter matching of electromechanical composite braking system
Serial compound brake control [43]	Developed wire-operated hydraulic brake valve	Realize the serial application of motor regenerative braking and friction braking
Energy flow method [44-45]	Designed an electro-hydraulic composite braking system with an integrated brake master cylinder assembly	Recover more braking energy and improve braking stability
PID control strategy [46-47]	Established EHB model	Achieve precise pressure control and improve vehicle handling stability
PID linear control [48]	Current controlled linear solenoid valve opened by solenoid valve	Real-time control of wheel cylinder pressure

2.4 Estimation and Identification

There are few literatures on the estimation and identification of electro-hydraulic composite braking systems of electric vehicles. Zhang Houzhong et al. [49] developed an electro-hydraulic composite braking vehicle control algorithm based on road surface recognition. Literature [50] analyzed the braking intention and evaluated the consistency of the integrated electro-hydraulic composite braking system, analyzed the driver action signal change mechanism during the braking process, built a simplified model of the integrated master cylinder and conducted parameter identification. Literature [51] proposed a driving state parameter estimation algorithm based on a composite braking system structure and a maximum energy recovery control strategy optimization algorithm based on driving state estimation to prevent premature wheel locking. Sun Daxu et al.[52] used a radial basis function neural network system to conduct online identification of the electro-hydraulic composite braking system of electric vehicles, and used the sensitivity information of wheel slip rate to changes in motor braking torque to roll the PID control parameters. Optimized to achieve adaptive composite anti-lock braking control, improving the response speed and accuracy of anti-lock braking control for dual-motor four-wheel drive electric vehicles. Li Yufang et al. [53] proposed the definition of braking feeling consistency of electric vehicle electro-hydraulic composite braking system and analyzed its influencing factors. Literature [54] uses EHB hardware-in-the-loop simulation to evaluate its dynamic characteristics and estimate the performance of each component of the hydraulic regulator. Literature [55] proposed a regenerative braking neural network control strategy and performed system state estimation. Paul et al. [56] used the estimated values of slip rate and road adhesion coefficient to propose a braking force distribution strategy for electric vehicles to improve the lateral stability of the vehicle.

From the above summary, it can be seen that adaptive parameter estimation in the estimation process is an effective means to improve estimation and identification accuracy. Especially when there are system model errors and parameter perturbations, how to improve the estimation accuracy of the algorithm is the next step that should be focused on. The problem.

3 TEST PLATFORM

In order to solve the problem of test verification in the product development process and reduce the cycle cost of the R&D process, Yan Weiguang et al. [57] developed an electric vehicle electro-hydraulic hybrid braking system test bench. Sun Zechang et al. [58] used MATLAB/Simulink to establish a vehicle model and a braking energy recovery strategy model, implemented a rapid prototype of the controller based on Moto Hawk, and built an xPC Target hardware-in-the-loop platform. Gao Feng et al. [59] developed an integrated electro-hydraulic braking system and formed a prototype. The prototype is composed of a hollow motor, a ball screw pair, a three-cavity master cylinder, a human cylinder and a pedal stroke simulator. It integrates functions such as brake assist, brake-by-wire and regenerative braking. Luo Yugong et al. [60] developed equipment with hydraulic braking and motor braking execution.

Mechanism, and a hardware-in-the-loop test bed that can simulate dynamic changes in road braking force in real time. Introduce components such as hydraulic brakes, motors, speed and pressure sensors, and comprehensively consider the dynamic response characteristics of the interaction between wheels, hydraulic braking systems and motor braking systems during the braking process, and measure the key parameters of the test bench and the electrohydraulics of electric vehicles. The slip rate coordinated control test of compound braking verified the effectiveness of the test bench. Gao Guotian et al. [61] proposed an electro-hydraulic composite control strategy based on multi-objective dynamic coordination, built a test platform, and compared and analyzed the control test results under the two conditions. Literature [62] designed an electro-hydraulic composite feedback braking simulation test bench to verify the feasibility of the proposed electro-hydraulic composite braking force coordinated control strategy based on maximizing braking energy recovery. Han Yunwu et al. [63] verified the electro-hydraulic composite braking control algorithm that comprehensively considers vehicle safety and economy through simulation and test platforms. Literature [64] used xPC target to build an integrated electro-hydraulic composite braking system hardware-in-the-loop simulation test bench, and conducted tests on non-emergency and emergency braking conditions and driver braking intention analysis and braking force application consistency. Test, it can meet the needs of energy recovery and coordinated control with anti-lock braking. The German Bosch Company has developed a composite braking system. It starts the motor braking first, and then starts the electro-hydraulic composite braking system after the idle stroke, and conducted a bench test [65]. In summary, the existing electro-hydraulic composite braking system pressure control algorithm verification mostly uses test benches, which lack real vehicle test verification. The real-time performance and robustness of the test bench under complex working conditions need to be further improved.

4 CONCLUSION

Conduct a systematic study on the structural characteristics and research progress of electro-hydraulic composite braking systems at home and abroad from three aspects: optimal design, system control, and test platform, and subdivide the core issue system control into braking dynamics control and vehicle control Four topics including strategy, wheel cylinder pressure control, estimation and identification were discussed. The study concluded that:

1) Electro-hydraulic composite braking can prevent wheel locking and recover braking energy, but it requires the motor to continuously switch working modes and is still insufficient in terms of control accuracy and stability.

2) Batteries and motors participate in the energy conversion of electric vehicles. Their operating conditions are dynamic and changeable, and working modes switch frequently, which affects the braking performance of electric vehicles and has obvious nonlinear coupling system characteristics.

3) Compared with pure hydraulic control, electro-hydraulic composite braking maximizes the braking energy recovery efficiency of electric vehicles and greatly optimizes braking stability and braking feel.

4) The hydraulic control algorithm is the key to achieving accurate real-time pressure regulation in the electro-hydraulic composite braking system. The accuracy of hydraulic pressure control and the robustness of the control algorithm must be further improved. There is a lack of in-depth discussion on the impact of the algorithm on the braking comfort and handling stability of the vehicle. The reliability of the algorithm in engineering practice should be verified by real vehicle tests. This will be an important development direction of electro-hydraulic composite braking systems.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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