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Review

Review of Brake-by-Wire Technology for Low-Speed and Autonomous Vehicles

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Abstract: With advancements in autonomous driving and intelligent transportation, the need for responsive, stable braking systems in low-speed vehicles (LSVs) has risen, especially in complex conditions where traditional systems fall short. Brake-by-Wire (BBW) systems, known for their efficiency, energy savings, and safety, are becoming increasingly popular. This paper provides a systematic review of BBW technology for low-speed vehicles (LSV-BBW), aiming to offer valuable insights for researchers, engineers, and decision-makers in related fields. This comprehensive review covers the application of BBW and its associated technologies in LSVs. First, the current state of research on BBW systems is assessed, both domestically and internationally. Next, the fundamental principles and components of LSV-BBW technology are detailed. Following this, the control strategies of the LSV-BBW system are elaborated, with a clear definition of its performance metrics and identification of the key technologies involved. By analyzing the current trends in LSV-BBW technology development, this paper highlights cutting-edge advancements in the field. Finally, the significance and application prospects of LSV-BBW technology in promoting the intelligent, safe, and efficient development of LSVs are emphasized.

Keywords: low-speed vehicles; brake-by-wire; electro-hydraulic brake (EHB); electro-mechanical brake (EMB); brake control strategy

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1. Introduction

Currently, the implementation of low-speed autonomous vehicles has gradually begun in various niche applications, including industrial parks, ports, mining areas, tourist attractions, and airports. Some of these scenarios have already entered the phase of exploring commercial operations, with 2021 being considered the "year of implementation" for low-speed autonomous vehicles. With the rapid advancement of autonomous driving technology and the ongoing development of intelligent transportation systems, there is potential to improve the safety, energy efficiency, and effectiveness of ground vehicle transportation systems [1,2]. As a crucial foundation for autonomous driving technology [3], the X-by-Wire of low-speed vehicle (LSV-XBW) is becoming an important development direction for future transportation tools. The stability, reliability, and level of intelligence of the LSV-XBW, as a key transportation tool, play a significant role in improving the efficiency and safety of transportation systems.

However, in recent years, low-speed vehicles have demanded higher requirements for the responsiveness and stability of braking systems, particularly when faced with complex road conditions, sharp turns, or congested traffic. Traditional braking systems can no longer meet the demands of low-speed vehicles (LSVs). Furthermore, within the

technology of electronic control chassis, the Brake-by-Wire (BBW) system is currently the most complex electronic control system [4]. With the current trend of electric vehicles becoming mainstream, internal combustion engines are being replaced by electric motors. However, electric motors cannot directly provide a vacuum source for vacuum boosters that rely on engine-assisted braking [5]. Therefore, the electronic control of braking systems is urgently needed. The BBW system is gradually becoming mainstream due to its efficient and energy-saving characteristics, ensuring driving safety and gaining increasing visibility among the public. This technology not only enhances vehicle handling performance but also provides the potential for achieving more precise driving control. This development enables us to reassess control strategies and explore how to utilize advanced electronic control technologies to improve vehicle safety and comfort [6].

The BBW system, as an important safeguard mechanism for active vehicle safety, offers advantages such as environmental friendliness, precise pressure regulation, and rapid response times. By implementing coordinated control technologies, the BBW system can easily integrate the Anti-lock Braking System (ABS), Electronic Stability Control (ESC), and Regenerative Braking System (RBS). Currently, researchers have conducted extensive studies to develop robust systems and achieve effective control of the BBW system. Several published articles regularly investigate ongoing technological advancements. Reference [7] systematically summarizes the system architecture and working principles of mainstream BBW systems. The basic structure of the EMB actuator was presented in [7], and, based on this fundamental design, a summary of the estimation algorithms for both indirect and direct clamping force control was provided. The structure, classification, and working principles of the BBW system were detailed in [8,9], along with an analysis of various control strategies for the BBW system, as well as a review and summary of brake fault-tolerant and regenerative braking technologies.

This paper is divided into six sections. First, it presents an overview of the current research status of the BBW system both domestically and internationally. Second, based on the existing research on BBW systems, it introduces the fundamental principles and components of the LSV-BBW technology. Next, the control strategies for the LSV-BBW system are discussed. Subsequently, the performance indicators of the LSV-BBW system are defined. Following this, the key technologies within the LSV-BBW are identified. Then, the current development trends of LSV-BBW technology are examined. Finally, a summary of the entire paper is provided. This review of LSV-BBW technology is expected to offer valuable references for researchers, engineers, and decision-makers, promoting advancements and applications in this field and thereby facilitating the intelligent, safe, and efficient development of LSV-XBW systems.

2. Main Types and Structures of LSV-BBW System

Similarly to traditional vehicle brake-by-wire chassis systems, the LSV-BBW system primarily consists of the Electro-hydraulic Brake system (EHB) and the Electro-mechanical Brake system (EMB) [10]. These systems integrate brake-by-wire technology with automotive braking systems, replacing traditional mechanical or hydraulic connections with electronic devices, offering rapid response and superior control performance. Structurally, EHB is similar to conventional hydraulic systems, retaining the hydraulic braking framework while substituting the vacuum booster with a motor-assisted system [11,12], which makes it widely used due to its high compatibility. EMB, on the other hand, adjusts mechanical components through electronic signals, eliminating traditional hydraulic transmissions parts and using an electric motor as the power source. This approach is more environmentally friendly and eliminates the response delays associated with brake fluid. Figure 1 summarizes the main BBW manufacturers and their representative products, with EHB products being the most prevalent. As intelligent vehicles continue to evolve, EMB is expected to replace EHB and become the mainstream choice. Currently, EMB has attracted global attention from automotive manufacturers, but due to its lower reliability and regulatory risks, commercially available products remain limited in the market.

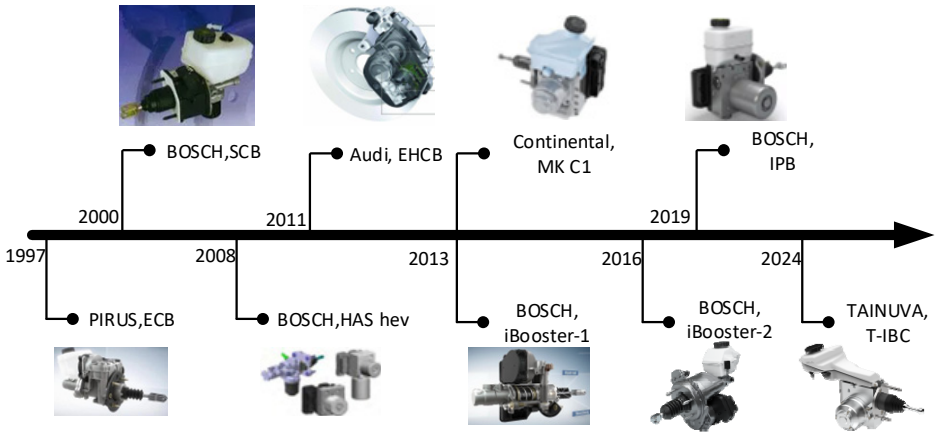


Figure 1. BBW main manufacturers and their representative products.

2.1. Electro-Hydraulic Brake (EHB)

The EHB serves as a transitional product between traditional braking systems and brake-by-wire systems, replacing the conventional hydraulic brake pedal with an electronic brake pedal and substituting the bulky vacuum booster with hydraulic devices. Its hydraulic control unit can automatically adjust the wheel braking pressure based on driving conditions, ensuring sufficient braking force. The EHB eliminates the direct coupling between the brake pedal and the driver, featuring a compact design, convenient control, low noise, and enhanced comfort. The composition of the EHB is illustrated in Figure 2 [13–15]. Figure 2 illustrates the schematic of BBW system, which is a critical component in modern automotive safety systems. The system includes a brake pedal that initiates the braking process, a pedal simulator valve that provides feedback to the driver, and a fail-safe valve to ensure system operation in case of failure. The brake cylinder, driven by a motor, converts hydraulic pressure into mechanical force, which is then transmitted to the four-wheel brake system through increase and decrease valves. These valves control the flow of hydraulic fluid to modulate the braking force applied to each wheel, ensuring precise and reliable braking performance. Additionally, the EHB can independently control the braking force of each wheel, optimizing the regenerative braking energy recovery in electric vehicles, thereby possessing significant application value. It is valuable to note that it is still possible to stop the vehicle with a "dead" EHB brake system as long as there is no fluid loss, although increased pedal actuation effort is necessary.

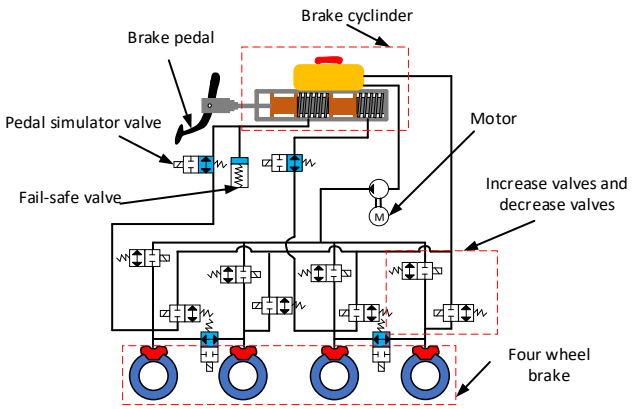


Figure 2. EHB schematic diagram.

The EHB, as shown in Figure 3, is divided into four parts: the brake pedal unit, hydraulic drive unit, brake actuator unit, and control system [16]. The brake pedal unit includes the brake pedal and pedal simulator, providing brake feel and obtaining the driver's intention [17]. The brake actuator unit consists of the master cylinder, hydraulic

pipes, and wheel cylinders. The control system includes the electronic control unit (ECU), hydraulic pressure control unit (HCU), hydraulic pressure sensors, pedal force sensors, and pedal displacement sensors. The hydraulic drive unit can be in the form of "motor + transmission mechanism" or "hydraulic pump + high-pressure accumulator". Since the maximum pressure requirement for the brake master cylinder in electric vehicles often exceeds 15 MPa, it is necessary to equip the electronic hydraulic braking system, which uses a motor as the hydraulic pressure power source, with a reduction torque mechanism to increase the motor's maximum output torque, reduce the motor size, and save costs. The "motor + transmission mechanism" hydraulic drive system operates by using a motor to drive the reducer, which reduces the motor's speed while increasing its torque and, in turn, drives the hydraulic pump, generating the required hydraulic pressure. The pressurized hydraulic fluid is then transmitted through pipes to the braking system, where it controls the brake calipers to achieve braking. The "hydraulic pump + high-pressure accumulator" provides the master cylinder's hydraulic pressure or wheel cylinder braking force through the high-pressure energy from the accumulator for active regulation. The system acquires braking driving intentions from the brake pedal unit and sends instructions to the vehicle controller to control the high-pressure accumulator, solenoid valves, and pump to generate the corresponding hydraulic pressure. When the pressure in the high-pressure accumulator is insufficient, the hydraulic pump will boost the high-pressure accumulator.

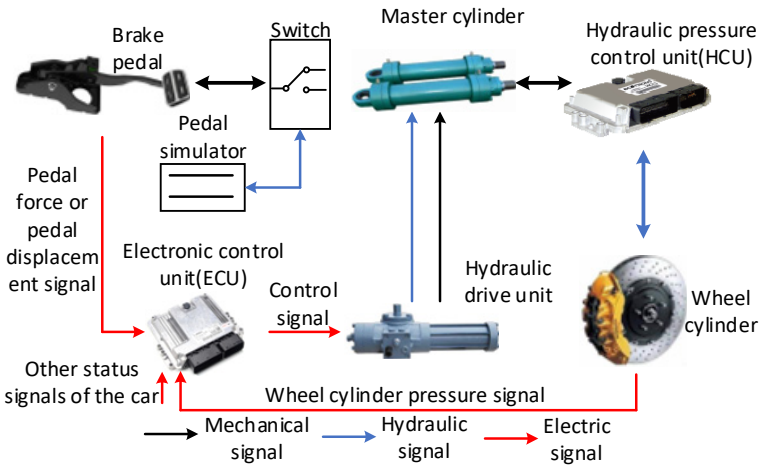


Figure 3. EHB structure diagram.

Hydraulic pressure control is a fundamental function of the electronic hydraulic braking system. The hydraulic pressure control in this system is categorized into master cylinder hydraulic pressure control and wheel cylinder hydraulic pressure control. The wheel cylinder hydraulic pressure control is further divided into upper-level control of wheel cylinder hydraulic pressure and lower-level control of the solenoid valve. The former is used to calculate the control commands for the solenoid valve, while the latter determines the control methods for the solenoid valve. The hydraulic pressure control architecture of the EHB is illustrated in Figure 4.

2.1.1. EHB Based on Wheel Cylinder Fluid Pressure Control

Wheel cylinder hydraulic pressure control is achieved by receiving the target pressure calculated by upper-level algorithms (such as anti-lock braking, vehicle stability, and electro-hydraulic composite brake distribution algorithms). This control incorporates wheel position and solenoid valve characteristics to generate control commands. Simultaneously, the system continuously monitors the actual pressure in the wheel cylinders against the target pressure to promptly adjust the solenoid valve commands, ensuring that the wheel cylinder pressure rapidly reaches the desired value.

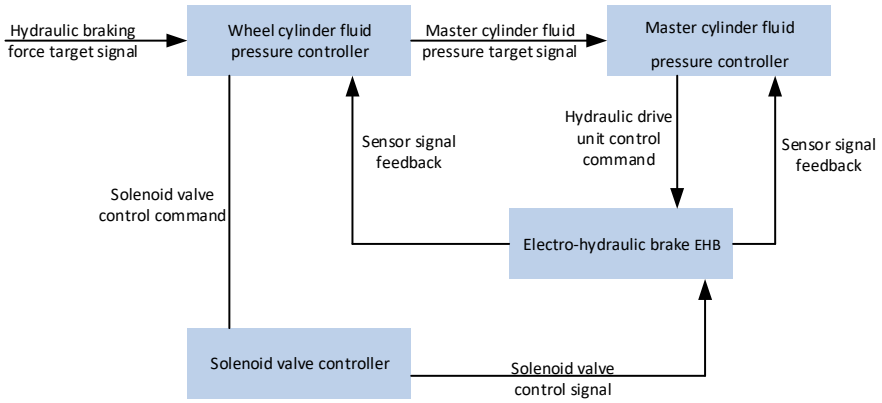


Figure 4. Hydraulic pressure control frame of electronic hydraulic brake system.

Researchers have conducted extensive studies on wheel cylinder hydraulic pressure control, proposing various control methods. Commonly used methods include Proportional–Integral–Derivative Control (PID) and its improved algorithms, feedforward control, feedback control, fuzzy control, robust control, sliding mode control, and active disturbance rejection control, among other mainstream control algorithms.

In the early stages of research, the predominant approach for designing wheel cylinder pressure controllers was the PID method [18–29], which is known for its high reliability and ease of control. Typically, the difference between the target braking pressure and the actual braking pressure in the wheel cylinder is used as the input to the PID controller. By experimentally adjusting the controller's parameters, the output is the duty cycle control signal for the pressure-increasing and pressure-decreasing solenoid valve, enabling the actual wheel cylinder pressure to follow the target pressure.

Due to the complexity and nonlinearity of the automotive braking system, the use of traditional PID control algorithms for wheel cylinder pressure control results in unsatisfactory system response and stability, failing to meet the requirements of the braking system. A variety of improved PID control methods have emerged from extensive engineering practice, significantly enhancing the control effectiveness of the system. Given the limitations of the microcontroller performance in the EHB, a recursive Proportional–Integral (PI) control method was employed in [30] to manage the wheel cylinder hydraulic pressure by accumulating the output of the previous electromagnetic valve control signal. The selection of optimal parameters for the PI controller varies across different pressure ranges; the operating range of the EHB was categorized into low, medium, and high pressure in [31], and fuzzy logic was utilized to determine the optimal PI parameters. Passenger vehicles equipped with the EHB were investigated in [32], where a new stability control strategy was proposed. Fuzzy reasoning was employed to determine the threshold values for yaw rate deviation and centroid side slip angular rate, with a logical threshold PI control used to calculate the additional yaw moment, which was implemented within the EHB. Furthermore, a fuzzy PI self-tuning algorithm was utilized to optimize the target pressure control of the wheel cylinder in the EHB. A characteristic analysis of linear solenoid valves was conducted in [33], where an accurate pressure control algorithm for the EHB was proposed, based on feedforward PID control of the linear solenoid valves. A motor-driven EHB was designed in [34], where the nonlinear friction caused by the deceleration mechanism was analyzed, and a chatter signal was incorporated into the controller input to compensate for this friction. Additionally, a fuzzy PI controller for the hydraulic pressure within the EHB was designed, based on the opening and closing characteristics of the solenoid valve. An estimation and control strategy for wheel cylinder pressure in an integrated electronic hydraulic braking system was proposed in [35]. The wheel cylinder pressure control algorithm was adjusted based on the relationship between the target pressure, the estimated pressure difference, and a set threshold. To enhance the robustness of the control algorithm,

a Radial Basis Function Neural Networks–PID (RBF–PID) controller was designed for the solenoid valve.

Feedback control adjusts based on the deviation between actual and target values, without requiring consideration of the type of disturbance. However, feedback control has the drawbacks of long signal transmission periods and poor real-time performance. The braking performance of hybrid electric vehicles was optimized in [36] by employing both feedforward and feedback control strategies. An electro-hydraulic composite braking control method was proposed in [37] to enhance the overall performance of downhill assist control in hybrid electric vehicles. By analyzing the variations in downhill assist braking torque and the characteristics of each auxiliary system, a torque distribution principle was established. Torque coordination between the motor and the hydraulic assist braking system was achieved through a combination of feedforward and feedback control strategies.

The fuzzy control algorithm [38] is utilized for wheel cylinder pressure control. Real-world testing indicates that at speeds below 25 km/h, the variation in speed only fluctuates by 2.5 km/h, a change that is imperceptible to the occupants. It was pointed out in [19] that the adaptability of fuzzy control systems to changes in model parameters and external random disturbances is limited, as evidenced by significant overshoot in system response and substantial oscillations during the pressure-holding process. A novel braking system based on proportional servo valves was proposed in [39], incorporating a new control block grounded in fuzzy logic to determine the optimal braking pressure. Kalman filtering was employed to estimate wheel adhesion and vehicle speed, while road types were detected. An artificial neural network, based on the road type, was used to estimate slip and enhance traction, ultimately determining the optimal pressure through fuzzy logic.

Active Disturbance Rejection Control (ADRC) is a model-free control technique proposed by Professor Jingqing Han of the Chinese Academy of Sciences. It inherits the PID algorithm's approach of eliminating error through error correction but can estimate and compensate for the total disturbances both inside and outside the system in real time. ADRC achieves ideal control performance through a nonlinear combination based on error feedback. ADRC technology was applied in [28] to control the wheel cylinder hydraulic pressure in the EHB, with the design and parameter tuning of the ADRC controller successfully completed. A new wheel pressure adjustment scheme, which directly coordinates the control valve with the electric booster and replaces the traditional plunger pump, was introduced in [40]. This scheme incorporates Disturbance Rejection Adaptive Control (DRAC) to handle parameter uncertainty and disturbances while maintaining stable back pressure. Additionally, an Adaptive Neural Network Controller (ANNC), consisting of two Radial Basis Function Neural Networks (RBFNNs), was developed to enable real-time learning of system dynamics while reducing computational resource requirements. To address the nonlinear issues in the Electric Boosted Brake System (E-booster) during active braking, a multi-loop control strategy based on pressure, position, and current was proposed in [41]. This strategy involved analyzing the working principle of the E-booster and establishing a simplified model to design an ADRC-based pressure controller, which compensates for time-varying disturbances in the hydraulic system. A robust sliding mode controller was implemented to manage friction and unmodeled disturbances, while a current controller based on Lyapunov stability theory was developed to resolve the motor current coupling problem.

Several other algorithms have been introduced for controlling the hydraulic pressure of the wheel cylinders. A pressure sensor-free integrated electro-hydraulic braking system employing a dual closed-loop cascade control structure was presented in [42], where the nonlinear pressure–position relationship was estimated through interconnected pressure estimators. To mitigate nonlinearity and uncertainty, a conditional integral sliding mode controller (SMC) was designed for the external pressure loop to ensure tracking accuracy, while the internal position control loop enhanced response speed. This design effectively facilitated the rapid elimination of disturbances. A nonlinear inversion control algorithm for the EHB, based on a key diagram model, was proposed in [43]. A nonlinear single-wheel braking

system model, which considers the effects of hydraulic oil capacitance, caliper damping, and inertia, was established in this work. A robust backstepping controller was designed, and a unified expression for the control signals of both the inlet and outlet valves was introduced. Additionally, the impact of controller parameters on brake pressure control was analyzed, which led to the selection of optimal design parameters. A chattering compensation method for hydraulic pressure control was employed to address the oscillation and low-speed creeping phenomena caused by friction in the pressure control of integrated electronic hydraulic braking systems in [44]. A novel integrated electro-hydraulic braking system (I-EHB) for automotive applications was introduced in [45], followed by experimental bench testing. The experiments revealed the presence of friction and nonlinear issues in hydraulic control. To address these challenges, the chattering compensation method was employed for testing and optimizing the algorithm, ultimately achieving precise control of hydraulic pressure.

2.1.2. EHB Based on Master Cylinder Fluid Pressure Control

Traditional braking systems struggle to achieve precise control of the master cylinder hydraulic pressure due to the lack of decoupling between the brake pedal and the master cylinder piston push rod, as well as the nonlinearity of the vacuum booster. In Electronic Stability Control (ESC), the limitations of the motor hydraulic pump and Hydraulic Control Unit (HCU) can adversely affect control performance. Accurately controlling the hydraulic pressure of the master cylinder can enhance control effectiveness and improve vehicle stability. In contrast to traditional systems, EHB utilizes control algorithms to precisely manage the master cylinder hydraulic pressure, allowing for rapid and stable tracking of the target pressure to meet the new requirements of braking systems. Common control methods are summarized in Table 1.

Table 1. Common control algorithms for master cylinder hydraulic pressure control. Adapted with permission from Ref. [8].

Hydraulic Drive Unit Form	Control Variable	Control Algorithm	Reference
Motor + decelerating mechanism	Master cylinder fluid pressure	Feedback control	[46–48]
		PID control	[49–51]
		Taguchi method + segmented proportional–integral control	[49]
		Gain scheduling proportional–integral control	[51,52]
		Feedforward + feedback control	[53]
		Friction compensation + proportional–integral–differential control	[50,54]
		Friction compensation + adaptive robust control	[54]
		Friction compensation + sliding mode variable structure control	[55]
	Master cylinder piston push rod displacement	PID control	[56,57]
		Prediction based on hydraulic model	[56]
		Sliding mode variable structure control	[57]
	Motor rotation Angle	Feedback control	[58,59]
	Master cylinder fluid pressure + master cylinder piston push rod displacement	Switching control	[60]
		Cascade control	[61]
		Cascade anti-winding control	[62]
	Master cylinder fluid pressure + motor current	Cascade control	[63]
Hydraulic pump + high pressure accumulator	Master cylinder fluid pressure	On-off control	[64]
		Pulse width modulation control	[65]
		PID control	[66]
		Sliding mode variable structure control	[67]

For the EHB with a hydraulic drive unit configured as "motor + reducer", the primary control variables are categorized into five forms: main cylinder liquid pressure, main cylinder piston push rod displacement, motor rotation angle, the combination of main cylinder liquid pressure + main cylinder piston push rod displacement, and the combination of main cylinder liquid pressure + motor current. In contrast, for the EHB with a hydraulic drive unit configured as "hydraulic pump + high-pressure accumulator", the main control variable is the main cylinder liquid pressure. The principal control methods employed include feedback control, feedforward control, PID control, PI control, and their composite control variations, as well as robust control, sliding mode control, switching control, cascade control, on-off control, and pulse width modulation control, among other composite control strategies.

For the EHB with a hydraulic drive unit configured as "motor + reducer", the control variable is the master cylinder hydraulic pressure. Both Bosch's iBooster system and Hitachi's e-ACT system [46–48] employ hydraulic closed-loop feedback control. The control algorithm compares the actual output value with the target value, using the controller to process the deviation and ultimately pass the result to the actuator. The key to this algorithm design is the effective utilization of the deviation to design the controller. A robust hydraulic pressure control system was designed in [49], proposing a robust control strategy using an improved Taguchi method. Experimental results demonstrated that the system maintained robustness over 500 trials, optimized performance, and enhanced resistance to disturbances. A mathematical model of the I-EHB was established, and friction force compensation using chatter was proposed and experimentally validated in [50]. A prototype of a linear control braking system—the Distributed Electro-Hydraulic Braking (DEHB) system was presented in [51]. DEHB offers advantages in terms of cost, installation, performance, and reliability. Based on these characteristics, a fault-tolerant control method using gain-scheduled PI control was proposed, and two DEHB architectures capable of implementing this control were described. The superiority of the control method and architecture was validated through simulations and Hardware-in-the-Loop (HIL) experiments. Fast, stable, and accurate hydraulic control was achieved through open-loop and closed-loop tests based on a self-developed actuator in [52]. The closed-loop control employed a gain-scheduled PI controller, and both the response time and root mean square error met the performance criteria. A high-precision electric servo braking system, which integrates braking pressure control with regenerative braking to ensure that pedal force remains unaffected by braking pressure, was proposed in [53], providing an optimal braking feel. A pressure ring controller for a hybrid line-controlled braking system was developed in [54]. To address friction disturbances, a parameterized linear model based on model-based friction compensation was investigated, incorporating an approximate Stribeck friction model. A braking pressure tracking control law was then designed using this model. The controller demonstrates robustness, employs a switch-σ adaptive mechanism, and reduces non-parametric disturbances through continuous sliding mode control. A simplified system model for hydraulic pressure control in the Integrated Electro-Hydraulic Brake (I-EHB) system was developed in [55] to address challenges arising from nonlinear factors such as friction, time delays, and low precision. The analysis was conducted using the Byrnes–Isidori canonical form method, which facilitated the design of a hydraulic pressure control algorithm incorporating feedforward–feedback control and friction compensation.

For hydraulic drive units configured as "motor + transmission mechanism" in EHB, the control variable is the displacement of the main cylinder piston rod. The Integrated Modular Brake System (IBS) proposed in reference [56] employs a model predictive approach based on hydraulic modeling to correct the target displacement of the main cylinder piston rod. The reliability and braking performance of the system were enhanced in [57] by designing a controller with precise target pressure tracking and robustness. A sliding mode controller was designed based on the Lyapunov function to improve robustness against model uncertainties and disturbances.

For hydraulic drive units configured as "motor + transmission mechanism" in EHB, the control variable is the motor rotation angle. The MK C1 of Continental [58] and the Integrated Brake Control System (IBC) of TRW [59] incorporate angle sensors within the

motor, using the motor rotation angle as the control variable, which effectively allows for the indirect determination of the main cylinder piston rod displacement, thereby enabling the control of the main cylinder hydraulic pressure.

For hydraulic drive units configured as "motor + transmission mechanism" in EHB, the control variables are the main cylinder hydraulic pressure combined with the main cylinder piston rod displacement and the main cylinder hydraulic pressure combined with the motor current. A hybrid position–pressure switching controller was proposed in [60] to mitigate the nonlinear challenges resulting from the degradation of closed-loop performance. Furthermore, a position–pressure map estimation algorithm was introduced, which significantly enhances the system's robustness against variations in temperature and brake pad wear. A cascade control structure for a linear braking system suitable for racing applications was presented in [61]. The approach began with a control-oriented model and proposed a cascade control strategy, in which the inner loop regulated position and the outer loop regulated pressure. An adaptive mechanism was incorporated into the outer loop to address the inherent time-varying nonlinearity of the position-pressure relationship. A comprehensive control architecture addressing the dead zone problem caused by saturation constraints on the fluid reservoir and drive pump motor input was proposed in [62]. The architecture consists of a linear controller, dead zone compensator, and anti-windup block, implemented through a cascade design. This configuration ensures the global asymptotic stability of the equilibrium point and enhances the system's robustness to variations in the position–pressure curve. A limitation on the motor command current due to actuator saturation, which impacts the accuracy of the main cylinder hydraulic pressure control, was highlighted in [63]. It was demonstrated that by employing an anti-windup controller, the global asymptotic stability of the system's equilibrium point could be ensured.

For the EHB configured as "hydraulic pump + high-pressure accumulator", the controlled variable is the hydraulic pressure in the master cylinder. Bosch's HAS HEV system [64] monitors the accumulator liquid pressure and the signal of the actuator chamber liquid pressure to control the switching valve and regulating valve, thereby adjusting the hydraulic path between the accumulator and the actuator chamber for pressurization or depressurization. A braking system designed to enhance vehicle safety and braking performance was presented in [65]. The system continuously monitored the wheel slip ratio and dynamically adjusted braking pressure to prevent wheel lock-up and improve stability. Intelligent control algorithms were integrated into the system to optimize brake force distribution, enhance response speed, and adapt to varying road surfaces and driving conditions, such as wet or rugged terrain. The EHB described in references [20,66] eliminates the high-pressure accumulator, instead utilizing a motor-driven plunger pump to directly supply high-pressure oil. By inputting the difference between the target hydraulic pressure and the actual hydraulic pressure into a PID controller, the motor speed is adjusted to achieve master cylinder hydraulic pressure tracking control. Honda's HSB (Hydraulic Servo Brake) system [67] addresses the model error induced by temperature variations during controller design. It employs a sliding mode variable structure control algorithm to separately manage the booster valve and the release valve, allowing for precise hydraulic control through parameter adjustment while ensuring braking comfort under various operating conditions.

2.2. Electro-Mechanical Brake (EMB)

The EMB primarily consists of a pedal module (sensors), a control module (ECU), and a driving executive module (electromechanical brake). The system includes four independent brake systems located at the wheel cylinders of each of the four hubs, each equipped with independent controllers to enable independent adjustment of the braking force for each wheel. In the EMB, all hydraulic components (including the master cylinder, hydraulic lines, and auxiliary devices) are replaced by an electromechanical system, and the regulators for hydraulic disk and drum brakes are also replaced by motor-driven devices. A typical EMB is illustrated in Figure 5 [68,69]. Figure 5 illustrates the structure of EMB. The

system comprises a brake motor that drives the screw, which in turn actuates the carrier and head to press the brake pads against the disk. The ring gear and sun gear facilitate the transmission of mechanical force, ensuring precise and reliable braking performance.

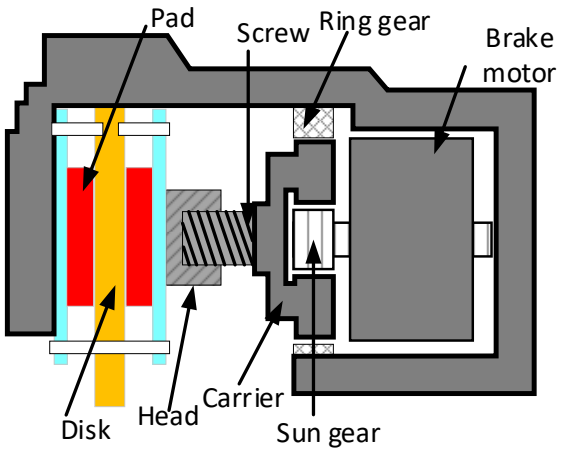


Figure 5. EMB structure diagram.

Compared to the EHB, the EMB completely replaces the hydraulic system, directly driving the brake actuator with a motor, which enhances the efficiency of the braking system. Utilizing easily controllable motors as the control module facilitates integrated control with other electronic systems, enables the incorporation of functions such as brake energy recovery, and allows for the modularization, intelligence, and multifunctionality of the vehicle.

In summary, the EMB offers several advantages over the EHB [70,71]:

1. Reduced system size and weight, increased modularity, and ease of installation and maintenance;
2. No issues with brake fluid leakage, resulting in minimal environmental pollution;
3. Easier integration of the parking brake in mechanical layout;
4. Faster braking response with no pedal oscillation and lower noise levels;
5. Facilitates integration with composite braking systems and active safety control systems.

However, the EMB is still in the theoretical or experimental stage, with no mature products available on the market, and it has not yet met safety regulatory requirements, which limits its application. Despite the numerous advantages of the EMB, several technical challenges persist, hindering its industrialization. The main technical issues associated with the EMB are as follows:

1. The braking system must quickly respond to the driver's braking intentions; however, replacing hydraulic brake lines with delicate electronic components raises safety concerns, making safety a key consideration for the EMB [72].
2. The torque motor encounters complex conditions during braking, including locking, frequent forward and reverse rotations, and harsh environments. Consequently, its reliability, compactness, and response characteristics are crucial components of the EMB [73].
3. The EMB relies on motors to provide braking force, which places high demands on battery capacity. However, the existing 12 V onboard batteries are insufficient to meet this demand, leading to 42 V high-capacity power sources becoming an important area of research [74].
4. The extensive use of numerous sensors and high-performance torque motors, along with the demand for controllers, significantly increases the cost of the EMB, slowing down its adoption.
5. The greatest issue with EMBs is the lack of a fallback to a direct connection from the foot pedal to the wheel brake elements in case of a malfunction, therefore, necessary redundancy technology and reliable backup mechanisms are essential.

Clamping force control is a fundamental function of the EMB and is key to achieving regenerative braking coordination and active braking control. Compared to the EHB, the EMB offers a higher closed-loop system bandwidth, allowing for more precise braking force control [75]. However, in the wheel-side integrated space, issues of actuator system nonlinearity and thermoelectromagnetic multiphysics couplings are particularly pronounced. The arrangement of pressure sensors is challenging and subject to significant interference. Therefore, accurately modeling and identifying parameters of the actuator system, achieving robust adaptive precise clamping force control, and implementing robust clamping force estimation and indirect control without pressure sensors have become urgent research challenges that need to be addressed.

2.2.1. EMB Based on Direct Clamping Force Control

The control algorithm based on the feedback value of clamping force can obtain the feedback signal through the pressure sensor to realize the closed-loop control of clamping force. The existing direct control algorithm of clamping force is shown in Table 2.

Table 2. Direct control algorithm of clamping force.

Category	Advantages and Disadvantages	Control Algorithm	Reference
PID control	Advantages: simple structure, easy implementation layer algorithm development and application Disadvantages: high parameter dependence and tuning difficulties, with certain limitations to time-varying nonlinear problems	Fuzzy PID control	[76–80]
		Feedback linearized PID control	[77,81,82]
		Cascade PID control (triple loop/Double loop)	[83,84]
Robust control	Advantages: Good anti-interference and fault tolerance, high stability Disadvantages: conservative control, difficult design and debugging	sliding mode control	[85–89]
Model predictive control	Advantages: Good dynamic control performance, can explicitly deal with constraints Disadvantages: high model dependence, large computation and poor real-time	Explicit nonlinear adaptive MPC control	[90]
		Linear unconstrained adaptive MPC control	[91]

PID control is the most commonly used algorithm for direct clamping force control, characterized by its simple structure, ease of application, and good adaptability. An adaptive clamping force control strategy for the EMB, which considers nonlinear friction resistance, was proposed in [76]. A cascade PI controller, consisting of clamping force, velocity, and current loops, was designed. Fuzzy theory was applied to adaptively adjust the PI control coefficients of the clamping force loop, and an Extended State Observer (ESO) was introduced in the current loop to dynamically estimate and compensate for friction resistance. A feedforward fuzzy adaptive PI pressure dual-layer control algorithm was proposed in [77], with the upper layer focusing on fuzzy PI pressure control and the lower layer managing the motor's position information and current control. This approach aims to improve the nonlinear pressure control issue during active braking of the self-designed Electro-Mechanical Brake Booster (EMBB) mechanism. A clamping force control method for the EMB was proposed in [78], based on a Variable Universe Adaptive Fuzzy PID (VUF-PID) controller, which incorporated a stretching factor into the fuzzy PID control. The fuzzy theory domain was adjusted in real-time according to the operating conditions of the controlled object, ensuring the system remained within optimal parameter values and thereby enhancing its adaptability. A piecewise closed-loop control strategy, based on the relationship between current threshold and clamping force, was designed in [81] to meet the dynamic stability requirements of the electromechanical braking system and identify critical points during the braking process. Furthermore, a fuzzy PID control strategy was applied to the pressure loop of clamping force control in [79]. The issues of nonlinearity and uncertainty in the control of linearly actuated braking systems

were addressed in [80], where a vehicle braking force control strategy based on fuzzy PID methods was designed. A precision clamping force control strategy for the Electro-Mechanical Brake (EMB), based on nonlinear characteristic compensation, was presented in [81]. A mathematical model of the motor, transmission mechanism, and friction was developed, with the parameters of the friction model determined experimentally. A PI cascade controller was designed for clamping force, velocity, and current, incorporating inverse gain function linearization and load feedforward compensation methods to mitigate nonlinear characteristics. The friction model was further utilized for dynamic compensation of nonlinear disturbances. A test bench for the Electro-Mechanical Brake (EMB) system was established, and a corresponding simulation model was developed in [82]. The model was verified through tests, demonstrating that it adequately reflects the characteristics of the EMB. Two clamping force control methods were designed for the EMB, and bench tests were performed to compare their control effects, achieving both sufficient braking strength and rapid braking response. A three-loop control system was proposed in [83]. The clamping force loop utilized fuzzy PID control, which combined the advantages of fuzzy control and PID to enhance adaptability and robustness. The speed loop employed traditional PID control to ensure speed stability, while the current loop applied hysteresis ring control, achieving precise control and disturbance resistance by adjusting the width of the hysteresis ring and compensating for current errors. Finally, a hydraulic braking system control algorithm based on the Ebooster was proposed in [84]. A model incorporating a Permanent Magnet Synchronous Motor (PMSM) and a hydraulic braking system was established in MATLAB/Simulink, with the introduction of a four-loop active braking pressure control algorithm.

To address the parameter perturbation issues caused by factors such as temperature and wear, robust control algorithms have been introduced for clamping force control. A novel sliding mode control strategy to overcome the limitations of sensor installation and control accuracy was presented in [85]. The performance of the EMB braking system was tested under simulated braking conditions on dry mixed concrete surfaces. A sliding mode control (SMC) strategy was applied to the constructed BBW model in [86], with a focus on compensating for the impact of wear pad degradation on braking performance. Experimental results demonstrated that the SMC effectively mitigates brake pad wear, while maintaining accurate tracking of the braking command. An improved sliding mode control method for the clamping force of an electromechanical brake based on an ultra-twisting extended state observer was proposed in [87]. The design incorporates an enhanced reaching law, which uses variable function gains and power terms in the sliding mode surface to improve the reaching rate and reduce chattering. This approach leads to the development of an advanced clamping force controller. The extended state observer of the ultra-twisting algorithm is employed to estimate system disturbances, with the estimated values being fed forward to the controller for compensation, thereby ensuring system stability as demonstrated through Lyapunov's theorem. In [88], an Enhanced Sliding Mode Reaching Law (ESMRL) was investigated to address issues related to EMB. A new strategy for gap distance elimination and adjustment was proposed to improve response quality in a simple and cost-effective manner, exhibiting minimal chattering and short reach times, thereby enhancing the dynamic performance and tracking accuracy of clamping force control. A sensorless robust force control method, which accurately regulates the clamping force of the EMB through independent motor control and avoids the need for mechanical components, was proposed in [89]. To address the issues of parameter variations and backlash in the EMB, a cascade control strategy coupled with a disturbance observer was employed to enhance control robustness. Additionally, a Clamping Force Observer (CFO) was introduced as a sensorless estimation method for clamping force.

The clamping force control method based on model predictive control is also widely applied. An adaptive control strategy for electromechanical brakes based on optimized generalized predictive control was presented in [90]. This strategy identifies the system transfer function parameters in real-time to provide control parameters for the controller.

Additionally, offline optimization is performed using stochastic search algorithms, such as evolutionary strategies, particle swarm optimization, and differential evolution, to design parameters—including control levels, prediction horizons, and weights—which enhance the system's robustness under conditions deviating from the nominal. A multi-source braking force system and its control strategy, aimed at improving braking strength, safety, and energy efficiency, were introduced in Reference [91]. The braking force control strategy, based on explicit nonlinear model predictive control (ENMPC), replaces the traditional ABS strategy, enhancing both braking strength and safety, while laying the foundation for the integration of the drive motor in ABS regulation. The gray wolf algorithm was employed to rationally allocate the electromechanical braking forces.

Many scholars and researchers have proposed various alternative methods for clamping force control. A braking control algorithm combining ABS and Electronic Brakeforce Distribution (EBD) based on the Electro-Mechanical Brake (EMB) was introduced in [92], demonstrating its feasibility. A clamping force control algorithm, based on the friction characteristics of a planetary gear EMB, was presented in [93] to estimate the clamping force. Given that clamping force estimation requires knowledge of the contact gap distance, a control algorithm utilizing the gradient change in motor torque to estimate the initial gap distance was proposed. A bionic control strategy based on the brain-edge system for electromechanical braking systems, suitable for dynamic and uncertain driving conditions, was investigated in [94]. The control parameters were optimized using a genetic algorithm to achieve this. A novel EMB featuring an automatic wear adjustment function was proposed in [95]. To investigate the parameter characteristics of the EMB and analyze the proposed functions, a mathematical model, which includes a DC motor, motor friction, worm gear drive, ball screw, and load, was developed using MATLAB/Simulink. The discrepancies between the simulation and experimental results under step, triangular wave, square wave, and sinusoidal wave input signals were discussed. The parameter relationships of clamping force with respect to motor current and clamping force with respect to ball screw displacement were presented, which validate the accuracy of the established model.

2.2.2. EMB Based on Clamping Force Estimation Control

The control based on the estimated clamping force aims to achieve stable tracking of the clamping force using the information from other sensors in the absence of pressure sensors. Currently, there is limited research on control algorithms based on estimated clamping force.

A novel clamping force estimation method, termed the force separation strategy, was proposed in [96] as a replacement for clamping force sensors. Unlike traditional nonlinear polynomial function estimations, this method does not consider the brake gap distance. Instead, an unknown input observer is employed to achieve decoupled estimation of both the state and input. A clamping force control algorithm, which takes into account the friction characteristics of a planetary gear-type EMB and the estimation of the clamping force, was introduced in [93]. Since the estimation of the clamping force requires the gap distance between the pad and the disk, a control algorithm based on the gradient change in motor torque for the initial gap distance was proposed. A clamping force tracking controller based on a disturbance observer, which combines PI control with zero phase error tracking control, was designed in [97], effectively reducing amplitude attenuation and phase lag under high-frequency signals. Furthermore, a unified structure for position/force control was proposed, in which motor angular displacement is transformed into a virtual force, thus enabling a smooth transition between gap elimination and clamping force tracking. A structure based on a three-loop cascading PID for force servo control, which utilizes dynamic stiffness characteristics, hysteresis effect correction of stiffness characteristics, and super spiral observers to estimate the clamping force magnitude, was adopted in References [98–100]. This approach leads to an improved clamping force tracking performance. A method for estimating the braking pressure of EMB actuators based on feature extraction algorithms was presented in [101], along with an analysis of the anti-lock

braking control algorithm for vehicles. An adaptive sliding mode control in the position closed-loop was introduced in [102], where load-dependent lumped friction characteristics were described using a second-order polynomial of motor angular displacement. Adaptive laws were employed to determine the friction correction coefficient, enhancing robustness under time-varying parameters. A third-order improved extended state observer based on the sigmoid function was designed in [103], which provides real-time estimation of unmodeled dynamics and parameter perturbations in the system. This observer supplies feedforward compensation to the integral backstepping controller, thereby eliminating observation errors and enhancing the precision and disturbance rejection capability of position servo control.

3. Control Strategy of LSV-BBW

3.1. Fault Diagnosis, Redundancy, and Fault Tolerance Control of LSV-BBW

The LSV-BBW replaces traditional mechanical hydraulic components with electromagnetic actuators to achieve high-precision braking. However, electronic components are susceptible to humidity and aging, which may lead to braking failure. Redundant design is an effective solution, with the current mainstream approach being a dual-redundancy system. A Double Redundant Electro-Hydraulic Brake (DREHB) system with a decoupled architecture, featuring dual redundant hydraulic modules to support both normal and degraded braking modes for fault safety, was proposed by Chao Li et al. in [104]. In 2021, Great Wall Motors launched a tri-redundant system that further enhances reliability; even if all three systems fail, the cross-system redundancy design can still ensure safety [105].

The LSV-BBW system detects, diagnoses, and handles faults in a timely manner through fault detection, diagnosis, and fault-tolerant control. Sensor failures (such as stalling or gain variation) can be compensated for using redundant components or algorithms. Diagnosis typically combines hardware and analytical redundancy to optimize the system and minimize impacts [106–108]. Numerous other researchers have proposed various algorithms for fault diagnosis and detection [69,109]. The controller, as a core component, also requires fault-tolerant control; to address Microcontroller Unit (MCU) failures, some chip manufacturers offer dual-core or tri-core MCUs to mitigate faults.

The LSV-BBW system achieves high-precision braking through the use of a controller and electromagnetic actuators. However, prolonged use can lead to component aging and failures, potentially resulting in safety incidents. Despite the implementation of redundancy designs to enhance stability and safety, the LSV-BBW system demands extremely high reliability. Future efforts should focus on strengthening research on redundancy technologies and improving fault diagnosis and tolerance techniques to ensure the application and reliability of the BBW system [110–114]. Effective fault diagnosis and fault tolerant control are a method to solve the brake fault, and the characteristics and solutions of the brake fault are shown in Figure 6. Figure 6 illustrates the fault characteristics and solution of BBW. The hardware layer includes sensors, an ECU, actuators, and cables, which can experience issues such as lost transmission signals, mechanical function failures, and control information mismatches. The fault diagnosis process employs knowledge-based and data-driven methods, signal analysis, fuzzy logic, and reasoning based on rules and probability theory. The fault-tolerant control mechanisms include active strategies such as control distribution and adaptive control, as well as passive strategies such as reliable stabilization and integrity checks, to ensure system reliability and safety.

3.2. Stability Control Strategy of LSV-BBW

The BBW is closely related to vehicle stability control, working together to enhance vehicle safety and maneuverability. The BBW precisely adjusts the braking force of each wheel through electronic control technology, achieving efficient braking response and improving stability under extreme conditions. At the same time, the vehicle stability control system monitors dynamic behavior and adjusts braking force in real time to prevent skidding and loss of control. The combination of these two systems allows for coordinated operation,

enabling rapid responses to driver inputs and changes in road conditions, effectively improving vehicle stability and maneuverability. This integrated control strategy ensures that the vehicle maintains optimal driving conditions under various circumstances, thereby reducing the risk of accidents. Therefore, in-depth research into the interaction mechanisms of both systems is crucial for enhancing the safety of future intelligent vehicles. Currently, many scholars have conducted extensive research in this area. For instance, a sliding mode wheel slip control algorithm, designed to maintain the target slip ratio, was proposed in [115] based on the optimization of braking torque distribution. A control strategy for vehicle stability within the EHB was implemented in [116], which adjusts the motion of the wheels and the vehicle to enhance both lateral and longitudinal stability. A nonlinear control system based on the I-EHB was designed in [117]. A sliding mode variable structure vehicle dynamics stability controller was developed in MATLAB/Simulink within a hierarchical control framework. The simulation results demonstrated effective coordination of hydraulic braking forces during typical braking processes. A motion tracking control algorithm based on DYC was proposed in [118], which calculates and distributes additional yaw moment to the acting wheels while adjusting the target hydraulic pressure of each wheel cylinder through individual wheel braking. A wheel cylinder pressure balancing control method was employed to track the target pressure, with the target boost rate determined using lookup tables and the relationship between duty cycle and boost rate fitted through formulaic methods. A vehicle stability control strategy based on linearly controlled braking was introduced in [119], where a hydraulic model for the linear brake actuator was established, and a yaw moment control approach was employed. A fuzzy controller was utilized to calculate the deviations in yaw rate and sideslip angle, thereby determining the required additional yaw moment.

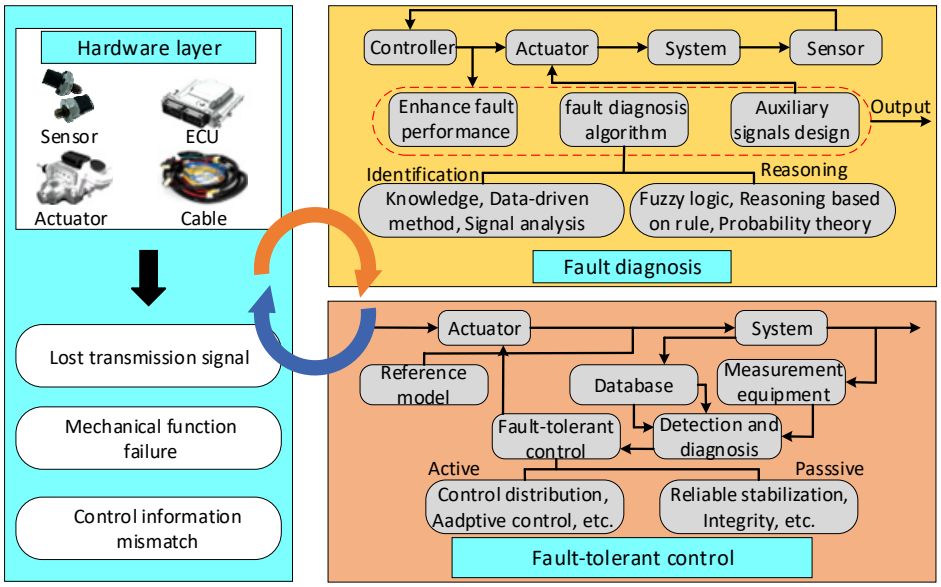


Figure 6. Brake fault characteristics and solutions. Adapted with permission from Ref. [5].

3.3. Braking Energy Regeneration Technology of LSV-BBW

The relationship between the BBW and regenerative braking technology is becoming increasingly close, driving advancements in modern automotive braking technology. The BBW precisely adjusts the braking force at the wheels through electronic control technology, achieving rapid response and high-precision control. Regenerative braking technology utilizes the electric motor to work in reverse, converting kinetic energy into electrical energy that is stored in the battery, thereby enhancing energy utilization efficiency. In electric and hybrid vehicles that combine electronic control and regenerative braking, the electronic brake control system can flexibly adjust the ratio of both based on the vehicle's status, optimizing energy recovery and braking performance. This synergistic

operation enhances braking efficiency, driving smoothness, and safety. Therefore, in-depth research on the integration of these two technologies is crucial for improving the performance and sustainability of intelligent vehicles. The schematic of the comprehensive vehicle energy recovery system can be seen in Figure 7. Fuel economy can be effectively improved by efficient utilization of regenerative braking and improvement of regenerative braking energy. In Figure 7, Z_s represents the vertical displacement of sprung mass, Z_t represents the vertical displacement of unsprung mass, Z_g represents the road excitations at the wheel, P_S denotes the suspension vibration energy recovery, P_B denotes the motor regenerative braking energy, F_b represents the braking force, V represents the velocity, and P_{TEG} represents the waste heat recovery energy.

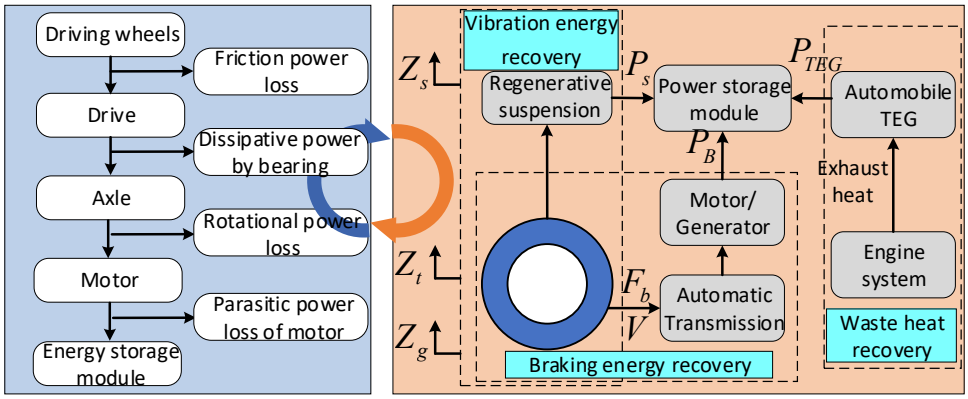


Figure 7. Schematic diagram of automotive integrated energy recovery system. Adapted with permission from Ref. [8].

Currently, many scholars have conducted extensive research in this area. For instance, in reference [120], a strategy for identifying emergency braking intentions based on hydraulic braking pressure was proposed for a 5-ton pure electric loader. This approach distinguishes braking intentions by recognizing the accelerator and brake pedals and enhances braking safety through hydraulic braking system pressure feedback. Additionally, a coordinated control strategy for regenerative braking and mechanical braking during travel was introduced. Simulation and experimental results indicate that this strategy effectively identifies the driver's braking intentions and optimizes the electro-hydraulic braking force distribution, thereby improving braking stability. Under single-cycle operating conditions, the energy recovery efficiency reached 71.64%, with a braking recovery rate exceeding 42.50%. A linear control braking system based on direct-drive electro-hydraulic units, capable of flexibly and independently adjusting braking force, was designed in [121]. The structure of the braking unit and the system composition are discussed in detail, and an in-depth analysis of the flexibility of friction force control in coordination with the regenerative system is provided. By establishing an electric vehicle model based on MATLAB/Simulink and AME/Sim, it was verified that the system can flexibly control the friction force according to the motor status, significantly enhancing regenerative efficiency. A novel combined braking system, aimed at simplifying the structure and enhancing energy-saving performance, was introduced in [122]. A fuzzy control method was proposed to coordinate the power of high- and low-pressure accumulators, and the model's accuracy was validated through experiments. A frictional heat recovery system for hydraulic linear braking systems in heavy vehicles was proposed in [123]. This system generates thermal energy through a friction generator and stores electrical energy in an onboard battery, which can be used to power lighting devices. A hierarchical cooperative control method for an electromechanical linear braking system, aimed at addressing the coordination issue between mechanical braking and regenerative braking when the ABS is activated, was presented in [124]. The hierarchical control strategy includes slip ratio control, braking torque distribution, and the control of motor torque and pneumatic pressure. Experimental results show that this

strategy outperforms conventional braking strategies in terms of braking safety and energy regeneration performance.

3.4. Coordinated Control Strategy of LSV-BBW

The BBW enables flexible control of braking force through electrical control technology, enhancing the stability of vehicles under complex driving conditions. The coordinated control technology intelligently allocates mechanical braking and regenerative braking to optimize energy recovery and braking performance. The combination of these two approaches improves the overall performance and safety of electric and hybrid vehicles while enhancing the driving experience and reducing energy consumption. A hierarchical coordinated control method for electromechanical brake systems, addressing the issue of coordinating mechanical braking and regenerative braking when the ABS is triggered in electric vehicles, was proposed in [124]. The hierarchical control scheme optimizes the control of slip ratio, braking torque, motor torque, and pneumatic pressure. A system for Automatic Emergency Braking (AEB) technology designed to prevent collisions was presented in [125]. To address the issue of loss of control caused by asymmetric braking forces, a coordinated control scheme for Steer-By-Wire (SBW) and Brake-By-Wire (BBW) systems was developed, utilizing a sliding mode controller to implement the anti-lock braking system. Additionally, two model predictive controllers based on a seven-degree-of-freedom vehicle dynamics model were developed to adapt to varying road adhesion conditions. Simulation and hardware experiments demonstrated that this approach effectively maintained vehicle stability and enhanced braking efficiency. A coordinated control strategy for an electric vehicle's electro-hydraulic braking system, integrating the Motor Braking System (MBS) and Hydraulic Braking System (HBS), was introduced in [126]. This strategy allocates braking force based on braking torque requirements, while considering battery status, braking intensity, and road adhesion coefficient. A coordinated control strategy for an energy-efficient electro-hydraulic hybrid braking system was presented in [127]. This strategy consists of two components: a braking force distribution control strategy, which optimizes both braking safety and charging efficiency, and a model predictive control-based coordination strategy for the RBS and ABS. A distributed coordinated control strategy for electric vehicle electro-hydraulic braking, which integrates the characteristics of motors and batteries to define the feasible region for maximum regenerative braking torque and evaluation metrics, was proposed in [128]. This strategy optimizes the distribution of hydraulic and regenerative braking forces using a genetic algorithm, while dynamically incorporating the driver's braking intention. The complexity and functional limitations of existing electro-hydraulic braking systems were addressed in [129], which investigated a novel electro-hydraulic braking pressure coordination control system designed to achieve efficient energy recovery and enhance braking safety. Based on ABS hardware, the system met the pressure coordination control requirements for conventional, regenerative, and ABS braking.

4. Technology Evaluation Index of LSV-BBW

4.1. Evaluation of Braking Performance of LSV-BBW

The LSV-XBW braking evaluation includes parameters such as braking distance, deceleration, delay time, build-up time, overshoot, and stability error [130]. During the engineering development phase, the LSV-XBW must undergo braking road tests under the conditions specified in Table 3, following the vehicle braking test scenario method depicted in Figure 8. The performance should meet the requirements outlined in Equation (1). The BBW test is conducted at constant speeds of 5, 10, 15, 20, and 25 km/h $\pm$1 km/h, with emergency braking at the braking line to measure the braking distance (S). According to references [131,132], the maximum operating speed of LSVs is no more than 50 km/h. Tests are repeated three times at each speed, both under unloaded and fully loaded conditions. If the LSV-XBW speed is insufficient, it is calculated using three values based on the maximum designed vehicle speed [131].

$$S \leq 0.1 \times v_0 + 0.006 \times v_0^2 \quad (1)$$

Table 3. Service brake test conditions of LSV-BBW. Reprinted from Ref. [131].

Vehicle Width/m	Minimum Width of Test Channel/m
<2.5	2.5
≥2.5	Vehicle width + 0.5

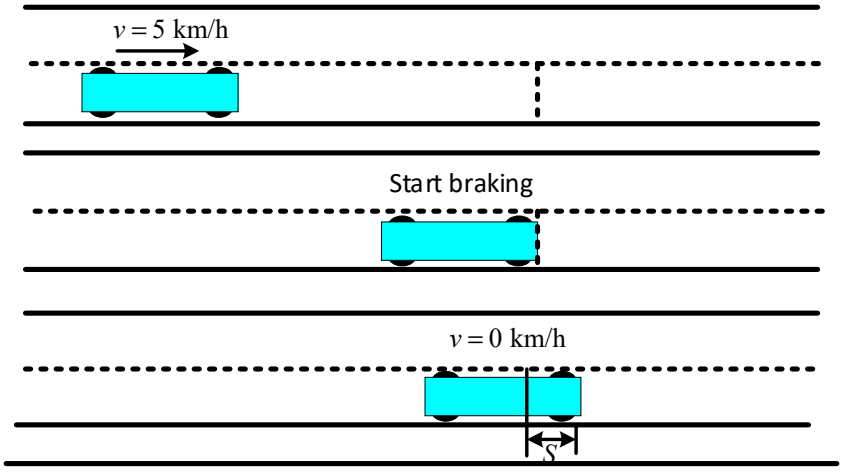


Figure 8. Service brake test scene. Reprinted from Ref. [131].

Parking Brake: The LSV-XBW must maintain a tire-to-road friction coefficient of ≥0.7 when unloaded/loaded and at a gradient of 20% (in both forward and reverse directions) for a duration of 5 min.

Braking Response Requirements:

1. During brake pressure control, the step response time should be ≤200 ms, with an overshoot of ≤0.3 MPa or ±10%;
2. During deceleration control, the step response time should be ≤250 ms, with an overshoot of ≤0.5 or ±10% [131].

4.2. Brake System Requirements of LSV-BBW

Basic Requirements for the Vehicle Braking System:

1. The vehicle braking system must ensure that the driver can safely and effectively control the deceleration and stopping of the chassis during operation.
2. The braking force should be distributed reasonably among the different axles.
3. The braking force must be distributed appropriately between the left and right wheels on the same axle relative to the longitudinal centerline of the chassis.
4. The vehicle braking system should incorporate a drive-by-wire function.
5. Upon receiving a braking command, the braking system must be able to effectively decelerate and stop the vehicle, with the time from command issuance to maximum pressure establishment being ≤300 ms.
6. The performance of the braking system should meet the requirements specified in Table 4 as well as Figures 9 and 10 [131].

Figure 9 illustrates the step response of a braking system, highlighting key performance metrics. The response value initially lags behind the target value, exhibiting a delay of t_1. As the system responds, it overshoots the target value before settling into a steady state with a steady-state error. The total response time t_3 is the sum of the delay time t_1 and the rise time t_2, which is the time taken for the response to reach the target value. This step response analysis is crucial for evaluating the system's dynamic behavior and stability.

Table 4. BBW performance requirements. Reprinted from Ref. [132].

Item	Index	Performance Requirement
Step response test	Response delay time	≤120 ms
	Build-up time	≤300 ms
	Maximum overshoot	≤10%
	Overshoot time	≤200 ms
	Maximum pressure	≥5 Mpa
	Pressure control accuracy	≤0.3 Mpa
Sine follow test	Maximum transient error	≤5%
	Pressure control accuracy	≤0.3 Mpa
	Maximum delay	≤200 ms

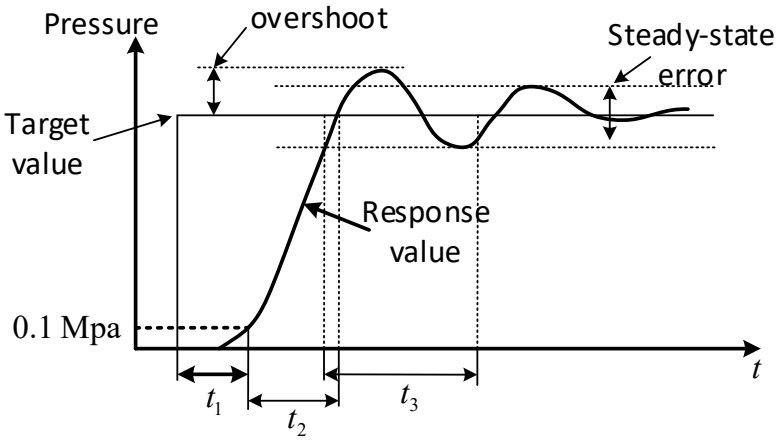


Figure 9. Brake step response test (t_1: response delay time; t_2: pressure building time; t_3: Overshoot time). Reprinted from Ref. [132].

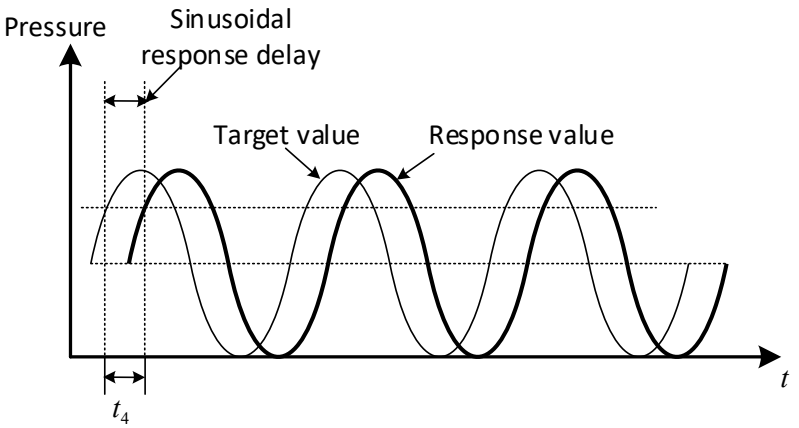


Figure 10. Brake sine follow response test (t_4: sine response delay time). Reprinted from Ref. [132].

Figure 10 illustrates the sinusoidal response of a braking system, highlighting the delay between the target value and the response value. The target value is a sinusoidal waveform, and the response value follows with a noticeable delay, denoted as t_4. This delay is a critical parameter in evaluating the system's dynamic performance and its ability to accurately track the target pressure over time.

Braking distance requirements: The braking distance shall meet the requirements shown in Table 5 below.

Table 5. Braking distance requirements. Reprinted from Ref. [132].

Pavement Condition	Category	Gross Mass	Initial Braking Speed	No-Load Braking Distance/m	Full Load Braking Distance/m	Test Channel Width/m
Dry road	Minor	≤300 kg	8 km/h	≤1.5 m	≤1.5 m	Vehicle width + 0.5 m
	Middle	≤1200 kg	15 km/h	≤2.5 m	≤3 m	Vehicle width + 0.5 m
	Large	≤4500 kg	15 km/h	≤4 m	≤5 m	Vehicle width + 0.5 m
	Heavy-duty	≤8000 kg	15 km/h	≤5 m	≤6 m	Vehicle width + 1.0 m

Requirements for the Parking Brake System:

1. In the absence of commands from the upper-level control unit, the LSV-XBW must be able to remain stationary on a slope.
2. The system must support mechanical locking and unlocking in the event of a power failure.
3. When using electronic control, the locking mechanism must be mechanical and remain effective even during power loss.
4. The spring energy storage braking device should be easily disengaged in the event of a failure, with the necessary tools provided on the vehicle.
5. Under fully loaded conditions, the urban LSV-XBW must achieve a parking gradient of ≥12%, while the outdoor LSV-XBW must achieve ≥15%.
6. The system must provide information on the parking gear and system status, including release and engagement states.
7. The parking brake system should remain stationary for 5 min on the designated slope.
8. The system must support a safety redundancy function for braking coordination across multiple systems [132].

5. Key Technologies and Development Trends of LSV-BBW

5.1. Key Technologies of LSV-BBW

5.1.1. Controller Area Network (CAN) Technology

The electronic communication system is crucial in modern vehicles' BBW systems. By replacing hydraulic signals with electrical signals, it enhances braking response speed and control accuracy, thereby improving the overall driving experience. Additionally, X-by-wire technology promotes the intelligentization and electrification of vehicles [133].

CAN technology plays a key role in automotive electronic systems by coordinating subsystems such as braking, suspension, and powertrain, ensuring rapid information transmission. It enhances system response speed, optimizes structural design, and reduces the number of connectors, which in turn lowers failure rates and maintenance costs, significantly improving stability and safety.

The synergy between brake-by-wire and drive-by-wire chassis systems is essential in complex driving environments. Real-time data exchange enables vehicles to swiftly adjust their control modules to ensure safety. X-by-wire technology supports autonomous driving by facilitating intelligent driving decisions and route planning, relying on CAN technology to propel the automotive industry toward safer and more intelligent development. In the future, these systems will become more mature, providing a safer and more comfortable driving experience [134].

5.1.2. Sensing Technology

The LSV-BBW system must provide real-time feedback of actuator position, speed, and pressure signals to the controller, which performs closed-loop control of the actuators based on the control strategy. The effectiveness of the system relies on the timeliness and accuracy of the sensors, which include brake system sensors such as pedal force, travel, torque, temperature, and motor angle, as well as environmental perception sensors like vehicle speed and engine RPM.

To ensure the stability and reliability of the LSV-BBW system, high-precision, low-cost, and compact sensors are required. Future braking systems will depend on intelligent active braking technologies, necessitating sensors with high precision and resolution. The trend

is towards multifunctional, intelligent, and integrated sensors combined with computer chips [135]. Methods to improve precision include enhancing robustness, increasing resolution, reducing the impact of contaminants, and lowering damping and temperature errors. Sensors need to be integrated and utilize large-scale integrated circuits, while accelerating the development of multi-sensor information fusion technologies [136–138]. This will address the challenges posed by LSV-XBW regarding precision, stability, real-time performance, and response speed while also tackling cost issues [139–141].

5.1.3. Intelligent Integrated Control Technology

In the future, the BBW will be integrated with intelligent scheduling and autonomous driving systems to enhance the automation of LSV-XBW transportation [6,10]. The intelligent integrated control technology optimizes the data processing and control of LSV-XBW with the central information system [142], improving stability and safety, enhancing subsystem collaboration, and promoting automation and production efficiency.

BBW can dynamically adjust braking force in real-time based on vehicle speed and road conditions to ensure safety and prevent loss of control [143,144]. The system monitors vehicle speed, position, and braking status to analyze efficiency and safety [143,145], and it can detect braking anomalies, automatically decelerate, and issue alerts to reduce accident risks [146,147].

Despite the fact that integrated control technologies have improved safety and stability in ground vehicles [148], the application of LSV-XBW faces challenges. In harsh environments, the system needs to reduce energy consumption, improve efficiency, and maintain stability in wet, dusty, and high-temperature conditions. Current technologies still require improvement under long-term high loads, and future intelligent control systems should possess adaptive capabilities to address these challenges.

5.1.4. Power Supply Technology

The significance of power supply technology in modern automobiles has become increasingly paramount, especially in the context of braking systems. The EHB relies on hydraulics to provide braking force and is less influenced by the power supply system, making it suitable for traditional internal combustion engine vehicles. However, with the advancement of electric vehicles and intelligent driving, the emergence of the EMB allows for braking torque to be directly provided by electric motors, which increases the load on the vehicle's power supply system.

The widespread application of EMBs poses challenges for power supply technology, making the enhancement of power supply performance a focal point in the research of BBW systems. Compared to traditional hydraulic systems, electric braking systems require higher power and faster response times, thereby increasing the demands on the onboard power source. Consequently, researchers have developed 42 V voltage systems to provide sufficient energy for electric vehicles, meeting the high power demands of electric motors while reducing cable weight and improving system integration [149].

Advancements in steer-by-wire chassis technology facilitate the synergistic development of motor control, energy management, and information communication, offering new insights into enhancing power supply performance. By leveraging real-time monitoring and intelligent scheduling, vehicles can utilize power supply resources more efficiently, ensuring the stability and safety of electronic control systems. The integration of steer-by-wire braking with steer-by-wire chassis technology, particularly in the context of EMBs, has propelled innovation in power supply technology, laying the foundation for the future intelligence and electrification of electric vehicles [150].

5.2. Development Trends of LSV-BBW

The future development of LSV-BBW technology is expected to be driven by several key trends that will significantly enhance its performance, safety, and efficiency. As this technology continues to evolve, we anticipate advances in intelligentization, automa-

tion, standardization, and maintenance management, all of which will contribute to the widespread adoption and integration of BBW systems in various transportation applications. The following sections outline these emerging trends and their potential impact on the future of LSV-BBW technology.

1. Intelligentization and Automation. In the future, the BBW system will integrate autonomous driving technology to achieve intelligentization and automation, automatically adjusting braking force and performing path planning and obstacle avoidance. Through networking, the system will enhance scheduling and control efficiency, ensuring the safe operation of the LSV-BBW [8,9,151].
2. Standardization and Normalization. With the widespread adoption of BBW, relevant technical standards and regulations will gradually improve. This will help ensure compatibility and interoperability among devices from different manufacturers, enhancing the overall safety and efficiency of the industry [5,8,135].
3. Maintenance and Management. The intelligent braking system can monitor the operational status of the braking system in real time through data collection and analysis, providing early warnings of potential failures. This predictive maintenance can reduce equipment downtime, lower maintenance costs, and improve the overall operational efficiency of the vehicles [8,135].

6. Conclusions

BBW technology plays a critical role in the braking systems of LSVs, and its importance in future technologies is evident. Compared with the traditional braking system, BBW has higher control precision and faster response, which also can lead to enhanced regenerative braking efficiency, fault tolerance and safety for LSVs. BBW shows great potential for development in the LSVs field. In this paper, a comprehensive analysis of the system structure, working principle, and control integration of the BBW system is provided. Then, the control framework and key methods are surveyed. Finally, some control technologies and other key technologies of BBW system are analyzed, and the performance evaluation indexes of LSV-BBW system are also pointed out. The purpose of this review is to provide a foundational framework and guidance for future research and applications. It is hoped that this review will inspire more innovative thinking, promote further development, and practical application of LSV-BBW technology, and ultimately contribute to enhancing the intelligence, safety, and efficiency of LSVs.

The research findings indicate that:

1. The collaboration between BBW and other drive-by-wire subsystems holds promise for realizing the potential of BBW systems in active safety control and autonomous driving;
2. Developing fault tolerance, redundancy, and brake energy recovery control technologies can further enhance the overall performance of BBW;
3. In future applications, more specific performance evaluation indexes for LSV-BBW need to be defined.

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