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A Review of Electro-Mechanical Brake (EMB) System: Structure, Control and Application

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Abstract: With the development of automobile electrification and intelligence, the demand for electro-mechanical braking (EMB) systems is increasing rapidly. This paper reviews the development status of the EMB actuator on the basis of extensive patent and literature research. By analyzing the basic structure of the EMB actuator, this paper decomposes the actuator into five modules: service brake module, parking brake module, brake clearance compensation module, quick-return module and sensor module. On the basis of basic structure, the estimation algorithm for indirect clamping force control and the direct clamping force control algorithm of the actuator are summarized. In addition, the requirements of the EMB system for intelligent vehicles and its typical architecture are analyzed, and the preliminary application of the EMB system in intelligent driving is summarized.

Keywords: automobile; electro-mechanical brake; actuator; clamping force control; application

1. Introduction

Under the development trend of the electrification and intelligence of automobiles, the braking system has ushered in revolutionary changes. To maximize the braking energy recovery rate and realize active braking control, it is necessary to decouple the braking force from the brake pedal, so that the frictional braking force can be accurately controlled by electrical signals [1]. The brake-by-wire (BBW) system is proposed to meet the above requirements, which can be divided into two types: electro-hydraulic brake (EHB) and electro-mechanical brake (EMB). Although EHB has become the mainstream scheme in the current market due to its advantages of good compatibility and easy implementation [2], it still retains most of the hydraulic components and adopts an electro-hydraulic control method. This leads to the problem of the slow braking response, complicated pipeline arrangement and brake fluid leakage [3].

In contrast, EMB completely abandons the hydraulic circuit. The actuator is directly driven by the motor to generate the clamping force, which has the following advantages [4–6]:

- Reduced system volume and weight, convenient installation and maintenance;
- No brake fluid leakage and less environmental pollution;
- Zero residual drag torque, lower power consumption and longer brake service life;
- Easy to integrate with a parking brake;
- Faster braking response and higher control precision;
- Easy to match with composite braking systems and active safety control systems.

As a complete form of the brake-by-wire system, EMB will gradually replace EHB in the future, which has become the consensus of the industry [1,3–7]. However, the design, control and application of the EMB still face many challenges. Moreover, the control and application of the EMB are based on the structure of the actuator. At present, there are many kinds of actuator schemes with different structures and functions, but no mature products. How to design a compact structure to achieve service brake, parking brake, brake clearance compensation and other functions is the first problem to be solved.

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As shown in Table 1, there are several published survey papers on the EMB. For example, Schrad et al. [8] provide a review of the EMB actuator, control topology, energy supply and communication architecture related to safety concepts. A market review of the EMB system for commercial vehicles with a focus on technical details and industrialization is provided in [9]. In [10], a joint review is provided on the clamping force control and sensor fault diagnosis. None of these studies give a comprehensive review on the structure, control, system architecture and application of the EMB. In the most related paper to our work, Gong et al. [11] provide a survey on the development, control method and application prospect of brake-by-wire actuators. However, to the best of our knowledge, actuator structure schemes have not been analyzed in detail in any paper. The integrated structure of the actuator will have a fundamental impact on the effectiveness of control algorithms and vehicle applications. We thus provide a research method to summarize the existing structural schemes. On the basis of extensive patent and literature research, we analyze the basic configuration of the EMB actuator and decompose it into five modules.

The rest of this paper is organized as follows: Section 2 reviews the development status of the EMB actuator. Section 3 analyzes the basic configuration and introduces the functions and schemes of each module. Section 4 summarizes the estimation algorithms for indirect clamping force control and the direct control algorithms. Section 5 analyzes the architecture of the EMB system under the requirements of functional safety, and briefly summarizes the research on the application of the EMB system in intelligent driving. The key concluding remarks are given in Section 6.

Table 1. Comparision of existing survey papers on the EMB.

Works	Summary	Actuator Structure	Control Algorithm	System Architecture	Application
[8]	EMB systems related to safety concepts	Brief summary	/	Detailed analysis of system architectures	/
[9]	Market review of EMBs for commercial vehicles	2 typical structures	/	Detailed information about EMB systems of 5 contacted manufacturers	Brief overview
[10]	EMB clamping force control and sensor fault diagnosis	4 typical structures	Comprehensive review of direct clamping force control (without force estimation)	Brief description	/
[4,5]	Brake-by-wire (BBW) or EMB system review	1–3 typical structures	/	1 typical structure	Brief overview
[11,12]	Brake-by-wire (BBW) system and control technology	1 typical structure	Comprehensive review of force control for BBW actuators	Brief description	Comprehensive review of BBW system application

2. Development Status of the EMB Actuator

To give an overview of the development of EMB actuators, a total of 21 related auto parts manufacturers are selected based on the industry background and their involvement in EMB research, as shown in Table 2.

Among the 21 relevant manufacturers, 6 representative manufacturers are selected according to the distribution of patents, including Bosch, Siemens, Continental Teves, Delphi, Hyundai and Mando. Moreover, a total of 169 related patents from these manufacturers have been investigated. The overall distribution of patents is given in Table 3 and Figures 1–3. These patents are divided into two categories according to the basic structure: schemes using reducing mechanisms and self-energizing mechanisms. Moreover, patents integrated with parking brakes are listed separately to demonstrate the overall distribution of parking brake schemes.

Table 2. Relevant manufacturers.

No.	Manufacturer	Nation	Applicable Vehicle Type
1	Bosch	Germany	Automotive and Commercial
2	Continental Teves	Germany	/
3	Siemens	Germany	/
4	Bendix	U.S.	Commercial
5	Chassis	U.S.	Automotive
6	Delphi	U.S.	Automotive
7	TRW	U.S.	Automotive
8	Brembo	Italy	Automotive
9	Vienna Engineering	Austria	Automotive and Commercial
10	Haldex	Sweden	Commercial
11	SKF	Sweden	/
12	Hyundai	South Korea	Automotive
13	Mando	South Korea	Automotive
14	Akebono	Japan	Automotive
15	Hitachi	Japan	/
16	NTN	Japan	Automotive
17	Great Wall Motor	China	Automotive
18	VIE	China	Commercial
19	Jiong Yi Electronic Technology	China	/
20	Figge Technology	China	/
21	FinDreams Technology	China	/

Table 3. Overall distribution of patents.

No.	Manufacturer	Period	Reducing Mechanism	Number of Patents Self-Energizing Mechanism	Integrated with Parking Brake
1	Bosch	1996–2019	29	19	19
2	Siemens	1996–2007	9	9	2
3	Continental Teves	1994–2020	15	1	6
4	Delphi	1999–2005	14	0	6
5	Hyundai	2006–2020	35	5	11
6	Mando	2009–2021	33	0	11
	Total	1994–2021	135	34	55

Furthermore, basic schemes of EMB actuators proposed by these manufacturers along the timeline are shown in Figure 4 (the specific structure will be introduced in the next section). Since the 1990s, with the application of BA and ESC, the superiority of EMB had attracted the attention of many manufacturers, among which Continental Teves, Bosch, Siemens and Delphi were the first to start research on the basic configuration of EMB actuators. By the beginning of the 21st century, with the development of advanced driver assistance systems such as ACC and AEB, higher requirements were put forward for the active braking control. Manufacturers such as Hyundai and Mando began to invest in the research of the structure and control strategy of EMB actuators for mass production and practical applications.

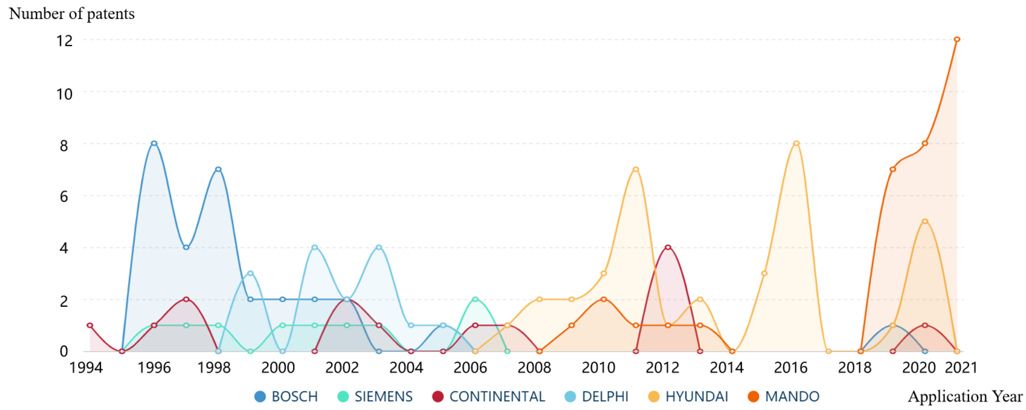


Figure 1. Overall distribution of patents with reducing mechanisms.

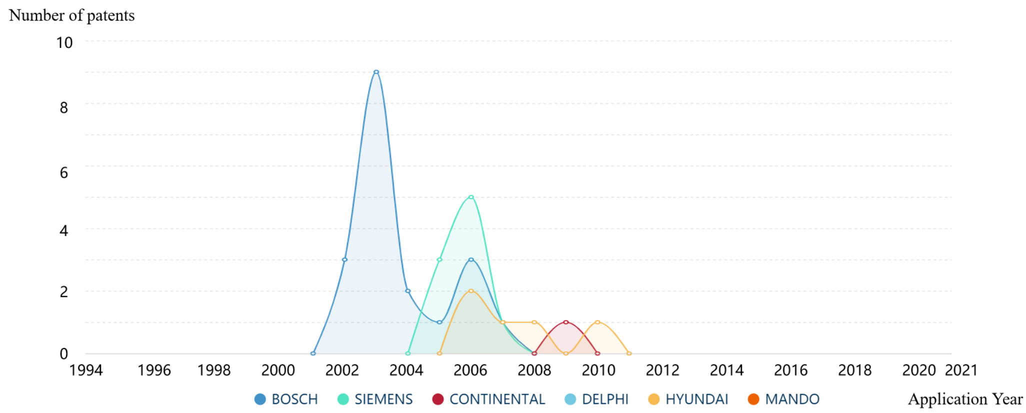


Figure 2. Overall distribution of patents with self-energizing mechanisms.

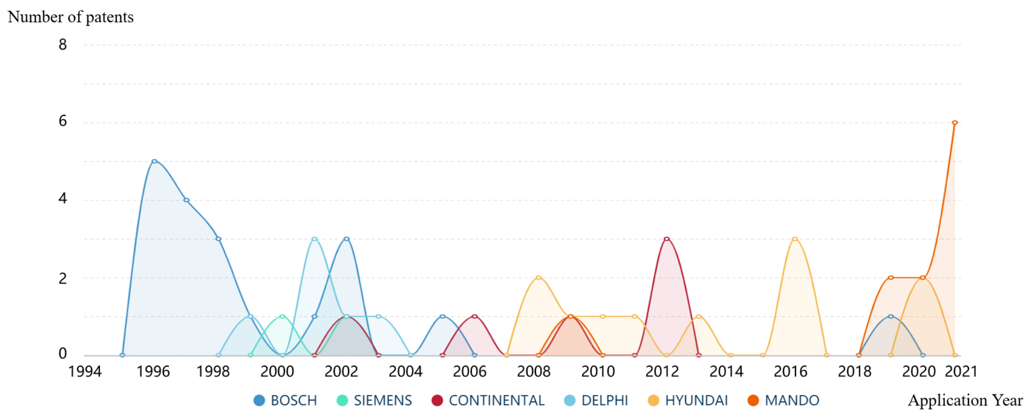


Figure 3. Overall distribution of patents integrated with parking brakes.

For the service brake mechanism, Continental Teves first proposed the integrated structure of "roller screw + planetary gear train". From 1994 to 1997, the motor structure, quick-return mechanism, sensor form and control method were successively investigated. Since 2002, Continental Teves has begun to use the ball screw as the motion conversion mechanism, forming the typical structure of "ball screw + spur gear/planetary gear train", and designed the corresponding brake clearance compensation mechanism, sealing device and bearing structure. From 1996 to 1998, Bosch proposed the scheme of "roller screw + different reducing mechanisms", successively using spur gears, worm gears, bevel gears and planetary gear trains as the reducing mechanism. Based on the above configurations, the active release scheme with dual motors and the passive release scheme with the electromagnetic clutch were designed for the case of brake failure. Moreover, the structure and function of the electromagnetic clutch were further improved. From 1999 to 2001, Bosch eventually adopted the typical scheme of "ball screw + planetary gear train", and optimized the motor's structure and brake return limit device. Since 2002, Bosch has been developing wedge-type self-energizing schemes. From 2002 to 2004, various schemes of "screw/rack and pinion + single/double/multiple wedge faces" were proposed, and the design of the wedge angle, braking force control method and brake clearance compensation mechanism was investigated. From 2005 to 2006, the self-energizing scheme of "rack and pinion + double wedge faces" was further improved and eventually adopted. Similarly, other manufacturers have also formed typical structure schemes after multiple rounds of iterative design, as shown in Table 4.

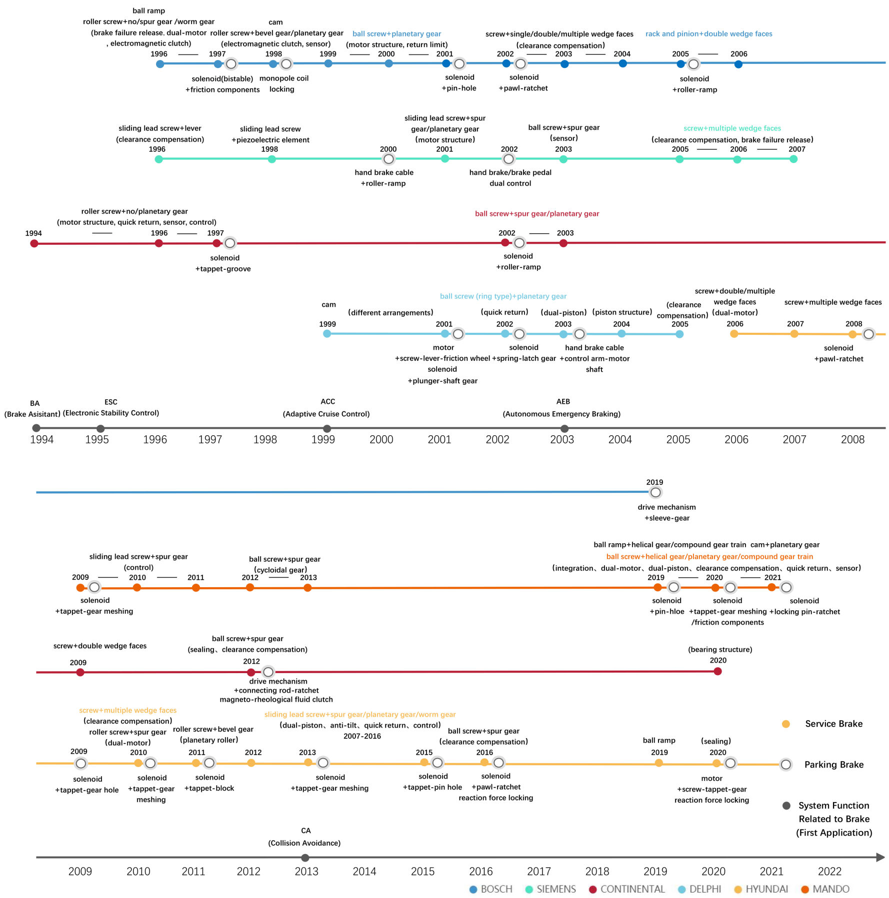


Figure 4. The development of EMB actuators by the 6 manufacturers. Service brake schemes (above the timeline) are represented by the form of "motion conversion mechanism + force-amplifying mechanism", and the innovation points of patents are indicated in brackets. Parking brake schemes (below the timeline) are represented by the form of "driving component + locking component". In addition, typical structure schemes proposed by the 6 manufacturers are marked with corresponding colors.

Driven by the demand for changes in the braking system of both commercial vehicles and passenger vehicles, manufacturers began to focus on the industrialization of EMBs. In 2020, the Technology & Maintenance Council (TMC) of American Trucking Associations partnered with PIT Group to conduct a market review on the EMB for commercial vehicles [9]. A total of 16 related manufacturers were surveyed with questionnaires, and 5 manufacturers provided effective responses, of which 3 were developing EMBs. The survey results are shown in Table 5.

Table 4. Typical structure schemes of EMB actuators proposed by the 6 manufacturers.

Manufacturer	Structure Schemes	
	Motion Conversion Mechanism	**Reducing Mechanism/ Self-Energizing Mechanism**
Bosch	Ball screw	Planetary gear train
	Rack and pinion	Double wedge face self-energizing mechanism
Siemens	Screw	Multiple wedge face self-energizing mechanism
Continental Teves	Ball screw	Spur gear/planetary gear train
Delphi	Ball screw (ring type)	Planetary gear train
Hyundai	Sliding lead screw	Spur gear/planetary gear/worm gear train
	Screw	Multiple wedge face self-energizing mechanism
Mando	Ball screw	Helical gear/planetary gear /compound gear train

Table 5. Survey results of TMC and PIT Group.

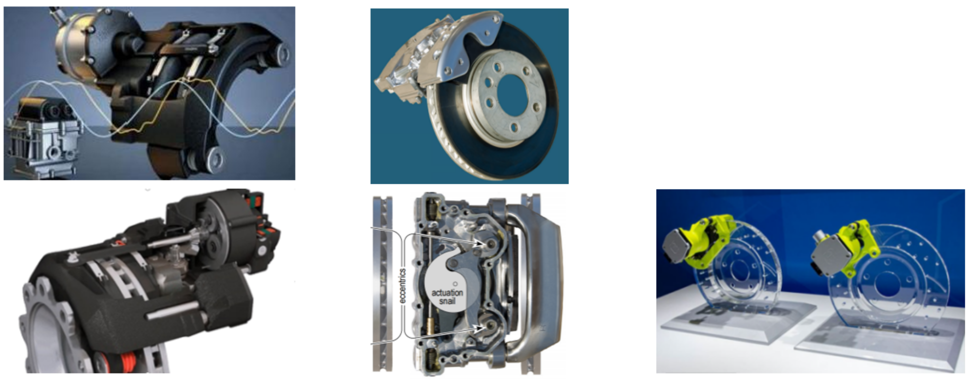
Manufacturer	Bendix	Haldex	VE
Brake Type	Disc	Disc	Disc
Applicable Vehicle Type	Trucks	Trucks, trailers and buses	Trucks, trailers and on-road vehicles in general
EMB Prototypes Developed	Yes	100	More than 20
EMB Prototypes Technology Readiness Level (TRL)	Pre-production	TRL 7	TRL 5
Prototype Phase Completion Estimate	Undefined	2020	Mid 2020
Expected Start of Production (SOP)	Undefined	2021	2025
Most Challenging Factors	Cost constraints	Regulation and testing requirements	Safety concerns and redundancies
Power Circuit Redundancy	1 for standard architecture + at least 2 for braking system	Each axle can power another, $n-1$ redundancies	Each EMB has 1 main and 1 redundant
Energy Storage System Redundancy	1 for standard architecture + at least 2 for braking system	Each axle can power another, $n-1$ redundancies	1 main and 1 redundant
Communication Networks redundancy	1 main and at least 1 redundant	2 in a 2-axle vehicle (1 redundancy per axle)	1 main and 1 redundant

Although these manufacturers have been working on electro-mechanical braking technology for around 15 years or more, neither have a product that is currently market ready [9]. The main obstacles include cost constraints, regulatory standards and safety requirements. To ensure safety, the EU along with the U.S. have implemented strict regulations on service braking systems. China and India have also implemented related specifications that are comparable albeit at a lower performance level [8]. Regulations related to the performance and design requirements concerning the failure tolerance of EMB systems are shown in Table 6.

Table 6. Sections of the standard documents related to the performance and design requirements for EMB systems [8]. The numbers listed in the right columns beneath the requirements refer to the paragraphs of the legislative documents. If the letter 'A' precedes a number, the relevant requirement can be found in the Annex.

Failure	Requirement	EU + UK	U.S.	China	India	Canada
1st Circuit	Provide more than 2.6 m/s^2 deceleration	A3.2	14.14	5.2.1	4.1.2	5.1.2.1
ASS	Provide more than 5.15 m/s^2 deceleration	A6.4	14.12	-	9.5.4	5.5.2
Brake Distr.	Provide more than 3.86 m/s^2 deceleration with the engine disconnected	A5.4	14.13 14.17	A6	-	-
Power Brake Unit	Provide more than 2.6 m/s^2 deceleration	-	14.18	-	-	5.1.3.1
Any 1st E/E	Provide more than 6.43 m/s^2 deceleration with the engine disconnected	-	-	-	-	5.1.3.5
Any	No unintended application	5.2.9	-	-	-	-
E-Supply	E-reserves must tolerate it	5.2.15	-	-	-	-
Transmission	No unintended application of parking brake	5.2.19	-	-	-	-

For commercial vehicles, whether the EMB system will replace the existing pneumatic braking system is still controversial. Bendix claimed that the cost of a sufficiently safe, redundant and robust system was too expensive to compete with current pneumatic braking systems. To justify the market acceptability and development potential of EMB technology, Haldex is currently highly active in China, where legislation imposes fewer constraints on EMBs. In May 2020, Haldex and VIE jointly established the Haldex VIE EMB in China, dedicated to the development and mass production of EMBs for commercial vehicles. For passenger vehicles, the process of replacing EHB systems with EMB systems is in progress. In the 2015 Le Mans 24-Hour race, Audi demonstrated a new generation of the R8 e-Tron, which used two EMBs on the rear axle, marking the first application of EMBs in customer-oriented passenger cars. In June 2021, Great Wall Motor released the intelligent drive-by-wire chassis with self-developed EMB systems for L4 and above automatic driving, and claimed to achieve mass production in 2023. The EMB prototypes of Haldex and other related manufacturers are shown in Figure 5.



Haldex Vienna Engineering Great Wall Motor

Figure 5. EMB prototypes of Haldex, Vienna Engineering and Great Wall Motor [13–16].

3. Basic Configuration of the EMB Actuator

Existing EMB actuators are designed based on the structure of traditional brakes, including disc brakes and drum brakes. Due to the advantages inherent in disc brake technologies and due to the difficulty of integrating drum-type EMBs onto a standard wheel-end, disc-type EMBs will be the main form in the future [9].

A disc-type EMB actuator proposed by Mando is shown in Figure 6 as an example. The actuator is decomposed into multiple modules, among which the service brake module is used to realize the basic braking operation. The service module is composed of a motor, a force-amplifying mechanism, a motion conversion mechanism and a pressing component. During braking, motor 1041 drives the spindle 1032 to rotate through the helical gear train 1050 (force-amplifying mechanism). The rotation motion of spindle 1032 is then converted into the translation motion of nut 1031 through the ball screw 1030 (motion conversion mechanism), thus driving the piston 1020 (pressing component) with the brake pad 1013 to press the brake disc 1011. At the shaft end of the input helical gear, a parking brake module is added to the actuator. The parking brake module is composed of a driving component, a moving component and a locking component. When parking is required, the parking brake force is first achieved through the service brake module, then the solenoid 2080 (driving component) is energized, and the tappet 2081 (moving component) is moved a certain distance to lock the ratchet (locking component), so that the vehicle can maintain a sufficient braking force when the power is cut off. In addition, the actuator is also equipped with a quick-return module at the shaft end of the output helical gear, that is, torsion spring 2090. One end of the torsion spring is fixed to the housing, and the other end is fixed to the output helical gear. The torsion spring stores elastic energy through torsional deformation which can be used for quick release of the brake.

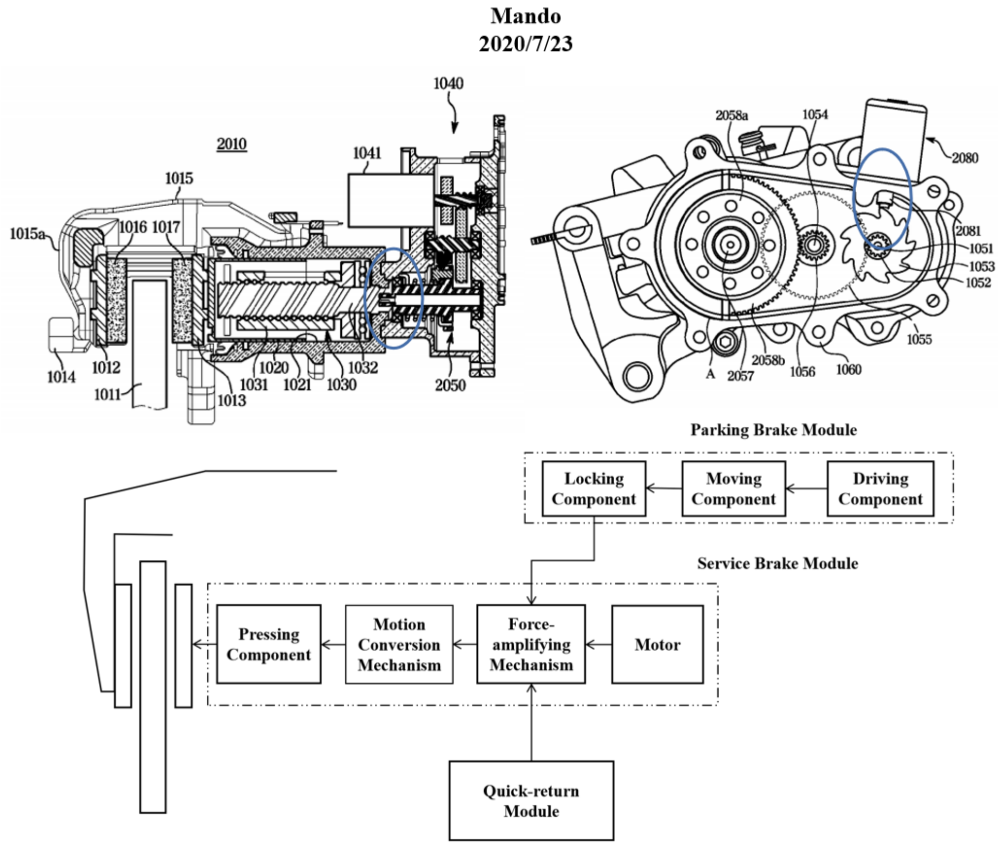


Figure 6. Structure of a disc-type EMB actuator proposed by Mando [17]. The quick-return module and parking brake module are shown circled in the figure.

In addition to the above three modules, an EMB actuator may also include a brake clearance compensation module to compensate for the wear of brake linings and a sensor module to detect signals such as the clamping force for precise braking force control. The basic configuration of the EMB actuator is shown in Figure 7 with five discomposed modules: service brake module, parking brake module, brake clearance compensation module, quick-return module, and sensor module. The functions of each module and typical schemes proposed by the six manufacturers are introduced in the following sections.

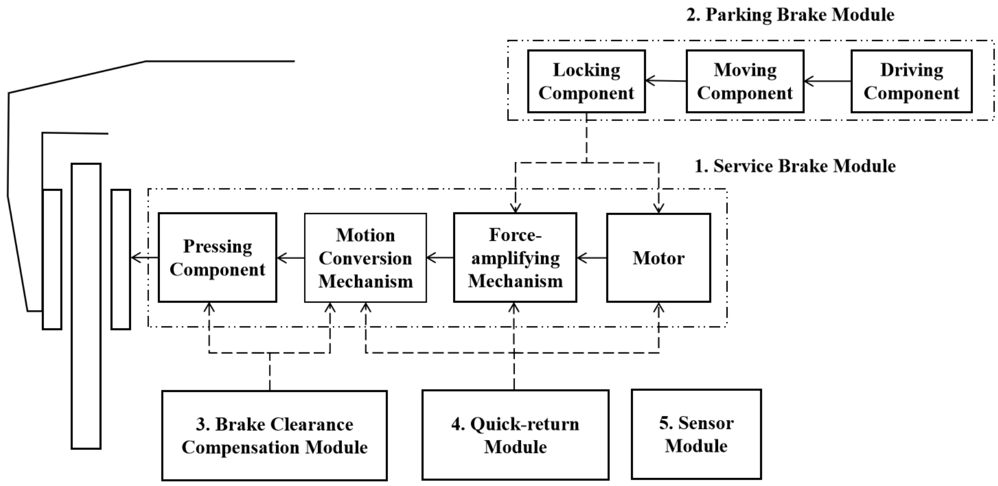


Figure 7. Basic configuration of the EMB actuator (disc type).

3.1. Pressing Component

The pressing component is arranged between the brake pad and the spindle or nut of the motion conversion mechanism to transmit the pressing force.

3.1.1. Basic Form

Most of the actuators adopt the basic form of a single pressing component with surface contact connections. The spindle or nut is fixed to the brake pad, or a piston is added in the middle to indirectly push the brake pad.

3.1.2. Dual Pressing Components

As shown in Figure 8, in the direction of rotation indicated by the arrow, the pressing force at the leading edge will be greater than that at the trailing edge, resulting in uneven wear of the brake pads and reduced braking force. To solve the above problem, Delphi designs a dual-piston structure to adjust the distribution of pressing force and generate a uniform and reliable braking force [18]. Subsequently, Hyundai also proposes a similar structure. Mando adds a floating component between the two pistons to achieve relative floating [19], as shown in Figure 9.

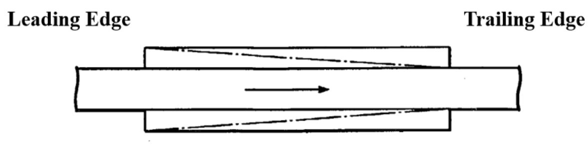


Figure 8. The tapered wear pattern across respective faces of the brake pads (indicated by the dashed lines) [18].

Mando
2021/8/11

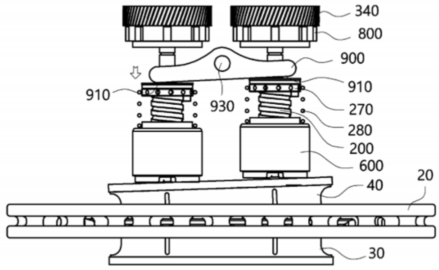


Figure 9. Mando's floating dual-piston structure [19].

3.1.3. Point Contact Connection

The deformation caused by the reaction force and friction force during braking will affect the transmission efficiency of the motion conversion mechanism, and even cause jamming. To reduce the influence of these forces, Continental Teves uses the form of point contact connections between the brake pad and the spindle. The brake pad is supported by a pressure rod with a ball socket at both ends [20]. Bosch and Hyundai use the form of ball bearings, ball tops or arc tops to achieve point contact. Several main forms are shown in Figure 10.

Continental Teves 1994/7/21 **Bosch 1997/11/13** **Hyundai 2011/11/11**

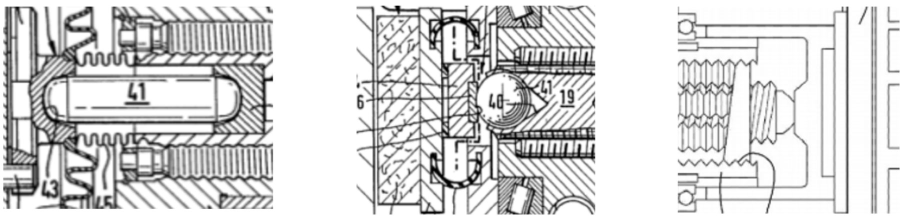


Figure 10. Main forms of point contact connections [20–22].

3.2. Motion Conversion Mechanism

The motion conversion mechanism converts the rotational motion of the motor into the translational motion of the spindle or nut. There are four main forms of the motion conversion mechanism, including the screw, cam, ball ramp, rack and pinion drive mechanism.

The screw drive mechanism realizes motion conversion through the screw pair composed of the spindle and the nut, which includes three types: sliding lead screw, ball screw and roller screw. The sliding lead screw has a simple structure, but suffers from a low transmission efficiency and precision, easy self-locking and serious wear. The ball screw and roller screw convert the sliding friction into rolling friction through balls or rollers, which have higher transmission efficiency and precision, smooth motion and good reliability. These two forms are commonly used in the EMB actuator. Moreover, the cam drive mechanism is also used to move the pressing component, which has a simple structure and reliable force transmission. However, the high-pair contact is easy to wear and cannot transmit a large clamping force.

The ball ramp drive mechanism utilizes the rolling motion of balls on the ramp to achieve axial translation. Bosch, Hyundai and Mando have successively proposed different structural schemes for the ball ramp. A typical structure [23] is shown in Figure 11. The ball ramp drive mechanism has a compact structure with a small axial size but is complicated in design.

Mando
2019/1/30

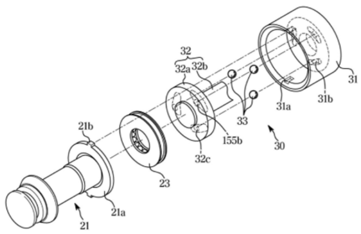


Figure 11. Mando's ball ramp drive mechanism [23].

3.3. Force-Amplifying Mechanism

In order to increase the driving force of the motor, generally two schemes are adopted: (1) Reducing mechanisms such as spur gear trains, helical gear trains, bevel gear trains, worm gear trains, planetary gear trains, pulleys, etc.; (2) self-energizing mechanisms such as the wedge mechanism, the lever mechanism, etc.

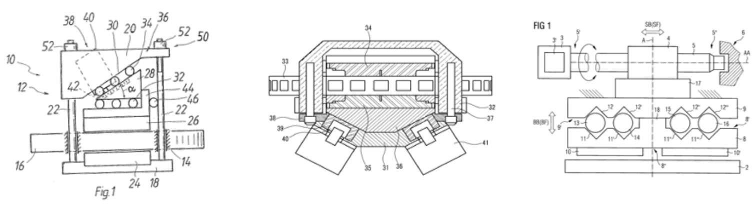
3.3.1. Reducing Mechanism

In the selection of the reducing mechanism, factors such as the structural layout, transmission ratio and efficiency are mainly considered. Spur gear trains are used for the transmission between parallel shafts, which have a simple structure but a small transmission ratio. Bevel gear trains are used for the transmission between intersecting shafts. The manufacturing of bevel gears is complicated and costly. Worm gear trains are used for the transmission between crossed shafts. The worm gear has a large transmission ratio and a high bearing capacity, but the transmission efficiency is low and is easy to wear. The planetary gear train is a widely used scheme that can achieve different transmission ratios through the combination of different input and output parts. It has a compact structure and high bearing capacity, but a complex assembly.

3.3.2. Self-Energizing Mechanism

A typical self-energizing scheme is the electronic wedge brake (EWB), which converts the tangential friction force of the brake disc into a pressing force through a wedge mechanism. Bosch, Siemens, Hyundai, and Continental Teves have all proposed different wedge-type self-energizing schemes. As shown in Figure 12, based on the number of wedge faces, it can be divided into three types: single wedge face mechanism, double wedge face mechanism and multiple wedge face mechanism. The single wedge face can only achieve a unidirectional self-energizing effect, while double wedge faces and multiple wedge faces can achieve a self-energizing effect in two directions. The distribution of the pressing force generated by the multiple wedge face mechanism is more uniform, but the structure is more complicated. Since the self-energizing effect is not linearly related to the displacement, and is affected by many factors such as machining errors and wear, the brake force generated by the wedge-type self-energizing scheme is difficult to control.

Bosch **2003/12/5** | **Hyundai** **2006/4/21** | **Siemens** **2008/4/3**



Single Wedge Face | Double Wedge Faces | Multiple Wedge Faces

Figure 12. Three forms of wedge-type self-energizing mechanism [24–26].

3.4. Motor Type and Arrangement

3.4.1. Motor Type

As the power input of the EMB actuator, the motor is required to be able to work in a locked-rotor condition for a long time with a large torque. Moreover, it is also supposed to have a small size, low cost, and good thermal stability. Motor types commonly used in the EMB actuator are shown in Table 7.

Table 7. Various types of motors commonly used in the EMB actuator [3,27,28].

Motor Type	Advantages	Shortcomings
Brushed DC Motor	Large starting torque, good controllability and overload capability, and excellent speed regulation performance.	The mechanical commutation device is used, has a short life and high noise, generates sparks easily and has low efficiency.
Brushless DC Motor	No spark interference, large starting torque, excellent overload capacity, high efficiency and relatively simple control method.	There is a certain torque ripple that causes vibration noise and has a risk of demagnetization.
Permanent Magnet Synchronous Motor	Small torque ripple, low noise and high control precision.	The control method is more complicated: an encoder is required and the price is higher.
Switched Reluctance Motor	Simple and reliable, large starting torque, good low-speed performance, wide speed range and high efficiency.	Large torque fluctuations and high noise; a position detector is required.

There are two types of motor structures: integral design and hollow design.

- Integral design, that is, a solid rotor is nested in the stator, and the end of the rotor is axially connected to other components to output power. As shown in Figure 13, this structure is simple but the axial or radial layout size is large;
- Hollow design, that is, a hollow rotor is nested in the stator, and the rotor is coaxially connected to other components to the output power. This structure has a high level of integration with reduced axial size, but is also complicated in design and the adaptability is relatively poor.

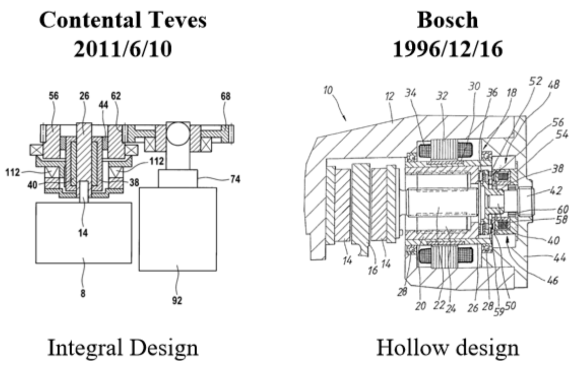


Figure 13. Two forms of motor structure design [29,30].

3.4.2. Motor Arrangement

In the limited space inside the wheel, there are rim restrictions along the radial direction and suspension rod restrictions along the axial direction. The arrangement of the motor is a key issue. According to the relative position of the motor and the pressing component, the arrangements can be divided into three types: coaxial, parallel and angled arrangement, as shown in Figures 14–16.

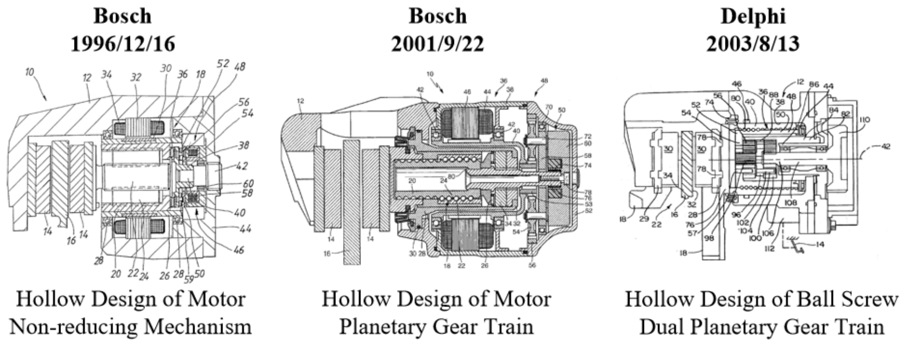


Figure 14. Coaxial arrangement [30–32].

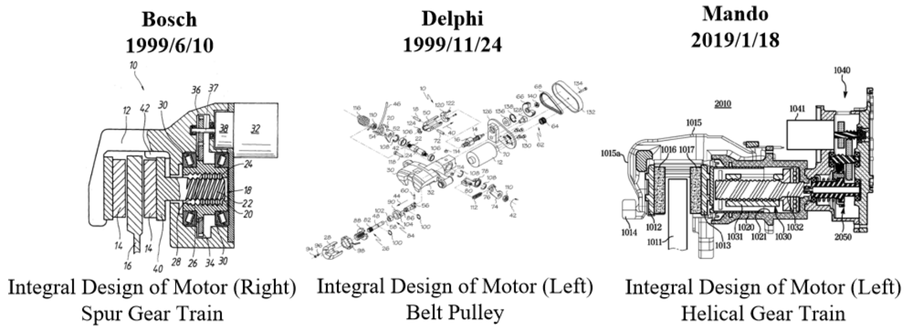


Figure 15. Parallel arrangement [17,33,34].

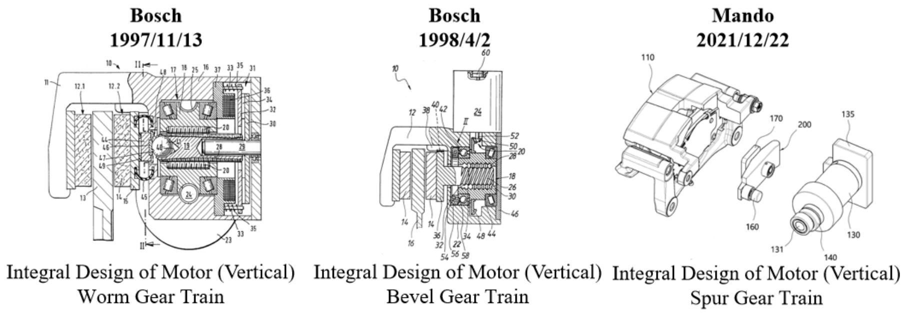


Figure 16. Angled arrangement [35–37].

The difference in motor arrangements is related to the form of the reducing mechanism, which determines the axial and radial size of the EMB actuator. The characteristics of various motor arrangements are shown in Table 8 below.

Table 8. Characteristics of various motor arrangements.

Types	Characteristics	Commonly Used Reducing Mechanism
Coaxial	Large axial size and small radial size	Planetary gear train
Parallel	Middle axial size and middle radial size	Spur gear train, helical gear train, compound gear train and pulley
Angled	Small axial size and large radial size	Bevel gear train and worm gear train

3.4.3. Dual-Motor Design

Dual-motor design, that is, two motors are used in the EMB actuator. This ensures redundant safety as the actuator can still generate part of the braking force when a single motor fails. Common dual-motor designs are shown in Figure 17 (the function of the secondary motor is marked at the bottom of the figure).

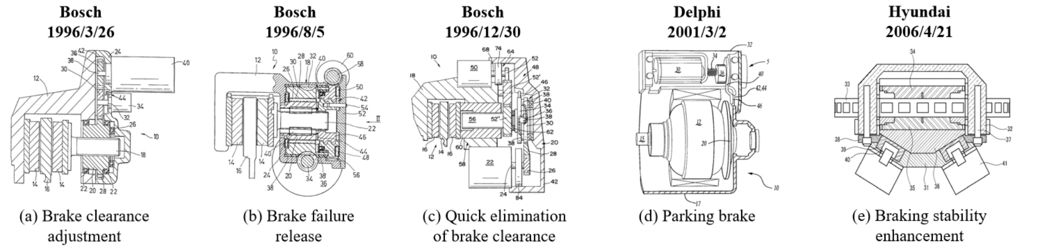


Figure 17. Dual -motor design [25,38–41].

In the dual-motor design, the main motor is often used for service braking, and the secondary motor cooperates to realize the following functions:

- Brake clearance adjustment: the release motor 34 can be controlled by the angular displacement sensor at the output shaft to adjust the braking clearance to ensure that the braking clearance is constant.
- Brake failure release: the secondary motor 60 drives the trapezoidal nut 48 to rotate, so that the hollow shaft 46 with the entire supporting drive device moves axially, thereby releasing the brake in the event of a failure.
- Quick elimination of brake clearance: the secondary motor 50 drives the gear trains 52 and the spindle 56 to rotate, so that the nut 60 is axially displaced to quickly eliminate the brake clearance. Then, the secondary motor 50 is stopped and the main motor 22 is energized to generate a pressing force.
- Parking brake: the parking brake motor 30 drives the trapezoidal screw 34 to rotate, driving the trapezoidal nut 36 to move, so that the lever 40 is pressed on the friction disc 20, thereby preventing the rotation of the motor shaft 15 and achieving brake locking;
- Braking stability enhancement: two motors 41 directly drive the wedge 36 to press the disc, producing a self-energizing effect while maintaining a stable pressure.

3.5. Parking Brake Module

The parking brake module is used to maintain the braking force when the vehicle is powered off. The existing parking brake module can be structurally decomposed into a driving component, a moving component and a locking component. According to the driving components commonly used, the parking brake module can be divided into three types: manual type, motor-driven type and solenoid-driven type.

3.5.1. Manual Parking Brake

Manual parking brake usually relies on the driver to pull the handbrake to achieve parking. In addition to the basic parking brake function, it can also be used to control the brake manually in the event of a power failure or electrical system failure.

Siemens designs an auxiliary brake on the basis of the traditional EMB structure, as shown in Figure 18. Through cable S, drum H is driven to rotate, and the rollers K1, K2 and K3 in the drum engage with the rotor shaft RW to lock the motor.

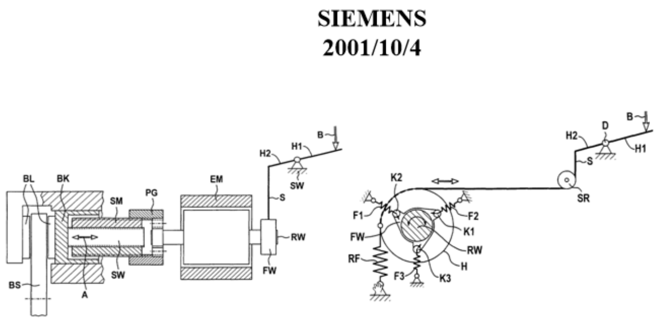


Figure 18. Manual parking brake of Siemens [42].

Delphi designs an emergency control device on the rear side of the caliper, as shown in Figure 19, which controls the rotation of the motor shaft 14a through the speed-increasing mechanism 21 with manual operation of the control arm 24.

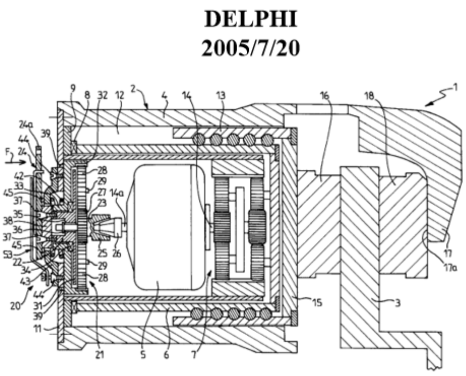


Figure 19. Manual parking brake of Delphi [43].

3.5.2. Motor-Driven Parking Brake

Motor-driven parking brake typically requires an additional motor. As shown in Figure 20, Delphi uses motor 30 to drive the nut 36 to move through the screw 34, and the lever 40 is pressed on the friction disc 20, thereby preventing the rotation of the motor shaft 15 and achieving a parking brake.

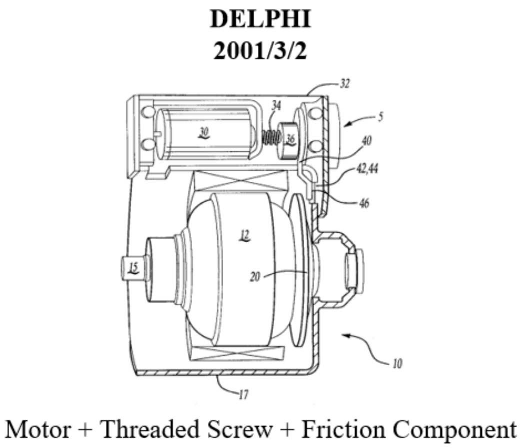


Figure 20. Motor-driven parking brake of Delphi [41].

The parking motor receives the brake signal from the control unit, and then precisely controls the feeding distance of the moving component. Compared with the solenoid-driven scheme, it can reduce the wear of the components caused by the excessive or insufficient feeding of the moving component.

3.5.3. Solenoid-Driven Parking Brake

Electromagnetic windings are used in the solenoid-driven parking brake to change the distribution of the magnetic field, thereby driving the relevant components to achieve brake locking. The solenoid component should have bistable characteristics, that is, it can maintain two stable states of locking and releasing when the power is off.

Figures 21–24 show some typical parking brake schemes driven by solenoid components (the driving component, moving component and locking component are marked at the bottom of the figure).

Bosch adopts the solenoid-driven parking brake scheme with an armature disc and friction components (clutch), as shown in Figure 21. The solenoid component 10 is energized to generate a reverse magnetic field to release the armature disc 28. With the elastic force of the coil spring 26, the armature disc 28 is pressed to the connection disk 36, thereby locking the motor shaft 38 and maintaining the parking brake force.

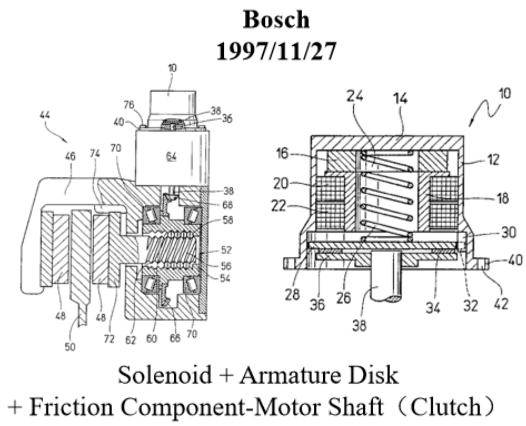


Figure 21. Solenoid-driven parking brake of Bosch [44].

Delphi adopts the solenoid-driven parking brake scheme with a pawl-ratchet locking mechanism, as shown in Figure 22. The solenoid component 68 is energized to drop the parking brake lever 64 down against the attractive force of the magnet 66 and engages with the ratchet 60. The ratchet 60 is then locked by lever 64 to maintain the required braking force for parking.

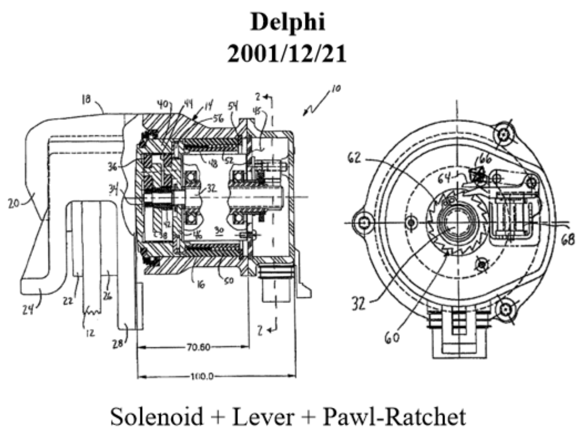
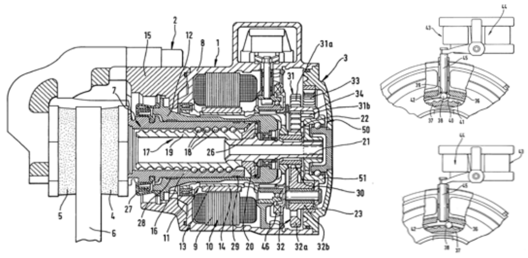


Figure 22. Solenoid-driven parking brake of Delphi [45].

Continental adopts the solenoid-driven parking brake scheme with a roller-ramp locking mechanism, as shown in Figure 23. The solenoid component 44 is energized to move the tappet 45 downward to press the roller 38 against the ramp 41 of the rotating component 37, thereby locking the rotating component 37 to maintain the braking force.

Mando adopts the solenoid-driven parking brake scheme with a locking pin-gear mechanism, as shown in Figure 24. The solenoid component 152 is energized to drive the locking pin 152a to protrude and insert into the restricting groove 151b of gear 151, thereby locking the rotation of the shaft 141 and maintaining the braking force.

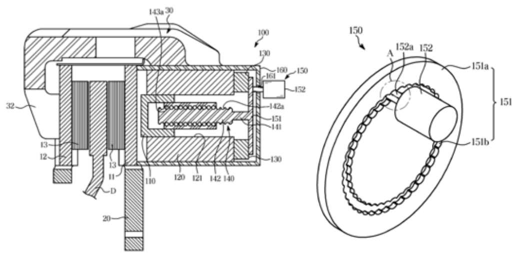
Continental
2002/8/13



Solenoid + Tappet + Roller-Ramp

Figure 23. Solenoid-driven parking brake of Continental Teves [46].

Mando
2019/2/12



Solenoid + Tappet + Locking pin-Gear

Figure 24. Solenoid-driven parking brake of Mando [47].

3.5.4. Summary

The typical parking brake schemes are summarized in Table 9.

Table 9. Typical parking brake schemes.

Manufacturer	Driving Component	Moving Component	Locking Component
Bosch	Solenoid	Armature disc/tappet	Friction components/pawl-ratchet/roller-ramp/self-locking
Continental Teves	Solenoid	Tappet/towing link	Locking pin-gear/roller-ramp/pawl-ratchet
Delphi	Motor/solenoid /manual	Threaded screw/lever/spring/plunger	Handbrake lock/protrusion-tooth/pawl-ratchet/tooth seat-gear
Hyundai	Motor/solenoid	Threaded screw/tappet/baffle/elastic plate	Locking pin-gear/baffle-gear/pawl-ratchet
Mando	Solenoid	Tappet	Pawl-ratchet/friction components/rotary pin-gear
Siemens	Manual	Cable	Roller-ramp/handbrake lock

Among these schemes, the solenoid-driven parking brake has become a major trend, since its structure is simple and compact. The advantages and disadvantages of various solenoid-driven schemes are as follows [17]:

- Solenoid-driven schemes using the friction components can achieve flexible locking and braking force control, and the braking process is stable without large impacts, but the nature of friction leads to the problem of poor thermal stability and durability.

- Solenoid-driven schemes using the pawl and ratchet can maintain a relatively large braking force, but the pawl may advance excessively, causing a continuous impact on the ratchet, and further problems such as wear and deformation may occur, reducing the durability and reliability of the parking brake.
- Solenoid-driven schemes using the roller and ramp have a smooth locking process and can produce a certain force-amplifying effect. However, the ramp angle and locking position are difficult to design to ensure the locking effect.
- Solenoid-driven schemes using the pin and gear are simple in design, but when the locking pin is separated from the gear teeth, the gear may be stuck, which reduces the response speed and stability of the parking brake.

3.6. Brake Clearance Compensation Module

The brake pads will gradually wear out with repeated brake operations. To maintain the braking performance of the vehicle, it is necessary to compensate for the wear of brake pads. According to the material properties of the components used, the brake clearance compensation module can be divided into three types: flexible type, rigid type, flexible and rigid type.

3.6.1. Flexible Compensation Mechanism

In the same way as the traditional hydraulic brake, the elastic deformation of the flexible body is used for the automatic positioning of the compensation mechanism. Flexible components such as sealing rings and springs are usually attached around the moving components of the EMB actuator. Since the elastic deformation is affected by various factors such as temperature, the brake clearance varies greatly, and even the phenomenon of incomplete brake return may occur. A typical scheme of the flexible compensation mechanism is shown in Figure 25, in which the annular sealing ring 76 is placed around the piston 62.

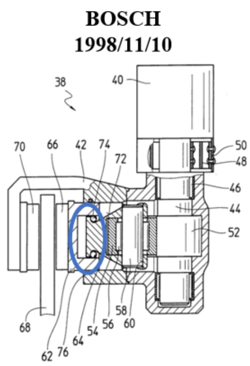


Figure 25. Flexible compensation mechanism of Bosch (circled in the figure) [48].

3.6.2. Rigid Compensation Mechanism

Rigid components are added to the basic structure in this compensation mechanism. Through active driving of the motor, the compensation component crosses the initial position to form a new rigid positioning, and maintains the gap between the brake pad and the brake disc. Compared with the flexible compensation mechanism, the control of the brake clearance is more precise in this scheme.

Bosch proposes to use an additional motor to adjust the brake clearance. When the main motor 40 drives the spindle 18 to push the brake pad 14 to complete normal braking, the secondary motor 34 continues to drive the spindle 18 to move axially, which adjusts the brake clearance, as shown in Figure 26.

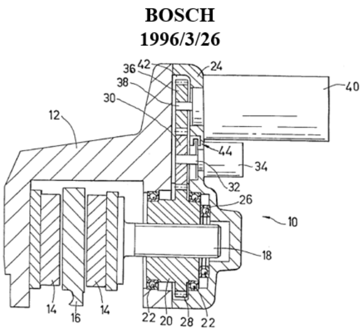


Figure 26. Rigid compensation mechanism of Bosch [38].

Hyundai proposes a latch locking device for the wedge-type brake, as shown in Figure 27, through which block 56 is moved to compensate for the brake wear.

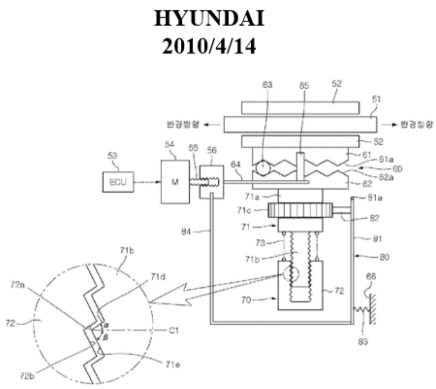


Figure 27. Rigid compensation mechanism of Hyundai [49].

Mando designs protrusions on the flange and nut outside the lead screw, as shown in Figure 28. The nut and piston are engaged by threads. The flange 136 is first driven to rotate by the spindle 121, then the protrusion 137 on the flange contacts the protrusion 130 on the nut, and relative rotation occurs between the nut 125 and the piston 110, thereby pushing the piston to move to adjust the brake clearance.

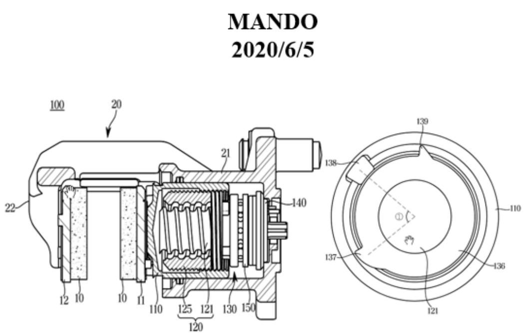


Figure 28. Rigid compensation mechanism of Mando [50].

3.6.3. Flexible and Rigid Compensation Mechanism

Flexible and rigid components are both used in this scheme. Thus, the compensation process is more reliable than only using flexible components, and smoother than only using rigid components with less noise and friction.

As shown in Figure 29, Delphi proposes a brake clearance compensation scheme combining the sealing ring and pawl mechanism. When the brake clearance increases, the sealing ring 152 slides accordingly, and the pawl 131 retreats along the groove 138 to the new position where the next tooth fits, realizing the automatic compensation of the brake clearance. Siemens also proposes a similar scheme, using the elastic potential energy stored in springs 9 and 10 to push slider 12 and pawl 11 to realize the automatic compensation of the brake clearance. Mando designs elastic arms 20 and 24 on the outside of the rotating plate of the actuator. The elastic arms drive the threaded screw 18 to rotate through gear 19, thereby pushing the pin 6 and the brake pad to move closer to the brake disc.

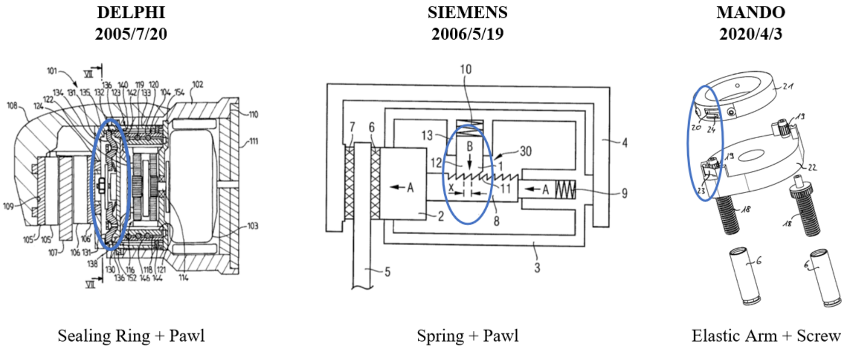


Figure 29. Flexible and rigid compensation mechanisms (circled in the figure) [51–53].

3.7. Quick-Return Module

The quick-return module is used to quickly release the brake through the elastic energy stored in the elastic component. This quick release can improve the dynamic performance of the brake response. Moreover, it can help to release the brake in the event of an actuator failure, which further improves the safety. The existing quick-return module can be divided into the following three types according to the elastic components used in the module.

3.7.1. Torsion Spring

The torsion spring stores elastic energy through twisting or rotating, which has the capacity for absorbing the vibration and large deformation. In the quick-return module, one end of the torsion spring is usually fixed to the housing and the other end is fixed to a rotating component of the actuator. Delphi, Hyundai and Mando have successively proposed different schemes which fix the end of the torsion spring to the motor rotor shaft, the spindle or the reduction gear, as shown in Figure 30. During braking, the torsion spring is twisted by the rotating component and stores elastic energy. When the motor reverses to release the brake, the torsion spring provides elastic restoring force to the rotating component connected to it, thereby realizing quick brake release.

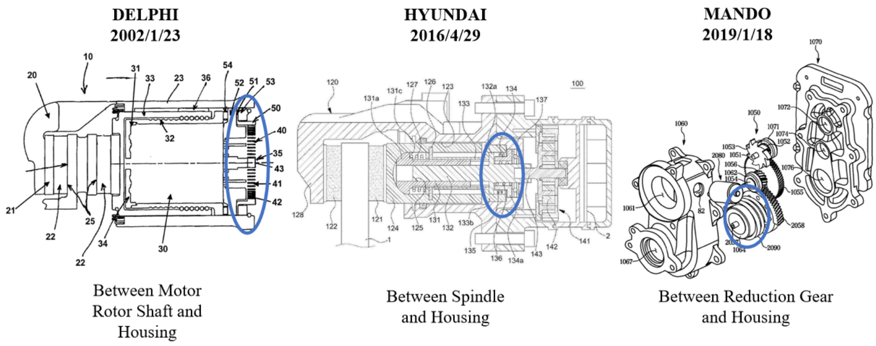


Figure 30. Torsion spring type quick-return module (circled in the figure) [17,54,55].

3.7.2. Compression Spring

The compression spring stores elastic energy through the axial compression or tension during braking. In the quick-return module, one end of the compression spring is usually fixed to the support, and the other end is fixed to a moving component of the actuator. Mando proposes to fix the end of the compression spring to the piston, which stores elastic energy through the axial movement of the piston, as shown in Figure 31. When the brake is released, the compression spring drives the piston away from the brake disc through the elastic recovery force, thereby realizing quick brake release.

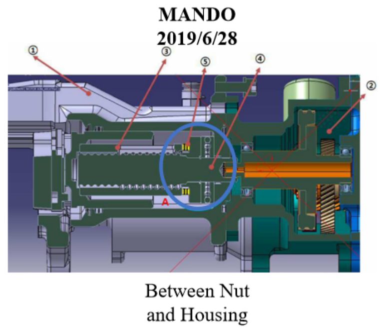


Figure 31. Compression spring type quick-return module (circled in the figure) [56].

3.7.3. Other Elastic Components

In addition to torsion springs and compression springs, other special-shaped elastic components are also used in the actuator for rapid brake release. Mando proposes to install a clutch unit at the end of the lead screw, as shown in Figure 32. The outer clutch unit 110 stores elastic energy during braking, and applies elastic restoring force to the inner clutch unit 120 through balls 133 when the brake is released.

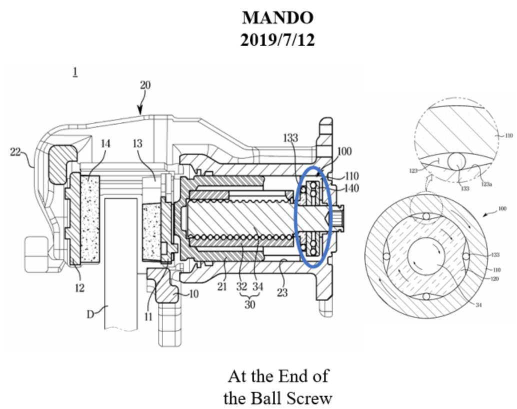


Figure 32. Quick-return module using other elastic components (circled in the figure) [57].

3.8. Sensor Type and Arrangement

Sensors commonly used in the EMB actuator include the following types: pressure, torque, angular displacement and axial displacement sensors for clamping force control; pad wear and contact sensors for brake disc wear detection; temperature sensors for detecting the operating temperature of the actuator. Sensors commonly used by the 6 manufacturers are shown in Table 10.

Pressure sensors are usually installed between two parts that transmit the pressing force such as the spindle and the housing, the nut and the housing, the spindle and the brake pad, and the piston and the brake pad. Some are also installed on the guide bracket. Angular displacement sensors are usually installed at the end of the rotating part, such as the end of the spindle, the nut and the motor output shaft. The pad wear and contact sensors are usually installed close to the outer brake lining.

Most of the sensors will be greatly affected by the external high temperature. Therefore, sensors should be arranged away from the brake disc or to add a heat insulation layer between the sensor and the brake disc.

Table 10. Sensor type.

Manufacturer	Sensor Type
Bosch	Angular displacement and pressure
Continental Teves	Angular displacement, pressure and contact
Delphi	Angular displacement and pressure
Hyundai	Angular displacement, axial displacement, pressure, torque, current and pad wear
Mando	Angular displacement, pressure and pad wear
Siemens	Angular displacement and pressure

4. Research on Control of the EMB Actuator

The EMB actuator is a highly integrated electro-mechanical system. How to control the motor to achieve rapid, accurate and reliable follow-up of the target braking force is the focus of current research. The control of the EMB actuator includes two methods: indirect clamping force control (clamping force estimation) and direct clamping force control.

4.1. Estimation Method for Indirect Clamping Force Control

To realize the closed-loop control of the clamping force, a pressure sensor is generally used in the actuator to obtain the value of the clamping force in real-time. However, the measurement accuracy of the pressure sensor is easily disturbed by the heat and magnetic fields. Once the pressure sensor fails, there must be a backup control method for the actuator. Moreover, the pressure sensor is expensive and large, making it difficult to integrate in the limited space of the actuator. In order to omit the pressure sensor, the clamping force needs to be indirectly controlled with an estimated force value. The existing methods for the clamping force estimation are summarized in Table 11.

Table 11. Clamping force estimation methods.

Estimation Method	Advantages	Disadvantages	Classification
Based on angular displacement	Simple	Requires contact point identification, affected by factors such as temperature	Average stiffness characteristic Thermal effect modified stiffness characteristic Hysteresis effect modified stiffness characteristic
Based on current	Simple and convenient current detection	Difficult in identifying model parameters	Simplified torque balance Fitting modified torque balance
Fusion estimation based on angular displacement and current	Good accuracy and robustness	Complex	Maximum likelihood estimation Genetic algorithm + Kalman filter

The estimation method based on the angular displacement uses the relationship between the clamping force and the angular displacement of the motor, namely the stiffness characteristic (Figure 33), to estimate the clamping force. It is the most commonly used estimation method and is simple and easy to implement. In order to determine the initial position and avoid the influence of brake pad wear on the estimation result, it is necessary to identify the contact point of the brake pad and the friction disc. Schwarz et al. [58] identify the contact point by setting the threshold differential value of the motor current with angular displacement. Based on the simplified brake model, a proportional coefficient is determined to modify the average stiffness characteristic and to accurately estimate the clamping force. Since the stiffness characteristic will be disturbed by factors such as temperature and friction, it needs to be modified to ensure the accuracy of clamping force estimation. Saric et al. [59] propose to use two temperature sensors to study the thermal distribution characteristics of brake pads, and establish an estimation model of stiffness characteristics under different thermal conditions, which improves the accuracy of the clamping force estimation. For the clamping force hysteresis effect caused by the friction and the elastic characteristics of the brake disc, Park et al. [60] propose a clamping force estimation method based on the hysteresis model, which guarantees the accuracy of the estimated clamping force during transient changes in the direction of motion. Moreover, the method of periodically updating the stiffness characteristics is used to improve the robustness of the estimation method.

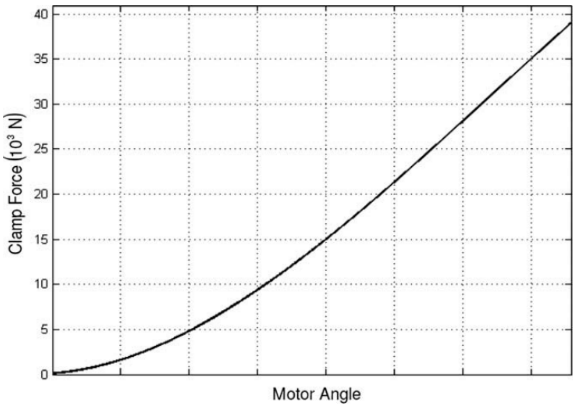


Figure 33. Stiffness characteristic curve [59].

The estimation method based on the motor current estimates the clamping force by establishing the torque balance equation at the output shaft of the motor, as follows:

$$F_{cl} \cdot \gamma = K_m I_m - J_m \frac{d^2\theta_m}{dt^2} - T_f, \quad (1)$$

where F_{cl} is the clamping force, γ is the total reduction ratio, I_m, θ_m is the current and angular displacement of the motor, K_m, J_m is the motor torque constant and the equivalent inertia moment at the output of the motor, and T_f is the friction torque. Since the friction and inertia links are involved in the torque balance equation, it is necessary to identify these parameters such as the Coulomb friction coefficient. In order to avoid the establishment of a complex friction model, Wang of Zhejiang University [61] uses the torque balance equations of the brake disc clamping and releasing process to offset the friction torque, and realizes a simplified estimation of the clamping force under the motor stall state. In a patent proposed by HYUNDAI, a mechanical device with spring components is added to monitor the relationship between the angular displacement and current of the motor. The torque characteristic of the motor is modified accordingly for accurately estimating the clamping force [62]. To reflect the real nonlinear characteristics, Wei et al. [63] obtain the characteristic curve between the clamping force and the motor torque through the bench test. Based on the characteristic curve, the ideal torque balance equation is fitted and modified to achieve a better clamping force tracking effect.

Fusing the signal of both the angular displacement and the current can improve the accuracy and robustness of the clamping force estimation method. Saric et al. [64] design two clamping force estimation models based on the dynamic stiffness characteristic and the torque balance equation. An in-service adaptation technique is used to adapt wear-dependent parameters from both models. Moreover, the outputs from these two independent models are fused using a maximum-likelihood estimator to give an optimized estimate of the clamping force, which is shown to have a good tracking performance in highly dynamic situations. Bae et al. [65] combine the genetic algorithm and Kalman filter approach to fuse the estimation results based on the dynamic stiffness characteristic and the torque balance equation to accurately estimate the clamping force. A real-coded genetic algorithm is used to optimize the noise matrices and improve the performance of the Kalman filter. Experimental results demonstrate that the estimation algorithm is less sensitive during dynamic braking.

4.2. Direct Clamping Force Control

The direct control algorithm realizes the closed-loop control of the clamping force by obtaining feedback signals from pressure sensors, angular displacement sensors, and current sensors. The existing direct control algorithms of the clamping force are summarized in Table 12.

Table 12. Direct clamping force control algorithms.

Control Algorithm	Advantages	Disadvantages	Classification
PID control	Simple structure, easy application and good adaptability	Difficult in parameter tuning and difficult to handle time-varying nonlinear problems	Cascaded PID control Adaptive PID control Feedforward compensation PID control Fuzzy PID control Compound PID control
Robust control	Good robustness	Conservative	Linear robust H_∞ optimal control Nonlinear robust control Disturbance observation robust control
Model predictive control	Explicitly deal with the constraint problem and good dynamic control performance	Large calculation	Model predictive control + PID control Explicit nonlinear model predictive control
Sliding mode control	Fast response, fewer tuning parameters and good robustness	Chattering problem	Sliding mode control Adaptive sliding mode control
Other algorithms			Near-time-optimal control Brain limbic system-based control

PID control is the most commonly used algorithm for direct clamping force control, which has the advantages of simple structure, easy application and good adaptability. Maron [66], Schwarz [67], Fox [68], Yang [69], Zhang [70] and Li [71] all adopt the cascaded PID control architecture with three closed loops, as shown in Figure 34, where F_{cl} is the clamping force, n_m, I_a is the motor speed and current, and E_a is the input voltage of the motor. During the braking process, the EMB actuator needs to go through three stages: eliminating the braking gap, generating a clamping force and releasing the brake. The cascaded PID control architecture fits very well for these three stages. For the first and third stages, the middle loop of speed is used to adjust the motor speed and improve the response speed of the actuator. When the braking gap is eliminated and the drive motor turns into a stalled state, the outer loop of the clamping force is used to accurately track the target clamping force. Moreover, the current loop is used as the inner loop to adjust the motor current, give full play to the overload capacity of the motor, and improve the dynamic response of the control system. Due to the coupling between the three closed loops, an iterative adjustment is required to achieve the best overall performance, and the workload of parameter tuning is large. Li et al. [72] use the frequency domain method based on Bode plots to tune the PID parameters, so that the controller has good tracking performance and the overshoot can be controlled within the required range. However, PID control with a fixed gain cannot effectively deal with time-varying nonlinear problems such as load-dependent friction and stiffness [3]. Jo et al. [73] propose an adaptive PID control algorithm, combined with the brake clearance control algorithm to estimate the clamping force, and adjust the proportional gain coefficient online according to the change of the clamping force to achieve a better control effect. To solve the problem of nonlinear disturbances such as friction under high load, Line et al. [74] add feed-forward friction compensation to the cascaded PI control framework, which improves the accuracy and tracking performance of the clamping force control.

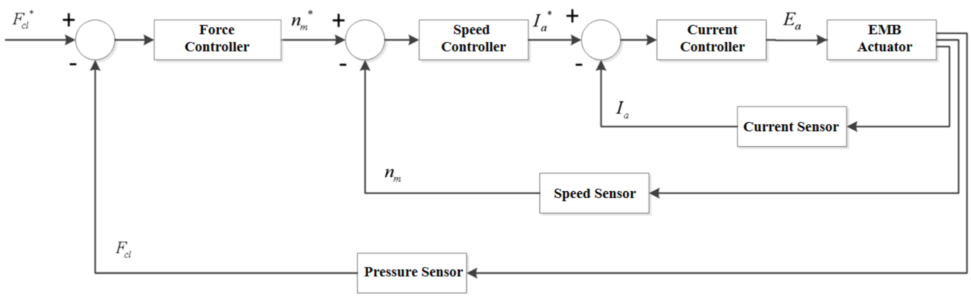


Figure 34. 'Force–speed–current-cascaded PID control architecture.

In order to achieve accurate control of the clamping force and improve the response speed at different stages, KI and LEE et al. [75] propose a compound PID control algorithm, which switches between the force loop and position loop according to the target clamping force. Zhang of Jilin University [76] divides the EMB execution process into four stages according to the change of the targeting power, actual braking force and the position of the motor corner, and designs the corresponding PID control strategy according to the control quality and feature of each stage. To improve the accuracy of the contact point identification at different stages, Zhang [77] of Hunan University designs a second-order Kalman filter to process the current, and identifies the contact point according to the relationship between the clamping force and the current during braking. On this basis, a control algorithm based on fuzzy PID with specific control objectives for different stages is proposed to achieve a better dynamic performance.

Enhancing the robustness of the control algorithm to external disturbances is the key to realizing precise control of the clamping force. Line et al. [78] design a robust H_∞ optimal controller, which considers the influence of uncertain parameters such as temperature, brake pad wear and unmodelled dynamics. The simulation results demonstrate that, compared with the standard cascaded PI control, this controller is less sensitive to external disturbances, and can guarantee the stability of the control performance. Krishnamurthy et al. [79] propose a nonlinear robust control algorithm for a switched-reluctance-motor (SRM) electro-mechanical brake system, assuming that the load is an unknown nonlinear function of the position, and design a torque-level control law via a robust-backstepping procedure. Two schemes to obtain control laws are proposed, one based on an additional step of robust backstepping and another based on the torque ripple minimization. Eum et al. [80] propose a robust clamping force control method based on the force-position cascade control structure, and the disturbance observer (DOB) is employed to enhance the control robustness against model variations. Although the robust algorithm reduces the influence of disturbances, it also leads to the problem of conservative control. Moreover, the design of a robust algorithm considering both the robustness and response performance is challenging.

The model predictive control (MPC) predicts the future dynamics of the system, solves the optimization problem online, and applies the optimal solution to the system to achieve a closed-loop control. It can explicitly deal with the constraint problem and has a good dynamic control performance. Line et al. [81] first modify the structure of the cascaded PI control using techniques of gain scheduling, friction compensation and feedback linearization, then further incorporate a model predictive control to better utilize the available motor torque. For practical implementation, an unconstrained MPC with dynamic constraints post-applied is used to reduce the computational demand. To avoid plant linearisation and simplify the controller, Lee et al. [82] design an explicit nonlinear MPC, and obtain an explicit control law by minimizing the quadratic performance index. The simulation results demonstrate that a 24% reduction in computation time is achieved in the explicit MPC compared to the existing linear MPC, with a marginally better performance on demanding brake maneuvres. The optimization of the algorithm is carried out offline, and the computational overhead is reduced by using a lookup table. The process of the continuous dynamic optimization of MPC requires a large amount of computation; thus, the method with a simplified model or offline calculation is usually used for real applications.

The sliding mode control (SMC) makes the control variables converge quickly by designing the sliding mode surface and reaching law. It not only has a fast response and few adjustment parameters, but also has strong robustness to uncertain parameters and external disturbances. Lindvai-Soos and Horn [83] design the sliding mode control law for the actuator based on the dynamic model of the vehicle braking system, taking the friction as the uncertainty factor into account in the sliding mode control. The experimental results demonstrate that the sliding mode controller has a higher tracking accuracy compared with the cascaded PI controller under different input signals. Han et al. [84] design a sliding mode controller based on the dynamic model of the electronic wedge brake (EWB). The clamping force is estimated based on the simplified electronic wedge brake model with contact point detection. Experiments show that the algorithm is robust to parameter changes and nonlinear factors. Park and Choi [85] design an adaptive sliding mode controller, which reduces the estimation error by adaptively adjusting the parameters of the friction model, and incorporating the feed-forward of friction compensation into the sliding mode controller to improve the robustness of the control algorithm. However, the sliding mode control has a chattering problem when the system state reaches the sliding mode surface, which will affect the control accuracy. Therefore, it is necessary to use methods such as filtering, adding observers, fuzzy control and genetic algorithms to optimize the control process.

To further improve the control accuracy, other intelligent control algorithms are proposed. Lee and Manzie [86] design a state-constrained, robust near-time-optimal clamping force tracking controller. They first design a controller for a generic second-order non-linear system with state constraints, then extend it to a perturbed system with a bounded, but potentially time-varying disturbance. The prototype test proves that the controller is robustly stable, with the tracking error asymptotically converging to a uniform ultimate bound that contains the origin. Kim et al. [87] apply a bio-inspired control strategy based on the limbic brain system to the EMB actuator, and optimize the control parameters through a genetic algorithm. The simulation results show that the control method is better than the traditional PID control in terms of control speed, reference tracking and robustness to the disturbance.

5. System Architecture and Intelligent Driving Application of EMB

The further development of intelligent driving puts forward higher requirements for the braking system. According to the survey results of the current technical level and demand in the industry, the basic requirements for brake response time, control accuracy, integrated control and functional safety from the L0 to L5 level automatic driving are shown in Figure 35. As the final scheme of the future braking system, the EMB system should meet the requirements of high-level automatic driving:

- Fast response and precise control: automated driving above L4 level puts forward higher requirements on the response speed and control accuracy of active braking in terms of vehicle dynamic control. For EMB systems, the braking response time should be within 100ms, and the steady-state control accuracy should reach 0.1MPa;
- Highly integrated control: the coordinated control of driving, braking and steering requires the control of each subsystem to be centralized in the chassis domain controller. Under the framework of the chassis domain controller, the EMB system needs to have a high degree of control freedom for integrated control;
- Good redundant safety: From assisted driving (L1 and L2 levels) to automatic driving (above L3 level), the functional safety of the intelligent driving system is a key issue, and it is necessary to ensure that the system can still take over in the event of a single failure. Brake redundancy is an important part of functional safety. For EMB systems, ASIL-D level functional safety must be met through the redundant design of actuators (dual-motor design), control algorithms (indirect control based on clamping force estimation) and system architecture. In addition, it is also necessary to meet the requirements of the intended functional safety and information security.

Level	L0 driver only	L1 driver assistance	L2 partial automation	L3 conditional automation	L4 high automation	L5 full automation
Example Features	Blind spot monitoring、lane departure warning	Lane keeping assist、adaptive cruise control	Emergency obstacle avoidance、Auto parking assist	Traffic jam chaufeur	Local driverless taxi	Automatic driving in all conditions
Response Time	500-600ms	500-600ms —— 100-150ms		100-150ms	≤100ms	
Control Accuracy	≤1Mpa	≤1Mpa —— ≤0.2Mpa		≤0.2Mpa	≤0.1Mpa	
Integration Control	Hydraulic brake	Hydraulic brake——Brake-by-wire		Chassis domain control		
Functional Safety	ASIL D			ASIL D + intended functional safety + information security		

Figure 35. Basic requirements of braking systems for L0–L5 automatic driving.

The following will first analyze the architecture of the EMB system under the requirements of functional safety, and summarize the research on traditional vehicle stability control (including ABS, EBD, TCS, ESC, etc.) based on the EMB system. On this basis, the preliminary application of the EMB system in intelligent driving, that is, the research on advanced driver assistance (including AEB, ACC, etc.), is introduced.

5.1. System Architecture

A typical EMB system consists of four actuators, several control ECUs (including a main ECU and four actuator ECUs), a power supply system, an electronic pedal (including a brake pedal, a pedal feeling simulator, a pedal displacement sensor and a pedal force sensor), a parking switch and other components. When the driver steps on the brake pedal, the pedal simulator gives the driver an appropriate pedal feeling, and the pedal signal is detected by the pedal sensors to obtain the driver's braking intention. The main ECU receives the driver's braking intention, combined with the wheel speed and other sensor feedback vehicle status signals, and formulates a braking force distribution strategy according to the control target. Then, the required braking force is sent to the actuator ECU to control the actuator at the wheel end to realize the brake operation.

The specific system architecture of EMB is related to the functional requirements, vehicle control requirements and redundancy requirements. Here is a brief analysis based on the system architecture design process [88] required by ISO 26262 functional safety:

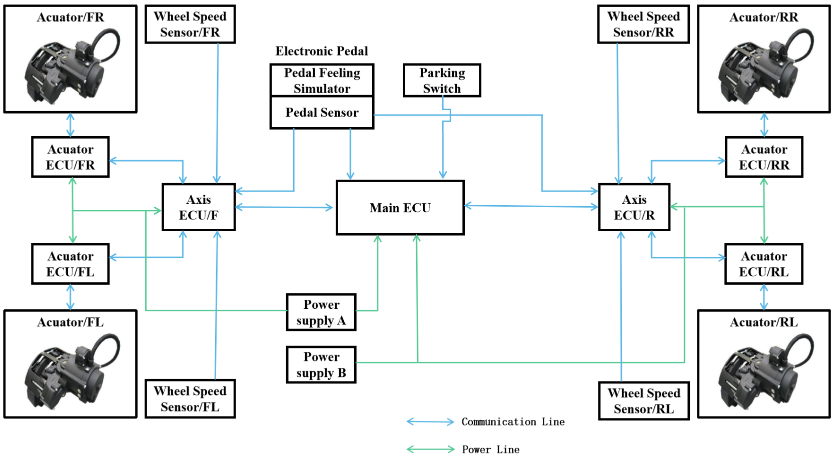
1. Hazard analysis: the Automotive Safety Integrity Level (ASIL) is first assigned by systematically assessing the hazard at the vehicle and subsystem levels based on three factors: severity, exposure and controllability. As shown in Figure 36, the fall mode of

"no braking" for various driving scenarios is analyzed as an example [88]; the braking system should meet the highest safety level, ASIL-D.
2. Safety function requirements: based on the hazard analysis, the overall safety goal is set as reducing the possibility of losing the braking ability. Specifically, it includes three different modes: (1) Full function mode: the system can tolerate at least one arbitrary fault and guarantee full braking capacity; (2) partial function mode: partial loss of braking capacity caused by a single failure should not affect the stability of the vehicle. (3) Emergency mode: the system must ensure that the vehicle can stop completely after the occurrence of a second arbitrary fault.
3. System architecture design principles: based on the safety function requirements, the main design principles are set as follows: (1) Avoid single point failure; (2) minimal dependency of the system on any condition that can suddenly become false; (3) conservative design with minimal dependencies and adequate fault tolerance.

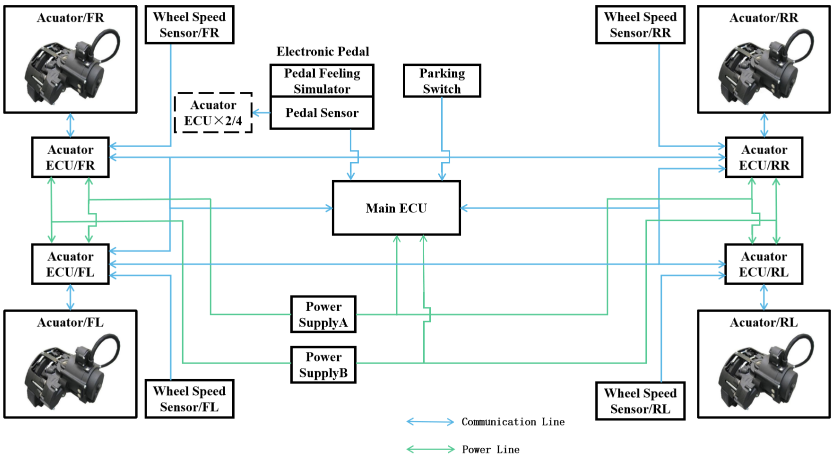
Level	Fall Mode	Effect of Failure	Driving Scenario	Severity	Exposure	Controllability	ASIL
Vehicle	No braking	Vehicle cannot stop	City	S3	E4	C3	D
			Highway	S3	E4	C3	D
			Tunnel	S3	E3	C3	C
			Ice road	S3	E2	C3	B

Figure 36. ASILs for "no braking" fall mode [89].

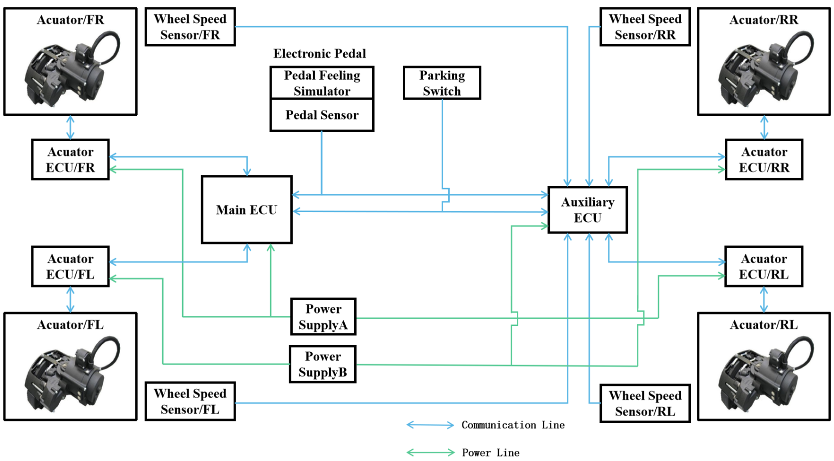
In order to meet the functional safety requirements of the ASIL-D level, a single-point failure of the system must first be avoided. Thus, a redundant backup design is required for control ECUs, power supplies, communication lines, etc. In terms of ECU layout, a minority of systems will abandon the controller of the EMB actuator itself and integrate the control into a centralized duplex module, and more common are systems that use four actuator ECUs [8]. Three typical EMB system architectures with different ECU layouts are given in Schemes. Scheme 1 uses a main ECU to control the actuator ECUs of the front axle and the rear axle, respectively, through two axle ECUs. This scheme has two power supplies with an H-arrangement and four communication lines as redundant backups. When the main ECU or axle ECU fails, it can guarantee 100% and 50% braking capacity, respectively. Scheme 2 uses a single main ECU to control four actuator ECUs, and has two power supplies with full redundancy and two communication lines. When the main ECU fails, the electronic pedal directly controls two or four actuators to ensure 50% or 100% braking capacity. Scheme 3 uses the main ECU to receive and analyze the braking demand, monitor the state of the motor, and issue a braking command, while the auxiliary ECU directly receives the brake pedal signal and wheel speed signal to control the actuator ECU. In this scheme, two power supplies with an X-arrangement and two communication lines are provided. When the main ECU or auxiliary ECU fails, 50% of the braking capacity can still be guaranteed. In addition to the above three schemes, some schemes may also use the ECU layout form of '2/3 main ECUs + 4 actuator ECUs'. For the power supply, two power supplies with an X or H arrangement and a fully redundant backup power supply are used to achieve triple redundancy. The comparison of various schemes is shown in Table 13.



Scheme 1. Main ECU+2 axis ECUs+4 actuator ECUs.



Scheme 2. Main ECU+4 actuator ECUs.



Scheme 3. Main ECU + auxiliary ECU + 4 actuator ECUs.

Table 13. Comparison of various system architecture schemes.

1	Scheme 1	Scheme 2	Scheme 3	Other Schemes
ECU Redundancy	Main ECU + 2 axis ECUs + 4 actuator ECUs	Main ECU + 4 actuator ECUs	Main ECU + auxiliary ECU + 4 actuator ECUs	2/3 main ECUs + 4 actuator ECUs
Power redundancy	2 power supplies (H-arrangement)	2 power supplies (full redundancy)	2 power supplies (X-arrangement)	2 power supplies (X/H-arrangement) + backup power supply (full redundancy)
Communication redundancy	4 communication lines	2 communication lines	2 communication lines	
Wheel speed sensor	Wheel speed sensor-axis ECU	Wheel speed sensor-actuator ECU	Wheel speed sensor-auxiliary ECU	
Voltage	12V/24V/48V			
Communication bus	CAN FD/FlexRay/Ethernet			

5.2. Vehicle Stability Control Based on the EMB System

Vehicle stability control refers to the ability of the vehicle to maintain a stable operation in the process of driving or braking in emergency situations such as sudden steering and sudden changes of road excitation. Based on the advantages of the EMB system, such as high precision and fast response, as well as electronic control, it is easier to combine the advanced compound assisted driving control algorithms to better maintain the stability of the vehicle, monitor and track the running state of the vehicle in real-time, and make feedback adjustments. Generally speaking, stability control can be divided into longitudinal stability control and lateral stability control. The existing vehicle stability control methods based on the EMB system are shown in Table 14.

Table 14. Vehicle stability control methods based on the EMB system.

Vehicle Stability Control	System Function	Control Methods
Longitudinal stability control	ABS/EBD	Optimized logic threshold control Integral sliding mode control Terminal sliding mode control Fuzzy Sliding Mode Control Fuzzy PI/PID control CNN neural network PI/PID control Non-integer order robust control (CRONE) Self-optimizing algorithm
	TCS	BP Neural network PI/PID control
Lateral Stability control	ESC	Fuzzy logic control Fuzzy PI/PID control PID+logic threshold value control LPV Control

(1) In terms of the longitudinal stability control, Xu [90] from Yanshan University adopts the logic threshold value control method to achieve the application of ABS. The logic threshold control method is to control the increase and decrease and maintenance of braking pressure according to the threshold of wheel acceleration and slip rate, so that the wheel slip rate can be maintained near the optimal slip rate, and the optimal ground braking force can

be obtained. The simulation result shows that the ABS control based on the EMB system is more accurate, more efficient and less energy-consuming. Based on the characteristic that the clamping force feedback signal can realize the continuous closed-loop control of braking torque, Xia [1] and Li [71] from Chongqing University put forward an optimized logic threshold control method. In the process of ABS control, according to the vehicle slip rate and braking deceleration, the gradient of increasing or decreasing the braking torque is directly given to realize the adjustment of the braking torque, and the slip rate is controlled in a stable region. The logic threshold control method does not involve mathematical models, and has the advantages of a fast response speed and low cost. However, its design and debugging are complicated and the control process is unstable. In addition, due to the nature of the switch, it cannot be constantly at the optimal slip rate.

Lee et al. [91] of the Korean Institute of Science and Technology calculate the expected motor speed through the longitudinal acceleration controller (PI) to dynamically control the clamping force, and use the trajectory update algorithm to solve the phase lag between the controller and the target to approach the preset expected acceleration curve. This is such that it achieves the reduction of the braking input before stopping under low-risk braking conditions, which improves ride comfort. Dong [92] and Tian [93] from Jiangsu University; Zhang from Huazhong University of Science and Technology [70]; Zhang from Hunan University [77]; and Han [94], Yang and Li et al. [95] from Jilin University put forward a fuzzy PID compound control method to realize ABS/EBD (shown in Figure 37). The differential of the difference between the expected optimal slip rate and the actual slip rate is input into the fuzzy controller, and the proportional, integral and differential parameters of the PID control are generated according to the fuzzy rules, such that it can perform a feedback control of the braking force. This control method not only has the advantages of a high PID control accuracy, but also has the advantages of the strong robustness of fuzzy control. Tang [96] and Rao [97] from Jilin University, Wang [98] from Jiangsu Industrial Normal University and Shen et al. [99] from Nantong University realize the control of ABS/TCS by combining the BP or CNN neural network with a PID control. After the longitudinal vehicle speed and wheel speed, the difference between the expected optimal slip rate and the actual slip rate and change rate are input into the BP or CNN neural network; the three parameters of the PID controller can also be obtained through neural network learning. The feedback control is carried out, which makes it more accurate, and it has a good tracking adaptability.

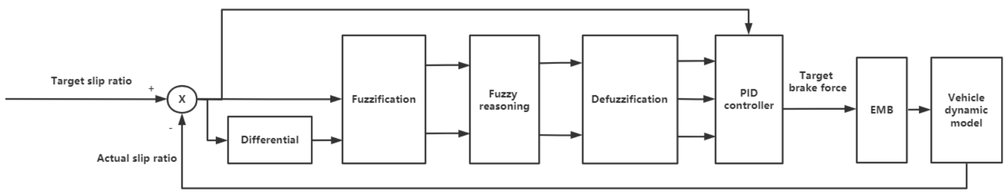


Figure 37. Control framework of the ABS using fuzzy PID control methods.

Huang [27] from Xihua University and Zhang [100] from Changan University realize the control of ABS through the fuzzy sliding mode control method. Firstly, the slip rate is used as the control object through the sliding mode controller to make the motion point always locate on the sliding surface generated based on the optimal slip rate, and then the fuzzy control corrector is further set to fuzzify the output of the sliding mode controller, so that the control value is optimized through the fuzzy control rule. After these processes, the defuzzification output is used to control the braking force. Therefore, the chattering of the conventional sliding mode control is effectively suppressed, while the robustness of the sliding mode control is maintained. Liang et al. [101] from the Northwestern Polytechnical University propose an adaptive non-singular fast terminal sliding mode (NFTSM) control scheme based on the sliding mode control, which uses the radial basis function (RBF) neural network method to solve the difficulty of estimating the upper bound of a complex disturbance in the system, reduce the conservatism of the sliding mode switching gain design and effectively eliminate the chattering.

Benine-Neto et al. [102] from the University of Bordeaux design a new non-integer-order robust controller (CRONE) with the ABS function. Its linearization model based on the frequency domain control enables it to track the reference angular velocity of wheels, and significantly reduce the fluctuation of the control input caused by the measurement noise in the presence of uncertain parameters such as vehicle quality, road conditions, etc.

Dinçmen et al. [103] from Isik University propose an extremum finding scheme for ABS controllers. By developing a self-optimizing algorithm and observer design, the braking force of road vehicles under emergency braking conditions can be maximized without estimating the road conditions.

(2) In terms of the lateral stability control, Xiang et al. [104] from the University of Michigan analyze the system architecture and fault-tolerant design of the brake-by-wire system, and study the effectiveness of using the differential braking torque to control the lateral and yaw stability. Therefore, a fuzzy logic control scheme is proposed, which applies the optimal braking torque to different wheels according to the vehicle state and road conditions, thus achieving lateral and yaw stability control, and the effectiveness of the control scheme is verified by the simulation of the vehicle braking model.

Zhang [76], Yang [69] and Wang [105] of Jilin University research the yaw control algorithm based on the EMB system. They all realize the application of the ESC function through the PID control. Aiming at the linear two-degree-of-freedom automobile model, the PID controller of the side slip angle of the center of mass and the PID controller of the yaw rate are used for the joint control. When the side slip angle of the center of mass is small, the PID controller of the side slip angle of the center of mass is adopted. Otherwise, the yaw rate PID controller is used. The system judges the driver's intention by collecting the steering wheel and brake pedal information, and compares the monitored actual value with the theoretical value through calculation, thus calculating the target braking force required for each wheel to reach the expected state. This feedback adjustment is performed to ensure the lateral stability of the vehicle. Zhou [106] from Wuhan University of Technology describes the PID controller of the side slip angle of the center of mass and the PID controller of the yaw rate by the fuzzy PID control method, which fuzzifies the input precise signal and obtains the corresponding fuzzy control output through fuzzy rule for the controlled object. It associates the control quantity of the side slip angle of the center of mass and the yaw rate through a non-mathematical model, which reduces the complexity of the model and facilitates control debugging. Yin et al. [107] from Jilin University have studied the yaw moment control algorithm in the vehicle stability control system (ESC) based on EMB (shown in Figure 38). Taking the sideslip angle of the center of mass and yaw rate as control parameters, the vehicle stability control is realized by using the yaw moment decision algorithm combining the PID algorithm and the threshold value, and the yaw control algorithm is verified by simulation experiments.

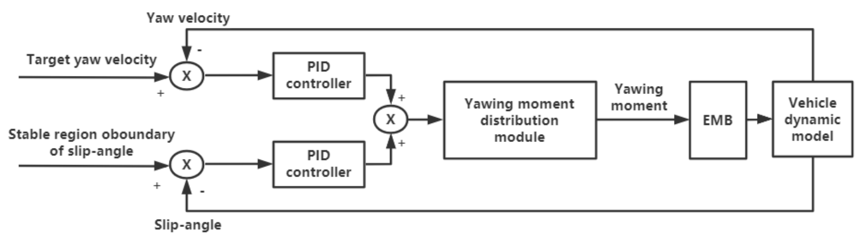


Figure 38. Control framework of the ESC system using PID control methods.

Fergani et al. [108] propose an LPV control method based on a lateral stability monitoring system, which allows a smooth transition between performance targets and handled nonlinearity in a simple way while maintaining sufficient robustness to better maintain vehicle stability.

To sum up, the application of the electro-mechanical braking system (EMB) makes it possible to realize the coupling of higher-order control auxiliary algorithms. Because of the characteristics of its brake-by-wire system, it not only ensures versatility and high stability, but also has the advantages of high integration, low energy consumption, fast response, etc. This guarantees the stability control of the whole vehicle and lays a foundation for the development of the electrification and intellectualization of vehicles.

5.3. Advanced Driver Assistance Based on the EMB System

Advanced driver assistance refers to obtaining the information of the surrounding environment through perception technology, and then sending an alarm to the driver or actively intervening with the driver for emergency treatment through data processing and analysis, which improves the safety and reliability of the vehicle in the process of running. The vehicle dynamics control based on the EMB active braking ability is the main focus of the current research, in order to realize advanced assisted driving, such as adaptive cruise control (ACC), automatic emergency braking (AEB), etc.

Yang et al. [109], from Jilin University, build an offline simulation platform for EMB and ACC with a virtual reality function, using a PI control for the throttle position and fuzzy PID control for the braking control. Under the virtual simulation of two typical follow-up conditions, they preliminarily explore the ACC function based on the EMB. Mou [3] from Jilin University establishes a longitudinal dynamics-layered control framework, including ACC and AEB systems based on the EMB multi-stage closed-loop control algorithm (shown in Figure 39). The lower control part designs the target braking pressure, the target driving torque and the switching control strategy between driving and braking based on the vehicle longitudinal dynamic equation, while the upper control part designs the constant speed cruise PID controller and the self-following LQR controller, as well as the AEB safe distance model and the hierarchical braking control strategy. Moreover, the simulation verifies the effectiveness of the longitudinal dynamics control strategy. Xu [110] from Shandong Jiaotong University precisely controls the clamping force of EMBs based on the three-closed-loop control strategy, establishes the ABS fuzzy PID controller based on the slip rate, and adopts the TTC collision strategy based on the collision time as the AEB control algorithm. The AEB function of the integrated EMB is simulated and verified.

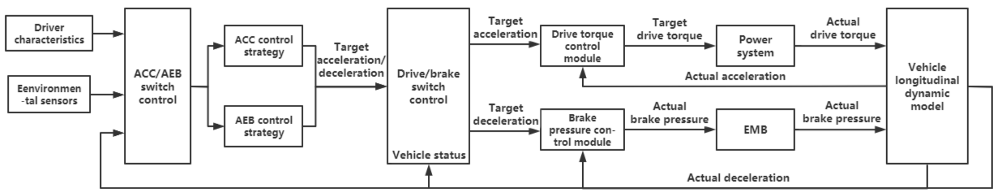


Figure 39. Control framework of the ACC/AEB system based on the EMB.

Miao [111] from Jiangsu University designs a control method for the joint action of ABS and AEB based on the wedge-type EMB. The logic threshold control method is adopted for the execution system, the slip rate is used as the second logic threshold value of AEB control, and the output braking torque is adjusted in conjunction with ABS to enhance the braking stability. Finally, under four different types of road surfaces, the performance of the braking system is verified by co-simulation.

6. Conclusions

As a complete form of the brake-by-wire system, the electro-mechanical brake (EMB) system has many advantages, such as rapid response, precise braking force control and easy integrated control. At the same time, there are still some problems, such as poor redundancy, high cost and serious thermal interference. Summarizing the existing structural schemes proposed by various manufacturers, the following conclusions can be drawn:

1. For the service brake module, the motion conversion is generally realized in the form of screw transmission (especially ball screw and roller screw). Moreover, the reducing mechanism (represented by the planetary gear train) or force increasing mechanism (represented by the wedge-type self-energizing mechanism) are mainly used to solve the problem of the insufficient driving force of the motor.
2. For the parking brake module, according to the different driving components commonly used, it can be divided into three types: manual type, motor-driven type and solenoid-driven type. Among them, the solenoid-driven scheme has become the mainstream scheme, since its structure is simple and compact.
3. For the brake clearance compensation module, according to the material properties of the components used, it can be divided into three types: flexible type, rigid type, flexible and rigid type. Among them, the flexible and rigid compensation mechanism combines the characteristics of the former two schemes, so that the control of the brake clearance is more accurate and reliable, and the compensation process is smoother.
4. For the quick-return module, torsion springs, compression springs or other elastic elements are generally used to store the elastic energy and realize the quick release of the braking force.

Regarding the clamping force estimation and control algorithm of EMB actuators, and the application research of EMB systems in intelligent driving, the current research progress and future research prospects are as follows:

1. For the estimation of the clamping force, there are three methods, respectively, based on the angular displacement of the motor, the motor current, and the fusion of the angular displacement and current. Most of them still use the approximate model for fitting, which is not robust in interference factors such as temperature and friction. A strong robust state estimation algorithm needs to be further developed.
2. For the control of the clamping force, the cascaded PID control algorithm is mainly used at present, and other algorithms such as robust control, model predictive control, and sliding mode control are also included. Given the nonlinear time-varying characteristics of the EMB system, the use of adaptive intelligent control algorithms to achieve a precise adjustment of the braking force is a major trend in the current research.
3. The research on the application of the EMB system in intelligent driving is currently mainly focused on vehicle stability control, and there are few studies on the application of the EMB system in advanced driver assistance. The application of the EMB system in the lateral and longitudinal dynamics control of the vehicle for L3-L5 automatic driving will be the focus of future research.

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