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Design and Control of New Brake-by-Wire Actuator for Vehicle Based on Linear Motor and Lever Mechanism

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ABSTRACT The brake-by-wire actuator was considered to be the next generation of vehicle brake, which uses cables to transmit signals and energy, and uses electric motor instead of hydraulic element or pneumatic element. This paper designs a new type of brake-by-wire actuator based on the special linear motor. First, the structure, composition and working principle of the linear motor are explained. Secondly, the caliper structure and amplification mechanism of the actuator are designed. Thirdly, the controller and control strategy based on dSPACE platform are introduced in detail. Finally, the electromechanical parameters of actuator were identified, and the experiment of the linear motor and brake-by-wire actuator were completed. The experiment results show that the new actuator has the advantages of fast braking response, low control difficulty and high control accuracy, etc. In conclusion, this paper provides a new design scheme for the brake-by-wire actuator, and has the potential to further research and replace the traditional hydraulic braking system.

INDEX TERMS Brake-by-wire actuator, linear motor, Halbach array, force increase lever amplifying, caliper design.

I. INTRODUCTION

Safety, energy saving and intelligence are the development trends of future automotive [1]. A key measure to improve the vehicle safety is to improve its braking system and braking performance [2]. At present, the hydraulic brake system is very mature and its performance is very stable, but it is difficult to further improve [3]. With the continuous development of automotive electronic technology and computer control technology, many traditional mechanical systems and hydraulic systems in vehicle have been replaced by precise electronic sensors and electronic control systems [4]. These new electronic control systems are called ‘‘X-by-Wire’’, where the ‘‘X’’ represents the various functional components in the vehicle that were originally controlled and driven by machineries or hydraulics [5]. The system that replaces the traditional hydraulic brake is brake-by-wire (BBW), which is represented by electro-mechanical brake (EMB) and electro-wedge brake (EWB) [6], [7].

The BBW removes the complex and bulky mechanical and hydraulic components. It has the advantages of fast response, stable performance, small size and easy integration of other functional modules [8]. Therefore, it gradually becomes the research hotspot in the fields of automotive safety [9]. BBW uses electric wires and electrical signals to convey the driver's braking intentions; and uses motors, drivers and transmission components to provide braking force,as shown in Figure 1 [10]. When the vehicle needs to brake, the driver steps on the electronic brake pedal simulator. The pedal simulator has pedal force sensor or pedal stroke sensor, which convert the

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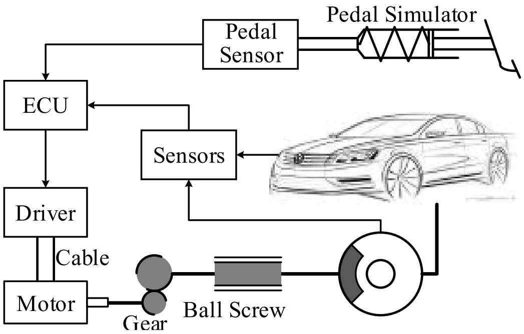

FIGURE 1. The principle and components of BBW (EMB).

driver's braking action into electrical signal and transmits it to the electronic control unit (ECU) through signal cables. The ECU also receives signals such as vehicle velocity, wheel speed, motor current, and rotor position at the same time [11]. After comprehensive calculation and analysis of all these signals, ECU sends the force control signals to the driver. The driver provides appropriate current to the motor according to the control signal, thereby controlling its speed, torque and rotation direction [12]. After the motor rotates, its torque is first amplified by the gear mechanism, and then converted into linear thrust by the ball screw mechanism, and finally pushes the friction linings to clamp the brake disc and slows down the wheel [13]. When the brake needs to be released, the motor is supplied with reverse current and rotates in the reverse direction, which drives the screw and friction linings back to their original position [14].

As shown in Figure 1, there is no mechanical or hydraulic connection between the pedal and wheel actuator in BBW, so the installation and maintenance of BBW are simpler and more convenient [15]. BBW does not require brake fluid, so it is more environmentally friendly. BBW does not require vacuum booster and master cylinder, so its layout is more flexible. BBW can be equipped with advanced functions such as anti-lock brakes (ABS), vehicle stability control (VSC) and adaptive cruise control (ACC) through software design and without adding additional devices, and it can also better match the regenerative brake system of electric vehicles [8], [16].

BBW is a key technology to improve vehicle safety in the future, so the design, manufacture and maintenance of BBW should be perfect. The current research on BBW mainly focuses on two points: one is to design actuator with excellent structure and compact size [10], [17]; the other is to develop control strategy with superior performance [18], [19]. After years of research, a large number of theoretical and experimental results have been obtained. However, EMB uses torque motor to provide power, which results in EMB having both motion conversion mechanism (rolling screw mechanism) and force/torque increase mechanism (wedge/gear mechanism) [20]. Therefore, EMB has complex structure, large size and heavy weight, and it is difficult to adjust the braking force, which limits the braking performance of vehicle [21].

TABLE 1. Linear motor parameters.

Parameter	Value/Unit
Total diameter	88 mm
Total length	70 mm
Diameter of connecting shaft	12 mm
Number of coils	2
Coil turns	144
Number of ring-shaped magnet	3
Number of arc-shaped magnet	16

In order to solve the above problems, this paper designs a new type of BBW actuator based on the linear motor, which utilizes the "linear drive" characteristics of linear motor and the force increase principle of lever, and is named as direct-drive-brake (DDB). Since the motion conversion mechanism similar to the ball screw is eliminated, this new actuator effectively reduces the size and complexity of the BBW actuator. In this paper, the design of linear motor, lever and caliper are introduced firstly in section II. Then, the controller and control strategy of the brake unit, as well as the power drive module are described in section III. Finally, the parameter identification of direct drive braking unit, the step response test of braking force and the following test of braking force are completed in section IV.

II. DESIGN OF DIRECT DRIVE BRAKE ACTUATOR

A. LINEAR MOTOR

Linear motor is a power device that directly converts electrical energy into mechanical energy with linear motion [22]. Compared with the traditional driving method of "rotating motor + ball screw", the linear motor has the advantages of simpler structure, more reliable operation, faster dynamic response and higher control accuracy [23]. Halbach array is an arrangement of permanent magnets, which can effectively improve the thrust of the linear motor [24]. If the permanent magnets with different magnetization directions are arranged in a Halbach array, the magnetic flux density on one side of the array is increased, while the other side is decreased [25]. In this way, the utilization of permanent magnet and yoke is higher, and the air gap flux density is significantly improved, thereby the thrust density of the motor is greater.

The permanent magnet linear motor with moving coil based on Halbach array is shown in Figure 2, and its main parameters are listed in Table 1. In the Figure 2(a), 1, 2 and 3 are the inner core, outer shell and end cover made of soft magnetic materials. The hysteresis, remanence and coercivity of soft magnetic materials are very small, so they have good magnetic permeability. The reciprocating frequency of the linear motor studied in this paper is low, so the hysteresis loss can be ignored. After comprehensive consideration, we use low-carbon steel with better machinability as the magnetic material. 4 is axially magnetized and ring-shaped permanent magnet made of $Nd_2Fe_{14}B$, as shown in Figure 2(b). The different magnetic field directions can be get by changing the installation direction of the ring magnet. The ring magnet at both ends improve the uniformity of magnetic field and

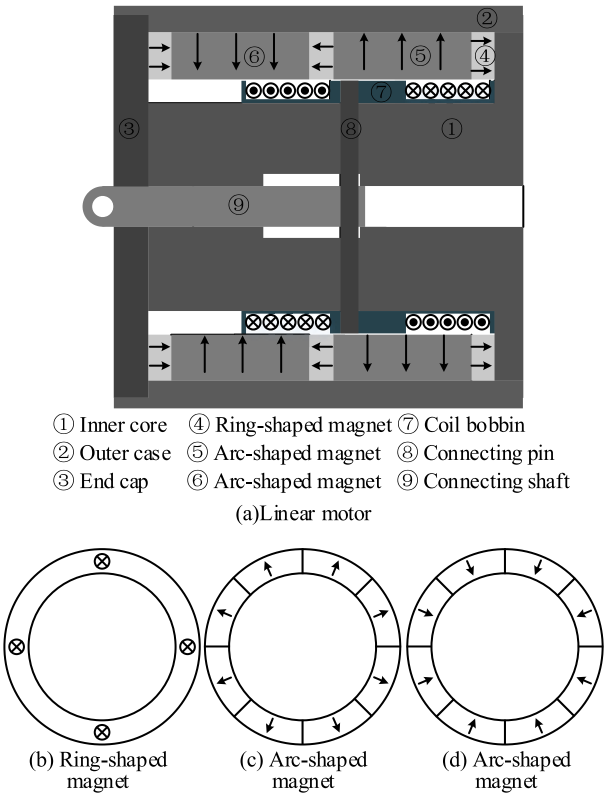

FIGURE 2. Linear motor and permanent magnet.

increase the magnetic flux density. The ring magnet in the middle reduces the magnetic flux density in the middle of the yoke, thus reducing the thickness of the yoke and increasing the power density of the motor. 5 and 6 are radial magnetized and arc-shaped permanent magnet, but the magnetization directions are opposite, as shown in figure (c) and figure (d). Due to the immature ring magnetizing technology, the radial magnetization is very difficult or even impossible. Therefore, the radial permanent magnet is machined into arc-shaped and magnetized separately as shown in the figure, and finally assembled them in combination to form a magnetic ring similar to radial magnetization. The coil 7 is wound by copper wire in the bracket slot. The winding directions of the two coils are opposite, and the current directions of the two coils are also opposite when energized. 8 and 9 are connecting pin and connecting shaft, which transmit the thrust of coil to the caliper.

The linear motor shown in Figure 2 is a permanent magnet linear motor that does not require current commutation. When the coil moves in one direction, the current does not commutate, so it can be controlled more accurately, and the motor force is approximately proportional to the coil current.

If the voltage applied to the linear motor is U, the total voltage of closed circuit is zero according to Kirchhoff's voltage law, which is expressed by the equation (1)

$$U = E + Ri + L\dot{i} \tag{1}$$

where: R is the coil resistance; i is the coil current; L is the coil inductance; E is the counter electromotive force which is calculated as equation (2).

$$E = NBlv \tag{2}$$

where, N is the number of coil turns; B is the air gap magnetic induction strength; l is the average length of each turn; v is the velocity of coil.

When the coil is energized, the ampere force on the coil in the magnetic field is the linear motor thrust, and its value is:

$$F_e = NBil \tag{3}$$

B. ACTUATOR CALIPER

Although the "linear drive" characteristics of linear motor is used in DDB and the "motion conversion" mechanism is eliminated, the "increasing force" mechanism must be used to amplify the electromagnetic force. Because the thrust force of linear motor with limited size is not enough to provide sufficient braking force, the friction linings and the friction plate cannot be directly driven.

EMB usually uses gear mechanism or wedge-shaped self-energizing mechanism to increase force. The gear mechanism can only amplify the torque, so it is not suitable for DDB. Although the wedge-shaped self-increasing mechanism can amplify the linear force, the increase coefficient is not large enough for DDB. The lever has the advantages of large force increase ratio and low friction loss. Taking into account the motion characteristics of linear motor and the requirements for the force increase ratio, we use the lever as the "force-increasing" mechanism and design it together with the caliper. The thrust provided by linear motor acts on the lever, which then pushes the friction linings against the brake disc.

1) FORCE INCREASE LEVER

The lever is a rigid body that can rotate around a fixed point under the action of force. The lever is a simple structure, which can be machined into any geometric shape as required. The lever applied to DDB must have sufficient force increase rate, otherwise it cannot provide sufficient braking force. The lever structure used in this paper is shown in Figure 3.

In the figure, A is the supporting point, and the lever rotates around it. B is the resistance point, which pushes the slider and friction linings to press the brake disc, and F_c is the clamping force. C is the power point, and the motor thrust acts on this point. l_1 is the resistance arm and l_2 is the power arm. If the friction and elastic deformation of the lever are ignored, the relationship between the motor thrust and the caliper clamping force can be obtained according to the principle of balance of the lever.

$$F_c l_1 = F_e l_2 \tag{4}$$

If the force increase rate is n, then the relationship between the caliper force and the motor thrust is:

$$F_c = nF_e \tag{5}$$

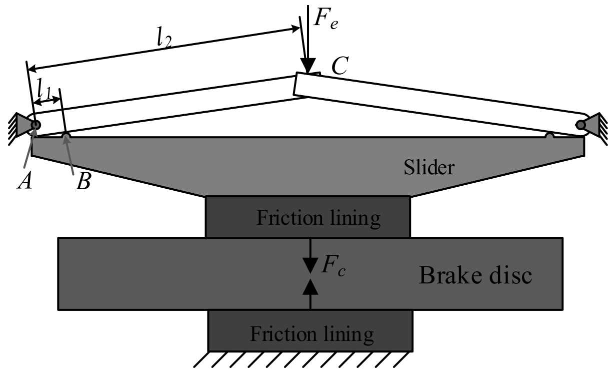

FIGURE 3. The structure and principle of lever.

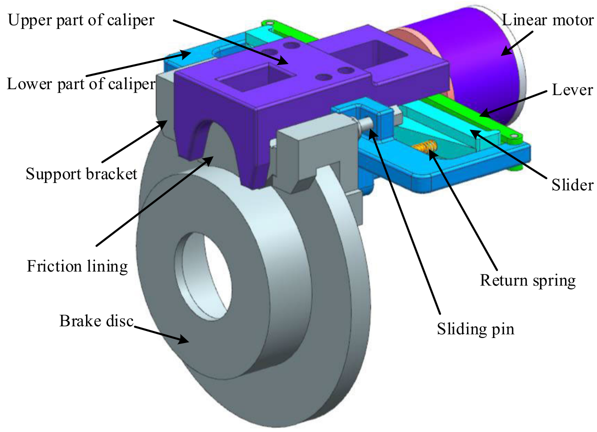

FIGURE 4. Main structure of DDB actuator.

TABLE 2. Lever parameters.

Parameter	Value/Unit
Increase rate	20
Caliper width	286 mm
Slider length	256 mm
Resistance arm	6 mm
Power arm	130 mm

TABLE 3. DDB parameters.

Parameter	Value/Unit
Total length	246 mm
Total width	286 mm
Maximum caliper force	11000 N
Diameter of brake disc	230 mm
Friction coefficient	0.38

Considering that friction and elastic deformation are inevitable, the relationship between the power arm and the resistance arm is as follows according to equations 4 and 5.

$$l_2 \geq nl_1 \tag{6}$$

In order to prevent uneven wear of the friction linings, two sets of left and right levers are designed. At the same time, a rigid slider is designed to disperse the caliper force and to prevent the lining from cracking due to the concentrated force. The specific designed lever parameters are listed in Table 2.

2) CALIPER

The main structure of the caliper is similar to the traditional hydraulic brake, which is also a floating caliper. Because DDB does not require brake fluid, the caliper does not have wheel cylinders, pistons and sealing rings. However, the DDB caliper is equipped with a slider inside, and is connected to the lever through the pin, and the linear motor is installed at the rear end. The structure of DDB is shown in Figure 4, which main parameters are shown in Table 3.

The hydraulic caliper is integral and rigid, which is formed by casting. However, the cost of casting during the research stage is too great. In order to reduce the research costs, we use machining methods to manufacture the caliper. But it is very difficult to manufacture the caliper integrally by machining, so the main body of the caliper is divided into upper and lower parts for machining, and the upper and lower parts are connected by screws. In addition, the DDB actuator also includes support bracket, friction linings, brake disc, sliding pin, return springs and other components, as shown in Figure 4. The support bracket is fixed on the axle. The caliper is mounted on the bracket through the sliding pin and can slide along the sliding pin. The brake disc is fixed to the wheel and rotates with the wheel. The return spring is installed between the caliper and the slider. It can not only buffer the impact force of linear motor at the beginning of braking; but also return the slider to its initial position at the end of braking, so that the friction linings and the brake disc are completely separated.

The friction linings of DDB is an important part, which rubs against the brake disc to convert the kinetic energy into heat and dissipates it in the air. The friction linings are generally formed by sintering metal-based powders and have high coefficient of friction. If the friction coefficient is μ, the friction between the brake disc and the caliper is:

$$F_f = 2\mu F_c \tag{7}$$

Therefore, the braking torque acting on the wheels is:

$$T_b = F_f r_d = 2\mu r_d F_c \tag{8}$$

where, r_d is the effective radius of the brake disc.

C. CONTROLLER AND POWER DRIVE MODULE

1) CONTROLLER

The controller regulates the coil current in real time according to the target braking force. The controller is responsible for analog-to-digital (A/D) conversion, data processing and pulse width modulation (PWM) output. Since DDB is still in the development, we chose the dSPACE's rapid control prototype (DS1104 R&D) to complete the experimental verification. The DS1104 R&D controller board has multiple I/O interfaces, PWM output modules and real-time processor, which can act to a standard automotive ECU, as shown in Figure 5.

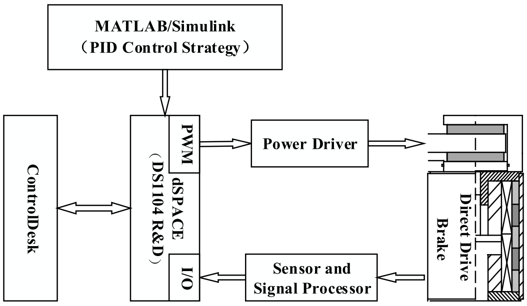

FIGURE 5. Rapid control prototype of DDB actuator.

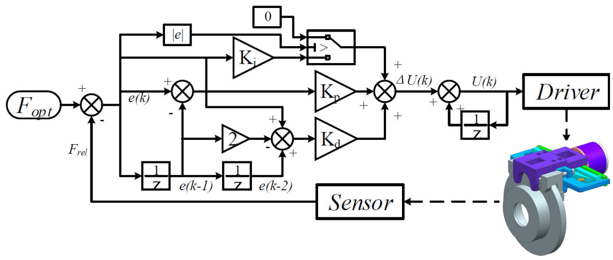

FIGURE 6. Incremental PID controller.

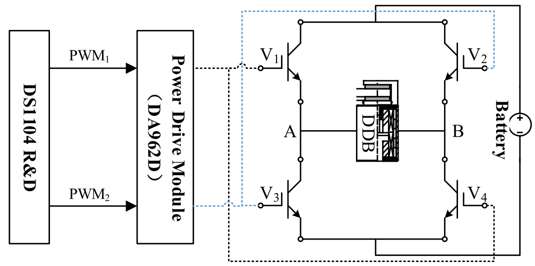

FIGURE 7. Power driver of DDB actuator.

The controller adopts the integral separated incremental proportional integral differential (PID) control strategy shown in Figure 6, which is mature and widely used control method. The controller input is the target caliper force F_{opt}, the feedback is the actual caliper force F_{rel}, and the control output is the linear motor terminal voltage U.

$$\begin{cases} e(k) = F_{opt} - F_{rel} \\ \Delta U_{pd}(k) = K_p[e(k) - e(k-1)] \\ +K_d[e(k) - 2e(k-1) + e(k-2)] \\ \Delta U_i(k) = K_i e(k) \end{cases} \quad (9)$$

where, K_p, K_i, and K_d are the proportional, integral and differential coefficients of the controller, and k is the sampling step.

When the difference between the target braking force F_{opt} and the actual braking force F_{rel} is large, the integral control is not applied. In other words, if $|e(k)| > \beta$,

$$U(k) = U(k-1) + \Delta U_{pd}(k) \quad (10)$$

where, β is the integral separation threshold.

When the difference between the target braking force F_{opt} and the actual braking force F_{rel} is small, the integral control is implemented. In other words, if $|e(k)| \leq \beta$,

$$U(k) = U(k-1) + \Delta U_{pd}(k) + \Delta U_i(k) \quad (11)$$

After building the control strategy in MATLAB/Simulink, the Simulink Coder^{TM} is used to generate the control program, which is then compiled and downloaded to the DS1104 R&D, as shown in Figure 5.

2) POWER DRIVE MODULE

The power driver converts the PWM signal of DS1104 R&D into electric current, which is mainly composed of power drive module and H-bridge, as shown in Figure 7. The Power drive module is selected and bought according to the drive current and voltage. The H-bridge is composed of 4 insulated gate bipolar transistors (IGBT) with fast switching speed, low loss, and low driving power. The 4 IGBTs are divided into 2 groups. V_1 and V_4 are one group; V_2 and V_3 are another group, which are controlled by the PWM_1 and PWM_2 signals of DS1104 R&D, respectively. The PWM_1 and PWM_2 signals do not overlap, and the motor thrust and direction can be changed by changing the duty cycle of two signals.

If $PWM_1 = D$ (D is the duty cycle of PWM signal) and $PWM_2 = 0$, then V_1 and V_4 are turned on, V_2 and V_3 are turned off. The DDB provides the braking force according to the target signal, the current of DDB is from A to B, and the voltage described as equation (12).

If $PWM_1 = 0$ and $PWM_2 = D$, then V_1 and V_4 are turned off, V_2 and V_3 are turned on. At this time, the motor moves in the reverse direction, and the braking force is cancelled. The current of DDB is from B to A, and the voltage described as equation (13).

$$U = D \times U_{Battery} \quad (12)$$

$$U = -D \times U_{Battery} \quad (13)$$

where, $U_{Battery}$ is the battery voltage.

Finally, the coil current, coil displacement and caliper force of DDB are feedback to DS1104 R&D by sensors, and these signals can also be recorded and viewed by ControlDesk, as shown in Figure 5.

III. EXPERIMENT OF DIRECT-DRIVE-BRAKE

According to the design size, we use machining methods such as wire cutting and milling to manufacture each part, and the permanent magnets are also customized by professional manufacturers. The completed motor and DDB are shown in Figures 8.

A. PARAMETER IDENTIFICATION

The parameters identification of motor can further study its characteristics after the components are manufactured, which provides convenient for simulation and controller design.

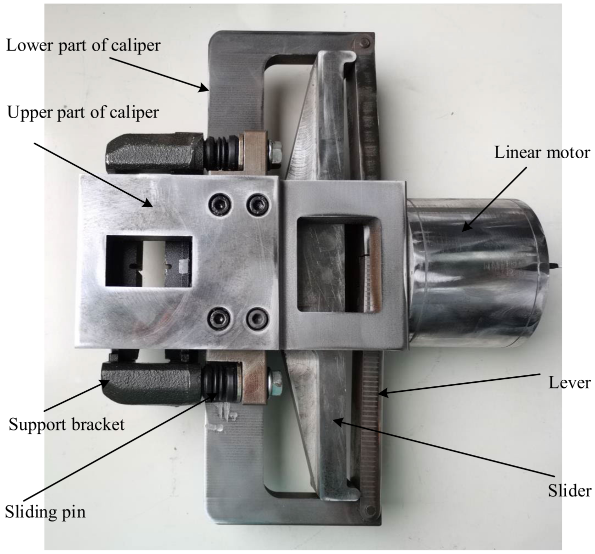

FIGURE 8. Prototype of DDB actuator.

TABLE 4. The mass of moving parts.

Components	Mass/g
Coil	78.22
Pin	5.47
Connecting shaft	39.97
Lever	507.6
Slider	1438.7
Friction lining	238.5

1) THE MASS OF MOVING COMPONENTS

The mass of the moving components is critical to the dynamic response of DDB. If the mass of moving parts is large, the response characteristics of motor will deteriorate. The moving parts include coil, pin, connecting shaft, lever, slider and friction linings, which are measured by a precision electronic scales. Table 4 lists the actual mass of each moving parts.

2) THE RESISTANCE OF COIL

The resistance describes the conductivity of the coil, which measures the resistance effect of the coil on current. The coil resistance of linear motor is small. Therefore, we use low resistance tester to measure, and the actual measured resistance is 0.764 Ω.

3) THE INDUCTANCE OF COIL

The inductance is a property of coil If the coil current changes, the counter electromotive force will be generated to prevent the current change. The coil inductance is measured by precision inductance tester, and the actual inductance is 342.8 μH.

4) THE TIME CONSTANT OF LINEAR MOTOR

The precise control of braking force requires the linear motor to move accurately and rapidly according to the target braking force. Therefore, the time constants of linear motor are very important parameters, which mainly include electrical time constant and electromechanical time constant.

TABLE 5. The electrical parameters of linear motor.

Parameter	Value/unit
Resistance	0.764 Ω
Inductance	342.8 μH
Electrical time constant	0.45×10^{-3}
Electromechanical time constant	3.8×10^{-3}

Due to the inductance of coil, the current does not change instantaneously if the voltage changes. The electrical time constant τ_e indicates how fast the coil current changes to follow the voltage change, which is defined as:

$$\tau_e = \frac{L}{R} \tag{14}$$

Due to the mass of moving parts, the velocity does not change instantaneously if the electromagnetic force changes. The electromechanical time constant τ_m indicates the velocity change of moving parts following the vary of electromagnetic, which is defined as:

$$\tau_m = \frac{mR}{K_m^2} \tag{15}$$

where, K_m is the thrust constant of linear motor and its average value is 20.38 N/A, m is the total mass of moving parts. In summary, the electrical parameters of the linear motor are shown in Table 5.

5) THE FRICTION OF MOVING PARTS

There is relative movement between the actuator components, which creates frictional forces on the contact surface to prevent movement. It is difficult to calculate the friction force accurately due to the many moving parts and complex structure. So we measured the total friction force directly by test.

The detailed measurement method is to provide the fixed voltage to the linear motor. Then, the PWM duty cycle is modified by the control program and increased by 1% each time. Finally, the displacement sensor is used to measure the displacement of friction linings. The rise of the displacement curve indicates that the electromagnetic force is greater than the friction force, as shown in Figure 9.

The frictional resistance of the moving components is about 6.8 N after several tests and calculations. Although there is a difference between the measured resistance in the static state and the actual resistance in the moving state, the difference is very small compared with the motor thrust, so its effect on the performance of brake actuator can be ignored.

B. THE EXPERIMENT OF LINEAR MOTOR

First, the thrust characteristics of linear motor were tested. During the test, a fixed voltage is applied to the power driver

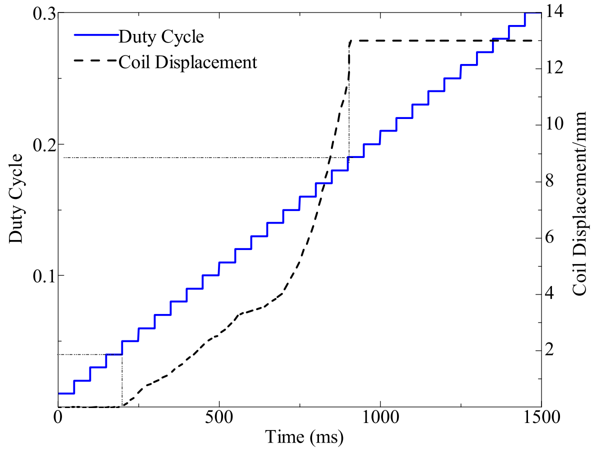

FIGURE 9. Coil velocity and duty cycle vs. time.

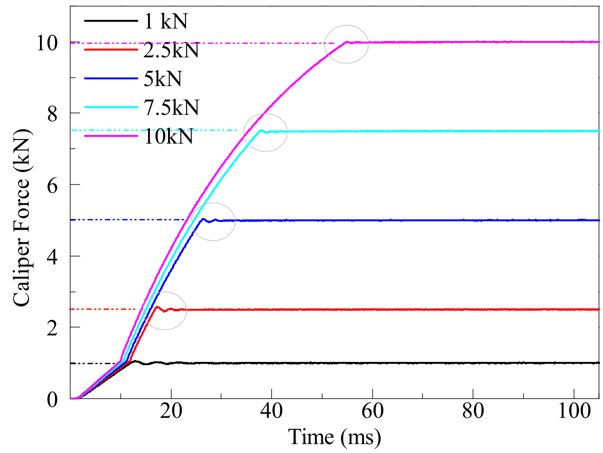

FIGURE 11. Caliper force step response test of DDB.

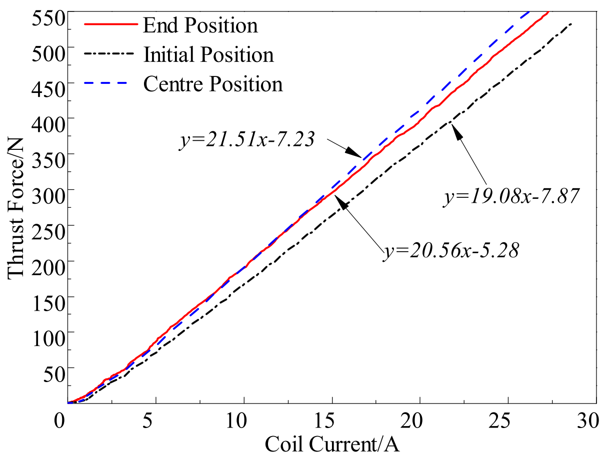

FIGURE 10. Thrust characteristics of linear motor.

of motor, which duty cycle is gradually increased from 0 to 100%. Therefore, the coil current increases from 0 to the maximum value. Finally, the current sensor and the force sensor are used to sample the current and thrust force.

When the coil is in the initial position, centre position and end position, the thrust force and current are shown in Figure 10. Due to the friction between the moving parts, the electromagnetic force is insufficient to overcome the friction if the current is too small. So it can be seen from the Figure 10 that the thrust is 0 when the current is small. However, once the electromagnetic force is sufficient to overcome the frictional force, the motor thrust increases in proportion to the coil current. Figure 10 also shows the fitting curve of the test data at each position. The coefficient of the first term is the thrust constant, and the constant term is the frictional resistance at that position. Due to the special magnetic field distribution of the Halbach array, the thrust constant is relatively small at the initial position. However, the motor does not need too much force at the initial position, and its thrust only needs to overcome the friction of moving parts and spring force of the return spring, so the performance of the DDB will not be reduced. The thrust constants at the centre position and end position are 21.51 and 20.56 respectively, and the measured maximum thrust reaches 550N. Therefore, the thrust of the motor is large enough to push the lever and the slider.

C. THE EXPERIMENT OF DIRECT-DRIVE-BRAKE ACTUATOR

1) STEP RESPONSE TEST

In emergency braking, the caliper braking force must rise rapidly, and it may be as high as 10 kN. For this reason, we designed caliper forces step response test to verify the response performance of direct drive braking actuator. The target caliper force are set to 1kN, 2.5kN, 5kN, 7.5kN and 10kN respectively, and the test results are shown in Figure 11. It can be seen from this figure that the caliper force rises rapidly, and there is almost no difference between the steady value and its target value. In addition, it can be seen from this figure that the caliper force curve rises relatively slowly at the beginning of braking, but it rises rapidly after exceeding 1kN. Because the coil is moving due to the braking gap at the beginning of braking, so the thrust is relatively small. Once the brake gap is completely eliminated, the coil is blocked, so the thrust rises rapidly. Moreover, the elasticity of the lever and return spring also has important influence on the increase of caliper force.

Figure 12 is partial enlarged views of the step response curve. It can be seen that the response times of 2.5kN, 5kN, 7.5kN and 10kN are 17ms, 27ms, 38ms and 55ms, respectively. Therefore, the braking actuator responds very fast, which can effectively improve the braking performance of vehicle. Although the caliper force overshoot and steady-state error are within the allowable range. But the steady-state error is smaller and the overshoot is larger when the target caliper force is smaller; the steady-state error is larger and the overshoot is smaller when the target braking force is larger. Because we use the general PID controller, which is not optimized for DDB. If the more suitable control strategy is designed for the actuator in the later research, the control

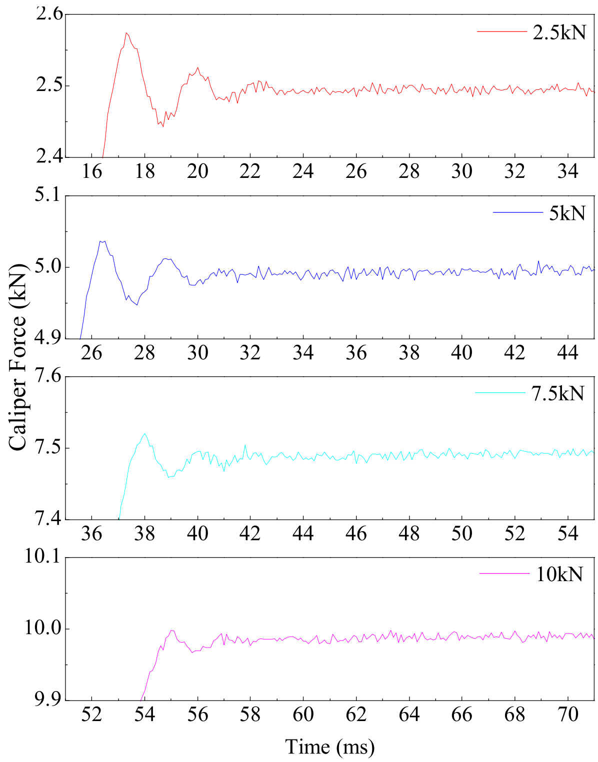

FIGURE 12. Partial enlarged view of step response.

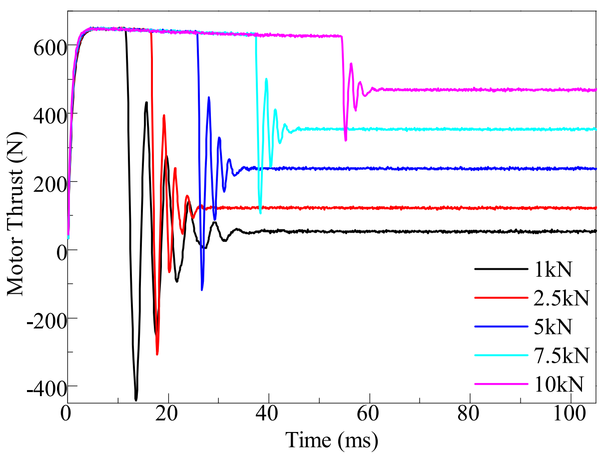

FIGURE 13. Thrust of linear motor.

performances such as steady-state accuracy and overshoot are expected to be further improved.

Figure 13 shows the thrust of the linear motor. It can be seen that the motor thrust of all working conditions increases rapidly and reaches its maximum value, because the actual caliper force at the beginning of braking deviates greatly from its target value due to the brake gap. Therefore, the braking gap can be quickly eliminated, and the target braking force can be quickly reached. When the actual caliper force reaches its target value, the thrust decreases; and the thrust remains stable after a period of adjustment time. It can also be seen that if the target caliper force is small, the high-thrust

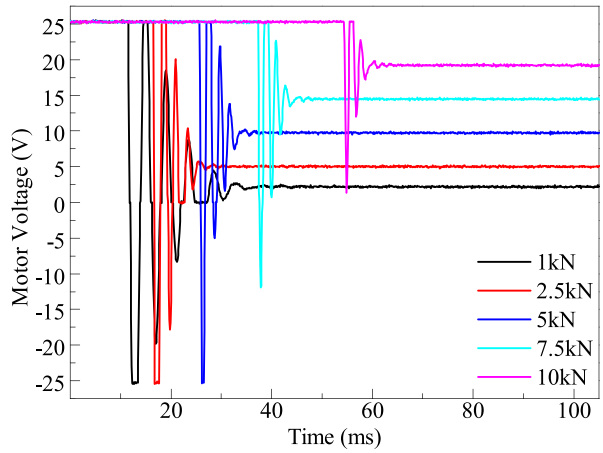

FIGURE 14. Voltage of linear motor.

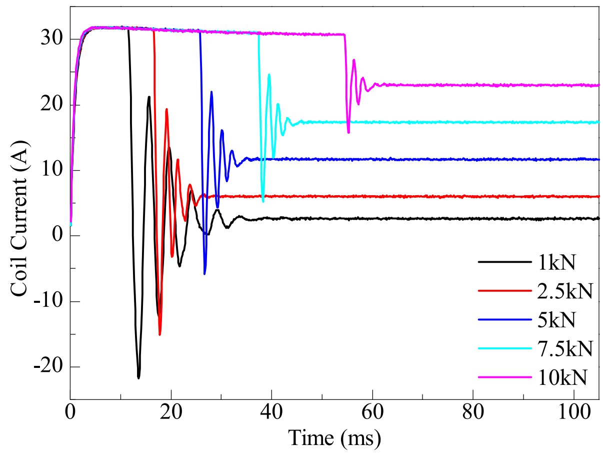

FIGURE 15. Coil current of linear motor.

operation time is shorter, but the adjustment time is relatively long and the fluctuation is large; if the target caliper force is large, the high-thrust operation time is longer, but the adjustment time is short and the fluctuation is relatively small.

Figure 14 shows the voltage of the linear motor. Before the caliper force reaches its target, the terminal voltage maintains the maximum voltage; but the maximum voltage is only 25.7V which is lower than the power supply voltage because of factors such as IGBT tube voltage drop and wire resistance. After the caliper force reaches the target value, the voltage drops rapidly or even negative voltage; but the voltage finally remains stable after adjustment. Similarly, if the caliper force is smaller, the voltage fluctuation is more severe and even reverse saturation voltage during the adjustment phase; if the caliper force is greater, the voltage fluctuation relatively smaller during the adjustment phase.

Figure 15 shows the coil current, and its changing trend is basically the same as Figure 14. However, it can be found that the coil current is slightly reduced although the voltage does not change before the caliper force reaches its target value. We believe that because the coil is in "blocked" state and the

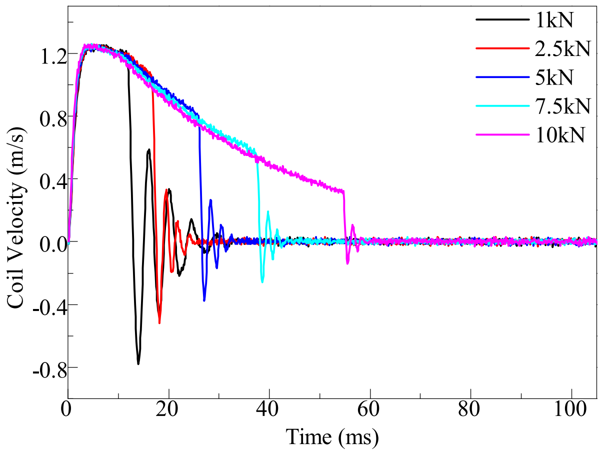

FIGURE 16. Coil velocity of linear motor.

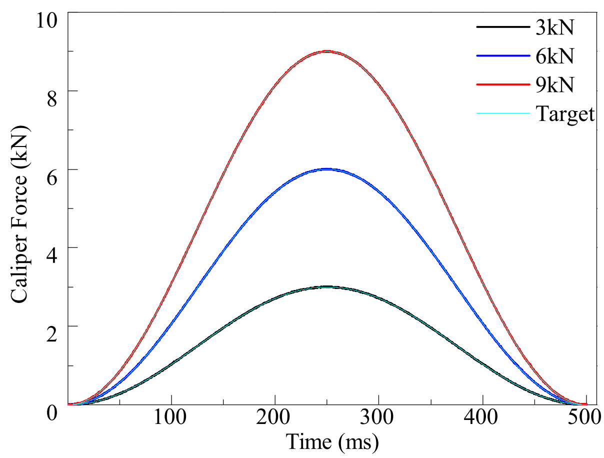

FIGURE 17. Caliper force follow test of DDB.

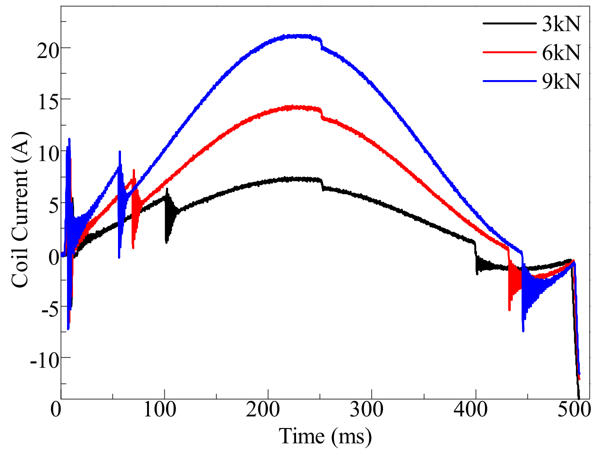

FIGURE 18. Coil current of follow test.

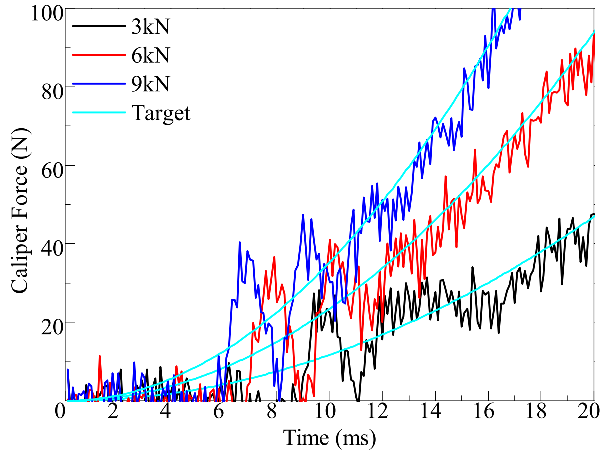

FIGURE 19. Partial enlarged view of caliper force.

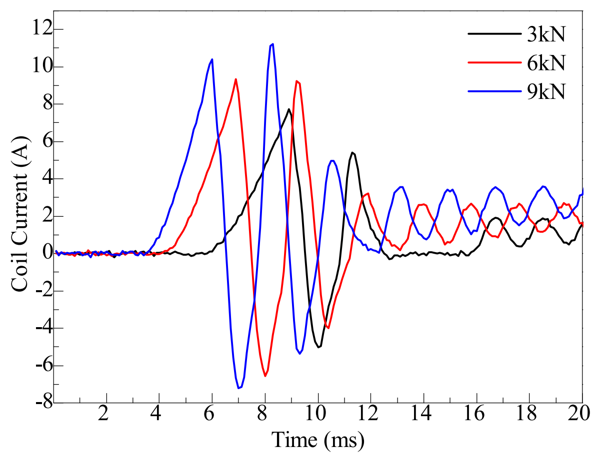

FIGURE 20. Partial enlarged view of current.

current is large when the motor is working, this will cause the coil temperature to rise, and the resistance is also increase, which eventually lead to a small decrease in current.

The coil velocity is shown in Figure 16. At the beginning of braking, the coil velocity rises rapidly to quickly eliminate the braking gap. When the braking gap is eliminated, the velocity gradually decreases and when the actual braking force stabilizes, the coil velocity remains at zero. Similarly, if the target braking force is small, the coil velocity will fluctuate greatly during the adjustment phase.

2) CALIPER FORCE FOLLOWING PERFORMANCE TEST

After completing the step response test, we further tested the caliper force following performance. During the test, the target caliper force are sine wave curve with period of 500ms and amplitudes of 3kN, 6kN and 9kN. Figures 17 shows the caliper force curve. It can be seen that the actual caliper force and its target are both standard sinusoidal curves, indicating that the controller can accurately adjust the caliper force so that the actual braking force changes with the target value.

Figure 18 shows the current curve. The current is also sine curve from global perspective, but there will be large fluctuations and adjustments locally, especially at the beginning of braking. We believe that the main reason is that there is friction between the moving parts of the actuator, and the designed PID controller cannot estimate the friction, nor can it compensate for the friction. Therefore,it is necessary to design a controller that can estimate and compensate the friction force to improve the control performance in the following research.

Figure 19 is the partial enlarged view of the caliper force at the beginning of braking. It can be seen that the actual caliper force fluctuates around the target value and increases as the target value increases. Figure 20 is the partial enlarged view of the corresponding current. The current fluctuates greatly at the beginning of braking, and the reverse adjustment current may even appear when the target value is small.

IV. CONCLUSION

This article utilizes linear motor and lever to design a brake-by-wire actuator, which provides a new design scheme for vehicle brakes. The permanent magnet array based on the Halbach arrangement effectively increases the thrust of linear motor, and the designed lever mechanism further amplifies the motor thrust to provide sufficient braking force. Compared with other brake-by-wire actuators such as electro-mechanical brake (EMB) and electro-wedge brake (EWB), direct-drive-brake (DDB) does not require motion conversion mechanism and has simpler structure. Because the moving parts only have linear motion, the control strategy is simple and effective. Even the general PID control strategy can achieve satisfactory performance.

In this paper, a preliminary test of the direct-drive brake actuator has been carried out. The vehicle test has not been carried out, and the reliability of the brake unit has not been studied. So the future works includes:

1. The volume and mass of the brake unit are further reduced by optimizing the design, and the actual vehicle test will be carried out.

2. Improve the safety and reliability of the direct drive braking unit by research on the communication network, energy supply system, and braking system redundancy design.

DISCLOSURE STATEMENT

The authors declare no conflict of interest.

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