Design and Simulation of a Novel Wedge Disc Brake

Junnian Wang, Nannan Yang, Zhe Wang, Yu Yang and Liang Chu

Abstract Though conventional hydraulic disc brake has better braking steadiness, it also has poor braking efficiency factor. As a fact, the conventional hydraulic disc brake has no large-scale application to heavy duty vehicle. A novel wedge disc brake is presented in this paper, which not only has the special characteristic of self-reinforcement, but also has better braking steadiness just like conventional disc brake. Firstly, the self-reinforcement principle of this kind of wedge disc brake is analyzed and concluded. The reasonable angle of wedge block is calculated and chosen according to the demand of self-reinforcement and unexpected self-lock phenomena. Based on that, the braking efficiency factor is derived from the wedge angle and the friction coefficient between the wedge block and brake disc. After that, the mechanical structure of designed wedge disc brake is presented, then some material strength of the components are revised. In order to validate this designed novel wedge disc brake, a AMESim vehicle model with Simulink wedge disc brake model are built. Several items such as the effect of self-reinforcement and reset of wedge block are simulated. Simulation results show that this novel wedge disc brake can generate the same brake force only at nearly one third multiple hydraulic pressure of conventional disc brake.

Keywords Disc brake · Wedge block · Design method · Self reinforcement · Simulation

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1 Introduction

In the development of automotive technology, vehicle safety gets more and more attention. As a core component of the vehicle active safety system, the performance of brake system has great effect on the vehicle safety. Currently, the service brake of passenger car is mostly hydraulic disc brake. And the heavy duty truck also has a tendency to use disc brake. So it is obvious that disc brake is going to be the main service brake in the near future. While the brake efficiency factor of the conventional disc brake is relatively lower which restricts the widely use of the disc brake. Focusing on this problem, this paper presents a novel wedge disc brake which has much bigger brake efficiency factor.

2 Research Background

The Bosch GmbH has invented a new kind of brake device in which the brake pad is replaced by a wedge block [1]. Then in the same brake intensity, a smaller actuator force is needed. While the same actuator force is exerted, a much bigger brake force will be generated. This brake device adopts electric motor as the actuator which pushes the wedge block through a ball screw. But the dynamic response problem generated by the inertia moment of the motor rotor is not discussed. Because of the widely use of hydraulic system in passenger car nowadays, the adding of motor will result in high modification cost. And thinking about the high price of motor, this new kind of brake device is hard to apply to compact low-cost car. In addition, Bosch only shows us the working principle of the brake device and its lay out in car, but the physical structure was not discussed.

The eStop GmbH and Siemens AG used to developed a novel electronic wedge brake (EWB) eBrake® [2]. Several references introduced the basic design [2], simulation study [3], test process [4], prototype development [5] and application to ABS/ESP [6] of eBrake. eBrake is designed as one kind of electromechanical brake (EMB) for electronic parking brake system (EPB). The actuator of earlier EWB is a double motor system. Under the synergy of the double motor system, the wedge block is moved along tangential direction through ball screw, and the extrusion between wedge block and rollers makes positive axial pressure, in hence the brake works. Then later a new prototype generation with only one motor is designed [7]. The structure of EWB is complex and it is hard to fix such double motors in the wheel. Meanwhile, it is extremely necessary to take into account the high-cost and reliability of double motors.

Emam et al. [8] also designed a electronic wedge brake and the performance of its prototype is simulated and compared between different structures and control parameters. The results showed that the lower wedge mass, the bigger caliper stiffness and reasonable control are better for braking force and operation response Mando Corporation designed a new electronic wedge brakes that have the feature of cross-wedge with optimized volume and use no roller due to its weakness. The proposed cross wedge mechanism showed good performance and volume metric by generating sufficient braking force without distortion due to equally distributing the braking force to pad surfaces and optimistically designed lead screw and worm gear mechanism [9]. Jongsung Kim invented a single motor electro wedge brake. Besides the main braking function, the electro wedge brake implements various additional functions, such as a function for maintaining a set clearance of a pad, a Fail-Safe function, and an EPB function, by using a solenoid mechanism interlocked with a main braking motor [10]. Dong Hwan Shin et al. [11] provided a simple design review of the wedge profile related to the calliper stiffness, and design of calliper stiffness for reducing he weight of an electro wedge brake . Kwangjin Han et al. presented a sliding mode controller for electronic wedge brake to effectively control its self-energizing effect. The performance of the proposed controller is verified in simulations and experiments using a prototype brake [12].

From the above discussion, it is obvious to see the existing self-reinforcement brakes often utilize electric motors as their actuators which result in high cost, but the dynamic response problem is not solved. They have complex structure and it is hard to mount in the wheel due to greater axial length. The brake in present paper is actuated by hydraulic pressure, has a simple structure and with little size, reduces the cost of transformation and maintains the fast response. In this paper, the basic structure and design process is presented firstly, then theoretical relationship between the wedge angle and the performance of self-reinforcement, self-lock and thermal decay are introduced. At last, simulation is performed to verify the effect of self-reinforcement.

3 Basic Principle

The wedge brake in this paper (as seen in Fig. 1) is designed based on conventional hydraulic disc brake in which the activity brake pad is replaced by a wedge block. Wheel cylinder thrust is applied to the surface which is on the side of the smaller leg of the triangle, while the wedge block can slide along the caliper inside surface where rollers are mounted. So under the thrust of the wheel cylinder as well as the additional kinetic energy of a vehicle from brake disc, the wedge block will squeeze the brake disc and causes braking torque. Because of the adding of wedge block, the kinetic energy of a vehicle is transformed into braking power, that is to say, the equivalent brake efficiency factor becomes bigger than before, in hence it is self-reinforced.

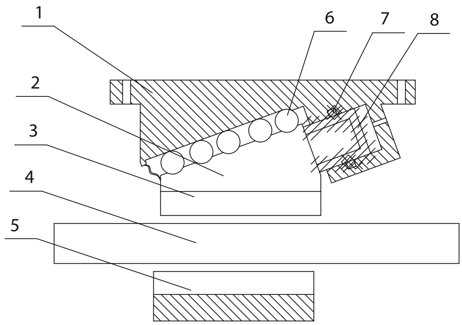


Fig. 1 Schematic diagram of the structure of the wedge brake. *1*—caliper; *2*—wedge block; *3*, *5*—brake pad; *4*—brake disc; *6*—rollers; *7*—sealing rubber ring; *8*—cylinder

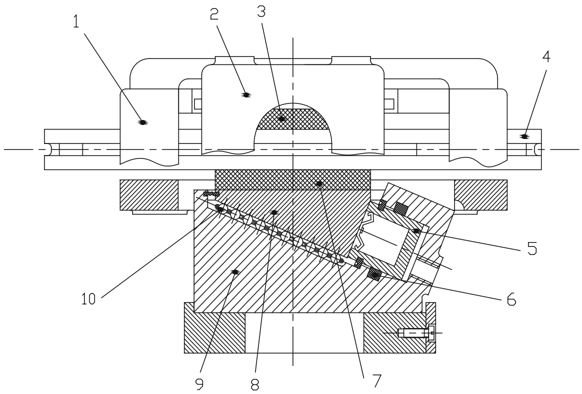


Fig. 2 Specific structure of wedge disc brake. *1*—brake caliper mounting bracket; *2*—brake caliper; *3*, *7*—friction plate; *4*—brake disc; *5*—brake cylinder; *6*—friction limit ring; *8*—wedge block; *9*—wedge mechanism; *10*—rollers

4 Structure

The specific structure of the wedge disc brake in this paper is shown in Fig. 2. It is designed based on traditional hydraulic disc brake, with only brake cylinder direction altered. The wedge angle is an important parameter which affects the self-reinforcement and self-lock. Several rollers are used to reduce the friction between the wedge block and calliper to prevent self-lock.

5 Performance Analysis

Based on the force analysis as shown in Fig. 3, it is easy to get the equation of force equilibrium:

x $F\cos\alpha + F_{f1} = F_{f2}\cos\alpha + N_2\sin\alpha$;

y $F\sin\alpha + N_2\cos\alpha = F_{f2}\sin\alpha + N_1$. *And:* $F_{f1} = \mu_1 N_1$, $F_{f2} = \mu_2 N_2$;

F_{f1} Friction between wedge block and brake disc;

F_{f2} Friction between wedge block and calliper;

μ_1 Frictional factor between wedge block and brake disc;

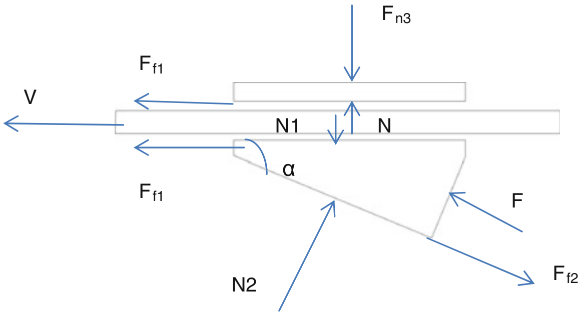


Fig. 3 Force analysis on an simple wedge disc brake working status

μ_2	Frictional factor between wedge block and wedge mechanism;
F	Thrust from wheel cylinder to wedge block;
α	wedge angle of wedge block;
N_1	Pressure between wedge block and brake disc;
N_2	Pressure between wedge block and calliper;

It can be solved from above equations that:

$$F_{f1} = \frac{F\mu_1}{\cos\alpha(\tan\alpha - \mu_1) + \mu_2\cos\alpha + \mu_1\mu_2\sin\alpha}$$

Because of the adding of rollers between wedge block and calliper, in this equation, the value area of μ_2 is 0.0008–0.0012. Since μ_2 is too small to effect the result of the equation, "$\mu_2\cos\alpha + \mu_1\mu_2\sin\alpha$" is approximately equal to 0. As α is comparative smaller, $\cos\alpha$ is approximately equal to 1. So the equation above can be simplified as follows:

$$F_{f1} = \frac{F\mu_1}{\tan\alpha - \mu_1}$$

So it can be seen that, the equivalent brake efficiency factor of the wedge disc brake is:

$$K'ef = \frac{2F_{f1}}{F} = \frac{2\mu_1}{\tan\alpha - \mu_1}$$

As we know, the brake efficiency factor of conventional disc brake is $K_{ef} = 2\mu_1$, so in the condition of the same actuator force, the brake torque generated by wedge disc brake is $1/(\tan\alpha - \mu_1)$ times bigger. In the present paper, this is named as reinforcement factor. The relationship curve between reinforcement factor and wedge angle is shown in Fig. 4. In Fig. 4 it can be seen that when wedge angle equals to $\arctan\mu 1$, the reinforcement factor changes suddenly, even changes to negative. At this point, wedge brake may work in bad condition such as getting lock. So it is required that $\alpha > \arctan\mu_1$. It also can be seen that if a bigger reinforcement factor is needed, the value of α should be close to $\arctan\mu_1$.

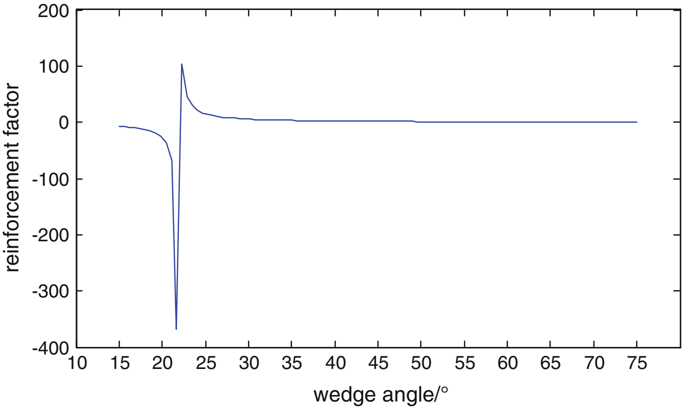
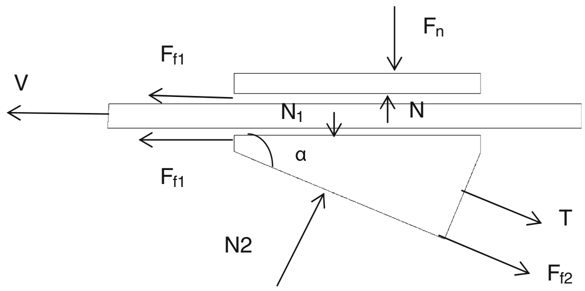


Fig. 4 Relationship curve between reinforcement factor and wedge angle

Fig. 5 Force analysis when wedge brake stops braking



Aiming at guarantee that the wedge brake can stop braking when the actuator force disappears, the condition when actuator force disappears should be taken into account. The force analysis in this condition is shown in Fig. 5. It is assumed that a return force T is required to pull back the wedge block, and at this moment the elastic deformation of wedge block keeps the same as that when wedge brake is braking, in other words, the pressure N_1 and N_2 do not change.

It can be got that:

$$T\cos\alpha + N_2\sin\alpha = \mu_1 N_1 + \mu_2 N_2\cos\alpha;$$
$$T\sin\alpha + N_1 = N_2\cos\alpha + \mu_2 N_2\sin\alpha.$$

It can be solved from equations above that:

$$T = N_1\cos\alpha(\mu_1 + \mu_2 - \tan\alpha).$$

It is already known that μ_2 is extremely small and μ_1 is very close to $\tan\alpha$. So the return force T is extremely small too. Therefore T can be ignored in the theoretical calculation.

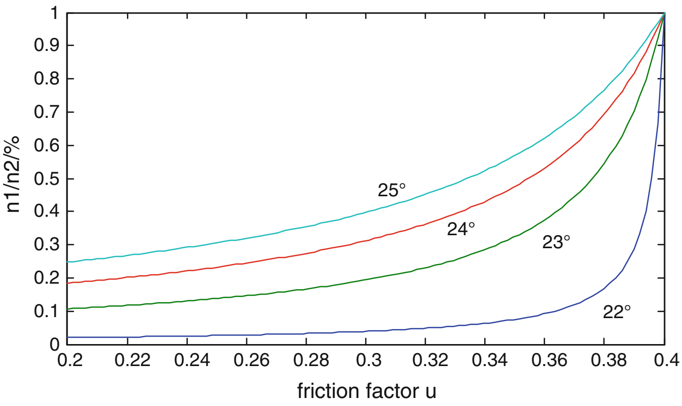


Fig. 6 Thermal decay tendency

In the working process of brake, big braking force may result in thermal decay and wearing happens all the times, and all these conditions lead to the change of friction factor. So it is necessary to study on the change of brake efficiency factor when friction factor changes. When all the components of the wedge brake are in good working condition, reinforcement factor is $n_1 = 1/(\tan\alpha - \mu_1)$. while after a long time of working or when the thermal decay happens, the friction factor changes to μ, reinforcement factor changes to $n = 1/(\tan\alpha - \mu)$. So n/n_1 can reflect the degree of thermal decay, the value is bigger, the thermal decay is slighter. Figure 6 shows relationship curve between n/n_1 and μ when α changes.

It can be seen from Fig. 6 that the value of α is smaller, the rate of change of n/n_1 is bigger, that is to say, a big reinforcement factor may cause a notable thermal decay. To prevent the wedge brake from losing brake capacity when thermal decay happens, the wedge angle α should be appropriately bigger.

6 Simulation

This present paper utilizes co-simulation of AMESim and Simulink to verify the performance of this novel hydraulic wedge disc brake. The AMESim vehicle dynamic model is built in AMESim (shown in Fig. 7) the conventional brake model is replaced by wedge brake model which is established in the Simulink (shown in Fig. 8).

In this model, the wedge angle is chosen as 23°. μ_1 is 0.1, μ_2 is 0.0001, so it can be calculated that the reinforcement factor is 3.3373. Given the same target velocity, two kinds of disc brake will generate the brake torque, then the input hydraulic pressure of the conventional disc brake should be 3.3373 times of that of wedge disc brake.

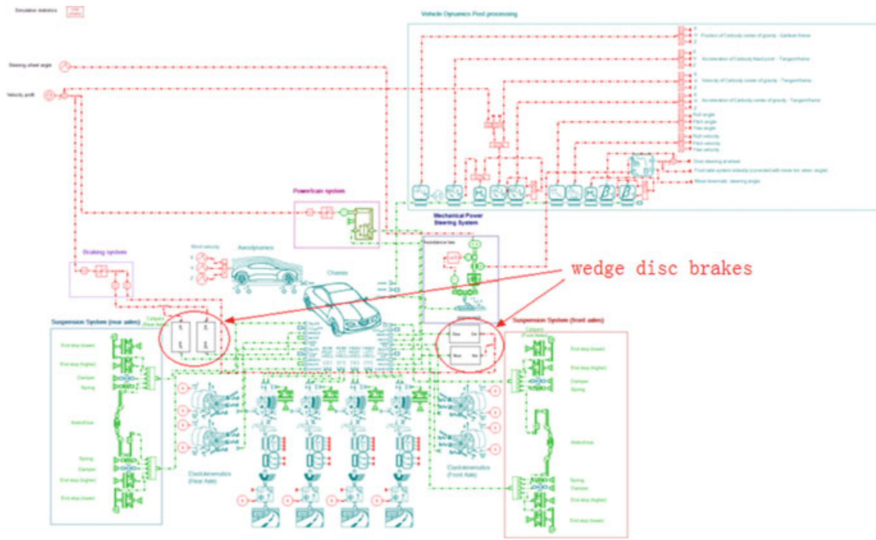


Fig. 7 Vehicle dynamic brake with wedge disc brake

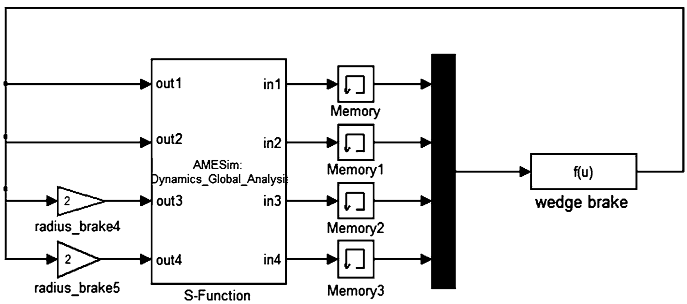


Fig. 8 Mathematical model of wedge disc brake

The result of simulation is shown in Figs. 9 and 10. Figure 9 shows the speeds of the same vehicle mounted different disc brake. Figure 10 shows the generated brake torque and applied brake press force. It is easy to see from the simulation results that two vehicles runs at the same velocity, two kinds of disc brake generate almost the same brake torque, but the input pressure of the wedge disc brake is much smaller, about 1/3 of that of conventional disc brake. These simulation results match the theoretical calculation.

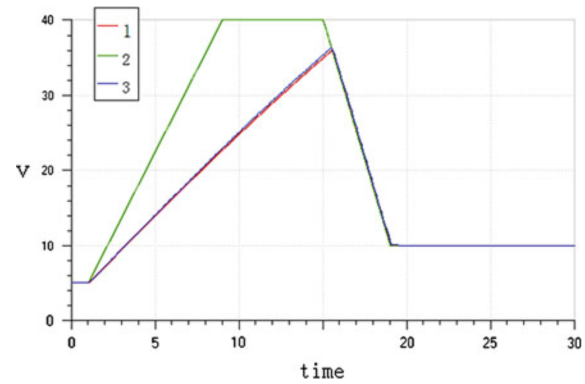


Fig. 9 Speed of the vehicle. *1*—real speed of the vehicle with wedge disc brake; *2*—target speed; *3*—real speed of the vehicle with conventional disc brake

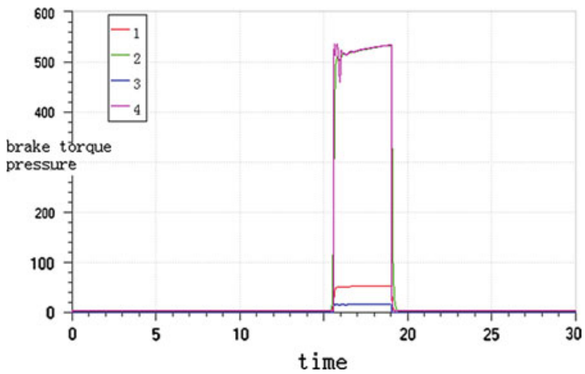


Fig. 10 Brake torque and pressure. *1*—input hydraulic pressure of conventional disc brake; *2*—brake torque of conventional disc brake; *3*—input hydraulic pressure of wedge disc brake; *4*—brake torque of wedge disc brake

7 Conclusion and Out Look

A novel low-cost hydraulic wedge disc brake is presented in this paper. Its mechanism and design process is introduced. As the most important structure parameter, wedge angle is calculated according to the its relationship with self-reinforcement, self-lock performance and thermal decay. Through theoretical analysis and computer simulation, it is proved that this novel wedge disc brake has a better self-reinforcement performance than the conventional disc brake. Given the same hydraulic pressure, the wedge disc brake can generate a bigger brake torque. While if the same brake torque is wanted, the wedge disc brake needs much smaller hydraulic pressure. Furthermore, prototype verification test is needed to conduct in near future.

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