Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Design and analysis of the hybrid excitation rail eddy brake system of high-speed trains*

Ji-en MA[1], Bin ZHANG[†‡2], Xiao-yan HUANG[1], You-tong FANG[1], Wen-ping CAO[3]
(*[1]College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China*)
(*[2]The Key State Lab of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*)
(*[3]Newcastle University, Newcastle upon Type, NE1 7RU, UK*)
[†]E-mail: zbzju@163.com

Received Sept. 23, 2011; Revision accepted Sept. 24, 2011; Crosschecked Sept. 24, 2011

Abstract: Compared to the current eddy braking patterns using a single magnetic source, hybrid excitation rail eddy brakes have many advantages, such as controllability, energy saving, and various operating models. Considering the large braking power consumption of the high-speed train, a hybrid excitation rail eddy brake system, which is based on the principle of electromagnetic field, is proposed to fulfill the needs of safety and reliability. Then the working processes of the mechanical lifting system and electromagnetic system are demonstrated. With the electromagnetic system analyzed using the finite element method, the factors such as speed, air gap, and exciting current have influences on the braking force and attractive force. At last, the structure optimization of the brake system is discussed.

Key words: High-speed train, Hybrid excitation, Eddy brake, Finite element method
doi:10.1631/jzus.A11GT002 **Document code:** A **CLC number:** U266.2

1 Introduction

The braking system, which is one of the most important technologies of high-speed trains, is very crucial to operation reliance and safety. The braking methods are mainly the regenerative braking system and disc braking system, which are widely used in high-speed trains under 300 km/h (Zhang, 2009). However, the velocities of present high-speed trains are over 350 km/h. Thus, it is very important to explore new braking methods that can be applied to these high-speed trains. The eddy brake can be used when the train velocities are very large. It can not only reduce energy consumption, but also produce economic benefits and improve technical features (Dietrich *et al.*, 2001).

The existing eddy brake system has some limitations. First of all, down pass system through pressure relief can ensure that the air cylinder acts when the air system is compromised. However, when the electric circuit is compromised, the loss of excitation can lead to loss of braking force. As a result, ICE3 (Inter City Express 3) installs a lot of batteries as back-up electrical sources, which adds to the weight of the train (Bottauscio *et al.*, 2006; Guo *et al.*, 2006). Secondly, if the electrical sources are switched off when the train stops, the eddy brake system cannot operate. In addition, the power of excitation and heat is too large (Graber, 2003; Kunz, 2005). This paper deals with a hybrid excitation rail eddy brake system, which can help deal with the limitations of steering malfunction and parking brake.

2 Theory of eddy brake system

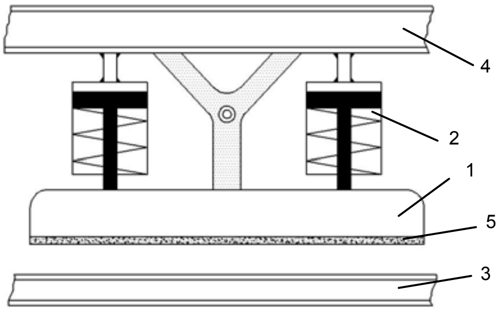
The structure of the hybrid excitation rail eddy brake system is shown in Fig. 1. This system is

---

[‡] Corresponding author

[*] Project supported by the National Natural Science Foundation of China (Nos. 50877070 and 51105331), and the Special Financial Grant from the China Postdoctoral Science Foundation (Nos. 201104720 and 201104721)

mainly composed of an air lift system, braking magnetic system, and braking auxiliaries. When the train is travelling at a high speed, the hybrid excitation rail eddy brake system causes an eddy brake through the excitation of the permanent magnet. At the same time, the exciting electricity in the exciting coils can be modified in order to assist the positive motivation, which can ensure that the train's braking process can be dynamically adjusted. When the train's speed reaches the threshold, which means that the condition of the friction braking is satisfied, the electronic magnetic system will contact the rail. The exciting electricity is reduced or disappears. The brake system presses the wearing plate on the rail through the attractive force of the permanent magnets. The energy of motion is changed into the energy of heat through the friction force.



1: brake magnet; 2: lifting air cylinder; 3: steel rail; 4: side beam; 5: wearing plate

Fig. 1 Structure of the hybrid excitation rail eddy brake system

The braking magnetic system includes the permanent magnets and the exciting coils (Fig. 2). When the high-speed train is braked, it produces the eddy brake through the permanent magnets. At the same time, we can input the auxiliary exciting electricity in the exciting coils so as to produce the positive excitation, and at the same time to keep the same negative acceleration, which allows the high-speed train to be controlled dynamically. When the train's speed reaches the threshold, which means that the condition of friction braking is satisfied, the auxiliary electricity in the exciting coils will be closed. Meanwhile, the attractive force of the permanent magnets and the wearing plates can help produce the friction brake and then realize the energy-saving effect in the braking process. When the brake system resumes to the relief state, the auxiliary electricity in the exciting coils produces a negative excitation, which can offset the attractive force of the permanent magnets. As a result, we can lift the brake magnetic system through only a small force, and the relief status can resume more quickly.

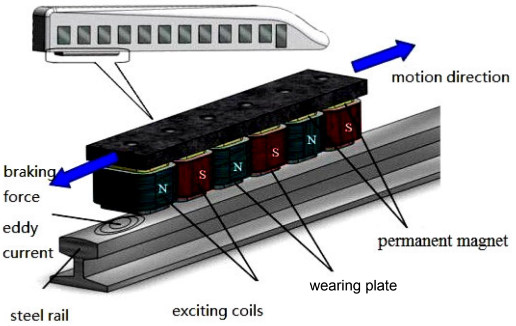


Fig. 2 Principle diagram of the electronic magnetic system of the brake system

The force of the electronic magnetic system is

$$F_k - mg - PS - F_{\mathrm{A}} - f = 0, \tag{1}$$

where F_k is the elastic force of the built-in springs, mg is the gravity of the magnetic system, P is the total pressure of the pistons, S is the cross-sectional area of the pistons, F_{A} is the attractive of the magnetic system, and f is the friction of the pistons.

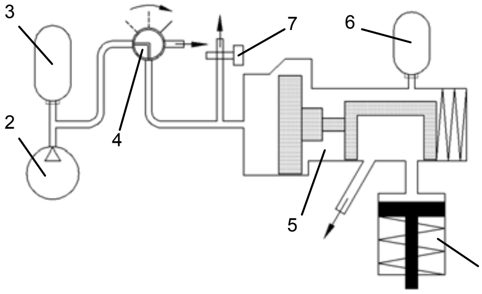
When the brake system is relieved, the electricity in the exciting coils produces reverse motivation, which can offset the attractive force of the permanent magnets. As a result, the lift system can use a very small force to hoist the magnetic system, which can help the recovery of the brake relief process. The two sub-systems of the brake system are shown in detail.

2.1 Lift system of the brake system

The hybrid excitation rail eddy brake system controls the up and down of the brake exciting system through the air cylinder, which makes the brake exciting system and the wearing plate reach or keep off the rail, and thus, the working status of the brake exciting system is determined.

2.1.1 Status of relief

When the brake system is relieved, the control valve is squeezed so that the up cavity of the lift air cylinder can be connected with the air. The lift air cylinder is hoisted via the built-in springs in order that the brake exciting system can maintain a certain distance off the rail. Fig. 3 shows the lift system of relief.

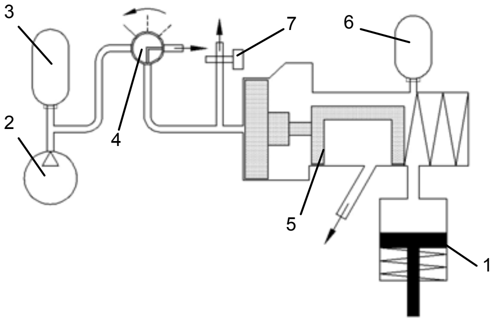


1: lifting air cylinder; 2: air compressor; 3: main air cylinder; 4: brake valve; 5: control valve; 6: auxiliary air cylinder; 7: urgent control valve

Fig. 3 Lift system of relief

2.1.2 Status of brake

When the brake system is broken, the left cavity of the control valve releases the pressure, and the control valve moves left through the built-in springs. The up cavity of the lift air cylinder is connected with the auxiliary air cylinder, and moves down via the pressure of the air in the auxiliary air cylinder, which brings the brake exciting system close to the rail (Fig. 4).



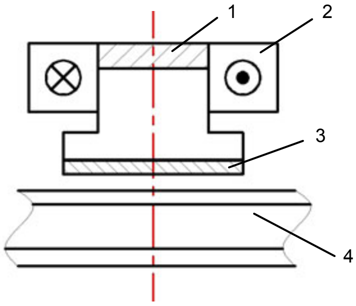
1: lifting air cylinder; 2: air compressor; 3: main air cylinder; 4: brake valve; 5: control valve; 6: auxiliary air cylinder; 7: urgent control valve

Fig. 4 Lift system of brake

2.2 Brake exciting system

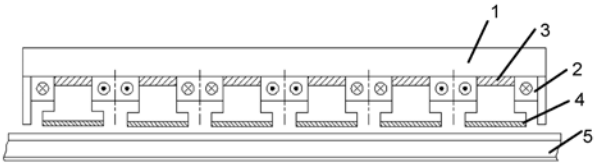
The magnetic pole of the brake system includes the permanent magnet and the exciting coils, whose structure is indicated in Fig. 5.

In principle, the hybrid excitation rail eddy brake system can be regarded as a kind of special induction linear motor whose magnetic field is non-sin and its primary is short. This motor includes the primary yoke, the primary exciting coils, the permanent magnets, the wearing plates, and the secondary steel rail. The primary exciting coils use DC. Each of the permanent magnets is set between the magnetic pole and the magnetic yoke. The secondary is the steel rail. The whole diagram of the brake magnetic system is shown in Fig. 6.



1: permanent magnet; 2: exciting coils; 3: wearing plate; 4: steel rail

Fig. 5 Brake exciting system



1: magnet yoke; 2: exciting coils; 3: permanent magnet; 4: wearing plate; 5: steel rail

Fig. 6 Whole diagram of the brake magnetic system

The air magnetic field between the brake system and the steel rail is produced by both the permanent magnet and the exciting coils. When the train travels, the air magnetic field is mainly produced by the permanent magnet, and the DC exciting coils only supply a small part. As a result, it can be modified by the electricity, which helps control the magnetic field and the braking force.

2.3 Main parameters of the brake system

In (Lu and Ye, 2005), the structural design of the hybrid excitation linear motor provides a model of the eddy brake and simulates this model (Table 1).

Table 1 Parameters of hybrid excitation rail eddy brake system

Parameter	Value
Pole number	6
Pole pitch (mm)	45
Measure of the permanent magnet (length×thickness) (mm)	20×4
Model of the permanent magnet	N35SH
Thickness of magnetic yoke (mm)	32
Length of the wearing plate (mm)	35
Thickness of the wearing plate (mm)	3
Turn number of primary exciting coils	395

In the hybrid excitation rail eddy brake system, the magnetic field that is produced by the permanent magnet is the main part of the air magnetic field. The air magnetic field is affected by both the eddy current magnetic field and the electrical exciting magnetic field. As a result, the largest degaussing working point must be paid attention to when the brake system is designed in order to prevent irreversible degaussing. Note that too strong of an electrical exciting magnetic field can lead to an over-saturation of the magnetic circuit (Graber, 2003). The permanent magnet in this study is NdFeB of N35SH. If the working temperature is assumed to be 75 °C:

$$B_{\mathrm{r}} = \left(1 + (t-20)\frac{\alpha_{B_{\mathrm{r}}}}{100}\right) B_{\mathrm{r}20}, \tag{2}$$

where the residual flux density B_{r} in the working temperature is 1.13 T. $B_{\mathrm{r}20}$ is the residual flux density when the temperature is 20 °C, t is the temperature, $\alpha_{B\mathrm{r}}$ is the irreversible conversion coefficient of the residual flux density, and it is often $-0.0012\ \mathrm{K}^{-1}$.

The coercive force of the permanent magnet in this temperature is often H_{c}=847 138 A/m.

The relative permeability of the degaussing curve is

$$\mu = \frac{B_{\mathrm{r}20}}{\mu_0 H_{\mathrm{c}20}} = 1.062,\ \ \mu_0 = 4\pi \times 10^{-7}. \tag{3}$$

In the above model, the magnetization of the permanent magnet is along the y axis, and its length is 4 mm. As a result, the calculating magneto motive force is

$$F_{\mathrm{c}} = H_{\mathrm{c}} h_{\mathrm{pm}} = 3388.552\ \mathrm{A}. \tag{4}$$

where F_{c} is the magneto motive force, and h_{pm} is the length of the permanent magnet along the y axis.

Because too large of an exciting electricity can lead to the over-saturation of the magnetic field in the motor, the positive exciting electricity should not be too large. If the exciting electricity is reversed, the electrical exciting can cause degaussing of the permanent magnet. As a result, the absolute value of the electrical exciting magneto motive force should be smaller than the calculating magneto motive force of the permanent magnet. According to calculations, when the exciting electricity is lower than 4.2 A, the magneto motive force produced by the exciting coils is always smaller than the calculated magneto motive force of the permanent magnet. As a result, the electrical exciting coils will not generate irreversible degaussing.

3 Simulation

3.1 Creating finite element method (FEM) model

The hypotheses are as follows (Gay and Ehsani, 2006):

1. In the studied electronic magnetic field, the magnetic field only has two elements, one is in the x direction, the other is in the y direction. In addition, both the vectors of the electricity density and magnetic potential only have element of the z direction.

2. Neglect the effect of the temperature on the iron's conductivity; that is to say, its conductivity is equal to zero.

3. Neglect the magnetic field outside the motor's shell. As a result, the outside surface of both the primary and secondary can be regarded as the equi-magnetic potential surface with the zero vector.

4. The electricity density inside the conductors is uniformly distributed, and there is no free charge inside the conductors.

According to the above-mentioned hypotheses and the brake system model, we can create a 2D FEM model using the ANSYS software (Fig. 7).

In this model, the brake system has no relative motion to the steel rail, and the gap between them is 2 mm. In addition, there is no electricity in the exciting coils. We can change this model into grids (Fig. 8).

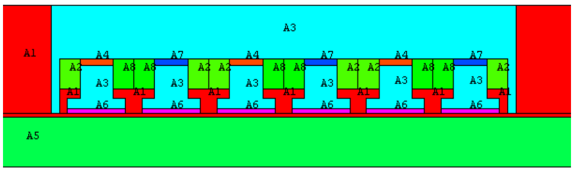


Fig. 7 FEM analyzing model of the brake system

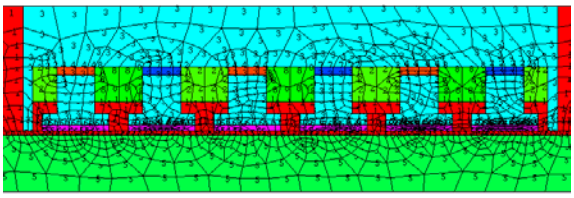


Fig. 8 Grids of the FEM model

When we have loaded the model, we can use the solution to obtain the magnetic field intensity distribution graph, and then use the postprocessor to gain the magnetic induction intensity, which is indicated in Fig. 9. In this graph, the magnetic induction intensity is larger where the color is deeper.

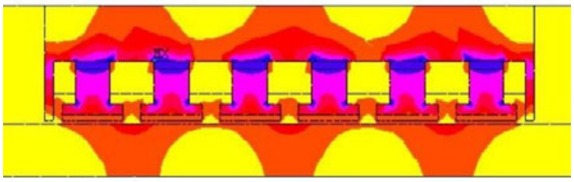


Fig. 9 Magnetic induction intensity diagram when the speed is zero and the gap is 2 mm

In the same way, we can obtain the distribution graph of the magnetic lines of force (Fig. 10).

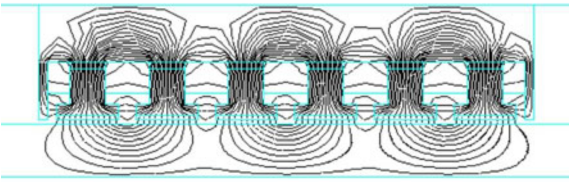


Fig. 10 Distribution of the magnetic lines of force when the speed is zero and the gap is 2 mm

The above-mentioned is on condition that the bake system has no relative motion to the steel rail. However, what this paper deals with is the magnetic field when the brake system is static, but the train is travelling at varying speed. The direction of the speed is horizontal-right and the gap is 2 mm.

From Fig. 11, we can safely come to the conclusion that the faster the speed is, the more seriously the gap magnetic field is distorted.

3.2 Effects of gap

The factors such as air gap and exciting electricity both can affect the braking force of the brake system when independent excitation is used (Tang and Ye, 2006; Cai *et al.*, 2007). To analyze the function of the hybrid excitation rail eddy brake system, one constructs the model, and then analyzes it both when there is exciting and when there is no exciting.

3.2.1 When there is no exciting

When there is no exciting, the hybrid excitation rail eddy brake system is changed into the eddy brake system when only the permanent magnet can excite. Simulating the eddy brake system when the value of the air gap varies, one can obtain the curve of the braking force with the velocity (Fig. 12). We can see that when the air gap is smaller, the braking force is larger, and the variation of the braking force is larger. However, when the velocity magnifies, this variation is smaller, which shows that the brake system can supply a steady force whose variation is rather small.

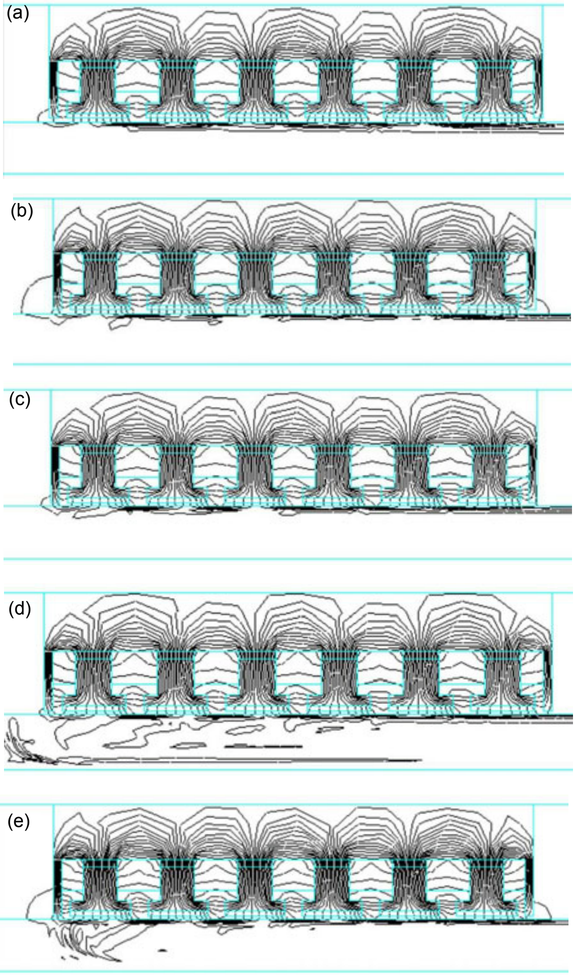


Fig. 11 Magnetic lines of force when the speed is (a) 100 km/h; (b) 200 km/h; (c) 300 km/h; (d) 400 km/h; and (e) 500 km/h

Because the attractive force has an effect on the lift system, the simulation can obtain the relation of the attractive force and the velocity (Fig. 13). When the air gap is thicker than 6 mm, both the braking force and the attractive force have little variation when the velocity varies. When the air gap is thicker, this kind of variation is smaller and the force is constant.

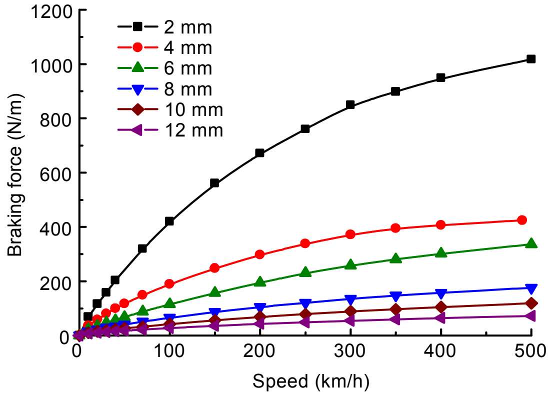


Fig. 12 Effects of different air gaps on the braking force

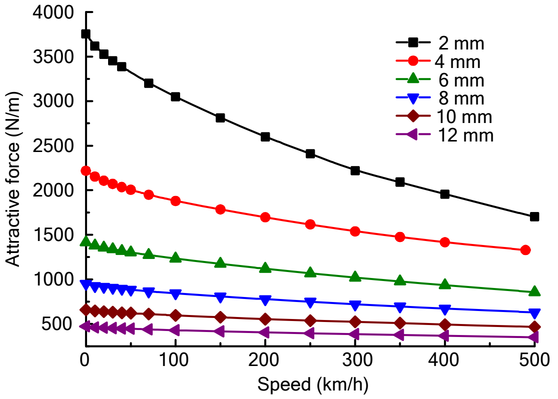


Fig. 13 Effects of different air gaps on the attractive force

3.2.2 When there is exciting

The DC exciting coils of the eddy brake system have 395 turns. When the electricity is 2 A, the relationship of the braking force and the velocity with different air gaps as shown in Fig. 14.

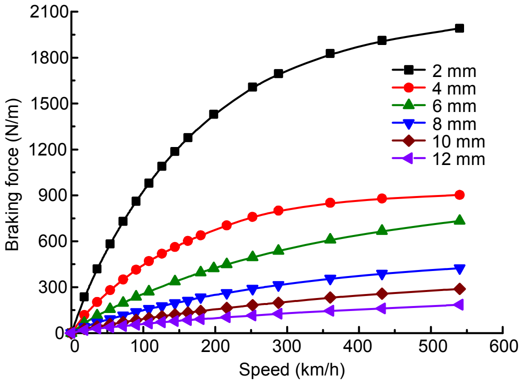


Fig. 14 Effects of different air gaps on the braking force in hybrid exciting

In the case of hybrid exciting, the variation range of the braking force is much larger than that when only the permanent magnets excite, which leads to the braking force being raised so that the brake distance can be reduced.

Of course, the variation range of the attractive force in hybrid exciting also magnifies a lot, which makes it easier for the lift system to raise or put down the brake system more easily. In addition, the braking force or the attractive force can be easily controlled through the regulation of the exiting electricity, such that the braking force is dynamically controlled and the braking force is kept constant. Fig. 15 shows the relationship of the attractive force and the velocity in hybrid exciting.

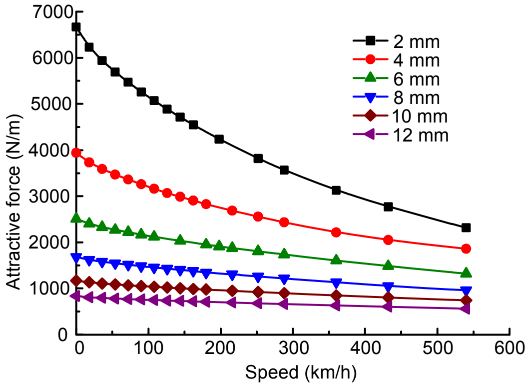


Fig. 15 Effects of different air gaps on the attractive force in hybrid exciting

3.3 Effects of electricity

We modify the exciting electricity so that we can control the value of the attractive force or braking force, and dynamically control the braking force or keep it constant. When the exciting electricity is positive, it will enhance the magnetic field; but when it is negative, it will decrease the magnetic field, so that we can lift the electronic magnetic system with a smaller force. As a result, we can examine how the braking force and attractive force of the brake system vary with the speed in different electricity. We suppose that the gap is 2 mm.

From Fig. 16, we can see that the smaller the electricity, the smaller the braking force. When the electricity is negative, the braking force reduces very quickly at the same speed, while the varying amplitude of the braking force is smaller and smaller when at different speeds. The reason is that when the electricity is negative, it will produce a negative magnetic field that is opposite to the permanent magnetic field. As a result, the total gap magnetic field decreases greatly, and then the braking force reduces very quickly. Likewise, the attractive force is smaller when the electricity is smaller.

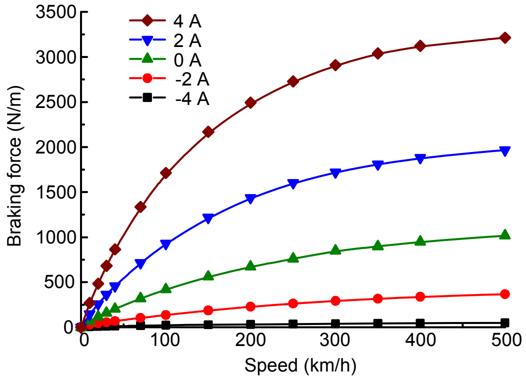


Fig. 16 Effects of different electricity on the braking force with the gap of 2 mm

From Fig. 17, we can see that when the electricity is negative, the attractive force decreases quite quickly. When the electricity is −4 A, it does not bring irreversible demagnetization of the permanent magnets, and it reduces the magnetic field, decreasing the attractive force considerably. As a result, the air lifting system uses little force to lift the magnetic system through the built-in springs.

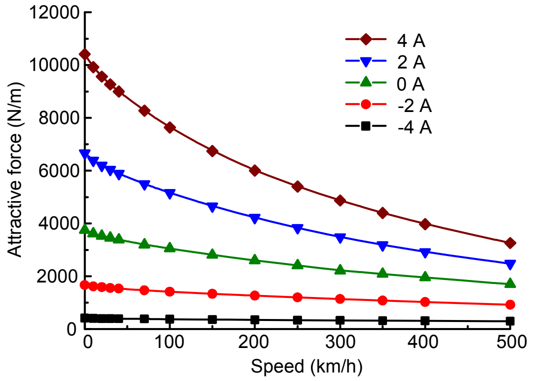


Fig. 17 Effects of different electricity on the attractive force with the gap of 2 mm

From the above analyses, we conclude that both the gap and the electricity have obvious effects on the performance of the braking system, and that the smaller the gap, the larger the braking force and the attractive force. In addition, the larger the electricity, the bigger the braking force and attractive force. When the speed increases, the braking force also increases, but the attractive force decreases. The larger the speed, the smaller the variations of the attractive force and baking force.

4 Optimization

The braking force is related with the magnetic induction density and its distribution. As a result, to choose the rational magnetic materials and to optimize the structure of the magnetic road and the shape of the permanent magnets both can improve the energy density of the braking system, such that the braking performances can be dynamically modified.

Form the above simulation analyses, we can see that the magnetic road of the original magnetic system needs further optimization. Because the magnetic leakage in the teeth of the magnetic poles is quite large, and that in the partition besides the two ends of the brake system is also large, the exciting magnetic field is coupled with the rail eddy current magnetic field. We try to add a magnetic shield material, and remove the partitions besides the two ends of the brake system, the optimized structure of the brake system is shown in Fig. 18.

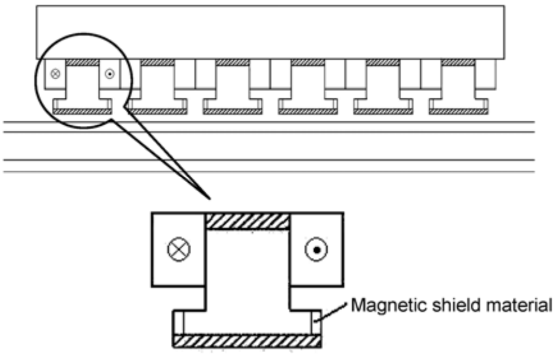


Fig. 18 Structure of the brake system after being optimized

When there is no electricity in the exciting coils and the gap is 2 mm, we simulate the brake system and then obtain the magnetic force lines distribution graph (Fig. 19). After optimization, the magnetic leakage is reduced, and at the same time the coupling between the magnetic system and the steel rail is also improved, such that the forces of the brake system and the steel rail are enhanced. As a result, it is beneficial to the brake process of the high-speed train.

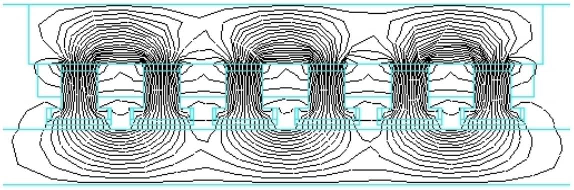


Fig. 19 Magnetic force lines distribution of the brake system after optimization

Likewise, the magnetic induction density of the brake system changes is shown in Fig. 20.

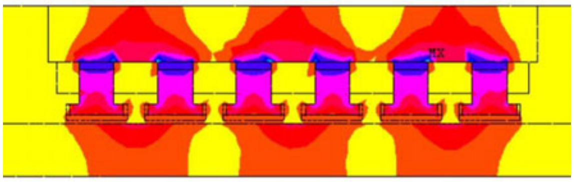


Fig. 20 Magnetic induction density of the brake system after optimization

From Figs. 19 and 20, we can conclude that, after structure optimization of the brake system, both of the two kinds of forces will be affected. Supposing that the gap is 2 mm, and there is no electricity, we simulate the brake system.

It is obvious that the optimization of the structure improves the gap magnetic field between the brake system and the steel rail; that is to say, the coupling of the exciting magnetic field with the eddy current magnetic field is enhanced, which leads to the addition of the braking force. As a result, we can say that the optimization of the magnetic road reaches its expected effects. Likewise, we can compare the variation of the attractive force. From Figs. 21 and 22, we can see that the optimization of the magnetic road also reaches its expected effects.

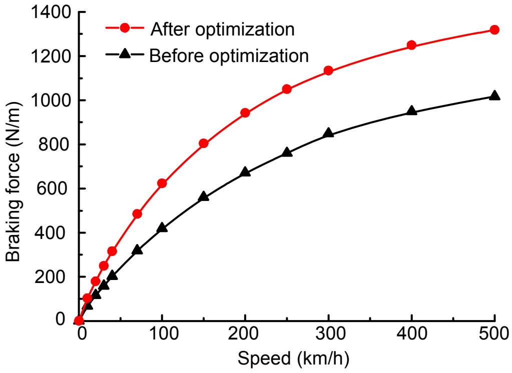


Fig. 21 Comparison between the braking force after and before optimization

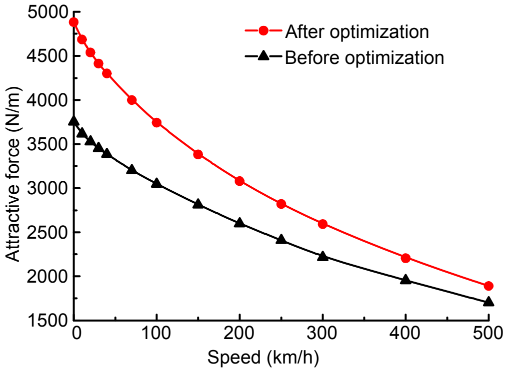


Fig. 22 Comparison between the attractive force after and before optimization

5 Conclusions

The hybrid excitation rail eddy brake system is a kind of non-adhesion brake system. As a result, it is not limited by the adhesion conditions and compared to the adhesion system. It has the advantages such as non-abrasion and better brake effects. In addition, compared to the single exciting eddy brake system, on one hand, it can be controlled well, because it can modify the exciting current to control the variation of the braking force. On the other hand, it does not consume a lot of electricity energy.

This system not only realizes the safety of the malfunction steering through the air lift system, but also uses the exciting electricity and reduces the attractive force of the permanent magnet to make the wearing plate touch the steel rail easily. As a result, it integrates the advantages of both the rail eddy brake and the magnetic rail brake. It not only saves a lot of energy, but also reduces the loss of the motive energy.

References

Bottauscio, O., Chiampi, M., Manzin, A., 2006. Element-free Galerkin method in eddy current problems with ferromagnetic media. *IEEE Transactions on Magnetics*, **42**(5):1577-1584. [doi:10.1109/TMAG.2005.863932]

Cai, J.L., Liu, Z., Zhang, Z.C., 2007. Analysis and design of electrical magnetic eddy brake. *Electromechanical Engineering*, **28**(8):84-86 (in Chinese).

Dietrich, A.B., Chabu, I.E., Cardoso, J.R., 2001. Eddy-current brake analysis using analytic and FEM calculations. *IEEE Transaction on Magnetics*, **37**(5):454-461.

Gay, S.E., Ehsani, M., 2006. Parametric analysis of eddy current brake performance by 3-D finite element analysis. *IEEE Transactions on Magnetics*, **42**(2):319-328.

[doi:10.1109/TMAG.2005.860782]

Graber, J., 2003. The linear eddy current brake system of ICE3 trains. *Technology of Trains Abroad*, **5**:1-6 (in Chinese).

Guo, Q.Y., Hu, J.T., Hu, X.Y., 2006. Features research of linear eddy brake in high-speed trains. *Journal of Tongji University (Natural Science)*, **34**(6):804-807 (in Chinese).

Kunz, M., 2005. The linear eddy brake of ICE3-technical views and operating experience. *Current Transformer and Electrical Haul*, **2**:4-8 (in Chinese).

Lu, Q.F., Ye, Y.Y., 2005. Magnetic field and thrust force of the hybrid exciting linear synchronous machine. *China Society for Electrical Engineering*, **25**(10):127-130 (in Chinese).

Tang, Y.C., Ye, Y.Y., 2006. FEM analysis and design of permanent magnetic eddy brake. *Micromotor*, **36**(3):34-36 (in Chinese).

Zhang, S.G., 2009. The Research of the Design Methods of High-Speed Trains. China Rail Publishing House, Beijing (in Chinese).