Research in Modeling and Dynamic Simulation of Linear Eddy Current Braking Force of High-speed Train

X. R. Zhang, Q. Y. Guo, J. Zhang, and M. S. Tong
School of Electronic and Information Engineering, Tongji University, Shanghai 200092, China

Abstract— In this paper, we introduce the principle of high speed train eddy current braking, and establish a complete mathematical model for solving eddy current force definite solution problem. The eddy current braking process is a dynamic process. The air gap distance between the magnetic pole and guide rail induction plate is constantly changing, and the change of air gap and the eddy current brake force are mutually coupled. Obviously, the dynamic coupling process of eddy current braking force with air gap cannot be characterized by static analytical expressions. We propose a method to calculate the dynamic simulation of eddy current braking force considering the change of air gap. First, the finite element method is used to establish the 2-dimensional (2D) model, and then the ANSYS software is applied to simulate the calculation. Finally, the results of eddy current brake force (i.e., horizontal braking force) and the normal force change with speed are obtained. We did the analysis on the simulation results, which were further compared with the experimental data. The reasons of the error were analyzed too. This paper provides a reference for the design of high speed train eddy current device.

1. INTRODUCTION

At present in China, the motor car of high speed multiple units uses the regenerative brake and disc friction brake, while the trailer only uses the disk friction brake. As the braking power of more than 300 km/h level train is very big, the brake disc will be under high heat load. Therefore the design of materials and structure is a challenge. Using eddy current brake can shorten the emergency braking distance and improve the safety of trains. The eddy current brake can also play a role in the normal braking. Using eddy current brake and regenerative brake for high speed scenarios, and using disc friction brake supplement in low speed scenarios, we can greatly reduce the wear of the brake disc and the brake pad.

2. THE PRINCIPLE OF THE LINEAR EDDY CURRENT BRAKING

As shown in Fig. 1, the magnet poles are alternately arranged in accordance with N S maintaining a certain air gap on the conductor. When the exciting coil is energized, the conductor and the electromagnet are not in relative motion ($v = 0$). The main magnetic flux is constant and the magnetic field is symmetric. The suction force is generated between the magnetic and the conductor.

When the electromagnet and the conductor are in relative motion ($v > 0$), the conductor cuts magnetic lines, generating eddy current, deflecting magnetic field lines, thus the tangential component is generated, which is the brake force.

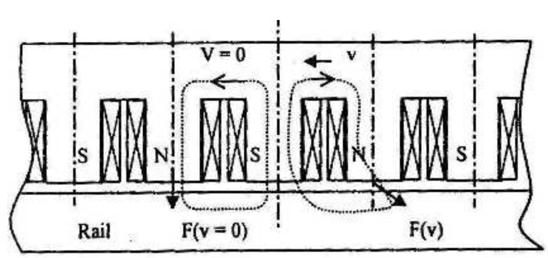

Figure 1: The structural drawing of the eddy current brake.

3. THE MATHEMATICAL EQUATIONS OF LINEAR EDDY CURRENT BRAKE ELECTROMAGNETIC FIELD

For general time-varying electromagnetic fields, Maxwell's equations in differential forms can be written as

$$\begin{cases} \nabla\times\vec{H}=\vec{J}+\dfrac{\partial\vec{D}}{\partial t} \\ \nabla\times\vec{E}=-\dfrac{\partial\vec{B}}{\partial t}+\nabla\times\left(\vec{V}\times\vec{B}\right) \\ \nabla\cdot\vec{B}=0 \\ \nabla\cdot\vec{D}=\rho \end{cases} \quad \text{Among them} \quad \begin{cases} \vec{D}=\varepsilon\vec{E} \\ \vec{B}=\mu\vec{H} \\ \vec{J}=\sigma\vec{E} \end{cases} \tag{1}$$

where ε, μ and σ, are the permittivity, magnetic permeability and electrical resistivity respectively, ρ is the electrical space charge density.

The eddy current field has the following characteristics:

1. We can ignore the effect of displacement current on the magnetic field.

2. After considering the relative motion of the magnetic field, we can think of the magnetic field is time invariant field.

3. There is no free charge in the field, so the electrical space charge density is 0, $\nabla\cdot\vec{D}=0$.

In a pair of magnetic poles, for example, the study area is divided into three parts:

the excitation coil region, including the air gap and iron core, and the magnetic yoke region, as well as the induction plate region.

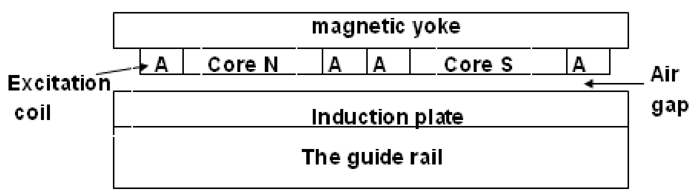

Figure 2: The cross section schematic of eddy current brake.

We divided the above fields into the eddy current region (induction plate) and the non-eddy current region (core, coil and air gap). In the eddy current region we use magnetic vector potential $\vec{A}$ and electric scalar potentials ϕ as unknown functions, and in the non-eddy region we only use $\vec{A}$ as the unknown function. We define

$$\vec{B} = \nabla\times\vec{A} \tag{2}$$

$$\vec{E} = \vec{V}\times\vec{B}-\nabla\phi=\vec{V}\times\nabla\times\vec{A}-\nabla\phi \tag{3}$$

Obviously $\nabla\cdot\vec{B}=0$ and $\nabla\times\vec{E}=\nabla\times(\vec{V}\times\vec{B})$ are established. The ν is reluctivity (without considering the magnetic saturation, can be considered to be constant), and

$$\vec{H}=\nu\vec{B}. \tag{4}$$

In order to ensure the uniqueness of the magnetic vector potential, the Coulomb gauge condition is introduced in the study area

$$\nabla\cdot\vec{A}=0 \tag{5}$$

On the outer boundary we define

$$\vec{n}\times\vec{A}=0 \tag{6}$$

At the same time, a penalty term $-\nabla(\nu\nabla\cdot\vec{A})$ is introduced in the control equations. Due to the addition of this term, the irrotationality of the electric field intensity $\vec{E}$ cannot be hidden, for which we need to list the explicit formulation. Finally the complete equations for electromagnetic field of eddy current brake are obtained.

$$\left.\begin{aligned}\nabla\times\left(\nu\nabla\times\vec{A}\right)-\nabla\left(\nu\nabla\cdot\vec{A}\right)-\sigma\left(\vec{V}\times\nabla\times\vec{A}-\nabla\phi\right)=0\\ \nabla\cdot\left(\sigma\vec{V}\times\nabla\times\vec{A}+\sigma\nabla\phi\right)=0\end{aligned}\right\}\text{ in the eddy current region} \quad (7)$$

$$\nabla\times(\nu\nabla\times\vec{A})-\nabla\left(\nu\nabla\cdot\vec{A}\right)=\vec{J}_s\text{ in the non-eddy current region} \quad (8)$$

$$\left.\begin{aligned}\left(\nabla\times\vec{A}_1\right)\cdot\vec{n}_{12}=\left(\nabla\times\vec{A}_2\right)\cdot\vec{n}_{12}\\ \left(\nu_1\nabla\times\vec{A}_1\right)\times\vec{n}_{12}=\left(\nu_2\nabla\times\vec{A}_2\right)\times\vec{n}_{12}\\ \nu_1\nabla\cdot\vec{A}_1=\nu_2\nabla\cdot\vec{A}_2\\ \vec{n}\cdot\left(\sigma\vec{V}\times\nabla\times\vec{A}+\sigma\nabla\phi\right)=0\end{aligned}\right\}\text{ on the internal boundary} \quad (9)$$

$$\left.\begin{aligned}\left(\nabla\times\vec{A}\right)\cdot\vec{n}=0\\ \vec{n}\times\vec{A}=0\\ \nu\nabla\cdot\vec{A}=0\end{aligned}\right\}\text{ on the outer boundary} \quad (10)$$

4. DYNAMIC SIMULATION OF LINEAR EDDY CURRENT BRAKE FORCE

In the process of eddy current brake, the air gap distance between the magnetic pole and guide rail induction plate is constantly changing. The change of air gap and the eddy current brake force are mutually coupled, and therefore the eddy current braking process is a dynamic process. Considering the change of air gap, we simulate the dynamics of eddy current brake force using the ANSYS software.

Since the eddy current brake pole is symmetric in the direction of the rail height direction, we established a two-dimensional model to calculate the eddy current field. The parameters of the Maglev Train TR08 are computed by using our program. Eddy current brake force (horizontal brake force) was obtained from the power of the eddy current loss and speed as

$$\overrightarrow{F}=\frac{P}{\overrightarrow{V}} \quad (11)$$

Normal force was calculated by Maxwell stress method

$$\vec{F}=\oint\!\!\!\oint_S\left[\frac{1}{\mu_0}\left(\vec{n}\cdot\vec{B}\right)\vec{B}-\frac{1}{2\mu_0}B^2\cdot\vec{n}\right]ds \quad (12)$$

5. THE SIMULATION RESULTS

By calculation, we obtained 7×21 sets of data, excitation current varying from 25 A to 55 A, the speed from 100 to 0 m/s (respectively 5 A, 5 m/s as a step). Fig. 3 depicts the eddy current brake force (horizontal brake force) and the normal force changes versus the speed (with the excitation current set to be 45 A).

From Fig. 3, we can see that the eddy current brake force increases rapidly along with the speed in the $0\sim50$ km/h speed region, while in the $50\sim100$ km/h region the brake force changes very little. It roughly reaches a maximum value at 80 km/h. Further more we observe that the normal force is of great value in the low speed region. This force can make the wear plate against the rail and produce the friction braking force. It can supplement the deficiency of the eddy current brake force in the low speed region. With the increasing of speed, the normal force decreases and is negligible in high speed region.

Our experimental data is shown in Fig. 4, where eddy current brake test bench is adopted.

Comparison of Fig. 3 and Fig. 4, we find that the eddy current brake force calculated theoretically is consistent with the actual experimental values, although there is some error in the numerical value. The errors existing in the numerical calculation are caused by the following two reasons.

1.When we built the mathematical model, the boundary conditions were calculated approximately.

2. The air gap of the eddy current brake bench adopted in experiments involves certain errors.

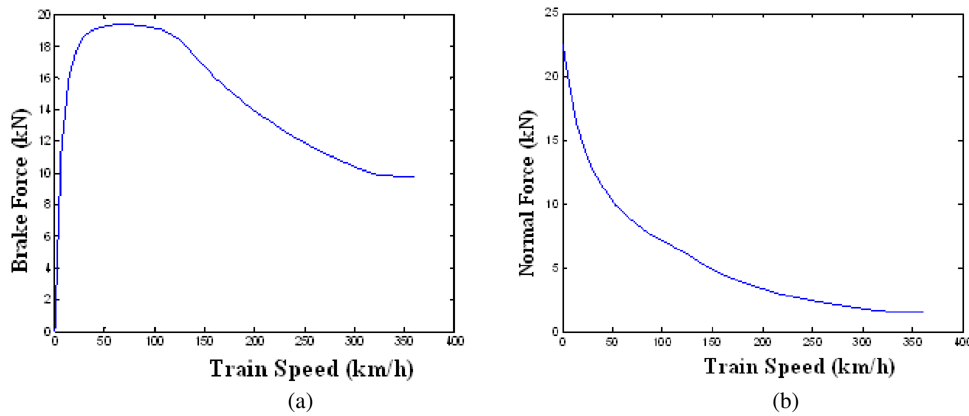

Figure 3: Horizontal brake force, normal force varies with speed (excitation current 45 A).

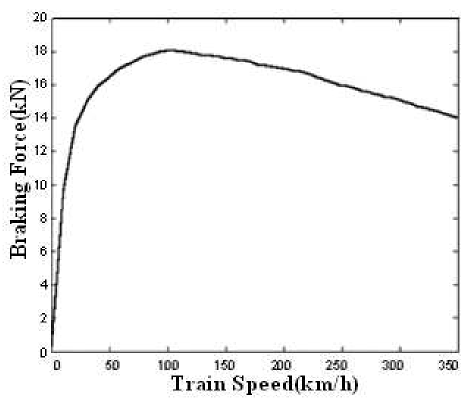

Figure 4: The test results of eddy current brake force.

6. CONCLUSION

In this paper, we proposed a method to calculate the dynamic simulation of eddy current braking force by taking into account the change of air gap. The results of eddy current brake force (i.e., horizontal braking force) and the normal force change with speed are obtained. The simulation results were observed to be consistent with the experimental data. This paper provides a reference for the design of high speed train eddy current devices.

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