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A Novel Approach to the Calculation of High-Speed Maglev Traction Force

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Abstract

The method is not affected by changes in the suspension gap of the train and avoids the deviation in traction force calculations caused by changes in the suspension gap. The accuracy of the method is verified using existing train operation data and related research results.

Keywords: ems maglev, traction force calculation, suspension control, traction control, resistance, linear synchronous motor.

1 Introduction

The EMS high-speed Maglev train represents an advanced form of transportation technology. Compared with the traditional high-speed wheel-rail system, it has the advantages of faster speed, frictionless operation, and low maintenance costs. The traction system is essentially a linear synchronous motor traction system. The calculation of traction force is a fundamental aspect of the research and design of linear motors, and the size of traction force is an important performance indicator of linear motors. For a high-speed Maglev system, the accurate calculation of traction force is of great significance. The calculation of traction force is a prerequisite for the system's operation planning, line selection, train climbing, speed acceleration determination, and a series of subsequent design.

The use of high-speed Maglev traction is generally employed in conjunction with the traditional traction force calculation method[1], which utilises the magnetic co-energy method to derive the traction force formula. In order to apply this method, it is necessary to have knowledge of the levitation current and the motor current cross-axis component I_q, as well as the motor stator-rotor mutual inductance between the M. The calculation of the parameter M is more complex, and M will be affected by changes in the levitation gap and the train's speed. In practice, the levitation gap of the train is adjusted in accordance with the speed of the train and is not fixed. Consequently, when the conventional calculation methodology is employed, the adjustment of the levitation gap by the train results in a significant discrepancy in the calculation of the traction force.

Conversely, the traction system of high-speed Maglev is a linear synchronous motor system. The principal distinction between this and general linear motors is that the levitation magnetic field of high-speed Maglev trains is also the excitation magnetic field of traction motors[2]. Consequently, the levitation and traction of the train are coupled with each other. This paper commences with an analysis of the traditional traction force calculation method, with a particular focus on the mutual flux linkage between the mover and stator. This is combined with an analysis of the levitation force under stable levitation conditions of high-speed Maglev trains, which enables the development of a new method of calculating the traction force that is not affected by changes in the levitation gap of the train. Finally, the accuracy of the method is verified by utilising existing train operation data and relevant research results on traction force. Finally, the accuracy of the method is verified by utilising the existing train operation data and related research results on traction force

2 Methods of calculating traction

2.1 Conventional Traction Calculation Method

The control of high-speed Maglev traction is generally achieved through the use of i_d=0 control method, which decouples levitation and traction. The magnetic co-energy method is then employed to derive the formula for the traction force:

$$F_x = \frac{3}{2}\frac{\pi}{\tau_s} M i_f i_q$$

Where τ_s is the motor pole pitch, M is the mutual inductance between the stator and mover, i_f is the levitation current, i_q is the motor q-axis curren.

When the train's levitation gap changes the mutual inductance M changes with it, at the same time the levitation current i_f changes accordingly. Consequently, the application of M and i_f in the calculation of the traction force will not be pursued.

2.2 Introduction to the new methodology

The product of M and i_f can be expressed as λ_m,which is the flux linkage between the stator and mover. Another expression for traction calculation is:

$$F_x = \frac{3}{2}\frac{\pi}{\tau_s} \lambda_m i_q \tag{1}$$

It is possible that the suspension gap may change without a corresponding change in λ_m , the following focuses on λ_m.

According to the definition of the flux linkage:

$$\lambda_m = N\phi_m = Nu_0A\frac{i_f}{\delta} \quad (2)$$

where δ is the levitation gap, ϕ_m is the magnetic flux, and the quantity N represents the number of turns of the electromagnet winding, u_0 denotes the vacuum permeability, and A is the pole area. N, u_0 and A are all constants, so λ_m is proportional to $\frac{i_f}{\delta}$.

On the other hand, since traction and levitation are coupled to each other, the calculation of levitation forces (considering the single-iron levitation case) is examined below

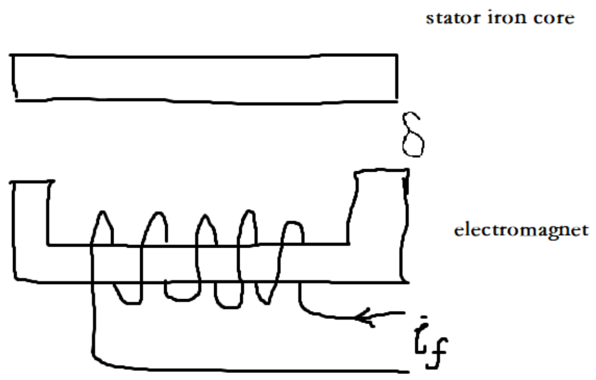

Figure 1: Single iron levitation model

The model of single iron levitation is shown above, and the calculation formula for the levitation force F_L is [3]:

$$F_L = \frac{u_0AN^2}{4}\left(\frac{{i_f}^2}{\delta}\right) = k\left(\frac{i_f}{\delta}\right)2$$

Where $k = \frac{u_0AN^2}{4}$

Without considering the aerodynamic lift, when levitating stably, the levitation force F_L is equal to the gravity of the train G. This can be expressed as follows:

$$G = F_L = k\left(\frac{i_f}{\delta}\right)2$$

thus $\frac{i_f}{\delta} = \sqrt{\frac{G}{k}}$, and substituting into (2) we have

$$\lambda_m = N\phi_m = Nu_0A\frac{i_f}{\delta} = Nu_0A\sqrt{\frac{G}{k}} = \sqrt{u_0AG} \quad (3)$$

It can be seen that with constant gravity of the train,λ_m also remains unchanged. That is, under the condition of stable levitation, even though the levitation gap changes, the mutual flux linkage between the stator and rotor remains unchanged and its value is $\sqrt{u_0 AG}$.

The physical essence revealed in this conclusion is that after the levitation gap adjustment, the levitation current i_f and mutual inductance M both change and adjust so that the train adjusts to another stable levitation state. However, the product of the two does not change, i.e., λ_m remains unchanged in the stabilized levitation state with different gaps.
Substituting (3) substituting into (1), we get

$$F_x = \frac{3}{2}\frac{\pi}{\tau_s}\lambda_m i_q = \frac{3}{2}\frac{\pi}{\tau_s}\sqrt{u_0 AG} * i_q \quad (4)$$

The new method of calculating the magnitude of the traction force, as expressed by equation (4), does not include the suspension current i_f and mutual inductance M. This means that the method is not affected by changes in levitation current and levitation gap. The traction force of the maglev train is proportional to the q-axis current of the motor.

3 Validity Verification

The following adopts the Shanghai high-speed maglev test line as an example to verify the above analysis conclusions.

Shanghai high-speed Maglev train adopts German TR08 type, the pole pitch τ_s of the long stator linear motor is 258mm, the train has 5 sets of vehicles, each vehicle has 8 levitation modules, each module has 11 magnetic poles, each magnetic pole area A is 17mm*17mm, and the weight of the train is about 300 tonnes in total[4]. When the train is running at a constant speed of 430 km/h, the two inverters are powered at the same time during double-ended power supply, total q-axis current approx. 500 A.

Substituting the above data into equation (4), the traction force can be obtained as 62.5KN

Since it is not possible to directly measure the traction force of the train at this high speed, only indirect verification is possible. When the train runs at a uniform speed, the traction force is equal to the running resistance. Shanghai Maglev train is of Germany TR08 type, operation is generally used in five vehicles grouping. The literature [5] introduced its operating resistance.

The running resistance of high-speed maglev train mainly includes three parts: magnetic resistance, linear generator resistance and air resistance. When the train is running at high speed, air resistance is the main resistance, which is basically proportional to the square of the train speed. As shown in the figure below, F_A is the air resistance, F_B is the resistance generated by the linear generator, F_M is the magnetic resistance, F_Z is the total operating resistance, $F_Z = F_A + F_B + F_M$

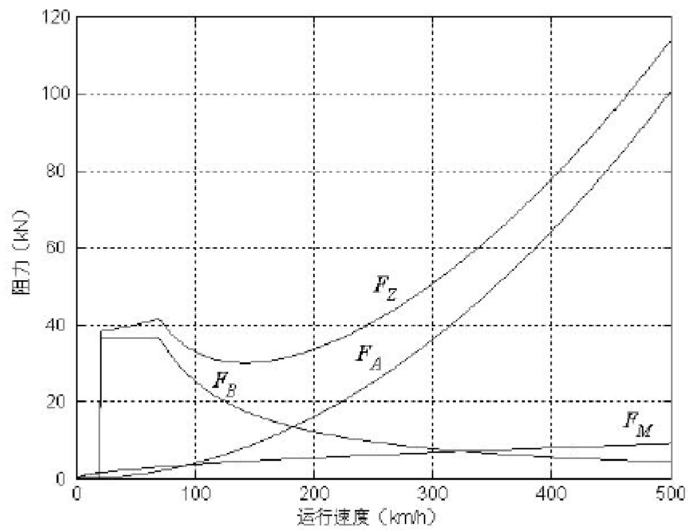

Figure 2: Resistance of Shanghai maglev train

From the figure, it can be seen that the resistance at 430 km/h is about 65KN or so, which is basically consistent with the above calculation.

4 Discussion

This study reveals the following physical fact: for different levitation gaps, the effective flux linkage between the stator and the mover is the λ_m, which is the same for all cases. Consequently, the magnitude of the train traction force remains proportional to the q-axis current. However, this conclusion is subject to the following constraints:

1. The above study did not consider the effect of aerodynamic lift. In fact, when the train speed is below 400 km/h, the effect of aerodynamic lift is very small [6]. However, when it reaches more than 450 km/h, the effect of aerodynamic lift cannot be ignored and significantly affects the traction force [7]. The effect of aerodynamic lift is equivalent to reducing the force of gravity.
2. The preceding analysis was employed in the single-iron levitation formula (2), which assumes that the electromagnet is in the linear region (Ref.). However, if the levitation gap is either excessively large or small, the electromagnet may be out of the linear region.
3. Both the traditional method and the method presented in this paper are based on circuit magnetic circuit analysis, which is only approximately accurate. Furthermore, the accuracy of the results is also affected by the fact that the weight of the train varies with the number of passengers carried.

5 Conclusions

In this paper, the traction force calculation for EMS high-speed Maglev is investigated, and a new method for calculating the traction force is derived by analyzing the connection between traction levitation. The method is based on the conclusion that as long as the train is levitated stably and the gravity force on the train remains constant, the mutual flux linkage between the stator and the mover remains unchanged even if the levitation gap is different. In this paper, the accuracy of the method is indirectly verified by analyzing the traction force on the train during operation.

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