Analysis of eddy current induced in track on medium-low speed maglev train

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Abstract. Electromagnetic levitation (EMS) maglev train relies on the attraction between the electromagnets and rails which are mounted on the train to achieve suspension. During the movement, the magnetic field generated by the electromagnet will induce the eddy current in the orbit and the eddy current will weaken the suspended magnetic field. Which leads to the attenuation of the levitation force, the increases of suspension current and the degradation the suspension performance. In this paper, the influence of eddy current on the air gap magnetic field is solved by theoretical analysis, and the correction coefficient of air gap magnetic field is fitted according to the finite element data. The levitation force and current are calculated by the modified formula, and the velocity curves of the levitation force and current are obtained. The results show that the eddy current effect increases the load power by 61.9% in the case of heavy loads.

1 Introduction

The maglev train is a new type of rail transportation that uses electromagnetic forces to suspend the vehicle over the track. At present, there are two kinds of suspension structure, the electromagnetic suspension (EMS) system by levitation and the electric suspension (EDS) system with the repulsive force suspension. And most of the world's commercial operation line adopts EMS type suspension structure, such as China Shanghai high-speed maglev airport line, Changsha low-speed maglev airport line, Beijing S1 line, South Korea Incheon airport line and Japan Aichi line [1]. The EMS system utilizes the attraction between the electromagnet and the magnetizing track which are mounted on the train to achieve suspension, ensuring stable suspension by controlling the current in the electromagnet. When the relative movement of the magnet and the track generates, the track will produce inductive eddy current, which will weaken the air gap magnetic field to reduce the levitation force and degrade the suspension performance. The vortex problem of the EMS-type suspension system has been studied by the scholars in the 1970s. Borcherts et al. show the eddy current characteristics of small electromagnets by means of experimental measurements and theoretical models [2]. S. Yamamura and T. Ito solve the general expression of the air gap magnetic field about the EMS suspension structure, and then give the calculation formula of the levitation force. The velocity characteristics of the levitation force, the electromagnetic resistance and the auxiliary ratio of the EMS system are obtained. In the meanwhile, the influence of System Suspension Structure Parameters on System Velocity Characteristics is analyzed [3]. Hiroyuki Ohsaki and Jian Du use the finite element numerical simulation method to show the influence of the eddy current effect of the EMS system on the suspension system under the speed of 200km/h. It is pointed out that the electromagnet at the front end of the moving direction is most affected by the eddy current.
Lili Zheng proposes the method that appending the permanent magnet at the front end of the electromagnet to weaken the eddy current effect which is based on the eddy current problem of EMS system And the effect of the modified suspension electromagnet is verified by the finite element numerical simulation [6]. Hexiang Liu and so on fit the EMS system levitation force and speed related formula according to the finite element simulation results [7].

The attenuation of the levitation force describes the effect of the eddy current effect on the suspension system in some degree. However, the system adjusts the suspension current in the dynamic process to ensure the suspension stability. The attenuation of the levitation force is finally compensated by the increase of the suspension current. And too large suspension current will make the solenoid core and track into the saturated area, resulting in poor control performance even failure in suspension. Therefore, the characteristic curve of the suspension current and the running speed can describe the influence of the eddy current effect on the suspension system more directly. According to the finite element simulation data, the saturation coefficient of the air gap magnetic field is fitted and the velocity curves of the levitation force and the suspension current are calculated according to the fitting formula. The results show that the levitation force decreases with the increase of the velocity; The suspension current increases with the increase of the velocity and it increase more greater with the heavier load.

2 The analysis of magnetic field at air gap

In the low-speed maglev train with the electromagnetic suction suspension structure, suspended magnet is located below the track which forms a closed loop with the F-type track. The magnet and the rail cross-section diagram are showed in Figure 1. As the track and the electromagnet core are the ferromagnetic materials with a high magnetic permeability and the suspension gap is very small, almost all of the magnetic potential generated by the electromagnet suspension current drop in the air gap, which results in a strong magnetic field in the air gap. So ignoring the magnetic flux leakage and core’s magneto resistance, according to Ampere loop theorem, air gap magnetic density can be expressed as:

$$B_0 = \frac{\mu_0 NI}{2\delta}$$  \hspace{1cm} (1)

However, due to the non-linear magnetization of ferromagnetic materials, with the increase of the suspension current, the track and the electromagnet core tend to saturate and the edge of the magnetic field lines and magnetic flux leakage increases which result in that the core magneto resistance can not be ignored and The calculated value of the gap magnetic field the formula (1) will deviate from the actual value. Therefore, in order to obtain accurate magnetic flux density of the main magnetic flux, the effect of the above factors can be corrected by using the proportion coefficient $k_\mu$ and the revised theoretical formula can be expressed as:

$$B_0 = k_\mu \frac{\mu_0 NI}{2\delta}$$  \hspace{1cm} (2)
The theoretical modeling and calculation based on the saturation characteristics and magnetic flux leakage of the electromagnet are very complicated and it is difficult to obtain an accurate analytical solution. In this paper, finite element simulation method is used to establish the finite element simulation model of electromagnets and rails. The parameters of the simulation are used to obtain the air gap fluxes of different current and different air gaps, and the coefficient $k_B$ are corrected according to the simulation data. Finite element simulation model of single module suspension electromagnet and track is shown in Figure 2. Length of single module is 2560mm and we take the track length as 3000mm. There is no lateral dislocation and side roll between electromagnet core and track. The B-H value of the track and core material is shown in Fig 3.

Figure 3: B-H curve of Track and core material

According to the fluctuation range of the suspension gap and the suspension current during the normal operation of the low speed maglev train, the variation range of the suspension gap is $6 \sim 12$mm and the variation range of the suspension current is $0 \sim 60$A. The finite element simulation results are divided by the theoretical values from formula (1), then we can get the proportional relationship between the two, as shown in Figure 4.
Figure 4: Curves of the correction coefficient $k_B$ and the current curve at different suspension gaps

What can be seen by the changes in the trend of $k_B$ is that with the increase of current, the difference value between the two is increasing, indicating that the increase of the suspension current leads to the magnetic field saturation phenomenon. Using 1stopt software, the correction coefficient is fitted with two-element polynomial fitting in condition that suspension current and suspension gap are regarded as variables. The following formula is obtain:

$$k_B = \frac{p_1 + p_2 I + p_3 I^2 + p_4 I^3 + p_5 \delta + p_6 \delta^2}{1 + p_7 I + p_8 I^2 + p_9 \delta}$$  \hspace{1cm} (3)

$p_1 \sim p_{10}$ are polynomial coefficients and the values are shown in Table 1.

| coefficient | value               |
|-------------|---------------------|
| $p_1$       | 0.939817726734252   |
| $p_2$       | -0.0999261091242649 |
| $p_3$       | 0.00186789069690677 |
| $p_4$       | -7.65519796583251e-6|
| $p_5$       | 188.506140579458    |
| $p_6$       | 668.642198834802    |
| $p_7$       | -0.102280623462625  |
| $p_8$       | 0.00171870328564531 |
| $p_9$       | 203.346187306468    |

Using the fitting formula, we can get relationship of the magnetic induction of electromagnetic field in conditions that the suspension gap is in the 6 ~ 12mm, the suspension current is in the case of 0 ~ 60A. The relationship is shown in Figure 5.
Figure 5: The relationship between magnetic flux and gap and current from the fitting formula

The results of the fitting formula and the finite element simulation are compared. The air gap is set at 8.5mm then the magnetic induction can be obtained during the range 0–60A of suspension current, shown as Fig. 6 (a). In another case, the suspension current is 25A and the suspension gap change range is 6 ~ 12mm. Then the magnetic induction is obtained and shown in Figure 6 (b). It can be seen from the figure that the results of the fitting formula and the finite element simulation can be well matched with different air gaps and different suspension currents.

Figure 6: The comparison of the fitting formula and the finite element simulation

3 Eddy current analysis

The running speed of the train is much smaller than the speed of light. The equivalent frequency of the electromagnetic field in the orbit is very low, which is the steady magnetic field. Therefore, the Maxwell equation is used to describe its state. Assuming that the direction of the air gap magnetic flux density \( B \)
is parallel to the z-axis direction and the electromagnet moves in the x-direction with respect to the orbit, the differential equation can be written as:

\[ J = \sigma (E + v \times B) \quad (4) \]
\[ \nabla \times E = 0 \quad (5) \]
\[ J = \nabla \times (B / \mu) \quad (6) \]

\( J \) is the induced current density in the rail; \( v \) is the velocity; \( B \) is the air gap flux density; \( E \) is the electric field strength; \( \mu \) is the air permeability and \( \sigma \) is the conductivity.

By formulas (4) and (5), we obtain:

\[ -\frac{1}{\mu \sigma} \nabla^2 B = \nabla \times (v \times B) \quad (7) \]

For the differential equation (7), S. Yamamura et al. [3] proposed the separation variable method and the Fourier transform method to find the air gap magnetic field:

\[
\begin{aligned}
  b(x,z) &= \sum_{n=1}^{\infty} \left[ C_n B_0 X_n(x) e^{\alpha_n x} - e^{-\alpha_n x} \right] \cos \lambda_n z, \quad 0 < x < L \\
  b(x,z) &= \sum_{n=1}^{\infty} X_n(x) \cos \lambda_n z, \quad x < 0, \text{or} \ x > L \\
  X_n(x) &= C_n B_0 \frac{\alpha_n}{\beta_n} \left( e^{\alpha_n x} - e^{-\alpha_n x} \right), \quad x < 0 \\
  X_n(x) &= C_n B_0 \frac{1}{\alpha_n - \beta_n} \left( \beta_n e^{\alpha_n x} - \alpha_n e^{-\alpha_n x} \right), \quad 0 < x < L \\
  X_n(x) &= C_n B_0 \frac{\beta_n}{\alpha_n - \beta_n} \left( e^{\alpha_n x} - e^{-\alpha_n x} \right), \quad x > L
\end{aligned}
\]

Where \( C_n = \frac{4}{\pi (2n-1)^2} \sin \frac{2n-1}{2} \pi \), \( \lambda_n = \frac{(2n-1) \pi}{2a} \), \( K = \frac{\sigma \mu_d v}{\delta} \), \( \alpha_n = \frac{1}{2} \left( -K + \sqrt{K^2 + 4 \lambda_n^2} \right) \), \( \beta_n = \frac{1}{2} \left( -K - \sqrt{K^2 + 4 \lambda_n^2} \right) \), \( \sigma \) is the suspension gap; \( d \) is the track magnetic path length; \( L \) is the length of the pole; \( B_0 \) is the magnetic field strength generated by the excitation coil in the air gap, it can be obtained from formula (2); The pole width \( 2a \).

According to Maxwell's stress tensor method, the levitation force \( F_y \) is:

\[
F_y = \frac{1}{2} \mu_0 \int_{-\infty}^{\infty} dx \int_{a}^{a} b(x,z)^2 dz
\]

When formula (5) is taken into formula (8), the following formula can be obtained:
$$F_y = F_0^y \sum_{n=1}^{\infty} C_n^2 f(n)$$

$$f(n) = \frac{1}{2L_1} \left[ L + \frac{2\alpha_n \beta_n - \beta_n^2}{\alpha_n (\alpha_n - \beta_n)^2} \left( 1 - e^{-\alpha_n L} \right) \right. \left. + \frac{\alpha_n^2 - 2\alpha_n \beta_n}{\beta_n^2 (\alpha_n - \beta_n)^2} \left( 1 - e^{\beta_n L} \right) \right]$$

$$+ \frac{2\alpha_n \beta_n}{(\alpha_n + \beta_n)(\alpha_n - \beta_n)^2} \left( e^{-\alpha_n L} - e^{\beta_n L} \right)$$

(11)

Where $F_0^y = \frac{B_0^2 A}{\mu_0}$.

4 Calculation results

Medium and low speed maglev train contains ten suspension modules totally and each suspension module contains two independent suspension control points. Therefore the suspension point is the most basic control module of the maglev train. The length of the electromagnet at the single suspension point is 1280mm.

The following analysis is carried out for the single suspension point. The relationship between the levitation force and the velocity can be obtained according to the formula (9). Set the suspension current at 20A, 30A, 40A, then the relationships between the levitation force and velocity are shown in Figure 7. The relationship between the suspension force and speed is shown at the upper part of Figure 7. The lower part of the figure shows the relationship between the attenuation of the levitation force and the velocity. It can be seen that the levitation force decreases with the increase of velocity, and the attenuation of the levitation force is different under different loads, but the decay rate is the same. When the speed is at 200km / h, the attenuation of levitation force is about 20% compared with the static state.

Set load at 12KN, 14KN, 16KN, 18KN, then the relationship between the velocity and the suspension current at different loads are shown in Figure 8. The upper part of figure 8 shows the relationship between the velocity and the suspension current. The lower part of figure 8 shows the increase ratio curve between the velocity and the floating current compared with the static state.

![Figure 7: Curves of Suspension force’s characteristics and velocity](attachment:image.png)
It can be seen from the figure that the suspension current increases with the speed increasing, and the load increases with the increase of the current. When the load is 18KN, the suspension current increases by 27.2%. When the velocity is 200km/h, Power consumption increased by 61.9%. The reason is that when the load is heavy, the air gap magnetic density is larger and the core tends to be saturated, so it needs larger current to compensate for the vortex effect loss of levitation force.

5 Conclusion
In this paper, the influence of the eddy current on the suspension characteristics of the medium and low speed maglev train is analyzed by finite element method and analytic method. The results show that the levitation force decreases constantly with the increase of the velocity and the attenuation rate keep unchanged. Suspension current increases with the increase of the speed, but the greater the load is, the greater the current increase.

The eddy current effect leads to that the suspension electromagnet and the track are easy to saturate at high speed, which not only limits the further speed rise of the EMS maglev train, but also increases the suspension power consumption. It is an unavoidable problem of the EMS system, and it needs to find the appropriate method to weaken the eddy current effect.

References
[1] G. Lin and X. Sheng, “Application and development of maglev transportation In China,” in Proceedings of the 22th international conference on magnetically levitated systems and linear drives (MAGLEV 2014),2014.
[2] Borcherts, R.H. and L.C. Davis, Lift and drag forces for the attractive electromagnetic suspension system. IEEE Transactions on Magnetics.
[3] Yamamura, S. and T. Ito, Analysis of speed characteristics of attracting magnet for magnetic levitation of vehicles. IEEE Transactions on Magnetics, 1975. 1(5).
[4] Du Jian and O. Hiroyuki, Influence of Eddy Current Induced in Steel Rails on Electromagnetic Force Characteristics of EMS Maglev Systems. 2004.
[5] Jian Du, H.O., Numerical analysis of eddy current in the EMS-Maglev system, in ICEMS. 2003.
[6] Lili Zheng, Jie Li, Jinhui Li,Research on Influence of Rail Vortex on Suspension Electromagnetic Force of Maglev Train. Computer Simulation 2011. 28(8).
[7] Hexiang, Li, et al. Analyzing and modeling of dynamic magnetic suspension plate in the electromagnetic launcher.
[8] TSIBOUKIS, E.E.K.D., Eddy currents theory and applications. PROCEEDINGS OF THE IEEE, 1992. 80(10).