Electromagnetic Characteristic Analysis of Low-speed Maglev on a Convex Curve

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ABSTRACT: In view of the problem that the levitation electromagnets are not parallel to the rail when the low-speed maglev train is on a convex curve, the electromagnetic levitation force supplied by suspension electromagnet on a convex curve is deduced by the flux tube method, suitable simplification and fitting is applied to the expression. The simulation results of the finite element method(FEM) show that the calculation of electromagnetic force based on flux tube method is approaching to the actual value, so that the validity and accuracy of the expression is proved. The electromagnetic characteristic of suspension system on a convex curve is analyzed, result of analysis shows that the stiffness and damping of suspension system on a convex is less than that on straight-line segment.

1 INTRODUCTION

The EMS(Electromagnetic suspension) low-speed maglev train is a new kind of transportation system which is suspended above the guideway by electromagnetic forces. Electromagnetic force calculation of suspension electromagnet is very important for the suspension system analysis and design, and also is regarded as the basis of maglev dynamics[1]-[5]. In view of electromagnetic force calculation of low-speed maglev, many scholars at home and abroad attempt modeling with kinds of ways[6]-[9]. On the premise of neglecting edge-effect of magnetic field, W.Brezina and J.Langerhole[10] proposed a two-dimensional electromagnetic force calculation formula used widely, as Equation 1. in which, μ_0 is the air permeability, S is the valid magnetic pole area, N is the number of turns of the coil, δ is the suspension gap, i is the current through the winding.

$$F = \frac{\mu_0 N^2 S}{4}\left(\frac{i}{\delta}\right)^2 \tag{1}$$

When the electromagnet is parallel to guideway, the calculation results of electromagnetic force based on Equation 1 have good precision. However when maglev runs along convex curve, electromagnets are not parallel to guideway, the calculation of the electromagnetic force based on Equation 1 is discontented, which will bring with difficulty for controller design and dynamic modeling.

Based on flux tube method, the paper deduces the analytic expression of electromagnetic force when maglev is on convex curve. However, the analytic expression is too complex to be put into practice. It's essential to simplify the expression suitably, three-dimensional electromagnetic field model is set up and electromagnetic force is computed by finite element method(FEM). The simulation results show that calculation of electromagnetic force by flux tube method is approaching to that of the FEM comparing to Equation 1, Meanwhile, the electromagnetic characteristic of suspension system is analyzed.

2 DESCRIPTION OF RELATIONSHIP BETWEEN MAGNETS AND GUIDEWAY

As usual, the vertical curve of maglev guideway is composed of straight-line segment, transition curve segment(concave curve and convex curve) and ramp segment, as shown in Figure 1.

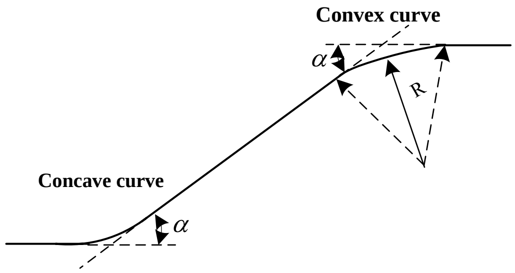

Figure 1. Sketch of vertical curve

Different from common train, suspension bogies are distributed under guideway and suspension electromagnets installed at the bottom of bogies supply levitation force. Both ends of suspension module track guideway on an expected suspension gap under suspension controller.

Restricted by dynamics, kinematics and radius of curve, suspension modules are not parallel to guideway when vehicle is running on convex curve. The gap of both ends of module is less than that of middle on convex curve. The relative position of suspension module and guideway is shown in Figure 2. In the following, L is the half length of module, δ is the gap of both ends of module, $\Delta\delta$ is the gap difference between both ends and middle.

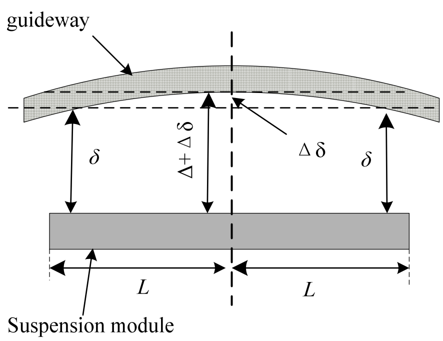

Figure 2. The relative position between suspension module and rail when maglev train is on vertical curve

Given the geometrical relationship between guideway and module, it is easy to get expression of gap difference, such as shown in Equation 2.

$$\Delta\delta = R - \sqrt{R^2 - L^2} \tag{2}$$

Here R is the radius of curve. Equation 2 shows that $\Delta\delta$ increases with the radius decreasing. For low-speed maglev with five bogies—CMS04 developed by National University of Defense Technology, $\Delta\delta$ will exceed 0.9 mm when R is less than 1,000 m. The expected levitation gap of low-speed maglev is 9 mm, there will be greater error when we calculate electromagnetic force with R is less than 1,000 m upon Equation 1.

3 CALCULATION AND SIMPLIFICATION OF ELECTROMAGNETIC FORCE

3.1 Calculation of electromagnetic force based on flux tube method

According to the electromagnetic field theory，the following equations can be obtained:

$$\begin{cases} L_m(\delta) = \dfrac{1}{2} N^2 G(\delta) \\ E_m(\delta, i) = \dfrac{1}{2} L_m(\delta) i^2 \end{cases} \tag{3}$$

Here L_{m} is the induction of the electromagnet, E_{m} is the magnetic field energy within the suspension gap, G is the magnetic conductance of the gap. The magnetic levitation force can be written as:

$$F = -\frac{\partial E_m(\delta, i)}{\partial z} = -\frac{1}{2}\left[\frac{\partial}{\partial z} L_m(\delta)\right] i^2 = -\frac{N^2 i^2}{2}\left[\frac{\partial}{\partial \delta} G(\delta)\right] \tag{4}$$

The magnetic levitation force can be obtained from Equation 4 by calculating the magnetic conductance of the suspension gap G.

The flux tube method is a general method of calculating the magnetic conductance[11]-[13]. Defining Lp and Sp as the average length and area of the flux tube. The magnetic conductance can be written as $G=\mu_0 Sp/Lp$. Because the magnetic field distribution is asymmetrical in the flux tube, the flux tube can be portioned into infinite unit elements dV, and the magnetic conductance can be written as:

$$G = \mu_0 \iiint_V \frac{dV}{L_p^2} \tag{5}$$

When electromagnet is on convex curve, the magnetic field distribution between electromagnet and rail is shown in Figure 3. in which, a is the width of the polar plane of the electromagnet.

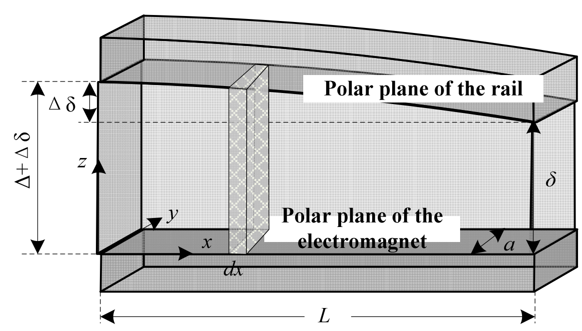

Figure 3. Sketch of computing magnetic conductance on convex curve based on flux tube