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ORIGINAL PAPER

Numerical Study of the Curve Route Levitation Performance of the HTS Bulk over NdFeB Guideway

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Abstract The passive levitation has a self-adjust characteristic to adapt to environmental changes. Levitation Height (LH) or Lateral Displacements (LD) of the high-temperature superconducting (HTS) Maglev vehicle, running over Permanent Guideway (PMG), will change respectively or synchronously due to some external reasons, which caused the vehicle move a certain distance in vertical direction (Y direction) or horizontal direction (X direction) according to a line space route curve along Y or X direction, or random route lying in a XY plane which is perpendicular to the vehicle running direction (Z direction) corresponding to a complicated space route curve. In these cases, how are the levitation performances of the HTS bulk? From a simplest space line route, this paper studied computationally the curve route levitation performance of the HTS bulk which is subject to a PMG applied field. Results show that the change of the levitation and guidance force is different when the HTS bulk moved along line space route. This provides important scientific theories for the numerical simulation of HTS Maglev vehicle.

Keywords HTS bulk · Numerical calculation · Levitation performance · Space route curve

1 Introduction

Based on the intrinsic magnetic flux pinning characteristics, a high temperature superconductor (HTS) exhibits when exposed to a magnetic field, the HTS Maglev system has a series of advantages such as completed passive property, without any input energy, self-stability without any control equipment needed [1–3], and continuous stability region [4]. One of the very important applications of HTS is the HTS Maglev vehicle. A lot of researches on the HTS Maglev vehicle system have been done since the first man-loading HTS Maglev test vehicle has been developed successfully in 2000 [5]. Now, on the study of superconducting levitation, the experimental researches are more than the theoretical ones; the researches on static or quasistatic characteristics are more than those on dynamic ones, and also the levitation performance researches are more than those of guidance performance ones. Especially, high nonlinearity of the E–J relation, electromagnetic coupling characteristics and anisotropic property of HTS materials make the theoretical researches on the HTS Maglev vehicle system very difficult. In the theoretical research, Wang Xiaorong built a 2D analysis model based on the Prigozhin model, studying the influence of all kinds of factors of a high temperature superconducting levitation system on the guidance force when the superconductor moves along a horizontal direction over a permanent guideway [6]. Wang Suyu et al. researched the levitation force and guidance force of the whole vehicle by the numerical method and it fits well with experimental results [7]. Lu Yiyun proposed a 3D levitation force numerical model [8] of HTS bulk over a permanent guideway, and reveals firstly ending an effect of electromagnetism distributing inside a finite HTS superconductor.

What is most significant is that the researches focus on the levitation performance of the bulk HTS over the guideway in the studies mentioned above; the relation between the levitation performance and space route curve was almost not involved when the vehicle's body became off-centered a certain distance from the PMG's centerline for reasons such as field nonuniformity due to cooling inhomogeneity or ex-

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Table 1 Parameters of HTS bulk passing a line route

Name	Values
Vertical distance from original point A to the surface of the PMG	15 mm
Horizontal distance from original point A to the central of the surface of the PMG	0 mm
Vertical distance from ending point A to the surface of the PMG	0 mm
Horizontal distance from ending point A to the central of the surface of the PMG	5 mm
Horizontal moving speed of HTS bulk	0.1 mm/s
Vertical moving speed of HTS bulk	0.3 mm/s
Field cooling height	10 mm

Table 2 Calculating parameters of YBCO bulk passing a line route over the peak PMG

Name	Value
PMG width	90 mm
PMG height	40 mm
Flux-concentration iron width	10 mm
Magnetization of the permanent magnet of PMG	85000 A/m
Bulk thickness	15 mm
Bulk diameter	30 mm
Bulk critical current density (J_c)	6.5×10^7 A/m^2
E_c	1.0×10^{-4}

ternal disturbances during practical applications. This paper will do the work for it.

2 Numerical Study of the Curve Route Levitation Performance of the HTS Bulk over NdFeB Guideway

The analysis model in the paper used has been proposed in [8, 9]. The effectivity and reliability of the model mentioned above has been verified; the details referred to [9].

2.1 Practical Running Analysis of HTS Maglev Vehicle

Levitation Height of the HTS Maglev vehicle, running over a permanent guideway, will change due to off-loading or on-loading, which caused the vehicle move a certain distance up and down in a vertical direction (Y direction) forming a line space route curve along the Y direction. A floating along the horizontal direction (X direction) and Y direction that the directions are perpendicular to the vehicle running direction (Z direction) will occur simultaneously when the vehicle passes the two parallel guideways which do not lie in a same plane because of distortion owing to roadbed falling or deforming, and the floating will also occur when the vehicle turns a curve. This paper studied the levitation characteristics of HTS bulk which is subject to an applied field when it passes a simple space line route.

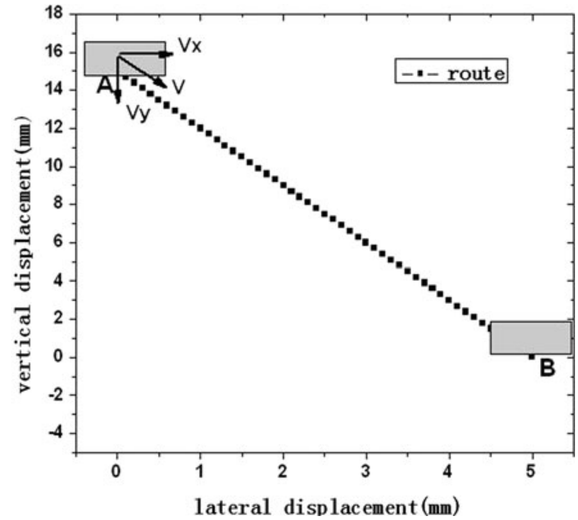

Fig. 1 Schematics of the HTS bulk passing a line route

Table 3 Calculating values of levitation force and guidance force over the peak PMG

Horizontal displacement (mm)	Vertical displacement (mm)	Guidance force (N)	Levitation force (N)
0.0	15.0	0.0	0.0
0.5	13.5	−0.06003	−1.045
1.0	12.0	−0.2208	−1.302
1.5	10.5	−0.5114	−1.111
2.0	9.0	−0.9214	−0.5191
2.5	7.5	−1.443	0.5088
3.0	6.0	−2.068	2.049
3.5	4.5	−2.787	4.211
4.0	3.0	−3.582	7.134
4.5	1.5	−4.428	11
5.0	0.0	−5.274	16.04

2.2 Simulation and Results

Regarding the study of the levitation performance of HTS bulk which passed a line space route, the change of the bulk along the x direction and the y direction is considered simultaneously, as Fig. 1 shows. The HTS bulk moves from A point to B point along line AB. In calculation, the related route curve parameters are showed in Table 1.

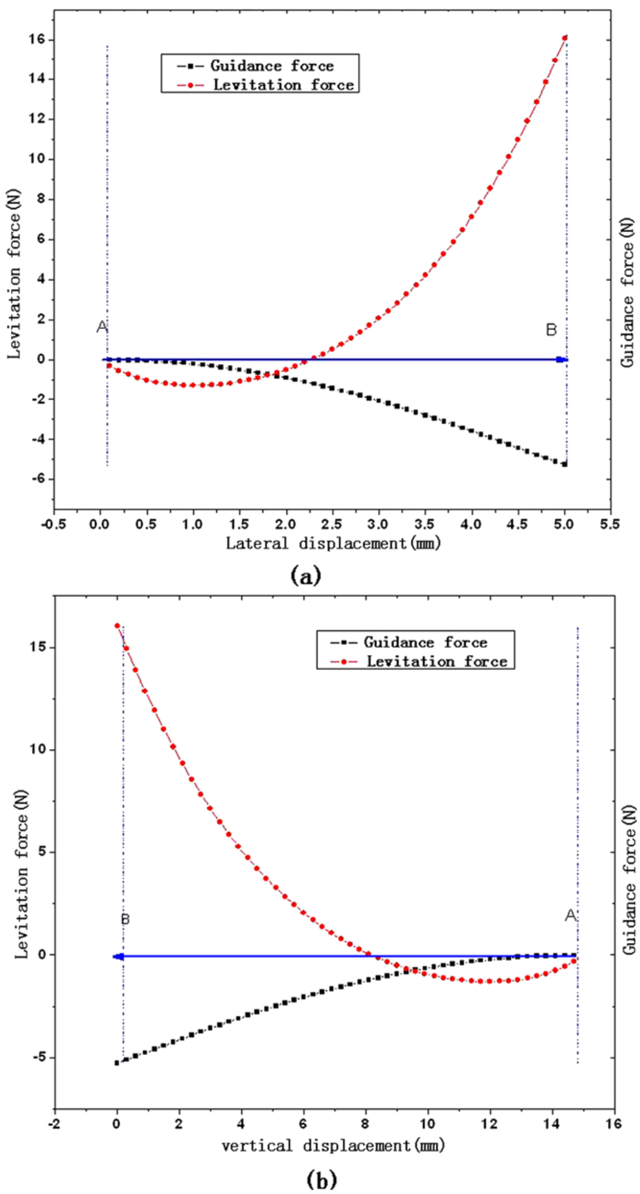

Fig. 2 The relations between the levitation or guidance force of the YBCO bulk which moves along line AB over peak PMG and (**a**) lateral displacement (**b**) vertical displacement

2.2.1 *Simulation Study on Levitation Characteristics of the HTS Bulk which Passed a Line Route over the Peak PMG*

The levitation characteristics of the HTS bulk which moves from point A to point B along line AB over the peak PMG are studied by the numerical calculation method. Calculating parameters are shown in Tables 1 and 2. The structure and the magnetic field distribution of the PMG which be used in this paper can be found in [9].

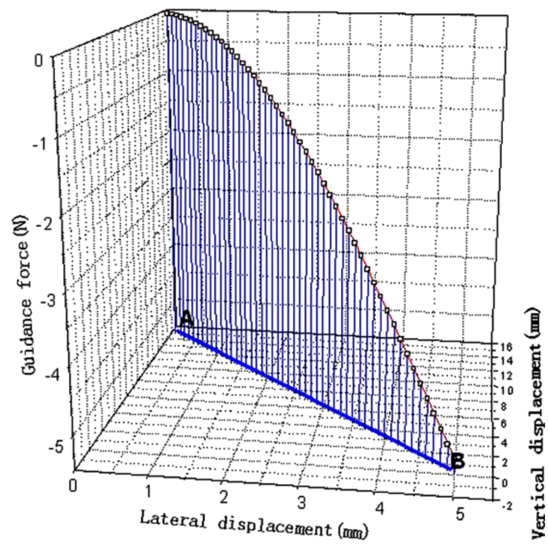

Fig. 3 The curves between the guidance force and lateral/vertical displacement when the bulk moving along line AB over the peak PMG

2.2.2 *Results*

Computed results of the levitation force and guidance force are given in Table 3 when the HTS bulk moves from point A to point B along line AB.

In order to clearly illustrate the relation between the levitation (or guidance) force of the YBCO bulk over peak PMG and the moving route of the bulk along line AB, Figs. 2, 3, and 4 have been drawn as follows.

From Fig. 2(a), we can see the levitation force decreases firstly to a negative value and reaches a minimum value when the HTS bulk is moved along the lateral direction off the centerline of the PMG to point B; afterward, the levitation force begins to increase gradually with increasing lateral displacement. When the bulk arrives at point B, the levitation force reaches a maximum value. The guidance force always increases with increasing lateral displacement. From Fig. 2(b), we can see the levitation force firstly decreases and then increases when the HTS bulk moves from up point A to down point B along line AB. The levitation force sharply increases when approaching the surface of the PMG, but the guidance force always increases during the sample moving from A to B. The most closely related thing to the levitation and guidance force is lateral displacement and vertical displacement of the HTS bulk moving along line AB. In order to describe the relation, we illustrate Figs. 3 and 4 as follows.

3 Conclusion

The change is different between the levitation and guidance force of the HTS bulk which moved along line space route

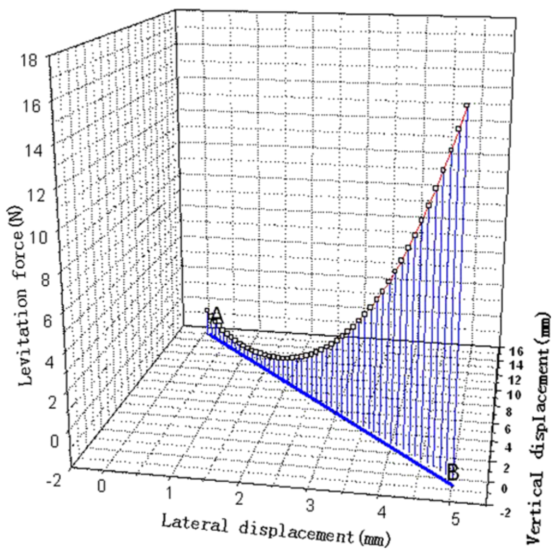

Fig. 4 The curves between the levitation force and lateral/vertical displacement when the bulk moving along line AB over the peak PMG

by the numerical calculation method. We can conclude that the levitation force and guidance force is closely related to the route the bulk passed. When the HTS bulk moves from the up position to the down position along the line route, both the levitation force and the guidance force increase with increasing lateral displacements, which makes the Maglev system reach a new equilibrium state self-adapted after the drift of levitated body is caused.

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