3D-Modeling Numerical Solution of Guidance Force of HTSC Bulk Above Permanent Magnetic Guideway

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Abstract This paper presents a 3D-modeling numerical method to simulate the electromagnetic behavior of high-temperature superconductors (HTSC) while the bulk departs from the center line of the guideway. In this paper, for a typical superconducting levitation style with a bulk superconductor suspended above a permanent magnet guideway (PMG), the guidance characteristics of the system were investigated computationally followed by experimental work. Based on the proposed 3D-modeling numerical solutions of electromagnetic behavior of a HTS bulk sample, we used the grid multiplexing technology in which the meshing nodes inside the HTS bulk represent the centers of pinning to simulate flux pinning of HTS bulk. The resolved code of the 3D-modeling of high-temperature maglev was developed with the FORTRAN language. Comparisons between the experimental and numerical results indicated the effectiveness of the method utilized in the paper.

Keywords Permanent magnetic guideway · Guidance force · Grid multiplexing technology

1 Introduction

The stability of bulk superconductor which can levitate over (or below) permanent magnets makes the potential engineering application possible [1, 2], especially in a high-temperature superconducting maglev vehicle system [3]. As

is known widely, the horizontal stability of the maglev vehicle arises from the guidance force. Research shows that the lateral guidance is dependent on the trapped flux lines, which are pinned by the pinning centers in the HTSC bulk. However, up to now, there has been no effective way to deal with the pinning properties of HTSC. On the other hand, the guidance force is closely related to the c -axial current; usually the critical current density along the a – b plane is about three times that along the c -axis in the bulk YBCO interior. But the proposed 2D-models, limited to relatively simple geometries under homogeneous or axially symmetric external fields [4–10] did not deal with it. In these numerical or analytical methods, a simple Bean critical-state model, a shielding-current model and a frozen-field model were used.

For a typical superconducting levitation style which is composed of a bulk superconductor suspended above a permanent magnet guideway (PMG), based on the Prigozhin model Wang Xiaorong et al. have built up a 2D model where a bulk superconductor moves horizontally along the guideway. The model assumed the bulk is isotropic, that is, the influence of the c -axial current on the magnetic force is ignored. Afterwards, Ren Zhongyou et al. proposed an isotropic model, a – b plane model and c -axial model based on it, and interpret that the c -axial current only contributes to the levitation force in an axially symmetric external field. When the applied field is non-symmetric, the c -axial current must be considered and we must deal with the anisotropic problem by weighting. But this method cannot describe the macro-current flowing in a finite-dimension superconductor. So it is necessary to be able to simulate well the guidance force properties in a 3D model. Based on the proposed 3D-modeling numerical solutions of electromagnetic behavior of a HTS bulk sample, this paper proposed firstly grid multiplexing to deal with the pinning properties of HTSC. The resolving code of the 3D-modeling of a high-temperature

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maglev was developed with the FORTRAN language. Comparisons between the experimental and numerical results indicated the effectiveness of the method utilized in the paper.

2 Numerical Method

2.1 Analytic Model

According to the 3D superconducting model, the partial equation [11] describing the magnetic intensity interior HTSC bulk is as follows:

$$\frac{\partial}{\partial t}(\mu \vec{H}) + \nabla \times \frac{1}{\sigma_{sc}} \nabla \times \vec{H} + \nabla \times \frac{1}{\sigma_{sc}} \vec{Q} = 0 \quad (1)$$

where $\vec{Q}$ is a vector parameter dealing with anisotropy of the HTSC bulk current. σ_{sc} is the effective conductivity of the superconductor.

For the high- T_c superconductors, we use (2) to describe their electrical behavior:

$$E_{sc} = E_{c0} \left(\frac{J_{sc}}{J_c(H_{sc})} \right)^n \quad (2)$$

Here E_{c0} is material- and temperature-dependent constant. E_{sc} , J_{sc} and H_{sc} are the electric field, current density and magnetic field of the high- T_c superconductor, respectively. J_c is the critical current density. In this paper, we choose the value $n = 30$. The relation between σ_{sc} and E_{sc} is as below:

$$\frac{1}{\sigma_{sc}} = \frac{E_{sc}}{J_{sc}} = \frac{E_{c0}}{J_c} \left(\frac{J_{sc}}{J_c} \right)^n \quad (3)$$

Superconducting constitutive relation is described through the Bean model:

$$J = \begin{cases} J_c \frac{E}{|E|} & |E| \neq 0 \\ \frac{\partial J}{\partial t} & |E| = 0 \end{cases} \quad (4)$$

For the Bean critical model the critical current density J_c can be a function of magnetic field, while the temperature T is a constant.

$$J_c(|\mathbf{B}|, T) = J_{c0}(T) \quad (5)$$

For (1), we use the FEM and finite differences to solve the nonlinear problem of the bulk YBCO electromagnetic behavior in applied non-uniform external magnetic field which is offered by a permanent guideway. In this solution, we can obtain H , then we will get the guidance force through $\vec{J}(H(r)) = \nabla \times \vec{H}(r)$.

Fig. 1 PMG vs. YBCO bulk levitation system

2.2 Pinning Properties

Based on the proposed 3D-modeling numerical solutions of electromagnetic behavior of a HTSC bulk sample, a grid multiplexing technology in which the meshing nodes within the HTSC bulk were used to represent the centers of pinning to simulate flux pinning of HTSC bulk is used. If the solution area lies in the interior of the HTSC bulk and the meshing nodes is within the HTSC bulk, each meshing node is defined as a pinning center to simulate pinning characteristic of flux, and an applied field value just at the position is forced to the node as an initial value in which the value is to solve at field-cooling position when the initial unit stiffness matrix is obtained. That is, the field cooling sense has been fixed. This process can be written by

$$H_i^n(x, y, z) = f(x, y, z) \quad (6)$$

where superscript number n is the n th element of the sample, and the subscript i denotes the i th node of the n th element, and $f(x, y, z)$ is the value of the external magnetic field caused by a permanent guideway at point (x, y, z) .

The merit of grid multiplexing technology lies in the facility to deal with solving codes. The nodes which simulate the pinning properties of HTSC overlap the meshing nodes which have been used to solve (1), but the shape function for interpolation is related to geometrical features of the solving areas. So it is effective to form stiffness matrices using the same shape function. When we use interior nodes to simulate the pinning centers, only dealing with a loading vector in unit stiffness matrices makes the computation simplified.

3 Simulation and Measurement Result

We used the proposed methods in Sect. 2 to simulate the guidance force of the simple levitation system, composed of a HTSC bulk and a permanent magnetic guideway. This levitation system is the prototype of the man-loading maglev system [3]. Figure 1 shows a schematic diagram of the lev-

itation system during lateral displacement of the simulation and experiment. Figure 2 shows the magnetic distribution of the guideway that the system offered.

In the figures, FH is the cooling field height, MH is measurement height or calculation height, and LD is lateral displacement. Positions A and B are at the right center above the PMG. The axis line of the cylinder YBCO bulk is parallel to the y -direction.

The cylindrical bulk YBCO is 30 mm in diameter and 15 mm in thickness. The PMG is made of NdFeBs of 40 mm in width, 40 mm in height and 80 mm in length and iron yokes. The cross section is parallel to the x - y plane of the PMG, and the magnetic field induced by the PMG is symmetric in the x - y plane. For the magnetic field, the usual analysis method with the equivalent surface current model is used to calculate. Figure 3 shows the calculated and measured results of magnetic flux density along the y -direction with gap 3 mm above PMGs. Figure 3 shows that the calculated values of magnetic flux density generated by the PMG are a little smaller than the measured values near the center

Fig. 2 Magnetic distribution of PMG

Fig. 3 The distribution of the calculated and measured results of magnetic flux density along the y -direction with gap 3 mm above PMGs

of PMG. This is because the calculation of the magnetic field of the PMG is carried out in a perfect state which ignores the influence of magnetic field concentration effect of the iron yokes.

As Fig. 1 shows, during the simulation, the bulk HTSC is in field-cooling (FC) mode. A simple magnetic force-displacement loop is simulated in this way: firstly, the sample was moved horizontally to 20 mm from the original point B (where B overlaps A) to point C of gap 10 mm, that is, FH = 10 mm, MH = 10 mm. Then we go back and forth from 20 mm to -20 mm above the PMG with velocity 1 mm/s. Because the velocity is small, the displacement current is ignored. Physical parameters in the calculation are shown in Table 1.

In similar experiments with these instruments progress is made to measure the guidance force between the bulk YBCO and the PMG. In the experiment the sample is cooled by liquid nitrogen (77 K) in the case of FC. Measurement and calculating results are shown in Fig. 4. In order to further verify the reliability of the model, comparison between calculating results and measurement results under different FH, with lateral displacement in the range from 0 to 20 mm, is shown in Fig. 5.

Table 1 Invariant parameters of the levitation system

Name	Value
PMG width	110 mm
PMG height	60 mm
Iron yokes width	10 mm
J_c	6.5×10^7 A/m ²
E_c	1.0×10^{-4}

Fig. 4 Experiment and calculation of guidance force–displacement loops plot

Fig. 5 Experiment value and calculation value of guidance force under different FH

From Fig. 4, we can see that the guidance force-displacement loop exhibits some small distinction between the calculation and measurement value. But the variable tendency has good consistency, as Fig. 5 shows well.

4 Conclusions

Based on the proposed 3D-modeling numerical solutions of electromagnetic behavior of a HTS bulk sample, a grid multiplexing method has been proposed to simulate flux pinning properties. The resolve code is successfully developed with the FORTRAN language. The guidance force of a simple cylinder shape bulk HTSC above PMG is successfully sim-

ulated by the proposed method. A similar experiment of the simulation is carried out and the measured results show that the calculated and measured values match well. It indicated the effectiveness of the method.

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