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Numerical evaluation of guidance force decay of HTS bulk exposed to AC magnetic field over a NdFeB guideway

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Abstract

The guidance force of the YBCO bulk over a NdFdB guideway used in the high-temperature superconducting maglev vehicle system was decayed by the application of the AC external magnetic field. In our previous work, we explained that the decay was due to the temperature rise of the HTS bulk caused by AC losses. In this paper, we adopted an analytic model to evaluate the decay of the critical current density of the bulk. And based on the analytic results and the Bean critical-state model, we calculated the guidance force as a function of times. Compared with the experimental results, the calculation results have almost the same trend and can qualitatively reveal the characteristics of guidance force of HTS bulk in this situation. Therefore, the guidance force decay of HTS bulk in the maglev vehicle system can be evaluated simply by this numerical method.

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Keywords: HTS bulk; AC loss; NdFeB guideway; Maglev vehicle system; Numerical

1. Introduction

Bulk superconductor can stably levitate over permanent magnets or vice versa, so it has significant potential for a variety of engineering applications [1,2], especially in high-temperature superconducting maglev vehicle system [3]. However, the HTS bulks in the system are always exposed to AC external magnetic field perturbations caused by the inhomogeneity of surface magnetic field of the NdFeB guideway [4]. Some people studied the trapped magnetic field characteristics of bulks exposed AC magnetic field and observed that the temperature of the bulk was increased due to effect of AC losses [5]. In our previous work, experimental results showed that the guidance force was decayed by the application of the AC external magnetic field [6]. We also attributed the decay of the guidance force to the attenuation of critical current density due to the temperature rise caused by AC losses. Therefore, it is necessary to evaluate the attenuation of the current density and the decay of the guidance force of the bulk over the guideway for designing high-temperature superconducting maglev vehicle system.

In this work, in order to get a better understanding and prediction of the decay of the guidance force due to the application of AC external magnetic field, we adopted an analytic model to study the attenuation of the current density caused by AC losses. And based on the analytic results and the Bean critical-state model, we calculated the guidance force as a function of times.

2. Numerical method

2.1. Analytic model

According to the critical-state model [7], for an infinitely long superconducting cylinder of radius R subject to external AC magnetic field of amplitude B_m parallel to the

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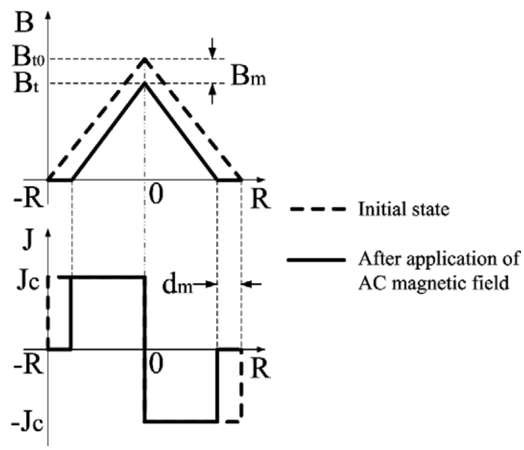

Fig. 1. Distributions of the trapped magnetic field B and current density J in the bulk exposed to AC magnetic field.

cylinder axis, the distributions of the trapped magnetic field B and current density J are shown in Fig. 1.

J_c is the critical current density of the bulk and dependent on the bulk temperature T. In the initial state, the distributions of the trapped magnetic field and the shielding current in the cylindrical bulk are shown by dashed line in Fig. 1. B_{t0} is the peak of the initial trapped magnetic field. When the bulk is exposed to AC magnetic field, the AC field will start to penetrate into the cylinder from the surface, and the penetration depth is d_m. When the AC field is decreased gradually to zero, the magnetic field and shielding currents in the penetration area will become zero [8], and the distributions of the trapped magnetic field and the shielding current in the cylindrical bulk are shown by real line in Fig. 1. B_t is the peak value of the trapped magnetic field in this state.

It must be pointed out that the temperature T of the bulk and J_c are assumed not to be changed in order to simplify the analysis. But the magnetic flux movements in the penetration areas will result in AC loss. However, the thermal conduction ability of the bulk is bad. So the temperature of the bulk will rise. Yamagishi et al. [5] observed this phenomenon in their experiments. So the critical current density J_c will be decreased due to the temperature rise. After the thermal equilibrium between the bulk and the liquid nitrogen is established, the bulk temperature T will not be changed any more, and the critical current density will be kept constant.

In order to study the time evolutions of J_c, an analytic model proposed by Zushi et al. [8] is adopted in this paper. The model is given by the following equations:

$$B_{t0} = \mu_0 J_c R$$

$$\beta = \frac{B_m}{B_{t0}}$$

$$d_m = \beta R$$

$$\begin{cases} B_t = \mu_0 J_c (R - d_m) \\ Q = 2B_m^2(2\beta/3 - \beta^2/3)/\mu_0 \end{cases} \quad \text{for } \beta < 1$$

$$\begin{cases} B_t = 0 \\ Q = 2B_m^2(2/3\beta - 1/3\beta^2)/\mu_0 \end{cases} \quad \text{for } \beta \geqslant 1$$

$$J_c(T) = J_{c0}(T_c - T)/(T_c - T_0)$$

$$C_p \frac{d\theta(t)}{dt} + \lambda\theta(t) = P(t)$$

where $\theta(t) = T - T_0$

$$P(t) = Qfv$$

$$v = \pi R^2 H$$

In this model μ_0 is the magnetic permeability of the vacuum, Q is the loss per cycle per unit volume, $p(t)$ is AC loss in the bulk, f is the frequency of AC magnetic field, v is the volume of the bulk, H is the height of the cylindrical bulk, C_p and λ are the heat capacity and the heat transfer coefficient. So the time evolutions of J_c can be evaluated based on the above equations.

2.2. Guidance force calculation

According to the critical-state Bean model, our laboratory had developed a numerical method [9] for evaluating the guidance force of the bulk over the NdFeB guideway, in which the current density distribution of the YBCO bulk was calculated by the method proposed by Prigozhin [10]. The guidance force was solved as a component of Lorentz force, which was induced by the current circulating in the HTS and the guideway magnetic field. And the guidance force F_{gui} of the bulk can be given by the following formula:

$$F_{gui} = \int_s J \times B \, ds$$

where J is the current density, B is the guideway magnetic flux density computed by the FEM method, and S denotes the cross-section of the HTS bulk. In these calculations, the HTS and the NdFeB guideway are treated as infinitely long and uniform along the guideway direction so as to simplify the calculation. And we have obtained that the calculations were agreement with the experiments in our previous work [11].

3. Experimental and numerical results

Fig. 2 is a schematic drawing of the experiment system, which was composed of a HTS maglev measurement equipment [12], a NdFeB guideway, an electromagnet, and a YBCO bulk. In this experiment, we employed the following procedure. Firstly, the YBCO bulk was placed at the center of the electromagnet, and both were fixed in the liquid nitrogen vessel, which was placed above the NdFeB guideway at a certain height. Secondly, the vessel was filled with liquid nitrogen at 77 K to let the bulk transit to the superconducting state in the presence of magnetic field generated by the guideway. We called this process field-cooling (FC).

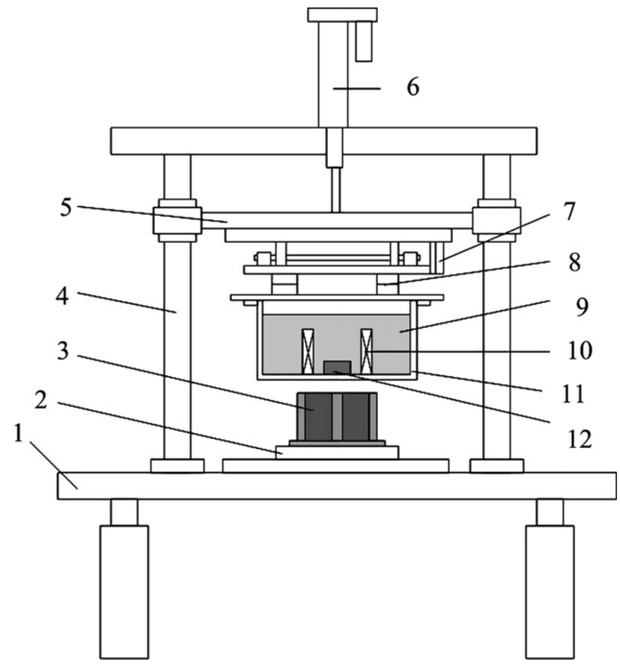

Fig. 2. Schematic drawing of the experiment system. (1) base, (2) lateral drive platform, (3) NdFeB guideway, (4) vertical guide way, (5) vertical drive platform, (6) servo motor, (7) guidance force sensor, (8) levitation force sensor, (9) liquid nitrogen, (10) electromagnet, (11) liquid nitrogen vessel, and (12) YBCO bulk.

The gap between the bottom of the bulk and the surface of the guideway was field-cooling height (FCH). Thirdly, AC external magnetic field generated by the electromagnet was applied to the bulk and the directions were paralleled to the *c* axis of the cylindrical bulk. Finally, the vessel was moved to a certain lateral displacement (LD) along the lateral direction and the guidance force as a function of time was measured. In this paper, all the FCH and the LD were kept constant and set to 15 mm and 20 mm, respectively.

Fig. 3 shows the experimental results of the time evolution of the guidance force. And the amplitudes of AC magnetic field were 0.033 T and 0.046 T. With the application of AC field, the guidance force decayed rapidly at the beginning and then relaxed to a certain lower level.

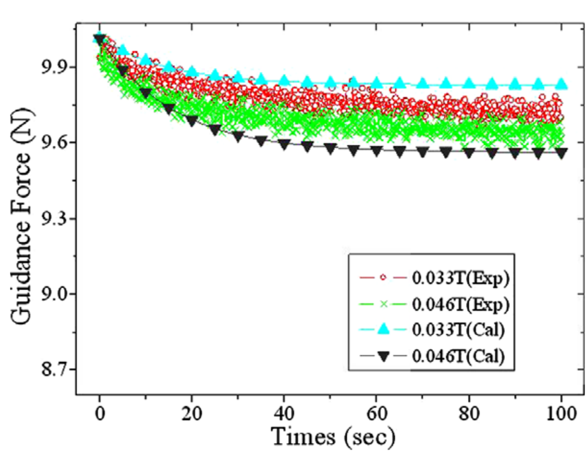

Fig. 3. Comparisons of experiment and calculated time evolutions of the guidance force.

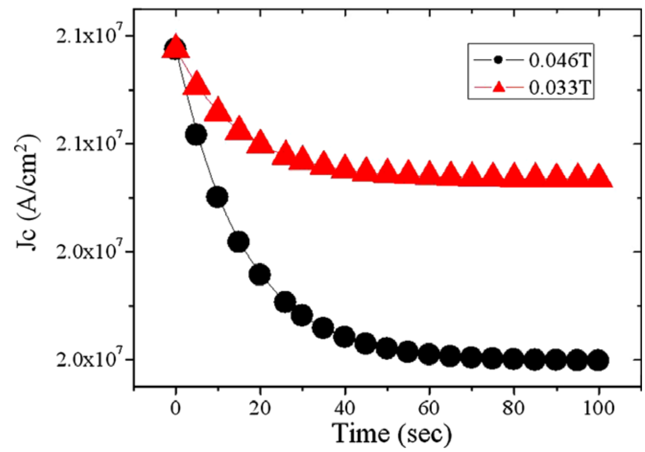

Fig. 4. Calculated time evolutions of the critical current density J_c.

Fig. 4 shows the time evolution of the critical current density J_c calculated based on the analytic model mentioned above. J_c is attenuated and finally kept constant. Based on the J_c results calculated above, we also calculated the time evolution of the guidance force. And the calculation results are shown in Fig. 3. There is a little difference in values between the experimental results and calculation ones, but the two cures have almost the same trend. In other words, the calculation results by this method can qualitatively reveal the characteristics of guidance force of HTS bulk exposed to AC magnetic field over the NdFeB guideway.

4. Conclusion

With the application of AC external magnetic field, the critical current density J_c was attenuated due to the temperature rise caused by AC losses. In this paper, J_c was calculated based on the analytic model. And according to the J_c values calculated above, the guidance forces of the YBCO bulk exposed to AC magnetic field over the NdFeB guideway was calculated. Compared with the experimental results, the calculation results have almost the same trend and can qualitatively reveal the characteristics of guidance force of HTS bulk in this situation. Therefore, the guidance force decay of HTS bulk in the High-temperature superconducting maglev vehicle system can be evaluated simply by this numerical method.

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