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Influence of the ramp angle on levitation characteristics of HTS maglev

Qingyong He *, Jiasu Wang, Longcai Zhang, Suyu Wang, Siting Pan

Applied Superconductivity Laboratory, Southwest Jiaotong University, P.O. Box 152, Chengdu, Sichuan 610031, PR China

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Abstract

The gradeability is one of the advantages of the high-temperature superconducting (HTS) maglev vehicle, and it is relative to the levitation characteristic of the maglev system on the ramp. The influence of the ramp angle on the levitation characteristics of the HTS maglev model was investigated. Some levitation characteristic parameters on the uphill guideway with different ramp angles were studied by the equivalent experiment, such as the levitation force, the levitation gap, the levitation stiffness and the guidance force. Compared with the experimental results on the horizontal guideway, it was found that the levitation gap increased, but the levitation force and the levitation stiffness decreased. The levitation gap and the levitation stiffness are considered as the main maglev characteristic parameters needed to be taken into account.

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Keywords: HTS; Maglev vehicle; Levitation characteristic; Gradeability; Ramp

1. Introduction

HTS maglev transport system is one of the perfectly prospective applications of the magnetic levitation using high-temperature superconducting (HTS) bulk [1–3]. The first man-loading HTS maglev test vehicle in the world was tested successfully on December 31, 2000 in Applied Superconductivity Laboratory, Southwest Jiaotong University, China [4]. Heretofore, more than fifty thousand passengers took the vehicle and it operated very well. At the same time, the HTS magnetic levitation measurement systems were developed [5,6] and many researches about the HTS maglev characteristics have been done. The feasibility of the man-loading HTS maglev system had been verified [7]. So the HTS maglev vehicle may be employed in the future. There may be some uphill and downhill guideway in the practical applications, but few people studied the maglev characteristic on the ramp. Compared with the operation on the horizontal guideway, some characteristic parameters of the maglev vehicle on the ramp are changed, such as the levitation gap, the levitation stiffness, the guidance force and the driving force. So it is necessary to analyze the climbing ramp process and the maglev characteristics on the ramp.

2. The analysis of the climbing ramp process

The HTS maglev vehicle system is composed of the maglev vehicle, the NdFeB guideway and the linear motor. The NdFeB guideway is composed of NdFeB, pure iron, stainless steel and screw, as described elsewhere [8]. The HTS maglev vehicle model is composed of seven HTS bulks and the liquid nitrogen vessel. To simplify the analysis, the double parallel guideways are substituted by the single guideway and the maglev model is assumed to be a rigid particle, as shown in Fig. 1. The ramp angle of the guideway is α, and the total mass of the model is m. The gravity acceleration is g.

* Corresponding author. Tel.: +86 28 87601794; fax: +86 28 87603310.
E-mail address: liand_he@163.com (Q. He).

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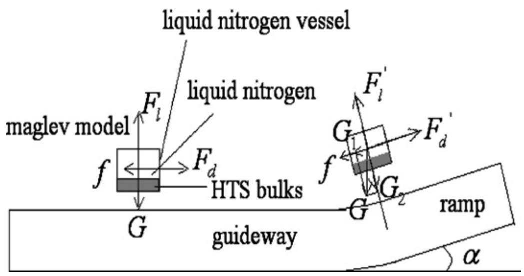

Fig. 1. Schematic diagram of the climb ramp process of the HTS maglev vehicle model.

When the HTS maglev model is on the horizontal guideway and the ramp, the mechanical relationships are given by the following Eqs. (1) and (2), respectively:

$$\begin{cases} F_l = G = m \times g \\ F_d = m \times a + f \end{cases} \tag{1}$$

$$\begin{cases} F'_l = G_2 = G \times \cos\alpha \\ F'_d = m \times a' + f + G_1 = m \times a' + f + G \times \sin\alpha \end{cases} \tag{2}$$

F_l and F'_l are the levitation force of the HTS maglev model on the horizontal guideway and the ramp. G is the total weight of the HTS maglev model. G_1 and G_2 are the component forces of G. F_d and F'_d are the driving forces on the horizontal guideway and the ramp. The acceleration of the model on the horizontal guideway and the ramp are a and a'. The air friction is f.

According to Lorentz theorem, the levitation force can be given by

$$F_l = \int_v J \times B \mathrm{d}v \tag{3}$$

J and B are the current density and the magnetic flux density, respectively.

Formula (3) shows the relationship between the levitation forces F_l and B. The magnetic flux density B over the guideway decreases with the increase of the levitation gap, so F_l also decreases with the increase of the levitation gap. From formula (1)–(3), it was concluded that the levitation force on the ramp with the angle α decreases to F'_l. Therefore, the levitation gap will increase on the uphill guideway. The maglev performance of the system will be influenced.

At the same time, because of the increase of the levitation gap, it means that the distance between the primary side and the secondary side of the linear motor which is employed to drive the HTS maglev vehicle increases, the driving force will be influenced.

Moreover, F'_d is required to overcome the component force G_1 which is caused by the ramp angle. G_1 is called as the additional driving force (ADF).

These changes may influence the operation of the vehicle and should be considered during the design.

From the horizontal guideway to the uphill guideway, although the vehicle kept paralleling to the guideway on the ramp, the relative distance between the vehicle and the guideway was not retained. Therefore, it can be thought that the change of the maglev characteristic is caused by the change of the levitation gap. Then the maglev characteristic on the ramp can be attained by the equivalent experiment on the horizontal guideway.

3. Experimental

A schematic diagram of the apparatus measuring levitation and guidance forces is shown in Fig. 2. It is a part of the superconducting magnetic levitation measurement system SCML-2, which is described elsewhere [9]. The liquid nitrogen vessel can be moved along z-axis direction and the guideway can be moved along x-axis direction by the drive platforms, so the levitation and guidance force can be measured easily.

During the experiment, the YBCO bulks array was composed of seven top-seeded melt-textured cylindrical YBCO bulks with 30 mm in diameter and 17 mm in thickness. They were arranged over the center of the NdFeB guideway as shown in Fig. 3. The YBCO bulks array was mounted in the bottom of the liquid nitrogen vessel, whose bottom thickness is only 3.5 mm. The YBCO bulks were cooled by liquid nitrogen in the magnetic field and this process is usually called field-cooling (FC). The gap between the bottom of the bulk and the surface of the guideway was field-cooling height (FCH). In this experiment, the FCH was 25 mm. When the YBCO bulks transited to the superconducting state, the levitation and guidance forces were measured.

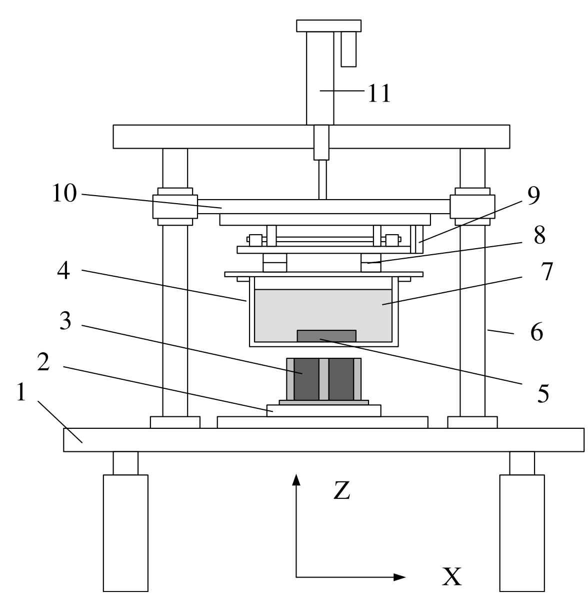

Fig. 2. Schematic diagram of the apparatus used in the experiment. 1 base 2 lateral drive platform 3 NdFeB guideway 4 liquid nitrogen vessel 5 YBCO bulk array 6 vertical guideway 7 liquid nitrogen 8 levitation force sensor 9 guidance force sensor 10 vertical drive platform 11 servo motor.

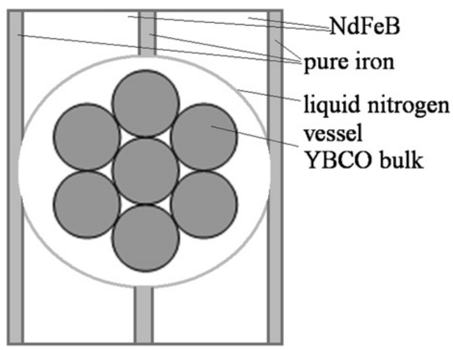

Fig. 3. Schematic diagram of the arrangement of the YBCO bulks.

4. Results and discussion

4.1. Levitation force

The data of the levitation forces of the HTS bulks array from the gap of 10–60 mm were obtained by this experiment, which is shown in Fig. 4. The influence of the weights of the components 4, 5 and 7 in Fig. 2 on levitation force was eliminated automatically by the measurement system. The relationship between the levitation force and levitation gap was fitted by exponential fit method [10] using the formula (4) and polynomial fit method using the formula (5). The results were shown in Fig. 5. It was found that the polynomial fitting curve was better. So formula (5) was adopted in the following analysis:

$$\begin{cases} F_1 = ae^{bz} \\ a = 634.3077 \\ b = -0.2065 \end{cases} \quad (4)$$

$$\begin{cases} F_1 = a_3 \times z^3 + a_2 \times z^2 + a_1 \times z + a_0 \\ a_3 = -0.0101 \\ a_2 = 0.8080 \\ a_1 = -22.6942 \\ a_0 = 222.9379 \end{cases} \quad (5)$$

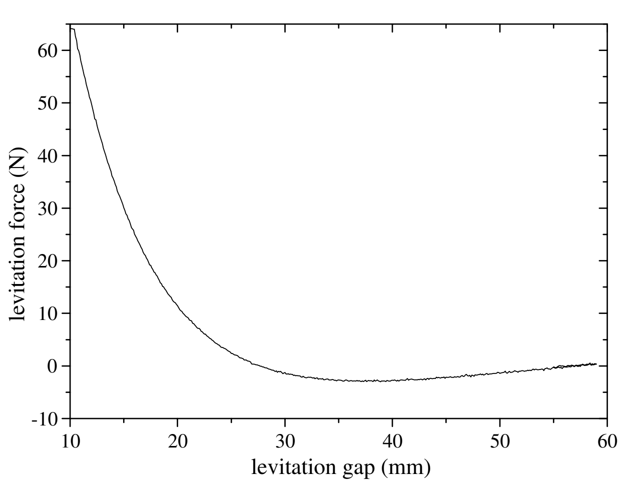

Fig. 4. The levitation forces of the HTS bulk array at different levitation gaps.

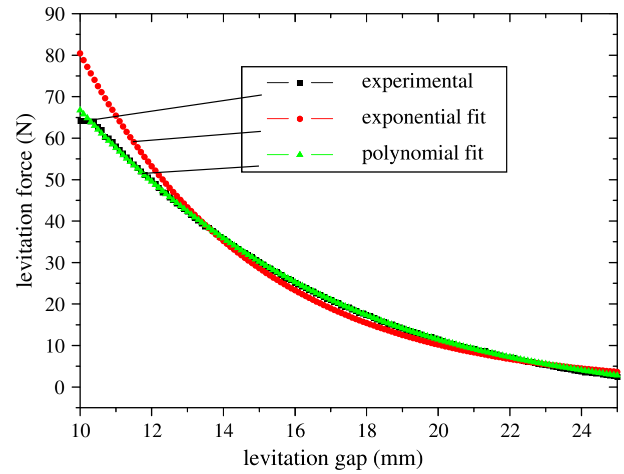

Fig. 5. Comparison of the experimental and the fitting curve.

4.2. Levitation gap

From formula (5), the levitation force at the levitation gap of 10 mm can be calculated easily and the value is 66.7 N. It was assumed that the weight of the model was 66.7 N. Taking into account that the weight of the levitator is equal to the levitation force in a stably levitating state, so it was concluded that the levitation gap of the model on the horizontal guideway was 10 mm. The levitation forces needed on different ramps can be calculated by the formula $F_1' = G \times \cos\alpha$. According to the levitation forces needed on different ramps and the formula (5), the levitation gaps of the model on different ramps were calculated, as shown in Fig. 6. It shows that the levitation gap increases with the ramp angle, and the increase is quicker and quicker.

4.3. Levitation stiffness

The levitation stiffness was defined as [11]

$$\kappa = -\frac{\partial F_1}{\partial z} \quad (6)$$

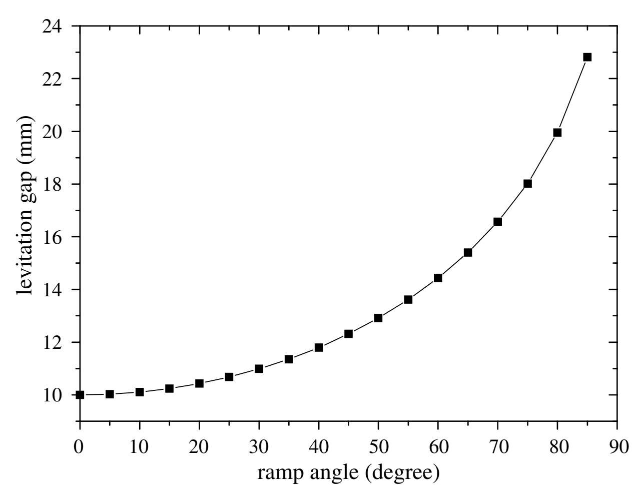

Fig. 6. The levitation gap of the model with the weight of 66.7 N on different ramps.

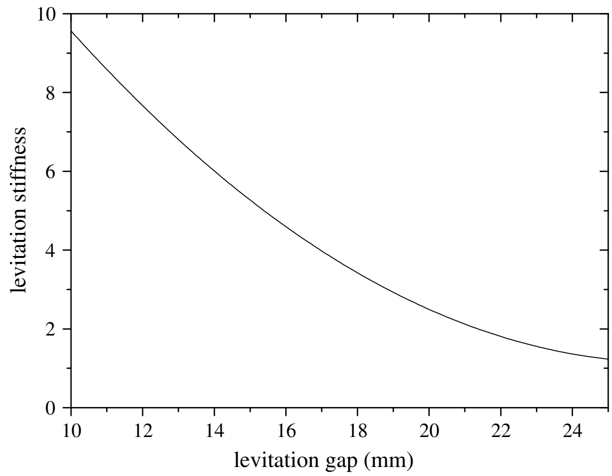

Fig. 7. The levitation stiffness of the model at different levitation gaps.

The levitation stiffness was calculated by formula (5) and (6). The stiffness curve is shown in Fig. 7. We can see that the stiffness decreases with the levitation gap.

4.4. Guidance force

Fig. 8 shows the guidance forces of the model with different lateral displacements (LD) at different levitation gaps. When the LD is 2, 4, 6, 8 and 10 mm, respectively, the guidance force almost did not decrease when the levitation gap increased 1 mm. So it can be thought that 1 mm increase of the levitation gap can not influence the guidance force. From Fig. 6, we can see the increment of the levitation gap reaches 1 mm when the ramp angle is 30°. That is, it can not influence the guidance performance of the system when the ramp angle is less than 30°.

4.5. Comparison

Table 1 shows the characteristic parameters of the maglev model on the ramp. When the levitation gap increases

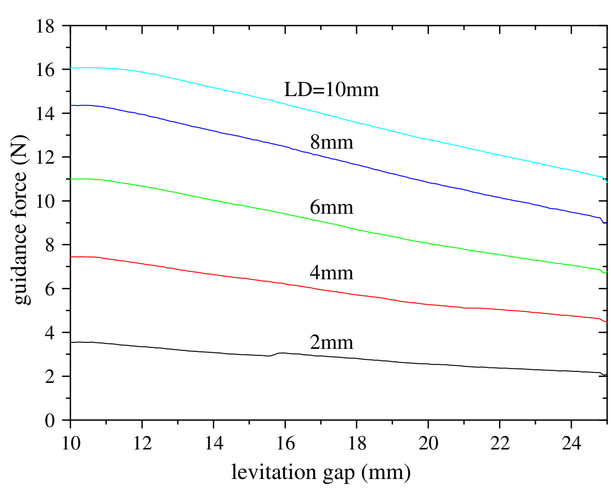

Fig. 8. The guidance forces of the model with different LD at different levitation gaps.

Table 1
The characteristic parameters of the model on the ramp

	Condition	
	A	B
Increase of the levitation gap (mm)	1	0.48
Levitation gap on the ramp (mm)	11	10.48
Decrease of the levitation force (%)	13.6	6.7
Decrease of the levitation stiffness (%)	10.2	5
Decrease of the guidance force with the LD of 6 mm (%)	0.59	0
Ramp angle (degree)	30.23	21.07

Condition A: increase of the levitation gap is 1 mm.
Condition B: increase of the levitation gap is 0.48 mm.

1 mm from 10 mm to 11 mm, the levitation force and the guidance force decrease by 13.6% and 0.59%, and the ramp angle reach 30 degrees. But the decrease of the levitation stiffness reaches by 10.2% which is disadvantageous for maglev system. When the levitation stiffness decreases by 5%, the levitation gap increases 0.48 mm. The ramp angle reaches 21°. The levitation force decreases by 6.7% and the guidance force does not decrease. So it is thought that the changes of the maglev characteristic on the ramp, which is less than 21°, are small and may be acceptable for the HTS maglev model. The result is advantageous for the gradeability of the HTS maglev vehicle. Certainly, there are some other factors which should be taken into consideration for the gradeability.

From the above analysis, we can conclude that the levitation gap of the HTS maglev model will increase, but the levitation force and the levitation stiffness will decrease. The guidance force almost will not decrease when the ramp angle is less than 21°. The levitation stiffness is relative to the levitation force. The increase of the levitation gap influences the driving force of the linear motor. Therefore, the levitation gap and the levitation stiffness can be considered as the main levitation characteristic parameters which should be taken into consideration during the climb ramp process.

More deep researches will be done next step, such as the climbing ramp experiment of the vehicle, the maximal gradeability of the HTS maglev vehicle, the connection between the horizontal guideway and the uphill guideway.

5. Conclusion

From the horizontal guideway to the uphill guideway, the levitation gap of the HTS maglev vehicle will increase, but the levitation force and the levitation stiffness will decrease. The levitation gap and the levitation stiffness are considered as the main maglev characteristic parameters which should be taken into consideration during the climbing ramp process. For the HTS maglev model, it is thought that the changes of the maglev characteristic on the ramp, which is less than 21°, are small and may be acceptable. The result is advantageous for the gradeability of the HTS maglev vehicle.

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