Characteristic of the Guidance Force in the High- T_c Superconducting Levitation System with Pre-Load Process

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Abstract The stable levitation above permanent magnet is an important characteristic of the bulk high- T_c superconductor (HTS). When an external force pushes the bulk HTS up, down or sideways, or tries to tilt it, a restoring force can return it to its initial position. The HTS Maglev relied on this characteristic can overcome the external force from wind or pass the curve lines successfully. The change of guidance force (GF) during many times lateral movement is studied. Experiments show that GF increases during the lateral movement, no matter what kind of PMG or HTS is used, and the change of the GF slows down after 5 times lateral movement. The pre-load method can reduce the levitation force decay during lateral movement. So the influence of GF by the pre-load method is needed to be studied. It is found that the pre-load method can increase GF and reduce the change of the GF during lateral movement. The Halbach permanent magnetic guideway (PMG) can offer much more GF but the change is larger just as the levitation force decays. The GF of cylindrical bulk HTS increases more than of the rectangular bulk HTS in the pre-load case. The characteristics of the GF during the lateral movement are explained. These results are important for further HTS Maglev vehicle system designs.

Keywords Guidance force (GF) · High-temperature superconductor (HTS) · Permanent magnetic guideway (PMG) · Pre-load

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1 Introduction

High-temperature superconducting levitation technology is widely studied for the applications in transportation system, bearing and so on due to the auto-stability without control. When the high-temperature superconductor (HTS) is pushed laterally, guidance force (GF) can pull it back to the original position. This characteristic ensures that the Maglev passes through the curve lines successfully. The maximum speed of high-temperature superconducting Maglev is deemed to reach over 600 km/h [1], so the Maglev will displace from the center line of the permanent magnetic guideway (PMG). Other reasons, such as the thrust of wind, will lead to lateral movement and lateral movement results in the levitation force (LF) decay [2]. But change of GF above PMG during lateral movements has not been researched widely.

Hull and Cansiz [3] studied the LF and GF between one permanent magnet (PM) and one HTS in the lateral movement. Zheng and Yang [4] studied the stable condition between cylindrical HTS and rectangular PM. Del-Valle et al. [5–7] theoretically analyzed the levitation force of a system consisting of an infinitely long superconductor over an infinitely long PMG using a realistic model, and gave the physical keys for reduction of the levitation force after lateral movement. Song et al. [2] studied the levitation capability of the HTS Maglev above PMG during the lateral movements and found that LF reduces but GF keeps constant. Ma et al. [8] pointed out that the pre-load method is very applicable to suppress LF decay of the bulk HTS, and this effect can be ascribed to the reduction of the hysteretic loss in the bulk HTS, i.e. more trapped magnetic flux after the pre-load case. Experimental results indicate that the Halbach

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PMG has an advantage to reduce the cost of the PMG, but its rate of the LF decay is also larger in lateral movement.

In this paper, the influence of GF by the lateral movements with and without pre-load will be discussed.

2 Experimental Details

For universality, two different YBCO samples and two types of PMGs are involved. The structures of the PMGs are different; the cross sections of PMG1 and PMG2 are shown in Fig. 1. The structure of PMG1 is similar to the PMG which was used in the first HTS Maglev system in the world [9–12]. PMG2 is named as Halbach PMG, and produces sinusoidal magnetic field on one side while a minimal field on the other side [13]. The C HTS sample is cylindrical with 48 mm diameter and 12 mm thickness. The R HTS sample is rectangular with of 68 mm length, 33 mm width and 13 mm thickness. The trapped magnetic field reaches 0.2 T in the excitation field of 0.9 T for the C sample and the R sample can reach 0.8 T in the field of 1.3 T. That is to say, the quality of the R sample is better.

Fig. 1 The cross sections of (a) PMG1 and (b) PMG2

Fig. 2 GF of the R sample above PMG1 for non-pre-load and pre-load cases (the horizontal lines represent the average of GF during the last 5 times lateral movement, the same as in Figs. 3–5)

The Maglev measurement system can record the vertical and horizontal force signals simultaneously during the lateral movement. More detailed information on the measurement system can be found in Ref. [14].

At the beginning of the experiment, the samples are put above the center of PMG, and the shorter side of the R sample is parallel to the direction of PMG. In the pre-load process, the samples are first field-cooled in liquid nitrogen at the height of 30 mm (distance between the bottom of the sample and the surface of the PMG) for about 15 minutes, and then lowered to 12 mm for a relaxation time of 360 s. Subsequently, the sample is raised to 15 mm, and after the second relaxation time of 360 s the PMG is driven by a motor along the lateral direction to move a displacement of 6 mm. At the endpoint of lateral movement, the GF is measured as the first data. Then the PMG is driven to the opposite direction for a displacement of 12 mm, and turned back to the original lateral position with 6 mm displacement to get the second GF data. The next 13 data are obtained by the same operation. In this course of lateral movements, the speed of the PMG is 0.5 mm/s. For the non-pre-load case, after the samples are lowered to 15 mm with a relaxation time of 360 s, the measurements are taken directly.

3 Results

Figure 2 shows the GF of the R sample during the lateral movement above PMG1. For a non-pre-load case, the first GF is 2.953 N. Then the value tends to increase with the time during lateral movements, despite that some values reduce. The 15th value becomes 3.347 N and is about 13.34% larger

Fig. 3 GF of the C sample above PMG1 for non-pre-load and pre-load cases

Fig. 4 GF of the R sample above PMG2 for non-pre-load and pre-load cases

than the first one. For the pre-load case, the GF increases from 3.582 to 3.644 N. The maximum value appears in the 5th time and is 3.648 N. The GF changes slightly in the pre-load case. The pre-load method is helpful to increase the GF and decrease the change of GF during lateral movements.

Figure 3 gives the GF curves for the C sample during the lateral movements above the PMG1. For the non-pre-load case, the GF increases almost linearly from 1.412 N to the 4th value of 1.663 N, and then the increase slows down. The last value is 1.888 N and about 133.71% of the first one. For the pre-load case, the maximum increase is 0.158 N between

the second and the first values. Change of GF is gradually decreasing during the continuing lateral movement and the last value is 2.942.

Figure 4 shows the GF curves for the R sample moving across the PMG2. In the non-pre-load case, the 1st and the 3rd GFs are 7.613 N and 9.042 N. Then the GF changes circuitously. The last GF is 9.379 N and 23.2% larger than the initial one. In the pre-load case, the curve can be divided into three phases: the increasing phase, the middle phase and the decreasing phase. The last GF is just 0.346 N larger than the initial one.

Fig. 5 GF of the C sample above PMG2 for non-pre-load and pre-load cases

Table 1 The GF parameters

Type	Process	$F_{g,av}$ (N)	K	T	U	D (N)
R sample, PMG1	Non-load	3.3246		109.19%	113.34%	1.4996
	Pre-load	3.6302			101.73%	0.3384
C sample, PMG 1	Non-load	1.8576		157.4%	133.71%	1.8946
	Pre-load	2.9238			115.24%	1.4498
R sample, PMG 2	Non-load	9.3382	280.88%	104.56%	123.2%	5.2648
	Pre-load	9.7636	268.95%		103.76%	2.1444
C sample, PMG 2	Non-load	8.1036	436.24%	127.43%	107.08%	2.692
	Pre-load	10.3266	353.19%		108.42%	3.5532

Figure 5 shows the GF curves for the C sample moving across the PMG2. The second value jumps to 8.896 N from 7.771 N for non-pre-load case. In succession, the value decreases to 8.567 N and the last GF is 8.321 N. For the pre-load case, change of the GF is fluctuant. The initial GF is 9.794 N and the last GF is 0.825 N larger than the initial one.

4 Discussion

For analyzing the change of GF during lateral movements, we will calculate the following parameters:

$$F_{g,av} = \frac{F_{g,11} + F_{g,12} + F_{g,13} + F_{g,14} + F_{g,15}}{5}, \quad (1)$$

$$K = \frac{F_{g,av,P2}}{F_{g,av,P1}}, \quad (2)$$

$$T = \frac{F_{g,av,lo}}{F_{g,av,non-lo}}, \quad (3)$$

$$U = \frac{F_{g,15}}{F_{g,1}}, \quad (4)$$

$$D = \sum_{i=1}^{15} |F_{g,av} - F_{g,i}|. \quad (5)$$

$F_{g,av}$ is the average of GF during the last 5 times lateral movements and it is considered to be the final value of the GF after many lateral movements. K is the ratio of $F_{g,av}$ above the PMG2 to PMG1 at the same measurement conditions and it represents the influence by different PMGs. T is the ratio of $F_{g,av}$ for pre-load to non-pre-load cases and represents the influence of GF by the pre-load method. U is the ratio of the last GF to the initial GF and it represents the change of GFs during the lateral movements. D represents the variation of all GFs relative to $F_{g,av}$. These parameters are listed in Table 1 and discussed below.

The GF above the PMG2 is larger than the PMG1. K of the R sample is 280.88% and 268.95% for non-pre-load and pre-load cases. For the C sample, it is 436.24% and 353.19%, respectively. This can be explained by the mag-

Fig. 6 The magnetic field distributions of two PMGs

netic field of the two PMGs. As shown in Fig. 6, the peak value of vertical and horizontal components of magnetic field of PMG2 is larger than that of PMG1. And the GF can be denoted by

$$F_{\text{gui}} = \int J \times B_z ds, \quad (6)$$

where J is the current density in the HTS, B_z is the vertical component of magnetic field, ds is the area where the superconducting current flows. J is determined by

$$J \propto \partial B / \partial z. \quad (7)$$

$\partial B_z / \partial z$ denotes the rate of change of magnetic field along the z axis. B_z and $\partial B / \partial z$ of PMG2 are larger than of PMG1, so the GF above PMG2 is larger.

The GF becomes larger after pre-load, T of the R sample above PMG1 and PMG2 is 109.19% and 104.56%. T of the C sample is 157.4% and 127.43%. As we know, at the same measure height, the GF increases when the decrease of the field cooling height is due to the increase of the trapping magnetic field [10]. In the procession of the pre-load cases, the HTS traps more magnetic flux, so the GF increases.

From the values of U , the last GF is larger than the first one. It is pointed out that when the magnetic field changes, the magnetic force increases caused by the hysteresis of shielding current. This is referred to as the hysteretic hardening effect [15]. And it is considered to relate to the interaction between the trapped magnetic field and the PM's magnetic field. Based on this idea, we think that the increase of GF is relative to the change of the magnetic field and the re-magnetization of the HTS during lateral movement.

The change of GF slows down during the lateral movement. This can be seen in Figs. 2–5, where the GFs during

the lateral movement approach toward the lines which denote the value of $F_{g,av}$. The result can be explained by the current profiles which become more similar to each other or even identical when the HTS move laterally [5]. When the current in the interior of HTS becomes identical, the change of GF slows down in the process of lateral movement.

From the value of D , the change of GF during the lateral movements is reduced after pre-load, but not for the C sample above PMG2. In the course of pre-loading, more magnetic flux is trapped by HTS at a lower height than the measure height before lateral movement. So during the lateral movements, the probability of changing the trapping magnetic flux inside the HTS reduces [8], and so the change of GF is reduced. The change of GF for the C sample above PMG2 is larger in the pre-load case, which may be relative to the higher magnetic field of PMG2 than PMG1, and the quality of the C sample is weaker just as mentioned above.

The change of GF is larger above PMG2 during lateral movement (see the values of D for the two PMGs). At the same time, the experiment showed that the LF decay is larger above PMG2 [8], and the levitation force is reduced when the HTS moves laterally, because some of the currents that have been induced contribute negatively to the vertical force. The reason why the change of the GF and the LF decay is larger above PMG2 may be that the magnetic field of PMG2 is larger than of PMG1, and the change of magnetic field is also larger during lateral movements.

GF of the C sample increases more in the pre-load case (see the values of T in Table 1). For example, T is 157.4% for the C sample above PMG1, but T is just 109.19% for the R sample. GF of the C sample increases more above PMG2 than above PMG1 (see the values of K). For example, K is 436.24% for the C sample in the non-pre-load case, but it is just 280.88% for the R sample. All of these can be explained

by the quality of the C sample being weaker, so that more magnetic flux penetrates into the C sample and is trapped by it during the course of pre-loading.

The GF of the R sample is much larger than that of the C sample, except for the pre-load case above the PMG2. It is easy to see that the bottom area (2244 mm^2) of the R sample is 24% larger than of the C sample (1809 mm^2), so the GF of the R sample is larger. Because the C sample will increase more than 2 N in the pre-load case and the R sample will increase about 0.43 N, the GF of the C sample above the PMG2 will larger than that for the R sample after pre-load.

5 Conclusion

The Halbach PMG can offer larger GF and LF due to its larger magnetic field. But the change of GF above PMG2 in the lateral movement is also larger. This is another point which we have to consider in practical application beside the larger rate of LF decay caused by the lateral movement.

The pre-load method can increase the GF and reduce the change of the GF and the LF decay by the lateral movement, so this method will be suitable for the practical applications.

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