Anisotropy effect on levitation performance of bulk high-$T_c$ superconductors above a permanent magnet guideway

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Abstract

The anisotropy properties of bulk high-temperature superconductors (HTSCs) are taken into consideration for the application of high-temperature superconducting (HTS) Maglev systems, which are especially based on the different flux-trapping capabilities as well as critical current density, $J_c$, values between the growth section boundary (GSB) and the growth sections (GS) in bulk superconductors. By adjusting the angle between the GSB of bulk HTSCs and the strongest magnetic field position of a permanent magnet guideway (PMG), the levitation force and its relaxation processes are compared at different field-cooling conditions. Experimental results show that the levitation capability and the suppression of levitation force decay can be enhanced by optimizing the GS/GSB alignment of every bulk HTSC above the PMG. Meanwhile, our conclusions may provide references to other HTS maglev systems with small levitation gaps, i.e., superconducting magnetic bearings.

1. Introduction

Up to now, top-seeded melt-textured (TSMT) bulk high-$T_c$ superconductors (HTSCs) have been widely applied to various industries, such as high-temperature superconducting (HTS) Maglev vehicles, HTS magnetic bearings and HTS flywheel energy storage systems. As a significant functional component, bulk HTSC can play the role of realizing a self-stabilizing levitation together with a magnetic field source. Lots
of attention and effort have been put into how to fabricate large-sized high-performance bulk HTSCs [1, 2], how to optimize the configuration of the applied magnetic fields [3, 4], explore the suitable magnetization methods [4, 5], study the coupling relation rules and other efficient improvement ways [4, 6].

Although the larger-sized higher-performance bulk HTSCs are desirable for the engineering application, the current fabrication technology cannot meet application demands. Consequently, researchers still have to arrange many bulk HTSCs together to accomplish their goals. On one hand, people began to pay more attention toward the anisotropy effects in normal-sized bulk HTSCs and the possible effects on levitation performance in an applied magnetic field. For example, a 2.27 times larger levitation force or 10.2 times larger guidance force was obtained above a Halbach permanent magnet guideway (PMG) when the about three times larger critical current density, \( J_c \), of \( ab \) plane compared with \( J_c \) of the \( c \) axis is made the best combination with the magnetic field distribution [7]. As to the other grain-growth anisotropy, it was found that the seed-face part of a bulk superconductor has a better superconducting performance and should be aligned as close as possible to the higher magnetic field density region for better magnetization, also referred to as the grain-alignment procedure. This grain-alignment way helped increasing the levitation force of the bulk HTSC array in the PMG magnetic field [6]. In addition to the optimization result of PMG configuration, it was reported that about a 15% enhancement of levitation or guidance force was achieved [8]. Taking the first man-loading HTS Maglev test vehicle as an example, considering the above grain-alignment effect and the optimized HTSC array, 344 TSMT onboard YBaCuO bulks were assembled and realize to operate stably for over ten years [9]. On the other hand, the TSMT bulk HTSC has 5 growth sectors (GSs), which macroscopically show different flux-trapping capabilities and different \( J_c \) values between GSs and their growth sector boundary (GSB) [10]. It was reported that the peak trapped magnetic field was increased by 18% and the total trapped flux was increased by 6.6% due to suitable GS/GSB alignment [11]. And it is still not clear how the difference in \( J_c \) influences the levitation performance of the HTS Maglev above the PMG. Thus, it is necessary to further investigate the GS/GSB anisotropy of YBaCuO bulks and their effect on levitation performance from the point-view of HTS Maglev applications. Moreover, in the present real HTS Maglev demonstration system, the onboard bulk HTSCs have usually been placed at random without optimizing each bulk to match them with the magnetic field distribution. Therefore, it is also desirable to find an easy and feasible guide for the HTSC arrangement like other improvement operation ways for the engineering of the HTS Maglev vehicle system.

2. Experimental

Three cylindrical YBaCuO bulks with 31 mm in diameter and 16 mm in thickness from Germany and the other three cylindrical YBaCuO bulks with 31 mm in diameter and 14 mm in thickness from Beijing were used as two respective arrays in zero-field cooling (ZFC) and field-cooling (FC) experiments as shown in Fig. 1. The applied magnetic field was supported by a Halbach PMG [8].

Similarly with the work of the \( ab \) plane/\( c \) axis anisotropy, the direct experiment purpose is to assemble better flux-trapping regions of each bulk HTSC at the high magnetic field region for better magnetization utilization as well as maglev performance. To display the comparison results better, three bulks were lined one by one along the extension direction of the PMG, whose seeds’ position was right above the highest magnetic field, \( B_{z_{-max}} \), position. Fig. 2 presents the typical magnetic field distribution of the Halbach PMG and the assembling position of bulks YBaCuO.

To find the suitable GS/GSB alignment, the angle between GSB and the \( B_{z_{-max}} \) position was set as 0º and 45º, respectively. When the angle was set as 0º and one GSB was in parallel with the \( B_{z_{-max}} \) line with a lateral displacement \( LD=-25 \) mm from the center of the Halbach PMG shown in Fig. 2, it is called as the
aligned growth section boundary pattern (AGSBP). The condition of 45° is so called as the misaligned growth section boundary pattern (MGSBP). All the ZFC and FC experiments were performed at liquid nitrogen temperature on an updated HTS maglev measurement system SCML-02 [12]. The FC heights (FCH) were 10 mm, 15 mm, 20 mm, 25 mm, 30 mm and 40 mm, which were the initialization cooling heights of the bulk array above the upper-surface of the PMG. ZFC means HTSC is far away from the magnetic field, which was set as 100 mm height above the upper-surface of the PMG. And the cooling time was 15 minutes to ensure that all YBaCuO bulks can enter the superconductivity state.

3. Results and discussion

The levitation force and its relaxation processes were measured above the PMG to fully explore the different effects on the load capability and the relaxation decay for the HTS Maglev application between AGSBP and MGSBP in the paper.

3.1. Effect on levitation force

By SCML-02, levitation force of each bulk array was respectively measured at different FCH conditions along the test loop from 60 mm to 10 mm height above the upper-surface of Halbach PMG after the 15 min initialization cooling process.

Fig. 3 - Fig. 6 show the comparison results of different YBaCuO arrays with the same GS/GBS alignment at the 10 mm, 15 mm, 20 mm, 25 mm, 30 mm and 40 mm FCH and ZFC conditions.

Firstly, it is found levitation force enhances with the increasing FCH regardless of the GS/GBS alignment and the material source. This phenomenon is the same as the previous conclusion of levitation force and FCH when HTSC bulks are assembled at random, which can be explained by the Bean model and Lorentz equation. Attributed to the exponential decay of the magnetic field along the height above the upper-surface of PMG, the quantity of flux trapped by HTSC bulk is reduced with the increasing FCH after the HTSC bulk enters the superconductivity state. The residual changeable flux of HTSC bulk can be more at the higher FCH condition than the lower FCH condition. After the same measurement loop as well as the same magnetic field variation, HTSC bulk with more residual changeable flux can trap more
flux and then produce the larger induction current inside the HTSC. According to the Lorentz equation, the larger levitation force will be produced as a result with the AGSBP.

This relationship exists and even displays more obviously as shown in Fig. 3-Fig. 6 when HTSC bulk is assembled orderly with consideration of the GS/GB alignment. It further proves the availability of the relationship between the levitation force and FCH in the HTS maglev system. Therefore, regarding the application of the HTS Maglev vehicle system, it is recommended to choose a suitable FCH as one initialization step. It is important for some more running factors including load capability, lateral recoverable capability, decay suppression etc.

Secondly, it is noticeable and interesting that the maximum levitation forces of AGSBP are larger than those of MGSBP as shown in Fig. 7. The difference between AGSBP and MGSBP with the decreasing FCH becomes smaller because the levitation force decreases with the decreasing FCH which makes the difference value not so viewable. But, about 10 N and the maximum 8.31%, levitation force increment per an YBaCuO array were obtained by changing the GS/GAB alignment from MGABP to AGSBP. It can be predicted that the average maximum 4.16% levitation force increment can be realized if people assemble the onboard HTSC with AGSBP consciously above the Halbach PMG.

![Fig. 3. Levitation forces of AGSBP of Germany YBaCuO array at different FCHs and ZFC.](image1)

![Fig. 4. Levitation forces of MGSBP of Germany YBaCuO array at different FCHs and ZFC.](image2)

![Fig. 5. Levitation forces of AGSBP of Beijing YBaCuO array at different FCHs and ZFC.](image3)

![Fig. 6. Levitation forces of MGSBP of Beijing YBaCuO array at different FCHs and ZFC.](image4)
3.2. Effect on levitation force relaxation

To compare and evaluate the levitation performance between AGSBP and MGSBP, levitation force relaxation experiments were further purposed between Germany YBaCuO array and Beijing YBaCuO array respectively at the 10 mm, 15 mm, 20 mm, 25 mm, 30 mm and 40 mm FCH and ZFC conditions. The levitation force relaxation experiments were carried on as follows: levitation forces of the different YBaCuO arrays were continuously measured for 300 s at a constant working height of 10 mm above the PMG after the initialization cooling. Then, the value of levitation force with time was plotted and usually displayed as an exponential decay and saturation process.

By the curve of levitation relaxation process, the levitation decay rate is defined as:

\[ \eta = \frac{F_{\text{lev}_\text{max}} - F_{\text{lev}_\text{min}}}{F_{\text{lev}_\text{max}}} \times 100\% \]  

(1)

where \( F_{\text{lev}_\text{max}} \) and \( F_{\text{lev}_\text{min}} \) are the maximum and minimum values of levitation force. This parameter can judge the load capability and levitation stability of the HTS Maglev vehicle system in practice.

Fig. 8 shows the different \( \eta \) between AGSBP and MGSBP. The levitation force decay rate of AGSBP is always smaller than that of MGSBP no matter what HTSC material source and FCH were decided. Compared with MGSBP, the maximum 2.26% decrease of the levitation decay was achieved in Fig. 8.

Moreover, combined with the results of Fig. 7, it implies that the GS/GB alignment of AGSBP produces larger levitation force and lower levitation force decay rate than that of MGSBP. It implies that the flux-trapping capabilities of GS and GSB of AGSBP were made the best of the magnetic field where their positions were placed, which is being simulated in the next step of the research.

4. Conclusion

The levitation force as well as its relaxation of two configurations that align and misalign the GS and GSB orientations of TSMT YBCO samples to the strongest magnetic field density values of a Halbach PMG was studied in order to apply it to the further development of the HTS Maglev system. Experimental results indicate that the aligned AGSBP configuration does help to enhance the levitation capability up to 8.31 % and suppress the relaxation decay of the levitation force down by 2.26% from the...
studies of two different batches of samples. This enhancement was also independent of the FCH conditions. The results of these experiments have allowed us to also calculate that the levitation force of the Century Maglev Vehicle can be further increased by 4.16% if the GS and GSM of the onboard HTSCs were realigned to the AGSBP configuration with respect to the applied magnetic field distribution of the PMG. Consequently, the levitation force relaxation, guiding forces and other running factors of the HTS Maglev vehicle system will also be enhanced.

Acknowledgements

This work was partially supported by the Science & Technology Pillar Program in Sichuan Province (2009SZ2012), Star of Sishi Program in Southwest Jiaotong University and Traction Power State Key Laboratory of Southwest Jiaotong University (2009TPL_Z01).

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