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Optimization study of the Halbach permanent magnetic guideway for high temperature superconducting magnetic levitation

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Abstract

Due to the combined advantages of no-contact friction and self-stable levitation, high temperature superconducting magnetic levitation (HTS Maglev) has significant potential for rail transit applications. In order to further improve the carrying capacity of the HTS maglev system, it is necessary to optimize the permanent magnet guideway (PMG). In this paper, the original Halbach PMG was optimized and a new PMG with better performance was designed and manufactured. The magnetic field and magnetic forces were calculated by the finite element method, and the size and magnetization direction of each PM in the PMG were optimized. Then, the magnetic field above the optimized PMG were measured and compared with the original Halbach PMG as well as the levitation and guidance force of the bulk high temperature superconductors. Experimental data show that the magnetic field above the optimized PMG is effectively enhanced and the levitation and guidance force of the superconductors increase by 12.2% and 11.3%, respectively. This study can provide the foundation for the further optimization of PMGs and the research of large load HTS Maglev technology.

Keywords: high temperature superconductors, Halbach PMG, maglev optimization, magnetic field, magnetic forces

(Some figures may appear in colour only in the online journal)

1. Introduction

High temperature superconductors (HTSCs) have aroused great interest since they were discovered [1]. Bulk superconductors have now been widely used in many fields, such as rail transit applications [2], superconducting bearings [3], no-contact superconducting mixers [4] and flywheel energy storage systems [5]. Especially in the field of rail transit, HTSCs have tremendous prospects for application. Because of the magnetic flux pinning characteristics of superconductors, they can be suspended in a magnetic field without consuming electricity. Based on this phenomenon, Southwest Jiaotong University developed the first people carrying high-temperature superconducting magnetic levitation (HTS Maglev) test vehicle in 2000 [2]. Subsequently, many countries begun to start development of HTS Maglev vehicles. At present, many countries have successfully developed HTS Maglev prototypes such as Brazil [6], Germany [7], Japan [8], Italy [9] and so on.

The applied magnetic field is an essential prerequisite for magnetic levitation. A permanent magnet guideway (PMG) is employed to provide the applied magnetic field in a HTS

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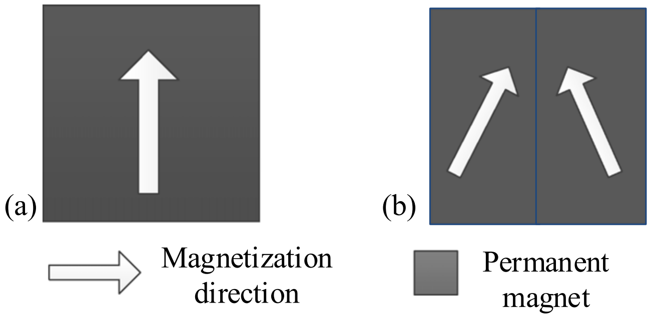

Figure 1. (a) Single permanent magnet; (b) Two pieces of permanent magnets.

Maglev system. The performance of the PMG directly determines the levitation performance of the HTS Maglev system. Therefore, researchers from different countries have carried out many optimization studies on PMGs. The world's first poeple carrying HTS Maglev vehicle adopted a single-peak PMG, which was composed of two permanent magnets (PMs) with opposite magnetization directions and iron plates. A series of size optimization studies were then carried out [10]. The HTS maglev system in Germany used a similar PMG [7]. Based on the Halbach array, Southwest Jiaotong University developed a bimodal PMG, whose performance was greatly improved compared with that of the single-peak PMG [11–13]. This Halbach PMG was successfully applied in the HTS Maglev ring test line [14]. Now, many researchers have applied the Halbach PMG to HTS maglev systems and made many optimizations. Researchers from the Federal University of Rio de Janeiro modified the Halbach PMG by replacing parts of the PM with iron blocks to generate a more uniform magnetic field above the PMG [15]. Researchers from the Huazhong University of Science and Technology improved the iron base of the Halbach PMG to make it easier to install [16]. Additionally, a series of optimization studies have been executed on the size and number of PMs required in the Halbach PMG [17–19]. It can be seen that current optimization of Halbach PMGs mainly focus on the size of the PMs and the distribution of iron plates, while ignoring the influence of the magnetization directions of PMs on the magnetic field above the PMG.

Nowadays, a large carrying capacity is still required for HTS maglevs towards the aim of realistic application. Additionally, because the PMGs are made of rare earth materials, the quantity of PM materials needs to be considered. In order to further improve the levitation performance of HTS maglevs, optimization studies for the PMG are necessary.

In this paper, by optimizing the size and magnetization direction of the PMs in the original Halbach PMG, the magnetic field is improved as well as the levitation and guidance forces of the HTSC above the PMG while keeping the PMG cross-sectional area unchanged. In addition, the original PMG and optimized PMG were actually manufactured. Experimental comparison was carried out to verify the improvement. This study can provide a reference foundation for the further optimization of PMGs and the research of large load carrying HTS Maglev technology.

2. Simulation design

PMs with stronger remanence can provide a stronger magnetic field. However, improved performance of PMs comes at a higher cost. Therefore, optimization of the structure of the PMG is the focus of research. The reason why the Halbach PMG has better performance than the single-peak PMG is because the magnetic field of the single-peak PMG is distributed symmetrically above and below the guideway. However, the superconductors are suspended above the PMG in a HTS Maglev system. In other words, only the magnetic field above the PMG is utilized and the other half of the magnetic field is wasted. Meanwhile, thanks to the special array of PMs employed, the Halbach PMG can gather most of the magnetic field above the guideway, which greatly improves the magnetic field utilization rate.

In our study, it was found that a single PM can also realize asymmetrical distribution of the magnetic field above and below it through appropriate modifications. Figure 1(a) shows a PM with an upward magnetization direction. The magnetic field above and below it is distributed symmetrically, but in opposite directions. Divide this PM into two parts, as shown in figure 1(b) in which the cross-sectional area of each piece of the PM is half of the original and the angle between the magnetization directions between them is 60°. From the point of view of vector synthesis, figures 1(a) and (b) are equivalent. In fact, as shown in figure 2, the magnetic field above and below these two pieces of PM is no longer a symmetrical distribution, but is more concentrated in the upper part. Thus, the magnetic field above the PM is enhanced.

According to this finding, the vertical magnetized PMs in the original Halbach PMG are replaced by two oblique magnetized PMs, as shown in figure 3.

The height and width of the optimized PMG are the same as the original PMG. If the width of the first PM is set as w, the width of the remaining PMs can be calculated. Taking w as the variable parameter, a series of simulation calculations were carried out on the magnetic field of the optimized PMG. As shown in figure 4, with the decrease of w, the vertical magnetic field ($|B_z|$) peak at the height of 20 mm above the PMG gradually decreases. But when w is too large, the $|B_z|$ outside the peak is too small. In general, the better choice is when w is 18 mm, which makes the width of the PMs almost the same as each other.

It can be seen from figure 3 that the angle (α) between the magnetization directions of two adjacent PMs is 90° for original PMG and 60° for the optimized PMG. In fact, the magnetic field of the PMG when α is 72°, 45°, 30° and 15° were also simulated. Figure 5 shows the magnetic field above the PMG with different α. It can be found that as α gradually

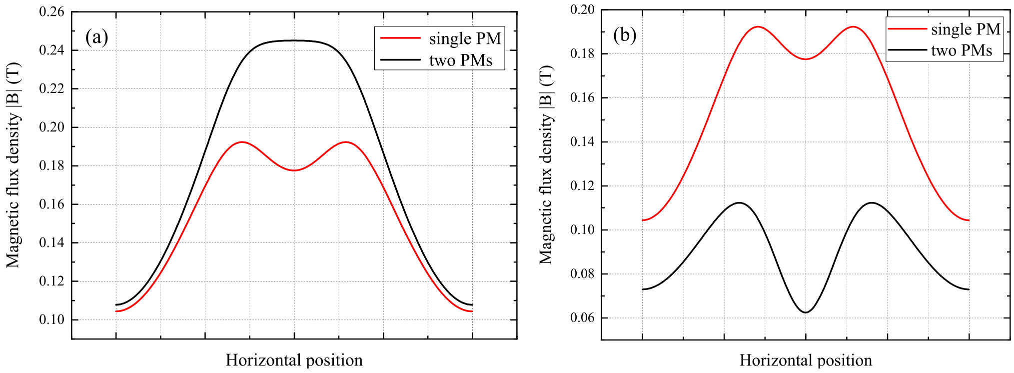

Figure 2. (a) Magnet field density ($|B|$) comparison at 10 mm above single PM and two PMs; (b) Magnet field density ($|B|$) comparison at 10 mm below single PM and two PMs.

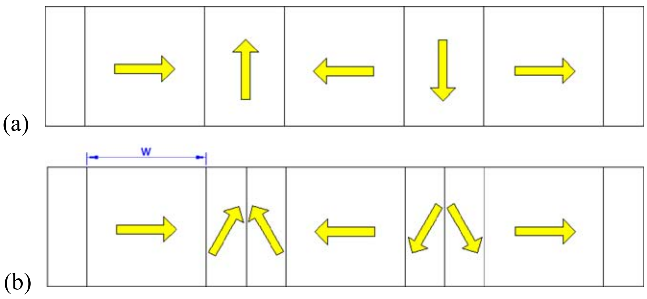

Figure 3. Structure diagram of original PMG and optimized PMG. (a) Original Halbach PMG; (b) Optimized PMG that uses two oblique magnetized PMs to replace the vertical magnetized PMs in the original PMG.

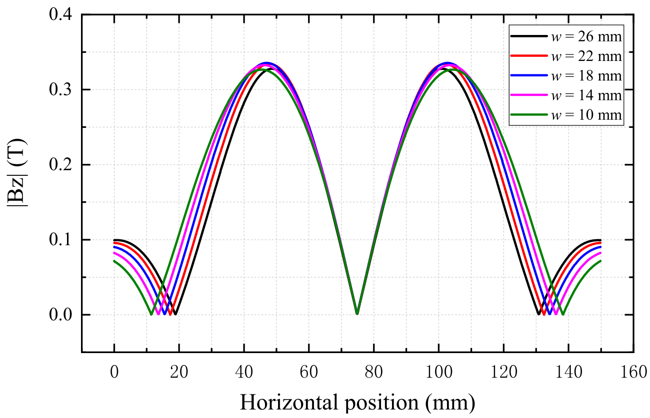

Figure 4. $|B_z|$ at the height of 20 mm above of the optimized PMG with different w.

decreases, the magnetic field gradually increases. But when α is reduced to below 60°, the magnetic field increases slowly. The relationship between α and the number of PM (N) can be determined as follow:

$$\mathrm{N} = 360°/\alpha + 1$$

The smaller α is, the more PMs are needed. In order to keep the cross-sectional area of the PMG unchanged, it is necessary to reduce the width-depth ratio of the PMs, which will increase the manufacturing cost. On the whole, 60° is a compromised choice. So far, the structure of the optimized PMG is determined, as shown in figure 6.

In order to verify whether the magnetic field of the optimized PMG is improved, a simulation comparison is carried out. Figure 7 shows the magnetic field curve at the height of 20 mm above the optimized PMG and the original PMG. The $|B_x|$ and $|B_z|$ of both PMGs reach the maximum at the position of x = 75 mm and x = 47 mm, respectively. Figure 8 shows the magnetic field curve at 0–60 mm above these two PMGs when x = 75 mm and 47 mm. It can be seen from figures 7 and 8 that the optimized PMG is an improvement for both the horizontal magnetic field and the vertical magnetic field at any height. For the optimized PMG, the position of x = 47 mm is exactly where the second PM and the third PM come into contact, which causes the high $|B_z|$ at 0–1 mm above the PMG.

In order to verify whether the optimized PMG can improve the levitation and guidance performance of the HTS Maglev system, a simulation is conducted to compare the levitation force and guidance force of the superconductors for the optimized PMG and original PMG by the finite element method. The established method of the simulation model and more technical details about the simulation are described in detail in [20]. In this simulation, four superconductors were employed. The width and height of each superconductor was 64 mm and 13 mm, respectively. Every two superconductors were arranged side by side, so the total width was 128 mm. In the levitation force simulation, the field cooling (FC) height of the superconductors was 30 mm above the PMG, then dropped to a height of 12 mm and returned to the original position. In the guidance force simulation, the FC height of the superconductors was 30 mm and dropped to a height of 15 mm. The PMG was then laterally shifted by ±20 mm and returned to the original position. The velocity was 1 mm s^{-1} in all simulations. Figure 9 shows the cross-section of the simulation model.

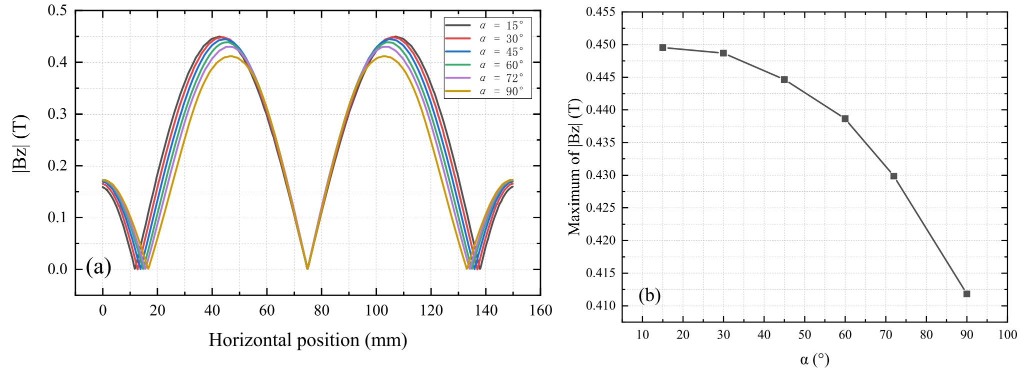

Figure 5. (a) $|B_z|$ above the optimized PMG with different α; (b) The maximum of $|B_z|$ varies with α.

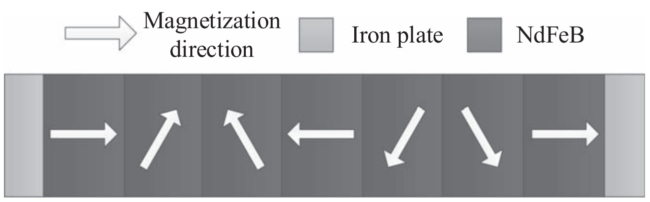

Figure 6. Structure diagram of the optimized PMG: the width of PMs is almost the same as each other and the angle between the magnetization directions of two adjacent PMs is 60°.

As shown in figure 10, the simulation results show that compared with the original PMG, the optimized PMG effectively improves the levitation force and guidance force of the superconductors.

3. Experimental verification

Simulations inevitably have errors and uncertainties. Therefore, in order to effectively verify the correctness of the optimization results and simulation comparisons, the optimized PMG and original PMG were actually manufactured according to the previous optimization design, as shown in figure 11. Due to the limitation of the size of the processing equipment, some PMs were divided into several pieces for manufacturing in the optimized PMG, which will not affect the magnetic field.

The magnetic field and levitation performance of these two PMGs were experimentally compared. The measurement of the magnetic field was completed with a three-dimensional magnetic field scanner [21]. As with the simulation, the vertical and horizontal magnetic field at a height of 20 mm above the optimized PMG and original PMG were measured. Figure 12 shows the measurement results of the magnetic field. The maximum of $|B_x|$ is 0.297 T and 0.336 T for the original PMG and optimized PMG, respectively and the latter is higher than the former by 12.8%. The maximum of $|B_z|$ is 0.296 T and 0.316 T for the original PMG and optimized PMG, respectively and the latter is higher than the former by 6.8%. It can be seen that the optimized PMG has an enhanced magnetic field in both the vertical and horizontal directions compared to the original PMG.

The measurement of levitation and guidance force is completed wtih the superconducting Maglev measurement system (SCML-01), which was independently developed by our laboratory [22]. The superconductors are fixed in a fixture and cooled by pouring liquid nitrogen into a foam box. A vertical motor can control the up and down movement of the fixture and a horizontal motor can control the lateral deviation of the PMG. Force sensors will collect the signals and send them to a computer. Thereby, the accurate measurement of levitation and guidance force is realized. Figure 13 shows the experimental photos.

The levitation force of the superconductors in zero field cooling (ZFC) and the levitation force and guidance force in FC were experimentally measured. In the ZFC test, superconductors were cooled to the superconducting state at a height of 80 mm above the PMG, then dropped to a height of 12 mm and returned to the original position. The experimental conditions of FC were exactly the same as those of the simulation.

The experimental results are shown in figures 14 and 15. It can be seen that the maximum levitation force of the superconductors is 616 N and 560 N respectively for the optimized PMG and original PMG, in the case of ZFC. The former is higher than the latter by 10.0%. In the case of FC, the maximum levitation force of the superconductors of the optimized PMG and the original PMG are 468 N and 417 N, respectively. The former is higher than the latter by 12.2%. The maximum guidance force of superconductors on the optimized PMG and the original PMG are 213 N and 189 N, respectively. The former is higher than the latter by 11.3%. The experimental results prove that the optimized PMG can effectively improve the magnetic field above it and the levitation performance of the HTS Maglev system, compared with the original PMG.

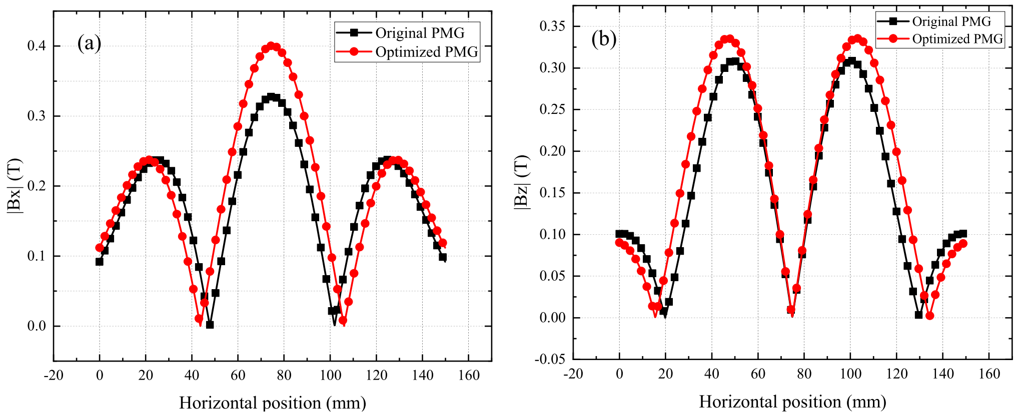

Figure 7. Simulation comparison of magnetic field at 20 mm above the optimized PMG and original PMG. (a) $|B_x|$ comparison; (b) $|B_z|$ comparison.

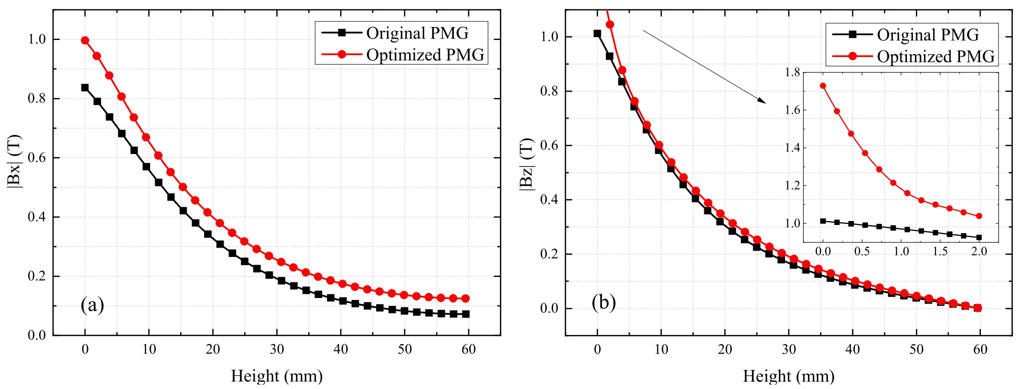

Figure 8. Simulation comparison of magnetic field at 0–60 mm above the optimized PMG and original PMG. (a) $|B_x|$ comparison at x = 75 mm; (b) $|B_z|$ comparison at x = 47 mm.

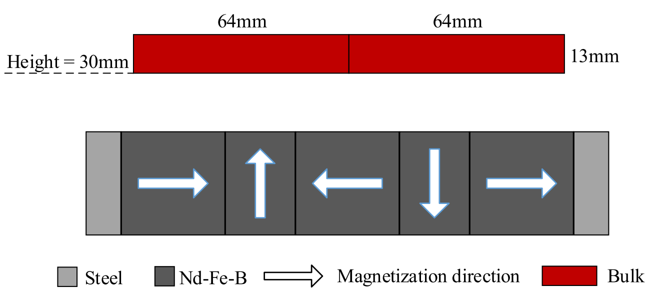

Figure 9. The cross-section diagram of the simulation model.

4. Conclusion

In order to improve the load capacity of HTS Maglev systems, the PMG has been optimized in this paper. Starting from the optimization of a single PM, two oblique magnetized PMs were used to replace the vertically magnetized PMs in the Halbach PMG. The size and magnetization angle of each PM are optimized and then a new type of PMG was designed. The original PMG and the optimized PMG were manufactured and the magnetic field as well as the levitation and guidance forces were compared. In the course of this research, the following conclusions have been drawn:

1. Replacing the vertical magnetized PM by two obliquely magnetized PMs can realize the asymmetric distribution of the magnetic field and achieve the purpose of enhancing the magnetic field on one side.
2. In the optimized PMG, the magnetic field distribution above the track is better when the width of each PM is almost the same.

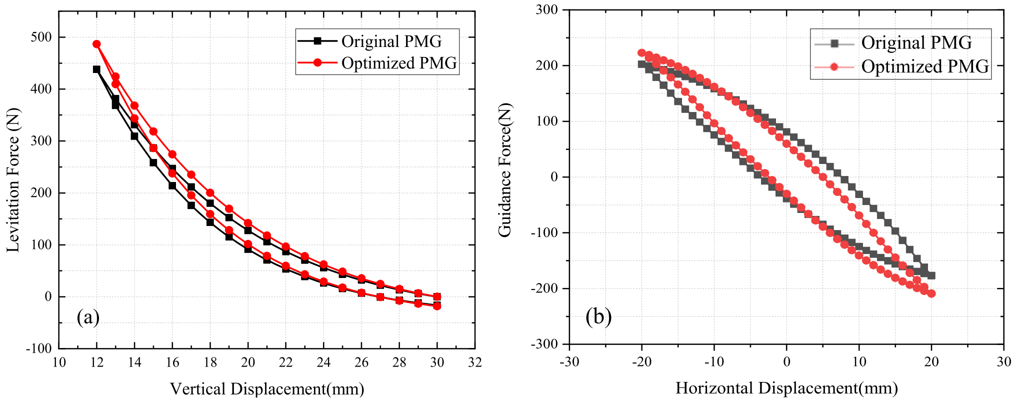

Figure 10. Simulation comparison of electromagnetic forces for optimized PMG and original PMG. (a) Levitation force comparison; (b) Guidance force comparison

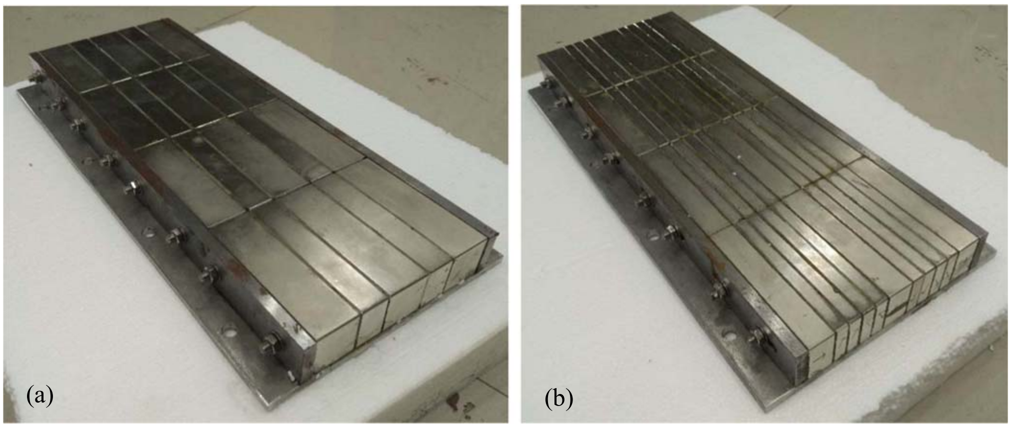

Figure 11. The manufactured PMGs. (a) The original PMG; (b) The optimized PMG.

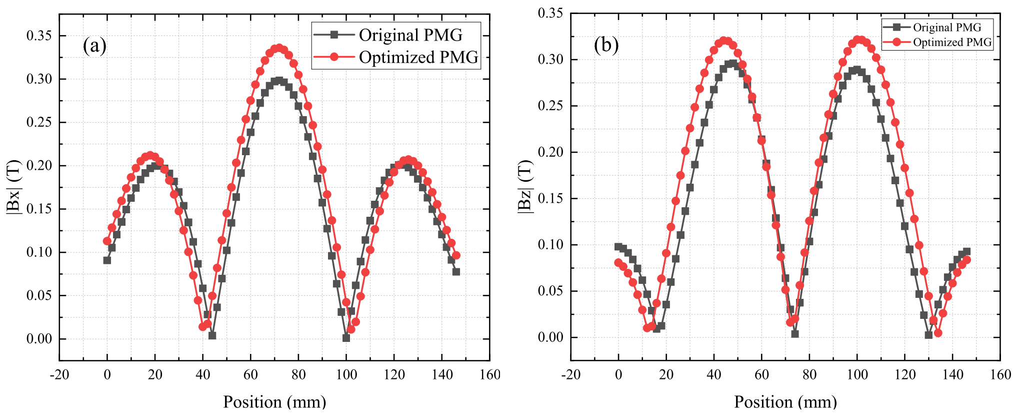

Figure 12. Experimental comparison of magnetic field at 20 mm above the optimized PMG and original PMG. (a) $|B_x|$ comparison; (b) $|B_z|$ comparison.

3. In the optimized PMG, the smaller the angle between the magnetization directions of the two adjacent PMs, the stronger the magnetic field above the PMG, however this increase is slow. Considering cost and other factors, 60° is the most suitable choice.
4. Compared with the original PMG, the magnetic field is effectively enhanced above the optimized PMG with the same cross-sectional area. The levitation force of superconductors is increased by 10.0% in the case of ZFC. The levitation force and guidance force of superconductors is increased by 12.2% and 11.3% in the case of FC, respectively.

This study can provide a foundation for the further optimization of PMGs and research of large load carrying HTS Maglev technology.

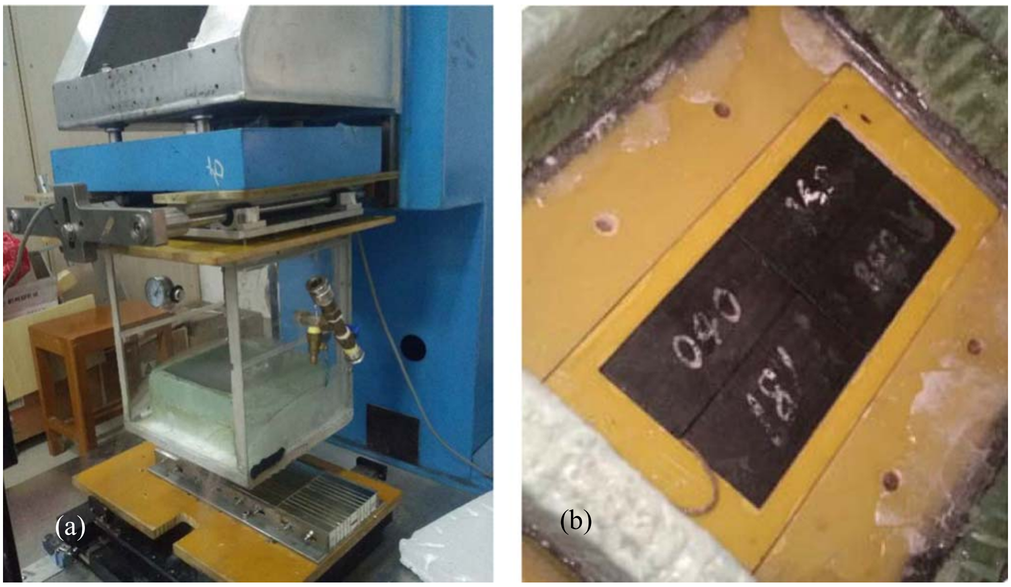

Figure 13. (a) Photograph of experiment with SCML-01; (b) Superconductors in the foam box.

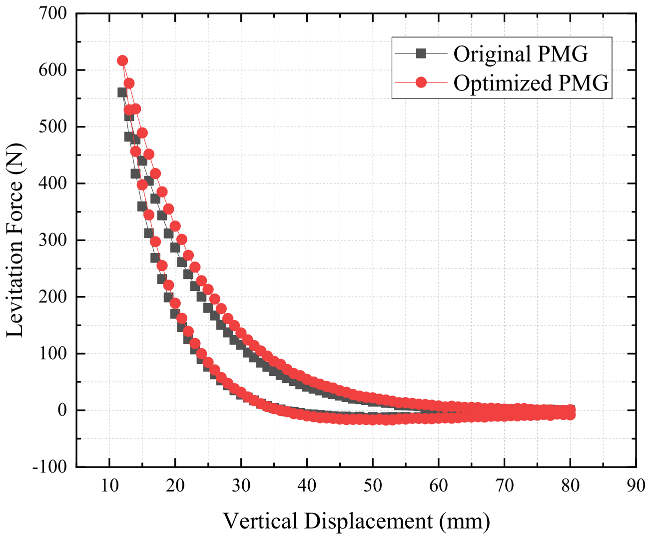

Figure 14. Experimental comparison of levitation force in ZFC case for optimized PMG and original PMG.

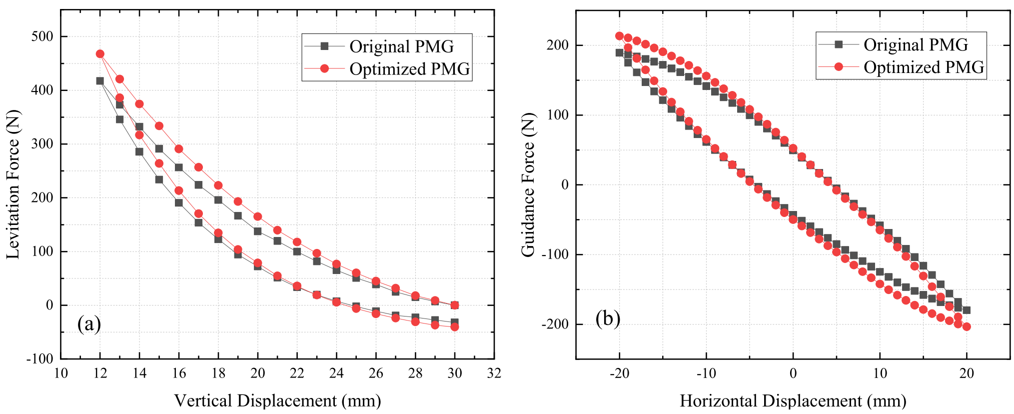

Figure 15. Experimental comparison of electromagnetic forces for optimized PMG and original PMG. (a) Levitation force comparison; (b) Guidance force comparison

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