Available online at www.sciencedirect.com

ScienceDirect

Physica C 463–465 (2007) 426–430

PHYSICA C

www.elsevier.com/locate/physc

A two-pole Halbach permanent magnet guideway for high temperature superconducting Maglev vehicle

H. Jing *, J. Wang, S. Wang, L. Wang, L. Liu, J. Zheng, Z. Deng, G. Ma, Y. Zhang, J. Li

Applied Superconductivity Laboratory, M/S 152#, Southwest Jiaotong University, Chengdu, Sichuan 610031, P.R. China

Abstract

In order to improve the levitation performance of the high temperature superconducting (HTS) magnetic levitation (Maglev) vehicle, a two-pole Halbach array's permanent magnet guideway (PMG) is proposed, which is called as Halbach PMG. The finite element method (FEM) calculations indicate that Halbach PMG has a wider high-field region than the present PMG of equal PM's transverse section. The levitation force of bulk HTSCs with the present PMG and Halbach PMG are measured. The results show that at different levitation gaps, the force ratios based on the Halbach PMG are about 2.3 times larger than that on the present PMG, which greatly increases the load capability of the system. Therefore, both the numerical analysis and experimental results have confirmed that the Halbach PMG will further enhance the performance of the vehicle and it is possible to decrease the total numbers of onboard HTSCs, reducing overall costs. So based on the Halbach PMG, we further study the width ratios between HTSCs and PMG for making the better use of the onboard HTSCs. Some preliminary results are given. These results are important for further HTS Maglev vehicle system designs using Halbach PMG.

PACS: 85.70.Rp

Keywords: High temperature superconductor (HTSC); Maglev; Halbach permanent magnet guideway; Levitation force

1. Introduction

Since the suspension of a permanent magnet (PM) above the high temperature superconductor (HTSC) was discovered in 1988 [1], people have paid more attentions to the application of the HTSC, especially in the field of magnetic levitation (Maglev) transportation system. In 2000 the first man-loading HTS Maglev test vehicle was tested successfully in China [2], and in 2004 Russia and Germany, respectively, developed HTS Maglev experimental vehicle [3]. How to improve the vehicle's levitation performance is one of the most important subjects. Our group has done a lot of works and some advancements have been achieved [4,5]. However, it is still far from the commercial application of the HTS Maglev vehicle. As known the levitation and guidance is result of the interaction between permanent magnet guideway (PMG) and onboard HTSC, so PMG plays an important role in HTS Maglev system and optimizing PMG is a direct and effective approach to improve the levitation performance of the vehicle. In 1985, Klaus Halbach presented a special array of high-field permanent magnets named as Halbach array [6]. So far it has been applied in particle accelerators, magnet bearings, electrical machines [7], and Maglev designs [8]. The ideal linear Halbach array produces sinusoidal magnetic profile in the horizontal direction with a strong periodic magnetic field on one side of the array while a minimal field on the other side [9]. This array is supposed to suitable for the present HTS Maglev vehicle system. However, there may be some questions to this answer. Is the levitation performance of the vehicle improved? Is the Halbach array's PMG superior to the present PMG? Which is the optimal

---

* Corresponding author. Tel.: +86 28 87601794; fax: +86 28 87603310. *E-mail address:* jinghua123456@126.com (H. Jing).

0921-4534/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2007.05.030

width ratio between onboard HTSCs and Halbach array's PMG? For these questions little work has been done, as in the case our study is focused. This paper explores and answers these questions.

2. Magnetic field simulation and discussion

In this paper, a two-pole Halbach array's PMG (Halbach PMG) is proposed for HTS Maglev test vehicle. Based on the maximisation of the ratio of magnetic field to magnet weight per unit area, the geometric optimisation has been studied using finite element method (FEM). The results are listed in Table 1. The Halbach PMG is composed of iron and Nd–Fe–B (N40) permanent magnets. The present PMG is composed of iron and Nd–Fe–B (N35) permanent magnets. Owing to the material difference between N40 and N35, which of different magnetic energy product $(BH)_m$, it is inappropriate to compare the magnetic field of two kinds of PMG directly through the measured data of the magnetic intensity, so FEM method, a numerical analysis method, is introduced for comparison. Assumed the present PMG and the Halbach PMG are infinitely long and uniform along the longitudinal direction, to simplify the analysis, only the cross-section of two kinds of PMG are considered, as shown in Fig. 1, where x and y are the horizontal and vertical axis, respectively. The center of the upper surface of each PMG is defined as the origin of the Cartesian co-ordinates. Geometric parameters of the two kinds of PMG are listed in Table 1. The parameters indicate that the cross-section areas of PMs of two kinds of PMG are almost the same in 2D models, which are propitious to compare the magnetic field. In the analysis, only the upper magnetic field of PMG is studied since the present HTS Maglev vehicle only utilizes PMG's upper magnetic field. Firstly, the physical parameters of the Halbach PMG are set, as shown in Table 2. According to the parameters values, the vertical component of the magnetic field (B_y) of the Halbach PMG is calculated at three different heights and compared with the measured value, as shown in Fig. 2. The results show that at different heights, the calculated curves agree well with the measured curves, except for the tiny errors that may result from the simplified Halbach PMG model. Therefore, the FEM method is feasible and parameters values are reasonable. In the following, using the same parameters as the Halbach PMG, we calculate the B_y of the present PMG along x-axis from −75 to 75 mm at 15 mm height and compare with that of Halbach PMG. Fig. 3 shows the comparison. In the analysis, considering seven HTSCs concentrically arrangements are actually used. Their widths along the x-axis of the PMG are from −45 to 45 mm. Therefore, we will focus on this displacement. The comparison results in Fig. 3 indicate that the maximum By of the Halbach PMG is not bigger than that of the present PMG, but the magnetic field distribution of the Halbach PMG has two peaks, especially the B_y of the Halbach PMG is larger than that of the present PMG, around the displacement of −45 to −15 mm and 15 to 45 mm. Therefore, the Halbach PMG is superior to the present PMG from the angle of magnetic field. In the following part, the levitation force of HTSCs above two kinds of PMG will be measured by experimental.

Table 1
The geometric parameters of 2D models of the two kinds of PMG

Parameter	The present PMG	Halbach PMG
Width of PMG (mm)	110	150
Height of PMG (mm)	50	30
Width of Nd–Fe–B with horizontal magnetization direction (mm)	40	30
Width of Nd–Fe–B with vertical magnetization direction (mm)	0	20
Width of iron (mm)	10	10
Cross-section area of PM (mm^2)	4000	3900
Cross-section area of iron (mm^2)	1500	600

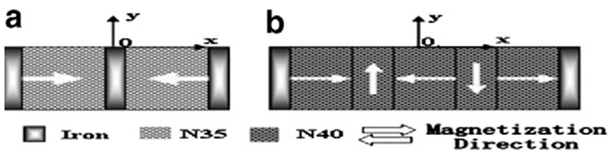

Fig. 1. The cross-sections of (a) the present PMG and (b) the Halbach PMG.

Table 2
The physical parameters of PMG

Parameter	Air	Iron	Nd–Fe–B
Relative permeability	1	14,872	1.045
Coercivity (A/m)			883,310

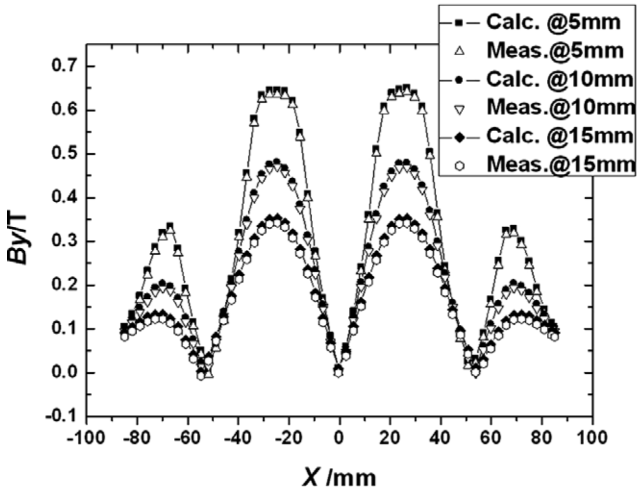

Fig. 2. Comparison between the calculated and measured the vertical component of magnetic field above Halbach PMG at three different heights, i.e. 5, 10 and 15 mm.

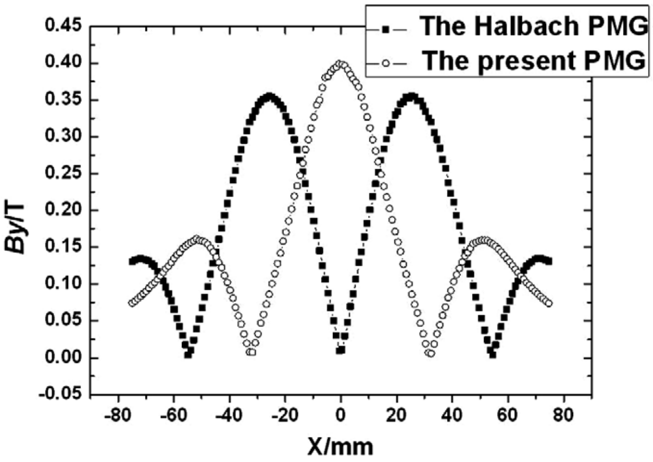

Fig. 3. Comparison between the present PMG and Halbach PMG, calculated the vertical component of magnetic field at 15 mm height.

3. Experimental measurement and discussion

Considering the practical running experiences of the vehicle, field-cooling height (FCH) is higher than 20 mm and bulk is usually seven-block arrangement. So the levitation force of seven HTSCs array above two kinds of PMG at 30 mm FCH is measured using high temperature superconducting magnetic levitation measurement system (SCML-02). The measurement system has been reported, whose photograph is shown in Fig. 4a, for details in Ref. [10]. The measured results of levitation force are shown in Fig. 4b, where the levitation gap is a distance between upper surface of PMG and under surface of HTSC, and the inset figure is the scheme of seven bulk HTSCs (30 mm in diameter, 18 mm in height) array. From Fig. 4b, the maximum levitation force reaches 231 N above the Halbach PMG. It is obvious that the levitation force with the Halbach PMG is larger than that with the present PMG. In the following analysis, owing to the different BH_m based on two kinds of PMG, it is inappropriate to directly compare the levitation force in order to illustrate PMG's property, but through the approach is reasonable, i.e. levitation force/BH_m, which is called as the force ratio. The larger the force ratio is, the better the PMG's property is. The BH_m of the present PMG and the Halbach PMG are, respectively, 36.5 MGOe and 42.74 MGOe. The force ratio results for different levitation gaps are presented in Table 3. When the levitation gap is 8 mm, the force ratio based on the Halbach PMG is about 2.4 times larger than that on the present PMG, and when the levitation gap is 15 mm the force ratio based on the Halbach PMG is about 2.24 times larger than that on the present PMG. Therefore, experimental results confirm that the property of the Halbach PMG is superior to the present PMG. It makes possible to reduce the total number of onboard HTSCs. In addition, the hysteretic behavior of force with the Halbach PMG is larger than that with the present PMG, which is able to enhance the vehicle's stability.

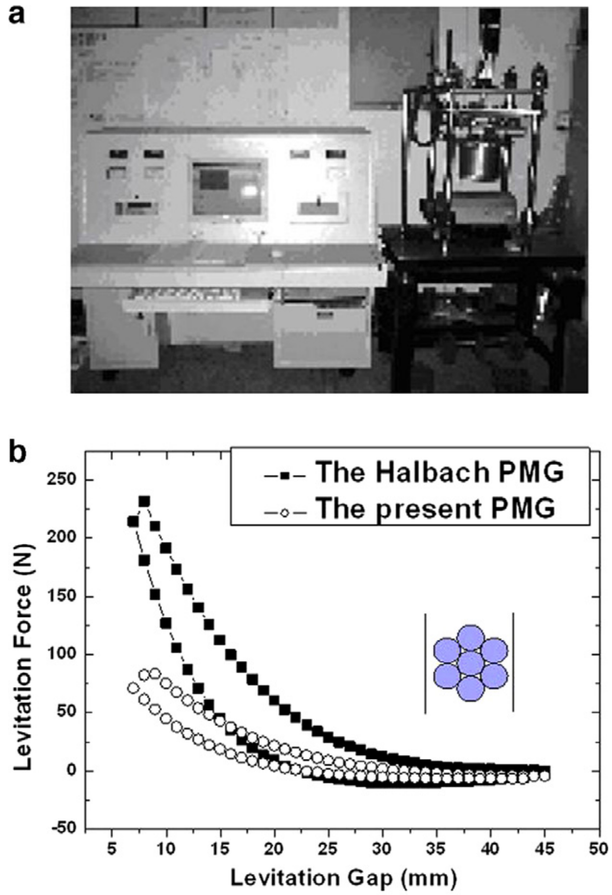

Fig. 4. Photograph of SCML-02 Maglev measurement system in (a) and the measured results of levitation force above two kinds of PMG in (b).

Table 3
The force ratio for different levitation gaps based on two kinds of PMG

Levitation gap (mm)	8	10	15	20
The force ratio of Halbach PMG	5.4	4.46	2.62	1.4
The force ratio of present PMG	2.24	2.05	1.15	0.57

4. The width ratio between onboard HTSCs and the Halbach PMG

In order to make the better use of the HTSC above the Halbach PMG, it is necessary to study the width ratio between onboard HTSC and the Halbach PMG. In the following discussion, the width ratio is defined as the total width of HTSCs array/the width of the Halbach PMG. Although the width of the Halbach PMG is fixed, i.e. 150 mm, the total width of HTSCs array is changeable. There are four width ratios between HTSCs array and the Halbach PMG, i.e. 60/150, 90/150, 120/150 and 150/150. For each HTSCs array, we measured the levitation force using SCML-02 Maglev measurement system with the same levitation gap but different FCHs, i.e. 35, 30, 25 and 20 mm. When test of all these FCHs are finished, we quench the HTSCs array and begin the measurements with another HTSCs array. The results of the experiments are shown in Fig. 5 with 10, 15 and 20 mm levitation gaps, respectively. By comparing the slopes of width ratios, we can see in Fig. 5 that although the levitation gaps are different, i.e. 10, 15 and 20 mm, the slopes of the width ratios with the same FCH have identical regularity. Therefore, we can conclude that the width ratios are significantly dependent on FCH. When FCH is 35 mm, the HTSCs should be wider than the PMG, but not much, the width ratio should be more than 1/1 at least. For 30 mm of FCH, the width ratio should be around 2/3, and for 25 or 20 mm of FCH, the optimal width ratio should be 4/5. Moreover, it is interesting to find out that when the width ratio is 3/5, the levitation force of HTSCs at 25 mm FCH as much as at 20 mm FCH, and when the width ratio is 4/5, the levitation force of HTSCs at 35 mm FCH as much as at 30 mm FCH. These data is helpful for designing the HTS Maglev system.

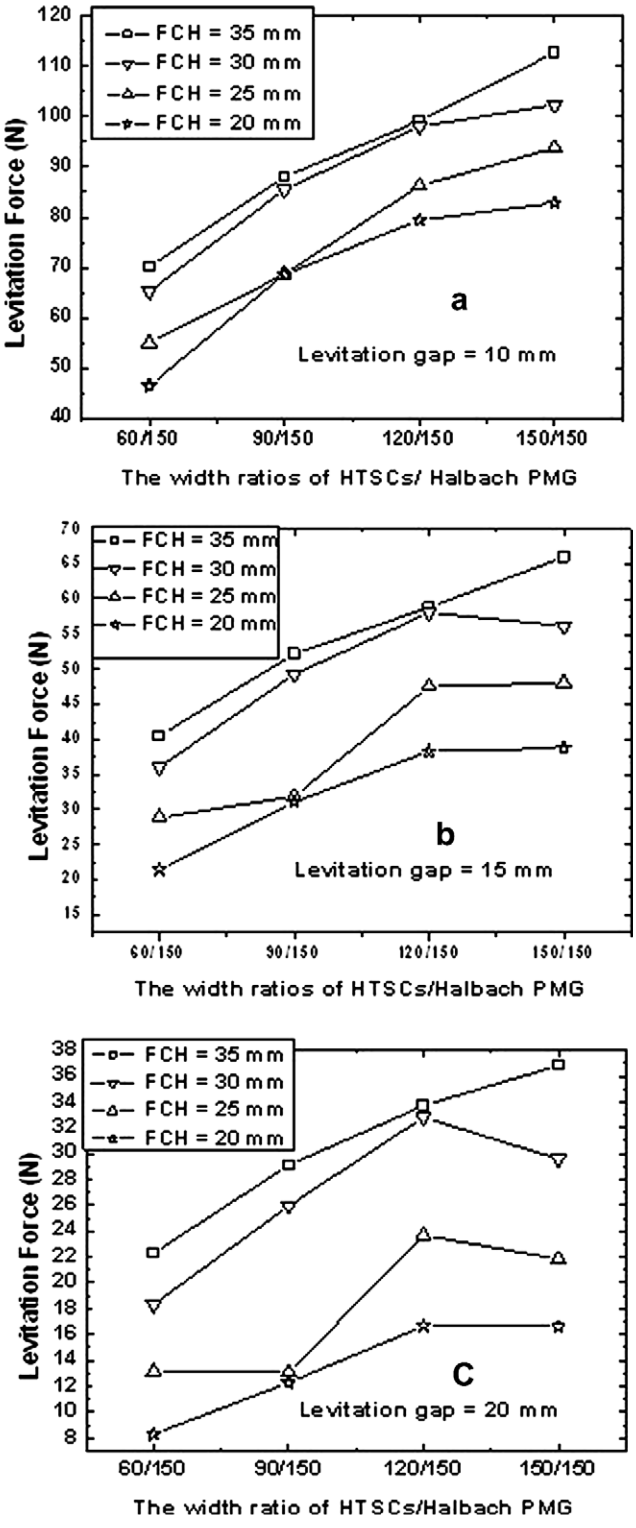

Fig. 5. At 5, 10 and 15 mm levitation gaps, the measured results of the width ratios between HTSCs and the Halbach PMG with different FCH are shown in (a), (b) and (c), respectively.

5. Conclusion

In order to improve the levitation performance of the vehicle, a two-pole Halbach array's PMG is presented. Numerical analysis and experimental results show that the magnetic field above the Halbach PMG is more efficient than the present PMG of equal PM's transverse section, and when levitation gaps are from 20 to 8 mm, the force ratios based on the Halbach PMG are about 2.3 times larger than that based on the present PMG. Therefore, the Halbach PMG greatly enhances the vehicle's levitation ability and it is possible to decrease the total number of onboard HTSCs, reducing the overall cost. Furthermore, we find that the width ratios between onboard HTSCs and the Halbach PMG are significantly dependent on FCH. When FCH is 35 mm, the width ratio should be more than 1/1. When FCH is 30 mm, the width ratio should be around 2/3, and for 25 or 20 mm of FCH, the width ratio should be 4/5. These results will be used as a technical framework for HTS Maglev system design using Halbach array's PMG.

Acknowledgements

This work is supported by the National High Technology Research and Development Program of China (2005AA306150), and the National Natural Science Foundation in China (50377036).

References

[1] F. Hellman, E.M. Gyorgy, D.W. Johnson Jr., H.M. O Bryan, R.C. Sherwood, J. Appl. Phys. 63 (1988) 447.
[2] J.S. Wang, S.Y. Wang, Y.W. Zeng, H.Y. Huang, F. Luo, Z.P. Xu, Q.X. Tang, G.B. Lin, C.F. Zhang, Z.Y. Ren, G.M. Zhao, D.G. Zhu, S.H. Wang, H. Jiang, M. Zhu, C.Y. Deng, P.F. Hu, C.Y. Li, F. Liu, J.S. Lian, X.R. Wang, L.H. Wang, X.M. Shen, X.G. Dong, Physica C 378 (2002) 809.
[3] L. Schultz, O. De Haas, P. Verges, C. Beyer, S. Röhlig, H. Olsen, L. Kühn, D. Berger, U. Noteboom, U. Funk, IEEE Trans. Appl. Supercond. 15 (2005) 2301.
[4] J.S. Wang, S.Y. Wang, in: Anant Narlikar (Ed.), Frontiers in Superconducting Materials, Springer, Germany, 2005, p. 885.

[5] H.H. Song, J. Zheng, M.X. Liu, L.C. Zhang, Y.Y. Lu, Y.G. Huang, Z.G. Deng, J.H. Zhang, H. Jing, S.Y. Wang, J.S. Wang, IEEE Trans. Appl. Supercond. 16 (2006) 1023.

[6] K. Halbach, Appl. Phys. 57 (1985) 3605.

[7] S. Jang, L. Sung, IEEE Trans. Magn. 38 (2002) 3264.

[8] R. Kratz, R.F. Post, IEEE Trans. Appl. Supercond. 12 (2002) 930.

[9] H.A. Shute, J.C. Mallinson, D.T. Wilton, D.J. Mapps, IEEE Trans. Magn. 36 (2000) 440.

[10] S.Y. Wang, J.S. Wang, C.Y. Deng, Y.Y. Lu, Y.W. Zeng, H.H. Song, H.Y. Huang, H. Jing, Y.G. Huang, J. Zheng, X.Z. Wang, Y. Zhang, in: Appl. Superconductivity Conference, paper No. 2LG06, 2006.