Design consideration of a super-high speed high temperature superconductor maglev evacuated tube transport (I)

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Abstract: The super-high speed high temperature superconductor (HTS) maglev evacuated tube transport (ETT) is a promising transport mode for the future. As a key component of the HTS maglev vehicle, the permanent magnet guideways (PMGs) with different geometrical configurations and iron yoke widths are analyzed by finite element method (FEM). The levitation force of a single onboard HTS maglev device over the designed PMG at different field cooling heights (FCH) is measured by magnetic levitation measurement system. Based on the designed PMG and experimental results, a preliminary scheme of subterranean super-high speed HTS maglev ETT is described in this paper. The HTS maglev ETT is mainly composed of an evacuated tube, HTS maglev vehicle, PMG, propulsion system, station, emergency rescue system, etc. In addition, a subterranean tube that consists of foundation tube and vacuum airproof layer is introduced. In order to convert the stress caused by the air pressure difference between inside and outside of the vehicle, a multi-circular vehicle body is designed. The vehicle is driven by a linear motor propulsion system under the control of a ground controlling system. The scheme of long-distance super-high speed passenger transportation is accomplished by the connection of different vehicles.

Key words: high temperature superconductor; permanent magnet guideway; levitation force; maglev; evacuated tube transport

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1. Introduction

It is well known that the ultimate economic speed of the conventional ground transportation is extremely limited by the earth's surface atmosphere. When the velocity of the conventional ground transportation is higher than 350 km/h, the aerodynamic resistance and the running noise are both greatly increased, which results in serious environmental pollution and increased energy demand. However, the aerodynamic resistance and noise of the maglev vehicle which runs in an evacuated tube are remarkably reduced [1-2]. Some preliminary investigations indicate that the driving power dissipation of the evacuated tube transport (ETT) is only 2% of the conventional ground transportation [3].

With the development of the high temperature superconductor (HTS), HTS has great potential applications in many engineering fields [4-8]. As one of the most popular applications of the HTS, the HTS magnetic levitation system shows many superior perform-

ances in self-stabilization, safety, frictional losses, energy consumption, transportation speed, etc [9-10]. From the viewpoint of the development of maglev vehicles, running tests conducted in air clarified that the pinning-type superconducting magnetic levitation guide with bulk high- T_c superconductors is useful as an excellent support system for transportation [11]. The first man-loading HTS maglev vehicle which was designed by the Southwest Jiaotong University, may be one of promising carrier of super-high speed ETT with the speed of 600–1 000 km/h [12-13]. Okano et al. [14] described theoretically a goods transportation system with the superconducting magnetic levitation guide set in the vacuum passage. Wang et al. [15] proposed a new ground transportation system of super-high speed HTS maglev vehicle. However, little work was done on designing a subterranean super-high speed HTS maglev ETT.

In this paper, a preliminary design scheme of a subterranean super-high speed HTS maglev ETT is presented on the basis of the numerical calculation of the permanent magnet guideway (PMG) and the experimental results of HTS magnetic levitation system.

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2. Numerical calculation of the PMG

PMG is one of important components of the HTS maglev vehicle system, and its magnetic field distribution has an influence on the levitation and guidance performance of the levitated vehicle. The geometrical shape and uniform magnetization of the PMG affects the levitation force, guidance force, and construction cost of the system [16]. Therefore, it is necessary to optimize the design of the PMG of the HTS maglev vehicle system. In previous studies, many methods have been used to calculate the magnetic field distribution of PMG [17-19]. In order to simulate the aerodynamic resistance of high temperature superconductor maglev ETT in the future, finite element method (FEM) is used to calculate the magnetic field distribution in this paper.

2.1 Material properties and 2D model of the PMG

A two-dimensional (2D) model of the PMG, which ideally assumes the PMG is infinite in the longitudinal propulsion direction and the magnetic field is uniform in this direction, is built in this paper. With this 2D model, the influence of geometrical configuration and iron yoke width of the PMG on the magnetic field is studied.

As shown in Fig. 1, the PMG is composed of the permanent magnet (PM) and iron plate (IP), which

works as the field source, the field concentrator, and the fixer of the guideway [20]. The PM used in this model is NdFeB with 1.045 relative permeability and 900 kA/m coercivity. The property of the IP in the model is considered as linearity with 2 000 relative permeability. The arrows in Fig. 1 indicate the magnetic directions of the PM. Since the PMG is considered as infinitely long and has a uniform magnetic field along the longitudinal direction (y axis), only the cross section of the PMG is modeled. The width and height of the PM and IP are designated by width_PM, width_IP 1, width_IP 2, and height respectively, as shown in Fig. 1. In order to investigate the influence of the iron yoke width and configuration of the PMG on magnetic field, we analyzed three types of PMGs, i.e., PMG I (A), PMG I (B) and PMG II. The PMG I (A) and PMG I (B) are composed of two rows of permanent magnets and three iron plates. The center iron plate works as the magnetic field concentrator. The PMG II consists of three rows of permanent magnets and four iron plates. The width of the middle two iron plates, used for the field concentrator, is not changed in this paper. The details of the geometric parameters of these three PMGs are illustrated in Table 1.

Table 1 Detail dimensions of the three PMGs mm

Parameter	PMG I (A)	PMG I (B)	PMG II
Height	80	80	80
Width_IP 1	10	20	10
Width_IP 2	10	10	10
Width_PM	80	80	80

2.2 Results and discussion

The magnetic field contours of B_z (the magnetic flux density in the z direction) of PMG I(A) and PMG II are shown in Fig. 2. We can see that the magnetic field distribution is symmetrical for both PMG I (A) and PMG II along the z axis and x axis. The iron yokes demonstrate good magnetic concentrator effect. In order to study the influence of the iron yoke width on the magnetic field, the simulation results by FEM of the surface magnetic field distribution of PMG I(A) and PMG I(B) along the x axis at different heights above the PMGs are shown in Fig. 3. The surface magnetic fields of the PMGs at the heights of 2, 10, 16, 26, and 36 mm are simulated. The magnetic field distribution along the z axis from $z=0$ mm to $z=50$ mm of the PMG I(A) and PMG I(B) with $x=0$ mm are shown in the insert picture in Fig. 3.

Because the surface magnetic field of the PMG is distributed symmetrically along the z axis, the B_z of two PMGs only along the positive x axis is demonstrated in Fig. 3. It can be seen from Fig. 3 that the center mag-

Fig. 1 2D model of two configurations of PMG in the xz plane

netic field of the PMG I(A) is up to 1.3 T at the height of 2 mm, reaching the maximum value at this height. However, it becomes very small at the height of 36 mm and the maximum value is not more than 0.3 T. The center magnetic field of the PMG I(B) is up to 0.9 T. The maximum magnetic field value is about 1.2 T and the position is not at the center of the PMG, but at the position of $x=10$ mm. From the calculated results, the five simulation curves almost have the similar shape except for the cases of $z=2$ mm and $z=10$ mm. It is found that the PMG I(A) has superior performance in magnetic concentration compared with PMG I(B). Thus, we can

conclude that the width of the iron yoke has an influence on the surface magnetic field distribution and the influence is strong at a low height. As the height from the surface of the PMG increases, the influence decreases. When the height is more than 10 mm, the surface magnetic field distribution of the two PMGs is almost similar, so the influence can be ignored. These results agree well with the results attained from the experiment and simulation [21-22].

Moreover, in order to investigate the influence of PMG configuration on magnetic field distribution, the PMG II as shown in Fig. 1(b) is also calculated.

Fig. 2 Magnetic field contours of two configurations of PMG: (a) B_z of the PMG I (A); (b) B_z of the PMG II

Fig. 3 Comparison of the calculated B_z along the x axis at different heights over the PMG I(A) and PMG I(B) surface. The insert is the center B_z along the z axis at the height of 0–50 mm over the two PMGs

Fig. 4 The calculated B_z along the x axis and z axis at different heights over the PMG II surface

It can be seen from Fig. 4 that the surface magnetic field of the PMG II presents anti-symmetry at $x=140$ mm. When the height is 2 mm, the positive and negative maximum magnetic fields are achieved at $x=100$ mm and 180 mm, respectively. The maximum value is about 1.4 T. The larger the height above the PMG, the more uniform the magnetic field distribution. The maximum value decreases with the increasing height. The insert diagram displays the B_z along the z axis from $z=0$ mm to $z=50$ mm at the position of the iron yoke. As shown in the insert picture, with the height above the surface of the PMG increasing, the surface magnetic field is also decreased. The maximum magnetic field is about 1.3 T above the surface of the PMG, but the magnetic field is only about 0.1 T at the height of 50 mm.

The calculation results of the three PMGs confirm that the present 2D model is suitable to simulate the magnetic field distribution and optimize the design of the PMG. Due to the fact that the levitation gap is always more than 10 mm in the practical operation of HTS maglev vehicle, the influence of iron yoke width on magnetic field distribution could be neglected during the calculation of the levitation and guidance force of the maglev system [23]. The above calculation results show that PMG I(A) has advantages of good magnetic concentration effect and large surface magnetic field. Compared with the other two PMGs, not only the structure of the PMG I(A) is more simple, but also the cost is much lower. So the PMG I(A) is a good option for PMG of HTS maglev evacuated tube vehicle system.

3. Experimental results of levitation force on PMG

As one of the important performance parameters of the HTS maglev vehicle system, levitation force directly determines the levitation carrying capability and levitation gap of the vehicle. In order to investigate the influence of HTS bulk arrangement and applied outer field of the PMG on levitation force, a number of experiments were carried out to measure the levitation force of a single onboard HTS maglev device on the designed PMG. The onboard HTS maglev device is composed of YBCO bulks and a rectangular liquid nitrogen vessel. The designed PMG has the same cross-section dimension as the PMG I(A) and the length of the PMG is 640 mm.

The YBCO bulks are all cylindrical shape with 30 mm diameter and 18 mm height. Considering that the practical levitation distance between the vehicle and the PMG surface is always more than 10 mm and the bottom thickness of the liquid nitrogen vessel is 6 mm, the levitation force of YBCO bulks with three different arrangements was measured under the condition of the field cooling height (FCH, i.e., the gap between the bottom of the HTS and the surface of the PMG) being 16 mm. The three arrangements of the HTS are 6 rows, 4 rows, and 2 rows. Because the bulks of each row are 19, the total numbers of the YBCO bulk of three arrangements are 114, 76, and 38, respectively.

Fig. 5 Levitation force curves of HTS bulk with different arrangement at 16 mm FCH. The insert is the levitation force curves of 38 HTS bulks at different FCH

In our experiments, all the levitation forces were measured with an HTS measurement system developed by the Superconductivity and New Energy R&D Center of Southwest Jiaotong University, China. In the measurement process, the onboard HTS maglev device which is controlled by a servo electromotor can move up and down above the PMG, and the center of the arranged YBCO bulks is just aimed at the center of the PMG. The measuring speed is 20 mm/min, and the whole measuring process is automatically controlled by a computer. The measurement results of the bulks when the FCH is 16 mm are shown in Fig. 5. The insert diagram of Fig. 5 shows the levitation force curves of 38 HTS bulks at 26 mm and 36 mm FCH. The levitation force of HTS bulks with the same arrangement differs with different FCH.

From the experimental results, we find that the three curves have the same change trends. The levitation force is hysteretic for movements and is exponential with the levitation gap. The maximum total levitation forces of 114, 76, and 38 bulks are 1 650, 1 105, and 895 N, respectively. It is obvious that the total levitation force of 114 bulks is the largest one and the value of the 38 bulks is the smallest one. On the contrary, the average levitation force of a single YBCO bulk of 38 bulks with 2 rows is the maximal value and the value of 114 bulks with 6 rows is the minimal value. These phenomena mainly result from the different magnitudes of the outer magnetic field of the single YBCO bulk. From these quasi-static results, we can conclude that there are many factors affecting the levitation force of the levitation

system, including the arrangement and FCH of the HTS bulks, the magnetic field distribution of the outer applied magnetic field of the PMG, etc.

Furthermore, the HTS maglev vehicle has a very high speed in practice, so the levitation force and guidance force of the system in the high speed case, i.e. in the dynamic state, should be investigated in the future.

4. Preliminary scheme of HTS maglev evacuated tube transport

As a new-style transportation system, HTS maglev evacuated tube transport can be seen as a stretch and supplement for the ground high speed transportation, especially for the maglev vehicle system. The HTS maglev evacuated tube transport is mainly composed of vacuum tube, vehicle body, permanent magnetic guideway, propulsion system, station and emergency assistance equipments. It should be superior in long-distance and super-speed passenger transportation compared to traditional transportation systems. According to the above numerical calculation and experimental results, the structure design of the vehicle body and the permanent magnetic guideway should be taken into consideration concurrently. Combined with the array of the HTS and the outer applied magnetic field, the design of the HTS maglev vehicle can be optimized.

A preliminary scheme of a kind of HTS maglev evacuated tube transport is presented in this paper. A linear motor is used for the propulsion system. In order

Fig. 6 Main structures of the designed HTS maglev evacuated tube vehicle system

to realize the long-distance super-speed passenger transportation, hydraulic connection equipment is used to complete the connection of the vehicle body one by one. A new type of subterranean evacuated tube consisting of foundation tube and airproof layer to bear load and airproof atmosphere, respectively, is introduced in this paper. The tube, which is placed beneath the ground, has the advantages of unrestricted routing via a nearly straight-line path to any desired location and avoiding the accidental damage resulting from interaction with any type of normal ground activity. In addition, considering the remarkable difference of the air pressure between the inside and outside of the vehicle body, a multi-circular body with rectangular section is adopted for the vehicle [24]. This scheme could change the stress caused by the difference of air pressure inside and outside of the vehicle body from radial direction to uniform pull in tangential direction. Additionally, this structure makes it easy to install driving and other auxiliary facilities of the vehicle, improving the utilization efficiency of the vehicle greatly. The connection view of two vehicles and the cross-section view of the vehicle system are shown in Fig. 6.

A “bearing-airproof separation arrangement” vacuum boundary is used in the subterranean tube. The subterranean tube not only has good airproof properties, but also good mechanical properties. These functions can be realized by utilizing some simple technologies such as reinforced concrete construction, and plastic or rubber film airproof. In addition, because the vacuum degree inside the tube is directly related to the designed speed and construction cost of the vehicle, the reasonable vacuum degree should be determined by optimized design and economical analysis. Nevertheless, because the HTS maglev vehicle system has not been used in practical application, the advantage of super-high speed should be explored in more detail in the future.

5. Conclusions

We calculate the surface magnetic field of three PMGs by FEM, and find out that the influence of iron yoke width on the surface magnetic field of the PMG only exists at low height. The influence decreases with the increase of the height from the surface of the PMG. When the height is more than 10 mm, the influence can be ignored. In addition, the influence of different PMG configurations on the surface magnetic field is also investigated. The simulation results confirm the validity of this method to calculate the magnetic field distribution of the PMG.

According to the simulation results, a PMG is designed for the levitation force measurement system. The levitation forces of HTS bulks with three different arrangements on the designed PMG are measured by the measurement system. The experimental results show that the levitation force of the maglev vehicle system is not only related to the HTS bulks arrangements, but also to the outer applied magnetic field.

Moreover, a preliminary scheme for a subterranean super-high speed HTS maglev evacuated tube transport is described based on the above simulation and experiment results. The HTS maglev evacuated tube transport mainly consists of an evacuated tube, HTS maglev vehicle, PMG, propulsion system, station and emergency rescue system, etc. A subterranean tube, which is composed of a foundation tube and a vacuum airproof layer, is introduced. In order to convert the stress caused by the air pressure difference inside and outside of the vehicle, a multi-circular vehicle body is designed. The vehicle is driven by a linear motor propulsion system which is controlled by a ground controlling system. The scheme of long-distance super-high speed passenger transportation is accomplished by the connection of different vehicles.

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