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ARTICLE

Improvement of the Side-Suspended High-Temperature Superconductor Maglev Rotating System in Evacuated Tube

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Abstract: A well-established side-suspended maglev rotating system possesses two permanent magnet guidways (PMGs) with unimodal magnetic field for every one of them. The maglev vehicle of the system can reach a speed over 80 km/h at the suspending gap of 6 mm in an evacuated circular tube. A way of raising the maximum speed of the system without changing the whole structure greatly was discussed. Putting two parallel PMGs together to form a single PMG with a trimodal magnetic field will obviously increase the levitation force of the system, which will be possible to increase the maximum speed of the system. However, the mass of the vehicle will be increased at the same time to contract the effect of the increase in the levitation force. The result indicates that the trimodal structure PMG (TMG) can support higher speed than the unimodal structure PMG (UMG). In addition, the maximum speed for TMG augments increases with the increase of the number of bulks. When the number of columns of bulks is 17, the speed for TMG is 8.2 % faster than that for UMG.

Key words: high-temperature superconductor (HTS) maglev; levitation force; side-suspended maglev

The typical high temperature superconductor (HTS), melt-textured YBaCuO bulk, has both high critical current density and critical magnetic flux. When it is turned into the superconducting state by cooling with liquid nitrogen over a permanent magnetic guideway, it obtains both a large levitation force and a stable equilibrium. This makes HTS particularly attractive for applications in maglev train[1-6]. Running over the PMG without any mechanical contacts allows the HTS maglev train to achieve a high speed. However, for the normal railway traffic transportation, when the speed is greater than 350 km/h, not only the running noise of it is higher, but also 90% of the driving power is dissipated in the aerodynamic resistance. Thus an assumption of running the maglev train in low-pressure tube or evacuated tube transport is proposed[7]. However, less effort has been performed to build a real evacuated tube to run maglev system. Recently, a side-suspended high-temperature superconductor maglev rotating system in an evacuated tube has been built in the Superconductivity and New Energy R&D Center of Southwest Jiaotong University, China. Its scheme was introduced in earlier reports[8-10].

In the system, the guidance force is designed to overcome the weight of the vehicle, while the levitation force is used to provide the centripetal force. When the maglev vehicle moves at different speeds along the circular PMG in the vacuum tube, the centrifugal effect will cause the variation of the suspending gap. As the levitation force is changed by itself according to the variation of the suspending gap, the side-suspended HTS maglev system will allow the maglev vehicle to continuously move at higher speed in the circular tube. As we know, there is a linear correlation between the centripetal force and the square of speed. The higher speed of the vehicle means a smaller suspending gap. The maximum

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speed of the system is thus limited to keep the vehicle from colliding with the guideway. As the system is designed to evaluate the dynamic response of the maglev running in the vacuumed tube, we hope that the system can support its vehicle to run as fast as possible.

In this paper, we try to adjust the structure of PMG of the established maglev system to increase its levitation performance, and evaluate the effects of it to augment the speed of the system preliminarily. Results indicate that it will increase the speed of the system. When the number of columns of bulks is 17, the maximum speed of the adjusted system is about 8.2% larger than that of the established maglev system at the same working gap of 6 mm.

1 Maglev System and Experiment

The well-established side-suspended maglev system is shown in Fig.1. Parameters of the system are introduced in detail in our earlier report[9,10]. As we know that the centripetal force (F_c) is given by the following equation:

$$F_c = mv^2 / r \quad (1)$$

where m is the mass of the vehicle, v is the speed of the vehicle and r is the radius of PMG. Although the circular PMG with a diameter of 6.5 m allows the side-suspended vehicle to move along it and to accelerate over a speed of 80 km/h, the higher speed of the vehicle leads to the increase of the centripetal force and thus the decrease of suspending gap. This may reduce the suspending gap to a dangerous region and even cause the maglev system to collapse. The maximum speed of the system is thus limited. As it is almost impossible to raise the radius of PMG, to increase the speed of the system means augmenting the levitation force or decreasing the mass of the vehicle. Thus we suggest putting the two parallel UMGs together to form a single TMG, as shown in Fig.2.

In Fig.2, each of the blocks with an arrow inside is a permanent magnet with the section size of 40 mm × 40 mm. The arrow stands for the direction of the magnetic field for each block. The black portion between two permanent magnets represents iron with the section size of 6 mm×40 mm, which provides a peak of magnetic field nearby. Different from the established maglev system with two UMGs, the TMG possesses three peaks of magnetic field, as shown in Fig.2a and 2b. Simulated magnetic field distribution of TMG is shown in Fig.3. We noticed that the intensity of magnetic field of the middle peak is weaker than that of the both top and bottom peaks. As there is an additional peak of magnetic field, we hope that the TMG can support more HTS bulks to suspend. Although more bulks mean larger levitation force for the TMG system, the increased mass of the vehicle will contract the effect of the increase of the levitation force at the same time. Thus we have to evaluate the effects of them generally.

Otherwise, as we know that the arrangement of HTS bulks plays a key role in the levitation performance of HTS maglev system. For the situation of only one UMG, our earlier results

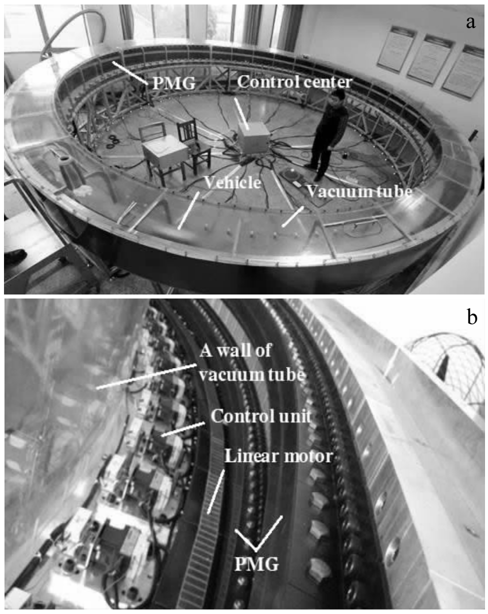

Fig.1 Photograph of the well-established side-suspended maglev rotating system in the vacuum tube: (a) a side-suspended vehicle running in the vacuum tube and (b) local structure of the system

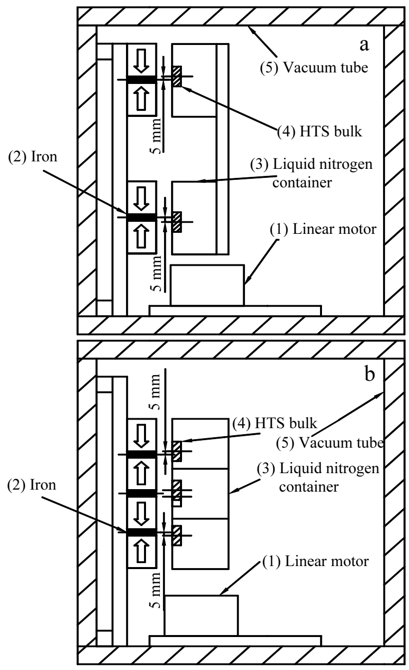

Fig.2 Cross-sectional structure of the side-suspended maglev system possessing two parallel UMGs (a) and one TMG (b) in the evacuated tube

indicate that the stability of the side-suspended maglev system is strongly dependent on the arrangements of HTS bulks along

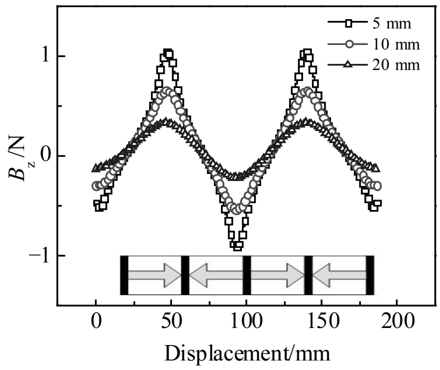

Fig.3 Distribution of magnetic field above TMG at the height of 5, 10 and 20 mm

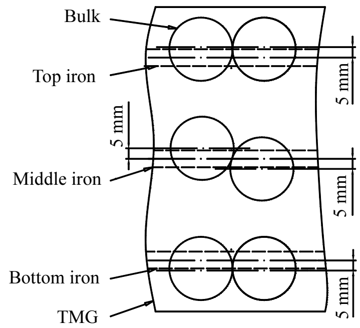

Fig.4 Arrangement of bulks for TMG

the peak of magnetic field[8]. For the linear arrangement of bulks at the magnetic field peak of UMG, the bulks are field cooled at larger working gap and capture some magnetic fluxes. Then the vehicle begins to move and to accelerate along the circular PMG, which increases the centrifugal effect with the increase of speed and further decreases the working gap. Thus stronger magnetic field will be experienced by the bulks at the same time. However, the bulks will tend to stay at the position with lower magnetic field intensity similar to that of their field cooling position. This will cause the bulks to move away from the peak of the magnetic field and further decrease the levitation force. It perhaps even leads to the collapse of the maglev system. While, self-stabilization can be achieved by distributing bulks symmetrically on two opposite sides of the peak of the magnetic field. In this way, the guidance force of the bulks on both sides of the peak of the PMG will counteract each other toward two opposite directions, and keep the levitation system self-stable when the gap decreases[8,9].

For the well-established system, linear arrangements are adopted for the UMGs, as shown in Fig.2a. The center of the top row of bulks is 5 mm higher than the peak of the top UMG, while the center of the bottom row is 5 mm lower than their corresponding peak. Thus the guidance forces from the top and bottom rows of bulks would counteract each other toward two opposite directions, and keep the levitation system self-stable when the gap decreases. For the system with TMG, as shown in Fig.4, three peaks of the magnetic field are presented at the center of the top, middle and bottom irons. The front view of the arrangement of bulks of TMG shown in Fig.4 indicates that the top and bottom rows of bulks are similar to those of UMGs. The bulks for middle row are arranged alternately on both sides 5 mm away from the center of the middle iron. In fact, for the well-established system with two UMGs, the arrangement of bulks shown in Fig.2a was proved to be able to sustain the system to run stably and to reach a speed over 80 km/h. Furthermore, referring to our earlier results[8,9], we consider that the arrangement of bulks can keep the system stable during its running along the circular TMG.

In order to estimate the effects of the TMG system of supporting a higher speed of the vehicle than two UMGs, we need to evaluate the increase of levitation force and the variation of the mass of vehicle at the same time when we put the two UMGs together to form a single TMG. We thus measured the levitation force varying with the gap for different magnetic field peaks when the bulk is 5 mm away from its corresponding iron center. The bulk was firstly field cooled at the gap of 30 mm, and its axis is 5 mm away from the corresponding iron center. Then it was pressed down to the position with the gap of 5 mm. The bulk is 30 mm in diameter and 10 mm in thickness. The results are shown in Fig.5. At the working gap of 6 mm, the bulk at the top or bottom peak presents the levitation force of 60 N, and that of the middle peak is about 50 N. We notice that the levitation force of the middle peak is lesser than that of the top and bottom peaks, which is consistent with the simulated magnetic field distribution of TMG.

2 Results and Discussion

It is obvious that the additional row of bulks for TMS will

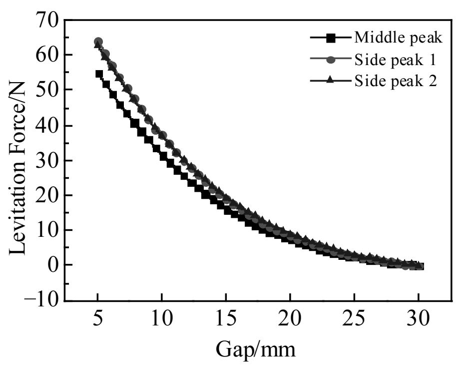

Fig.5 Levitation force varying with gap for different magnetic field peaks of TMG when the bulk is 5 mm away from its corresponding iron center

increase the total levitation force of the system. However, this may cause the weight of vehicle to increase at the same time. Thus we have to calculate the weight of the vehicle for the UMG and TMG systems separately.

As shown in Fig.2a, the vehicle of the established maglev system consists of two independent containers and one bridge. While the vehicle for TMG system, as shown in Fig.6, consists of one container which is divided into three separated chambers with thin stainless sheet. Each chamber has an arrangement of HTS bulks aimed at its corresponding magnetic field peak of TMG. When liquid nitrogen is put into the container from the inlet of the vehicle, it will fill the separated chambers one by one via their own inlets. This allows all the bulks in different chambers to get the same cooling condition.

The vehicle for UMG system possesses two containers. Each container has an inner width of 60 mm and a height of 102 mm. For the container of TMG, as there is an additional row of bulks inside, the inner width and height of it are set as 85 mm and 204 mm, respectively. Larger width of the container for TMG is set to keep almost the same volume of liquid nitrogen as for UMGs to cool each bulk. The length of container along PMG depends on the number of the columns of bulks. The inner length is set as 35 mm for only one column, and increases by 30 mm for every added column of bulks. The thickness of the wall of the vehicle close to PMG is 3 mm. The suspending height between the vehicle and the PMG surface is set as 3 mm for the purpose of safety. This means that the working gap between bulks and PMG is 6 mm. The levitation force presented by each column of bulks is 170 N for TMG, and 120 N for UMG system. Otherwise, the increased mass of the container for every added column of bulks is 272 g for TMG and 305 g for UMG (without considering the mass of bulks). Each YBaCuO bulk is 30 mm in diameter and 10 mm in thickness with the mass of 40 g. Considering that the container is filled with liquid nitrogen, the velocity of the maglev systems can be given by the following equation:

$$V = \left[F_C \cdot r / \left(m_C + m_B + m_{LN}\right)\right]^{1/2} \quad (2)$$

where v is the speed of the vehicle, F_C is the centripetal force in maglev system, r is the radius of PMG, m_C is the mass of container, m_B is the mass of bulks and m_{LN} is the mass of liquid nitrogen.

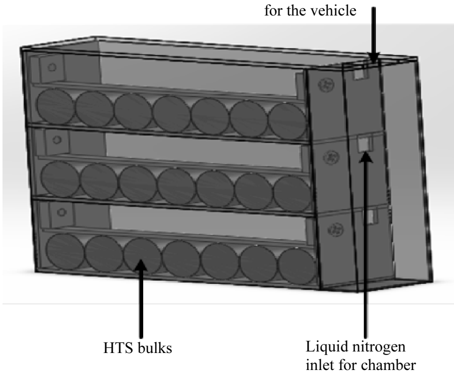

Fig.6 Sectional view of the container for the TMG

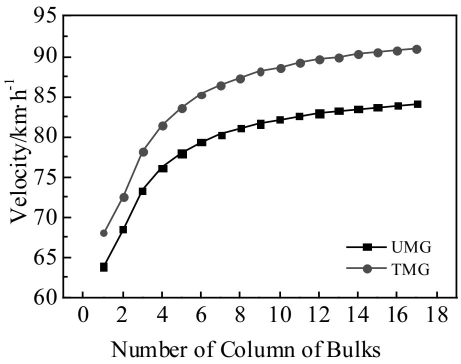

Fig.7 Velocity with different columns of bulks for the UMG and TMG

To keep the working gap of 6 mm, the variations of velocity with the increase of the number of columns of bulks for the UMG and TMG systems are shown in Fig.7. The results indicate that the TMG can provide higher velocity than UMG, and the difference in velocity between them increases with the increase of the number of the columns. For the number of the columns of 17, the velocity for TMG is 8.2% larger than that for UMG system. Furthermore, as the distribution of the magnetic field of TMG is more complicated than that of UMG, it is possible to increase the ability of TMG to support higher velocity by adjusting arrangement of bulks. This means that the way of putting two UMGs together to form a TMG is helpful to increase the speed of the vehicle.

3 Conclusions

1) Putting two parallel UMGs together to form a single TMG can obviously increase the levitation force of the system. At the same time, the increased mass of the vehicle can counteract the effect of the increase in the levitation force to enhance the speed of the system.

2) TMG system can support higher speed than UMG. With the increase of the number of bulks, the increase of speed for TMG is larger than that for UMG at the gap of 6 mm. When the number of columns is 17, the velocity for TMG is 8.2% larger than that for UMG.

3) TMG is helpful to increase the speed of the vehicle without changing the whole structure of the system greatly since it is easier to adjust the PMG structure. It is also possible to increase the ability of TMG to support higher velocity by adjusting the arrangement of bulks.

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真空管道高温超导侧挂磁悬浮旋转运动系统的改进

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摘　要：侧挂式磁悬浮回转系统拥有两根具有单磁场峰值的永磁轨道。在环形真空管道中，该系统的磁悬浮车可以在 6 mm 悬浮间隙下达到 80 km/h 的运行速度。在不大幅改变整体结构的条件下，探讨了一种增大系统运行速度的途径。通过将 2 个平行的永磁轨道合并成 1 个具有三磁场峰值的单轨，将显著增强系统的悬浮力，从而有望提高系统的运行速度。然而车体质量的增加将抵消悬浮力增加带来的效应。综合评估二者的影响，结果表明，相比较于具有单磁峰的双轨，具有三磁场峰值的单轨能让系统获得更高的运行速度。并且，对于三磁峰单轨系统，其最大运行速度随超导块数量的增加而增加。相比较于单峰磁轨而言，当超导块列数为 17 时，三峰磁轨系统的运行速度可以增大 8.2%。

关键词：高温超导磁悬浮；悬浮力；侧挂式磁悬浮

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