Study of Running Stability in Side-Suspended HTS-PMG Maglev Circular Line System

Dajin Zhou¹, Lifeng Zhao¹, Linbo Li¹, Chenyu Cui¹, Chang-Chun Hsieh¹, Yong Zhang¹, Jianqiang Guo¹ and Yong Zhao¹,²,*

¹Key Laboratory of Maglev Train and Maglev Technology of Ministry of Education, Superconductivity and New Energy R&D Center, Southwest Jiaotong University, Chengdu 610031, China,
²School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China

*Corresponding author: Prof. Yong Zhao, e-mail: yzhao@home.swjtu.edu.cn

Abstract. A research on stability of the side-suspended HTS-PMG maglev circular line system is carried out through simulation experiment. The results show that the maglev vehicle will gradually get close to the track surface during acceleration under the action of centrifugal force, leading to decay of guidance force and occurrence of vertical eccentric motion. In case of linear array of YBa₂Cu₃O₇₋ₓ (YBCO) bulks, the guidance force will be changed with the decreasing of the levitation gap. It can be suppressed through the complex arrangement of YBCO bulks. Fortunately, triangle array of YBCO bulks can effectively keep the guidance force constant and realize stable running during accelerating process of the prototype vehicle. Based on the research on stability of side-suspended maglev vehicle, a side-suspended PMG circular test track with diameter of 6.5 m and circumference of 20.4 m is successfully designed and established, enabling the prototype vehicle to run stably at up to 82.5 km/h under open atmosphere (9.6 × 10⁴ Pa).

1. Introduction
Taking advantage of flux pinning characteristic of YBCO bulk, HTS maglev system has excellent self-stability [1]. It is widely used in magnetic bearing [2, 3], maglev vehicle [4-6], maglev launch [7, 8] and other fields. Compared with conventional wheel rail train, maglev vehicle operates more stably without noise, and has smaller turning radius. It is an important solution for high-speed ground transportation in the future.
Currently, mature maglev train technologies mainly include TR train of Germany [9] and electric dynamic suspension (EDS) train of Japan [10]. It has already been commercialized in TR train and achieved a high speed of 603 km/h in the test of EDS train. Although 29 years has passed since YBCO high-temperature superconductor was discovered, research and development of HTS maglev vehicle is still under laboratory study, mainly in China, Germany, Brazil and Japan [11-14]. In 2016, the team from Federal University of Rio de Janeiro of Brazil designed a full-size manned HTS maglev vehicle and a 200 m-long straight track to carry out the test with a speed of only 7 km/h. Though it is theoretically predicated that the highest speed of HTS maglev vehicle is up to 2900 km/h, there is no actual dynamic test for verification.

Continuous acceleration of maglev vehicle can be realized in a finite-length circular track. Huge centrifugal force, however, will be generated during high-speed operation of maglev vehicle, even causing the maglev vehicle to run off the track. For locomotive, the track is designed with a proper inclination to increase the centripetal force of the train when making a turn. Similarly, the permanent magnetic guideway (PMG) is inclined by 90 ° along the horizontal plane and the HTS maglev vehicle is placed beside the track. The guidance force counteracts the weight and the levitation force counteracts the centrifugal force. It will greatly improve the speed of maglev vehicle by this method. The proposal of side-suspended HTS (SS-HTS) maglev system effectively solves the problem of insufficient centripetal force and off-track of the maglev vehicle along the tangential direction of the track when the maglev vehicle runs above circular track. Currently, there are only a few research reports on SS-HTS maglev system due to a lack of theory and experimental study. When running “sticking to wall” at a high speed, the SS-HTS maglev vehicle will get closer to the track surface under the action of centrifugal force. The dynamic process of maglev vehicle running above a circular track can be simulated by using a servo motor to control the change in levitation gap between the maglev vehicle and the track. In the SS-HTS maglev circular line system, a simulation test for the guidance force is carried out to analyze the stability of guidance force under different arrays of YBCO bulks.

2. Experiments

2.1. Magnetic track

In order to provide a high-density magnetic field for the HTS maglev vehicle, the magnetic track is usually assembled with permanent magnet (PM) and iron plate to press PMs with the same pole closer to each other and gather magnetic field through iron plate, thus obtaining a magnetic field stronger than that of a conventional PM. Figure 1(a) shows cross-section structure of the PMG which consists of two PMs with opposite magnetization direction and an iron plate in between. The PM is made of NdFeB (grade: N52), 40 × 40 ×52.5 mm³ in size, and the iron plate is 6 mm in thickness. As shown in figure 1(c), the characteristics of magnetic field distribution above the PMG are that z-component of B (Bz) forms a primary magnetic peak above the center of the PMG and two secondary magnetic peaks located at both sides edges of the PMG respectively, and presents an symmetrical distribution on both sides of the PMG while x-component of B (Rx) presents an anti-symmetric distribution. Actually, the distribution of Bz along x-axis and y-axis direction is asymmetric and inhomogeneous respectively due to the difference in PM performance and gaps between PM and PM, PM and iron plate.
2.2. Experimental principle and equipment

The operating principle of SS-HTS maglev circular line system shown in figure 2 mainly involves the following three processes: (1) Initial field cooling (FC) process: where the relative position of YBCO bulk and PMG is fixed by the aid of a fixture, then liquid nitrogen is injected into the cryogenic container for cooling YBCO bulk. The corresponding levitation gap \( l \) is called field cooling height (FCH); (2) static suspension process: after YBCO bulk fully gets into the superconducting state, the fixture is removed. YBCO bulk moves downwards under the action of gravity until a balance between guidance force and gravity is achieved, a static vertical displacement \( d \) is generated; and (3) dynamic operation process: during acceleration in circular track, YBCO bulk gets close to the PMG under the action of centrifugal force. The guidance force is decreased with the reduction of levitation gap (as shown in figure 4). YBCO bulk moves downwards until a new balance between guidance force and gravity is achieved, a dynamic vertical displacement \( s \) is generated.

![Figure 1. (a) The structure of PMG segment; (b) Photograph of the PMG segment; (c) Distribution of magnetic field intensity at position 10 mm above the PMG segment.](image)

![Figure 2. The static and dynamic suspension process of SS-HTS maglev circular line system, \( l \) is the levitation gap, \( d \) is static vertical displacement and \( s \) is dynamic vertical displacement, \( F_c \) is centrifugal force, \( F_l \) is levitation force, \( F_g \) is guidance force, \( G \) is gravity.](image)

A simulation test platform as shown in figure 3(c) is designed and established according to the operating principle of SS-HTS maglev circular line system. Columnar single-seed crystal melt-processed YBCO bulk with 30 mm in diameter and 18 mm in thickness is used in the test. Multiple
YBCO bulks are fixed on the inside wall of the cryogenic container. The levitation gap $l$ and the displacement $d, s$ are controlled by servo motors in horizontal and vertical direction respectively. The simulation test mainly involves two processes: (1) the servo motor in vertical direction is actuated after YBCO bulks get into the superconducting state to cause a vertical displacement of the PMG along $x$-axis direction, to simulate that YBCO bulks move downwards under the action of gravity until a balance between gravity and guidance force is reached; and (2) the servo motor in horizontal direction is actuated to make the cryogenic container get close to the PMG along $z$-axis direction, to simulate that YBCO bulks get close to the PMG under the action of centrifugal force. During the entire test process, the guidance force is measured by a pull-pressure sensor.

For the purpose of dynamic test in SS-HTS maglev vehicle, a SS-HTS maglev circular track with diameter of 6.5 m and perimeter of 20.4 m is established and an evacuated tube is added to decrease aerodynamic drag, as shown in figure 3(a). A superconducting prototype vehicle adopting triangular array of YBCO bulks is also designed for high-speed dynamic test, as shown in figure 3(b). Linear motor is used for continuous driving during operation of the prototype vehicle and a vehicle-mounted gyroscope is used to measure the speed of prototype vehicle.

![SS-HTS maglev circular track](image1)

**Figure 3.** (a) Panoramic photograph of SS-HTS maglev circular track; (b) local features of PMG and prototype vehicle, 1-prototype vehicle, 2-PMG; (c) the experimental setup for measuring the guidance force change with levitation gap, 3-PMG, 4-cryogenic container.
3. Results and discussion

3.1. Linear array of YBCO bulks
The guidance force of YBCO bulks in linear array (see Array 1 in figure 6(a)) is tested. The detail test process is: (1) Make axis of YBCO bulk coincide with symmetry axis of PMG (see Position 3 in figure 5(a)) and inject liquid nitrogen into cryogenic container until all YBCO bulks get into the superconducting state; (2) Start the servo motor in vertical direction to drive the PMG upward by 2 mm (equivalent downward movement of YBCO bulk by 2 mm); (3) Keep the relative position between PMG and container unchanged in vertical direction, start the servo motor in horizontal direction to drive container to get close to PMG until the rated levitation gap of 5 mm is reached. At FCH of 10 mm, 15 mm and 20 mm, the change in guidance force with reduction of levitation gap are obtained respectively, as shown in figure 4. The guidance force decreases with reduction of levitation gap, and becomes negative value at FCH of 15 mm and 20 mm when levitation gap is less than 6 mm and 10 mm respectively. These results show that the instability of guidance force exists in the dynamic operation of SS-HTS maglev circular line system. Thus further research on maintaining the stability of guidance force is required for safe operation of SS-HTS maglev circular line system.

Figure 4. The change in guidance force with the decrease of levitation gap under different conditions of FCH, where the axis of YBCO bulks overlapping with the centerline of PMG (e.g. Position 3 in figure 5(a)).

Through changing the initial field cooling (FC) position between YBCO bulk and PMG in vertical direction, five different linear arrays are obtained, as shown in figure 5(a). According to the foregoing test procedure, the change in guidance force under different initial FC positions is acquired at FCH of 20 mm, as shown in figure 5(b). When the axis of YBCO bulk located in the area of \( x < 0 \) during static suspension (the location is not the initial FC position, because YBCO bulk drops downward by 2 mm from the initial FC position, as shown in figure 2 ), the guidance force increases with reduction of levitation gap, corresponding to Position 1 and Position 2. On the contrary, when the axis of YBCO bulk located in the area of \( x > 0 \) during static suspension, the guidance force decreases and gets negative with reduction of levitation gap, corresponding to Position 3 and Position 4. But the guidance force of Position 5 presents different changing law compared with Position 3 and Position 4. Possibly
because the YBCO bulk located at Position 5 is more closer to the lower edge of PMG during side suspension, the guidance force is affected by magnetic field nearby the secondary magnetic peak of $B_z$, as shown in figure 1(c). These results indicate that the relative position in vertical direction between YBCO bulk and PMG plays a key role in the changing law of guidance force with decreasing the levitation gap. The instability of guidance force still exists in the system with linear array of YBCO bulks. According to the results from figure 5(b), choose proper YBCO bulks located upper half area ($x < 0$) and lower half area ($x > 0$) of PMG to combination, the positive guidance force can be overlaid with the negative guidance force to decrease the change of guidance force. It is a feasible method to realize the stabilization in guidance force. Thus, the fluctuation in guidance force during dynamic process of SS-HTS maglev circular line system can be optimized through complex array of YBCO bulks.

Figure 5. (a) Five different types of linear arrays (e.g. Array 1 in figure 6(a)) of YBCO bulks with the condition of $FCH = 20$ mm; (b) the change of average guidance force reduced to one bulk with the levitation gap from 20 mm to 5 mm for five types of linear array of YBCO bulks in static experiment.

3.2. Complex array of YBCO bulks

Figure 6(a) gives five different complex arrays of YBCO bulks. By reference to the test procedures of guidance force in linear array of YBCO bulks, the guidance force under different complex arrays of YBCO bulks is tested with levitation gap decreasing from 20 mm to 5 mm. As the quantity of YBCO bulks varies in different complex arrays, the average guidance force reduced to one YBCO bulk is taken for discussion to facilitate comparison and analysis, as shown in figure 6(b). Compared with the linear array (Array 1) of YBCO bulks, it can be found that all other complex arrays (Arrays 2–5) restrain the variation of guidance force in different extent. Complex arrays of YBCO bulks can improve the dynamic stability of SS-HTS maglev circular line system.
Figure 6. (a) Five different types of complex arrays of YBCO bulks with the condition of FCH = 20 mm; (b) the change of average guidance force reduced to one bulk with the levitation gap decreasing from 20 mm to 5 mm, among which Array 2 (triangular array) presented the minimum change.

According to figure 5(a, b), when the axis of YBCO bulk located in the area of \( x < 0 \) (the upper half area of PMG) during static suspension, the guidance force increases and keeps positive value with the levitation gap decreasing from 20 mm to 5 mm. Apart from the case of Position 5 (possible reason was given in the previous section), the guidance force decreases and becomes negative value under the axis of YBCO bulk located in the area of \( x > 0 \) (the lower half area of PMG) during static suspension. When the upper YBCO bulks and lower YBCO bulks are combined together, the variation in complex guidance force will be reduced due to the superposition of positive force and negative force. In fact, when the initial FC positions of two YBCO bulks are symmetrical at both sides of PMG, the absolute values in guidance forces of two YBCO bulks are not equal. Due to the YBCO bulks drop downward by 2 mm during static suspension, result in the upper YBCO bulk is more closer to \( z \)-axis (symmetry axis of PMG) compared with the lower YBCO bulk. The absolute value in guidance force of upper YBCO bulk is greater than lower YBCO bulk in the symmetrical initial FC position.

During static suspension, Array 1 only consists of three lower YBCO bulks, the average guidance force presents negative force and maximal variation. Array 3 consists of two upper YBCO bulks and two lower YBCO bulks, positive force dominates in the average guidance force. Array 4 consists of one upper YBCO bulk and three lower YBCO bulks, negative force dominates in the average guidance force. Array 5 consists of three upper YBCO bulks and four lower YBCO bulks, but one lower YBCO bulk closed to the lower edge of PMG presents positive force, result in positive force dominates in the average guidance force. Finally, it can be found that almost constant in average guidance force occurs in triangular array (Array 2), which consists of one upper YBCO bulk and two lower YBCO bulks. It indicates that test vehicle can run in SS-HTS maglev circular line system with the highest dynamic stability under Array 2. For the test results of figure 6(b), in this paper, we only make a qualitative
discussion. In the further research, we will give the quantitative interpretation through theoretical
calculation and simulation.

A SS-HTS maglev prototype vehicle with triangular array of YBCO bulks is designed, as shown in
the illustration of figure 7. The prototype vehicle consists of two cryogenic containers which are
respectively placed above the upper PMG and the lower PMG. They are connected by two metal
conduits, one for liquid nitrogen injection and the other for gas exhaust. A vehicle-mounted three-axis
gyroscope is used to measure the running path and obtain the speed-time curve (include acceleration,
constant speed and deceleration process) of the prototype vehicle, as shown in figure 7. Under open-
air atmospheric pressure (9.6×10^4 Pa), actual test speed of the prototype vehicle reaches to 82.5 km/h,
which is the highest ever recorded without vacuuming.

4. Summary

SS-HTS maglev system helps maglev vehicle break through the restriction of centrifugal force in
circular line, greatly improves the running speed of maglev vehicle above circular track and prevents
maglev vehicle running off the track along tangent direction. An effective research on dynamic
operation process of the SS-HTS maglev circular line system is made through simulation test. The
results show that the prototype vehicle gets close to the track surface during acceleration, the guidance
force will vary with the reduction of levitation gap, leading to instability of the guidance force.
Researches on guidance force under linear and complex arrays of YBCO bulks show that variation of
guidance force can be reduced under complex array of YBCO bulks, especially triangular array where
the guidance force almost remains unchanged with the reduction of levitation gap, thus ensuring stable
high-speed operation of the prototype vehicle above the circular track. Finally, the prototype vehicle
based on triangular array of YBCO bulks realizes to run stably above SS-HTS maglev circular track,
with the highest speed of 82.5 km/h under open-air atmospheric pressure (9.6×10^4 Pa).
Acknowledgments
We thank the financial support from the Program of International S&T Cooperation (Grant No. 2013DFA51050), the National Nature Science Foundation of China (grant No. 51271155, 51377138), the Fundamental Research Funds for the Central Universities under the No. 2682016ZDPY10, Science and Technology Project in Sichuan Province (2017JY0057), and the Doctorial Innovation Funds under the No.A0920502051410-3.

References
[1] E. H. Brandt, “Levitation in physics,” Science, vol. 243, no. 4889, Jan. 1989, pp. 349–355.
[2] W. Liu et al., “Design of a high-Tc superconductive maglev flywheel system at 100-kW level,” IEEE Trans. Appl. Supercond., vol. 26, no. 4, Jun. 2016, Art. ID. 5700805.
[3] F. N. Werfel et al., “Towards high-capacity HTS flywheel systems,” IEEE Trans. Appl. Supercond., vol. 20, no. 4, Aug. 2010, pp. 2272–2275.
[4] F. N. Werfel et al., “Superconductor bearings, flywheels and transportation,” Supercond. Sci. Technol., vol. 25, no. 1, Dec. 2011, Art. ID. 014007.
[5] F. N. Werfel et al., “Experiments of superconducting maglev ground transportation,” IEEE Trans. Appl. Supercond., vol. 26, no. 3, Apr. 2016, Art. ID. 3602105.
[6] S. Y. Wang et al., “High temperature superconducting Maglev equipment on vehicle,” Physica C, vol. 378–381, Oct. 2002, pp. 809–814.
[7] W. J. Yang et al., “Construction and performance of HTS maglev launch assist test vehicle,” IEEE Trans. Appl. Supercond., vol. 16, no. 2, Jun. 2006, pp. 1108–1111.
[8] W. J. Yang et al., “Levitation characteristics in an HTS maglev launch assist test vehicle,” Supercond. Sci. Technol., vol. 20, Feb. 2007, pp. 281–286.
[9] E. Gottzein, K. -H. Brock, E. Schneider and J. Pfefferl, “Control aspects of a tracked magnetic levitation high speed test vehicle,” Automatica., vol. 13, no. 3, May 1977, pp. 205–223.
[10] S. Kusada et al., “The project overview of the HTS magnet for superconducting maglev,” IEEE Trans. Appl. Supercond., vol. 17, no. 2, Jun. 2007, pp. 2111–2116.
[11] J. Wang et al., “The first man-loading high temperature superconducting maglev test vehicle in the world,” Physica C, vol. 378–381, Oct. 2002, pp. 809–814.
[12] L. S. Mattos et al., “MagLev-cobra operational tests,” IEEE Trans. Appl. Supercond., vol. 26, no. 3, Apr. 2016, Art. ID. 3600704.
[13] L. Schultz et al., “Superconductively levitated transport system—the SupraTrans project,” IEEE Trans. Appl. Supercond., vol. 15, no. 2, pp. 2301–2305, Jun. 2005.
[14] M. Okano, T. Iwamoto, M. Furuse, S. Fuchino, and I. Ishii, “Running performance of a pinning-type superconducting magnetic levitation guide,” J. Phys. Conf. Ser., vol. 43, 2006, pp. 999–1002.