Side-suspended High-$T_c$ Superconducting Maglev Prototype Vehicle Running at a High Speed in an Evacuated Circular Test Track

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Abstract. High-$T_c$ superconductor (HTS) and permanent magnetic guideway (PMG) based maglev train is intensively studied in China, Japan, Germany and Brazil, mainly through static or vibration test. Amongst these studies, only a few of reports are available for the direct and effective assessment on the dynamic performance of the HTS maglev vehicle by running on a straight or circular PMG track. The highest running speed of these experiments is lower than 50 km/h. In this paper, a side-suspended HTS permanent magnetic guideway maglev system was proposed and constructed in order to increase the running speed in a circular track. By optimizing the arrangement of YBCO bulks besides the PMG, the side-suspended HTS maglev prototype vehicle was successfully running stably at a speed as high as 150 km/h in a circular test track with 6.5 m in diameter, and in an evacuated tube environment, in which the pressure is $5 \times 10^3$ Pa.
1. Introduction

Taking advantage of pinning force generated under the interaction between high-$T_c$ superconductor (HTS) bulks and permanent magnetic guideway (PMG), HTS maglev vehicle has excellent autostability [1]. In comparison with Transrapid series electromagnetic suspension (EMS) maglev vehicle of Germany and low-temperature superconducting electrodynamic suspension (EDS) maglev vehicle of Japan, the HTS maglev vehicle dispenses with complex control system. No matter the HTS maglev vehicle under a certain load is static or dynamic, a large suspension gap can be maintained. Further more, the HTS maglev system realizes suspension in any direction, e.g. side suspension, in addition to conventional horizontal suspension.

Currently, research on dynamic operation of HTS maglev vehicle is made mainly through test on a short-distance linear or small-radius circular track. The first HTS maglev circular track co-designed by Chinese and German researchers in 1997 adopted air-core linear synchronous motor with track diameter of 3.5m and the highest speed of 6.5 km/h [2]. At the end of 2000, the research team led by Wang et al from Southwest Jiaotong University (hereinafter referred to as SWJTU) of China designed a manned HTS maglev prototype [3] with a 15.5 m linear test track. In 2004 and 2011, German IFW team designed linear and circular test track systems respectively for manned HTS maglev vehicle [4-5], the latter with length of 80m, allowing for vehicle speed of up to 20 km/h. In 2014, Deng et al established an HTS maglev prototype as well as a 45 m circular track with diameter of 12 m where the manned maglev prototype was driven by a linear motor with the highest speed of 50 km/h [6]. In 2015, a research team from Federal University of Rio de Janeiro of Brazil designed a full-size manned HTS maglev vehicle driven by on-board motor with improved structure as well as a 200m linear test track allowing for test speed up to 7 km/h [7].

Figure 1. (a) The HTS maglev loop track system in an evacuated tube with a up-down levitation configuration; (b) The SS-HTS maglev loop track system in an evacuated tube.

In order to reduce the air resistance for HTS maglev vehicle, evacuated tube technology was cooperated with the HTS maglev system (see Fig.1(a)) [8]. The first circular track system for evacuated tube HTS maglev vehicle (driven by linear motor) with track diameter of 3 m allowing for vehicle speed up to 21 km/h. The test speed of HTS maglev vehicle, from model vehicle, prototype vehicle, full-size test vehicle to evacuated tube vehicle, has been low due to limited length or radius of linear or circular test track. Though it is theoretically predicated that the highest speed of HTS maglev vehicle is nearly 2,900 km/h, there is no specific dynamic test for verification. In order to demonstrate the potential of higher running speed for HTS maglev system, it is necessary to make new design for the HTS maglev system if the experiments has to be performed in a limited laboratory space. In this paper, we report the design and construction of a side-suspended-HTS maglev circular track system (see Fig. 1(b)), in which the PMG track was laid on the wall to allow the vehicle to operate at a high speed. Since the strong centrifugal force during a high speed running in the circular track was overcome by the repulsive force between the HTS bulks and PMG, a running speed up to 150 km/h
was achieved for the testing maglev vehicle in the circular test track with track diameter of 6.5 m and track length of 20.4 m, and in an evacuated tube environment of a pressure $5 \times 10^3$ Pa.

2. **Structure of HTS maglev loop track in an evacuated tube**

The evacuated tube SS-HTS maglev circular track system is mainly composed of SS-HTS maglev system, evacuated tube system and driving system, as shown in Fig. 2. The outer circle diameter and inner circle diameter of the system are 6.77 m and 5.8 m respectively; the system base is 1.33 m high; and the diameter and perimeter of circular PMG are 6.5 m and 20.4 m respectively. As shown at the top left corner of Fig. 2, the SS-HTS maglev system consists of a wall-attached track and a SS-HTS maglev vehicle prototype. The prototype vehicle is placed beside the track and driven by a linear motor after it reaches the superconducting state. Given energy consumption and efficiency of the driving system, segmented power supply control technology is adopted for the linear motor. As shown on the right of Fig. 2, 96 linear units are laid along the entire circular track and powered by a 30 kw three-phase frequency converter while power-on/off of the liner motor unit is controlled by the corresponding solid state relay. Meanwhile, 96 optoelectronic switches are also laid along the circular track to detect the position of the maglev vehicle and a segmented power supply controller is used to control power supply of the motor unit near the maglev vehicle. A 7.5 kw vehicle-mounted vacuum pump is used to control the air pressure in the tube and, in combination with a 1.5 kw small-power mechanical vacuum pump to maintain the set pressure therein.

![Figure 2. Structure of SS-HTS maglev test circular track system with an evacuated tube, which is consist of SS-HTS maglev system, Evacuated tube system, and the segmented power supply control system.](image)

3. **Side-suspended HTS maglev system**

SS-HTS maglev system mainly consists of side-suspended track and side-suspended superconducting vehicle, the value of maglev vehicle mass is 5.67kg filled with liquid nitrogen, as shown in Fig. 3(a), 2D cross-section diagram of the system. Different from conventional up-down configuration, superconducting bulks are laid beside the track and through the field cooling process, enable free suspension of the maglev vehicle beside the track. The centrifugal force generated during operation of the maglev vehicle is overtaken by suspension force and gravity by guidance force, as shown in Fig. 3.
3(b) below. When the huge centrifugal force is overtaken by suspension force, a greater centripetal force will be obtained to make the maglev vehicle reach a higher speed in the circular test track, thus preventing the maglev vehicle running off the track along the tangent direction and providing a solution for the maglev vehicle to run across a small-radius curve.

![Figure 3](image-url)

**Figure 3.** (a) The cross-sectional view of SS-HTS maglev test circular track, 1-evacuated tube, 2-PMG, 3-multiple YBCO bulks, 4-liquid nitrogen, 5-prototype vehicle, 6-photodetector, 7-linear motor, 8-solid state relay; (b) the force of prototype vehicle under the stable operation, $F_c$ is centrifugal force, $F_l$ is levitation force, $F_g$ is guidance force, $G$ is gravity.

As shown in Fig. 4(a), PMG is assembled by two N52 permanent magnet units with opposite polarity and an iron plate (technically pure iron) in between. A higher magnetic intensity can be achieved above the track surface due to aggregation of magnetic field through the iron plate. The permanent magnet unit is $40 \times 40$ mm in size, the iron plate is 6 mm in thickness, and the center-to-center spacing between upper and lower tracks is 220 mm. Fig. 4(b) shows the intensity distribution along the $x$-axis of $z$-axis and $x$-axis components ($B_z$ and $B_x$) of magnetic fields obtained with the measurement 5 mm and 20 mm above the PMG respectively. Symmetric distribution of $B_z$ and antisymmetric distribution of $B_x$ are seen around the center of PMG. $B_z$ forms a primary magnetic hill above the track center and two secondary magnetic hills with opposite polarity at two sides of the track. The intensity of $B_z$ above the track center is up to 1.5 T and that 5 mm and 20 mm above the track surface, 0.9 T and 0.3 T respectively. The support wall of the track is precisely assembled with high-strength metal components, as shown in Fig. 4(c). The maglev vehicle will get closer to the track under the action of centrifugal force during acceleration. It is found through static simulation test that guidance force will change due to continuous reduction of suspension gap. As shown in Fig. 4(d), triangle array of YBCO bulks can effectively keep constant the guidance force, ensuring high suspension stability of the maglev vehicle during dynamic operation, single YBCO bulk is 30 mm in diameter and 20 mm in thickness.
Figure 4. (a) The configuration and dimensions of PMG; (b) distribution of $B_z$ and $B_y$ along the x-axis at positions 5 mm and 20 mm above the top surface of PMG; (c) the local feature photo of side-suspended PMG; (d) triangle arrangement of YBCO bulks.

4. Evacuated tube system

In order to reduce the influence of air flow upon high-speed operation of the maglev vehicle, an evacuated tube is established along the circular track, as shown in item 1 of Fig. 3(a). The evacuated tube, with sectional dimension of $48.5 \times 55$ cm, is composed of metal base plate and outer wall and acrylic top plate and inner wall. The tube is divided into multiple components for assembly to facilitate transportation and installation and the joint between adjacent components is subject to vacuum sealing. Reinforcing ribs are provided along the inner side of the evacuated tube to prevent excessive deformation of the tube wall under low pressure. Air pressure in the evacuated tube is adjusted and stabilized by primary pump and holding pump, with the specific control principle shown in Fig. 5(a). Assembled by multiple components, the tube may be subject to leakage on a certain degree, leading to pressure drop in the tube. When the pressure is adjusted to the specified value by the primary pump, the power supply of the primary pump will be cut off by air pressure sensor built in the tube and the holding pump will be started to maintain the pressure in the tube. Finally, the air pressure in the tube will be reduced to 650 Pa by the 7.5 kw mechanical vacuum pump within 19 minutes, as shown in Fig. 5(b).
5. Drive system

The driving system is mainly composed of weak current controller, linear motor and three-phase variable frequency power supply. The operating principle of the system is as shown in Fig. 6(a): segmented power supply control of linear motor is realized through FPGA and MCU. MCU refers to the microprogrammed control unit, which is mainly used for receiving address signal of maglev vehicle and sending control signal of linear motor. High-speed encoding of 96 parallel binary address signals (0: maglev vehicle not at current position; 1: maglev vehicle at current position) detected by 96 photoelectric detectors is carried out based on high-speed parallel processing through multiple peripheral ports of FPGA, and then single-character signals are sent to the MCU. MCU will send driving control signals to FPGA according to set power supply parameters and FPGA will convert these signals into 96 parallel binary control signals (0: close solid state relay; 1: open solid state relay) through high-speed decoding and control the power supply of 96 linear motors. Parameters for segmented power supply of linear motor mainly include the number of front, middle and back motors and can be set through operation panel as shown in Fig. 6(b). During operation of the maglev vehicle, it is only necessary to supply power for front, middle and back motors, thus saving the power capacity and effectively improving the driving efficiency of the linear motor, as shown in Fig. 6(c).

Figure 5. (a) The schematic diagram of evacuated tube system; (b) the curve of pressure in evacuated tube from local atmosphere down to 650 Pa during 19 minutes.
Dynamic operation of the evacuated tube SS-HTS maglev circular track system is successfully realized through integration of SS-HTS maglev system, evacuated tube system and segmented linear motor driving system. As is shown in Fig. 7(a), a vehicle-mounted three-axis gyroscope is used to test the instantaneous speed of the maglev vehicle during high-speed dynamic operation. Under tube pressure of $5 \times 10^3$ Pa, the maglev vehicle can operate stably at an average speed of 150 km/h, the highest ever recorded in tests of HTS maglev vehicle, as shown in Fig. 7(b). The photo of maglev vehicle during static suspension and that during high-speed dynamic operation are respectively shown in Fig. 7(c) and 7(d).

**Figure 6.** (a) Block diagram of drive system, which is mainly consist of traction motor and weak current controller; (b) power supply parameter setting for linear motor; (c) the schematic of sectional power supply for linear motor, where is covered and closed to maglev train.
Figure 7. (a) The prototype vehicle with triangle arrangement of YBCO bulks; (b) the maximum speed curve of 150 km/h under $5 \times 10^5$ Pa; (c) the local feature photo of prototype vehicle under static state; (d) a snapshot for prototype vehicle running at a high-speed of 150 km/h in SS-HTS maglev test circular track.

Commissioning and test in the latest two months show that the maglev vehicle can operate stably at high speed with vertical displacement change not exceeding 1mm, as confirmed through inspection of air gap of linear motor during operation of the maglev vehicle. So far, the test vehicle has run approximately 1,000 km in the evacuated tube SS-HTS maglev circular track system with zero accident, even though the superconducting bulks has been used for 10 years, directly verifying the long-term stability and safety of HTS maglev vehicle running at high speed.

6. Summary
As is demonstrated through high-speed dynamic test in the evacuated tube SS-HTS maglev circular track system, the maglev vehicle adopting triangle array of YBCO bulks realizes stable operation of up to 150 km/h, a remarkable improvement in the speed of free suspension operation and the highest speed ever recorded in current reports on HTS maglev system. And the operation stability and reliability at 150 km/h of HTS maglev system is proved through long-term commissioning and high-speed operation test.
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References

[1] E. H. Brandt, “Levitation in physics,” Science, vol. 243, no. 4889, Jan. 1989, pp. 349–355.
[2] J. R. Wang et al., “High-\( T_c \) superconductive vehicle for maglev model,” Rare Metal Materials and Engineering, vol. 27, no. 4, Aug. 1998, pp. 240–243.
[3] 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.
[4] L. Schultz et al., “Superconductively levitated transport system—the SupraTrans project,” IEEE Trans. Appl. Supercond., vol. 15, no. 2, Jun. 2005, pp. 2301–2305.
[5] L. Schultz et al., “Static and dynamic behavior of a superconducting magnetic bearing using YBCO bulk material,” IEEE Trans. Appl. Supercond., vol. 17, no. 2, Jun. 2007, pp. 2079–2082.
[6] Z. Deng et al., “A high-temperature superconducting maglev ring test line developed in chengdu, Chian,” IEEE Trans. Appl. Supercond., vol. 26, no. 6, Jun. 2006, Art. ID. 3602408.
[7] L. S. Mattos et al., “MagLev-cobra operational tests,” IEEE Trans. Appl. Supercond., vol. 26, no. 3, Apr. 2016, Art. ID. 3600704.
[8] J. Ma, D. Zhou, L. Zhao, Y. Zhang, and Y. Zhao, “The approach to calculate the aerodynamic drag of maglev train in the evacuated tube,” J. Mod. Transport., vol. 21, no. 3, Sep. 2013, pp. 200–208.