Recent Development of High Temperature Superconducting Maglev System in China

Jiasu Wang, Suyu Wang, and Jun Zheng

***Abstract*—After the first man-loading high temperature superconducting (HTS) Maglev demonstration had been tested successfully years ago, its future application attracts more and more researchers and engineers. This paper reviews the recent development of HTS Maglev system in China. In the past seven years, quasi-static forces, dynamic characteristics and running performances have been studied by three self-developed HTS maglev measurement systems and 11-ch vibration measurement apparatus. Some practical problems are considered in details for further engineering application of HTS Maglev train, such as running along the forward direction with inhomogeneous magnetic field, construction cost estimation, propulsion optimization, and so on. On the other hand, a systematic method is introduced to analyze or optimize the force interaction between bulk high temperature superconductor and permanent magnetic guideway. Primary running parameters and data are obtained for the safety design of future HTS Maglev system. Furthermore, a low-mid speed HTS Maglev test line is blueprinted with a maximum speed of 100 km/h, which will be the first step of practical HTS Maglev engineering application.**

***Index Terms*—high temperature superconductor, levitation, Guidance, Maglev train, permanent magnet guideway**

I. Introduction

A HIGHLIGHTED as a potential ground rail transit tool in the future, high temperature superconducting (HTS) Maglev system has an un-substitutable characteristic of passive self-stable levitation compared to all the other magnetic levitation (maglev) technologies. Since the man-loading HTS Maglev demonstrations were successfully tested in China, Germany and Russia [1]-[3], more and more scientists and engineers began to focus on this flux-pining type HTS Maglev system using bulk high temperature superconductor (HTSC). Different from fabricating the short beeline test line, a group at Universidade Federal do Rio de Janeiro (UFRJ) in Brazil built a small scale Maglev vehicle prototype with a circular line in 2004 [4]. Based on a similar scale circular line, a running velocity of 42 km/h was achieved by M. Okano et al. [5]. In order to construct a more stabilized HTS Maglev system, lots of permanent magnetic guideway (PMG) optimizations are studied [6]-[9]. Moreover, hybrid HTS Maglev system prototypes have been designed or optimized by adding magnetic or ferromagnetic materials [10], [11]. Besides detailed design and fabrication of HTS Maglev system prototypes, economic issues have also been taken into consideration. Reference [12] predicted that construction cost of a 1.0 km full scale HTS Maglev line is cheaper than that of a light rail vehicle mainly because of the low infrastructure cost. However, a few principium and prototype obstacles still remain for the HTS Maglev system as a future ground rail transit tool. Even though significant efforts are focusing on the high-speed application and commercialization of the HTS Maglev system, it's still difficult to get sufficient financial support for a full -scale test line.

In China, the earliest attempt to use bulk HTSC into the Maglev transport system had been succeeded by a China-Germany cooperation project [13]. The feasibility of the man-loading HTS Maglev vehicle was verified by the Applied Superconductivity Laboratory (ASCLab) of Southwest Jiaotong University in China in 2000 [1], [14]. In the next seven years, the ASCLab continued to work on the detailed problems in order to make the HTS Maglev satisfy the engineering requirements as a practical ground rail transit tool Some of the problems that have been studied include PMG optimization [8], [9], simulation and calculation of levitation force and guidance force of HTSC above PMG[15]-[17], vibration characteristics [18], low speed operation stability [19], influences of AC magnetic field [20], propulsion method [21], and other problems [22], [23]. All these issues emphasize on practical problems, which is essential for the engineering application. At the same time, more Chinese groups have joined in the research of the HTS Maglev system [24]-[26].

Recent development of the HTS Maglev system in China, especially on the cost control and performance optimization, is reviewed in the paper. The basic investigation of onboard bulk HTSC and PMG applied field (HTS-PMG system) are shown as the basic HTS Maglev system. Moreover, a systematic method is presented to analyze and optimize the low-cost high-efficiency HTS-PMG system in the following section. Some practical problems and improvement methods are considered and demonstrated in details. Furthermore, the on-going research plan is introduced in the last section.

II. Basic Experiments and Simulation

In an ideal HTS Maglev system, onboard bulk HTSCs are working in the 2D applied PMG magnetic field which is

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J. Wang, S. Wang, and J. Zheng are with Applied Superconductivity Laboratory (ASCLab), M/S 152#, Southwest Jiaotong University, Chengdu, 610031, P. R. China (corresponding author to provide phone: 86-28-87634065; fax: 86-28-87634065; e-mail: asclab@asclab.cn).

inhomogeneous in both vertical and horizontal directions but uniform in forward direction. This simplified HTS-PMG system can be regarded as the fundamental structure of the HTS Maglev system. In reality, magnetic resistance due the non-uniform magnetic field along the guideway could be an issue. This will be discussed in Section X. Due to the inherent electromagnetic properties of the HTS-PMG system, the onboard bulks over the designed PMG have a high load/weight ratio higher than 120 [27], a strong lateral restoration characteristic [28], and no resistance in forward direction. As three essential research fields in the HTS Maglev system, vertical levitation, horizontal guidance and forward resistance could decide whether an HTS Maglev system design is successful and cost-saving. Experimental apparatuses are indispensable to measure those properties. In the ASCLab, three HTS maglev measurement setups and a vibration measurement apparatus have been developed for different research requirements [18], [29]-[31].

A. PMG Parameters k_1 and k_2

Supported by the above experimental apparatuses, a lot of data of levitation forces, guidance forces, static stiffness, vibration parameters (dynamic stiffness, damping coefficient, and resonance frequency) and et al., have been analyzed and synthesized on different shapes, sizes and arrangements of PMG, and cooling conditions [8], [9], [18], [19], [27], [28]. With the properties of bulk HTSC materials given, PMG take on the main task for levitation and guidance performance of the HTS-PMG system. From the viewpoint of economy, the PMG costs almost half of the total investment excluding the infrastructure cost. Because the PMG is paved along the long running line, the optimization of PMG plays a vital role in order to get a low-cost but high-performance HTS Maglev system. Two parameters, k_1 and k_2, are defined to estimate the efficiency of the PMG magnetic energy in different HTS Maglev system. Three kinds of PMG structure are compared using k_1 and k_2, as shown in Fig. 1.

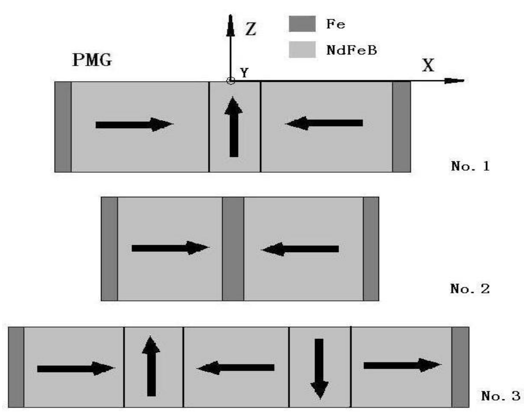

Fig. 1. Sketch of the PMG's Structures. The arrows represent the magnetization direction of the permanent magnets.

Parameter k_1 is defined by the magnetic circuit rule, as shown in equation (1).

$$k_1 = {B_w^2 S_w}\Big/{S(BH)_m} \tag{1}$$

, where B_w is the average magnetic flux density at the working position of bulk HTSC in PMG magnetic field, S_w is the area of the working position of bulk HTSC. Their product represents the levitation force in some extent. S represents the cross-sectional area of permanent magnet in PMG, and $(BH)_m$ is the magnetic energy produced by the PM material.

To evaluate the performance of the HTS-PMG system, the levitation force of HTSC induced by magnetic field is considered and k_2 is defined as

$$k_2 = {(F_{lev})\max}\Big/{S(BH)_m} \tag{2}$$

, where $(F_{lev})max$ is the maximum levitation force. The levitation force determines the load capability of the HTS Maglev transportation system, which can be increased by involving more magnetic materials. However, this could lead to the rise of the PMG cost. In (2), k_2 means the maximum levitation force per unit PMG and could evaluate the cost of the PMG design.

The guidance force, F_{gui}, is usually not included in the definition of k_2. The reason is that the load capability, which is determined by levitation force, is typically the most important requirement in an HTS Maglev system. It is found that levitation force and guidance force could increase simultaneously in an optimized PMG design. The cost performance of F_{gui} is not included here.

Table I shows the tested k_2 values of two melt-processed single domain $YBa_2Cu_3O_{7-x}$ bulks for different PMG designs as shown in Fig. 1.

TABLE I k_2 OF DIFFERENT HTS-PMG SYSTEMS

$YBa_2Cu_3O_{7-x}$	Conditions	No. 1 PMG	No. 2 PMG	No.3 PMG
30 mm diameter, 18 mm thickness	ZFC	4.58	2.15	4.17
	FC37	3.38	1.58	3.5
	FC27	2.82	1.35	2.98
50 mm diameter, 12 mm thickness	ZFC	5.37	3.6	5.91
	FC37	4.63	3	5.15
	FC27	4.26	2.60	4.79

ZFC is zero-field cooling while FC is field cooling. FC37 and FC27 represent $YBa_2Cu_3O_{7-x}$ bulks are put at 37 mm and 27mm above the PMG by field-cooling.

From Table I, one sees that $k_{No.3}>k_{No.1}>k_{No.2}$ exists in all cooling conditions [8].

It is also found that PM plays the main role in producing more magnetic flux into the useful upper surface of PMG. But iron lacks the magnetization energy and direction as magnetic flux collector in No. 2 PMG.

One can directly judge whether PMG is able to offer enough magnetic energy for the levitating bulk HTSC through k_1. One can also evaluate which HTS-PMG system is better for the design of future HTS Maglev based on k_2. k1 and k2 also imply that the magnetic density B rather than B_z or B_x determine the overall performance of the HTS Maglev system, which represents the total magnetic energy. It indicates that the optimized design of the HTS-PMG system may not concentrate on any single magnetic component of B_z or B_x or their gradients.

B. Optimization of HTS-PMG System

Onboard bulk HTSC and PMG are closely related in the optimization processing of the HTS Maglev system. In this section, a systemic method is presented to analyze and optimize the basic HTS-PMG system. Its flow diagram is presented in Fig. 2.

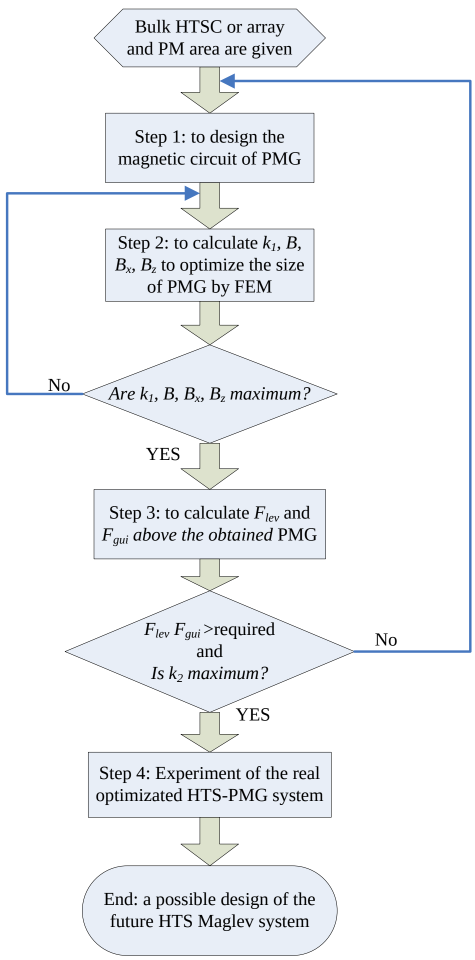

Fig. 2. Flow diagram of the optimization method of the HTS-PMG system.

According to the properties of given HTSC and the requirements of levitation force and guidance force, the magnetic circuit and configuration of PMG is proposed in Step 1. It is an important step because the number of PMG configuration almost determines the amount of the optimization. In Step2, a finite element method is used to calculate and compare the PMG's magnetic field and k_1. The aim of Step 2 and Step 3 is to find possible PMGs with bigger magnetic field, smaller size and lower cost. And it is possible that several optimized PMGs will be proposed with different configurations. The "largest" in the judgment between Step 2 and Step 3 implies the most efficient PMG.

Among the chosen PMGs after the above initial optimization (the first judger), levitation force and guidance force are considered in Step 3. In the calculation, Bean model [15] or Flux flow-creep model [16] is used. As is well-known, the assembly and position of the bulk HTSCs is helpful for high performance of the HTS-PMG system. Thus, some helpful empirical results will be used in the calculation of Step 3. For example, the bulk HTSC should be arranged closely around the position of maximum B_z to obtain the largest levitation force while it should be centralized around the position of maximum B_x for the largest guidance force [8].

If the calculation results of levitation force and guidance force meet the requirements, k_2 will be the next criterion. What should be mentioned is that it's possible to have several PMG designs after Step 3. In this case, the best PMG configuration will be chosen with the maximum k_2.

The aim of Step 2 and Step 3 is to find possible PMGs with higher magnetic field, smaller size and lower cost. It is possible that several optimized PMGs are proposed with different configurations. The maximization in the judgment between Step 2 and Step 3 leads to the most efficient PMG design.

In the last step, a PMG segment based on the optimized design is fabricated and the relative maglev performances are measured and evaluated.

Based on the optimization step discussed here, a few optimized HTS-PMG system designs have been proposed for the future HTS Maglev system [8], [9].

III. Practical Considerations

In practice, the present HTS Maglev system is driven by the linear motor along the guideway. Two issues, magnetic resistance along the guideway during the operation and the cost and efficiency of the linear motor become challenging in the engineering application.

A. Magnetic Resistance

The guideway for a real HTS maglev is an assembly of many short PMG segments. A typical PMG segment consists of PM blocks, screws and irons [32-34]. The magnetic field gradient along the PMG could lead to the magnetic resistance and hence resistive force to the HTS maglev during the operation. To minimize the magnetic resistance, manufacturers try to make the PMG magnetic field in forward direction as uniform as possible [33], [34]. However, limited by the mechanical assembling technology, non-uniformity such as small air gaps between PM blocks exists along the guideway and therefore, the magnetic resistance exists where the PMG magnetic field fluctuates in the forward direction.

Fig. 3 shows the small magnetic field fluctuation and related resistance force of the PMG No. 3 (see Fig. 1). Because of the exponential decay of the magnetic field above the PMG, one sees that the magnetic field fluctuations are reduced by increasing the working height (WH). At the lowest permitted WH of 5 mm, the PMG magnetic field is most non-uniform and the fluctuation rate is 3.5%. At the WH of 15 mm, which is also the typical WH for the HTS Maglev system, the rate is 1.8%. The force due to the field gradient is measured by using seven-YBCO bulk levitation unit over the No. 3 PMG in the case of FCH 30 mm WH 15 mm as shown in Fig. 3. The maximum resistance force is 0.06 N with 10% fluctuation (including 0.03 N precision of experimental apparatus [30]). The maximum 0.06 N magnetic resistance force is too small to be ignored at low-middle speed running case of the HTS Maglev unit. Moreover, it has proven that No.2 PMG with iron as flux collector has a smaller magnetic field fluctuation than that of No. 3 PMG with PM as flux collector indicating that PMG design with iron as flux collector could be more suitable for future long-distance high-speed HTS Maglev transportation system. It doesn't mean that No. 2 PMG is better than the other two PMGs from the prospect of cost performance. On the contrary, it implies No. 3 PMG needs improvements by considering add iron as flux collector which is going on in our group.

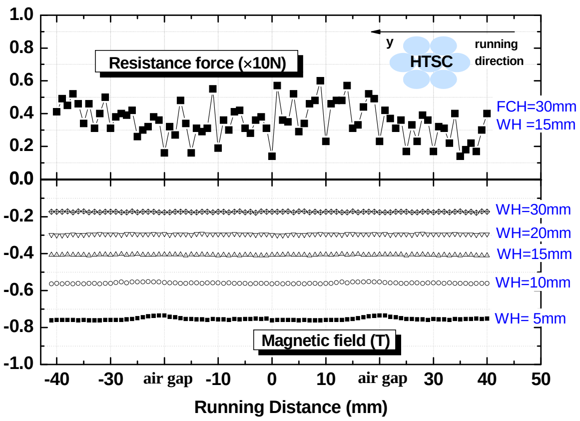

Fig. 3. Magnetic field fluctuation and related resistance force of PMG No. 3.

Fig. 3 also shows that the air gaps between two adjacent PMs is the main reason for the PMG magnetic resistance compared with the effect of screws used in the assembly. For example, in the WH 5 mm, the PMG magnetic field is much smaller around y=20mm or -20mm where air gaps exist. So to avoid air gaps is important during the construction of the PMG and some useful methods to achieve this have been proposed in [33].

B. Novel Driving Design

Inductive linear motor has always been paved along the guideway in the existing HTS maglev system [1], [2], [4]. The primary shortcomings of the inductive motor are low-efficiency and huge cost due to its length. Based on the PM linear motor design, a novel idea was proposed for the HTS Maglev system [21]. In this method, the PMG magnetic field is used to induce the propulsion force in substitution of any expensive long rotor or stator of linear motor. Three primary functions, levitation, guidance, and propulsion, are integrated in one system by PMG, which could reduce the total cost significantly. The outline of the HTS Maglev system with the new driving tool is shown in Fig. 4. It is mainly composed of PMG and an inverse E shape ferromagnetic device (IESFD) core [21].

As shown in Fig. 4, the winding direction on the surface of the concentrated pole is very important to make the full use of the ampere force. One of the key issues is that the current flowing in the coil on the side and middle concentrated pole must be opposite. The inset in Fig.4 shows a possible winding structure, where the current direction of the side and middle concentrated pole is opposite. The other part of the coil (not laid on the surface of the concentrated pole) is in a weak magnetic field because there is no ferromagnetic material to concentrate the magnetic field and its position is low. In addition, the ampere force produced by it is almost the same in quantity but opposite in direction of different area, i.e., the area under the side and middle of the PMG. Therefore, the total propulsion force produced by the IESFD is the sum of the ampere force from the coil laid on the side and middle concentrated pole.

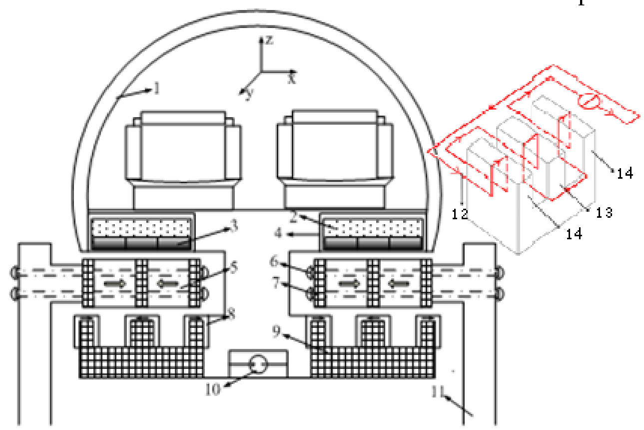

Fig. 4. Schematic drawing of the overall maglev system Magnetization and the upper-right figure is 3D sketch of the IESFD associated with the winding of lead.
(1) Vehicle body, (2) Liquid nitrogen, (3) HTS bulk, (4) Low-temperature vessel, (5) Permanent magnet (arrow shows the magnetization direction), (6) Screw, (7) Iron, (8) Coil (arrow shows the direction of current), (9) Iron, (10) On-board DC power supply, (11) Elevated girder, (12) Lead, (13) Middle concentrated pole, (14) Side concentrated pole.

The geometry of IESFD is optimized by the Ampere's theorem. The magnetic field of the PMG is calculated by finite element analysis. As a primary study, the external magnetic field is assumed to be the magnetic field on the surface of the concentrated pole. This new propulsion tool can generate a driving force of more than 1000 N/m with a single PMG with a current flowing area of 2500 mm^2 and a current density of 6 A/mm^2. Although the simulation by Bean model [15] shows that the levitation performance reduces about 10% with the IESFD equipment fixed. If it is fabricated successfully, the cost of about 14000 RMB/m inductive linear motors can be saved. The new driving design could be considered as an important choice of the future's flux-pinning type HTS Maglev system.

In addition to the IESFD, superconducting linear motors [5], PM linear motors [12], [35] and an HTS Maglev system with integrated levitation-guidance-propulsion functions have also been proposed and considered.

IV. Useful Methods for Performance Improvement

A. Pre-load Method

Pre-load method was found to be effective to suppress the levitation height and force decay and improve the stability of the HTS maglev vehicle system [22], [36]. Typical pre-load steps include: a. lower the on-board bulk HTSCs and the related levitation part of vehicle to a height lower than the WH after FC by adding additional load; b. keep the system at the above lower levitation position for certain amount of time; c. release the system. Finally, better performance could be obtained.

Table II compares the measured results of the pre-load method tested with an HTS Maglev vehicle model. After the pre-load the HTS maglev vehicle becomes more stable indicated by higher stiffness and damping coefficient and better anti-vibration performances. It is also found that the levitation height decay is suppressed by the pre-load method. For example, by using the pre-load method, the levitation decay rate is reduced from 14% to 2.5% in the cases of the same repeated lateral movement [35].

TABLE II DYNAMIC STIFFNESS *k* AND DAMPING COEFFICIENT *c* OF HTS MAGLEV VEHICLE MODEL BY PRE-LOAD EXPRIMENT

Pre-load	*k* (N/m)	*c* (Ns/m)
No	53740	144
Yes	87050	214

B. *Pre-magnetized Bulk HTS magnets*

In the present HTS maglev test vehicles or prototypes, directly field cooling magnetization (DFCM) above the PMG is typically used [1-7]. The maximum magnetic field of PMG is 1.2 T but it is believed that HTSC can trap the higher magnetic field over 5 T at 77 K [37], even 17.24 T at 29 K [38]. Due to the limited magnetic energy of permanent magnet material, the high flux-pining performance of bulk HTSC is mainly limited by the PMG's magnetic field. Thus the feasibility of introducing pre-magnetized HTS bulk magnet into the present HTS Maglev system is investigated to break the limitation. The bulk HTS magnets are magnetized by the magnetic field generated by other other magnetic field rather than the PMG magnetic field [23], [39].

It is found that the pre-magnetized bulk HTS magnet can stably levitate above PMG due to the flux-reform or re-magnetization effect [23]. Compared to the magnetization by the PMG, it is easier and more flexible to control the trapped flux of the HTS bulk material. Higher trapped flux could lead to larger guidance force and smaller repulsion levitation force [39]. Therefore, the HTS bulk magnet is a feasible alternative to the present HTS maglev vehicle system with the same low temperature environment [40].

V. ON-GOING RESEARCH PLAN

Supported by the National High Technology Research and Development Program of China (2007AA03Z210), a research plan for the HTS maglev with a designed speed of 100 km/h has been initiated. The key issues of study will be the realization of 100 km/h speed and the associated operation performance of the HTS Maglev vehicle. Several new designs for the full-scale HTS Maglev will be tested, e.g., a PMG structure with an Halbach PMG and iron flux collector, a body design of high-speed vehicle, the new propulsion scheme and possible solutions to large eccentricity.

As an attempt, it is believed that this on-going research plan will be helpful to the first step of the HTS Maglev engineering application.

VI. CONCLUSION

After about seven years of efforts from China and other countries, the feasibility of the HTS Maglev has been fully proved and tested. Its engineering problems become more and more challenging and attract the ASCLab and other groups to work in many research fields like the optimization of the basic HTS Maglev system, reducing the system cost, improving efficiency and so on.

Recent progresses in the R&D of the HTS maglev system in China are reviewed. A plan for a 100 km/h test vehicle for the near future is presented. Together with the colleagues both in China and abroad, the ASCLab is dedicated to the application of HTS Maglev. It is believed that all the recent developments are helpful for the engineer application of the HTS Maglev system in the future.

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