Advances in High-speed Rail Technology

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High-Speed Maglev Train's Levitation and Guidance Control

The Key Technologies

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Preface

Maglev trains represent a novel approach to rail transit that use electromagnetic force to levitate the vehicle body above the guideway and utilize the linear motor for propulsion operation, which have the advantages of high travel speed, no friction loss, low noise, flexible line selection, and less maintenance workload at the later stage. Germany, Japan, China, the United States and South Korea have researched on maglev train technology, and the application areas include urban maglev transit with a maximum speed of 160 km/h, high-speed maglev transit with a speed of 400 km/h or higher, and ultra-high speed low-vacuum tube maglev system with a speed of 800 km/h.

Since 1980, the National University of Defense Technology, the Southwest Jiaotong University, the Institute of Electrical Engineering of Chinese Academy of Sciences, and other institutes in China have successively carried out research on maglev train technology. Under the leadership of Profs. Wensen Chang, Jisan Lian, Xiangming Wu, and Academician Luguang Yan etc., China has overcome a number of key technologies of urban maglev trains and high-speed maglev trains such as levitation and guidance control, which has promoted the progress of engineering application of China's EMS-type maglev train technology. China has successively built urban maglev operation lines in Beijing, Changsha, Fenghuang in Hunan, and Qingyuan in Guangdong. In December 2002, China and Germany cooperated to build an EMS-type high-speed maglev operation demonstration line in Pudong, Shanghai. On this basis, China researched on the localization and technological innovation of EMS-type high-speed maglev transit technology, and developed an EMS-type high-speed maglev test vehicle and a PEM hybrid levitation based high-speed maglev test vehicle. In July 2021, CRRC Qingdao Sifang Co., Ltd. led the development and test of a high-speed maglev train with a maximum design speed of 600 km/h.

Based on the academic researches, engineering applications, and technical innovations of high-speed maglev trains carried out by the maglev team of the National University of Defense Technology, this book summarizes the technical achievements in the field of levitation and guidance control technology of high-speed maglev train. The specific contents are as follows.

In Chap. 1, the definition and types of maglev transit systems in the world are introduced, and then the three stages of development of EMS-type high-speed maglev train technology are analyzed. Finally, a discussion on the current research status and principal achievements in the field of high-speed maglev trains is conducted.

In Chap. 2, the basic structure of the high-speed maglev transit is introduced, and then the technical analysis is carried out for the complex high-speed maglev vehicle system, and the composition of each subsystem is analyzed. Finally, for the key technical problems of the high-speed maglev train, the basic structures, basic requirements and control schemes of the levitation system and the guidance system are analyzed respectively.

In Chap. 3, the levitation control strategy of high-speed maglev train is mainly studied. Through the analysis of the levitation system model of high-speed maglev train, the nominal controller design based on linear quadratic regulator and the controller design based on active disturbance rejection control are carried out. Then, the designed control schemes are verified by the experiments of high-speed maglev train levitation double maglev bogies and the whole vehicle.

In Chap. 4, the guidance system of high-speed maglev train is taken as the research object, and the guidance system model considering disturbance and fault is analyzed in combination with practical engineering problems. The research of the nominal controller design and the robust controller design are carried out, and relevant verification experiments are carried out using single bogie and whole vehicle of high-speed maglev train.

In Chap. 5, aiming at the control performance evaluation of the levitation system after the design of the nominal controller is completed, the nominal performance and nominal performance index of the levitation system are introduced, then the performance index and performance evaluation method of the levitation system under various working conditions are analyzed respectively.

In Chap. 6, aiming at the control performance evaluation of the guidance system after the design of the nominal controller is completed, a quantifiable evaluation index is proposed based on a fuzzy comprehensive evaluation method by using the state information of guidance gap, current and acceleration, then the performance evaluation of the guidance system under different curve radii, running speeds and payloads are analyzed respectively.

In Chap. 7, the levitation control technology for permanent and electric magnet (PEM) hybrid levitation type high-speed maglev train is mainly analyzed. Firstly, the PEM hybrid levitation technology and the structural design scheme of the PEM hybrid levitation electromagnet are analyzed. Then, the PEM hybrid levitation system is modeled and analyzed. Finally, the zero-power controller based on state feedback is designed, and test research is carried out on the double maglev bogies and the whole vehicle.

In Chap. 8, aiming at the possible faults of the levitation system of the high-speed PEM hybrid levitation train, the sensor fault diagnosis problem is studied, and the fault diagnosis methods based on Kalman filter, data-driven, and signal analysis are analyzed, respectively.

In Chap. 9, the fault-tolerant control of the levitation system of the high-speed PEM hybrid levitation train is studied. Firstly, the hierarchical fault-tolerant control framework of the levitation system is introduced and analyzed. Then, the fault-tolerant control based on the online optimization of Youla parameters is analyzed. Finally, the active fault-tolerant control method based on signal reconstruction and control law switching is studied.

The whole book was edited and unified by Prof. Zhiqiang Long of the National University of Defense Technology. Among them, Chaps. 1–4 were written by Prof. Zhiqiang Long, Chaps. 5 and 6 were written by Dr. Mingda Zhai, Chap. 7 was written by Prof. Xiaolong Li and Zhiqiang Long, Chaps. 8 and 9 were written by Dr. Zhiqiang Wang. Professor Wensen Chang, and Yungang Li, Longhua She, Jie Li, Jun Wu, Zhisu Zhao, Shaoke Liu, Guirong Chen, Kun Luo, Ning Wang, Aming Hao, Hu Cheng, Huixing Chen and more than 10 other doctors have directly participated in the research work related to the book. Numerous high-level references from around the globe were consulted during project research and manuscript writing.

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Changsha, China
June 2024

Zhiqiang Long

Contents

Chapter 1
Introduction

Maglev trains use maglev technology to achieve support and guidance between vehicle and track, and realize propulsion and electric braking through linear motors. Its application scenarios include the urban maglev transit, the high-speed maglev transit, and the ultra-high-speed low vacuum tube maglev transit. This chapter gives the definition of maglev trains, classifies maglev trains from the perspective of levitation principle and propulsion principle, and describes the electromagnetic suspension (EMS)-type system, the electrodynamic suspension (EDS)-type system and the high-temperature superconducting (HTS) flux-pinning maglev system in detail. What's more, this chapter reviews the development history and technical evolution of maglev train technology in terms of structure schemes for levitation systems, and introduces the three technological stages of the rigid body vehicle scheme, the magnetic wheel structure scheme and the modular structure scheme that the EMS-type maglev train has gone through. Finally, this chapter discusses the research and application results of high-speed maglev based on the relevant technology researches in Germany, Japan, and China.

1.1 Definition and Classification

The maglev technology has been studied for more than a century. Currently, many countries are still conducting extensive researches on maglev technology, which mainly includes the urban maglev trains, the high-speed maglev trains used in the intercity rail transit, the maglev momentum flywheels, the maglev reaction flywheels, the maglev energy storage flywheels, the maglev gyro torques used in satellites and space stations, and the high-speed rotating machinery supported by different kinds of magnetic bearings such as various types of pumps, centrifugal machinery, grinders, etc. Besides, some high-precision and high-sensitivity instruments such as maglev

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gyros and maglev gravimeters, also adopt maglev technology. Among all kinds of applications, the field of maglev transit is attracting more and more attention.

Maglev trains use maglev technology to achieve the support and guidance between vehicle and track, and linear motors to achieve propulsion and electric braking.

According to the different principles of maglev forces, maglev systems can be mainly classified into EMS-type maglev system, EDS-type maglev system, and HTS flux-pinning maglev system.

According to the speed range, maglev systems can be further divided into the urban maglev (maximum speed of 160 km/h), the high-speed maglev (maximum speed of 600 km/h), and the ultra-high-speed maglev (maximum speed of 800 km/h or higher, using low vacuum tube technology, currently in the exploration stage).

In terms of propulsion principles, maglev systems can be divided into the long-stator synchronous linear motor propulsion and the short-stator asynchronous linear motor propulsion. The high-speed and urban maglev systems mainly utilize the long-stator synchronous linear motor propulsion, while the urban maglev systems and some urban maglev systems equip with the short-stator asynchronous linear motor propulsion.

(1) EMS-type maglev system

EMS-type maglev trains utilize actively controlled electromagnetic force between the electromagnet and the track to levitate the vehicle. At present, Germany, Japan, China, and Korea are the representatives, and research primarily focuses on the development of the urban maglev trains and high-speed EMS-type maglev trains. Among them, the urban maglev trains mainly solve the problem of intra-city transit. Its cost is comparable to light rail, and the biggest advantage of this type of train is that it does not pollute the environment. The high-speed maglev trains are suitable for inter-city transit. Although there are major differences in propulsion, power supply and operation control between the urban maglev and the high-speed EMS-type maglev trains, the levitation principles are the same, using the active electromagnetic levitation principle, and the levitation gap is about 8~10 mm. Therefore, there are many similarities in the design of the levitation control systems for both high-speed EMS-type maglev trains and urban maglev trains. The schematic diagram is shown in Fig. 1.1.

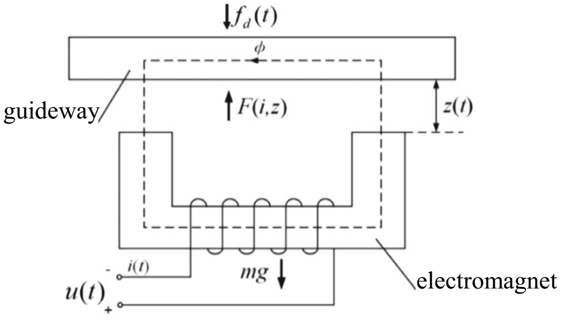

Fig. 1.1 Levitation schematic diagram

In Fig. 1.1, $f_d(t)$ is the external disturbance force, $F(i, z)$ is the equivalent levitation force, mg is the gravitational force, $z(t)$ is the levitation gap, $u(t)$ is the voltage of the electromagnet coil, and $i(t)$ is the current of the electromagnet coil.

In the field of urban maglev trains, many countries have built the test line and operating line. In May 2003, Japan firstly completed the Nagoya East Hills operating line. In March 2016, Korea completed the Incheon Airport operating line. Germany proposed an embedded urban maglev scheme and built a test line. Since 1980, China has started the research on maglev transit technology, which has been commercialized or engineered so far. Since June 2016, China has started the construction of the urban maglev operating lines or maglev tourist lines in Beijing, Changsha, Qingyuan, and Fenghuang. Meanwhile, China has carried out innovative research on permanent and electric magnet (PEM) hybrid levitation technology and developed the experimental vehicles.

In the field of high-speed maglev trains, in December 2002, China and Germany cooperated to build a high-speed maglev commercial operating demonstration line from Shanghai Longyang Road to Pudong Airport. With the support of the 863 Program of the 10th Five-Year Plan, and the Science and Technology Support Program of the 11th Five-Year Plan and 12th Five-Year Plan, China has conducted the localization and innovative research on the high-speed maglev, and has developed single maglev bogie, double maglev bogies and a two-vehicle high-speed maglev test train based on the PEM hybrid levitation. The technology of the high-speed maglev trains has been rapidly promoted.

(2) EDS-type maglev system

For the EDS-type maglev systems, the levitation derives from the repulsive force generated by the interaction of source magnetic field and induced current, which is produced by the relative motion between the permanent magnet/superconducting magnet and the rail. According to the source magnetic field, the EDS-type systems can be divided into superconducting magnet type and permanent magnet type.

The EDS-type maglev technology is represented by the low-temperature superconducting magnet high-speed maglev trains of Japan and the permanent magnet low-speed maglev trains of USA. Initially, the research of the EDS-type maglev systems was mainly focused on superconducting magnets because the permanent magnet materials could not provide sufficient magnetic field.

With the adoption of permanent magnet materials with high remanent magnetic strength and the continuous application of Halbach-structured permanent magnet arrays in maglev technology, the permanent magnets can provide sufficient levitation force, which is gradually being introduced as an electrodynamic levitation technology based on the permanent magnet. Since the permanent magnet electrodynamic levitation technology does not require complex cooling devices, and it can achieve a high ratio of levitation to magnetic resistance at a certain speed, it becomes one of the maglev technologies with good development prospects.

In the USA, the applications of the permanent magnet electrodynamic levitation technology are typically represented by the Magplane maglev train, the GA Urban maglev train and the MIT Hyperloop. Professor Montgomery of MIT proposed the design of Magplane based on the permanent magnet electrodynamic scheme. Langley Aerothermodynamics Laboratory in the USA carried out the research of the permanent magnet electrodynamic levitation technology with the background of electromagnetic-assisted emission and developed the test vehicle for NASA's rocket boosting program.

In China, the Institute of Electrical Engineering of the Chinese Academy of Sciences, the National University of Defense Technology, the Southwest Jiaotong University, and the Naval Engineering University have carried out basic research work on the permanent magnet electrodynamic levitation technology one after another.

(3) HTS flux-pinning maglev system

The basic principle of HTS flux-pinning maglev system is to use the unique strong magnetic flux pinned ability of high-temperature superconductors in the external magnetic field, which makes it difficult for captured magnetic lines of force to escape from the pinned center, and difficult for uncaptured free magnetic lines of force to penetrate the superconductor. The pinned property enables the superconductor to induce a superconducting strong current that hinders this change in response to the change in the external magnetic field. This unique electromagnetic interaction achieves self-levitation and guidance of the levitating body at a macroscopic level without active control, and with zero magnetic resistance in the direction of operation, which in principle can achieve the high-speed stable operation. China, Germany, and Brazil have carried out relevant basic research and are currently in the verification stage of experimental line technology. In January 2021, the world's HTS flux-pinning high-speed maglev experimental prototype and the test line developed by the Southwest Jiaotong University was officially opened in Chengdu, Sichuan.

Among the various types of maglev technology, EMS is the only maglev transit technology that has entered commercial application stage. This book focuses on the EMS-type maglev transit system as the background and mainly studies the levitation and guidance control issues of the EMS-type high-speed maglev train.

1.2 The Development History of EMS-Type Maglev Trains Technology

The world's first maglev train levitation system was proposed by German engineer Kamper in 1922. In the 1970s, Germany began research on Transrapid (TR) maglev transit technology. And the initial TR01, TR02, and TR04 trains were also of its structure, advancing with the short-stator asynchronous linear motors for propulsion. But this structural solution was only suitable for the middle-low speed. Germany later abandoned Kamper's short stator and inverted U-shaped track scheme, and switched to the high-speed maglev technology with long-stator synchronous motor propulsion. Japan, Korea, and China insist on EMS technology, inverted U-shaped track structure, short-stator asynchronous linear propulsion, and outsourced vehicle structure.

In terms of the evolution of the structural scheme of the levitation system, the EMS-type maglev train has experienced the rigid body vehicle scheme, the magnetic wheel structure scheme and the modular structure scheme. From the view of the evolution of the structural scheme of the guidance system, the EMS-type maglev train mainly has passive guidance control scheme and active control guidance scheme. The evolution of the levitation system is described below.

1.2.1 Rigid Body Vehicle Scheme

The TR0l, TR02 and TR04, developed in Germany in the early years, have the following characteristics.

(1) A levitation system consisting of an inverted U-shaped track and a U-shaped electromagnet with lateral self-stabilization, eliminating the need for an additional active guidance system.
(2) Four electromagnets fixed directly on the carriage floor, which are a rigid structural constraint with no relative degrees of freedom of movement between the four electromagnets.
(3) A short-stator (on board) asynchronous motor is used for propulsion. The system structure is relatively simple and easy to implement. Later, Japan developed the HSST-01 maglev train based on the short-stator asynchronous motor.

In this period, it was thought that the concept of a rigid-free motion vehicle should be used to design the maglev train system by fixing four electromagnets directly on the carriage floor and using the concepts of yaw and pitch to describe and control the motion of the maglev train, such as TR01, TR02, TR04, MBB of Krauss-Maffei in Germany.

For lower operating speed, the contradictions of this structure are not prominent. However, when the speed is slightly increased, the problem becomes very serious. For example, Germany's TR04, originally designed to target 250 km/h, but in the experiment, serious vibration and swaying occurred with a speed less than 200 km/h. In addition, when the vehicle was levitated statically on the steel track beam, vibration instability occurred.

The Japanese HSST-01 and HSST-02 both adopted this concept, and the HSST-01 had the same shape as an airplane. A similar phenomenon occurred with the HSST-01, which led to the gradual realization that the concept of understanding the maglev train as a rigid-body free-degree vehicle was wrong.

The mistake is that although there is no mechanical contact between the electromagnet and the track, the motion of the electromagnet is strictly constrained by the track due to the levitation control system. According to the test results of the low-speed maglev trains, the control stiffness between the electromagnet and the track is above tens of thousands of N/m. It is due to this constraint that the vehicle body, as a whole rigid, suffers from at least the following problems.

(1) The track cannot be absolutely flat. The unevenness error of any local processing on the track will cause the adjustment effect of the point levitation controller. The whole vehicle body is a rigid body again.
(2) The four groups of controllers are coupled together and adjusting the parameters of anyone controller will affect the movement of the other levitation points. Thus, the four controllers of the whole train must be adjusted at the same time, which is very difficult to debug.
(3) Failures of any of the electromagnets or controllers under the carriage floor will result in levitation failure of the entire vehicle, thus causing a vehicle-wide failure.
(4) The two tracks where the train crosses the curve are not coplanar, resulting in conflicting levitation control objectives at each point.

Ultimately, the problem is the decoupling between the levitation points. Once the problem was identified, a flexible carriage floor was used to reduce the coupling between the electromagnets.

Japan Airlines developed HSST-02 based on HSST-01, and it did not achieve the expected results. The carriage floor adopts a flexible structure, and the connection between the electromagnets is flexible and can have a certain elastic deformation. Therefore, the coupling between the relative motion of the electromagnets has weaken a lot, and the decoupling effect is fine at low-speed operation, but when the speed adds up to 100 km/h, there is a more obvious vibration.

In addition, the structure of the maglev train at the 640 m line at Birmingham Airport in the UK in 1984 was similar to that of HSST-02, with electromagnets fixed to a carriage floor with a flexible base plate. The performance was moderate as the maximum speed of operation was only 40 km/h.

Since the carriage floor is also used to carry passengers or cargo, there are certain requirements for its overall stiffness, there is a limit to the use of flexible carriage floor decoupling structures. No application has been seen other than a demonstration of small maglev model vehicle with very low speed.

The small maglev experimental vehicle developed by the National University of Defense Technology in 1989 used the structure with a decoupled flexible carriage floor.

1.2.2 Magnetic Wheel Structure Scheme

After the TR04 failed to achieve the expected results, the German companies Krauss-Maffei and MBB Aerospace decided to join forces at the end of 1974 to revisit the concept of maglev trains. They abandoned the Krauss-Maffei structure in favor of the MBB structure with active lateral control and proposed a hierarchical progressive system concept based on the “magnetic wheel” concept (Fig. 1.2). To test whether this levitation system structure could meet the requirements of high-speed operation, they developed the test system Komet, which was propelled by rocket technology

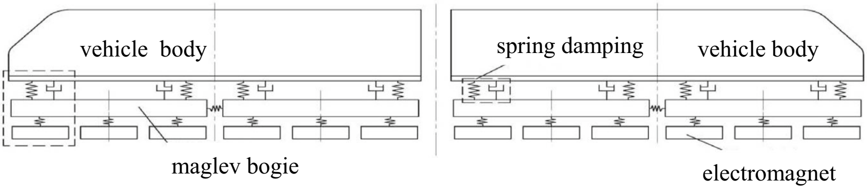

Fig. 1.2 Hierarchical progressive structure based on the "magnetic wheel" concept

and could reach a speed of 401.3 km/h (in 1976). The test achieved the expected results, which confirmed the necessity and feasibility of this mechanical decoupling system.

In this structure, each electromagnet (levitation or guidance) is individually connected to the maglev bogie by a spring damping, and the electromagnet has control freedom in only one direction with respect to the bogie (Fig. 1.3). Since each electromagnet acts like a wheel for support, it is called a "magnetic wheel". Each maglev bogie has three independent (motion and control) electromagnets on each side, allowing for lateral and yaw-wise movements relative to one another. This structure completely ensures decoupling of the motion between the electromagnets.

In parallel with the development of the hierarchical progressive control structure, Thyssen developed the HMB2 maglev train with the long-stator synchronous motor propulsion in 1976, which is 5 m, weighs 2.5 t, and can operate at speeds up to 36 km/h.

This was followed by Germany's combination of the levitation and guidance structure of the hierarchical progressive "magnetic wheel" concept and long-stator propulsion technology, resulting in the TR05 system.

The "magnetic wheel" structure completely ensures the decoupling of the motion between the electromagnets and the ability of the train to pass through the curves. It can be considered that the "magnetic wheel" concept has gone from one extreme

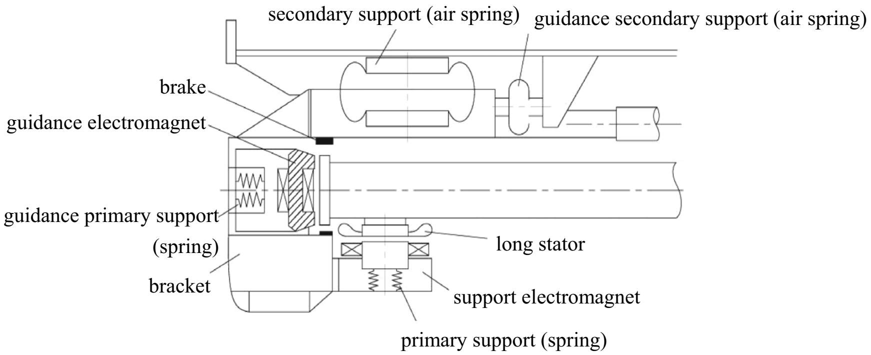

Fig. 1.3 Principle of levitation and guidance in the "magnetic wheel" structure

to another after the “rigid body vehicle” concept hit a wall. Although it solves the problem of mechanical decoupling very well, it brings some new problems as follows.

(1) As each “magnetic wheel” independently support the vehicle body, although the whole vehicle will not occur the phenomenon of overall vibration, the individual “magnetic wheel” is susceptible to levitation instability phenomenon.

(2) The failure of any one of the electromagnets or controllers of the “magnetic wheel” will cause the levitation and guidance to fail, and there is no redundant relationship between the “magnetic wheel” and the “magnetic wheel”, thus causing a total vehicle failure.

(3) The vehicle based on the “magnetic wheel” concept is not compact enough structurally and is prone to mechanical failure during the high-speed operation, making it difficult to engineer.

1.2.3 Modular Structure Scheme

After theoretical analysis and engineering tests of the “rigid body vehicle” concept and the “magnetic wheel” concept in Germany, a compromise between the two was made and an “electromagnetic module”-based vehicle structure concept was gradually established. This concept was adopted in both TR07 and TR08. Figure 1.4 is a schematic diagram of the vehicle structure based on the “electromagnetic module” (the part circled with a dashed line in the figure) concept, without considering the joint structure between the two vehicles, each high-speed maglev vehicle has seven sets of independent electromagnetic modules on each side, which is a mechatronic functional structure formed by the combination of bracket arms, levitation electromagnets, guidance electromagnets, levitation sensors, guidance sensors, connecting parts, etc.

With the “electromagnetic module” concept, the vehicle system has the following advantages.

(1) The mechanical decoupling of each control point can be achieved by the displacement deformation of the primary hinge or primary spring and the torsional stiffness of the maglev bogie itself.

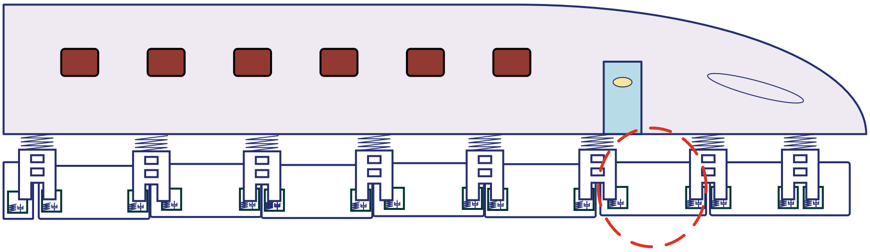

Fig. 1.4 Side view of the high-speed maglev vehicle based on “electromagnet module + joint structure”

(2) The levitation function and guidance function corresponding to each bracket arm are redundant, ensuring the functional safety of the system.
(3) The vehicle substructure is compact, which is conducive to the high-speed operation and easy to install and maintain. Also, it meets the needs of engineering and practical application.
(4) Due to the multiple degrees of freedom of movement provided by the connecting parts between the electromagnet and the maglev bogie, the vehicle is ensured to have a good curve passing capability.

The successful operations of the TR07 and TR08 have demonstrated that the "electromagnetic module" concept is mature and viable.

1.3 Research Status and Main Achievements of High-Speed Maglev

The main countries engaged in the research of maglev transit technology are Germany, Japan, China, UK, Korea, and USA. The research and application fields mainly relate to the urban maglev, the high-speed, and the ultra-high-speed maglev transit. The staggered development of the urban maglev technology and the high-speed maglev technology drives the exploration and research of ultra-high-speed pipeline maglev.

The urban maglev train adopts non-contact operation mode. Compared with ordinary inner-city wheel-track trains, it has the advantages of low noise, low vibration, small turning radius, relaxed line laying conditions, low construction cost, easy implementation and easy maintenance, etc. Moreover, because its propulsion force is not affected by the adhesion coefficient between wheels and rails, the urban maglev train also has the characteristics of strong climbing ability.

The high-speed maglev transit system mainly solves the problems of transit between big cities. And now Germany, Japan, and China are the main countries to develop the high-speed maglev technology.

1.3.1 Progress of High-Speed Maglev Research in Germany

The German high-speed maglev transit system uses EMS technology. In 1971, the first German maglev prototype vehicle was tested on a 660 m-long test line. In 1975, Thyssen Henschel pioneered the operation of line side long-stator linear synchronous motor driven maglev train on the HMB1 test line at the Kassel plant. In 1976, Thyssen Henschel carried out the operation of a manned long-stator test vehicle on the HMB2 test line.

In 1979, the TR05 maglev railroad demonstration line with a track length of 900 m and a maximum designed speed of 100 km/h was exhibited at the Hamburg

International Transport Fair for passenger operation, and the demonstration speed reached 75 km/h.

The German industrial circles formed the Transrapid consortium to build the Transrapid test line (TVE) in Emsland, northwestern Germany. The first phase included a 21.5 km-long test line, test center, and test vehicle TR06. The first phase was completed from 1979 to 1984. And the first section of the test line was officially put into operation on June, 1983.

From 1986 to 1989, Thyssen led the development of the application-oriented maglev train TR07. An independent, comprehensive evaluation and qualification of the Transrapid system was led by the Federal Railroad Central Bureau. After nearly two years of evaluation and qualification, it was concluded at the end of 1991 that the system was technically mature for its application. At this point, it can be said that the technology of high-speed EMS maglev train is mature enough to enter the line selection and construction phase of commercial operation line project. In 1993, the TR07 maglev train reached a maximum speed of 450 km/h on the TVE test line.

In September 1999, the TR08 (in three-section formation) was delivered to the test line and began tests in October, reaching a maximum speed of more than 400 km/h.

1.3.2 Progress of High-Speed Maglev Research in Japan

Japan began research on EDS-type high-speed maglev technology in 1962. The first vehicle model, ML100, was successfully verified in 1972, while a 7 km-long test line was opened in Miyazaki City. In 1979, the ML-500 set a speed record of 517 km/h. Subsequently, two test vehicle models, MLU001 and MLU002N, were tested in succession.

In 1991, the Yamanashi Line began to construct. The vehicle model of this test line was MLX001, which left the factory in 1995. The line, also completed in 1997, is 18.4 km long, with a maximum grade of 4%, and a minimum turning radius of 8000 m, and the tunnel length accounts for approximately 80% of the total length, all of which are substantial improvements over the Miyazaki City test line.

The first maglev train was successfully tested on the Yamanashi line in 1997, and the maximum speed was then continuously increased, achieving 550 km/h by the end of that year. At the same time, the multi-vehicle train tests and control tests have started one after another. In 2000, an evaluation by the Japanese Ministry of Transportation stated that superconducting maglev technology could already be applied to high-volume transit systems.

To get into service as soon as possible, research since 2000 has focused on reliability verification, system durability, cost control, and improvements in body streamlining. A new group of vehicle models MLX01-901 was put on Yamanashi Prefecture in 2002. The speed records were continuously broken in the following years, and the tests also focused on testing the reliability of the system and the vehicle over long periods and long distances.

From 2006 to the present, this phase began to focus on the commercial application of superconducting maglev, and the design of the vehicle models began to consider the transport of passengers. In 2010, the L0 was confirmed as the final vehicle model, after which L0 was put into mass production. At the end of 2011, the technology standard of superconducting maglev was also adopted by the competent authority.

In 2013, the Yamanashi Prefecture test line was opened with a total of 42.8 km and started running L0 series vehicles. On December 17, 2014, the world's first superconducting maglev high-speed railroad with a maximum speed of 505 km/h officially started construction. On April 16, 2015, at the Yamanashi Maglev test line, a high-speed operation test was conducted using the "L0 series" superconducting maglev train, which reached the world's highest speed of 590 km/h for manned travel. In 2015, Japan conducted a high-speed maglev operation test with a maximum speed of 603 km/h, setting another world record in railroad history. In December 2014, the Chuo Shinkansen, which used L0 series maglev technology, began construction and is scheduled to open the Tokyo-Nagoya section in 2027 and the Tokyo-Osaka section by 2045.

1.3.3 Progress of High-Speed Maglev Research in China

In December 2000, China decided to build a high-speed maglev transit line from Longyang Road Metro Station to Pudong International Airport in Pudong, Shanghai. Construction officially started in March 2001, and a three-section high-speed maglev train was tested on a single line in January 2003. In September 2003, the entire line was opened, and on December 31, 2003, the entire line was completed for examination and acceptance. The line is about 30 km, using the German TR08 high-speed maglev train technology, and has been operating safely for nearly 20 years, as shown in Fig. 1.5.

With funding from the 863 Program of the 10th Five-Year Plan and the Science and Technology Support Program of the 11th Five-Year Plan and the 12th Five-Year Plan, the Tongji University National Maglev Engineering Research Center has made significant studies in the localization of high-speed maglev trains. During

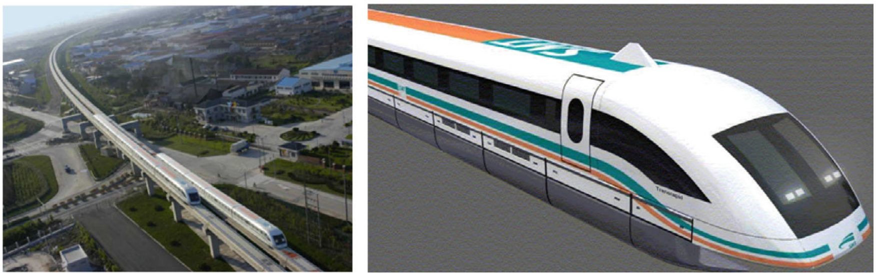

Fig. 1.5 Shanghai high-speed maglev train

Fig. 1.6 Tongji University high-speed maglev test line and PEM hybrid maglev train

this period, the National University of Defense Technology has carried out research on PEM hybrid levitation system, and gradually completed the development and commissioning of PEM hybrid levitation control system of single bogie, double bogie, single vehicle and two-section high-speed maglev test vehicles. In November 2017, the project task of the National Science and Technology Support Program of the 12th Five-Year Plan, "Research on levitation, guidance and eddy current brake controllers of the PEM hybrid high-speed maglev train", successfully passed the acceptance of the project. The localized PEM hybrid high-speed maglev train (as shown in Fig. 1.6) has completed the basic function tests such as levitation and guidance, and completed the propulsion operation test on the 1.5 km-long high-speed maglev test line in Tongji University. Due to the limitation of the length of the test line, the speed-related operational tests are not sufficient, so the main task in the next phase will be to improve the research on the levitation system of high-speed maglev trains based on the existing research and to promote the commercial operation of localized high-speed maglev trains.

With the support of the National Key Research and Development Program during the 13th Five-Year Plan, CRRC Qingdao Sifang Co., Ltd. took the lead in developing the first engineering prototype of a high-speed maglev train with a design speed of 600 km/h on May 23, 2020. On July 20, 2021, a five-carriage set of high-speed maglev train with a design speed of 600 km/h was officially unveiled and successfully underwent integrated testing on a 665 m test line in Qingdao. And the National University of Defense Technology provided the technology of levitation and guidance control and positioning test.