State of Art and Future Development of Magnetic Levitation Technology

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Abstract. Nowadays, with the development of the times, maglev technology is becoming more and more mature. The author of this paper focuses on the development and technology of maglev trains, introduces the development process of maglev trains in China, Japan, Germany and other countries, and describes the similarities and differences in the technology of maglev trains in each country. In the following, three types of maglev technologies are illustrated: electromagnetic levitation, electric levitation, and high-temperature superconducting maglev. The three technologies have a certain intersection in principle and use the magnetic force between the track and the train to levy. At the same time, the author introduces the different applications of each technology. In the latter part of the article, the author briefly introduced another application of magnetic suspension - magnetic suspension bearing and described its application in many fields. In the end, the author puts forward the existing problems of maglev trains and the necessity of solving them according to his point of view.

Keywords: Maglev train; superconducting; electric magnetic levitation; electric levitation; magnetic levitation bearing.

1. Introduction

Magnetic levitation technology is a technology that uses magnetic force to overcome gravity to make objects levitate. It has been used in many fields such as transportation, wind power, aerospace, centrifuges, bearings and so on. The advantages of magnetic levitation technology are also obvious, it can achieve no friction, no noise, and the non-contact operation mode also makes it faster and more efficient. To sort out the application of maglev technology in many fields, this paper takes the maglev train as the main body, describes the development of the maglev train, expounds on its application technology, and describes other applications of maglev technology.

2. Maglev train

2.1. The development of maglev trains

From the perspective of human transportation development, with the three industrial revolutions, transportation has changed from the first two feet to carriages and then developed into cars, trains and airplanes. In the transformation of industry, technology is also changing. In the process of continuous progress, human beings continue to explore and discover, and brand-new means of transportation are coming one after another, and the maglev train is one of them.

Tracing the origin of the suspension train, it can be seen that it is electromagnetic induction. As early as 1750, John Mitchell discovered the repulsive force between two magnets at the same level, and 80 years later Faraday discovered the phenomenon of electromagnetic induction and explained it in detail. This laid the foundation for the invention of the maglev train. In 1912, Herman began to study the maglev train. In 1934 Herman filed the patent and the world's first patent for maglev technology was born [1]. Then in 1937, Kemper of Germany obtained the first patent for a magnetic levitation train driven by a linear motor [2], and in 1959, Richard, an American, filed a patent application for a maglev transportation system, and after that, countries around the world also started to develop this topic. Researching widely. So far, China has the most patents in this area. Fig. 1 shows the number of maglev patents in the top five countries.

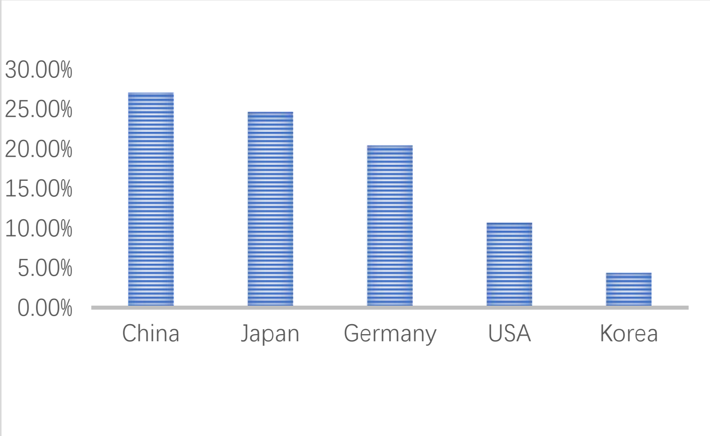

Fig. 1 Top five countries with magnetic levitation patents

2.1.1 Development of Japanese maglev trains

Japan started research on maglev trains in the early 1960s. Based on the idea of using superconducting magnets to levitate trains through electromagnetic force proposed by Powell and Danby in the United States [3], Japan focused on tackling high-speed superconducting maglev trains. After more than half a century of research, Japan already has advanced infrastructure. In 1979, the speed of Japan's maglev train reached 517km/h, exceeding the expected standard [4]. Japan first used the technology of Germany's KM company to research maglev technology. The most representative is the HSST series, which is a maglev train. From 1978 to 1987, the Japanese HSST series has been improved for four generations in nine years and has mature technology. The HSST-100 maglev train is a low-speed maglev train in Japan. During the two years from 1991 to 1993, more than 100 items such as weather, signal, electricity, and track were tested [5], and it achieved great success. The HSST-100L was also tested in 2003 and reached a speed of 100km/h.

In 2003, the MLX01 maglev train was tested on the Yamanashi test line, and the speed reached an astonishing 552km/h. In April 2015, the L0 series trains of Japan's low-temperature superconducting maglev trains were tested on the Yamanashi test line, a succession of 590 km/h [6], 603 km/h [7] speed, and many new world records. In the research and development of maglev trains, Japan has applied for a huge number of patents, only behind China, ranking second in the world, as high as 24.66%, as shown in Fig. 1.

2.1.2 The development of German maglev trains

The development of German maglev trains is also relatively early. In the 1970s, Germany built the world's first maglev train - the MBB demonstration car and officially unveiled it to the public in Munich. It has been more than 50 years. The MBB demonstration vehicle has many unprecedented features, such as an independent support and guide system, and is driven by a short-stator linear motor, which can reach a speed of 90km/h [8]. Compared with the low-speed magnetic levitation represented by the Japanese HSST series, the German TR is represented by a long primary drive high-speed magnetic levitation. With its development of more than 50 years, German maglev technology has also been very mature. As early as 1976, the TR 06 test car was developed and reached a top speed of 413km/h in the 1988 test, and its next-generation TR 07 reached a speed of 450km/h. At the beginning of this century, the TR 08 maglev vehicle was tested in Shanghai, China, with a maximum speed of 501km/h, and the TR 09 train also ran a speed of 550km/h on the TVE test line six years later. As an old industrial powerhouse, Germany ranks third in the number of patents in the field of maglev, reaching 20.44%, as shown in Fig. 1.

2.1.3 The development of China's maglev train

China carried out reform and opened up in the 1980s. After that, China also vigorously developed maglev technology and achieved world-renowned achievements. In one fell swoop, it surpassed Japan, Germany and other maglev countries and became the first country in maglev patents. It can be said that it is a rising star. In 1989, China's first small maglev prototype vehicle was born, and five years later, Southwest Jiaotong University developed a manned low-speed maglev train with a weight of 4 tons and a suspension height of 8 mm. People Maglev train. At the beginning of the 21st century, Southwest Jiaotong University developed the Century train, which is also the world's first manned high-temperature superconducting maglev train, and then developed the future normal-temperature and normal-conducting maglev train. Since then, China and Germany have cooperated closely, and the above-mentioned TR 08 train is the embodiment of the cooperation, as shown in Fig. 2.

Fig. 2 Shanghai high-speed maglev demonstration line

Then in 2012, the Wind Chaser rolled off the assembly line, which is China's first medium and low-speed maglev train. The performance of the Wind Chaser has reached the world's leading level. Since then, China has become the fourth country in the world that can independently develop medium and low-speed maglev trains. Four years later, the Changsha operating line faces the world. This so-called world's longest operating line has a total length of 18.54km, adding a beautiful landscape to Changsha, China [9], as shown in Fig. 3.

Fig. 3 Changsha medium and low-speed maglev train

In 2019, in Qingdao, China, China's ultra-high-speed maglev train was officially unveiled. The maximum speed of this car is as high as 600km/h. This train also marks a breakthrough in China's high-speed maglev technology [10]. At present, China leads the world in maglev patents. As shown in Fig. 1, China's maglev patents account for 27.11% of the world's total.
Many other countries have also developed the maglev, but the author does not do much in detail here.

2.2. Classification and applied technology of maglev trains

There are many forms of magnetic levitation The author focuses on three in this article: electromagnetic levitation, electric levitation and superconducting magnetic levitation.

2.2.1 Electromagnetic levitation

Electromagnetic levitation is also known as magnetic suction type. Its structure is mainly composed of two parts, namely electromagnet and magnetic conductive material. It uses the attraction between the magnetic conductive material and the electromagnet to make the train levitate.

Most of the magnetic suspension adopts a "T" type track. When the vehicle is running, the electromagnet under the guide rail generates a strong magnetic field through electric excitation, which can generate a huge attraction with the magnet on the train. The direction of the attraction is upwards, which balances the weight of the train so that it can levitate. The distance between the magnet and the track is about 8-12mm. When the number of passengers changes, the weight of the train also changes, and the train can control the attractive force between the magnet and the track by controlling the excitation current of the levitating magnet, so that the balanced with different gravity, the train maintains a stable distance. This suspension method can produce a suspension effect when the train is stationary, so there is no need for wheels, as shown in Fig. 4.

According to whether there is an independent guidance system, the electromagnetic suspension system can be divided into two categories, one is a high-speed magnetic suspension system with independent suspension and guidance functions, which is represented by the German Transrapid; The medium and low-speed maglev system with guiding function is represented by the Japanese Linimo line and the above-mentioned Changsha line.

The guiding system principle of electromagnetic levitation is similar to the principle of magnetic levitation. Electromagnets specially used for guiding are installed on the side of the vehicle, and at the same time, it is necessary to ensure that the train and the guiding track maintain a certain distance. When the vehicle deviates, the guide magnet on the car and the electromagnet on the guide track generate a magnetic force, and this magnetic force can neutralize the force generated by the offset so that the train returns to its normal position. The control system controls the magnetic force through the current in the conductor magnet, to control the distance between the train and the guide rail, thereby achieving the purpose of controlling the stability of the train.

Nowadays, electromagnetic levitation has been applied in many countries and places, and the reliability of this technology has also been affirmed. For example, in the Japanese HSST series, medium and low-speed electromagnetic levitation trains also have this technology. Of course, the differences in this technology are also exposed in practice. It has extremely high requirements for its own structure, overhead lines and control systems. Since the suspension interval is small, only 10mm, the trajectory needs to be very smooth. It also increases the difficulty and cost of construction. Some special interaction between trains, suspension control and bridge lines also makes the train's stability system unable to be fully guaranteed, resulting in potential safety hazards. At the same time, the relatively complex structure also makes maintenance more difficult.

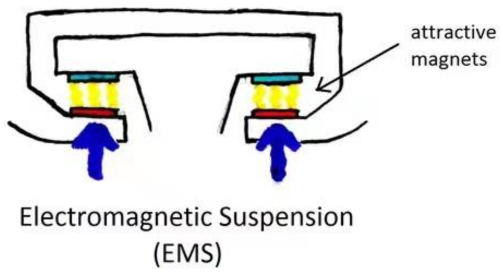

Fig. 4 The principle of electromagnetic levitation

2.2.2 Electric suspension

Electric suspension is also known as magnetic repulsion suspension. When the train is running, the moving magnetic field of the onboard magnet generates an induced current in the coil on the track, thereby generating an induced magnetic field, which generates a force with the magnetic field of the onboard magnet, which is expressed as repulsion. Therefore, it is balanced with the gravity of the train to achieve the suspension effect, and the gap generated by the suspension is 100-150mm. Due to the repulsive force and conductor cutting magnetic line speed is closely related, the faster the cutting, the greater the induction magnetic field strength, so the greater the repulsion, the greater the suspension force.

There are many types of guide systems for electric suspension: 1. Guide wheels can be installed on the side of the train. This method is the simplest and uses the principle of small rolling friction. When the train is offset, the guide wheels are in contact with the guide rails. The support force is generated to make the train return to the normal running state, but the drawbacks of this method are also obvious. The guide wheels will be worn during use and need to be replaced regularly. At the same time, the contact guide mode will also have a certain impact on the train. 2. The guiding superconducting magnet is installed on the train. The principle is similar to that of the electromagnetic suspension guiding system. The magnetic repulsion force is generated between the superconducting magnet and the guiding track, thereby offsetting the deviation of the train. The author also explains superconductivity below. 3. Using the "8" coil, the magnetic field inside the coil is 0, but when the vehicle deviates, the magnetic field inside the coil and the magnetic force interact with the electromagnet on the train to offset the offset. This method is more special, it can not only achieve guidance and lateral stability but also can use the coil mutual sense to generate the upward suspension force, to achieve the suspension effect [11], as shown in Fig. 5. Since the structure of electric levitation is simpler than that of electromagnetic levitation, it is more widely used.

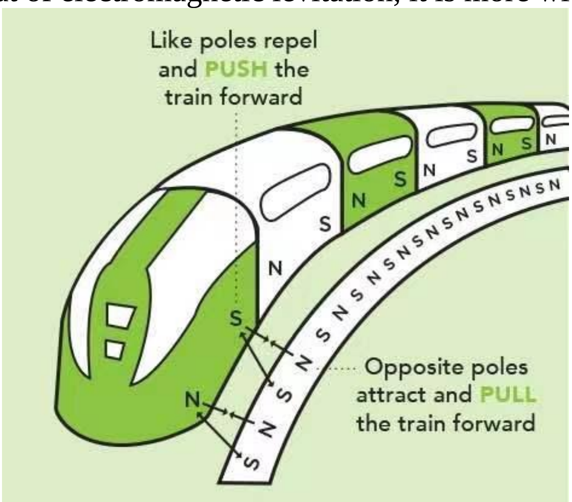

Fig. 5 "8" coil Suspension principle

2.2.3 High-temperature superconducting maglev

The superconducting magnetic levitation is the same as the above-mentioned electric levitation principle, both of which use repulsion to suspend. When it comes to superconductivity, the author of this paper believes that it is necessary to briefly explain the phenomenon of superconductivity.

The superconductivity phenomenon is very simple to explain, as the name implies, it has strong electrical conductivity. When the temperature of the material changes, its resistance also changes. Then, when the temperature of some substances reaches a certain value, the resistivity will be 0. Of course, it is difficult to achieve zero resistance in reality. Therefore, in the test, when the resistance is lower than 10 -25 Ω, the resistance is considered to be 0. At this time, its conductivity reaches the strongest, which can form a strong current and generate a strong magnetic field. When the superconductor enters the superconducting state, the electromagnet has complete diamagnetic properties [12].

Although high-temperature superconducting maglev also uses repulsive suspension, its suspension mechanism is different from electric suspension. High-temperature superconducting maglev using the second type of superconductor magnetic nailing characteristics to achieve suspension, make high-temperature superconductor in a superconducting state, placed above the permanent magnet, using the magnetic field gradient, high-temperature superconductor surface induction current, superconducting state of superconductor resistance is 0, lead to the induction current can persist and current is very large, creating a strong magnetic field, macroscopic is suspension force between a superconductor and permanent magnet, as shown in Fig. 6. Sometimes the initial speed is not enough to maintain the train suspension, and wheels are needed to ensure the normal start and stop, which is more common in Japan. The high-temperature superconducting maglev system is mainly composed of three parts: vehicle conductor material, ground permanent magnet track and linear propulsion motor [13].

The vehicle-mounted conductor material is mainly made of superconducting blocks, and the track is assembled with permanent magnets and other substances, which can generate a huge magnetic field on the track, and through the coil on the track, the body can obtain a huge repulsive force and achieve a suspension effect.

Superconducting maglev technology has been applied and developed in many countries. The development of superconducting maglev in China is very early. In 1997, Southwest Jiaotong University conducted in-depth research on high-temperature superconducting maglev trains. At the beginning of the 21st century, the world's first manned high-temperature superconducting maglev train was born. The suspension spacing of Century is more than 20mm, and the maximum suspension weight is 700kg.

After China, Germany also increased its efforts to develop superconducting maglev. In 2004, it developed the first-generation high-temperature superconducting maglev train, Supra Trans. It has a suspension distance of 8mm, is driven by a linear motor, and has a maximum suspension force of 7840N. Although the total length is 7m, the test was successful. The second generation was born 7 years later. The load test of two people was carried out on a circular test line with a total length of 80m. The suspension distance was maintained at 8-10mm. The maximum suspension force exceeded the previous generation, reaching 8900N, and the maximum acceleration was 1m/s. The top running speed reached 20km/h and achieved great success.

Brazil built a mature high-temperature superconducting maglev train line in 2014. This car is a medium and low-speed maglev train, the purpose is to relieve traffic pressure.

In 2008, Italy constructed a track with a special V-shaped structure for the high-temperature superconducting maglev train test. This V-shaped structure increases the levitation force. This train is a simulated test vehicle with a total length of 0.72m, a track length of 3.72m and a maximum speed of 37km/h.

Now scientists are exploring the possibility of superconductivity at room temperature. The latest test in 2019 showed that lanthanum hydride, a combination of lanthanum metal and liquid hydrogen, has superconductivity at 250 Kelvin, or minus 23 °C [14], although this research It is currently difficult to apply to reality, this is a huge step towards room temperature superconductivity. If normal-temperature superconductivity is realized in the future, and is applied to maglev trains, it will have the same effect as high-temperature superconducting maglev, and the superconducting maglev effect will also be formed, and it will not be affected by the external ambient temperature, which is better. Due to the two existing superconducting maglev technologies [15], the maintenance cost can also be reduced.

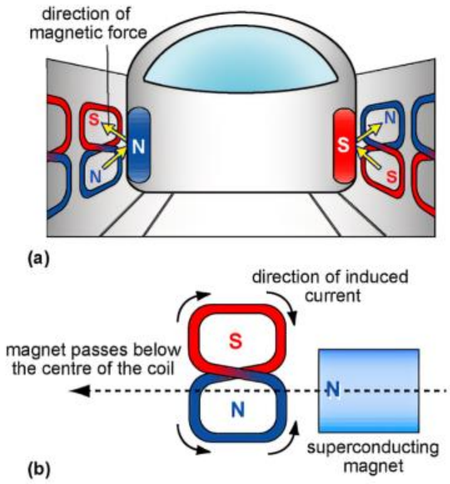

Fig. 6 Superconducting magnetic levitation principle

2.3. Comparison between the three maglev technologies

The three forms of maglev intersect in many ways, but there are also many differences. The author uses a table form to show the differences between these three forms in suspension mode, advantages and disadvantages, as shown in Table 1.

Table 1. Comparison table between the three suspension modes

Suspended way	**principle**	**structural complexity**	**Suspension conditions**	**advantage**	**shortcoming**
Electromagnetic levitation	Suspension using attraction	The structure is more complex	Static suspension can be achieved without wheels	Suspended at rest, reducing the use of wheels and small suspension distance	Unstable operation and complex structure
Electric suspension	Suspended by the repulsive force	The structure is simpler	Can not achieve static suspension, need wheels	Simple operation, uncomplicated track, no built-in, simple maintenance	The speed needs to reach a certain value to levitate
High-temperature superconducting suspension	Suspended by the repulsive force	The structure is simpler	Can not achieve static suspension, need wheels	The suspension is stable, no control is required, the superconductor generates a strong magnetic field, and the maintenance is simple	It is necessary to maintain high-temperature superconducting conditions, and the suspension has initial velocity requirements, sometimes needs wheel

3. Other applications of maglev technology

The application of maglev technology is not only in this aspect of maglev trains but also in transportation, aerospace, military and other fields that also have different degrees of application, the representative ones are magnetic suspension bearings and electromagnetic launch.

3.1. Magnetic bearing

Magnetic bearings are widely used in many fields.

In 1976, the magnetic suspension bearing was used for the first time to replace the mechanical bearing in the satellite guide flywheel, and achieved remarkable results; in the space flywheel test, Japan applied the magnetic suspension bearing technology to the rocket, and the United States applied the magnetic suspension bearing technology to the space test cabin. in the vacuum pump. Compared with ordinary aero engines, the magnetic bearing has many advantages. It realizes frictionless rotation, solves the problem of large friction under high-speed rotation of traditional mechanical bearings, and increases the service life. At the same time, it has the advantages of small mass, high efficiency, and excellent reliability and maintainability [16].

In terms of transportation, the application of magnetic bearings on ships is also extremely extensive. With the development of transport ships, warships and other ships, the requirements for various mechanical rotating devices on ships are getting higher and higher. Magnetic suspension bearings meet the advantages of noise reduction, energy saving and emission reduction, and are not easy to wear. In addition, this Technology can make the rotor rotate at a higher speed while increasing the accuracy and service life [17]. Of course, maglev-bearing technology also has some problems to be solved on ships. Here the author summarizes two types of shortcomings:

The first point: the ability to adapt to the environment is not strong. When the ship encounters severe weather at seas such as typhoons and rainstorm, the accuracy of the magnetic suspension bearing may be affected to varying degrees. This influence often leads to the instability of the magnetic suspension bearing, or even can not work normally, affecting safety. When encountering strong electromagnetic interference, the rotor suspension accuracy will also be affected, and the noise will increase, so the magnetic suspension bearing system must have the ability to resist electromagnetic interference.

The second point: the carrying capacity is limited. Ships such as transport ships and warships often need to carry a large amount of equipment in a limited space, which also makes the magnetic bearing need to have a strong carrying capacity. If the carrying capacity of the magnetic shaft is strengthened, the volume of the magnetic shaft will increase. How ensure At the same time of large carrying capacity, it can also reduce the volume of the magnetic shaft so that other equipment can have more space, which is an urgent problem to be solved.

3.2. Application of magnetic levitation technology in the industry

Magnetic levitation technology also has many applications in industry. A large number of factories use magnetic levitation technology to increase efficiency and reduce energy consumption. In this part, the author conducts a simple analysis with the magnetic levitation blower. Magnetic levitation blowers can reduce the noise problems caused by traditional blowers in industrial production, while also improving operating quality and efficiency, and their frictionless nature also greatly reduces maintenance costs.

4. Maglev Technology Expectations

Maglev technology is still a hot topic today. The mainstream long-distance transportation urgently needs in-depth research on many projects: 1. How to effectively brake and guide ultra-high-speed maglev trains. This problem is directly related to the safety of passengers. If the problem of efficient braking and guidance at high speed is solved, the reliability of maglev trains can be increased, and the research and development of ultra-high-speed maglev trains can also be promoted. 2. The perfection of the connection technology of the carriages. In medium and low-speed maglev trains, the existing high-speed rail connection technology is fully applicable, but for ultra-high-speed trains with a speed of more than 600km/h, a safe and reliable connection is essential. To receive a very large amount of traction, the connection must be able to withstand this traction. 3. Improve the convenience of rescue in emergencies. Ultra-high-speed maglev trains often use vacuum-tight pipelines, which have excellent compression performance and strong impact resistance. Although safety is guaranteed during operation if an accident occurs, how can passengers escape in time through the life-saving tools in the car, is a problem that must be solved. The research results of the above problems may further enhance the popularity and practicability of maglev trains.

The replacement of traditional mechanical bearings with magnetic bearings is an inevitable event, and how to reduce the volume and cost of the magnetic shaft, while making it small and fine, while further improving the performance of the magnetic shaft and resisting external interference, is also a problem that needs to be solved.

5. Conclusion

This paper first briefly introduces the maglev technology, and then focuses on maglev trains. Combined with the existing literature, it discusses the development process of maglev trains in China, Japan, and Germany, three major maglev countries. Item Maglev Technology: Electromagnetic levitation, electric levitation, superconducting magnetic levitation and the specific models in the application of these three technologies, looking forward to the possibility of normal temperature superconductivity. In the second half of the article, the author focuses on maglev bearings and maglev blowers, discusses the application of maglev technology in aerospace, military industry, people's livelihood, and industrial fields, and at the end of the article, the two important applications of maglev trains and maglev bearings are carried out. Analysis and outlook of the problem. Although the development of magnetic levitation technology is very mature now, how to further increase the popularization of magnetic levitation technology and better apply it to life requires the continued efforts of scholars all over the world.

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