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Development of the Guideway Deviation Measurement Technology for High-Speed Maglev System

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Abstract

Guideway of high-speed maglev is a large-scale, complex, and precision-demanding infrastructure system. It is necessary to have different technologies and equipment for guideway deviation measurement at different stages like construction, acceptance, operation and maintenance. Along with the construction and operation of Shanghai Maglev Line and Jiading experimental line, NMTC (National Maglev Transportation Engineering R&D Centre) have developed such technology in the past twenty-three years, including precise manufacturing technology, high-precision measuring technology for guideway acceptance, high-speed online track inspection technology and corresponding data processing technologies. Through the continuous improvement of guideway deviation measurement technology, NMTC not only improves the measuring efficiency and maintenance accuracy of the guideway, but also prepares the technical reserves for future higher speed (like 600km/h class) maglev projects.

Keywords: high-speed maglev, guideway, inspection, measurement, technology, equipment.

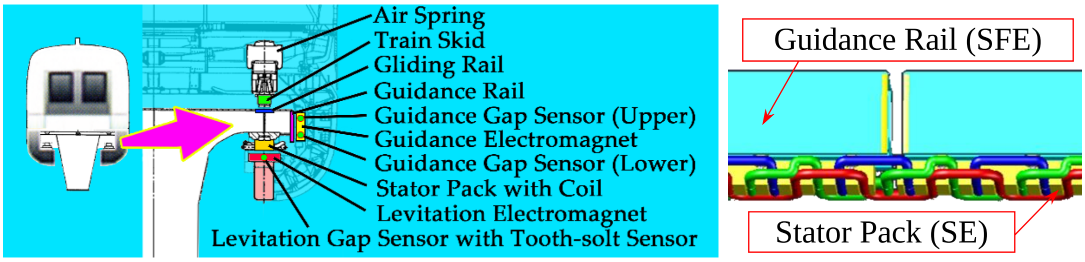
1 Introduction

Guideway system of high-speed maglev is a large-scale, complex, and precision-demanding infrastructure. At different stages like construction, acceptance, operation and maintenance, there are different needs for guideway deviation measurement. Therefore, it is necessary to have corresponding technology and equipment.

1.1 Deviations of the Maglev Guideway

The interface between high-speed maglev train and the guideway is shown in Figure 1 [1]. There're three main functional surfaces on each side of the guideway named gliding rial (GLE), guidance rail (SFE) and stator pack (SE) [2] [3].

Different from the traditional wheel-rail system which uses smooth and continuous flexible steel rails as the contact interface of the track, the guideway of high-speed maglev adopts a discrete rigid plane (or curved surface) of limited length (usually about 1~3m) as the track surface. The deviation of the guideway mainly refers to the position deviation of the three pairs of functional surfaces, including the absolute deviation of the position of the surfaces and the relative deviation between adjacent functional surfaces.



(a) (b)

Figure 1: (a) High-speed maglev system; (b) Surfaces of the maglev track.

1.1.1 Short-wave Deviations （SWDs）

Short Wave Deviations (SWDs) are the relative deviation between adjacent functional surfaces which are important space geometry and position indicators for the track surfaces. SWDs will affect the safety of the train.

According to the maglev system's requirements, most of the SWD indicators are millimetre accuracy, and the measurement accuracy must achieve at least 0.1mm. Main SWD indicators are shown in Table 1 [4].

Indicator	Remark
Offset	Vertical displacement between two adjacent track surfaces.
NGK	Angle between two adjacent track surfaces.
T_{ZM}	Tong size, vertical distance between gliding rail and stator surface.
Torsion	Torsion angle between two adjacent track surfaces.
Gauge	Distance between two guidance surfaces.

Table 1: List of main SWD Indicators

1.1.2 Long-wave Deviations （LWDs）

The definition of the Long Wave Deviation (LWD) is in principle based on the elastic line properties of the supporting structure, and for each girder (beam segment) considered, the maximum permissible offset ("deflection") is assigned in both positive and negative directions. LWDs are the absolute deviations of the position of the functional surfaces and the maximum allowable plastic deformation of the substructure. LWDs will affect the riding quality of the train.

1.2 Requirements at different Stages of the Project

1.2.1 Construction Stage

In this stage, the maglev guideway is still under construction and the whole project has not yet been completed. Thus, the tracks are not yet passable by trains or inspection vehicles. Guideway deviation measuring can only be done manually or slowly by special inspection vehicles because large amount of construction equipment that may still appear on the track, or even the functional surface of the track itself may not be completed.

The main requirement for track inspection at this stage is to carry out high-precision point-by-point measurement of long-wave and short-wave deviations of the track to guide construction operations. Since the inspection schedule only needs to be synchronized with the construction, there are sufficient day and night conditions for precise manual measurement of the track.

1.2.2 Acceptance Stage

In this stage, the construction of the guideway has completed and the guideway will be delivered from the builder to the operator after the acceptance.

The main requirement for track inspection at this stage is still to inspect the LWDs and SWDs of the track with high accuracy in order to carry out the completion acceptance of the guideway and the clearance confirmation inspection. Although it can still be continuously inspected during the day and night, the efficiency of long-distance track inspection needs to be considered compared to the construction stage, so the quasi-static continuous inspection of the track can be carried out by special guideway inspection vehicles.

1.2.3 Operation and Maintenance Stage

After the completion and opening of the maglev line, under normal conditions, the substructure of the track naturally exists slight and uneven slow settlement affected by the geological conditions. At the same time, with the development of the city, it is inevitable to encounter the impact of post-construction projects on the existing maglev line (such as new subways or tunnels under the maglev line, new viaducts or buildings across the track, new large-scale infrastructure along the maglev line, etc.). These construction projects will lead to tiny changes in the foundation around the maglev track, which will cause minor deformation of the maglev track, and thus affects the quality of the operation of the train. Therefore, the guideway itself needs to be regularly maintained and inspected, including the inspection of LWDs of the track. Considering the safety of the trains, it is necessary to conduct a quick check to confirm the clearance limits and SWDs of the track before operation every day. In addition, after localized maintenance or construction modifications to the track, it is also necessary to conduct SWD inspection of the track at the maintenance position to ensure safety.

The biggest difference with the previous two stages is that when the maglev line is put into commercial operation, all the maintenance and manual inspection operations that will affect the operation can only be carried out sequentially during the limited window of time when the guideway is out of service at night, thus introduced a very high demand on the efficiency of the inspection works.

2 New Technologies for Guideway Deviation Measurement

2.1 Contactless Sensor Technology

With the progress of sensor technology and the development of AI data processing algorithms, intelligent non-contact sensors with excellent performance have begun to be increasingly applied to the track inspection of maglev. Examples include multifunctional eddy-current sensors, point laser displacement sensors, structured light laser sensors, and smart cameras based on AI image recognition technology. These sensors are used in various stages of construction, acceptance, operation and maintenance of the maglev tracks. The main applications of the sensors are shown in Table 2:

SN	Sensors	Typical Application Scenarios	Stage
1	Eddy-current sensor	Displacement measuring, velocity pulse generating for LWDs.	Operating
2	Laser displacement sensor	Displacement measuring for SWDs.	Construction, acceptance, maintenance.
3	2D Laser sensor	Guideway contour scanning for SWDs and clearance inspection.	Construction, acceptance, maintenance.
4	Cameras	Image recognition and clearance inspection.	Construction, acceptance, maintenance.

Table 2: Contactless Sensors Used for Guideway Inspection and Measurement

2.2 SWD Measuring Technology

The SWD Measuring Technology calculates the data measured by a group of displacement sensors mounted on a rigid longitudinal measuring beam to obtain the offset and NGK deviation values of the measured guideway surface at the same time based on data differential algorithm.

This algorithm is suitable for static or low-speed quasi-static measurements and can be used for manual measurements of SWDs or for automated measurements with specialized guideway inspection equipment. When used for manual measurements a dialgauge or an electrical dialgauge can be used as a data source, and for automated measurements a laser displacement sensor can be used as a data source. Figure 2 shows a scenario of an automated measurement of SWDs using dialgauges (a) and laser displacement sensors (b). [5]

(a) (b)

Figure 2: SWDs Measuring with Dialgauge (a); with Laser Sensor(b).

2.3 LWD Fast Measuring Technology

The LWD fast measuring technology evaluates the long-wave deviation of the track surface by calculating the gap between the train electromagnet and the track surface and the deviation of the electromagnet with respect to an inertial reference. This algorithm is suitable for dynamic onboard measurements after the guideway is put into operation. The gap between the electromagnet and the track surface is captured by an eddy-current displacement sensor and the deviation of the electromagnet with respect to an inertial reference is measured by an inertial unit. Figure 3 shows an inertial measurement unit mounted on a train levitation electromagnet. [6]-[12]

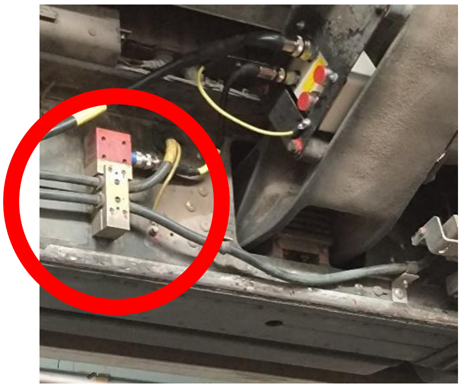


Figure 3: Inertial Measurement Sensor for LWD Evaluation.

2.4 Online Automatic Control Technology

The online automatic control technology of track inspection equipment based on fusion of multi-sensor is able to automatically determine the running status of the track inspection equipment carrier and the relative position on the track beam through the real-time analysis of the signals of different measurement sensors, this enables the automatic control and quasi real-time locating function of the guideway inspection system. At the same time, it provides the running direction and speed and other state information of the carrier to the inspection equipment. The locating accuracy of the device is better than the one stator cogging. Figure 4 shows the running status information of the carrier on the track beam measured in real time during the track inspection process.

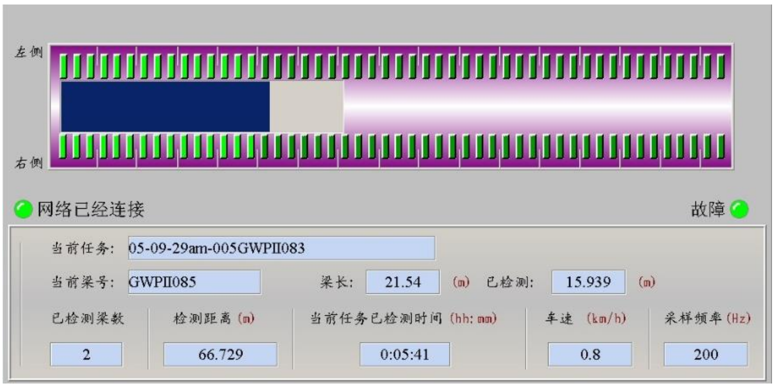


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Figure 4: Interface of Locating System at Guideway Measuring

2.5 Guideway Evaluation Technology

At present, there is no international evaluation method or standard specifically for maglev guideways. Through nearly 25 years of research on track maintenance technology, NMTC has proposed a track evaluation technology based on train swaying level, ridding comfort and vehicle dynamic response analysis. This technology collects the acceleration signals in the carbody and the bogie of the commercial maglev train during normal operation, as well as the levitation and guidance currents and other parameters to comprehensively evaluate the dynamic response of the vehicle in operation, and thus make a comprehensive evaluation of the state of the guideway.

2.6 Offline Guideway Inspection Data Locating Technology

The offline guideway inspection data locating technology [1] can recognize the precise location and automatic identification of the track inspection route only through the results of the measurement sensors used for track inspection without using additional positioning sensor sources (e.g. Global Navigation Satellite System GNSS, Location Reference Flag LRF, etc.) or on the basis of the above mentioned online automatic control system.

2.7 Intelligent Guideway Monitoring Technology

Intelligent big data track monitoring technology integrates intelligent low-power wireless transmission sensors, Iot (Internet of Things) sensor, big data cloud platform and digital twin technology, which can recognize long-term unmanned remote automatic monitoring of the track status and rapid retrieval and analysis of large amounts of monitoring data in the later stage. Figure 5 shows some of the track monitoring sensors on the Jiading experimental line.


(a) (b) (c)

Figure 5: Guideway Monitoring Sensors Mounted in the Test Line Jiading

3 Some Examples of Guideway Deviation Measurement Technology

3.1 Long-wave Set for LWD Manual Measurement

The Long-wave set for LWD manual measurement consists of an industrial tacheometry, a fast-positioning prism holder for high-speed maglev tracks and two measurement prisms, which can be used to measure the three-dimensional coordinates of specified feature points on the track rapidly by manual measurement. Among them, the fast-positioning prism holder can quickly allow for three-dimensional positioning of the measuring prisms to the specified track position. This equipment can be used for construction measurement during track construction or manual recheck of key points during track maintenance.

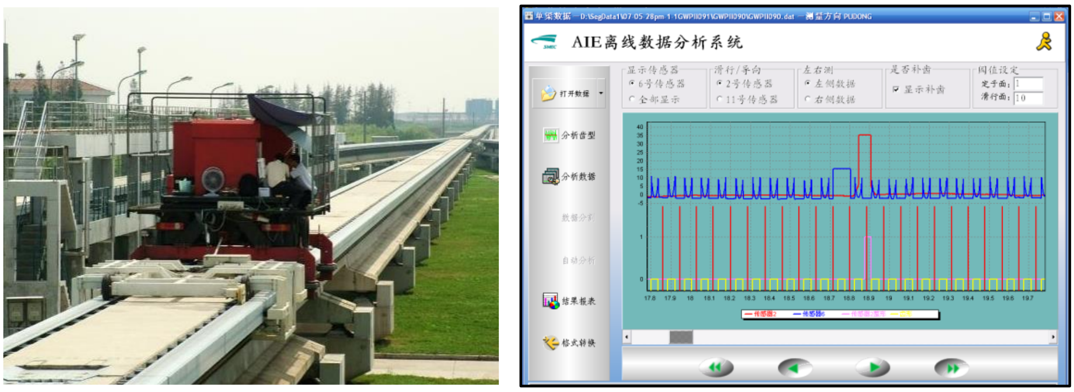
Figure 6 shows a scenario where the device is used.

Figure 6: Using Long-wave Set to Measure the Girder Alignment Manually

3.2 Automatic Inspection Equipment for SWD Measurement

AIE (Automatic Inspection Equipment) [4] is a high-precision quasi-static automatic measuring equipment for SWDs inspection. It can apply automatic continuous measurement of all 17 kinds of SWD indexes at three pairs of functional surfaces of the track through the non-contact sensors installed on the measuring trolley combined with the short-wave measuring technology and on-line automatic control technology. The inspection speed is up to 5km/h, and the inspection accuracy is better than 0.1mm, which is applicable to the acceptance of the guideway, and can also be used for the SWD verification of the track after overhauling or local maintenance of the guideway.

In addition, for acceptance inspections of new guideways, where long-distance fieldwork tasks are performed continuously for long stages of time, the equipment has been specially designed with a dual-computer redundancy system that is able to be downgraded in order to maintain measurements with an online data analysis system in quasi-real time. Figure 7 shows the AIE hardware and its software in operation.



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左右测: ● 左侧数据 ○ 右侧数据

是否补齿: ☑ 显示补齿

阈值设定: 定子面: 1 滑行面: 10

(a) (b)

Figure 7: Hardware and Software of the Automatic Inspection Equipment

3.3 Track Inspection System for Online Fast Measurement

TIS (Track Inspection System)[10],[12],[13] is a track LWD/SWD fast measuring system installed on commercial maglev trains or specialized inspection vehicles during operation. It combines LWD fast measuring technology based on inertial reference, online automatic control technology and offline guideway inspection data positioning technology, which can apply the fast measurement of track LWD and some of the SWDs on 430km/h or even higher speed (e.g., 600km/h) maglev trains, and also provides a data platform for track assessment based on train sway, ride comfort and vehicle dynamic response analysis. Currently, the on-board fast track inspection equipment developed by NMTC has developed into the third generation, and its mainframe is available in two configurations, portable and rack-mounted, which can be converted according to the needs. Figure 8 shows the portable TIS main chassis.

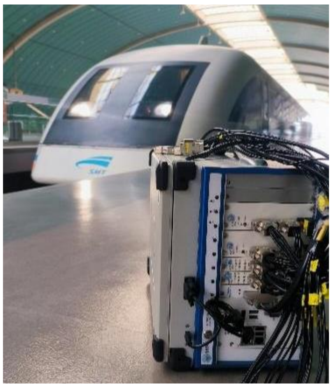

Figure 8: Main Chassis of the TIS (Portable)

Taking the Shanghai Maglev Demonstration Line as an example, the short-wave safety inspection of the whole guideway is currently carried out by a combination of manual measurement at key points and the use of on-board inspection equipment on the first unladen maglev trains with reduced speeds of 150km/h every morning, while the long-wave deviation is regularly measured by the on-board inspection equipment of the commercial maglev trains in their daily operation, the monitoring of the key SWD indicator offset is also carried out automatically during each train run.

4 Issues and Challenges Associated with New Development

Problems found in the operation and maintenance of the current maglev system for more than twenty years, as well as new problems brought about by the application of new track inspection technologies are continuously putting forward new needs and challenges for the track inspection system.

Unlike traditional wheeled trains, high-speed maglev trains have fewer mechanical components in the bogie and most of them are designed to be maintenance-free, so the maintenance cycle and service life of the bogie are longer [14]. This places higher demands on the durability of the track inspection equipment installed in the bogie. Taking the maintenance experience of Shanghai maglev as an example, due to the fact that the trains operating in an environment close to the East China Sea (the straight-line distance between the maintenance base and the coastline is only about 2km), the air is salty. Under this circumstance, the aluminum-based nickel-coated military standard cable connectors of the inspection equipment installed on the levitation electromagnet, where rainwater is easy to reach, showed a certain degree of corrosion after nearly two decades of use, while the same connectors installed near the guidance magnets during the same stage were in normal condition. Therefore, the future design of track inspection equipment will be considered according to the locations where the device installed to choose devices with different levels of protection.

The guideway deviation caused by the deformation of the substructure of the maglev line is small and slow, and the way to conduct long-term, stable and accurate measurement has always been a difficult concern for the industry.

For another example, in order to realize more function at fast online inspection, more inspection equipment and sensors need to be arranged on the maglev train. Whether it is the existing commercial train or the future higher speed maglev train, the arrangement space both at bogie and inside the carbody are very compact, so how to utilize the remaining space of the existing train bogie for the effective arrangement of track inspection equipment is also a challenge.

In addition, the radio transmission environment along the maglev is becoming increasingly complex as a variety of equipment with wireless transmission devices and high-power frequency converters are being used. The developing automatic measurement systems based on wireless transmission will also have to face the challenge of more radio interferences.

5 Future Direction

While presenting new challenges for track inspection technology, the experience of operation and maintenance from existing maglev lines, the introduction of new technologies and the development of new high-speed maglev systems with 600km/h or even higher speeds also provide new ideas for the development of track deviation inspection technology.

The future direction of the development of guideway inspection technology will be surrounded with the developing of intelligent track construction and maintenance system throughout the entire life cycle of the guideway. Including:

During the construction stage, building a database for the guideway and a digital twin system for the entire line through intelligent high-precision measurement; during the operation and maintenance stage, obtaining the maintenance data through the combination of online fast inspection, unmanned automatic monitoring and manual inspection at key positions, intelligently generating technical solutions to guide the track maintenance through AI or big data platforms, and finally automatically assessing the effectiveness of the guideway maintenance through post-measurements.

For guideway deviation measurement equipment, an independent, modular and systematic design should be adopted: minimizing the dependence of track inspection equipment on external auxiliary devices and sensors through smarter algorithms, enabling more inspection functions and higher inspection and locating efficiency through its own sensor arrangement, achieving better functionality and field maintainability through modularized system architecture design, etc. will be the future direction of development.

6 Concluding Remarks

Through the continuous improvement of guideway deviation measurement technology to meet the needs of controlling and maintaining the deviation for the guideway at all stages in the past twenty-three years, NMTC developed a series of guideway deviation measurement technologies including contactless sensor technology for deviation measuring; SWD measuring technology for construction; LWD fast measuring technology for daily inspection; online automatic control technology and offline guideway inspection data locating technology for SWD and LWD inspection; guideway evaluation technology for guideway maintenance; and intelligent guideway monitoring technology for long-term unmanned remote guideway monitoring. With these technologies, NMTC not only improves the measuring efficiency and maintenance accuracy of the guideway, but also prepares the technical reserves for future higher speed (like 600km/h class) maglev systems and projects. Powered by new technologies and driven by data, maglev guideway deviation measurement technology is developing constantly into the future.

Acknowledgements

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