Research and Development of Maglev and Application of Related Technologies to Conventional Railways

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This paper presents recent findings from RTRI regarding the development of fundamental technologies for maglev (magnetic levitation) and the application of maglev technology to the conventional railway system. This paper also introduces the latest developments regarding the future use of maglev, information reported at WCRR2019, and related news from and outside Japan.

Key words: maglev, conventional railway, high-temperature superconducting magnet, ground coil, condition monitoring, rail brake

1. Introduction

The development of superconducting maglev technology has been promoted based on a Master-plan for Superconductive Maglev Technological Development, jointly drafted by the Central Japan Railway Company (“JR Central”) and RTRI, in response to a circular issued in 1990 by the then Minister of Transport. RTRI’s “Master plan – Research and Development Creating the Future of Railways – RESEARCH 2025 [1],” which started in FY2020, states that “R&D of superconducting maglev will be conducted as research activities while focusing mainly on the ongoing application of technologies such as superconductors and linear motors to conventional railways. At the same time, R&D for maintaining necessary technological capabilities will be conducted as fundamental research.”

The following sections describe trends in research and development related to maglevs worldwide. In the second half, we will mainly introduce RTRI’s basic research on maglev and its application to the conventional railway.

2. Recent trends in maglev-related research

2.1 Presentations at the World Congress on Railway Research (WCRR)

RTRI held the 12th World Congress on Railway Research WCRR 2019 at the Tokyo International Forum over five days from October 20, 2019 [2]. The WCRR was established to overview the state of railway technological development worldwide and discuss the future direction of work. It is the world’s largest international conference on railway research. This time, it was held in Japan for the first time in 20 years and welcomed 424 participants from 37 different countries and 569 participants from Japan. Details of the conference were published in RTRI’s bulletin Ascent [3]. In addition, the maglev-related presentations were made in the “Maglev and Other Fixed Guideway Transport” session out of the eight organized sessions and in the “Maglev and Rolling Stock” interactive poster session. The contents of these events are briefly described below.

2.1.1 Organized session, “Maglev and Other Fixed Guideway Transport”

One of the authors of this paper chaired this session. We invited two speakers from Japan to overview the current state of Japanese maglev-related work, a speaker from Germany also made a presentation to describe the application of high-temperature superconductors to maglevs, and a speaker from Spain described the Hyperloop, which has recently become a major topic of discussion. Hyperloop is a high-speed transportation system concept that started with a proposal by the American businessman Elon Musk, in which a train runs in a vacuum or decompression tube in order to reduce running resistance, aiming for a maximum speed of 1,200 km/h. Several companies are developing this system.

At the beginning of the session, Professor Osaki of the University of Tokyo gave a lecture entitled “Linear Motor Powered Urban Transportation in Japan.” Professor Osaki reviewed the technology and results of the commercial operation of the Linimo (Japanese medium-low speed maglev on Aichi Rapid Transit Eastern Hill Line) and the Linear Metro subway (a non-maglev system that uses a linear motor). According to Prof. Osaki, these linear motor-driven urban transportation systems have the advantage of offering smooth operation whilst being economical, environmentally friendly, and providing good ride comfort. He added that considering the declining birthrates/aging population issues and global environmental issues in the future, it is important to improve these systems and encourage the spread of their use worldwide [4].

In a lecture entitled “Progress of the Superconducting Maglev Chuo Shinkansen,” Dr. Kitano of JR Central gave updates regarding the technology, including on progress in the construction of the Chuo Shinkansen project by the Superconducting Maglev (SC-MAGLEV), long-term durability of high-temperature superconducting magnets, wireless power supply systems for on-board power supply, research on passenger comfort, and new vehicle models [5].

In a lecture entitled “Maglev Ground Transportation with High-Temperature Super-conductors (HTS),” Dr. Werfel of ATZ in Germany began a technical discussion on two types of maglev technology: normal conducting maglev “Transrapid” which was developed in Germany and put to practical use in Shanghai, and the superconducting maglev “SCMAGLEV,” developed in Japan. Dr. Werfel also talked about the advantages and development challenges of replacing low-temperature superconducting magnets with high-temperature ones in maglev, high-temperature superconducting magnets using Bi2223 high-temperature superconducting wire developed by JR Central, and high-temperature superconducting magnets using REBCO (rare-earth-based) high-temperature superconducting wire, being developed by RTRI. Finally, Dr. Werfel in-
introduced a system for developing a demonstration vehicle equipped with a high-temperature superconducting bulk cooled with liquid nitrogen on a track with permanent magnets. In this system, the magnetic field generated by the permanent magnet track is trapped by the high-temperature superconducting bulk, thereby enabling it to levitate stably regardless of the vehicle’s running speed. After the first test carrying passengers was conducted on this type of maglev train in Chengdu, China, in 2000, similar demonstration experiments have been conducted as “SupraTrans” in Dresden, Germany, and as “Maglev Cobra” in Rio de Janeiro, Brazil. In addition, in China, they are studying a system that enables high-speed transportation of cargo by running this system inside a decompression tube. He noted that most demonstration experiments of this sort used high-temperature superconducting bulk vacuum vessels designed by ATZ [6].

A representative of a Hyperloop developer, Zeleros, from Spain, gave a lecture entitled “Optimal characteristics of an evacuated-tube high-speed Hyperloop maglev (hyperloop) transport system for long distance travel.” Like other presentations about the Hyperloop, the principle of levitated propulsion of the system was not covered. However, the speaker explained that 10 kPa (0.1 atm) was appropriate for the pressure inside the tube, considering the safety of passengers and the cost of infrastructure. This lecture also made comparisons with aircraft and railways showing predicted Hyperloop energy consumption, travel times between specific destinations, and so on [7].

This session also included a presentation entitled “Condition Monitoring System for Ground Coils of Superconducting Maglev using Opportunistic Communications and Wake-up Receivers,” presented by a researcher from RTRI. It reported the development and experimental verification of a condition monitoring method that efficiently evaluates a huge number of ground coils of superconducting maglev trains by using opportunistic communications [8].

The last presentation, “Development of a Superconducting Magnetic Bearing Capable of Supporting Large Loads in a Flywheel Energy Storage System for Railway Applications,” was also made by an RTRI researcher. A report on a power storage system applies a refrigerator using solid nitrogen (SN2), which has a high specific heat, as a heat capacity medium. This may be based on RTRI’s previous presentation [9].

### 2.1.2 Interactive poster session “Maglev and Rolling Stock”

This session included two presentations from China regarding decompression tube transportation.

“Study on aerodynamics of ultra-high-speed train for tube transportation,” presented by the China Academy of Railway Sciences, adopted a typical high-speed railway vehicle as an analytical model instead of necessarily a maglev. It presented the numerical analysis of the relationship between tube cross-sectional shape, vehicle/tunnel cross-sectional area ratio, the pressure inside the tube, and aerodynamic drag [10].

“The Heat Generation Condition of High Temperature Superconducting Maglev in the Evacuated Tube,” presented by CRRC Corporation Limited, reported on results of a numerical analysis of the temperature distribution inside the tube and that around the maglev vehicle running inside it. The vehicle and guideway diagrams in the paper closely resembled the structure of a normal maglev Transrapid type. Details remained unknown because the content of the presentation did not explain the high-temperature superconducting magnet, which was included in the title [11].

This session included a presentation entitled “Development of High Temperature Superconducting Magnets Using REBCO Coated Conductors for Maglev,” which reported RTRI’s development of high-temperature superconducting magnets. This presentation will be described later in the paper [12].

### 2.2 Trends in China

Since China launched the world’s first commercially operated high-speed maglev line, the Shanghai Maglev could run at 430 km/h in Shanghai in 2002, other maglev operations have followed. For example, medium- and low-speed maglev technology is used for the Changsha Maglev Express, which started operations in 2016, and Line S1 of the Beijing Subway in 2017.

China is now developing a 600 km/h high-speed maglev, mainly by CRRC. Completing a test car for this maglev was reported in 2019, and a successful test run of the test vehicle was reported in June 2020. However, the success of the test run was only a verification of the levitated running, not a verification of the 600 km/h running speed.

These reports suggest that the system consists of a combination of the normal conducting “Transrapid type” maglev (put into practical use in Shanghai) and permanent magnets, from the track structure and vehicle shape: this may be motivated by an idea to reduce energy consumption and temperature rise and reduce the weight of normal electromagnets.

Meanwhile, CRRC and Shanghai Jiao Tong University are developing a high-temperature superconducting magnet for maglev. It is a high-temperature superconducting magnet using REBCO wire. They aim to develop a magnet operable for a certain period without a refrigerator using solid nitrogen (SN2), which has a high specific heat, as a heat capacity medium. This may be based on RTRI’s previous development examples [13]. China also has a development plan for a maglev aiming for a maximum speed of 4,000 km/h by China Aerospace Science and Industry Corporation (CASIC). Information presented to date suggests that it would use superconducting magnets and decompression tubes. However, details are unclear regarding how this plan relates to the research and development for Chengdu, presented in Dr. Werfel’s lecture mentioned in Section 2.1.1. In 2020, the regularly held International Conference on MAGLEV (MAGLEV 2020) was scheduled to be organized in Changsha City, China, but was postponed to 2021 due to the COVID-19 pandemic. The situation in China is expected to be clarified at this congress [14]. Another unexpected development was the announcement after the peak of COVID-19 in China by the Zhejiang Provincial Government on April 17, 2020, to build a maglev connecting Shanghai to Ningbo via Hangzhou (the capital of Zhejiang Province). Although this line would be about 400 kilometers long, it is thought to be an infrastructure project to support the economy following its sharp slowdown due to COVID-19.

### 3. RTRI’s basic research on maglev and its application to conventional railway

Figure 1 shows RTRI’s basic research on maglev and research on its application to the conventional railway. We are trying to transfer as much as possible of the technological findings obtained by developing the superconducting maglev to technology applicable to the conventional railways. They are described after the arrows in Fig. 1.

#### 3.1 Basic research on maglev

At present, in basic research we are focusing mostly on the de-
development of ground coil condition monitoring technology and high-temperature superconducting magnets. Condition monitoring of ground coils research puts emphasis mainly on the development of partial discharge detection technology. There are two types of ground coil for maglevs: levitation/guidance coils used for levitation and guidance of vehicles, and propulsion coils used for propulsion of vehicles. When a vehicle passes through a propulsion coil, it experiences an induced high-voltage pulse, and it may result in partial discharge as a sign of insulation abnormality. Focusing on this, we are studying and verifying a method for efficient insulation diagnosis. A paper in the RTRI Report, “Method for Detecting Partial Discharge of Ground Coil from the Vehicle,” presents the results of running verification tests and detection tests using test vehicles on the Miyazaki maglev test track [15].

As mentioned above, the development of high-temperature superconducting magnets for maglevs seems to have also started in China; however, RTRI has been paying attention to rare-earth-based high-temperature superconducting wires, which are expected to have a high critical current density in magnetic fields and low cost, from an early stage and has been intensively researching and developing this application. Before the above research in China, RTRI made a prototype of a high-temperature superconducting magnet operable without a refrigerator [16], followed by introducing of a superconducting coil winding machine, and started full-scale development. As a result, we devised RTRI’s original method using thermoplastic resin for coil molding after winding and repeated evaluation tests to establish a coil manufacturing method without performance deterioration. Using this technology, we have completed a high-temperature superconducting coil with the same size and performance (magnetomotive force) as an actual machine. We have recently completed a superconducting magnet with this coil built-in and conducted an electromagnetic vibration test of the ground coil reported in “Electromagnetic Vibration Test of a Ground Coil Using a REBCO Magnet,” also published in this issue [17].

3.2 Research on application of maglev technology to conventional railways

In applied research, we are developing a heat pump that uses the principle called the magnetocaloric effect. This method uses the property of absorbing and exhausting heat (i.e., magnetocaloric effect) when a specific substance undergoes a change in the magnetic field. Unlike vapor-compression refrigeration, which is the primary method for current cooling systems, it uses no alternative CFCs (greenhouse gases) or other similar things and is expected to be highly efficient. As a consequence, it has garnered significant attention from around the world. Furthermore, this research applies the technologies cultivated in the development of the maglev, such as magnetic field control and refrigeration technologies. We have manufactured a prototype with a built-in ring Halbach-array magnet circuit already proposed by RTRI and have achieved Japan’s largest capacity of 1 kW (at room temperature) as a magnetic heat pump. Meanwhile, a practical air conditioning technology has to secure the operating temperature range and be capable of refrigeration. “Extension of Operational Temperature Range on Magnetic Heat Pump Aimed at Application on Onboard Air-conditioner,” which appears in the RTRI Report, presents the results of experiments aimed at increasing the operating temperature range by devising the magnetic material that is the source of the magnetocaloric effect [18].

We are also considering ways to utilize linear motors for deceleration rather than acceleration. This linear motor type rail brake has the feature of being able to suppress increases in rail temperature, which is a problem on conventional eddy current type rail brakes. This brake can regenerate a part of the vehicle’s kinetic energy as electric power by a linear motor (linear armature mounted on the vehicle). Energy is consumed by both the rails and the vehicle, making it possible to suppress a temperature rise in a rail by the amount of energy consumed in the vehicle. Another feature of this brake is that the regenerative energy can be used as the power source for the brake system. Thus the power to the brake can be secured even in an emergency such as a power outage, which is helpful as an emergency brake.

To put the brake into practical use as a safety device, it must have a condition monitoring method to self-diagnose malfunctions in addition to essential functions and performance. For example, in armatures, it is necessary to know the gap between the armature and the rails. “State Monitoring Method for a Linear-Motor-Type Rail Brake Using an Excitation Inverter,” a paper in the RTRI Report, reports on a method for estimating the size of this gap by utilizing the inverters that make up the system instead of adding any special equipment [19].

“Development of Condition Monitoring System for Railway Facilities Using Low Power Wide Area Wireless Communication Network,” a paper in the RTRI Report, presents an effort to make wireless technology (available for ground coil condition monitoring of maglevs) more widely used for condition-based maintenance (CBM) of the railway infrastructure [20]. We consider it a valuable technology for the future, where labor-saving and efficiency are required due to the decrease in the working population and the spread of COVID-19.

“Development of the Magneto-Optical Probe for Environmental Magnetic Fields Measurement,” a paper in the RTRI Report, presents the development of a magneto-optical probe that can measure different fields from a DC magnetic field to an AC magnetic field [21]. The magneto-optical probe uses the Faraday effect to measure the environmental magnetic field. In 2018, a magneto-optical material exhibited a giant Faraday effect 40 times that of the conventional material found in this field [22]. Further performance improvement can be expected by applying it.

In addition, as shown in Fig. 1, efforts are being made to apply high-temperature superconducting magnet technology to flywheel energy storage systems for the railway to prevent regeneration disabled. We are also working on the development of wireless power

**Fig. 1 Outline of basic research on maglev and research on its application to the conventional railway at RTRI**

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supply technology for trains. This technology makes it possible to reduce the amount of battery installed in the battery train [23].

4. Conclusion

This paper reported recent research trends related to maglev, focusing on presentations made at the WCRR 2019 and studies currently underway at RTRI. It also described trends in China, where maglev R&D has been active recently. In China, research projects on different contents are concurrently underway in various places, but we will continue to pay close attention to them as much as possible.

The Maglev Systems Technology Division, established in 2005 following the dissolution of the Maglev Systems Development Department, has entered its 16th year. Although in 2020, our R&D activities were affected by COVID-19, we believe that the nature of R&D underway at RTRI will become increasingly necessary in the current context, and we will continue to steadily accumulate research results.

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