Research and Development Concerning Superconducting Maglev and Research on Applying Its Technology to Conventional Railways System

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RTRI is advancing fundamental research and development into superconducting maglev. Topics covered include characteristics of maglev vehicle dynamics, experimental production, and evaluation of REBCO high-temperature superconducting coils. RTRI is also promoting research on the application of maglev technology to conventional railways system. Examined issues include contactless power supply systems for railway vehicles and flywheel energy storage systems.

Keywords: maglev, superconducting maglev, conventional railway, superconducting magnet, ground coil

1. Introduction

On April 15, 2015, RTRI announced the completion of the development of a superconducting flywheel energy storage system test machine as an application of levitation railway technology to conventional railways. The development had been pursued jointly with Kubotek Corporation, Furukawa Electric Co., Ltd., Mirapro Co., Ltd. and the Public Enterprise Bureau of Yamanashi Prefecture, and supported by the New Energy and Industrial Technology Development Organization (NEDO) [1]. This was a significant achievement which came 10 years after RTRI started related research on such a system in FY2005.

Earlier in 2014, contactless power supply technology for railway vehicles, another research application to conventional railways, was verified as feasible in the experiments conducted on RTRI premises using a test railway vehicle (R291), in which the railway vehicle was successfully fed electric power while it was stopped as well as running, the first success of its kind in Japan.

Along with these activities, RTRI has been advancing basic research on levitation railways as part of the Master plan for Superconducting Maglev Technological Development approved by the Minister of Land, Infrastructure, Transport and Tourism, in such areas as vehicle dynamics simulation, use of high temperature superconducting material for superconducting magnets and ground coils.

This paper discusses the following subjects: the process for the development of the superconducting flywheel energy storage system, the current status of research on the application of levitation railway technology to conventional railways and some of the latest achievements in basic research on levitation railway.

2. Research on the application of levitation railway technology to conventional railways

2.1 Process for the development of the superconducting flywheel energy storage system

In 2005, RTRI started full-scale research on the application of levitation railway technology to conventional railways. Following a review of the essential roles and characteristics of superconducting magnets in levitation railway systems, research subjects were selected including; linear rail braking in the field of linear motor technology, and superconducting flywheel energy storage systems in the field of superconducting technology.

As shown in Fig. 1, superconducting magnets can be used to levitate, propel and guide heavy objects (such as railway vehicles), thereby allowing them to travel in contactless fashion and at high speed. Discussion on how to put these principles to practical use led to an idea that the heavy flywheel rotor of a flywheel energy storage system, an effective solution to cancelled regeneration, can be lifted and run at high speed, with no contact and with minimal loss by using superconducting coils in the bearing of the system. Back then, basic research was underway on the possibility of using REBCO high temperature superconducting coils for the next-generation on-board superconducting magnets in levitation railway. It was thought that if REBCO high temperature superconducting coils were to be used for the flywheel’s magnetic bearing, knowledge and experience could be shared between the two fields of research in a mutually beneficial manner.

With the finding in 1986 of high temperature super-
conductive materials, avid development started worldwide of superconducting flywheel energy storage systems with superconducting magnetic bearings. Nearly all of these systems used permanent magnets in the rotor and liquid nitrogen-cooled superconducting bulk material in the stator. With that design, the performance (bearing capacity) of the superconducting magnetic bearing was determined by the performance of the permanent magnet, which prevented the use of the full potential of superconducting bulk material and resulted in low electromagnetic-force density. To overcome this drawback, multiple pieces of superconducting bulk material and permanent magnets were needed to secure necessary levels of electromagnetic force.

RTRI pursued its own development of a superconducting flywheel energy storage system, using superconducting coils, which generate more powerful magnetic fields, instead of permanent magnets forming a combination with superconducting bulk material. With this design, the electromagnetic-force density increases as the square of magnetic flux density, making it possible to secure sufficient electromagnetic-force density with fewer pieces of superconducting bulk material. As it was difficult to use superconducting coils in the rotor, superconducting bulk material was used in the rotor while superconducting coils were used in the stator, as shown in Fig. 2.

To verify that concept of the superconducting magnetic bearing, experiments were conducted. It was found that a combination of superconducting bulk material pieces and superconducting coils substantially increased electromagnetic force density as had been envisioned.

Both the stator and rotor of the superconducting magnetic bearing needed to be cooled as they were both made of superconducting material. To accommodate that requirement on the first test machine, the superconducting bulk material pieces on the rotor were cooled with liquid nitrogen to 77 K while the liquid nitrogen reservoir was integrated into the flywheel shaft. To help minimize cost, low temperature superconducting NbTi was used as the coils on the stator, which was cooled to 4 K by a refrigerator. Experiments found that the first test machine was capable of running at a maximum speed of 3600 min⁻¹ while supporting a 2000 kg flywheel.

That said, putting the design, i.e. storing liquid nitrogen into the shaft of the flywheel while it is running for extended periods, is not practical. To overcome this hurdle, the following idea, also outlined in Fig. 1, was studied. That is, the superconducting coils on the stator are conduct cooled with a refrigerator while the levitated superconducting bulk material pieces are cooled by means of molecular gas conduction via the coils. Subsequent experiment and analysis produced the results shown in Fig. 3. While results can vary depending on the size of the experimental device used, Fig. 3 indicates that the measured thermal conductivity agreed with the theoretical radiant heat transmission values when the pressure of helium gas used was below 10³ Pa; and that the measured thermal conductivity agreed with the much higher theoretical molecular conduction values when the helium gas pressure was above 10 Pa. It was also found that the aerodynamic loss (frictional resistance), which was created as the flywheel ran in the environment where the superconducting bulk material pieces and coils and helium gas were all put together, started increasing rapidly at 10⁵ Pa. Consequently, it was thought that using thin helium gas of around 10 Pa would create minimal aerodynamic loss for the flywheel while offering substantially increased thermal conductivity over negative pressure helium gas for the superconducting bulk material pieces.

The findings described above were reflected on the next test machine, a smaller version than the first test machine, where high temperature superconducting coils were used while the superconducting bulk material pieces on the rotor were cooled indirectly by means of helium gas. Bismuth high temperature superconducting coils were used instead of REBCO high temperature superconducting coils, which at that time were still difficult to obtain and manufacture. The test machine proved effective in cooling the thin helium gas used as well as successfully levitating and turning the rotor without contact. Subsequent full-scale load and speed testing of a superconducting magnetic bearing using bismuth high temperature superconducting wire coils confirmed a range of matters being studied, including the question of whether the bearing was capable of supporting a maximum load of 60 kN. The series of activities described thus far formed part of the basic research conducted into superconducting magnetic bearings, subsidized by the Min-
industry of Land, Infrastructure, Transport and Tourism.

Today, work continues under the project “safe and low cost, large scale power storage systems technology development” sponsored by the New Energy and Industrial Technology Development Organization (NEDO), with the participation of Kubotek Corporation, Furukawa Electric Co., Ltd., Mirapro Co., Ltd., the Public Enterprise Bureau of Yamanashi Prefecture and RTRI, which has been coordinating not only the development of a superconducting magnetic bearing but of an entire flywheel energy storage system. On April 15, 2015, the completion of a superconducting flywheel energy storage system test machine, shown in Fig. 4, was announced [1]. The superconducting coils of the magnetic bearing were provided by Furukawa Electric, a manufacturer of REBCO high temperature superconducting wire. For the first time, REBCO wire was used for the coils, as had been envisioned since the start of the development program. The completed system is now much closer to the one depicted in Fig. 1.

![Image](image_url)

**Fig. 4 Superconducting flywheel energy storage system test machine**

2.2 Development of magnetic heat pump and contactless power supply technologies

In addition to the superconducting flywheel energy storage system described above for application to conventional railways, the November 2015 issue of RTRI REPORT features the development of a magnetic heat pump and contactless power supply technologies.

The concept of magnetic circuits used for magnetic heat pump technology was derived from a study on the refrigeration system for superconducting magnets for levitation railways, a kW-class magnetic heat pump system of a refrigeration system for superconducting magnets, is covered by the report “Improvement of Sensitivity at the Cryogenic Temperature of the Optical Fiber Sensor and Its Durability Evaluation” in the November 2015 issue of RTRI REPORT. The report describes power supply experiments conducted on a test track in RTRI premises in which power was transmitted as well as a train run battery charged while the train was both stopped and running, the first trial of its kind in Japan. The experiments went successfully, thereby verifying that contactless power supply systems can be used as a power source for railway vehicles and that on-board power supply systems from levitation railways can also be applied to contactless power supply systems. RTRI’s exclusive figure-8 shaped coil concept reduces magnetic field leakage and does not require ferrite cores on power supply coils on the ground, only requiring the installation of 4-line cables.

![Diagram](image_url)

3. Basic research on levitation railway

The three key areas of RTRI’s basic research on levitation railways are: vehicle dynamics simulation, research on the application of high temperature superconducting material to onboard superconducting magnets and ground coils diagnostics. Many of the reports in the November 2015 issue of RTRI REPORT relate to high-temperature superconducting magnets, like the one shown in Fig. 5.

One of the key areas, research on the application of high-temperature superconducting material to on-board superconducting magnets, is covered by the report “Experimental Production and Evaluation of Racetrack Coils for On-board REBCO Magnets” in the November 2015 issue of RTRI REPORT. The report describes the manufacturing of element coils for full-scale high-temperature superconducting magnets using REBCO high-temperature superconducting wire. Experiments showed that the coils manufactured using RTRI’s expertise permanently retain their original conducting performance. The RTRI’s original method for manufacturing REBCO high-temperature superconducting coils can be applicable to the superconducting flywheel energy storage system that also uses REBCO high-temperature superconducting coils, thus offering the possibility to cut manufacturing costs for superconducting coils. If that were possible, that would offer mutual benefits from shared knowledge and experience, as mentioned in Fig. 1.

The report, “Improvement of Sensitivity at the Cryogenic Temperature of the Optical Fiber Sensor and Its Durability Evaluation” in the November 2015 issue of RTRI REPORT, describes the development of fiber optical temperature sensors. Cooling high-temperature superconducting magnets by means of conduction cooling with a refrigerator, not of liquid refrigerant, provides benefits in terms
of handling. With conduction cooling, however, maintaining magnets at the same temperature is not possible whereas it is possible with the boiling of liquid refrigerant.

As a temperature difference is created around superconducting coils, conduction cooling requires the monitoring of temperature distribution. Resistance thermometers (temperature sensors), which are normally used in cryogenic temperature environments, require four wires per bulb for measurement. If multiple bulbs are used, numerous wires that are required for those bulbs can effuse considerable heat. On the other hand, a single fiber optical temperature sensor is capable of multipoint measurement with a single optical fiber, and the fiber has low thermal conductivity and therefore low heat effusion. Fiber optical temperature sensors are also immune to electromagnetic noise and offer further benefits. Against this background, RTRI has been working on the development of fiber optical temperature sensors that appear suitable for measuring the temperature distribution of superconducting coils.

Vehicle dynamic simulation is discussed in the report “Characteristics of Maglev Vehicle Dynamics Considering Cars with On-board REBCO SCMs” in the November 2015 issue of RTRI REPORT. In the report, vehicle dynamics are simulated with numerical calculations for vehicles with on-board REBCO high-temperature superconducting magnets that are known to contribute to downsizing and weight reduction, and a quantitative evaluation was made of the related benefits for vehicles. In addition, the report looks at high-temperature superconducting magnets that are reduced in size through the simplification of the heat insulation structure and obtained the electromagnetic and vehicle dynamics characteristics that result from reduced magnetomotive force. The results indicate that it is possible to reduce magnetomotive force while at the same time having the same characteristics as conventional vehicles.

Ground coil diagnostics are discussed in the report “Development of Efficient Contactless Insulation Diagnosis for the Propulsion Coil of the Superconducting Maglev” in the November 2015 issue of RTRI REPORT. In the diagnostics being developed, a running levitated vehicle measures ground propulsion coils for partial discharge-caused electromagnetic noise, which is typically generated by coils with reduced insulation performance. The early detection data thus obtained is utilized to efficiently maintain failing coils. Following related trials including the one conducted on the Miyazaki Maglev Test Track, an insulation diagnostics system with automatic diagnosis and recording of partial discharge is now being built.

4. Conclusion

As part of our research on the application of levitation railway technology to conventional railways, a superconducting flywheel energy storage system test machine was developed jointly with external organizations under the NEDO program. The test machine uses REBCO high-temperature superconducting coils for the magnetic bearing. From now on, a series of verification tests will be conducted at a large-scale photovoltaic power plant in Komekurayama, Yamanashi Prefecture. As part of the ongoing development of contactless power supply technology, power supply tests are being conducted on a test track at RTRI.

REBCO high-temperature superconducting magnets are also the subject of ongoing basic research on levitation railways. The program has reached the stage where full-scale REBCO high-temperature superconducting coils are being manufactured. Besides the physical aspect of the program, simulation of vehicle dynamics, involving on-board magnets, is being pursued within different research bodies in various related fields.

Building on this expertise and external inputs, basic research will be actively pursued into levitation railways and the application of its fruits to conventional railways, and the results will be shared for efficient progress in research and development.

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References

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