

Development of new-type superconducting magnets for the Superconducting Maglev

Yoichi Nishikawa & Motohiro Igarashi & Shigehisa Kusada

Maglev System Development Division, Central Japan Railway Company, Tokyo, Japan

ABSTRACT: Superconducting magnet (SCM) and the on-board refrigeration system (REF) are the core technologies for the Superconducting Maglev. Several types of SCMs and REFs had been developed so that their performance and characteristics could be compared. Based on data obtained from test runs and daily maintenance, their characteristics were analyzed and their advantages were integrated. Consequently, a new type SCM and REF were designed under the unified specifications. Following trial production and bench tests, the new-type SCMs and REFs were introduced to the test vehicles. Test runs and daily maintenance proved their remarkable performance at which we had aimed. In addition, JR Central has developed an innovative SCM, which consists of coils made of high temperature superconductors.

1 INTRODUCTION

Test runs of the Superconducting Maglev were started in April 1997 on the Yamanashi Maglev Test Line (the Test Line). The tests have been progressed successfully for ten years. Two world records were recorded, the maximum speed of 581 km/h by one trainset and the maximum relative speed of 1,026 km/h by two trainsets. Also, a daily running distance of over 2,800 km was achieved. No test ride events have been cancelled since its start in 1998. At the end of April 2006, the cumulative number of test ride passengers exceeded 110,000 and the total test running distance reached 510,000 km.

In March 2005, the Practicality Evaluation Committee under the Ministry of Land, Infrastructure and Transport concluded that all technologies for the Superconducting Maglev for future revenue services had been established. The committee also recommended that consecutive test runs should be conducted to verify its durability and to upgrade the total system.

Since April 2005, test runs have been carried out on the Test Line to verify the longer-term durability. We have continued to make efforts at research and development to enhance the quality of the technologies. Especially, we have endeavored to upgrade the SCMs and ground coils (levitation-guidance coils and propulsion coils) since they are the core technologies peculiar to the Superconducting Maglev system.

2 FUNCTION AND STRUCTURE OF THE SCM

2.1 Functions

A function of the SCM for the Superconducting Maglev is equivalent to that of a combination of a pair of wheels and a rotor of a traction motor for the conventional railway vehicles. Accordingly, the SCM is recognized as one of the essential components for the Superconducting Maglev system. The vehicle is levitated and guided by electromagnetic forces between the SCMs and the levitation-guidance coils on the guideway, and is propelled and braked by a linear synchronous motor, which is composed of the SCMs and the propulsion coils on the guideway.

Thus, the SCM has fundamental and important functions of levitation, guidance, propulsion and braking, which suggests that the stable performance is required for the SCM.

2.2 Structure of the SCM

Figure 1 shows the schematic view of the SCM. Superconducting coils made of niobium titanium (NbTi) wires are wound in a racetrack configuration, and the intensive magnetic field is generated in a persistent current mode. NbTi wires are widely used for superconductivity-applied equipments, such as a magnetic resonance imaging (MRI) for medical treatment. The superconducting coil is installed in a component called 'inner vessel' and cooled down by

liquid helium, namely, pool cooling, at a temperature of 4.2 K.

Inner vessels are covered by a radiation shield plate, which is cooled down by liquid nitrogen at 77 K. The inner vessels are insulated by the radiation shield plate from radiant heat from the outside.

The radiation shield plate is covered by a vacuum vessel, called 'outer vessel'. High vacuum performance is realized within the outer vessel so that heat like convection is not transferred to inner vessels from the outside.

Forces loaded on the superconducting coils, that is, levitation, guidance, propulsion and braking forces, are transferred to the outer vessel by support components, called 'heat insulated supports', and then to the truck on which the SCM is fixed. 'Heat insulated' means that the supports hold a variety of forces without transferring heat from the outside.

Storage tanks for liquid helium and liquid nitrogen are installed on the outer vessel to supply liquid helium for the inner vessels and liquid nitrogen for the radiation shield plate. Helium and nitrogen evaporated by heat generation during the vehicle's running are re-liquefied by REFs, which are equipped on the end of each tank. The feature of this system is that the supply of the liquids from the outside is not required for years.

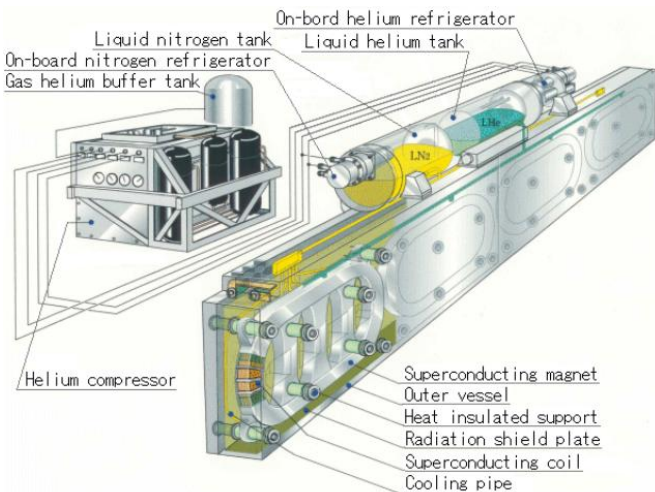


Figure 1: The schematic view of the SCM

3 INITIAL SCMS FOR YAMANASHI MAGLEV TEST VEHICLE

3.1 Important items to develop the SCM for Superconducting Maglev

The equipments to which the superconducting technologies are applied, MRI, for example, are usually used in static circumstances. However, the SCMs for the Superconducting Maglev are operated under severe mechanical or electromagnetic vibrations caused by various forces produced when the vehicle

is running. This shows that severer specifications are required for the SCM than general superconducting equipments.

The significant technological items to be solved were to improve anti-quenching durability and to diminish heat generation, while satisfying the basic specifications for the SCM, such as 'lightweight' and 'compact'.

In the beginnings of the construction of the Test Line, the causes of quenching or heat generation could not be made clear. Computational simulations had been introduced, and a number of trial products of inner vessels had been produced and tested practically. One of the causes assumed from the studies is given below.

The SCMs are exposed to the harmonic components of the magnetic field (harmonic magnetic field) from the ground coils when the vehicle is running. The harmonic magnetic field whose frequency is proportional to the vehicle's speed is caused by the discrete arrangement of the ground coils. The SCMs are vibrated electromagnetically by the harmonic magnetic field. The vibrations result in heat generation by friction or eddy current in or on the inner vessels. Fig. 2 illustrates a presumed process of heat generation.

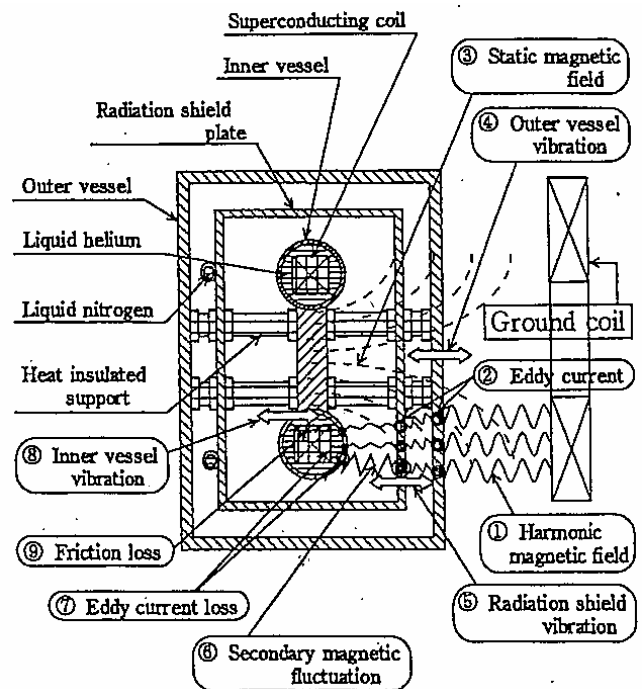


Figure 2: A presumed process of heat generation

When the harmonic magnetic field (1) from the ground coils penetrates the outer vessel or the radiation shield plate, it induces eddy current (2) on them. The interaction between the induced eddy current and the superconducting coil's intensive magnetic field (3) generates electromagnetic force on the outer vessel and the radiation shield plate. Thus, the outer vessel or the radiation shield plate vibrates

relatively to the inner vessels (4, 5). When these relative vibrations arise in the intensive magnetic field (3), secondary magnetic fluctuation is generated again (6), which induces eddy current on the inner vessel. In addition to this, the harmonic magnetic field, which is reduced on the outer vessel or the radiation shield plate, reaches the inner vessel. It generates the eddy current (7) on the inner vessel to heat it. On the other hand, inner vessel's vibration (8) caused by electromagnetic force generates the frictional heat between the inner vessel and the superconducting coil (9).

Based on the assumption, studies for the solution, trial production, tests and evaluations had been conducted. Thus, the SCMs for Superconducting Maglev, which achieved the improved anti-quenching performance and the suppression of heat generation, had successfully been developed.

At the same time, the REFs for the Superconducting Maglev had also been developed, which had marginal refrigerant performance against the overall heat load. The overall heat load is defined as the sum of heat load and static heat leak. Heat load means the quantity of heat generation when the vehicle is running. Static heat leak means the quantity of heat transferred into the SCM constantly by conduction and radiation from the outside.

3.2 Initial SCMs for Yamanashi Maglev Test Vehicle

Initial SCMs and REFs for Yamanashi Maglev test vehicles, what we call 'initial SCM', had been designed and produced in consequence of the above-mentioned developments. Table 1 shows the main specifications of the initial SCM.

Table 1: The main specifications for the initial SCM

| |
|--|
| Dimension: 5.4m (length) × 1.17m (height) |
| Weight: 1,400kg or less |
| Magnetomotive force: 700kA |
| Levitation force: 231kN per two SCMs |
| Static heat leak: 5W |
| Overall heat load: 8W or less under the condition of double-layered propulsion coils |
| Refrigerant capacity: 8W or above |

On premise that the main dimension and the interface with other subsystems were unified, plural types of the components were adopted so that their performance could be compared. The following are the main examples.

3.2.1 Radiation shield plate

Two types were adopted. One was made of a high resistance material, based on the assumption that the vibration of the shield plate could not be cancelled completely. Even if the shield plate was vibrated, eddy current would not be induced on the high resis-

tance shield plate and therefore the generation of the secondary magnetic field would be suppressed.

The other was made of a low resistance material, which was adopted from a point of view that the harmonic magnetic field that arrives directly at the inner vessel should be reduced by the shield plate. In order not to vibrate the shield plate and the inner vessel relatively, the special structure was contrived.

3.2.2 On-board refrigeration system (REF)

Gifford-McMahon (GM) refrigerators and Stirling refrigerators were adopted. The former was a simple composition, which did not have many components. The latter had a higher refrigerant capacity, while its structure was rather complex.

Test runs of the initial SCMs were started in April 1997. In December 2003, they were operated at the speed of 581 km/h, exceeding the designed maximum speed of the Superconducting Maglev system. At the end of April 2006, the most cumulative running distance reached over 280,000 km. Since the start of the test runs, liquid helium had scarcely been supplied for the REFs. This implies that the initial SCMs and REFs stably showed expected performance.

4 DEVELOPMENT OF A NEW-TYPE SCM

4.1 Conceptions of development

Based on the results of the test runs, a new-type SCM had been developed so that superior performance could be realized. The conceptions of the development were the following:

4.1.1 Improved characteristics of the electromagnetic force

Owing to the addition of service equipments for future revenue services, the increase in the vehicle's weight was planned from 22 tons to 24 tons per vehicle. Also, in order to reduce maintenance costs, the landing speed of the vehicle should be lowered. To realize these items, electromagnetic performance needed to be improved.

The electromagnetic performance is closely related to the specifications of the ground coils and the SCMs. It was supposed to be a hard task to alter the specifications for the ground coils installed on the guideway. Accordingly, the specifications for the SCM installed on the vehicle were modified. Concretely, the electromagnetic performance was improved by increasing the magnetomotive force from 700 kA to 750 kA and by reducing the distance between the center of the cross section of the levitation-guidance coil and that of the SCM coil. This reduction was realized by diminishing the distance

between the center of the cross section of the SCM coil and the surface of the outer vessel.

4.1.2 SCMs suitable for single-layered propulsion coils

On the Test Line, the propulsion coils are arranged in double layers so that the influences of the harmonic magnetic field on the SCM from the propulsion coils can be reduced. However, high construction costs are required to place propulsion coils in double layers. Therefore, a plan to place them in a single layer was studied. In the plan, the number of the propulsion coils is decreased by half, which leads to cost reduction for manufacturing and installing the coils on the guideway. In this case, however, the SCM's performance would be unfavorably affected by the single-layered propulsion coils. In other words, vibrations of the SCM components and heat generation caused by vibrations would be increased. For this reason, the performance of the SCM needed to be improved against vibrations, and the new-type REF had also been developed to improve the refrigerant performance and to overcome the heat generation of the SCM.

4.1.3 Unification of the specifications

As mentioned before, several types of components were adopted in the initial SCMs to compare their performance. From the findings of the test runs, more efficient structures and more effective functions were selected, and the components were unified. The main reasons to unify the specifications were to simplify the handling for the operation and to reduce production costs as several manufacturers could supply each other with the components.

Table 2 shows the main specifications for the new-type SCM. The items in italic type show different ones from those of the initial SCM.

Table 2: The main specifications for the new-type SCM

| |
|--|
| Dimension: 5.4m (length) × 1.17m (height) |
| Weight: 1,400kg or less |
| <i>Magnetomotive force: 750kA</i> |
| <i>Levitation force: 251kN per two SCMs</i> |
| Static heat leak: 5W |
| <i>Overall heat load: 10W or less under the condition of single-layered propulsion coils</i> |
| <i>Refrigerant capacity: 10.5W or above</i> |

4.2 Examples of the unified specifications

Based on the conceptions of the development, the new-type SCM was designed. In this paper, some typical examples are shown.

4.2.1 Radiation shield plate

The high resistance material was selected. Test runs results revealed that there were no differences in

performance between high and low resistance shields was found.

In case of the single-layered propulsion coils, the interval of coil is twice as much as the double-layered coil. When the vehicle runs at the same speed, the frequency of the harmonic magnetic field from single-layered coils is half as much as double-layered coils. The quantity of the harmonic magnetic field that should be reduced on the outer vessel is rather decreased, and the quantity to reach the radiation shield plate is therefore increased. If the radiation shield plate were made of the low resistance material, more eddy current would be induced on the radiation shield plate, resulting in heating the shield plate more. To cool down the shield plate whose temperature is higher, the refrigerant capacity of the nitrogen refrigerator has to be increased. This is the reason why the high resistance shield plate was selected.

4.2.2 On-board refrigeration system (REF)

Theoretically, Stirling refrigerators are operated with higher refrigerant performance than GM refrigerators. The structure of the Stirling system is complex, while that of GM system is simple. These two types of REFs had been boarded on the initial SCMs and operated for 24 hours a day for several years. The results of the tests indicated that there was little difference in the refrigerant performance between the systems. However, the longer time was required for inspections and repairs of the Stirling system than the GM system. Considering that REFs and SCMs are not operated during the maintenance period, we reached the conclusion that the operational efficiency of the GM system is much better than the Stirling system, and finally the GM system was adopted for the new-type SCM.

Furthermore, the refrigerant capacity against the increased heat load in case of the single-layered propulsion coils had to be improved. To realize it, the compressor capacity was increased, compared with the initial SCM.

4.3 Running tests of the new-type SCMs

Based on the conceptions for development and the specifications, the new-type SCM was designed. After trial production and bench tests of basic components, such as inner vessels, and of a full-sized model SCM, the new-type SCMs had been produced. Test runs were started in November 2002. The main results are given below.

4.3.1 Characteristics of the electromagnetic forces

In case of the magnetomotive force of 700 kA, it was confirmed that the levitating characteristics of

the new-type SCM were almost the same as the initial SCM although the weight of the vehicle that installed the new-type SCMs was 2 tons heavier than the initial SCM-installed vehicle. Also, it was verified that the guiding characteristics were similar. These characteristics resulted from the reduction in the distance between the center of the cross section of the levitation-guidance coil and that of the new-type SCM coil.

Besides, when the new-type SCM was excited to the magnetomotive force of 750 kA, one of the specifications, the levitation and guidance characteristics were improved as expected. In particular, the landing speed of the vehicle that installed new-type SCMs, one of the significant conceptions for the new-type SCM development, was decreased by approximately 15 km/h, compared with the vehicle that installed the initial SCMs.

4.3.2 *Vibration characteristics of the new-type SCM*

The data obtained indicated that the acceleration of each component in the new-type SCMs was within 10 g under the condition that the vehicle's weight was 24 tons and the running speed was up to 550 km/h. The data also revealed that the acceleration was proportional to the vehicle's weight. Fig. 3 shows an example of the acceleration.

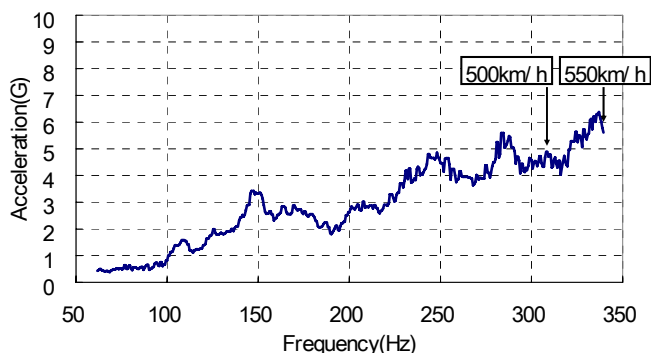


Figure 3: The acceleration of the new-type SCM

In addition to this, the acceleration of each component in the SCMs when the vehicle runs through the single-layered propulsion coils was measured. The data indicated that the specifications were satisfied.

4.3.3 *Characteristics of the REFs*

On one hand, helium refrigerators have maintained the stable refrigerant performance with no supply of liquid helium from the outside. This means that the non-helium-supplied operation have been realized even on condition that heat generation occurs when the new-type SCMs are magnetized or demagnetized and when the vehicle runs.

On the other hand, nitrogen refrigerators need to be supplied with liquid nitrogen from the outside only for a short period of time in summer, indicating that the refrigerant performance of the nitrogen refrigerator has to be improved.

For reasons mentioned above, the remarkable performance of the new-type SCM was verified. Particularly, it should be noted that both weights are almost the same although the new-type SCM's performance is superior to the initial SCM

4.4 *Development of the low-cost SCM*

The low-cost SCM whose performance was the same as and whose manufacturing cost was less than the new-type SCM had newly been designed.

After trial production and bench tests of basic components, such as inner vessels, and of a half-sized model SCM, the low-cost SCM was produced.

The following are the main items for cost reduction. First, the imported superconducting wires less expensive than domestic ones were adopted. Secondly, a low resistant and less expensive material of the inner vessel was developed. Thirdly, the production cost of the radiation shield plate was reduced by reviewing the production method.

Test runs using the low-cost SCM were started in March 2005. A speed of 530 km/h was achieved on the first day, and 550 km/h, the designed maximum speed of the Superconducting Maglev system, was recorded on the second day.

It was verified that the vibration characteristics of the low-cost SCM were almost the same as the new-type SCM.

5 DEVELOPMENT OF HIGH TEMPERATURE SCM

In 1998, a bismuth-based high temperature superconducting material that showed a superconductivity state at slightly below 110 K was discovered. In general, high temperature superconducting materials are copper oxides that show a superconductivity state at 23K or above. When high temperature superconducting materials are used in a superconductivity state, no liquid helium, whose temperature is 4.2 K, is required. So far, the production of Bismuth-based and Yttrium-based wires has been progressed. At present, the development of Bismuth-based wires is more advanced.

JR Central has been following the development trend of the high temperature superconducting wires, and started to develop the High Temperature SCM (HTS) using Bi2223 wires in 1999.

On one hand, it has been verified that the Low Temperature SCM (LTS) whose coils are made of niobium titanium (NbTi) wires can be applied to the Superconducting Maglev system. On the other hand, with the HTS, improvements in reliability and reductions in costs are expected. Specifically, the structure to cool down the high temperature superconducting coils can be simplified as the HTS is operated at higher temperature. Fig. 4 shows the structural comparison between LTS and HTS.

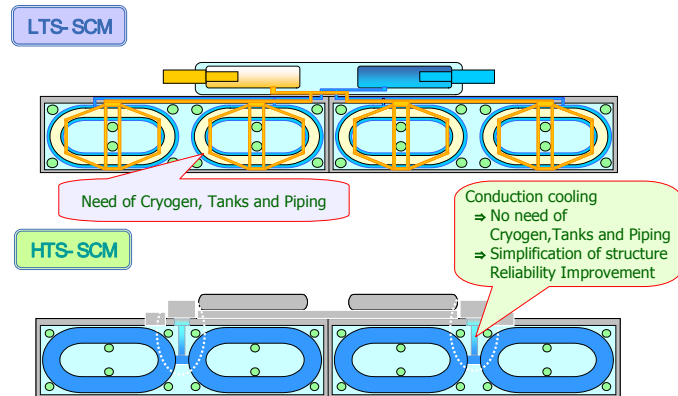


Figure 4: The structural comparison between LTS and HTS

The superconducting coils of the HTS show a superconductivity state at slightly below 20 K. Therefore, the coils can be cooled down directly by conduction cooling from the cold head of the on-board refrigerator. This indicates that refrigerants like liquid helium or liquid nitrogen and pipes in which refrigerants circulate can be made redundant. The LTS cannot be operated without them, suggesting that the HTS is expected to realize higher reliability and lower cost

5.1 Overcoming subjects concerning the high temperature superconducting wire

Bi2223 is a copper oxide. The mechanical strength of Bi2223 wires in terms of bending and tension is weaker than niobium titanium wires, resulting in the inferior performance of superconductivity and the generation of electric resistance on wires.

Besides, the high temperature superconducting wires have minute electric resistance on itself in a superconductivity state. In order to apply the HTS wires to the Superconducting Maglev, the electric resistance of the coils should be lowered and the current decay rate in a persistent current mode should be decreased. It seemed to be a hard task, however, the wire specifications required could be made clear and the R&D has been progressed intensively by reviewing the process of winding wires and producing coils. Ultimately, the high performance HTS with current decay rate of only 0.44 % a day was realized.

5.2 Running test of the HTS

Making use of advantages of the high temperature superconducting coils, an HTS using Bi2223 high temperature superconducting wires had been developed and produced for the Superconducting Maglev. Fig. 5 shows a photograph of the HTS.

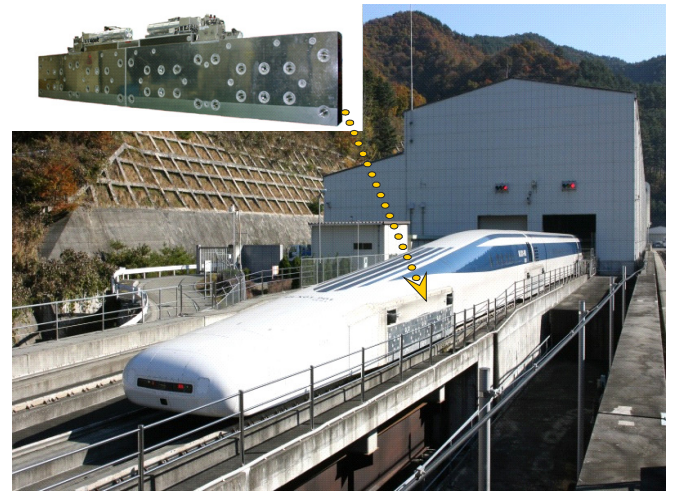


Figure 5: A photograph of the HTS

Test runs using the HTS were started in November 2006. The speed of 501 km/h was achieved on the first day and 553 km/h was recorded on the eighth day. The test runs had been conducted favorably, which proved the availability of the HTS to the Superconducting Maglev.

6 CONCLUSION

In this paper, the outline of the new-type LTS, the low-cost LTS and the HTS was introduced. These SCMs have been successfully developed, as the key technologies for the Superconducting Maglev, by JR Central. The data obtained from the test runs proved the remarkable performance of the SCMs.

Hereafter, the performance of the SCMs will be further improved for future revenue services by making use of data that will be acquired from the test runs.

7 REFERENCES

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