Study of Superconducting Magnetic Bearing Applicable to the Flywheel Energy Storage System that consist of HTS-bulks and Superconducting-coils

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Abstract. The Railway Technical Research Institute conducted a study to develop a superconducting magnetic bearing applicable to the flywheel energy-storage system for railways. In the first step of the study, the thrust rolling bearing was selected for application, and adopted liquid-nitrogen-cooled HTS-bulk as a rotor, and adopted superconducting coil as a stator for the superconducting magnetic bearing. Load capacity of superconducting magnetic bearing was verified up to 10 kN in the static load test. After that, rotation test of that approximately 5 kN thrust load added was performed with maximum rotation of 3000rpm. In the results of bearing rotation test, it was confirmed that position in levitation is able to maintain with stability during the rotation. Heat transfer properties by radiation in vacuum and conductivity by tenuous gas were basically studied by experiment by the reason of confirmation of rotor cooling method. The experimental result demonstrates that the optimal gas pressure is able to obtain without generating windage drag. In the second stage of the development, thrust load capacity of the bearing will be improved aiming at the achievement of the energy capacity of a practical scale. In the static load test of the new superconducting magnetic bearing, stable 20kN-levitation force was obtained.

1. Introduction
Recently, prevention of global warming using advanced technologies has become more activated, and railways with a level of energy efficiency superior to that of other forms of transport are no exception. Accordingly, energy conservation technology is an important theme within the framework of environmental problems, rather than this being a framework of simply improving the performance of equipment. The application of the energy storage is an example of efficient recycling of the regenerative electric power generated when inverter trains brake.
In this study, a flywheel is adopted for energy storage. The flywheel energy storage system has high energy density, and offers excellent performance in the areas of start/stop operation and load response. However, there are still a number of problems in terms of durability and economy. This study aimed to improve driving efficiency by reducing frictional loss and to solve maintenance-related problems for the bearing parts of rotors by applying superconducting technology to them. In this paper, we report on the basic study of a magnetic bearing involving the coupling of superconductors that is applicable as a support bearing for flywheel energy storage systems.
2. Developed superconducting magnetic bearing

In this study, a superconducting magnet was combined with a high-Tc bulk superconductor (HTS bulk) to increase the load capacity of the superconducting bearing. In the first step of the study, a thrust rolling bearing was selected for application. A liquid-nitrogen-cooled HTS bulk was adopted as a rotor, and a superconducting coil was adopted as a stator for the superconducting magnetic bearing.

Figure 1 shows a schematic diagram of the developed superconducting magnetic thrust bearing [1]. The bearing consisted of superconducting magnet and rotatable Dewar, these were functions as rotor and stator, respectively. The HTS bulks were installed into rotatable Dewar. Liquid nitrogen was used to cool the bulks. Gd-Ba-Cu-O material was used to give a high $J_c$ (=critical current density) value at a temperature of 77 K under a high magnetic field comparable to that of other materials. For the shape of the sample, a diameter of 60 mm and a thickness of 20 mm were adopted to facilitate stable superconductivity performance. The magnet consists of two superconducting coils vertically arranged in series. NbTi superconducting winding is used. In order to generate a high magnetic force field, one of the superconducting coils combines a main coil and a reverse coil, which generate a cusp field. The rotatable Dewar was placed in the room-temperature bore of the superconducting magnet. After the HTS bulks have been cooled, the superconducting magnet is energized.

3. Electromagnetic properties of the test bearing

The load capacity of the superconducting magnetic bearing was confirmed up to 10 kN by static loading. Subsequently, a rotation test on the bearing with an added thrust load of approximately 5 kN was performed with a maximum rotation of 3000 rpm.

3.1. Static load test

In a static load test, different shapes of HTS bulks were tested. The one is a ring shape with 20 mm inside and 60 mm outside diameters and the other is a disk shape with 60mm of outside diameter. Figure 2 shows the relation between output of the superconducting magnet and the generated levitation forces. The output of superconducting magnet is standardized by current rating. The lines in the figure indicate calculation values of levitation force corresponding to magnet output, which were calculated as a perfect diamagnetism. Electromagnetic force which acts on sample was calculated by 3D magnetic field analysis software “ELF/MAGIC” to consider the test result. The plane element in which an orthogonal magnetic flux is able to define in 0 was applied to the HTS bulk modeling. A diamagnetic effect of the HTS bulk was evaluated by this element. 10 kN levitation force was generated by 78% of the rated power of the superconducting magnet. A levitation load capacity (load pressure) in a conventional superconducting bearing that consists of the HTS bulk and permanent magnet is approximately 100 kN/m$^2$ [2]. The load pressure of the bearing is about ten times the conventional ones, when comparing in the area of the HTS bulk on which electromagnetic force acts.

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**Figure 1.** Developed superconducting magnetic.

**Figure 2.** A result of static load test.
In the case of disk shaped HTS bulks, levitation force is almost proportional to square of the magnet output. However, in the case of ring-shaped HTS, force gradient is decreased when magnet output over 60%. In the case of ring shaped one, magnetic flux penetration growing. However, in the case of disk shaped one, nearly state of the perfect diamagnetism was maintained where the coil output is lower than 60%. Therefore, disk shaped HTS bulks were adopted to rotation test from the viewpoint of having the high resistant property concerning the magnetic flux penetration.

3.2. Rotation test with 5 kN of added thrust load

A bearing testing stand which added 5 kN thrust load by using a 500-kg solid of revolution was produced. The flywheel and its main shaft were levitated with a superconducting magnetic bearing. The main shaft was then driven and the dynamic stability of the superconducting magnetic bearing was examined. A schematic diagram and a photograph of the bearing testing stand are shown in Figs. 3 and 4, respectively.

The superconducting magnet that becomes the stator of the magnetic bearing is fastened at the center of the main frame. The rotatable Dewar that forms the main shaft rotor of the magnetic bearing is installed in the room-temperature bore of the magnet. The flywheel and driving shaft of the motor are connected to couplings arranged below and above the rotatable Dewar, respectively. Radial roller bearings forming a rotation axis are arranged at the top and bottom of the Dewar and the flywheel, and a thrust roller bearing is arranged under the bottom of the rotation axis. The thrust roller bearing supports the axle load when the superconducting magnetic bearing is not energized.

![Figure 3. Drawing of bearing testing stand.](image1)

![Figure 4. Photograph of bearing testing stand.](image2)

![Figure 5. A data of 2h continuous rotation.](image3)

![Figure 6. A data of rotation speed up-and-down.](image4)
Examples of time charts from the bearing rotation test are shown in Figs. 5 and 6. Figure 5 is a time chart of the rotation test at a fixed rotational speed of 1000 rpm. The 500-kg flywheel levitated by the magnetic bearing was rotated at 1000 rpm for two hours. It was confirmed that the levitation position of the rotor have not been changed during the rotation. Figure 6 shows a time chart from the bearing rotation test in which the rotational speed was changed repeatedly between 3000 rpm and 1500 rpm. These results demonstrated that levitation force was stable during the rotation.

4. Basic study of a rotor cooling method without direct conduction
In the superconducting magnetic bearing consisting of coupled superconductors, the cooling method of a superconductor on the rotor side is very important. The stability of the electromagnetic properties of an HTS bulk is improved by lowering their cooling temperature to increase the critical current density. Accordingly, an HTS bulk on the rotor side should be cooled at a cryogenic temperature lower than 77 K. Ideally, a superconducting magnetic bearing consisting of coupled superconductors will be cooled in the same vacuum vessel for reasons of improvements of cooling-efficiency and electromagnetic coupling.

Rotor cooling methods involve only radiation heat or the low pressure helium gas. The basic heat transfer properties of these two conditions were studied by means of an experiment [3]. Figure 7 shows a schematic diagram of the experimental apparatus, which consists of inner and outer vessels, a vacuum chamber, a radiation shield plate and a refrigerator.

Figure 8 shows the relationship between pressure and the heat transfer coefficient, and that between pressure and windage drag. In this figure, theoretical and experimental values are compared. The heat transfer coefficient value obtained from the experiment are marked by red circles. The theoretical calculation values for conductivity in gas molecules and radiation are indicated by the solid red line and the broken red line, respectively.

The calculation values of the windage drag of helium gas are indicated by blue diamonds. The windage drag was calculated where solid of rotation was in the open space. The heat transfer coefficient values obtained from the experiment are small under low-pressure conditions. However, the coefficient’s value rapidly grows when the gas pressure exceeds $1.72 \times 10^{-1}$ Pa. When the pressure is lower than $1.72 \times 10^{3}$ Pa, the experimental value of the heat transfer coefficient is almost equivalent to the calculated radiation. When the gas pressure is higher than $2.2 \times 10^{5}$ Pa, the experimental value of the heat transfer coefficient is almost equal to the calculated gas molecule conductivity. The critical pressure of $1.72 \times 10^{5}$ to $2.2 \times 10^{6}$ Pa corresponds to the pressure of the mean free path of the helium gas, which corresponds to the heat distance between the specimens. However, the calculation value for the gas windage drag increases rapidly from a pressure value of $1 \times 10^{7}$ Pa. This result demonstrates that optimal gas pressure can be obtained by appropriately setting the gas pressure and the heat distance between the cooling and heat receiver bodies without generating windage drag.

![Figure 7. Experimental apparatus.](image)

![Figure 8. Pressure vs. heat transfer, windage drag.](image)
5. Second stage of the development

In the second stage of the development, thrust load capacity of the bearing will be improved aiming at the achievement of the energy capacity of a practical scale. It has been aimed at the load capacity of 20kN. The necessary capacity applicable to regenerative brake cancellation was calculated for the flywheel energy-storage system. This can be estimated as 10 kWh (36 MJ) from the results of investigation under actual conditions using a commercial train[1]. The mass of a flywheel with an energy storage capacity of 10 kWh (36 MJ) was calculated using formula of rotation inertia.

Figure 9 shows an example of the calculation results. This is a calculation of the mass of a flywheel that accumulates 10 kWh (36 MJ) of energy with rotational speeds varying from the 1500 to 3000 rpm. In the calculation, the minimum of 2000 kg-flywheel is necessary to store 10 kWh (36 MJ) of energy. This is an example of a target for superconducting magnetic bearings applicable to flywheel energy storage systems for railways. A schematic drawing of a new rotational Dewar is as shown in Fig. 10. In this figure, a new Dewar is compare with one previous product. HTS bulks were enlarged from 60 mm to 80 mm in diameter, and the number of the bulks increased to 4.

Figure 11 shows the relation between output of the superconducting magnet and the generated levitation forces. This figure shows comparisons of calculated levitation forces for the previous and the new superconducting magnetic bearings and a result of static load test of the new bearing. From the comparison of the calculation results, capacity of levitation force is improved up to 20kN in a new bearing. In the static load test, 20kN of levitation force was obtained by 64 % of power of the superconducting magnet. The state of nearly perfect diamagnetism was maintained.

![Figure 9. Example of the 10kWh-flywheel.](image)

![Figure 10. Drawing of new Dewar for 20kN-levitation.](image)

![Figure 11. Magnet output vs. levitation force.](image)

![Figure 12. A result of 10-hours holding static test.](image)
A time chart of the static load test for 10 hours is shown in Fig. 12. In this test, 24kN of pre-load was added first in a short time (10 min.) before add a normal load. Adding pre-load is an effective method to achieve stable levitation that was reported previously by Ichihara et al.[4]. In the static load test, stable levitation force was confirmed for 10 hours.

6. Conclusions
The Railway Technical Research Institute conducted a study to develop a superconducting magnetic bearing applicable to flywheel energy storage systems for railways. In the first step of the study, a thrust rolling bearing was selected for application, a liquid-nitrogen-cooled HTS bulk was adopted as a rotor, and a superconducting coil was chosen as a stator for the superconducting magnetic bearing.

The load capacity of the superconducting magnetic bearing was verified up to 10 kN in a static load test. After that, a rotation test with a thrust load of approximately 5 kN added was performed at a maximum rotation of 3000 rpm.

In the results of the bearing rotation test, it was confirmed that the levitation position could be stably maintained during rotation by using a bearing testing stand to add a high speed in support of the 500-kg solid of revolution.

The basic heat transfer properties under radiation in a vacuum and conductivity in tenuous gas were studied in an experiment to verify the rotor cooling method. The experimental results demonstrated that optimal gas pressure can be obtained without generating windage drag.

In the second stage of the development, thrust load capacity of the bearing will be improved aiming at the achievement of the energy capacity of a practical scale. It has been aimed at the load capacity of 20kN. In the static load test of new superconducting magnetic bearing, stable 20kN-levitation force was obtained.

7. Acknowledgement
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References
[1] Seino H, Nagashima K, Arai Y 2008 Development of Superconducting Magnetic Bearing using Superconducting Coil and Bulk Superconductor, *Journal of Physics Conference Series* 97, 012101.
[2] Koshizuka N, Matsunaga K, Yamauchi N, Kawaji A, Hirabayashi H, Murakami M, Tomita M, Une S, Saito S, Isono M, Nasu H, Maeda T, Ishikawa F 2004 Construction of the stator installed in the superconducting magnetic bearing for a 10 kWh flywheel, *Physica C, Elsevier*, Vol. 412-414, pp756-760
[3] Tanaka Y, Furusawa T, Nakauchi M, Nagashima K 2009 Heat Transfer characteristics under cryogenic, low pressure environments, *Physica C, Elsevier*, Vol. 469, pp.1862-1865
[4] Ichihara T, Matsunaga K, Kita M, Hirabayashi I, Isono M, Hirose M, Yoshii K, Kurihara K, Saito O, Saito S, Murakami M, Takabayashi H, Natsumeda M, Koshizuka N 2005 Fabrication and evaluation of superconducting magnetic bearing for 10 kWh-class flywheel energy storage system, *Physica C, Elsevier*, Vol. 426-431, pp.752-758