Development of Superconducting Magnetic Bearing using Superconducting Coil and Bulk Superconductor

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Abstract. The authors conducted a study on superconducting magnetic bearing, which consists of superconducting rotor and stator to apply the flywheel energy-storage system for railways. In this study, high temperature bulk superconductor (HTS bulk) was combined with superconducting coils to increase the load capacity of the bearing. In the first step of the study, the thrust rolling bearing was selected for application by using liquid nitrogen cooled HTS bulk. 60mm-diameter HTS bulks and superconducting coil which generated a high gradient of magnetic field by cusp field were adopted as a rotor and a stator for superconducting magnetic bearing, respectively. The results of the static load test and the rotation test, creep of the electromagnetic forces caused by static flux penetration and AC loss due to eccentric rotation were decreased to the level without any problems in substantial use by using two HTS bulks. In the result of verification of static load capacity, levitation force (thrust load) of 8900N or more was supportable, and stable static load capacity was obtainable when weight of 460kg was levitated.

1. Introduction
Electric power is an important element in the social life, and the power consumption intensively affects the global environment like global warming. Recently, levelling of electric load by the power storage technology is expected as one of the measures of the global warming.

In railways, regenerative brakes of inverter trains were adopted to advance energy conservation. In addition, the electric power storage technology has been studied to use the regenerative energy more efficiently. Under such a background, a study of the magnetic bearing using superconducting technology was been begun by the authors to apply the flywheel energy-storage system for railways. The flywheel energy-storage system has high energy density, and excellent in the start/stop operation and the load response. Nevertheless, there are problems in terms of durability and economical aspects. The study has intended to improve the driving efficiency by decrease in the frictional loss and to solve the problems concerning the maintenance by applying the superconducting technology to the bearing part.

2. Proposal for development of superconducting magnetic bearing
It has been already tried to apply high temperature bulk superconductor (HTS bulk) and superconducting coil to bearings which supports the flywheel for electric power storage. There were examples of superconducting bearings where a HTS bulk which combined with permanent magnet [1], superconducting coil which combined with a ferromagnet [2], respectively.

However, the magnetic field applied to the HTS bulk or ferromagnet in such combinations was limited by a magnetization limit of permanent magnet and the saturation flux of ferromagnet.
Therefore, load capacities were limited in these conventional superconducting bearings. In this study, superconducting coil was combined with HTS bulk to increase the load capacity of the superconducting bearing.

3. Superconducting magnetic bearing which consists of superconducting rotor and stator
The electromagnetic force between a HTS bulk and a superconducting coil is given by bulk shape, shielding current on the HTS bulk and magnetic force field which generated by superconducting coil, as apparent in equation (1) [3,4].

\[
F_z = \frac{\pi^2 R_d^4}{L_{cyl}(R_d, t)} B_z \frac{\partial B_z}{\partial z}
\]

\(R_d\): radius of HTS bulk \(L_{cyl}\): Inductance of the cylindrical loop current on HTS bulk \(t\): Bulk thickness \(B_z\): magnetic force field

The electromagnetic force strongly relates to cooling temperature of HTS bulk. However, it is difficult to cool the superconducting rotor. 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. Table 1 has summarized specifications of the superconducting thrust bearing for the experiment.

| Table 1. Specification of superconducting magnetic bearing. |
|-------------------------------------------------------------|
| HTS bulk | Superconducting coil |
| Material | Gd-Ba-Cu-O | Material | Nb-Ti |
| Shape | Disk shape, \(\phi 60 \text{mm} \times 20 \text{mm} \) (2 disks) | Properties | Room temperature bore\(\phi 120 \text{mm}\), Cusp field, Magnetic field 5T (Max) |
| Cooling method | Liquid nitrogen (77K) | Cooling method | Cryocooler direct (4K) |

3.1. HTS bulk as a rotor of superconducting magnetic bearing
Figure 1 delineates a schematic diagram of a rotatable Dewar. Inner vessel and vacuum chamber are installed in a boring spindle. This spindle becomes a rotation axis for the thrust rolling bearing. HTS bulks were set in the inner vessel and then cooled by liquid nitrogen. Levitation force which acts on the HTS bulks was transmitted to the outer vessel of the boring spindle through the thermal insulated support column.

Gd-Ba-Cu-O material was used for the reason of high \(J_c\) at a temperature of 77 K under a high magnetic field which compared with other materials. A shape of the sample was adopted in a diameter of 60 mm and thickness of 20 mm, in view of obtaining stable superconductivity performance readily.

3.2. Superconducting coil as a stator of superconducting magnetic bearing
In design of the superconducting rotor, a shape of HTS bulk and temperature of that cooling were decided first. Therefore the remaining parameter is only the magnetic force field. Nevertheless, applied magnetic field is not increasable for the reason of deterioration in \(J_c\) at 77 K. The parameter that finally remains is a gradient of magnetic field as shown in equation (1).
Then, the superconducting coil was developed to achieve a high gradient of magnetic field, applying a magnetic field less than 2 T.

Figure 2 delineates a schematic diagram of superconducting coil. The superconducting coil consists of two coils which vertically arrange in series. In order to generate a high magnetic force field, a superconducting coil is combined with main coils and a reverse coil. These two coils generate a cusp field. As the result, a zero magnetic field space generated at the vertical center of two coils, and if the position is vertically moved slightly from the center, the magnetic force field becomes the maximum. 140 T²/m or more magnetic force field with magnetic field under 2 T was produced in this area. HTS bulks are set in here. The gradient of magnetic field at a designed position of HTS bulk is approximately three times when compared with that generated by the same coil in single use. Moreover, the leakage magnetic flux to the outside of superconducting coil is less.

Dry-type magnet was adopted. Ni-Ti superconducting wire was used, and GM cryocooler was used for directly cooling. The diameter of room temperature boa is 120 mm. HTS bulks installed rotatable Dewar is inserted in the room temperature boa.

4. Experimental results

4.1. Measurement of degradation of levitation force caused by static flux penetration and rotation

4.1.1. Experimental apparatus

Figure 3 shows the experimental apparatus. Two HTS bulks can be stored in a sample holder. The HTS bulks were put in the liquid nitrogen Dewar which installed in the room temperature boa of the superconducting coil. The HTS bulks were rotated by the motor with a thrust load impressing which was electromagnetically generated between the HTS bulks and superconducting coil. The HTS bulks are movable laterally (radially) and vertically in the apparatus by using feed controlling devices. The vertical and lateral (radial) directions of electromagnetic force which acts on the HTS bulks are measured by a load cell. Moreover, it is able to monitor the position of the HTS bulks by the encoders that installed in each feeding device. The load limit in the vertical direction of the experimental apparatus is 2500 N.

4.1.2. Degradation of levitation force caused by static flux penetration

Degradation of levitation force caused by static flux penetration was measured for several magnetic force fields by adjustments of vertical position of the HTS bulk and an input current of the superconducting coil. Magnetic field which generated the superconducting coil was fixed to 2.54 T. The magnetic force field was set to 51, 35, and 25 T²/m. Each numerical value
of the magnetic field and the magnetic force field is a calculation value in the air at the vertical center position of the HTS bulk. A center in a horizontal plane of HTS bulk is matched to that of the superconducting coil. The experiment was performed with one or two bulks to evaluate an effect of the bulk shape.

Figure 4 shows the results, which obtained by a combination of one HTS bulk and superconducting coil. The X-axis indicates the initial levitation force acting on the HTS bulk when superconducting coil energized. The levitation force corresponds to the thrust load of the superconducting magnetic bearing. In the left-side figure, the Y-axis indicates the amount of a decrease of levitation force after 10 minutes. In the right-side figure, the Y-axis shows the decreasing of levitation force as a ratio to an initial levitation force. The deterioration rate of levitation force has become less due to the magnetic force field, that is, the levitation force becomes less.

Figure 3. Experimental apparatus.
The comparison of degradation in the levitation force between one HTS bulk and two bulks is shown in Figure 5. These data were obtained by same magnetic filed and magnetic force field (2.54 T, 25 T²/m). In the case of using two HTS bulks, the initial levitation force almost doubles and the decreasing of levitation force became intensive, however the ratio of decreasing in levitation force has not changed.

When the HTS bulk increased, required levitation force is obtainable in a lower magnetic force field, as seen in comparing blue-diamonds in figure 4 and orange-circles in figure 5. If the magnetic force field is less, the rate of decreasing in the levitation force is decreased as shown in Figure 4. Therefore, it can be confirmed that it is an effective method that increasing the number of HTS bulk may decrease the creep of the electromagnetic force.

4.1.3. Degradation of levitation force caused by AC loss due to rotation

An AC loss caused by eccentricity of rotation axis in the superconducting magnetic bearing was measured for several magnetic force fields. The AC loss was evaluated by the decrease in the electromagnetic force when HTS bulks were rotated. The magnetic field, which generated the superconducting coil, was fixed to 2.54 T. The magnetic force field was set to 51, 35, and 25 T²/m.

The HTS bulks were rotated after 10 minutes when superconducting coil had reached a setting output, to stabilize a creep of the levitation force due to flux penetration. The AC loss was measured under the eccentricity of rotation axis setting 0, 4, 6 and 8 mm. The rotational speed was fixed to 1000 rpm (revolutions per minute). The AC loss was evaluated by the amount of a decrease of levitation force after 10 minutes rotation.

Figure 6 shows the results of the rotation test. In the figure, the X-axis indicates radial displacement of rotation axis, which corresponds to an eccentricity of the rotation axis. The Y-axis indicates the degradation of levitation force after 10 minutes rotation. The initial levitation forces of 1935N, 1300N and 770N correspond to the magnetic force field of 51, 35, and 25 T²/m where the HTS bulk set, respectively. When two HTS bulks were installed, the initial levitation force of 1871N was generated in the magnetic force field of 25 T²/m.

In the case of one HTS bulk installing, the degradation of levitation force was less, when the levitation force under 1300N. Nevertheless, an extreme degradation of levitation force was visible, when levitation force of 1935N generated. On the other hand, degradation of levitation force was small as well as that of one HTS bulk rotation under 1300N levitation force when
two HTS bulks were eccentrically rotated under 1871N levitation force. Therefore, it was confirmed that the AC loss caused by eccentric rotation will be able to control by increasing the number of HTS bulks, as well as the control of the creep of the levitation force.

4.2. Measurement of levitation force capacity in the superconducting magnetic bearing

4.2.1. Experimental apparatus
The static load test of the superconducting magnetic bearing, which consisted of the HTS bulks and superconducting coil, was performed. Figure 7 shows the experimental apparatus. A rotor of the rotatable Dewar, which installed HTS bulks and stator of the superconducting coil were already introduced in Figure 1 and 2.

In this experiment, two HTS bulks were installed in the Dewar. The rotatable Dewar was placed in the room temperature bore of the superconducting coil with a prescribed height, and then the HTS bulks were cooled by liquid nitrogen. The rotatable Dewar was connected with the ground by tension wire, and a load cell was installed between the Dewar and the ground.

![Figure 7. Setting of the superconducting magnetic bearing for a static load test](image_url)
The vertical position of the rotatable Dewar was fixed by tension wire, then levitation force which generated by electromagnetic force between superconducting rotor and stator was measured by the load cell.

4.2.2. Static load capacity of superconducting magnet bearing
The static load test with less than 10000N, which was decided by considering the designed load limit, was performed. Figure 8 shows the results of static load test. These data obtained under several sample positions. The positions indicate the vertical distance from the center of superconducting coil to the center of HTS bulk. The minus means that there was a center of HTS bulk below the superconducting coil center.

The X-axis indicates the output power of superconducting coil. The Y-axis indicates the levitation force acting on the rotatable Dewar. When the HTS bulk was adjusted to the position that fell from the superconducting coil center by 16mm, a levitation force of over 8000N was generated by a 100% output of superconducting coil. Moreover, the levitation force was reached to 10000N by less than 80% of superconducting coil output when arranging the position that fell from the superconducting coil center by 37mm.

![Figure 8. Results of static load test by levitation.](image)

4.2.3. Supporting stability of superconducting magnet bearing
The supporting stability of the static load on the superconducting magnetic bearing was verified. Figure 9 shows an example of the data, when a weight of 460kg (including Dewar) was levitated by superconducting magnetic bearing. The vertical position of HTS bulk fell from the center of superconducting coil by 20mm.

The output of the superconducting coil was approximately 63 %, and the maximum magnetic field in the vertical direction at position of HTS bulk was 1.8 T. The creep in positioning of the rotatable Dewar was hardly visible; therefore, creep of electromagnetic force was least. In the experiment, stable levitation maintained for three hours. The result demonstrated that stable static load support is obtainable by using the superconducting magnetic bearing.
Superconducting magnetic bearing which, consists of superconducting rotor and stator was studied to apply the flywheel energy-storage system for railways. In the study, the HTS bulk was combined with superconducting coil to increase the load capacity of the superconducting magnetic bearing.

In the first step of the study, the thrust rolling bearing was selected for application by using liquid nitrogen cooled HTS bulk. Disk shaped Gd-Ba-Cu-O HTS bulk (60 mm diameter, 20 mm thickness) and superconducting coil which generated a high gradient of magnetic field by cusp field were adopted as a rotor and a stator of superconducting magnetic bearing.

The results of the static load test and the rotation test with the maximum levitation force (thrust load) of 2500N, the creep of the electromagnetic forces caused by static flux penetration and AC loss due to eccentric rotation were decreased to the level without any problem in substantial use by using two HTS bulks. In the result of verification of the static load capacity, levitation force (thrust load) of 8900N or more would be supportable, and stable static load capacity would be obtainable when the weight of 460kg was levitated.

Large loading capacity and stable supporting were verified in the static load test. In the future, dynamic bearing properties when rotating with 500 kg-weight will be examined.

5. Conclusions

6. Acknowledgement

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