Numerical Analysis and Evaluation of Electromagnetic Forces in Superconducting Magnetic Bearings and a Non-contact Permanent Magnetic Clutch

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We are currently developing a superconducting magnetic bearing and a non-contact permanent magnetic clutch applicable to flywheel energy storage systems for railways. This paper reports on electromagnetic force analysis concerning these developments. In the analysis, the electromagnetic force generated in superconducting magnetic bearings and non-contact permanent magnetic clutches was estimated based on the magnetic field distribution ascertained through 3D numerical analysis. The validity of this analysis was then evaluated by comparing the results with experimental outcomes, and the two were found to be consistent. It was therefore confirmed that the analysis was an effective way of estimating the electromagnetic force of electromagnetic equipment containing the bulk superconductor for use in application design.

Keywords: energy storage system, flywheel, magnetic bearing, superconducting magnet, bulk superconductor

1. Introduction

We are currently developing a superconducting magnetic bearing (SMB) and a non-contact permanent magnetic clutch (PMC) applicable to flywheel energy-storage systems for railways. The aim of this study was to improve driving efficiency by reducing frictional loss and to solve maintenance-related problems for the bearing parts of flywheel energy-storage systems. The SMB consists of a superconducting rotor and a stator to obtain a high load capacity [1]. A high-Tc bulk superconductor (HTS bulk) and a superconducting coil are adapted to the rotor and the stator of the bearing. The SMB required the refrigeration in the cryogenic temperature. On the other hand heat generation in a motor/generator becomes large heat load in cryogenic temperature. For the reason of separation of the heat of a motor/generator from refrigerator heat load, a flywheel and a motor/generator are arranged inside and outside the cryostat, respectively. The PMC is an element part that transfers the flywheel's stored energy to the motor/generator through the cryostat in a non-contact way. In this paper, we report on the basic study of a magnetic bearing involving the coupling of superconductors and the PMC. Electromagnetic forces generated by the SMB and the PMC were calculated using 3D numerical analysis. Then, we compared the analytical results with experimental results and confirmed the validity of the analysis. Finally, we designed an enhanced

model representing the SMB and the PMC and their properties according to the analysis.

2. 3D numerical analysis - a method of analyzing electromagnetic force

We used the ELF/MAGIC 3D non-linear static magnetic field solver for the electromagnetic force analysis. This is a software solver that adopts the integration element method to solve Maxwell's integral equations. It uses a network approach combining the magnetic moment method, the surface magnetic charge method and the surface current method for improved accuracy. The integral element method is advantageous in terms of mesh generation. The mesh partition is only necessary in material. Space meshes, and boundary conditions are not required.

3. 3D numerical analysis of SMB and evaluation of SMB properties

3.1 SMB basic properties test (test SMB)

In this study, we developed a superconducting bearing (referred to as the test SMB) to allow examination of the load capacity and confirm practicality. In the first step

of the study, we selected a thrust rolling bearing 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. We verified the load capacity of the SMB up to 10 kN in a static load test. A rotation test with a thrust load of approximately 5 kN added was then performed at a maximum rotation speed of 3,000 rpm [2]. We continued development aimed at increasing the thrust load to 20 kN, which is considered a practicable load level. The 3D numerical electromagnetic force analysis concerning the SMB is explained below.

Figure 1 shows a schematic diagram of the test SMB. The dimensions of the cryostat are approximately 600 mm (outside diameter) and 500 mm (height). The rated magnetomotive force is 1,032 kA, and the magnet consists of two superconducting coils vertically arranged in series. In order to generate a high magnetic force field, two superconducting coils are energized reversing the polarity to generate a cusp field. Consequently, a zero magnetic field space is generated at the vertical center of the two coils; if the position is shifted slightly from the center, the magnetic force field reaches its maximum. A magnetic force field of 140 T²/m or more is produced in this area with a magnetic field of under 2 T. The HTS bulks are set in this location. The gradient of the magnetic field at a specific position of the HTS bulk is approximately three times larger than that generated by the same coil with single use. We adopted a dry-type magnet and used Ni-Ti superconducting wire, then introduced a GM cryocooler for direct cooling. The diameter of the room-temperature bore was 120 mm, and a rotatable Dewar with the HTS bulks installed was inserted into it. The analytical model and the element type used are as shown in Fig. 2 and Table 1, respectively. We analyzed the electromagnetic properties of the SMB for two kinds of HTS bulk – one a disk shape and the other a ring shape. Table 2 shows the shape properties of the models.

A plane element that defined the magnetic field at the center position of the element was applied to simulation of the HTS bulk. We calculated the magnetic field using a current loop on the plane edge. The outside of the simulated HTS bulk was enclosed by Maxwell's stress evaluation planes. The electromagnetic force caused by the shield current of the HTS bulk surface was evaluated using these stress evaluation planes.

Figure 3 shows an example of the analysis results for magnetic field distribution, and these outcomes were compared. The left-side figure is for an energizing coil only, and the center figure is for the HTS bulk in the energizing coil. This bulk was defined with perfect diamagnetism. The right-side figure is for the HTS bulk with a simulated 1 T magnetic flux passing. These figures show the analytical results for magnetic flux distribution in a ring-shaped HTS bulk. A high magnetic flux area was visible in the inside-diameter edge on the upper and lower plates of the simulated bulk due to micro-pinholes. The pinholes were installed for the sake of calculation convergence in the enclosed loop current elements. The magnetic field distribution confirmed that perfect diamagnetism or controlled magnetic flux (1 T) was maintained at inside the HTS bulk.

Fig. 1 SMB for basic properties test (test SMB)

Fig. 2 Analytical model of the test SMB

Table 1 Element type for SMB simulation

Simulation parts	Type	Functions
Superconducting coil	Solid (3D)	Current
HTS bulk	Plane (2D)	Loop current surface
Stress		Maxwell's stress evaluation surface
Magnetic field		Magnetic field evaluation surface

Table 2 Model shape properties

Simulation model	Stress evaluation surface			Stress evaluation surface		
	Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)	Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)
Disk shape	60	-	40	66	-	44
Ring shape	60	20	40	66	18	44

Figure 4 shows a comparison between the analytical and static load test results. For the ring-shaped HTS bulk, a difference between the analytical and experimental results is seen, for a superconducting coil output exceeding 70%. On the other hand, the analytical and experimental results correspond satisfactorily for the disk-shaped HTS bulk. It can be presumed that the increase in the rate of levitation force in stronger magnetic fields decreases in high magnetic field conditions due to magnetic flux pen-

Fig. 3 Analysis results for magnetic field distribution

etration. In the case of the disk-shaped HTS bulk, it is presumed that a nearly state of the perfect diamagnetism was maintained at a superconducting coil output of less than 60% (maximum magnetic flux under 2 T at the HTS bulk position).

We identified the amounts of magnetic flux penetration with levitation forces in the experimental results through numerical analysis. Figure 5 shows the simulated levitation force when magnetic flux penetration occurred in a high magnetic field. The magnetic flux penetration

Fig. 4 Analysis results for magnetic field distribution

Fig. 5 Simulation of magnetic penetration

starts gradually from nearly 70% of the superconducting coil output. It can be thought that magnetic flux penetration of about 0.5 T occurred with a superconducting coil output of 100%.

3.2 Design of an SMB consisting of HTS coil and bulks

The second stage of the development was aimed at supporting the flywheel magnetically through non-contact operation. To this end, one SMB coupling was made to support thrust and radial loads simultaneously. Figure 6 shows an illustration of a small-scale pilot machine. In the plan, a flywheel is supported magnetically by two SMB couplings inside a cryostat. The SMB consists of HTS bulks and a high- T_c tape winding coil (i.e., an HTS coil). This new combination is referred to as an HTS-SMB. Kinetic energy of the flywheel is translated from the inside to the outside through the cryostat using the PMC. The flywheel mass was approximately 50 kg. The electromagnetic properties of the HTS-SMB to be applied to the pilot machine were designed using 3D numerical analysis.

As stable levitation in the SMB is difficult to achieve with a single-coil stator, a double-coil magnet that generates a cusp field was adopted to provide stable levitation similar to that of the test SMB. In this case, the levitation force was approximately 2/3 that of the single coil, even using the double-coil winding. Accordingly, higher costs will inevitably be involved in making stator coils when the cusp magnetic field is adopted. Comparison of the HTS bulk compared with the HTS coil in terms of production costs shows that the coil is more expensive. The HTS-SMB, which consists of a single HTS coil and HTS bulks to provide stable levitation, was found to be applicable using 3D numerical analysis. The key to the analysis is the combination of differently shaped HTS bulks.

Fig. 6 Illustration of the small-scale pilot machine

Fig. 7 3D analytical model of the HTS-SMB

Fig. 8 Analysis results for HTS bulk position versus levitation force

We defined the HTS bulk for the disk shape. The diameter of the HTS bulk are 60 mm and 46 mm, respectively, and thickness of them are 20 mm and 15 mm. The magneto motive force of the coil was defined as 314 kA. Figure 7 shows an example model of the 3D analysis. The relationship between the position of the HTS bulk and the electromagnetic force generated when it moves vertically (in the axial direction) is as shown in Fig. 8. The HTS bulk is defined with perfect diamagnetism, and a 1 mm displacement in the radial direction was given in the bulk to allow evaluation of the radial restitute force.

In Figure 8, the horizontal axis shows the relative axial displacement between the HTS bulk and the superconducting coil in the axial direction. Relative position = 0 means that the vertical center position of the HTS bulk corresponds to the vertical center of the coil. When the relative position has a positive number, the HTS bulk is located higher than the coil, and a negative number indicates a lower location. The axial-direction electromagnetic force becomes a levitation force for positive numbers ($z > 0$ mm). When the relative displacement is less than 18 ($z < 18$ mm), the levitation force decreases in line with the reduced relative displacement. Conversely, the levitation force increases in line with the relative displacement reduction when the relative displacement is greater than 18 mm ($z > 18$ mm). A stable levitation force will be achieved in this relative displacement area. The electromagnetic force in the radial direction reaches its maximum for a relative axial displacement of around 0 mm. However, the radial electromagnetic force will be unstable when the relative displacement is over 20 mm and under -20 mm. As the relative axial displacement exceeds these values, a stable radial force can be achieved with an un-

stable levitation force. When the relative displacement is over -18 mm and less than 18 mm, a stable levitation force can be achieved with an unstable radial force. Stable magnetic levitation cannot therefore be achieved when a single coil is used for a magnetic field source. On the other hand, it is possible to achieve stable levitation using a combination of HTS bulks. A radial stabilization HTS bulk is located in the inner bore of the coil to generate a radial restoring force, and a levitation HTS bulk is located on the upper side of the coil. The levitation HTS bulk is set to be larger than the radial stabilization HTS bulk in order to prevent unstable levitation force generated by the latter. The electromagnetic force properties were confirmed using 3D numerical analysis.

Figure 9 shows the model of the HTS superconducting bearing (HTS-SMB). The relationships governing the relative displacement between the superconducting coil and HTS bulks and the generated electromagnetic force in the axial and radial directions are as shown in Fig. 10. These results were obtained by 3D numerical analysis; they indicate that the levitation force decreased in positive axial displacement and increased in negative axial displacement. A restoring force to adjust the position was

Rotor side				Stator side			
HTS bulk				HTS coil			
Shape	Outer diameter (mm)	Thickness (mm)	Amount	Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)	Magneto motive force (kA)
Disk	60	20	1	56	270	30	314
	46	15	2				

Fig. 9 Analytical model of the HTS-SMB for the small-scale pilot machine

Fig. 10 Relationship between HTS bulk displacement and electromagnetic force

generated when the levitation height changed. In the radial direction, a restoring force to adjust the radial position was generated when there was radial movement. We can therefore conclude that it is possible to achieve stable levitation in this way.

A flywheel was supported by two sets of HTS-SMB and arranged with an upper and lower flywheel formation as shown in Fig. 6. The flywheel was levitated at a height balancing the flywheel mass. Twice the axis support rigidity can be expected from this setup.

4. Analysis and evaluation of permanent magnetic clutch (PMC) properties

In this chapter, we report on the results of 3D numerical electromagnetic force analysis and examination in relation to a non-contact permanent magnetic clutch (PMC).

The PMC is an important element that transfers the flywheel's stored energy to the motor/generator through the cryostat in a non-contact way. A permanent magnet is used to transmit the driving torque without contact. We estimated the characteristics of the magnetic clutch through 3D numerical electromagnetic force analysis. In addition, we evaluated the analytical results by comparing them with experimental results. Figures 11 and 12 show the experimental clutch and analytical models, respectively. In the analysis, we examined a simulated experimental model and a Halbach array model that concentrated the flux of magnetic induction. A Halbach array is a special arrangement of permanent magnets that augments the magnetic field on one side of the array. Additionally, magnetic field on the other side of the array is almost cancelled. Each model is composed of eight poles. In the simulated experimental model, permanent magnets are magnetized in the horizontal plane. In the

Fig. 11 Experimental PMC

Fig. 12 Analytical model of two kinds of PMC

Halbach array model, permanent magnets magnetized in the vertical direction are intermediately added between the horizontally magnetized magnets. The permanent magnets in both models are approximately the same size and are arranged at the same radius.

The residual flux density, magnetic coercive force and maximum energy product of the permanent magnets were defined as 12.85 kG, 12.217 Oe and 39.34 MGOe, respectively. Figure 13 shows example analytical results for magnetic field distribution. A comparison of the transmission torque between the analytical and experimental

Fig. 13 Analytical results for magnetic field distribution in the PMC

Fig. 14 Comparison of transmission torques

Fig. 15 Analytical results for enhanced torque models

results is shown in Fig. 14. In the analysis, we calculated the maximum torque in an ideal position. The experimental value was a measurement of the step-out torque in ultra-slow rotation. The horizontal axis shows a gap between the magnet surfaces. We confirmed the validity of the analysis through comparison between the analytical and experimental values as shown in Fig. 14. In the analysis results, the transmission torque in the Halbach array magnet is three times that of the experimental value.

Figure 15 shows analytical values for the maximum transmission torque between a PMC coupling when the number of poles in the models is enhanced to 16 and 24. The gap between the surfaces of the facing permanent magnets was set to 16 mm. The Halbach array magnet, which consists of a combination of permanent magnets as shown in Fig. 13, and simulated experimental model were adapted to the analytical model. The number of poles in the PMC was increased by enhancing the arranged radius of the permanent magnets. The rated torque in a 22 kW motor that was applied to the SMB test stand and the estimated rated torque in the IHI-developed flywheel system [3] are indicated in this figure. From the analysis results, it was confirmed that a practicable torque could be transmitted by multi-polarizing.

5. Conclusions

We are currently developing a superconducting magnetic bearing (SMB) and a non-contact permanent magnetic clutch (PMC) applicable to flywheel energy storage systems for railways. The SMB consists of a supercon-

ducting rotor and a stator to obtain a high load capacity. A high- T_c bulk superconductor (HTS bulk) and a superconducting coil are adapted to the rotor and the stator of the bearing. A flywheel and a motor/generator are arranged inside and outside the cryostat, respectively. The PMC is an important element that transfers the flywheel's stored energy to the motor/generator through the cryostat in a non-contact way. The electromagnetic forces generated by the SMB and PMC were calculated using 3D numerical analysis. We used the ELF/MAGIC 3D non-linear static magnetic field solver for the electromagnetic force analysis. A plane element that defined the magnetic field at the center position of the element was applied to the HTS bulk. We calculated the magnetic field using a current loop on the plane edge. The results can be summarized as follows:

- (1) The analytical and experimental results corresponded sufficiently. It was demonstrated that the electromagnetic properties for a coupling of HTS bulks and a coil or a coupling of permanent magnets could be evaluated accurately using 3D numerical analysis.
- (2) An SMB consisting of a single coil and HTS bulks achieving stable levitation was considered using 3D numerical analysis. The key to the analysis was a combination of differently shaped HTS bulks. The analysis results showed that it was possible to achieve stable levitation.
- (3) We estimated the PMC's characteristics through 3D numerical electromagnetic force analysis. The results confirmed that a practicable torque could be transmitted by multi-polarizing.

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