1. Introduction

In 1987, a group led by C.W. Chu et al. discovered high-Tc superconductor Y-Ba-Cu-O with critical temperature (Tc) of 90K\(^1\). Since then, superconducting phenomenon has become able to be obtained comparatively easily by cooling with liquid nitrogen (77K), which is easier to handle than liquid helium (4.2K). Using the diamagnetic property due to flux pinning force of bulk superconductors, practical research regarding superconducting magnetic bearings (SMB), which cause a permanent magnet to levitate, is being conducted. Magnetic levitation of SMB generally does not require control, and rotation loss of SMB is said to be ideally zero.

On the other hand, the demand for electric power has been increasing in recent years, and the introduction of a flywheel energy storage system (FESS) using a superconducting magnetic bearing (SMB) is needed to make the daily electric power load as level as possible. We have studied rotation loss characteristics of SMB with high-Tc superconductors (YBCO) and permanent magnets for supporting a flywheel in FESS. We have designed and manufactured a testing machine for measuring rotation loss characteristics of SMB. The rotor is suspended by two sets of radial active magnetic bearings (RaAMB), a set of axial active magnetic bearings (AxAMB), and a set of SMB. We obtained rotation loss characteristics of the rotor levitated by RaAMB, AxAMB and SMB on this testing machine.

2. Test Equipment and Method

2.1 Test Equipment

Fig. 1 shows a cross section of the rotation loss measurement apparatus designed and fabricated\(^8\). The test apparatus was placed inside a vacuum chamber, and consists of the following parts: (1) main shaft, (2) induction motor, (3) two sets of radial active magnetic bearings (RaAMB), (4) one set of axial active magnetic bearings (AxAMB), and (5) SMB [superconductor (SC), cryostat (C/S), and permanent magnet (PM)].

The stator of the SMB (SC and C/S) is able to move in the axial direction through the load cell by Z stage.

Either a radial superconducting magnetic bearings (RaSMB) or axial superconducting magnetic bearings (AxSMB) can be mounted at the lower part of main shaft. In this research, however, a RaSMB (hereinafter referred to as "SMB") was mounted.

At present, although the rotation loss of SMB is reported to be extremely low, there are many unknown points concerning characteristics under actual conditions\(^3\), \(^4\), \(^5\). A reduction of levitation force has also been reported, and if applied to FESS, improvement is an important theme\(^6\), \(^7\).

This research was therefore conducted for the purpose of clarifying SMB rotation loss characteristics and a method of improving the reduction of SMB levitation force under actual conditions set to various SMB loads and rotation speeds.

**Fig. 1 Cross section view of apparatus**
2. 2 Levitation Force Characteristics of SMB

A ring-shaped YBCO to which eight bulks were attached in the circumferential direction and contained in a SUS304 C/S was used as the SMB stator (see Fig. 2). The PM magnetized in the directions indicated by the arrows (↑↓) shown in Fig. 3 and consisting of three-layer magnets and four-layer yokes in the axial direction was used as the SMB rotor. The gap between PM and SC is 1.4 mm (radial direction: includes C/S seal thickness 1 mm).

As indicated in Table 1, in this research, two types of PM with differing irregularity of magnetic flux in the circumferential direction $\Delta B/B_{\max}$ were prepared. The table shows that magnetic flux density $B_{\max}$ is larger for an Nd-type magnet (RaPMNd2) than for a Pr-type magnet (RaPMPPr), and $\Delta B/B_{\max}$ is small.

Static magnetic force of SMB in the axial direction is shown in Fig. 4, but SMB levitation force is larger when RaPMNd2 is used.

2. 3 Test Method

The test was conducted as follows:

1. Rotor (main shaft + PM) was levitated by RaAMBs and AxAMB. At this time, rotor weight was supported by AxAMB.
2. SMB stator is placed at normal position relative to the rotor, and the SC is cooled with liquid nitrogen in magnetic field of PM.
3. After SC is cooled below critical temperature ($T_c$), the SMB stator moves in the upward axial direction. At that time, the SC generates magnetic force against the PM, and the SMB begins to support the rotor weight. (At the same time, the supporting force of AxAMB becomes smaller.)
4. After about 20 minutes elapse, the rotor is rotated and accelerated to the target rotational speed. After that, the rotor spins down with inactive motor drive.
5. Rotation loss of the rotor levitated by RaAMBs, AxAMB and SMB without contact is calculated from rotation decay at time of spin-down by the following formula.

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3. Test Results and Consideration

3.1 Rotation Loss Characteristics of High-Tc Superconducting Magnetic Bearings

SMB rotation loss characteristics were measured under conditions given in Table 3.

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<tr>
<td>Permanent magnet</td>
<td>Pr (RaPMPr) · Nd (RaPMNd2)</td>
<td></td>
<td></td>
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<tr>
<td>Initial SMB load, F_{init}</td>
<td>Loss of AMB &amp; C/S &amp; SC (0 N)</td>
<td>Loss of AMB &amp; C/S</td>
<td>Loss of AMB</td>
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</table>

The SMB is actuated or not\(^{10}\). On the other hand, the diamonds \(\bigcirc\) indicate AMB and C/S loss as a result of the SMB stator is placed at its normal position in the vacuum chamber and the rotor is supported by AMB alone. At this time, the difference with the black dots is equal to loss of C/S. C/S loss, however, is a result at room temperature, and strictly speaking, is different from C/S loss at low temperature when the SMB is actuated.

Other results show loss of AMB, C/S and SC as a result of various initial SMB loads and the rotor is supported by AMB and SMB. The difference with the diamonds is equal to SC loss at various initial SMB loads.

From this result, it is known that SC loss is quite large in comparison with AMB loss. It is also known that SC loss increases with increasing initial load.

The relationship of SC loss and initial load at 6 000 min\(^{-1}\) is shown by the white circles \(\bigcirc\) in Fig. 6. The figure shows that SC loss increases with increasing initial load.

From these results, it is possible the following phenomena are occurring in the SC: (1) magnetization of SC is changed when SC is moved in the upward axial direction in order to generate magnetic force for the SC that has achieved superconducting status in the magnetic field of the PM, (2) irregularity of magnetization of SC in the circumferential direction has become large, and (3) as a result, hysteresis loss increases when rotating, and SC loss increases. (A detailed study of these phenomena will be required in the future).

The results of SMB using RaPMNd2 are also shown by the black dots \(\bullet\) in Fig. 6. The figure shows the SC loss is smaller than for RaPMPr when RaPMNd2 is used. As indicated in Table 1, this result is the effect of irregularity of magnetic flux in the circumferential direction, this result suggests that SC loss can be reduced if irregularity of magnetic flux in the circumferential direction is made smaller.

3.2 Reduction of Levitation Force of SMB

Levitation force of SMB decreases as time elapses, and is notable in the process of A) and B).

A) Several minutes immediately after applying initial SMB load: mainly originates from SC flux creep. (In the case of Fig. 7, reduction of levitation force is F1 = 6.3 N.)
3. 3 Effect of Cooling Superconductor below 77K

As previously mentioned, SC loss was quite large in comparison to AMB loss. Thus, the effect of cooling the SC below 77K was studied for the purpose of reducing SC loss. The following experiment was conducted in order to study the effect of applying a pre-load with this test equipment. Experimental conditions are given in Table 4.

Fig. 8 gives typical results for the case where a pre-load of \( F_p = 534 \text{ N} \) is applied immediately before applying \( F_{init} = 293 \text{ N} \). The figure shows that F1 and F2 have been further reduced from that of Fig. 7. Fig. 9 shows the relationship of F2 and \( F_p/F_{init} \). Regardless of \( F_{init} \), F2 is reduced with increasing \( F_p/F_{init} \) (in other words increasing pre-load). Furthermore, when \( F_p/F_{init} \leq 2 \), F2 is almost 0 N. Thus, if a larger pre-load is applied, reduction of levitation force of SMB can be improved.

At this time, it is thought that the following phenomena are occurring in the SC: (1) magnetization of SC is changed when SMB stator is moved in the upward axial direction to apply \( F_p \) for the SMB, (2) at this time, SC begins to receive the influence of PM magnetic field when \( F_p \) is applied, (3) next, when magnetic force decreases to \( F_{init} \) when the SMB stator is moved in the downward axial direction, there is an area which is affected by the PM magnetic field before pre-load \( F_p \) is applied, and an area which is affected by the PM magnetic field when \( F_p \) is applied inside SC. (4) Here, magnetic force of SC in the former area decreases as time elapses, and increases in latter area, and (5) as a result, reduction of levitation force of SMB is improved as a whole.

Here, the relationship of pre-load and rotation loss is studied. The relationship of rotation loss at 6 000 min\(^{-1}\) and \( F_p/F_{init} \) is shown in Fig. 10. The figure shows the results of \( F_{init} = 300 \text{ N} \); rotation loss (including AMB, C/S and SC loss) increases with increasing \( F_p/F_{init} \).

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Experimental conditions are given in Table 5 and results in Fig. 11. The figure shows that if initial SMB load is the same, the rotation loss (AMB, C/S and SC loss) is reduced with decreasing SC cooling temperature.

Although not so notable as the technique of applying pre-
4. Conclusions

A summary is provided below.

(1) Rotation loss characteristics of a rotor supported without contact by active magnetic bearings and superconducting magnetic bearing could be measured under various conditions with the rotation loss measurement apparatus.

(2) Loss of superconductor increased with increasing initial load of the superconducting magnetic bearing. On the other hand, rotation loss of superconductors reduced with decreasing irregularity of magnetic flux of permanent magnet in the circumferential direction.

(3) Reduction of levitation force of superconducting magnetic bearings occurred in the following process: A) several minutes immediately after applying initial load, B) during acceleration process.

(4) Reduction of levitation force of superconducting magnetic bearings was improved by applying a pre-load. However, rotation loss of superconductors increased with increasing pre-load.

(5) Rotation loss of superconductors reduced with decreasing cooling temperature.

5. Final Summary

This research shows that although SMB loss is small when SMB loads is low, SMB loss becomes large when SMB load is high, and that it was the same level as AMB loss. Further reducing SMB loss will probably require development of a PM with ultra-small irregularity of magnetic flux in the circumferential direction and an SC of uniform material.

On the other hand, the test equipment used a low loss homo-polar type RaAMB electromagnet structure. The effect enabled AMB loss to be reduced by approximately 20% compared to the case where a conventional hetero-polar type is used. This is also the effect of this research.

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References


