Numerical and Experimental Analysis of the Rotation Speed Degradation of Superconducting Magnetic Bearings

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***Abstract*—The suppression of the rotation speed degradation of the Superconducting Magnetic Bearing (SMB) with the Permanent Magnet (PM) rotor including the layered insulator thin films is studied.**

The SMB system consists of the superconductor stator and the PM rotor, and is a no-contact bearing system using the levitation force between them. The SMB was expected to be applied to the electric power storage flywheel system because friction causes the rotation speed degradation and decreases the energy storage capability. However, it was found that the electromagnetic friction of the SMB was not zero, due to electromagnetic forces; 1) the magnetic force interaction between the inhomogeneous magnetic field of the PM rotor and the eddy current it induces in the cryostat, 2) the magnetic force between the inhomogeneous magnetic field of the PM rotor and the shielding current it induces in the superconductor, 3) the magnetic force between the magnetic field of superconductors yielding the levitation force and the eddy current induced in the PM rotor. This magnetic field of superconductor is inhomogeneous too, because the superconductors consist of several HTSC bulks. In this research, it was found that the 3rd phenomenon is most significant. So, we use the advanced PM rotor including the layered insulator thin films to suppress its eddy current and the degradation of the rotation speed. Using our SMB equipment, the rotation speed degradation was measured using the PM rotors with/without the insulator thin films and the electromagnetic frictions were compared to each other.

***Index Terms*—Eddy current, insulating film, rotation speed degradation, superconducting magnetic bearing (SMB).**

I. Introduction

THE FLYWHEEL system is developed as the electric power storage equipment to decrease the difference of electric power consumption between the daytime and the nighttime. In this system, the electric energy is stored as the kinetic energy of the rotation of the wheel on bearings. From the point of view of the electricity storage efficiency, the rotation speed degradation is an undesirable phenomenon because it is equal to the loss of the stored energy. But the ‘usual’ bearings cannot help generating the loss due to the physical contact between the stator and rotor. And so, they need the frequent exchanges of lubricant.

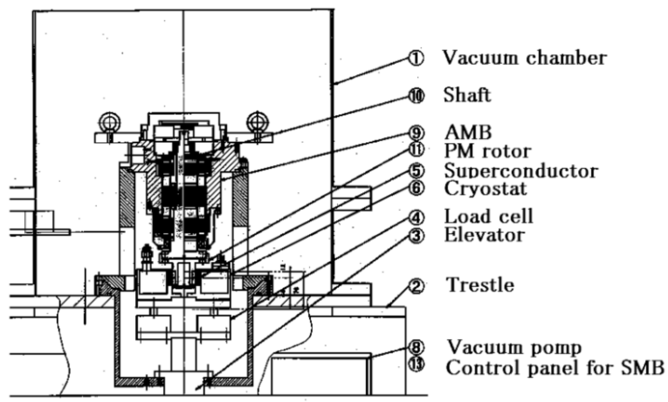

Fig. 1. Schematic drawing of SMB equipment.

Recently, the Superconducting Magnetic Bearing (SMB) applying the magnetic levitation force of the superconductor is expected as a good candidate of the bearing of the flywheel system. The SMB consists of the Permanent Magnet (PM) rotor, and the High Temperature Superconductor (HTSC) stator. The SMB has many advantages over the usual bearing: i) No energy loss by friction will be realized by the no-contact rotation due to the magnetic levitation. ii) The frequency of maintenance may be drastically decreased because of the lack of lubricant. iii) The good stability of PM rotor’s posture will be satisfied without the active stabilizer as the trapped magnetic field in the superconductor can automatically correct the displacement of the rotation axis from the initial position. For the above reason, research of the SMB is useful for the development of the flywheel system.

Against the prediction of advantage, however, it has been found that even the SMB has remarkable rotation speed degradation by the electromagnetic phenomena.

II. Mechanism of Rotation Speed Degradation in SMB

The rotation speed degradation of the SMB is the matter of the great importance to the development of the flywheel system. To evaluate it and to make clear its causes will lead to better performance of the flywheel. From this point of view, we developed the SMB experimental equipment shown in Fig. 1. In this equipment, the Active Magnetic Bearing (AMB) is adopted besides the SMB. The AMB is at the top of the rotation axis and the SMB is at the bottom. The AMB is a magnetic bearing with actively controlled feedback system, so while it is sensing

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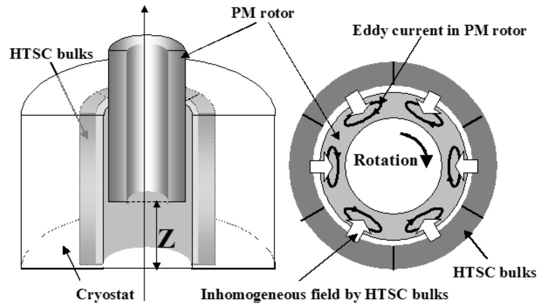

Fig. 2. SMB: composed of the PM rotor, the cryostat, and six HTSC bulks

PM rotor's position and posture with the sensor it is controlling them by the electromagnetic force. The rotation speed degradation by the AMB is much larger than the SMB in our equipment because its electromagnetic force is produced by the magnetic field of the active normal conducting coils and the eddy current induced in the rotor axis which is a normal conductor. But it has reported that this degradation has a possibility to be suppressed to almost zero [1]. So, in this research, our interests were paid mainly to the degradation by the SMB.

At first, we supposed the cause of the rotation speed degradation by the SMB is only the magnetic force interaction between the inhomogeneous magnetic field of the PM rotor and the eddy current induced in the cryostat (cause-A), or the shielding current induced in the superconductor (cause-B). But the characteristics of measurement results were against the prediction derived from cause-A and B. Namely, the degradation was remarkably enhanced when the levitation force of the SMB increased [2]. Such an enhancement cannot occur due to cause-A and B, because the degradation by the inhomogeneous magnetic field of the PM rotor should be independent of the levitation force [3], [4].

For explaining such 'anomalous' characteristics of the rotation speed degradation by the SMB, we noticed the shape of the HTSC stator. It consists of the cryostat and six HTSC bulks as in Fig. 2. The magnetic field distribution made by the six bulks is periodic in the circumference direction in each 60 degrees, because the shielding current does not flow across the boundaries between HTSC bulks. Looking from the rotating PM rotor, the magnetic field becomes like the AC field. As a result, the eddy current is induced in the PM rotor by this magnetic field. So this is the third mechanism of the rotation speed degradation (cause-C).

As one of the techniques to suppress the rotation speed degradation due to the cause-C, we proposed the advanced PM rotor with many insulator thin films to reduce with the eddy currents.

III. SMB Equipment

The SMB equipment has the AMB, the SMB and so on as shown in Fig. 1. The SMB is composed of the PM rotor, the cryostat and six HTSC bulks (Fig. 2). The cryostat is made of SUS304 stainless steel, and the HTSC bulks are YBCO. The outer and inner radius of the HTSC bulks are 34.4 mm and 24.4 mm, the height is 30.0 mm. The thickness of the cryostat is 1.0 mm. When the SMB is used, the cryostat is filled with nitrogen

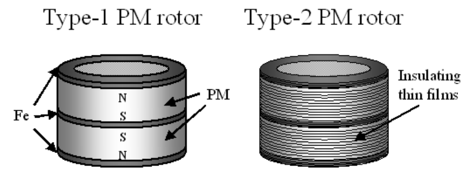

Fig. 3. Type-1 PM and type-2 PM rotor.

liquid, and the HTSC was cooled soaking in it. As the HTSC stator moves by a motor in Z direction from $Z = 0$ mm to $Z = 65.0$ mm, the relative position between the PM rotor and the HTSC stator can be changed. Another motor accelerates the PM rotor's rotation. The levitation force of the SMB is measured with three load cells. The rotation speed of the PM rotor is measured with a laser counter.

The PM rotor consists of two permanent magnets and three iron plates. The iron plates' role is to enhance the magnetic field. The outer and inner radii are 23.0 mm and 17.0 mm. The heights of PM's and iron plates are 12.0 mm and 2.0 mm, respectively. In this study, we made experiments using two types of PM rotors. One is the PM rotor without the insulating thin films, another is the advanced PM rotor with the insulating thin films. Their dimensions are the same, but the latter's two PM's consist of 2 mm thick PM plates and very thin insulating films as shown in Fig. 3. Here we named the former the type-1 PM rotor, and the latter the type-2 PM rotor. It is expected that the eddy current in the type-2 PM rotor is forcibly intercepted by the insulator films comparing with the type-1. As a result, the rotation speed degradation due to cause-C will be suppressed if the type-2 PM rotor is used.

IV. Experimental Method

A. This Experiment Were Made in the Following Processes

1) The pressure in the vacuum vessel is kept under 3.0 Pa.
2) The AMB levitated the PM rotor.
3) The relative position of the PM rotor and the HTSC stator is set at the initial position Z_{init}. This position was the 'field cooling position'.
4) The liquid nitrogen was filled in the cryostat and the HTSC bulks are cooled.
5) The levitating PM rotor was rotated by a motor and the speed is kept at 100 rps.
6) The motor was switched off.
7) The time-variation of the rotation speed of the PM rotor was measured for 20 minutes.
8) The relative position Z of the PM rotor and the HTSC stator was changed.
9) The processes from 5 to 8 were repeated for other Z values.

B. Measurement of the Degradation by the AMB

First of all, the time-variation of the rotation speed degradation due to only the AMB was measured, when the HTSC is located at the farthest from the PM rotor : $Z = 65.0$ mm. It has been already confirmed that this degradation is independent from the SMB.

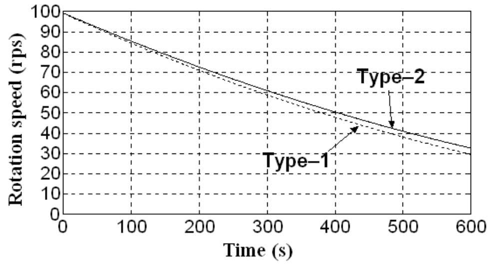

Fig. 4. Time-variation of the rotation speed using only the AMB.

C. Measurement of Contribution of the Cryostat to the Rotation Speed Degradation

The time-variation of the rotation speed degradation by the effect of the cryostat (cause-A) were measured when the PM rotor was inserted into the HTSC stator without cooling. The effect due to cause-A can be evaluated as the difference from the result of the first experiment. The position Z of the HTSC stator was 30 mm, 20 mm, 10 mm and 0 mm.

D. Measurement of the Contribution of the SMB to the Rotation Speed Degradation

The time-variation of the rotation speed degradation by effect of the superconductor (cause-B and -C) was measured. We selected two cases of Z_{init} : 30 mm and 10 mm. The measurements were performed at $Z = 30$ mm, 20 mm, 10 mm and 0 mm for $Z_{\text{init}} = 30$ mm, and $Z = 10$ mm, 7.5 mm, 5 mm, 2.5 mm, and 0 mm for $Z_{\text{init}} = 10$ mm.

These measurements were done using both PM rotors, type-1 and type-2.

V. ANALYSIS OF FRICTION

If there is no displacement of the PM rotor from the z-axis, the kinetic equation of the PM rotor can be written as,

$$I\dot{\omega} = N_z, \tag{1}$$

where I, ω, N_z are the inertial moment of the PM rotor, the rotation speed and the z component of torque. Because the torque N_z should be proportional to the rotation speed ω, the following equation is obtained,

$$\eta\omega = N_z, \tag{2}$$

where η is the friction constant. From (1) and (2), the rotation speed ω is denoted by the following equations,

$$\begin{aligned} \omega =& \omega_0 \exp\left(-\frac{\eta}{I}t\right), \\ \log\omega =& \log\omega_0 - \frac{\eta}{I}t, \end{aligned} \tag{3}$$

where ω_0 is the initial rotation speed. Assuming a linear relation between each friction coefficient due to the AMB (η_{AMB}), the cryostat (η_{cryo}) and the HTSC bulks (η_{SC}), (3) are expressed as

$$\log\omega = \log\omega_0 - \frac{\eta_{AMB} + \eta_{cryo} + \eta_{SC}}{I}t. \tag{4}$$

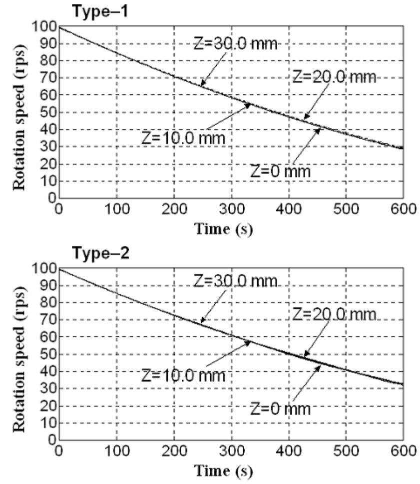

Fig. 5. Time-variation of the rotation speed using type-1 and type-2 PM rotor.

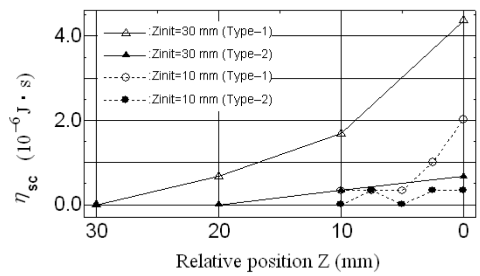

Fig. 6. η_{AMB} of η_{cryo} of type-1 and type-2 PM rotor.

Using (4), we evaluated each friction coefficient η_{AMB}, η_{cryo} and η_{SC} at $\omega = 100$ rps from the measurement of the time-variation of ω. The inertial moment I was 3.363^{-3} J $\cdot$ s^2.

VI. EXPERIMENTAL RESULTS

A. The Degradation by Only the AMB and Contribution of the Cryostat to the Rotation Speed Degradation

Fig. 4 shows the experimental result of the measurement of the degradation by only the AMB. The degradation of the rotation speed was about 70 rps at $t = 600$ sec. The coefficient η_{AMB} of the type-1 and type-2 at $\omega = 100$ rps could be obtained as $\eta_{AMB} = 6.1 \times 10^{-6}$ and 0.5×10^{-6} J$\cdot$s^2 respectively.

Fig. 5 shows the experimental result of the measurement of the degradation by the AMB and the cryostat. It was found that the contributions by the cryostat are very small. The friction coefficient η_{AMB} and η_{cryo} could be obtained as Fig. 6 for both cases of the type-1 and type-2 PM rotors.

B. Contribution of the SMB to the Rotation Speed

Fig. 7 shows experimental results of the rotation speed degradation due to the AMB, the cryostat and the HTSC in the case of the field cooling position $Z_{\text{init}} = 30$ mm and 10 mm. It is found that the degradation of type-2 PM rotor is smaller than that of type-1.

C. Comparison of η_{SC} of Ttype-1and Type-2 PM Rotor

Fig. 8 shows the friction coefficient due to the cause-B and -C. In the case of type-1 PM rotor, η_{SC} is enhanced as Z de-

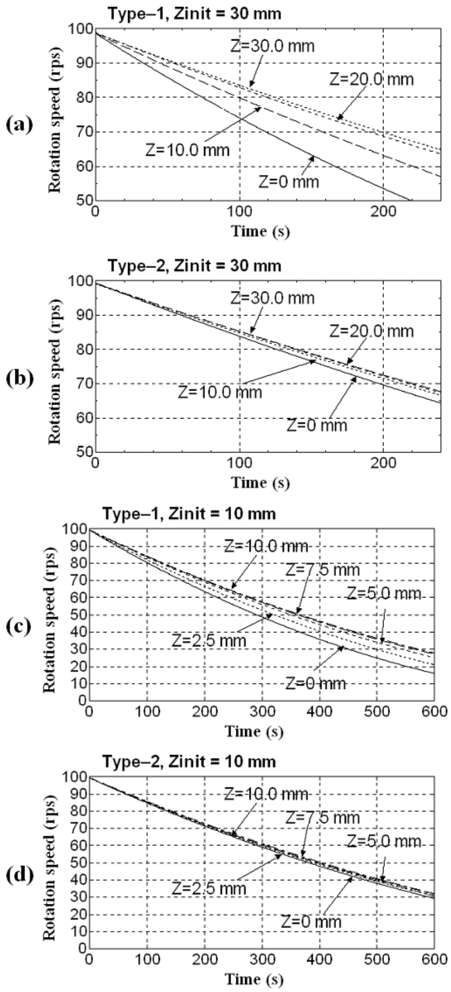

Fig. 7. Time-variation of rotation speed at $Z_{\text{init}} = 30$ mm and 10 mm using type-1 PM rotor.

creases, on the other hand, the enhancement is suppressed in the case of type-2. This result indicates the following two facts: i) The PM rotor with the insulating thin films are very effective in suppressing the rotation speed of degradation of the SMB because it interferes with the eddy current in the PM rotor. ii) The main cause of the enhancement of η_{SC} is the cause-C. The

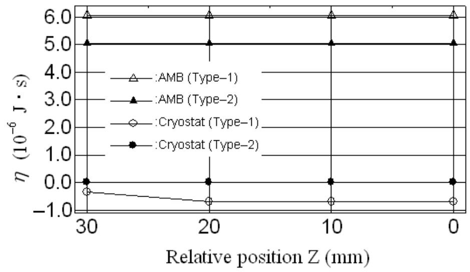

Fig. 8. Comparsion of η_{SC} of type-1 and type-2 PM rotor.

cause-B's contribution on the rotation speed degradation is negligibly small, because if this is remarkable, the rotation speed degradations in Fig. 7(a) and (7) at $Z = 0$ mm must be same by the same amount of the magnetic field of PM rotor.

VII. Conclusion

We proposed an advanced PM rotor with insulating thin films on the assumption that the biggest cause of the rotation speed degradation of SMB system is the in homogeneous magnetic field by the divided HTSC bulks and the eddy current in the PM rotor induced by the field.

The measurement showed that the advanced PM rotor gave much less rotation speed degradation than the PM rotor without the insulator thin films. This suggests that the SMB with the advanced PM rotor is very useful for the development of the energy storage flywheel system.

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