Modelling the Energy Losses of a Superconducting Magnetic Bearing due to the Change of the Levitation Height Under Gravity

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Abstract. This paper describes the losses of the rotor of the prototype superconducting magnetic bearing (SMB) that is employed for a polarization modulator of a Cosmic Microwave Background polarization experiment. The stator is composed of 20 segmented YBCO bulks, and these multiple superconductors produce the inhomogeneous magnetic field particularly due to the gravitational displacement of the rotor magnet position from the initial field cooling. This inhomogeneity causes the power dissipation to the spinning rotor. We estimated the power dissipation originating from this inhomogeneous magnetic field by using a numerical approach. The superconductors were modelled as electrically conducting components in the numerical simulation to avoid the complexity in modelling superconductivity. The results show about 4 mW dissipated at the rotor.

1. Introduction
One of the recent challenges in cosmology is to probe the theory of cosmic inflation, which is the exponential expansion of space in the early universe at around $10^{-36}$ seconds after the beginning of the universe. This theory predicts the existence of the odd parity polarization pattern, so-called B-mode, in the Cosmic Microwave Background (CMB) radiation and is potentially probed by the measurement of this electromagnetic radiation. A number of the CMB polarization experiments are in progress [1-3]. One of the space-borne missions is called LiteBIRD, Lite (Light) satellite for the studies of B-mode polarization and Inflation from background Radiation Detection [1-2]. The CMB radiation is observed as the 3 K blackbody radiation. However, the signal amplitude of the B-mode CMB radiation is predicted to be about $10^9$ times smaller than that of the 3 K black body radiation.

One of the key instruments for this precise measurement is a Half-Wave Plate (HWP) polarization modulator. We have been developing the rotational mechanism for the HWP that rotates at about 1 Hz. The temperature of the HWP has to be kept below 20 K in order to minimize the thermal emission. Due to the limited cooling capacity in a satellite, the acceptable energy dissipation at the rotational mechanism should be lower than 4 mW in order to be compatible with the system requirement. Thus, a
superconducting magnetic bearing (SMB) is a natural candidate as the rotational mechanism of the polarization modulator due to low energy dissipation from the operation at the cryogenic temperature.

In the past studies, we reported the energy loss of our prototype SMB system (see figure 1) at below 10 K [4]. The prototype SMB consists of a rotor and a stator. The rotor consists of an array of segmented SmCo permanent magnets sandwiched between iron magnetic circuit components, and the stator consists of an array of YBCO bulks. In this configuration, the rotor is fully levitating at the time of the rotation, thus, the rotor is thermally isolated except through a radiative coupling and an electromagnetic coupling in a cryostat or in space environment. Any heat input can raise the rotor temperature due to the poor heat exchange through radiation. We observed the increase of the rotor temperature, and we derive the heat into the rotor from the rotation to be about 9 mW.

While there are a number of electromagnetic couplings with multiple loss mechanics [5-6] as shown in figure 2, in this paper we focused on the loss mechanism associated with the SMB rotor in order to explain the source of the temperature rise of the rotor. Any inhomogeneity of the trapped magnetic field in YBCO can be a source of the AC loss with respect to the spinning magnet via both the hysteresis and eddy current losses. We simulated the change of the magnetic field inhomogeneity due to the displacement of the levitation height under the gravity from the initial position at the field cooling. While it is desirable to model the properties of a superconductivity fully, this is numerically challenging because of the strong nonlinear electromagnetic characteristics. Thus, we have taken an effective approach to treat a YBCO as an electrically conducting component by obtaining approximate current paths in the YBCO superconductors.

In Section 2, we describe the properties of our SMB and its configuration. In Section 3, we describe the analysis method, i.e. modelling the effect of the gravity to the trapped magnetic field, effective way of modelling the YBCO, and loss calculation given the modelled inhomogeneity. In Section 4 and 5, we show the results and summary.

Figure 1. Prototype rotation mechanism of LiteBIRD polarization modulator.

Figure 2. A tree of the provisional sources of loss in the constructed rotation mechanism.
2. **Superconducting magnetic bearing (SMB)**

Figure 3 shows the schematic overview of the SMB and its cross section. The rotor consists of 64 SmCo permanent magnets (Shin-Etsu R33H). The permanent magnets are also placed in the ring-shaped iron yokes (S45C), which serves as a magnetic circuit, and it homogenizes the magnetic field that is within the range of 2.1% at the surface of the YBCO bulk [4]. The stator is a YBCO bulk ring that has an inner diameter of 380 mm. The YBCO ring is divided into 20 three-seed pieces in the circumferential direction. The rotor weight of this prototype SMB is 18 kg.

When the stator YBCO bulks produce the levitation force under gravity, the induced superconducting current flows within the individual YBCO bulks and also around each domain. As a result, they create an inhomogeneous magnetic field. We measured the magnetic field at the rotor surface with and without a 20 kg weight, and their difference is shown in Figure 4. It represents the magnetic flux density distribution due to the induced current for the levitation force of 20 kg. This distribution is experimentally measured along the circumference of the magnet at the radius of 215 mm. Since the magnetic flux density distribution is repeated at each angular range that corresponds to the angular width of the YBCO bulk, figure 4 only shows the range of 18 degrees, i.e. one YBCO bulk width. This magnetic field inhomogeneity can contribute as a cause of the eddy current loss and hysteresis loss at the rotor during the rotation.

![Figure 3](image1.png)

**Figure 3.** (a) A schematic overview of the SMB and the corresponding pictures. (b) A cross-sectional view of the SMB system

![Figure 4](image2.png)

**Figure 4.** Difference of measured magnetic flux density distribution on the rotor surface with and without a 20kg weight along the radius of 215 mm. It is originated by the induced current in the stator YBCO bulks by the change of the magnetic field.
3. Analysis method

We describe the analysis method to estimate the energy loss in the rotor from the magnetic field inhomogeneity caused by the YBCO bulk. The analysis method consists of three steps; 1) estimate the induced current path in the stator YBCO bulks with a transient magnetic field analysis, 2) analyse the induced current distribution with mock coils, and 3) compute the rotor losses, which are generated by the current in the mock coils. In each analysis step, we used the electromagnetic analysis software, JMAG-Designer® Ver. 18. 1. Note that the ring magnet is also segmented, but we neglected the inhomogeneity from this segmentation for simplicity and treat the ring magnet as a radially magnetized permanent magnet ring.

3.1 Estimation of the current path in the YBCO bulk

This section describes the step 1. We conducted a finite element method (FEM) analysis with a 1/20 model shown in figure 5 using an approximate conductor model for the YBCO bulk superconductor. The $A-V$ formulation was used in the analysis. The induced current distribution in the YBCO bulk was analysed when the rotor moved downward by 1 mm from the starting levitation height of 5 mm with a speed of 0.01 m/s. We adopted anisotropic conductivity, in-plane and axial directions, in modelling the YBCO bulk as an electrically conducting component. The one bulk YBCO has three domains and each domain is grown from each seed. We arranged junctions between YBCO domains in the FEM model in order to model the induced current that flows in overall bulk as well as within the domain. The in-plane conductivity of YBCO bulk was set at $1.0 \times 10^{15}$ S/m, which is higher than the assumed minimum conductivity of YBCO bulks, $1.0 \times 10^{12}$ S/m [5]. The electrical conductivity of the junction is set at $8.0 \times 10^{8}$ S/m, which is lower value as compared to the other regime. We checked if the choice of the conductivity at the junction in a range of $1.0 \times 10^{7}$ to $1.0 \times 10^{12}$ S/m did not affect the induced current distribution qualitatively. The analytical condition is summarized in table 1.

![Figure 5](image)

**Figure 5.** 1/20 FEM model of the SMB (a) Overview (b) Top view of the YBCO bulk

| Parameter                                           | Value       |
|-----------------------------------------------------|-------------|
| Initial levitation gap                              | 5 mm        |
| Final levitation gap                                | 4 mm        |
| Speed                                               | 0.01 m/s    |
| In-plane electric conductivity of YBCO domains      | $1.0 \times 10^{15}$ S/m |
| In-plane electric conductivity of junctions         | $8.0 \times 10^{8}$ S/m |
| Axial electric conductivity of YBCO                 | $1.0 \times 10^{3}$ S/m |
3.2 Modelling the induced magnetic field from YBCO using a mock coil

In order to model the induced magnetic field from the YBCO bulk, we created the three mock coils in the YBCO as shown in figure 6. This shall be the input, inhomogeneity of the magnetic field in the stator side, in order to compute the energy loss in the rotor. We have tuned the current injected into the three coils in order to match the magnetic field distribution that is measured experimentally as shown in figure 4. Given the tuned magnetic field, we also check the consistency between the computed levitation force and the actual weight, 20 kg which corresponds to the levitation force of 196 N.

3.3 Loss analysis with mock coils

Loss analysis was conducted when the rotational speed of the SMB was 1 Hz with the mock coils. The inhomogeneity of magnetic field distribution that originates from the PMs at the rotor is quite small. Therefore, the change of the induced current at the YBCO bulk would be sufficiently small and the current was assumed to be fixed in this loss analysis. The levitation height was assumed to be 4 mm. Table 2 describes the conductivity of components in the rotor for the eddy current analysis. The conductivity of aluminium alloy and iron yoke was the measured value at the cryogenic temperature \([7]\). Due to the lack of the information, we assumed the conductivity of the permanent magnet is twice that at room temperature and used the hysteresis loss characteristics of S45C at the room temperature. The injected current obtained by the analysis described in section 3.2 is multiplied by 0.9 based on the SMB rotor weight, 18 kg, while the levitation force generated by the injected current is 20 kg.

| Material                  | Electric conductivity |
|---------------------------|-----------------------|
| Aluminium alloy           | \(3.3 \times 10^7\) S/m| |
| Iron yoke (S45C)          | \(1.3 \times 10^7\) S/m| |
| Permanent magnet (R33H)   | \(2.5 \times 10^6\) S/m| |

4. Results

Figure 6 shows the distribution of the induced current in the YBCO when the rotor moved 1 mm downward from the field-cooled position due to the gravity. This current distribution indicates that there are three types of current paths. Therefore, three types of coils were created based on the current distribution as shown in the right panel of figure 6. We labelled the coils as coil 1 (green), coils 2 red, and coils 3 (blue), respectively.

Figure 7 shows the magnetic flux density distributions when 100 A was injected into each coil. Each current in the three mock coils was fitted by minimizing the difference between the data (figure 4) and the magnetic field from the three coils using the least square method. Figure 7 shows the magnetic flux density that is generated by each mock coil. The current in the three mock coils is summarized in table 3. Figure 8 shows the comparison between the experimentally measured magnetic field distribution along the circumference at the radius of 215 mm and the simulation result. We concluded that the computed magnetic flux distribution well represents the experimental data within 15%.

| Mock coil | Fit result of coil current | Current in loss analysis (Fit result of coil current times 0.9) |
|-----------|----------------------------|---------------------------------------------------------------|
| Coil 1    | 136 A                      | 122 A                                                          |
| Coils 2   | 355 A                      | 320 A                                                          |
| Coils 3   | 255 A                      | 230 A                                                          |
Figure 6. Induced current distribution and mock coils

Figure 7. Magnetic flux distribution on the rotor surface along the circumference at the radius of 215 mm when the current of 100 A is injected into each mock coil

Figure 8. Comparison of the experimental data and FEM analysis result with mock coils
Figures 9 and 10 show the loss analysis result when the rotor rotates at 1 Hz. In figure 9, each line corresponds to each component of the rotor. The largest contribution comes from aluminium alloy and the value is about 2.5 mW. Total power dissipation from the eddy current is about 3 mW. Hysteresis loss at the iron yoke is 1.0 mW as shown in figure 10. Therefore, we conclude the total power dissipation including eddy current loss and hysteresis loss of iron originating from the induced current at the stator YBCO bulks due to gravity is 4.0 mW.

![Figure 9. Eddy current loss as a function of time](image1)

![Figure 10. Hysteresis loss at the yoke as a function of frequency](image2)

5. Summary and future work
This study specifically focused on the loss at the SMB rotor. We have conducted the loss analysis when the rotor of the SMB rotated at 1 Hz under the gravity. We employed the effective method to model the superconducting material by using the high electrical conductivity material. Furthermore, we introduced the mock coils to generate the magnetic flux density from the YBCO. In this way, we bypassed the modelling of superconductivity.

The validity of the modelling method was checked by the consistency between the reproduced current distribution and the levitation force within 10%. The estimated power dissipation in the rotor due to the segmented YBCO together with the effect of the gravity is less about 4 mW, including 3 mW of eddy
current loss and 1 mW of hysteresis loss while the past experiment showed 9 mW. This result indicates that nearly a half of the loss in the rotor of the SMB system can be explained by the magnetic field inhomogeneity originated from the gravity. We should stress that the superconductor was modelled as a conducting component in this analysis to estimate the current path for simplicity. Hence, the more precise loss estimation shall be carried out by taking into account the modelling of superconductivity.

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