Evaluation of loss characteristics of superconducting magnetic bearings for LiteBIRD satellite by three-dimensional finite element method analysis

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Abstract. The polarization modulator of LiteBIRD satellite is required to be used by continuously rotating the half-wave retarder under a low temperature environment of about 10 K. Then, it becomes an important issue to reduce heat generation due to rotation loss. Therefore, a rotation mechanism in a cryogenic environment by a superconducting magnetic bearing (SMB) using the pinning effect of the bulk superconductor has been studied. In SMB, because of the pinning effect of superconductor, it is possible to rotate the half-wave retarder stably floating, and it is possible to avoid frictional heat due to contact. The half-wave retarder is incorporated inside the rotating part of the superconducting magnetic bearing composed of the permanent magnet ring and the iron yoke. At this time, since the permanent magnet ring divides the parallel magnetized permanent magnets into pieces, a gap is formed at the joint of the permanent magnets. For this reason, the magnetic field distribution generated by the permanent magnet ring is not uniform. Although SMB can reduce friction as compared to mechanical bearings, the magnetic properties of the bulk superconductor change due to the magnetic field fluctuation caused by such ununiformity of the magnetic field, resulting in energy loss. In this study, heat generation in bulk superconductor in SMB is evaluated by three-dimensional finite element method. First, using JMAG Designer 17.0, the magnetic field distribution created by the rotor side is obtained by static magnetic field analysis. Next, using the COMSOL Multiphysics 5.3a, by applying the magnetic field distribution created by the rotor side obtained above and rotate the magnetic field, the loss generated in the bulk superconductor is investigated. The resulting loss value satisfied the required value.

1. Introduction

1.1. LiteBIRD and the polarization modulator

LiteBIRD is a medium size artificial satellite planned by JAXA and others with the intention of launching in mid-2020's. The aim is to observe the polarization of the cosmic microwave background radiation (CMB) and to detect polarization signals [1, 2]. They have traces of "primitive gravity wave" which is evidence of inflation. The appearance of LiteBIRD is shown in Figure 1.
One of the observation instruments installed in this satellite is a polarization modulator, and an optical element called a half wave plate is continuously rotated in a low temperature environment below 10 K. The low temperature environment is realized by a refrigerator for space. But since the refrigerating capacity is limited, it is necessary to suppress the heat dissipation caused by continuous rotation of the half wave plate. In general mechanical bearings, it is difficult to use in low temperature environments because of heat generated by friction. Therefore, it is studied to adopt superconducting magnetic bearing (SMB). Figure 2 and Figure 3 show the appearance of the LiteBIRD polarization modulator targeted in this study.

Figure 1. LiteBIRD satellite

![LiteBIRD satellite](image)

Figure 2. Structure of LiteBIRD polarization modulator

![Structure of LiteBIRD polarization modulator](image)

Table 1. Requirement of the heat dissipation

|          | Rotor | Stator | Total |
|----------|-------|--------|-------|
| Drive    | < 1   | < 1    |       |
| SMB      | < 3   |        |       |
| Total    | < 1   | < 4    | < 5   |

Figure 3. Experimental model of LiteBIRD polarization modulator

1.2. Superconducting Magnetic Bearings (SMB)

Figure 4 show the fundamental structure of the SMB. The rotor side is a ring of Nd-Fe-B magnet magnetized in the radial direction. Also, the PM ring is sandwiched between two iron yoke rings to form a magnetic circuit [3]. Although the iron yoke is not divided, the PM ring is divided into 64 pieces in the circumferential direction. The stator side is YBCO bulk ring. Bulk is divided into 20 pieces in the circumferential direction. The rotor side can stably levitate due to the pinning effect and its height is 3 to 5 mm. The rotor continuously rotates at 60 rpm.

In this structure, the magnetic field created in the circumferential direction by the rotor side is non-uniform. The reasons for this are as follows: 1) there are gaps between the magnets, 2) each magnet is magnetized parallel to the radial direction, 3) an error occurs in the magnetization of the magnet in assembly, as shown in Figure 5. Since such a non-uniform magnetic field rotates over YBCO bulk, an alternating magnetic field is applied to YBCO bulk, eddy current is induced, and the heat loss occurs [4]. The purpose of this paper is to estimate the loss of YBCO bulk in SMB by three-dimensional finite element method analysis.
2. Analysis Procedure

The analysis procedure to estimate the value of the AC loss is shown below.

1) FEM analysis with using conductors instead of superconductors is carried out. The electric conductivity of conductors is varied in the range of $10^4$ to $10^{13}$. Thus, the electric field distribution in the conductor and the dependence of the loss on the electric conductivity are obtained. At this time, for the equation (1) below, the electric field is determined only by the distribution of the magnetic flux density.

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Therefore, the electric field distribution obtained by this analysis is considered to be equivalent to that applied to YBCO bulk.

2) According to the $n$-value model, the electric conductivity ($\sigma$) in the YBCO bulk differs depending on the location. But the minimum value of $\sigma$ can be estimated based on the electric field distribution obtained in 1) and the equation (2), which is the electric field dependency of the electric conductivity obtained from the $n$-value model [5, 6].

$$\sigma_{sc} = \frac{J_c}{|E|} \left( \frac{|E|}{E_c} \right)^{\frac{1}{n}}$$

Figure 4. Structure of SMB

Figure 5. Cause factors of magnetic field inhomogeneity
3) The maximum value of the energy loss in YBCO bulk is determined, based on the minimum electric conductivity in YBCO bulk obtained in 2) and the relationship between loss and electrical conductivity obtained in 1).

By the above flow, the upper limit of the energy loss in YBCO bulk can be estimated.

3. Result and Discussion

3.1. FEM Analysis

We analyzed the 1/64 model using the conductor replaced with the superconductor. The model is shown in Figure 6. Finite element method (FEM) analysis was carried out with $A-V$ formulation. The results are shown in Figure 6 to Figure 10. Figure 6 shows the eddy current distribution on the conductor surface. And we saw the eddy current moves with the rotation of the rotor. The electric field distribution applied to the conductor is shown in Figure 7, and from this result, the maximum value of the electric field estimated to be $1 \times 10^{-4}$ [V/m]. This is necessary for evaluating the heat loss in YBCO bulk. Figure 8 and Figure 9 shows the magnetic flux density distribution. Figure 10 shows the loss as a function of the electrical conductivity: $\sigma$. In the region where $\sigma$ is small, loss increases as $\sigma$ increases. On the other hand, in the region where $\sigma$ is large, the influence of the shielding effect by the eddy current becomes dominant and the AC loss is reduced.

![Figure 6. Induced current on the top surface of the conductor](image)

![Figure 7. Electric field](image)

![Figure 8. Magnetic flux density distribution in the circumferential direction](image)
3.2. Estimation of the energy loss in YBCO bulk

Figure 11 and Figure 12 show how to estimate the upper limit of loss in YBCO bulk using the above results. The parameters used in estimation is shown in Table 2. First, as shown in Figure 9, we estimated the minimum value of the electric conductivity in YBCO bulk: $1 \times 10^{12}$ [S/m]. This is because equation (2) is a monotonically decreasing function of $|E|$. In Figure 11, $E_{\text{max}}$ was set to $1 \times 10^{-4}$ [V/m] according to the above result and $J_{\text{max}}$ was calculated from $E_{\text{max}}$. From the results in Figure 10, loss tends to decrease near $1 \times 10^{12}$ [S/m]. Therefore, the value of 2.2 mW is considered to be the maximum value of loss in YBCO bulk, as shown in Figure 12.
4. Conclusion and Future Works
In this paper, we estimated the AC loss in YBCO bulk of SMB mounted on LiteBIRD satellite. In consideration of the period in the circumferential direction of the SMB, analysis was carried out using the 1/64 model and conductors instead of YBCO bulk. From the results of the analysis, it was possible to obtain the loss as a function of the electrical conductivity. Next, from the maximum value of the electric field obtained by this analysis and the n-value model, the minimum value of electric conductivity in YBCO bulk was estimated. Finally, from minimum value of the electric conductivity and the loss graph, the upper limit of loss occurring in YBCO bulk was estimated. We concluded it as 2.2 mW.

However, we measured the magnetic field distribution in the circumferential direction with a prototype machine to find that it is very different from numerical analysis here. This seems to have a large influence by individual differences of the divided NdFeB magnets. From now on, it is necessary to analyze with considering the actual magnetic field distribution and we need find the method of analysis with the superconducting model.
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