Vibrational characteristics of a superconducting magnetic bearing employed for a prototype polarization modulator

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Abstract. We present the vibrational characteristics of a levitating rotor in a superconducting magnetic bearing (SMB) system operating at below 10 K. We develop a polarization modulator that requires a continuously rotating optical element, called half-wave plate (HWP), for a cosmic microwave background polarization experiment. The HWP has to operate at the temperature below 10 K, and thus an SMB provides a smooth rotation of the HWP at the cryogenic temperature of about 10 K with minimal heat dissipation. In order to understand the potential interference to the cosmological observations due to the vibration of the HWP, it is essential to characterize the vibrational properties of the levitating rotor of the SMB. We constructed a prototype model that consists of an SMB with an array of high temperature superconductors, YBCO, and a permanent magnet ring, NdFeB. The rotor position is monitored by a laser displacement gauge, and a cryogenic Hall sensor via the magnetic field. In this presentation, we present the measurement results of the vibration characteristics using our prototype SMB system. We characterize the vibrational properties as the spring constant and the damping, and discuss the projected performance of this technology toward the use in future space missions.

Introduction

A cosmic microwave background (CMB) is electromagnetic microwave radiation from the big bang. It is still observable isotropically from the whole sky today. One of most important research topics in the current cosmology and high-energy physics is to study the cosmic inflation theory, which predicts a rapid expansion of the universe after $\sim 10^{-38}$ seconds from the beginning of the universe [1, 2]. The inflation solves several mysteries of the standard cosmology and it can provide a foothold for new physics in high energy physics. The theory predicts that the inflation left the divergence free pattern in the CMB polarization, called "B-mode". Therefore, the experimental discovery of the cosmic inflation is possible by observing the CMB B-mode polarization. A world-wide keen discovery race is spreading among many CMB polarization experiments. Correspondingly, the instrumental development has progressed remarkably.

One of the critical instruments for a precise measurement of the CMB polarization is a "polarization modulator". It consists of an optical element, a half-wave plate (HWP), and a rotational mechanism. The continuously rotating HWP modulates the CMB polarization signal synchronously at the four times of the rotational frequency of the HWP, a few Hz. The continuously rotating HWP have to be maintained at cryogenic temperature ($\sim$ 10 K) in order to reduce the detector noise originating from the excess thermal emission of the HWP itself to the detector. It is therefore necessary to use a rotational mechanism which allows to rotate with minimal heat dissipation at cryogenic temperature.

An superconducting magnetic bearing (SMB) is a contactless bearing [3]. it employs an array of high temperature superconductor tiles as a stator and a permanent magnet as a rotor. The rotor levitates above a stator and spins without contact. There is no friction due to the physical contact, and thus this technology is well matched for use in the polarization modulator, which is required to operate at the cryogenic temperature with minimal heat dissipation. This unique application is first investigated for use in a balloon-borne CMB polarization experiment, called EBEX [4]. The successful implementation accelerates the interest for further development toward the next generation experiment from a ground telescope to a satellite mission [5].

While the heat dissipation is expected to be smaller than that from a conventional mechanical bearing, the stiffness of the rotor over the stator is expected to be less rigid as compare to the mechanical bearing. Therefore, the levitation based bearing has an inherent tradeoff between the heat dissipation and the stiffness. In this paper, we discuss the design tradeoff for use of this SMB technology for a future CMB polarization experiment. We present our prototype SMB system, rotor diameter of 384 mm, and the measurements of the spring constant and the damping coefficient to characterize the mechanical properties. In order to characterize the mechanical properties, we use a laser displacement gauge, which we can use in a lab but cannot use during observations. As an alternative solution, we also introduce a Hall sensor to monitor the mechanical properties simultaneously. We discuss the consistency between the two independent measurements and propose the concise passive technic to monitor the vibrational motion of the rotor magnet at the cryogenic temperature. Finally we projects the results toward the design of the SMB system for the polarization modulator.

Experimental Setup

We conducted vibration measurement using a Styrofoam bucket with liquid nitrogen as shown in the left pannel of the Figure 1. Although the SMB system is operated inside the 4 K cryostat in an actual CMB observation, a liquid nitrogen temperature (77 K) is sufficient for the vibration measurement.

We prepare the SMB system with inner diameter of 384 mm. Due to the relatively large diameter, The ring shaped magnet, which consists of 16 segmented NdFeB magnets, are used as the rotor magnet. Each segmented magnet is magnetized axially with the magnetic remnance of 1.24 T. A $\mathrm{Y_{1.65}Ba_2Cu_3O_x}$ (YBCO) superconductor is used as the stator, which is one of High Temperature Superconductors and its transition temperature is $\sim$ 95 K. The YBCO array is formed in a ring shape using three-seeded YBCO tiles. The NdFeB ring magnet and the YBCO array are fabricated by Adelwitz Technologiezentrum GmbH (ATZ) company in Germany [**?**]. The YBCO array is submerged by the liquid nitrogen but the rotor magnet is exposed to the room environment. We set a space between the rotor magnet and YBCO array with aluminum plates at room temperature environment, and then a liquid nitrogen was poured. After the temperature of the YBCO array becomes below its transition temperature, the plates are removed for magnetic levitation. The levitation height, defined as the distance between the bottom of the rotor magnet and the top of the YBCO array, is controlled by the thickness of the aluminum plate. We measure the rotor vibration in the axial direction with four different levitation heights (3 mm, 6 mm, 9 mm and 12 mm). In order to enhance the vibration amplitude, an external impulse force was applied by hand in the axial direction.

The displacement of the rotor is monitored by a laser displacement gauge, which is mounted on an aluminum frame at a distance of 260 mm from the rotor magnet as shown in the left pannel of the Figure 1. We also monitor the magnetic field by a cryogenic Hall sensor installed between the rotor magnet and YBCO array.

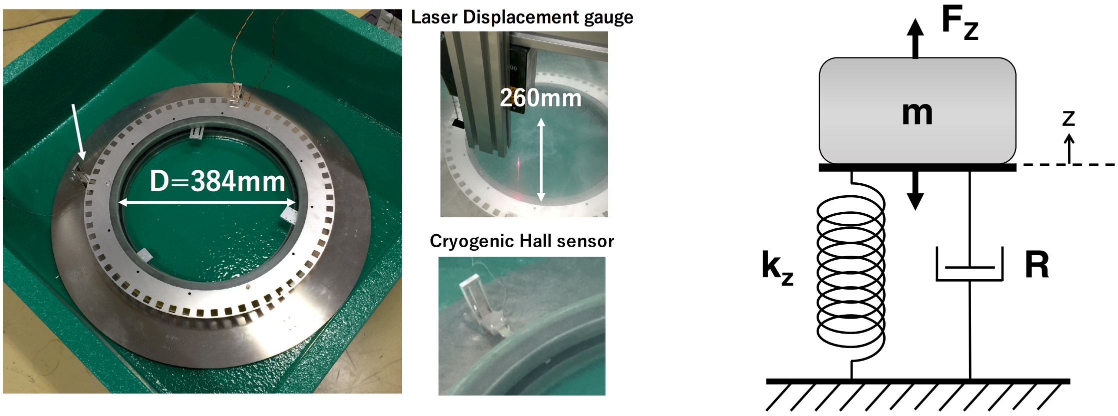

Figure 1. (Left) The experimental setup for the vibration measurements for D = 384 mm. (Right) Mass-Spring-Damper model.

Result and Discussion

An axial vibration of the rotor can be described by a damping motion of a mass-spring-damper model [cite!] shown in the right pannel of the Figure 1. The motion of this model is expressed by

$$m\frac{\partial^2 x}{\partial^2 t} + R\frac{\partial x}{\partial t} + k_z x = 0, \tag{1}$$

where m is the mass of the rotor (3.0 kg), R is the damping coefficient and k_z is the spring constant. Under the condition of the damping motion, the solution of the equation (1) is

$$x = A\mathrm{e}^{-\zeta\omega_0 t}\cos(\sqrt{1-\zeta^2}\ \omega_0 t + \phi), \tag{2}$$

where $\zeta = R/2\sqrt{mk_z}$ is the damping ratio and $\omega_0 = \sqrt{k_z/m}$ is the undamped angular frequency. The parameters of A and ϕ are the amplitude and the phase determined by the magnitude and the timing of the external impulse force. Thus, these values are treated as an arybitary values.

Figure **??** shows the laser displacement gauge output and the Hall sensor output as a function of time at the levitation height of 9 mm. We fit the data with equation (2) and derive the fitting parameters of ζ and ω_0 for each levitation height. The fitting result of the Hall sensor output with the levitation height of 12 mm is shown the right plot of Figure 2. The fitted parameters are summarized with their statistical error values in Table 1. As a first order, the parameters from the laser displacement gauge and the Hall sensor are consistent. In an actual application, the measurement by the laser displacement gauge is not ideal from the view points of heat dissipation and interference with the signal. This result indicates that the Hall sensor can be an alternative to the laser displacement gauge for the vibration measurement.

We also perform a Fourier transformation to the data from the Hall sensor. The left pannel of the Figure 3 shows the result of Fourier transformation for each levitation height. The

h [mm]	ζ	ω_0 [rad/s]	R [N·s/m]	k_z [Nm]
		laser displacement gauge		
3	$2.1 \pm 0.3 \times 10^{-2}$	331.8 ± 0.8	42.0 ± 5.6	$3.3 \pm 0.02 \times 10^{5}$
6	$2.7 \pm 0.1 \times 10^{-2}$	194.0 ± 0.2	31.0 ± 2.5	$1.1 \pm 0.01 \times 10^{5}$
9	$2.3 \pm 0.1 \times 10^{-2}$	138.2 ± 0.2	19.1 ± 2.5	$5.7 \pm 0.02 \times 10^{4}$
12	$1.8 \pm 0.1 \times 10^{-2}$	111.7 ± 0.1	11.8 ± 1.2	$3.7 \pm 0.01 \times 10^{4}$
		Hall sensor		
h [mm]	ζ	ω_0 [rad/s]	R [N·s/m]	k_z [Nm]
3	$2.4 \pm 0.1 \times 10^{-2}$	299.3 ± 0.2	43.5 ± 2.5	$2.7 \pm 0.03 \times 10^{5}$
6	$2.3 \pm 0.1 \times 10^{-2}$	195.7 ± 0.1	27.1 ± 1.3	$1.2 \pm 0.01 \times 10^{5}$
9	$2.4 \pm 0.1 \times 10^{-2}$	136.4 ± 0.2	20.2 ± 2.8	$5.6 \pm 0.01 \times 10^{4}$
12	$2.4 \pm 0.1 \times 10^{-2}$	108.0 ± 0.1	15.7 ± 0.8	$3.5 \pm 0.01 \times 10^{4}$

Table 1. The summary of the fitted parameters from the vibration measurements for each levitation height (h). The parameters of ζ and ω_0 represent a damping ratio and an undamped angular frequency. The variables of R and k_z represent a damping coefficient and a spring constant.

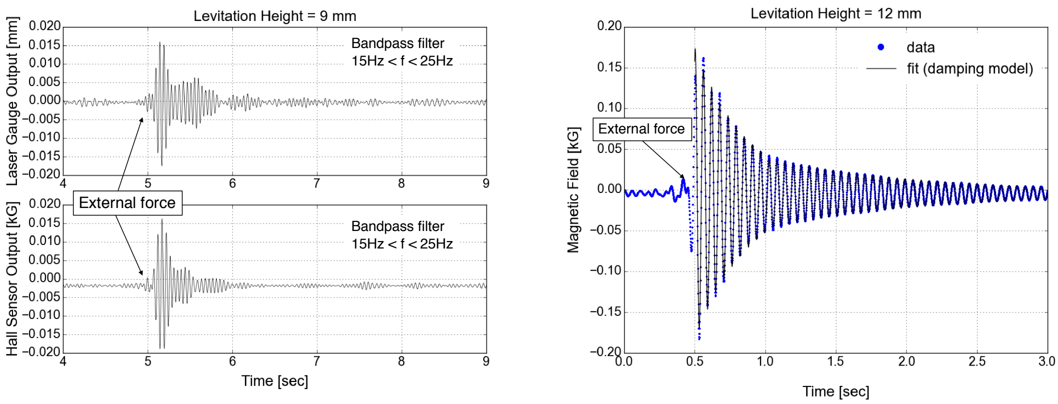

Figure 2. (Left) The laser displacement gauge output and the Hall sensor output as a function of time with the levitation height of 9 mm in top and bottom panels, respectively. (Right) The fitting result of the Hall sensor output with the levitation height of 12 mm.

distinctive peak in the plot corresponds to the natural frequency of the SMB system. The modulation frequency of the signal by the polarization modulator is less than 20 Hz. Thus, the natural frequency does not resonate if the levitation height is higher than 12 mm. The spring constant is also derived calculating by

$$k_z = m(2\pi f_0)^2, \tag{3}$$

where f_0 is the natural frequency of the SMB. The spring constant from the Fourier transformation is compared with the fitting result in the right pannel of the Figure 3. There is no significant difference depending on the analysis method. For the polarization modulator, the typical requirement of the spring constant is 10^5 Nm. The SMB system in this paper can satisfy the requirement the levitation height is less than 6 mm.

We demonstrate that the spring constant and the damping coefficient increase by reducing

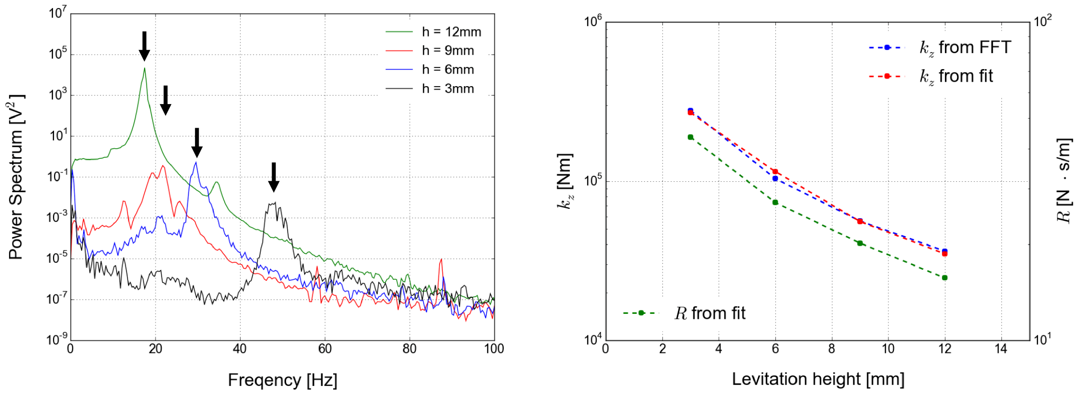

Figure 3. (Left) The power spectrum of the Hall sensor output as a function of frequency for levitation height of 3 mm, 6 mm, 9 mm and 12 mm. (Right) The spring constant and the damping coefficient as a function of levitation heights. The red and green points are derived from the fit with damping model, and the blue points are derived from the Fourier transformation.

the levitation height from the measurement. The spring constant corresponds to the stiffness of the SMB. On the other hand, the damping coefficient corresponds to the heat dissipation of the SMB from an energy loss associated with magnetic hysterisys. The heat dissipation from a magnetic friction during the rotation also increases with the smaller levitation height. This indicates that the SMB has a tradeoff between the stiffness and the heat dissipation.

The damping coefficient corresponds to an energy loss by an eddy current, and it leads to the heating of the HWP. The requirement of the damping coefficient depends on the experiment, while we indicate it is adjustable by the levitation height. From the viewpoint of vibration, it is efficient to set the levitation height as less as possible. However, we have to consider the increase of the HWP heat due to magnetic friction. A trade-off study with enough knowledge of both vibrational and thermal characteristics will be discussed in the future paper. In addition, the further effort of designing a new magnetic circuit can be improve the SMB system.

Conclusion

We have conducted the vibration measurements of the prototype SMB system with the diameter of ϕ=384 mm for the polarization modulator used in CMB polarization experiments. From the measurement, we derive the spring constant and the damping coefficient for each levitation height. The spring constant is important to minimize the deviation of the HWP optical axis. The damping coefficient is important to minimize the heat due to a disturbance. The spring constant is in the order of $10^4 \sim 10^5$ Nm and the damping coefficient is $15 \sim 45$ depending on levitation height. If we assume the rotor mass with the HWP, we conclude the spring constant satisfies the typical requirement of $> 10^6$ Nm when the levitation height is less than 6 mm. As a future study, it is important to design a magnetic circuit in order to improve total performance of the SMB system in the polarization modulator.

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