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 an 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.

1. 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 hunting race is ongoing among CMB polarization experiments. Correspondingly, the instrumental development has progressed rapidly.

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.

A 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, 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 we gain the benefit of low heat dissipation by using the SMB as compare to a 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 trade-off between the heat dissipation and the stiffness. In this paper, we discuss the design trade-off for use of this SMB technology for a future CMB polarization experiment. We present our prototype SMB system, the rotor diameter of 384 mm, and the measurement results of a spring constant and a 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 project the results toward the design of the SMB system for the polarization modulator.

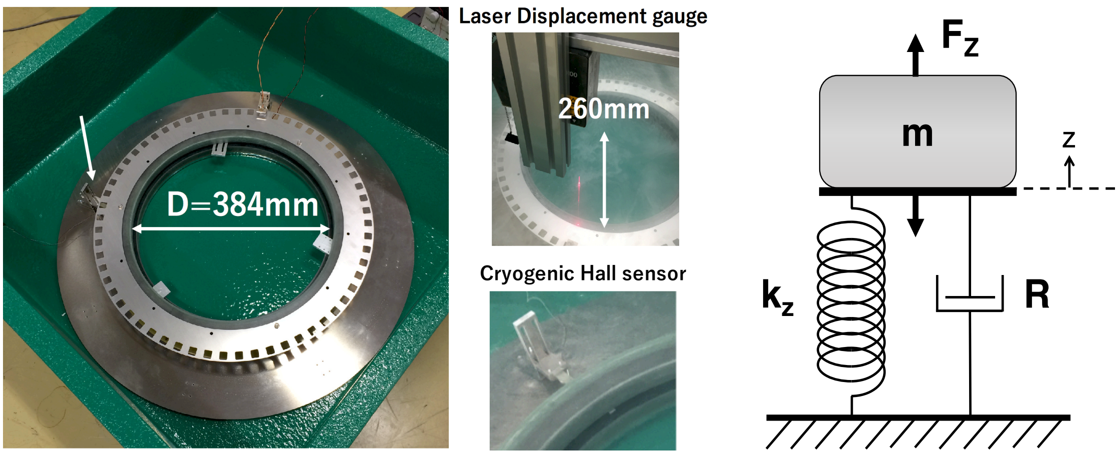
2. Experimental Setup

We conduct vibration measurements using a Styrofoam bucket with liquid nitrogen as shown in Figure 1 (a). Hull et al. reported the vibrational properties of the SMB system at both the liquid nitrogen and the liquid helium temperature. The results show no significant difference between the two temperature ranges. Furthermore, the rotor diameter of about 400 mm requires a large diameter cryostat for testing, and thus we start characterizing the vibrational properties at a liquid nitrogen temperature although the SMB system is operated inside the 4 K cryostat in an actual CMB observation.

We prepare the SMB system with inner diameter of 384 mm. Due to a large diameter, a ring shaped rotor magnet consists of 16 segmented NdFeB magnets. Each segmented magnet is magnetized axially with a magnetic remnance of 1.24 T. A $Y_{1.65}Ba_2Cu_3O_x$ (YBCO) superconductor is used as a stator. The critical temperature of this high temperature superconductor is $\sim$ 95 K [7]. The YBCO array is formed in a ring shape using three-seeded YBCO tiles.

The YBCO array is submerged by the liquid nitrogen but the rotor magnet is exposed to the room environment. We set a gap between the rotor magnet and YBCO array with aluminum plates at room temperature, and then a liquid nitrogen is poured with a presence of the magnetic field, i.e. field-cooling process. 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, 6, 9 and 12 mm). In order to enhance the vibrational amplitude, an external impulse force is 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 Figure 1 (a). We also monitor the vibration via magnetic field using a cryogenic Hall sensor installed between the rotor magnet and the YBCO array.



(a) (b)

Figure 1. (a) The experimental setup for the vibration measurements for $D = 384$ mm. (b) The Mass-spring-damper model.

3. Result and Discussion

An axial vibration of the rotor can be described by a damping motion of a mass-spring-damper model [8] shown in Figure 1 (b). 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 can be any values.

Figure 2 (a) shows representive outputs of the laser displacement gauge and the Hall sensor as a function of time at the levitation height of 9 mm. The laser displacement gauge output represents the position displacement of the rotor. The Hall sensor measures the magnetic field corresponding to the position of the rotor magnet.

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 in Figure 2 (b). The fitted parameters are summarized with their statistical error values in Table 1. The parameters from the laser displacement gauge and the Hall sensor are consistent. The detailed comparison between the two results is beyond the scope of this paper. In order for the two methods to be identical, the change of the rotor magnetic field and the spatial displacement of the rotor have to be linearly related, but this is not necessary guaranteed. In an actual application, the measurement by using a laser displacement gauge is not ideal because entire SMB system has to be kept below 10 K. This result indicates that the Hall sensor can be an alternative tool against to the laser displacement gauge for the vibration measurement passibly.

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.

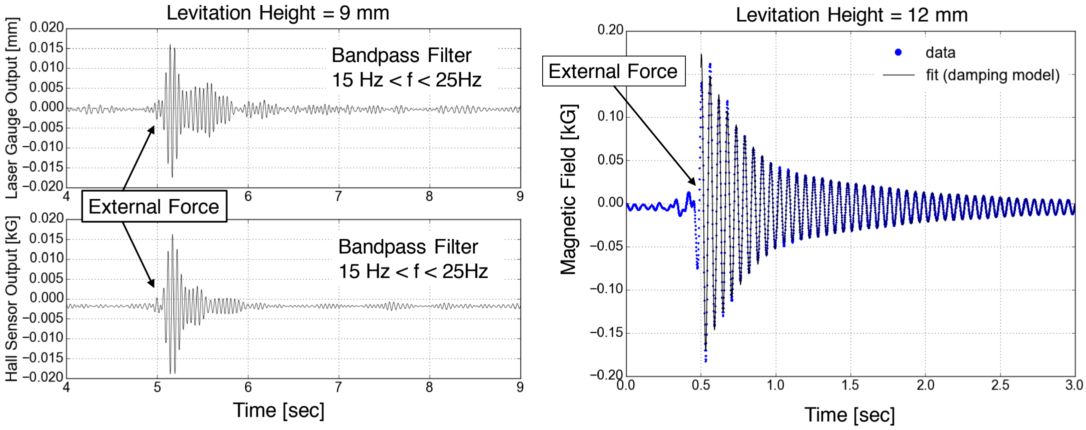
	laser displacement gauge			
h [mm]	ζ	ω_0 [rad/s]	R [N·s/m]	k_z [N/m]
3	$2.1\pm0.3\times10^{-2}$	331.8 ± 0.8	42.0 ± 5.6	$3.3\pm0.02\times10^{5}$
6	$2.7\pm0.1\times10^{-2}$	194.0 ± 0.2	31.0 ± 2.5	$1.1\pm0.01\times10^{5}$
9	$2.3\pm0.1\times10^{-2}$	138.2 ± 0.2	19.1 ± 2.5	$5.7\pm0.02\times10^{4}$
12	$1.8\pm0.1\times10^{-2}$	111.7 ± 0.1	11.8 ± 1.2	$3.7\pm0.01\times10^{4}$
	Hall sensor			
h [mm]	ζ	ω_0 [rad/s]	R [N·s/m]	k_z [N/m]
3	$2.4\pm0.1\times10^{-2}$	299.3 ± 0.2	43.5 ± 2.5	$2.7\pm0.03\times10^{5}$
6	$2.3\pm0.1\times10^{-2}$	195.7 ± 0.1	27.1 ± 1.3	$1.2\pm0.01\times10^{5}$
9	$2.4\pm0.1\times10^{-2}$	136.4 ± 0.2	20.2 ± 2.8	$5.6\pm0.01\times10^{4}$
12	$2.4\pm0.1\times10^{-2}$	108.0 ± 0.1	15.7 ± 0.8	$3.5\pm0.01\times10^{4}$

We also perform a Fourier transformation to the data from the Hall sensor. Figure 3 (a) shows the result of Fourier transformation for each levitation height. The 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 about 20 Hz. Thus, the natural frequency does not resonate if the levitation height is higher than 12 mm. The spring constant is also derived by

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

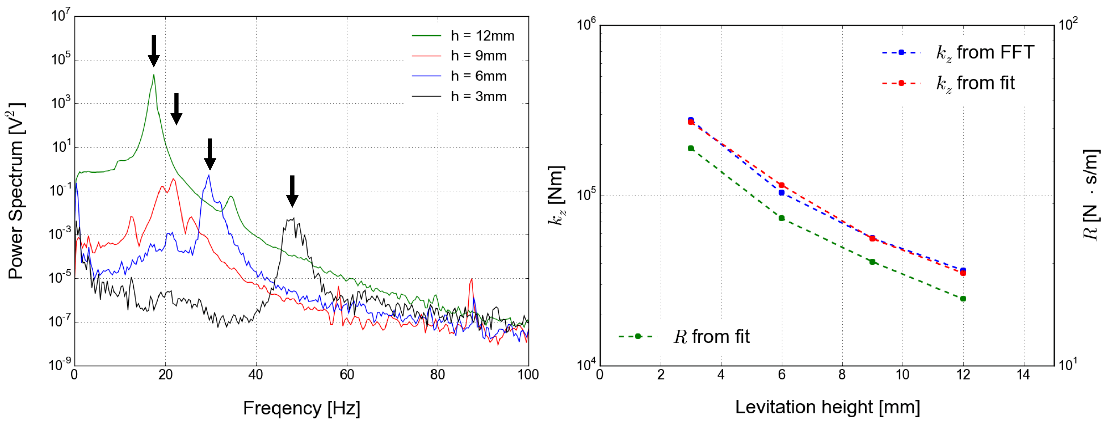
where f_0 is the natural frequency of the SMB. The spring constant from the Fourier transformation is compared with the fitting result in the figure 3 (b). There is no significant difference depending on the analysis method. For the polarization modulator, the typical requirement of the spring constant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

From this measurement, we demonstrate that the spring constant and the damping coefficient are inversely proportional to the levitation height at the first order. The damping coefficient corresponds to an energy loss associated with magnetic hysteresis. From the viewpoint of the stiffness, it is efficient to set the levitation height as low as possible. However, the increase of the energy loss leads to the noise from the heat dissipation of the HWP. In addition, the heat dissipation from a magnetic friction during the rotation also increases by reducing the levitation height. Thus, the SMB system has a trade-off between the stiffness and the heat dissipation. For



(a) (b)

Figure 2. (a) 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. (b) The fitting result of the Hall sensor output with the levitation height of 12 mm.



(a) (b)

Figure 3. (a) 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. (b) 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 polarization modulator, the levitation height of the SMB is an important parameter to be determined by the experimental requirement. In this measurement, we use the segmented ring magnet with axial magnetization. The further effort of designing an optimal magnetic circuit can be improve the total performance of the SMB system. The measurement and evaluation of the magnetic circuit will be discussed in future papers.

4. 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 using both the laser displacement gauge and the cryogenic Hall sensor. The spring constant is in the order of $10^4 \sim 10^5$ N/m and the damping coefficient is $15 \sim 45$ depending on levitation heights. The result has consistency between the laser gauge and the Hall sensor. We conclude that the Hall sensor can be an alternative method to monitor the vibration of the SMB system. We demonstrate the spring constant and the damping coefficient are inversely proportional to the levitation height. We discuss the trade-off of the SMB system between the stiffness and the heat dissipation. The further effort of designing an optimal magnetic circuit can be improve the total performance of the SMB system.

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