Development of a Vacuum Pump using Axial-Gap Self-Bearing Motor and Superconducting Magnetic Bearing

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Abstract: In recent years, superconducting technology has rapidly advanced and has been applied to several devices like magnetoencephalography(MEG) and magnetic resonance imaging(MRI). Superconductivity occur at extremely low temperatures, hence liquid helium is always used to achieve it. In order to conserve liquid helium, a circulation system has been recently developed. In the developed system, a pump will be used for cooling liquid helium. In addition, this pump will improve the capability of medical devices that use superconducting coils.

In this paper, we propose the development of a vacuum pump that can be used at extremely low temperatures by using axial self bearing motor (ASBM) and superconducting magnetic bearing (SMB). The pump has the advantages of no friction, as there is no contact, high efficiency and no maintenance. The design of the pump is presented, and the control method is theoretically and practically analyzed. We performed an experiment to confirm that the reliability of the proposed vacuum pump.

Keywords: Rotary Machinery, Magnetic Bearing, Superconducting Magnetic Bearing, Vacuum Pump

Introduction

Superconducting technology has rapidly advanced and has been applied to several medical image-processing devices like magnetoencephalography (MEG) and magnetic resonance imaging (MRI). Superconductivity occurs at extremely low temperatures, so liquid helium is always used to achieve superconductivity. However, it is very expensive to use high-priced liquid helium to maintain low temperature. This disadvantage has limited the number of medical devices having superconducting coils. Therefore, in order to conserve liquid helium, a new circulation system has been recently developed [1,2]. In this system, a pump is used for reducing the pressure of liquid helium in the frozen chamber. So, the liquid helium transmute to superfluid state. Superfluid helium has good cooling capability. So, the performances of MRI and MEG will be improved. The pump using axial self-bearing motor (ASBM) and superconducting magnetic bearing (SMB) has three advantages. It is maintenance free, has no friction, and can be miniaturized. Above all, it is difficult to use a pump, which is composed of mechanical bearings with lubrication at low temperature because the bearings will freeze at low temperature.

In this paper, we propose the development of a vacuum pump that can operate at extremely low temperatures using ASBM[3,4] and SMB. The design of the pump has been presented, and the control method is theoretically and practically analyzed. It was experimentally confirmed that the proposed vacuum pump is reliable.

Components

Axial Self-Bearing Motor (ASBM). This motor is composed of a disc type AC motor and axial magnetic bearing. The stators are placed on one side of the disc rotor. The motor can control magnetic suction power and rotation speed for changing the phase and amplitude of AC current. A rotating field can generate rotation torque and control the axial direction at the same time. The positions in the radial direction are controlled by PMB. The structure of the motor is shown in figure 1.

In this study, the synchronous type motor was adopted. The stator has a three-phase circuit winding, and generates a rotating magnetic field in the airgap between stator coils and rotor magnets by throwing alternating current. The rotor consists of two permanent magnets (OD 50 [mm], ID 36 [mm], thickness 1 [mm] sector form) and a ring of silicon steel (OD 50 [mm], ID 36 [mm], thickness 5 [mm]). The structure is shown in figure 2.

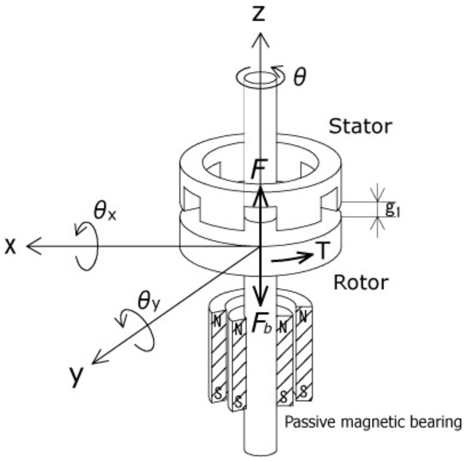
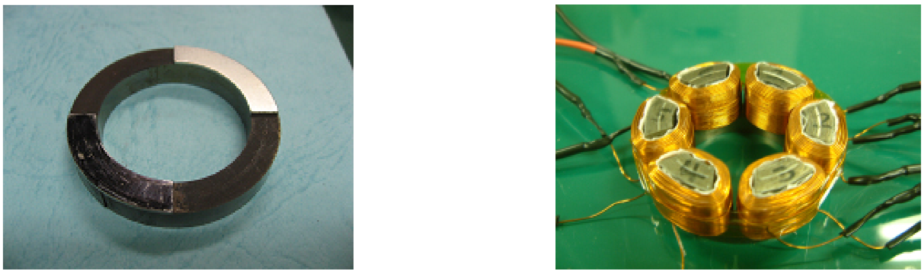


Fig. 1 Schematic of Axial Self-Bearing Motor

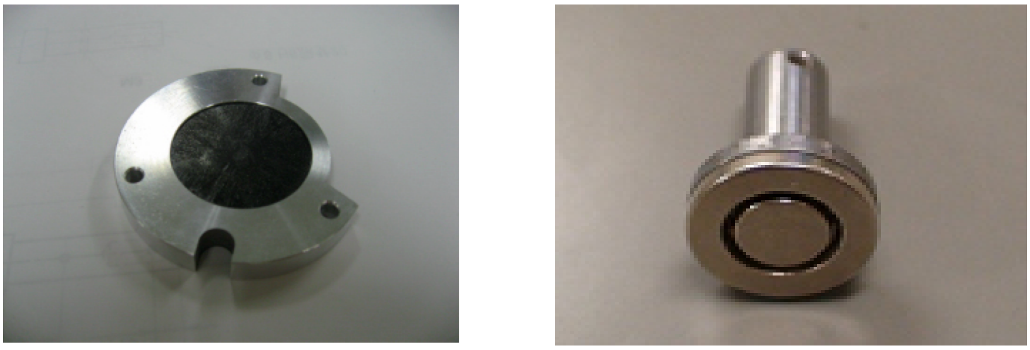


(a) Motor rotor (b) Motor stator

Fig. 2 Stator and Rotor of Axial Self-Bearing Motor

Superconducting Magnetic Bearing (SMB). Superconducting magnetic bearing is a magnetic bearing that applies magnetic levitation by perfect diamagnetism and pinning effect, which is a feature of superconductivity. The bearing can support all directions without control; therefore a controller is not required. In addition, this bearing has a simple structure and consists of only a permanent magnet and a superconductor. However, in order to make use of the superconductivity, its range of use is limited to low-temperature environments. However, the SMB can use only low temperature environment.

In this study, SMB is used for vibration control in the axial and radial directions. The SMB consists of a button YBaCuO high-Tc superconductor (OD; 30[mm], width 5.5[mm]) and neodymium magnets. In order to generate large flux, the magnet shapes chosen ring type (OD; 20[mm], ID; 12[mm], width; 3[mm]) and button type (OD; 10[mm], width; 3[mm]). The design is shown in the figure 3.



(a) Superconducting Bulk (b) Superconducting Bulk

Fig.3 Superconducting Magnetic Bearing

Passive Magnetic Bearing (PMB) PMBs make use of the repulsion force between permanent magnets. The advantages of using PMB are: no friction, maintenance free and can work under special environment, for example extremely low temperature, high temperature, vacuum state etc. In addition, this bearing does not require a control device; therefore, the system using PMB can be downsized. In this pump, PMBs are installed on the upper part and under the rotating shaft. PMBs consist of two ring type magnets for the stator (OD; 30[mm], ID; 22[mm], Width; 3[mm]) and rotor (OD; 20[mm], ID; 14[mm], Width; 3[mm]).

Structure of the Vacuum Pump

Mechanical Structure. In this study, we have manufactured a prototype pump by remodeling the molecular pump MDP 5011 (Alcatel Vacuum Technology). The pump uses systems, such as, ASBM, superconducting magnetic bearing and passive magnetic bearing for rotor levitation and rotation. These magnetic bearings require neither winding nor control systems and can support the pump rotor without contact. Table 1 shows the specifications of MDP 5011 and the target specifications of the proposed vacuum pump. Radial displacement sensors at the upper and the lower of the rotation axis measure radial vibrations of the rotor.

An axial displacement sensor is attached at the top of the pump axis. These displacement sensors are eddy-current-type (LS500 Sentec Co.). The schematic model of the levitation system is shown in figure.4. The internal structure of the pump is shown in figure 5.

Table.1 Pump Specification

	MDP 5011	Vacuum Pump
Maximum Suction Pressure	1 [kPa]	100 [kPa]
Flow Volume	240 [l/min]	10 [l/min]
Rotating Speed	27,000 [rpm]	130,000 [rpm]
Discharge Pressure	4 [kPa]	100 [kPa]
Compaction Ratio	20,000	—

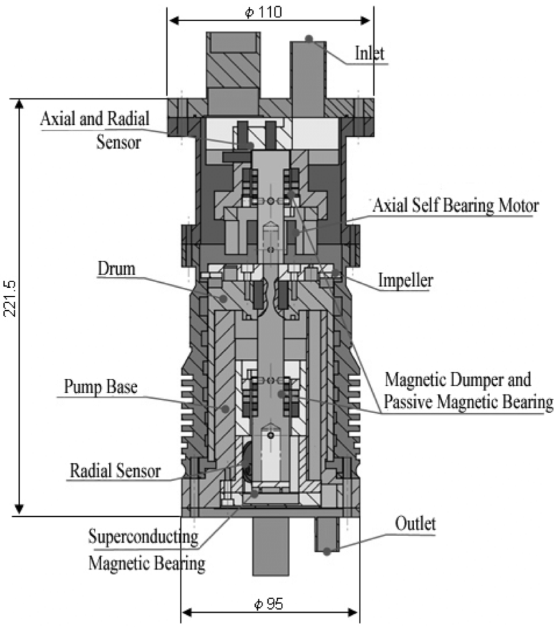


Fig.4 Model of levitation system

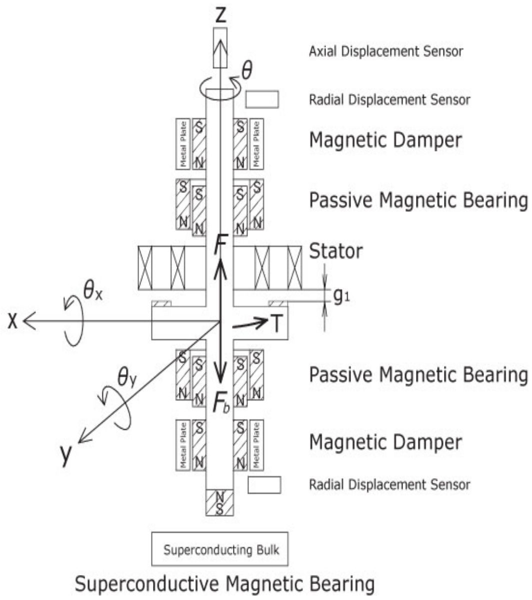


Fig.5 Model of vacuum pump prototype

Control System. We use digital signal processor (DSP dSPACE DS1104) for the control system. The schematic block diagram of the controller is shown in figure 6.

Control of axial direction: The analog signal from axial displacement sensor is converted into a digital signal using an AD converter and is sent to the DSP. The appropriate current value is calculated in the DSP, and the current is converted to an analog signal using DA converter. The signal is outputted via ASBM stator coils through the power amplifier. Digital PID controller is used for the axial direction control of the rotor. Open loop torque control is used for the rotation of control rotor. The control drives the motor using the following current in equations.

$$i_u = (I_m - I_c)\cos(\phi) \tag{1}$$

$$i_v = (I_m - I_c)\cos(\phi - 2\pi/3) \tag{2}$$

$$i_w = (I_m - I_c)\cos(\phi - 4\pi/3) \tag{3}$$

Where, I_m [A] is constant motor current, I_c [A] is output from PID controller, and ω [rad/s] is angular velocity. The difference between I_m and I_c is assumed to be amplitude of stator current. In addition, phase) is calculated from ordered rotation speed ω. Stator current is calculated using equation (1), (2), and (3).

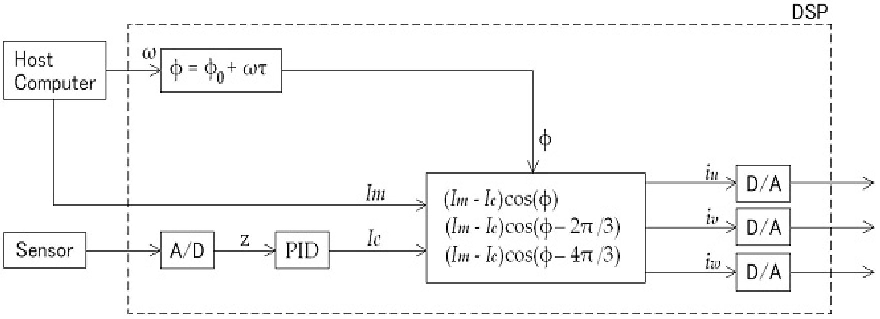


Fig. 6 Schematic of Controller

Stiffness of the SMB

In this section, measurement results of the stiffness of the SMB are shown. We measured the stiffness of the SMB, which consists of a bulk superconductor and a neodymium magnet. The superconductor and permanent magnet have same dimensions as the developed pump as mentioned above. In order to measure the stiffness of the axial and radial directions, a load cell was used.

Stiffness of the axial direction for SMB. In case of the axial direction, we measured repulsion force between the superconductor and permanent magnet. Then, the equivalent spring constant (force / displacement) was calculated. The initial gaps were set at 0.2 mm, 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm, respectively. The liquid nitrogen was used to cool the superconductor. The experimental results are shown in figure 7.

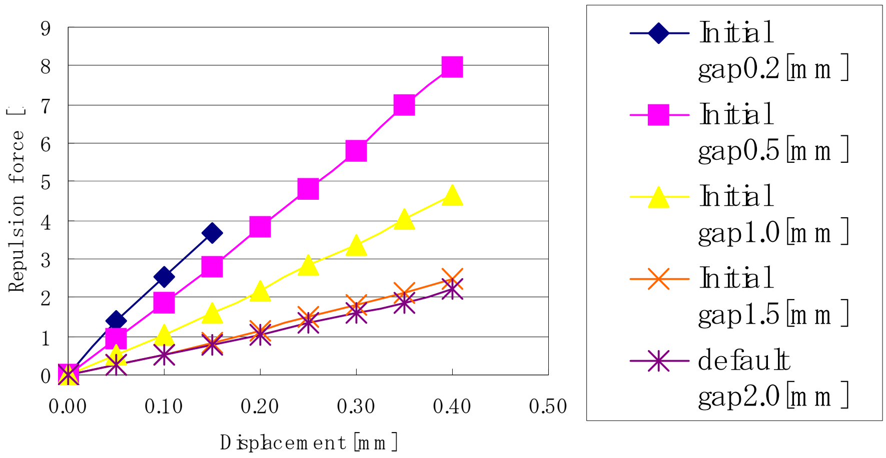


Fig. 7 Experimental results for the repulsion force axial direction

In these results, the repulsion force of the SMB is proportional to displacement from the initial position. Furthermore, the shorter the air gap makes higher stiffness. The relationship the axial stiffness with initial gaps is shown in figure 8. Obviously, the stiffness is inverse proportion to the initial air gap. It is thought that the superconductor catches more magnetic flux.

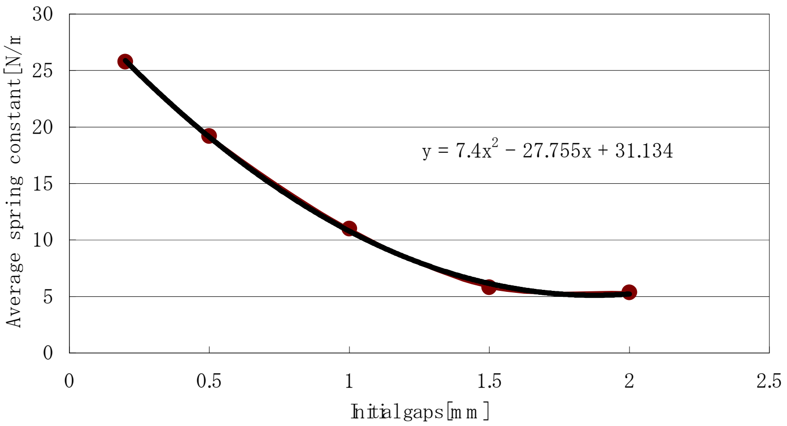


Fig. 8 The relationship axial stiffness with initial air gaps

Stiffness of the radial direction. Next, we measured the stiffness of the radial direction. The initial gap was set at 0.2 mm. We measured restoring force loaded a magnet by the SMB. In the pump, the restoring forces control the rotor axis, and reduce the radial displacement from rotational center. The results are shown in figure 9.

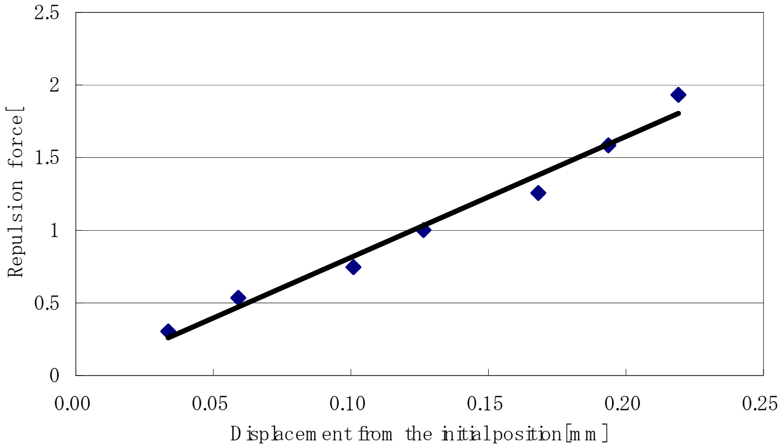


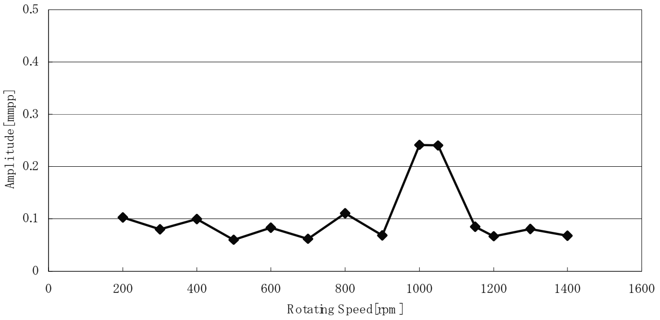
Fig. 9 The radial stiffness of SMB

From this result, the repulsion force of the SMB is proportional to displacement from the initial position. The spring constant was about 8.5 [N/mm]. The SMB in radial direction can work well. It is important for rotor rotation to reduce the vibration. Especially in case of high-speed rotation, there is a risk for the pump when the rotating rotor stops at large vibration and it can sideswipe at pump base. So, it is necessary to enforce the rotor stiffness for rotating the rotor in safety.

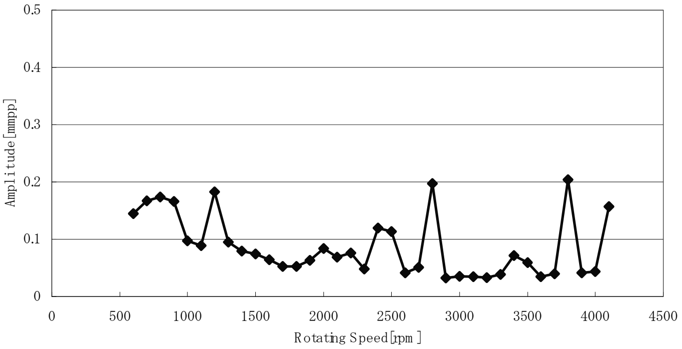
Rotor Rotation Experiment

In this section, we have presented the rotor rotation experiments that were performed. The rotor levitation height from contact area is 0.2[mm], and the stator current range is 0.5 ~ 3.0 [A]. The PID parameters were proportional gain k_p = 70 [A/mm], differential gain k_d = 0.25 [As/mm], and integral gain k_i = 0.5 [A/mms]. Figure 7 shows the results of the rotation experiment for the rotor vibrations. This experiment was performed in two conditions, without using SMB at normal temperature and using SMB at low temperature. For cooling the superconductor, we have used liquid nitrogen. Figure 7 indicates (a) axial vibration at normal temperature, (b) axial vibration at low temperature, (c) radial vibration at normal temperature, and (d) radial vibration at low temperature. The horizontal axis of the graph shows rotating speed [rpm], and the vertical axis shows amplitudes of the rotor vibration. The solid line shows upper part of the rotation axis of radial vibrations and the short dashed line shows the lower part, because the displacement sensors for radial vibrations are attached at the upper and lower parts of the axis. The highest rotation speed of the pump rotor is about 1400 [rpm] at normal temperature (without using SMB), whereas it is about 4100 [rpm] at low temperature (using SMB).

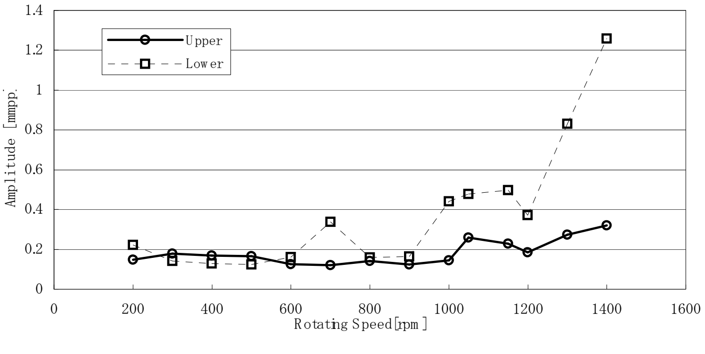
When the low temperature condition is compared to the normal condition, it is observed that both axial as well as radial vibrations were suppressed at low temperature, especially the lower side of rotation axis, where SMB is installed. The results show that the rigidity of pump axis of axial and radial was enforced by SMB. Therefore, the advantages of SMB were confirmed in this study. However, the maximum rotation speed was significantly below the target speed for radial vibrations. The vibrations occurred due to the resonance of rotation axis. It seems that this cause is in the weakness of the rigidity and the viscosity in the upper part of the rotation axis. In future, in order to solve this problem, we plan to install SMB in the upper part of the axis.



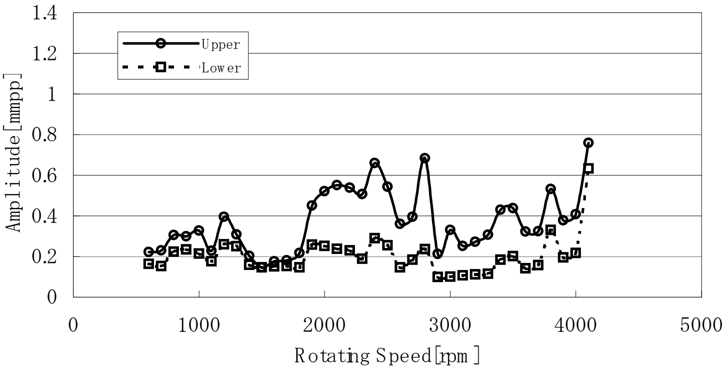
(a) Axial vibration at normal temperature



(b) Axial vibration at extremely low temperature



(c) Radial vibration at normal temperature



(d) Radial vibration at extremely low temperature

Fig.10 Results of rotation experimental

Conclusion

In this study, magnetic levitation and rotation system using superconducting magnetic bearing (SMB) was developed for a vacuum pump that can be used at extremely low temperatures. In addition, the rotor rotation experiment was performed in two conditions: without using SMB and using SMB. The highest rotation speed of the pump rotor is about 1400 [rpm] at normal temperature (without using SMB), and about 4100 [rpm] at low temperature (using SMB). The results of this study confirm the advantages of including SMB in the configuration of this levitation and rotation system for the vacuum pump. However, the maximum rotation speed was significantly below the target speed for radial vibration.

In the future, it will be necessary to study the structure to improve the rigidity and the viscosity of the axis. The rigidity of the axis will possibly improve by installing SMB in the upper part of the axis.

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