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Development of a Centrifugal Cryogenic Fluid Pump using an Axial Self-bearing Motor

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Abstract

This paper proposes a new centrifugal cryogenic fluid pump. It employs an axial self-bearing motor (ASBM), a superconducting magnetic bearing (SMB), and a passive magnetic bearing (PMB). As the device does not require seal material and bearing, it has the advantages of long life, no risk of leakage of cryogenic fluid, and no maintenance. The ASBM in this device can control the axial position and rotation torque of the rotor. In detail, PID controllers control axial position, and an open-loop torque control method generates rotation torque. The shaft is supported by PMB and SMB in the radial direction. Liquid nitrogen is injected into the device to cool the superconducting magnetic bearing. The impeller transports the LN2. A flying test, a rotation test in air or water, and a rotation test with SMB are carried out. When the rotation test is conducted without water, a rotation speed of up to 1300 rpm is observed. When the rotation test is conducted with water, a rotation speed of 600 rpm was observed.

Keywords : axial self-bearing motor, centrifugal pump, super conducting magnetic bearing, cryogenic fluid, passive magnetic bearing

1. Introduction

In general, a pressurization method based on the pressure difference between two containers is used widely for transferring cryogenic liquefied gases such as liquid nitrogen and helium. However, pressurizing the container and then transporting the liquid is time consuming. On the contrary, a centrifugal pump, such as a submerged pump and a magnet pump, is used for quick transportation. However, these pumps have shaft seals and special bearings for a cryogenic environment. The drawbacks of these shaft seals and special bearings include a short lifetime and leakage of cryogenic fluid [1].

To solve these problems, a centrifugal cryogenic fluid pump without shaft seals and mechanical bearings is proposed. An axial self-bearing motor (ASBM) and passive magnetic bearings (PMB) were used to simplify the structure and control system of the pump. The axial self-bearing motor is combined with an axial magnetic bearing and a disk-type AC motor. The ASBM can control the axial position and rotation torque by the same winding wire. As this device can only control the axial position, the PMB, which uses a permanent magnet, and a superconducting magnet bearing (SMB), which uses the superconducting phenomenon of superconductors, are attached to an experimental device to increase the radial stiffness. The above mechanisms are used for developing completely non-contact rotation. Seal materials and bearings are not required in this device. The developed centrifugal pump has a long life, no risk of leakage of fluid, and no maintenance as no lubricating oil is required in the bearing.

Tests, such as the floating test and the rotation test were carried out under various conditions.

The rest of this paper is organized as follows: section 2 describes the mechanism of the experimental device, section 3 discusses the experimental device and the control system, section 4 discusses the experimental results, and section 5 draws the conclusions of the experiment.

2. Mechanism used in experimental device

A schematic of the experimental device is shown in Fig. 1. The ASBM was used to control the rotation and axial position. Supporting in the radial direction was performed by two PMBs. The SMB was used to support the five-axis direction except the rotation function. The above-mentioned mechanisms are described in the following sections:

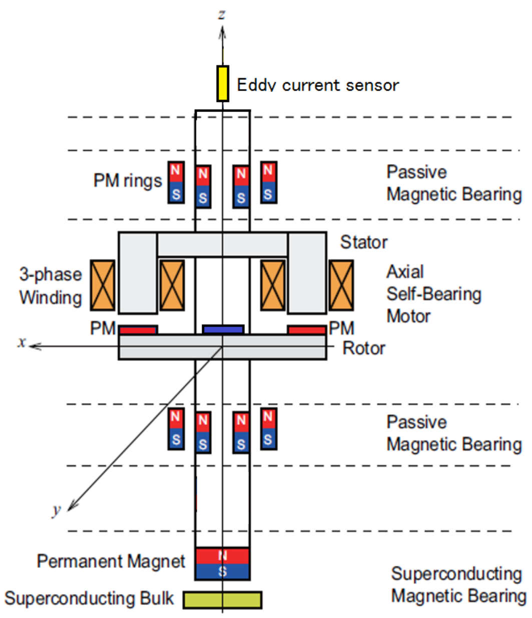

Fig. 1 Schematic of experimental device

2.1 Axial self-bearing motor

2.1.1 Structure of axial self-bearing motor

In this study, a single type axial self-bearing motor was used; a schematic of this is shown in Fig. 2. It has a stator with six coils and a rotor with four neodymium magnets. A rotating magnetic field generated by the stator produces a rotation torque and a magnetic attractive force. The rotation torque and axial position are controlled by the amplitude and phase of the rotating magnetic field.

2.1.2 Principle of the axial direction control

The principle of generating axial force is shown in Fig. 3. Current is applied to the coil so that the magnetic poles of the stator become opposite to the rotor, thus generating an attractive force. By increasing or decreasing the current to match the attractive force to the bias force generated by gravity, the SMB, and the PMB, the floating position is adjusted to the target position.

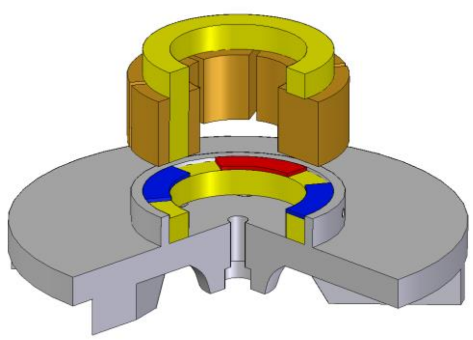

Fig. 2 Schematic of axial self-bearing motor

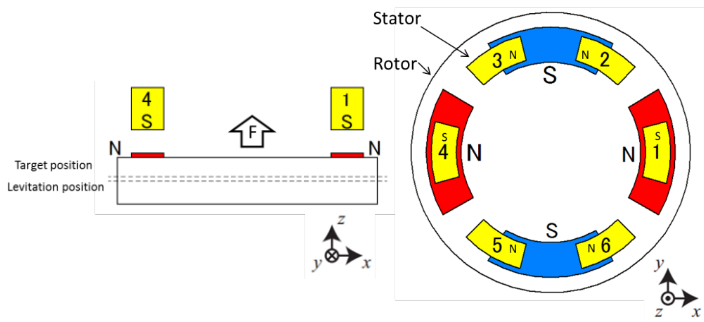

Fig. 3 Principle of axial direction control

2.1.3 Principle of generation of rotation torque

The magnetic field generated for controlling the axial direction was rotated, thus creating the rotation torque required to allow the rotor to follow the magnetic field. In this study, the rotation torque was controlled by an open loop. The phase angle of the stator current was determined by calculating the angular velocity from the target value of the rotational speed and integrating the angular velocity.

2.1.4 Control current

An axial position control current was applied to the coil in order to control the axial position of the rotor. The equation for calculating this current is shown in Eq. 1.

$$i_k = \sqrt{\frac{2}{3}}\left[i_z \cos\left\{2\psi + \frac{2\pi}{3}(k-1)\right\}\right]$$

Equation 1

where i_z is the magnitude of the axial position control current, ψ is the phase angle of stator current, and k is the coil number (k=1~6).

2.2 Super conducting magnetic bearing

A schematic of a superconducting magnetic bearing is shown in Fig. 4. This mechanism uses the Meissner effect and the pinning effect that occurs when the superconductor is cooled down to a certain temperature. After a magnet approaches a second type superconductor and cools the superconductor, the a magnetic flux within the superconductor is bound by the pinning effect. Until the superconducting phenomenon stops, magnet float and keep the distance from the superconductor. This mechanism can support the five-axis direction except the rotation.

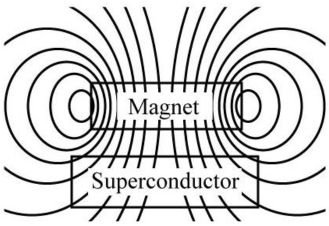

Fig. 4 Superconducting magnetic bearing

2.3 Passive magnetic bearing

A schematic of a PMB is shown in Fig. 5. Two ring-type neodymium magnets are magnetized in the thickness direction. When the inside magnet approaches the outside magnet, the repulsive force increases and keeps the PMB centered. In addition, the bias force in the axial direction is obtained by shifting two neodymium magnets axially. Two sets of PMBs were used in the experimental device described in this paper.

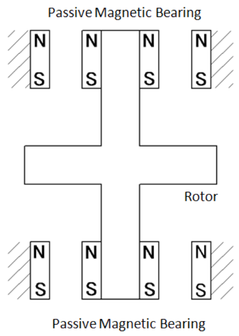

Fig. 5 Passive magnetic bearing

3. Experimental device and control system

3.1 Experimental device

A CAD drawing of the experimental device is shown in Fig. 6, and a photograph of the experimental device and impellor that is attached to the rotor is shown in Fig. 7. The stator is a silicon steel sheet and it has a six slot concentrated winding structure. The concentrated winding structure, which uses a φ5 mm polyurethane copper wire (2-UEW), has a 180 turns. The rotor has four poles. Four segment-type neodymium magnets are attached in the alternating direction about the poles. The size of the stator and rotor is shown in Fig. 8. The rotor is attached to an impellor with blades just under the rotor. Neodymium magnets for the PMB are attached above and below the shaft, which are fixed to the impeller. Neodymium magnets for the SMB are attached to the bottom, as shown in Fig. 9, and the superconductor is placed under it. An eddy current displacement sensor (SENTEC LS-500-2B HA-101S) measured the top of the shaft, and the axial displacement was calculated.

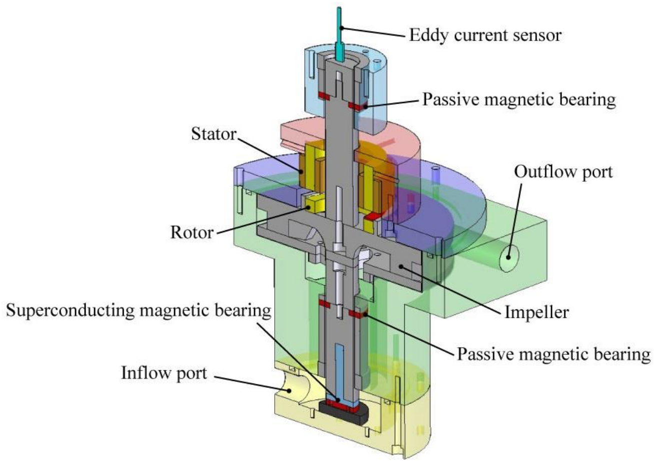

Fig. 6 Experimental device

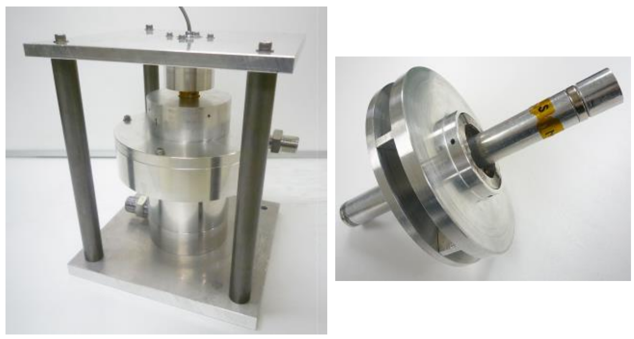

Fig. 7 Overview of experimental device and impellor

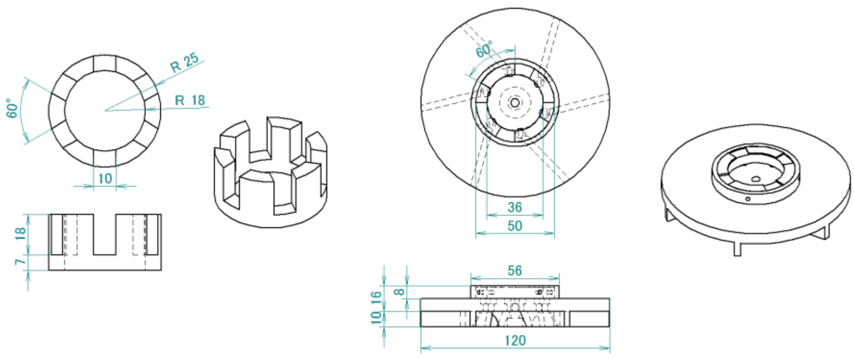

Fig. 8 Stator and rotor

Fig. 9 Magnet of SMB

3.2 Control system

A schematic of the control system is shown in Fig. 10. An A/D converter imported the signal of the eddy current sensor, and the control current was calculated by DSP (dSPACE DS1103). The control current was exported to the power amplifier by a D/A converter, and the current was supplied to the coils. A PID controller calculated the axial position control current. The transfer function of the controller is as follows:

$$G(s) = K_p + \frac{K_d s}{T_d s + 1} + \frac{K_i}{s}$$

Equation 2

where K_p is the proportional gain, K_d is the differential gain, and K_i is the integral gain.
A schematic of the controller is shown in Fig. 11.

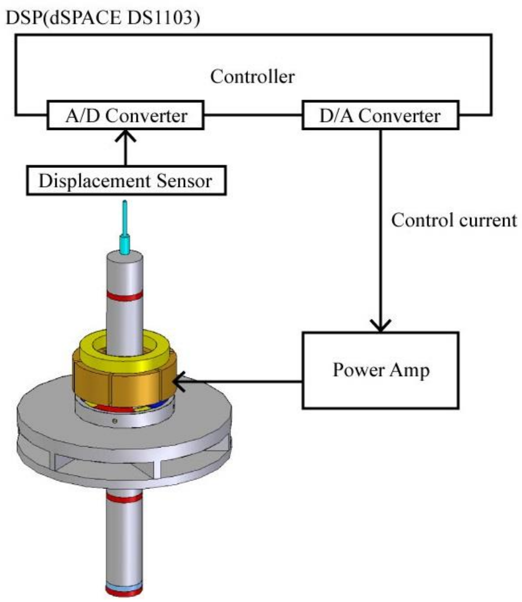

Fig. 10 - Control system

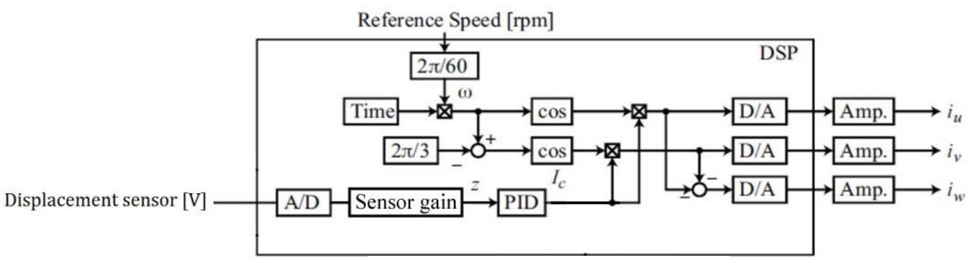

Fig. 11 Open loop controller

3.3 Flow path

A sectional view of the experimental device and the flow path are shown in Fig. 12. Liquid nitrogen was selected as the cryogenic fluid in this study. The liquid nitrogen enters the inflow port of the device and cools the superconductor of the SMB. It reaches the impeller through the flow path, which is located around the shaft of the impeller. It is released from the outflow port by the blades.

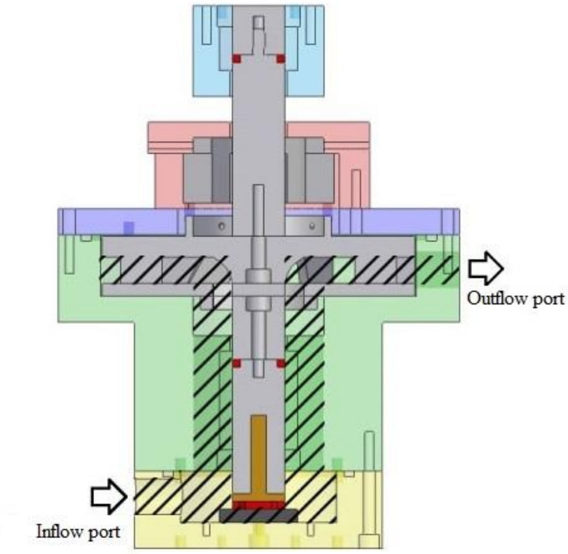

Fig. 12 Flow path

4. Experimental results

Levitation and rotation tests were carried out on the developed device. The obtained experimental results are reported in the following sections. The parameters of the PID controller are shown in Table 1. There are two patterns of parameters: activating the SMB and not activating the SMB.

Table 1. Parameter of controller

	K_p	K_i	K_d
Activating SMB	40 [A/mm]	500 [A/(mm·s)]	0.05 [A/(mm·s)]
Not activating SMB	70 [A/mm]	500 [A/(mm·s)]	0.1 [A/(mm·s)]

4.1 Levitation test

The levitation test was carried out without fluid. As the superconducting phenomenon did not occur, the SMB did not work in this test. Fig. 13 shows the response of the axial displacement. The target position was 0.5 mm. First, only PD controllers were used for the levitation test, and then the I controller was manually turned on.

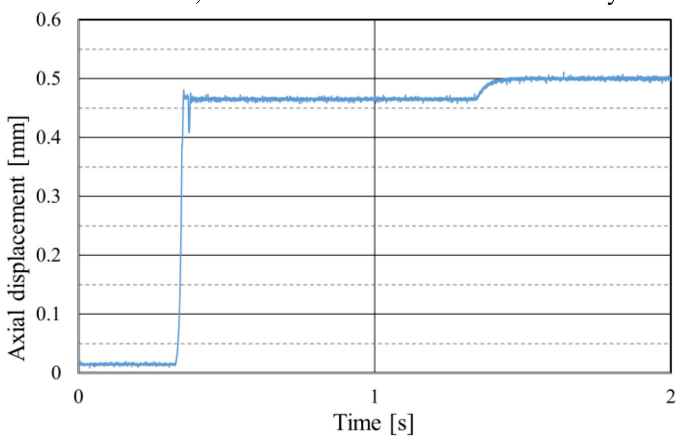

Fig. 13 Levitation test

4.2 Rotation test in air

The rotation test was carried out without fluid. The results are shown in Fig. 14. The SMB did not work in this test; however, in this test, it could rotate until it reached 1500 rpm, and could not exceed the resonance point and lost synchronism.

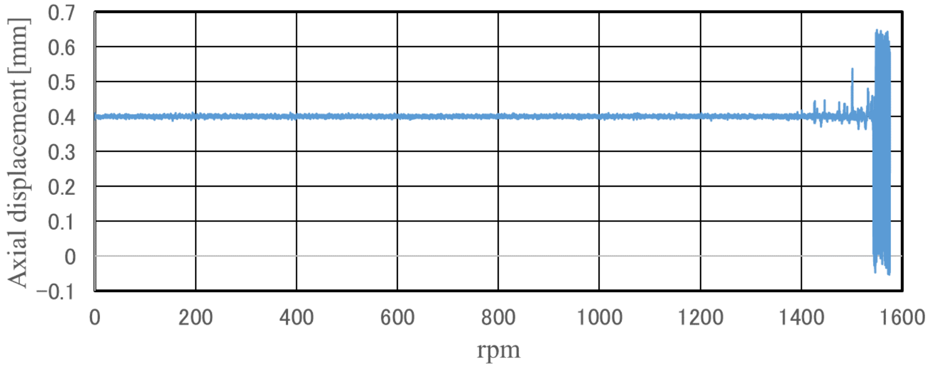

Fig. 14 Rotation test in air

4.3 Rotation test in water

The rotation test in a water-filled state was carried out. The result are shown in Fig. 15. The SMB did not work in this test and could rotate until it reached 500 rpm, after which, since the torque was insufficient, the rotor could not keep up with rotation speed.

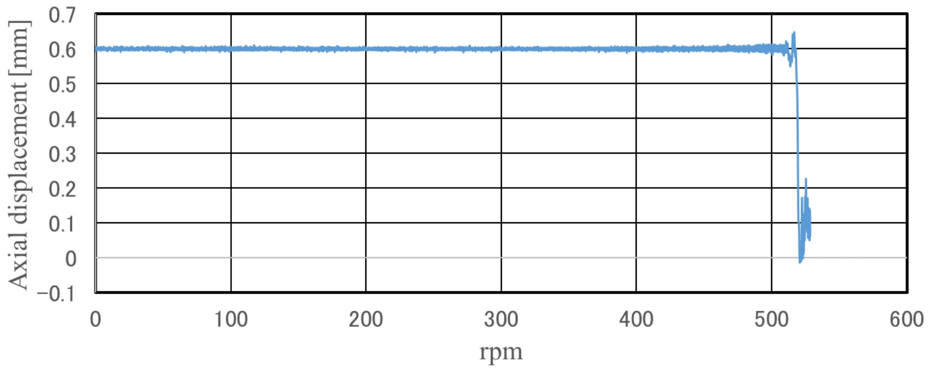

Fig. 15 Rotation test in water

4.4 Rotation test with SMB

Pouring liquid nitrogen into the bottom allows it to function like a SMB. Liquid nitrogen was not filled in the impellor area and the result are shown in Fig. 16. The SMB could rotate until it reached 1300 rpm, however, it also could not exceed the resonance point even in this state.

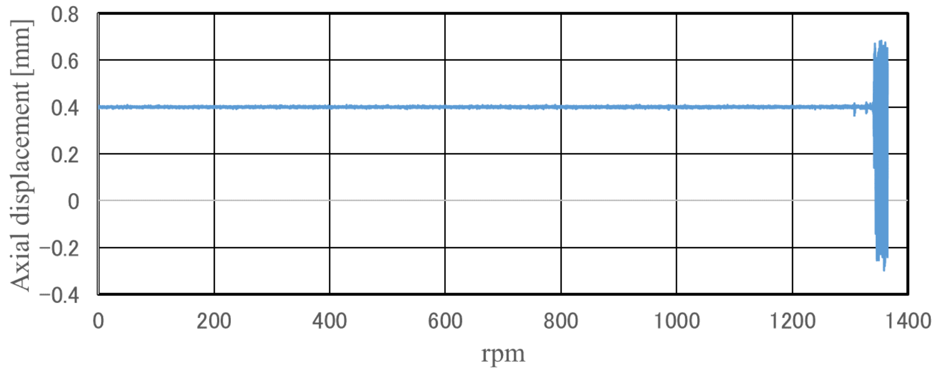

Fig. 16 Rotation test with SMB

5. Conclusion

In this paper, we proposed a new centrifugal cryogenic fluid pump by using an axial self-bearing motor. The control theories of the axial and rotation direction and the structure and control system of the experimental devise were then introduced. Finally, a flying test, a rotation test in air or water, and a rotation test with SMB were carried out. When the rotation test was carried out without liquid, a rotation speed between 1300–1500 rpm was achieved. When the rotation test was conducted with water, a rotation speed of 500 rpm was achieved. In these test, the experimental device was able to flow the water.

In the future, we plan to eliminate torque shortage and performed the rotation test with liquid nitrogen. As the supporting force in the radial direction is increased by the wedge effect, it can be expected to exceed the resonance point.

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