Development of Magnetically Levitated Motor Driven at Extremely Low Temperature

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Abstract

A cryogenic motor with active magnetic bearings (AMBs) which works in liquid nitrogen is discussed in this paper. The cryogenic motor is composed of two AMBs, four displacement sensors, a permanent magnet (PM) motor, etc. In order to check the stability for the rotor, FFT (fast Fourier transform) analysis for the levitated rotor in the radial direction is performed. Displacement of rotor in the axial direction is studied during rotation.

1 Introduction

A cryogenic motor with active magnetic bearings (AMBs) which works in liquid nitrogen (-196 degrees centigrade) is discussed in this paper. The cryogenic motor is composed of a rotor, 6-pole motor, AMBs, passive magnetic bearing (PMB), two displacement sensors, etc. Some experiments for the AMB are performed in liquid nitrogen. This paper discusses static and dynamic characteristics of the cryogenic motor.

The cryogenic motor working in liquid nitrogen is very interesting and special, because conditions in liquid nitrogen are very different from those at room temperature. Thus, there are few papers concerning cryogenic motors with AMBs working in liquid nitrogen (Kajikawa, Teion Kogaku, 2012), (Komori, IEEE Trans. on Applied Superconductivity, 2004), (Komori, Mechanical Engineering Journal, 2017).

2 Cryogenic Motor Structure

Figure . 1 shows a photo of the cryogenic motor with two radial AMBs working in liquid nitrogen (-196 degrees centigrade). The cryogenic motor is composed of a rotor, two AMBs, four displacement sensors, a permanent magnet (PM) motor, etc. The upper and lower black parts are the same AMBs. The PM motor is set in the center of the cryogenic motor. The stator of the AMB has eight electromagnets with 250 turns. The displacement sensors are inductance-type sensors based on

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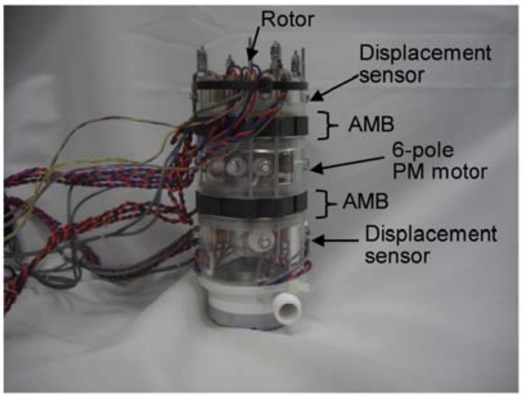

Figure 1: Photo of a cryogenic motor which works in liquid nitrogen.

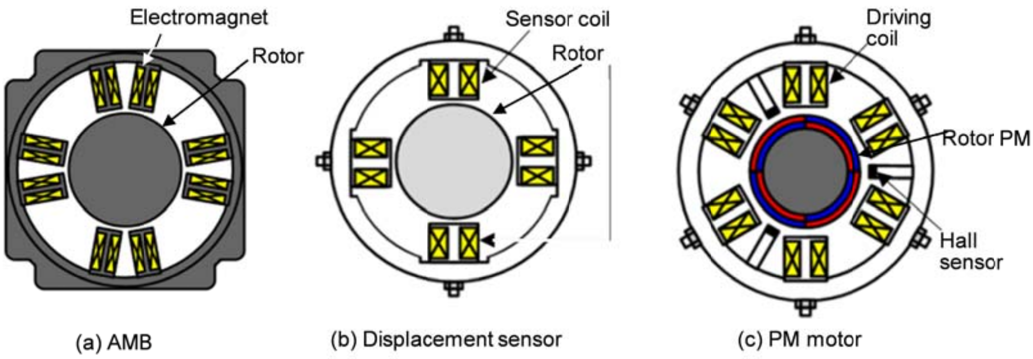

Figure 2: Cross sections of the cryogenic motor

detecting the inductance difference between two sensing coils. The detail of the inductance-type sensor is reported in Refs. (Hirose, IEEE Trans. on Magnetics, 2015), (Wang, Sensors and Actuators, 2010). A PMB composed of a couple of PMs facing each other is set at the bottom of the rotor. Thus, the rotor is levitated completely without any mechanical contacts.

Figure 2 shows the cross sections of the cryogenic motor showing (a) the cross section of AMBs, (b) the cross section of displacement sensors and (c) the cross section of PM motor. The AMB shown in Figure 2(a) has the same structure as other commercial magnetic bearings. The AMB has eight electromagnets with 250 turns. The cross section of displacement sensor is shown in Figure 2(b). A couple of sensor coils in the vertical direction are set for detecting the displacement in the vertical direction, and a couple of coils in the horizontal direction are set for detecting the displacement in the horizontal direction. The cross section of PM motor is shown in Figure 2(c). Six electromagnets for stator and four arc-shaped PM for rotor are set as shown in Figure 2(c). Hall sensors are used for detecting the rotor angle to drive the electromagnets.

Detecting the rotor displacements accurately is very important in the temperature range from room temperature to liquid nitrogen temperature. Thus, the relationship between sensor output and displacement are studied at room temperature and liquid nitrogen temperature. In the experiment, a laser displacement sensor is used to measure the correct displacement. The experimental result is shown in Figure 3 representing the relationship between sensor output voltage and displacement. In

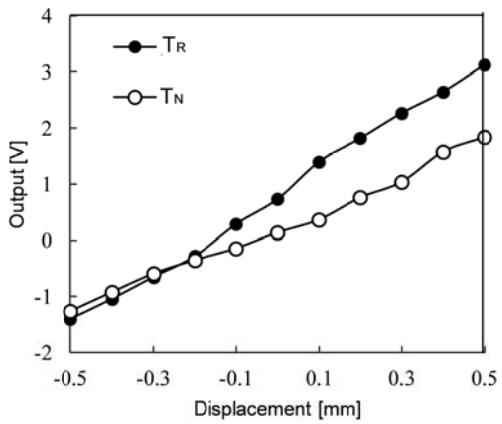

Figure 3: Relationship between output voltage from the displacement sensor and rotor displacement.

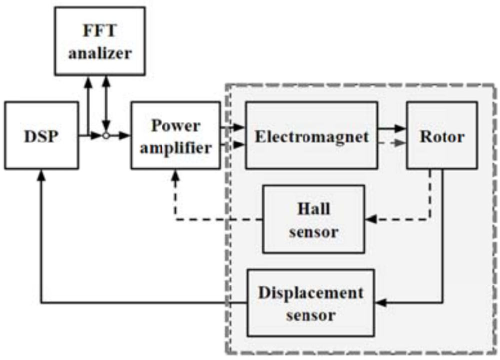

Figure 4: Block diagram of the cryogenic motor with power amplifier, DSP controller and FFT analyzer.

the Figure ure, TR and TN mean room temperature and liquid nitrogen temperature, respectively. From the result in Figure 3, both relationships at TR and TN are linear in the displacement range from -0.5 mm to 0.5 mm. However the difference between the output at TR and that at TN is observed. Thus, the displacement sensor in liquid nitrogen has to be adjusted to the same gain as that at room temperature.

Figure 4 shows the block diagram of cryogenic motor with power amplifier, DSP (Digital Signal Processor) controller and FFT (fast Fourier transform) analyzer. The cryogenic motor is shown inside the dotted line which is composed of electromagnets, rotor, Hall sensor and displacement sensor. The driving current is applied to the electromagnet using the power amplifier. The DSP applies the control signal to the power amplifier according to rotor displacement.

3 Characteristics

Figure 5 shows a photo of cryogenic motor in liquid nitrogen. The rotor is set in the center of the motor. Four sensor coils are set around the rotor. The motor is immersed in liquid nitrogen. That is,

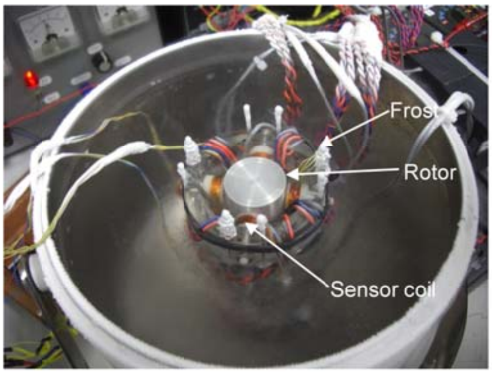

Figure 5: Photo of cryogenic motor in liquid nitrogen. The rotor is set in the center of the motor.

the level of liquid nitrogen is almost equal to the top of the cryogenic motor. Dynamic experiments are performed in the same condition as Figure 5.

Figure 6 shows the relationship between rotor displacement and rotation speed for the cryogenic motor working in liquid nitrogen. x1 and y1 represent the displacements in the x and y directions at the upper part of rotor, respectively. x2 and y2 represent the displacements in the x and y directions at the lower part of rotor, respectively. The rotor displacements are measured in the rotation speed range from 1,000 rpm to 4,500 rpm. The result shows that each displacement is smaller than 0.2 mm, which is very small. There is no vibration peak in the speed range from 1,000 rpm to 4,500 rpm, which means that the rotor spins stably in this speed range.

4 Some Experiments and evaluation

Figure 7 shows the experimental setup for studying dynamic performances of the cryogenic motor in liquid nitrogen. The experimental setup of cryogenic motor is the same as that shown in Figure 5. In the Figure, the cryogenic motor is connected to turbine blades at the bottom for pump performance.

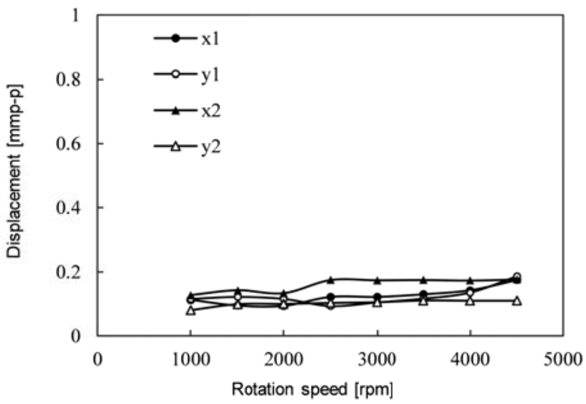

Figure 6: Relationship between rotor displacement and rotation speed for the cryogenic motor working in liquid nitrogen.

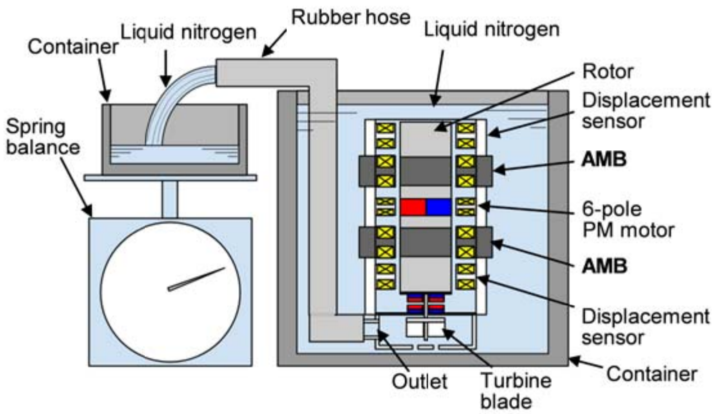

Figure 7: Experimental setup for studying dynamic performances of cryogenic motor in liquid nitrogen.

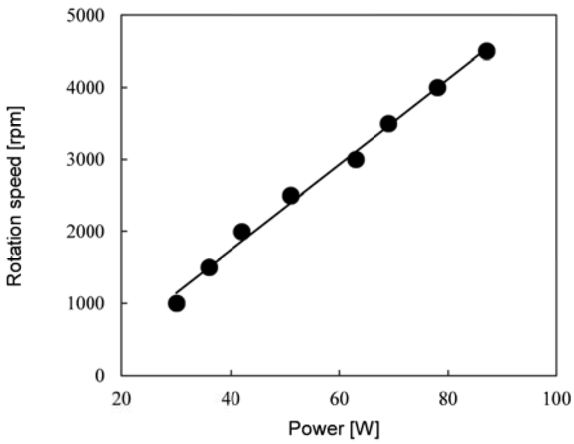

Figure 8: Relationship between pump flow and rotation speed for the cryogenic pump working in liquid nitrogen.

The outlet of the cryogenic motor is connected to a rubber hose. Thus, liquid nitrogen flows through the rubber hose into the small container which is set on a spring balance. The weight of liquid nitrogen in the container for a minute is measured in order to estimate the pump flow of liquid nitrogen.

During the pump performance, the applied power to the cryogenic motor is measured in the rotation speed range from 1,000 to 4,500 rpm. The applied power is estimated by measuring the voltage and the current of electromagnet. Figure 8 shows the relationship between rotation speed and applied power. The result shows the linear relationship in the speed range from 1,000 and 4,500 rpm. The cryogenic motor does not spin in the speed range more than 4,500 rpm, because the rotation torque is limited in the speed range higher than 4,500 rpm.

Figure 9 shows the relationship between pump flow and rotation speed. The pump flow is measured in the speed range from 2,000 rpm and 4,500 rpm. The result shows the good linear relationship between pump flow and rotation speed. The pump flow is not measured in the speed range more than 4,500 rpm, because the rotation torque is limited at speeds higher than 4,500 rpm.

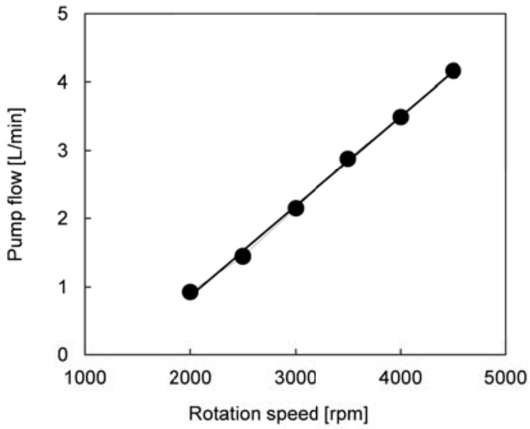

Figure 9: Relationship between pump flow and rotation speed for the cryogenic pump working in liquid nitrogen.

5 Summary

This paper discusses the cryogenic motor which works in liquid nitrogen (-200 C). The cryogenic motor is composed of two AMBs, four displacement sensors, a PM motor, etc. Some static and dynamic characteristics are studied in liquid nitrogen.

Some experiments are performed at room temperature and in liquid nitrogen. From the result of FFT analysis, it is found that the rotor is stabilized in the radial direction and that the rotor spins stably in the speed range 1,000 rpm to 4,500 rpm. From the result of spin test, it is found that the displacements in the x and y directions are smaller than 0.2 mm and that there is no vibration peak in the speed range from 1,000 rpm to 4,500 rpm. From the result of pump performance, it is found that the relationship between rotation speed and applied power is linear and the relationship between pump flow and rotation speed is also linear.

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