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Basic Study on Active Magnetic Bearing working in Liquid Nitrogen

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Abstract

This paper discusses an active magnetic bearing (AMB) able to work in liquid nitrogen, which is composed of a stator with four electromagnets (EMs), a rotor, displacement sensors, a permanent magnet (PM) motor, etc. In this paper, two types of AMBs are discussed. The one AMB is made to study basic characteristics of the AMB in liquid nitrogen. The other one is made to study basic characteristics of the pump able to work in liquid nitrogen. The rotor is levitated in the center of the stator with a pivot bearing at the rotor bottom. The pump performances using the AMB are studied by measuring the displacement of the spinning rotor at extremely low temperature -200 C.

Keywords : Active magnetic bearing, Magnetic levitation, Liquid nitrogen

1. Introduction

Extremely low temperature liquids such as liquid nitrogen, liquid helium and liquid hydrogen are necessary for cryocoolers, fuel cells, etc (Hirabayashi, 2005). These liquids are usually transferred from storage tanks to many small application tanks under their pressures. For these transfer operations, special engineering skills are required, because high pressure gases (liquids) are used. Thus, cryogenic mechanical pumps are needed for the gas (liquid nitrogen)

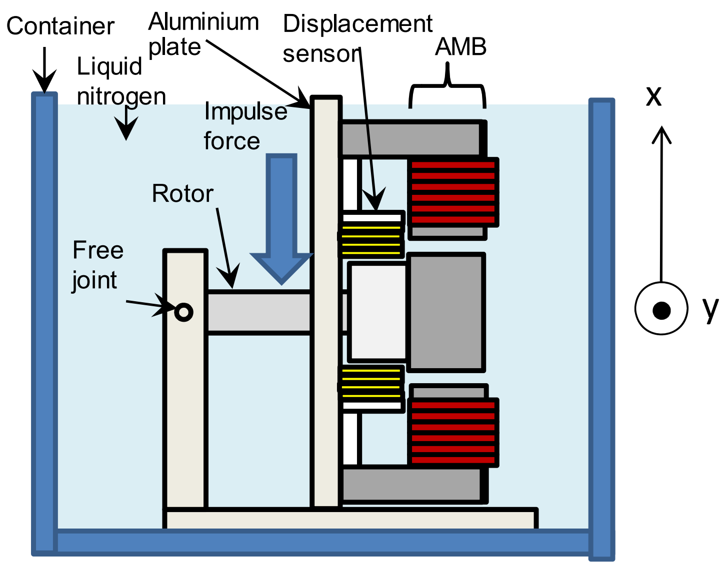

Fig. 1 Experimental setup for AMB which works in liquid nitrogen. The experimental setup is composed of the AMB, displacement sensors and a rotor supported by a free joint. The x and y directions are indicated in the figure.

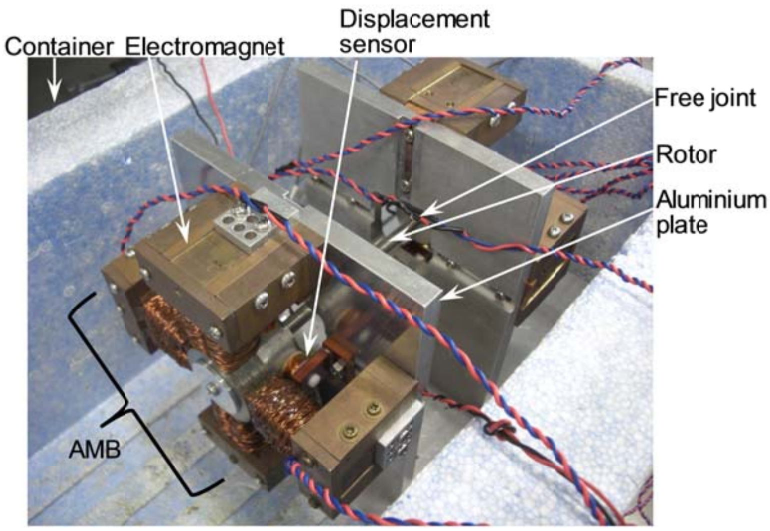

Fig. 2 Photo of the experimental setup. The experimental setup is composed of the AMB, displacement sensors and a rotor supported by a free joint.

transfer. However, there are not so many cryogenic mechanical pumps like conventional water pumps, because mechanical bearings don't work well in the extremely low temperature and are expensive due to their special mechanisms (Kajiwara, et al., 2012), (Okada, et al., 2014). Then, inexpensive and easy cryogenic pumps are needed for these applications (Komori, et al. 2014). Then, cryogenic pumps without mechanical bearings are proposed in this paper. Static and dynamic characteristics for the proposed cryogenic pump are discussed.

2. Active magnetic bearing in liquid nitrogen

Fig. 1 shows an experimental setup for the AMB which works in liquid nitrogen. The experimental setup is composed of an AMB, two displacement sensors, a PM motor, a rotor supported by a mechanical free joint, etc. The stator of the AMB has four EMs with 250 turns per EM. The displacement sensors are inductance-type sensors based on detecting the inductance difference between two sensing coils. The experimental setup shows that the right end of the rotor is levitated using the AMB and that the left end of the rotor is supported by a mechanical free joint. Then, the right end of the rotor easily moves in the vertical and horizontal directions. The x and y directions are indicated in the figure. Fig. 2 shows a photo of the experimental setup. The left side of the experimental setup is the AMB showing the four EMs, the displacement sensors, etc. These are set on an aluminum plate (thickness: 10 mm). The experimental setup is in a styrene-foam container to be cooled down using liquid nitrogen.

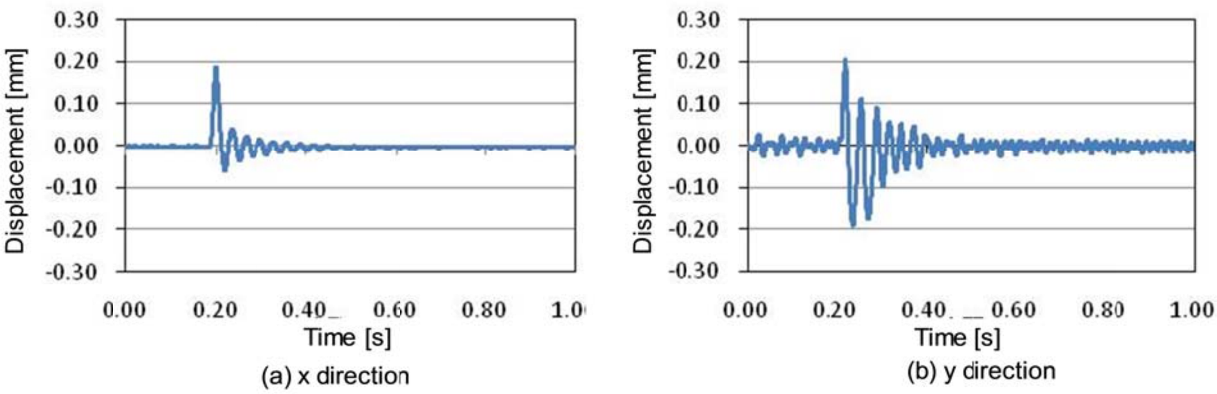

Fig. 3 Impulse responses of the rotor at room temperature in (a) the x direction and (b) the y direction The x and y directions are indicated in Fig. 1. Impulse responses are performed at room temperature.

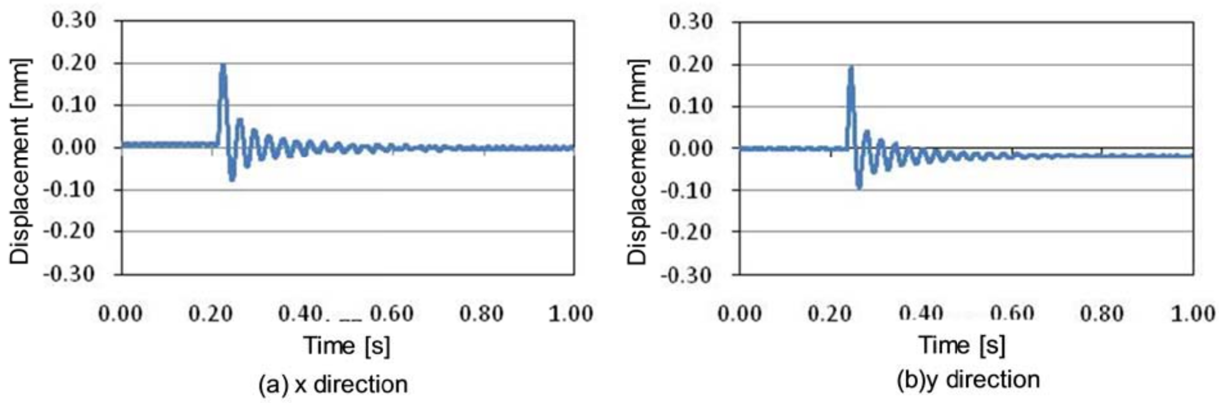

Fig. 4 Impulse responses of the rotor in liquid nitrogen in (a) the x direction and (b) the y direction The x and y directions are indicated in Fig. 1. Impulse responses are performed in liquid nitrogen.

3. Experiments and results

3.1 Impulse responses

Impulse responses for the AMB rotor at room temperature in the x and y directions are performed. The x and y directions are indicated in Fig. 1. As shown in Fig. **1**, impulse forces are applied to the rotor using an impulse hammer (aluminum bar ϕ 5 mm × 100 mm). During the experiment, the experimental setup is at room temperature. One of the results for impulse responses is shown in Fig. 3, indicating the results in (a) the x direction and (b) the y direction. From the result, it is found that the damping vibrations in Fig. 3(a) and (b) are observed and that the vibrations disappear within $\approx$ 0.2 s. The damping in Fig. 3(b) is smaller than that in Fig. 3(a). Anyway, these show that the AMB works well at room temperature.

Impulse responses for the AMB rotor in liquid nitrogen in the x and y directions are performed. The x and y directions are indicated in Fig. 1. Impulse forces are applied to the rotor using the same impulse hammer as that in Fig. 3. During the experiment, the experimental setup is in liquid nitrogen. One of the results for impulse responses is shown

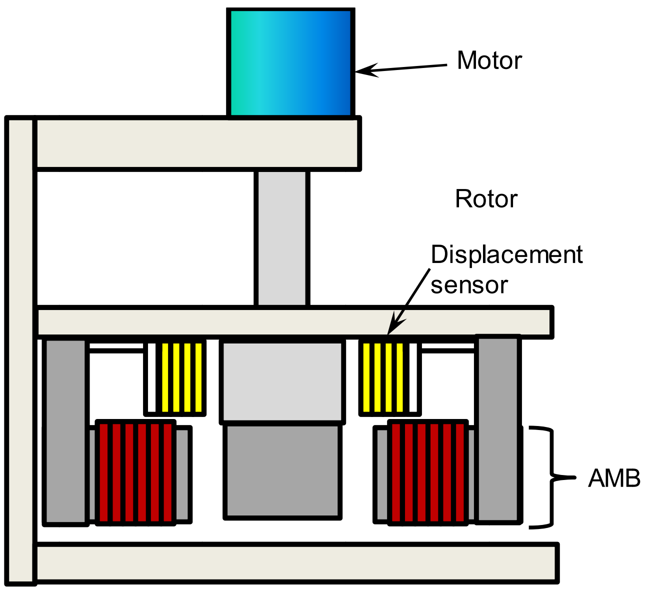

Fig. 5 Experimental setup of AMB for rotation tests. The x and y directions are the same as Fig. 1. The experimental setup is composed of the AMB, displacement sensors and a rotor whose end is connected to a DC motor. Experiments are performed in liquid nitrogen.

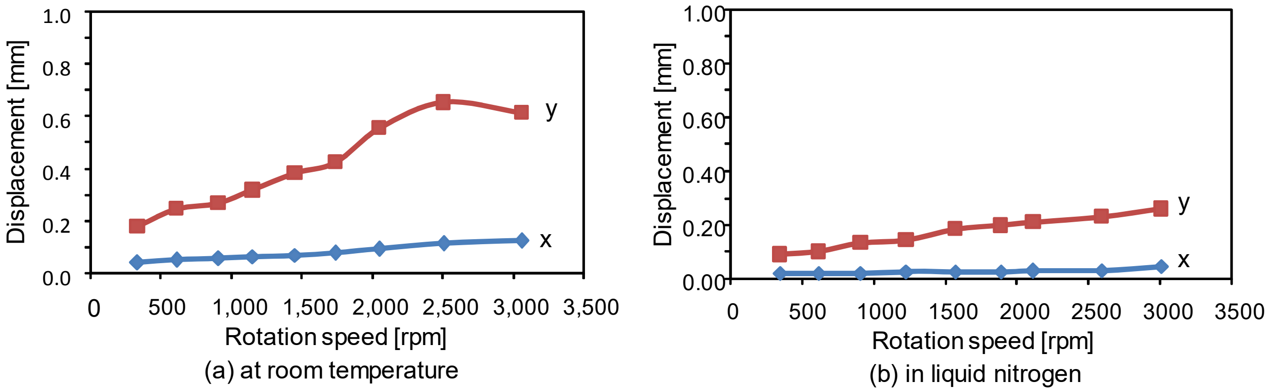

Fig. 6 Relationship between displacement and rotation speed for the AMB working (a) at room temperature and (b) in liquid nitrogen. The x and y directions are the same as Fig. 1.

in Fig. 4, indicating the results in (a) the x direction and (b) the y direction. From the result, it is found that the damping vibrations in Fig. 4(a) and (b) are observed and that the vibrations disappear within ≈ 0.2 s. These show that the AMB works well in liquid nitrogen. The vibrations in Fig. 4(a) are almost the same as those in Fig. 4(b). The damping in Fig. 4 is rather larger than that in Fig. 3 due to the viscosity of liquid nitrogen.

3.2 Rotation tests

Fig. 5 shows an experimental setup of an AMB for rotation tests. The x and y directions are the same as Fig. 1. The experimental setup is composed of the AMB, two displacement sensors and a rotor whose end is connected to a DC motor. The lower part of the experimental setup is the same AMB as that in Fig. 1. The upper end of the rotor is connected to a DC motor. Rotation tests are performed at room temperature and in liquid nitrogen. During the rotation tests, rotation speeds and driving currents are measured.

Fig. 6 shows the relationships between displacement and rotation speed for the AMB working (a) at room temperature and (b) in liquid nitrogen. The x and y directions are the same as Fig. 1. Fig. 6(a) shows that the

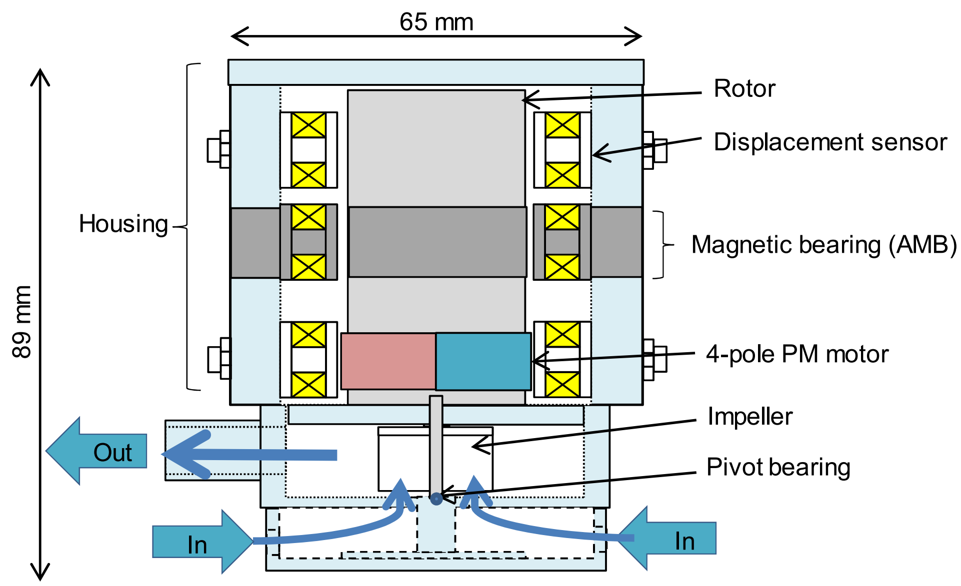

Fig. 7 Schematic illustration of a pump with a magnetic bearing working in liquid nitrogen. The pump is composed of a magnetic bearing, a PM motor, displacement sensors and a rotor supported by a mechanical pivot bearing at the end.

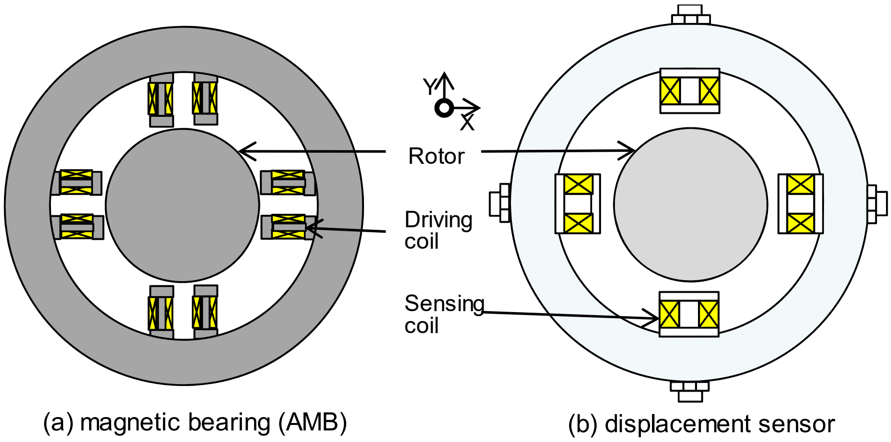

Fig. 8 Cross sections of the pump showing (a) the magnetic bearing and (b) the displacement sensors. The AMB and the displacement sensors are different from those of Figs. 1 and 2.

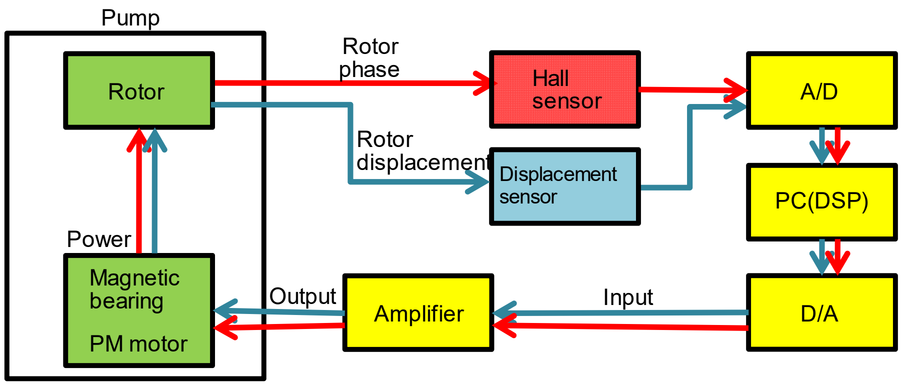

Fig. 9 Block diagram of the pump with a control system and a driving system. The rotor displacements are detected using displacement sensors. The Hall sensor detects the rotation angle of the rotor. PID control for the AMB is performed using the DSP.

displacements in the x and y directions gradually increase with increasing rotation speed. The displacement in the y direction is larger than that in the x direction. This is because the damping in the x direction is larger than that in the y direction. The larger displacement in the y direction in Fig. 6(a) is corresponding to the larger displacement in the y direction in Fig. 3(b). Fig. 6(b) shows that the displacements in the x and y directions gradually increase with increasing rotation speed. The displacement in the y direction is a little larger than that in the x direction. The displacements in Fig. 6(b) are smaller than those in Fig. 6(a). This is because the damping in liquid nitrogen (Fig. 6(b)) is larger than that at room temperature (Fig. 6(a)). That is, the viscosity of liquid nitrogen in Fig. 6(b) is larger than that of air in Fig. 6(a). Anyway, the rotor spins without mechanical contact because the AMB works well in liquid nitrogen.

Fig. 7 shows a schematic illustration of a pump with an AMB working in liquid nitrogen. The pump is composed of an AMB, a PM motor, two displacement sensors and a rotor supported by a mechanical pivot bearing at the bottom end. Turbine blades (five blades) are set to the upper part of the pivot bearing. The AMB and the displacement sensors are the same as those used in Fig. 5. The stator of AMB, the rotor and the displacement sensors are set in the housing for pumping liquid nitrogen. The stator of AMB is a part of the housing as shown in Fig. 7. The pump measures 65 mm in diameter, 89 mm in height. When the turbine blades rotates in the housing, liquid nitrogen comes into the housing from the bottom inlet and goes out from the outlet as shown in Fig. 7. Fig.8 shows the cross sections of the pump showing (a) the AMB and (b) the displacement sensors. The displacement sensors are the same as those in Figs. 1 and 5. The AMB is in the center of the pump as shown in Fig. 7. The displacement sensors are set just upper part of the AMB.

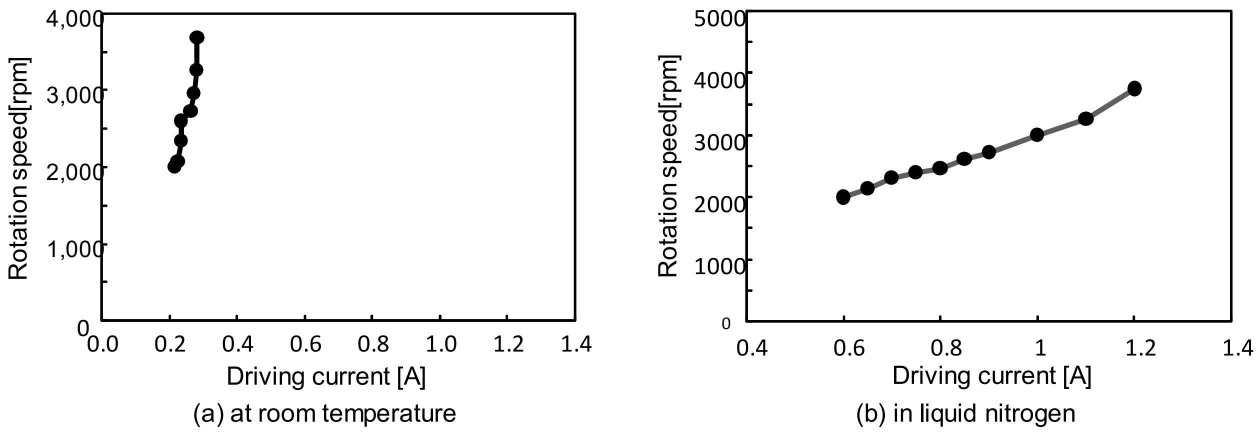

Fig.10 Relationships between rotation speed and driving current (a) at room temperature and (b) in liquid nitrogen. The driving current means a total applied current to the motor. The relationship at room temperature and the relationship in liquid nitrogen are almost linear. The gradient in (a) is much larger than that in (b).

Fig.9 shows a block diagram of the pump with a control system and a driving system. The pump is composed of the AMB, the PM motor, the two displacement sensors, a Hall sensor and the rotor. The rotor displacements are detected using displacement sensors. The Hall sensor detects the rotation angle of the rotor. PID control for the AMB is performed using the DSP. The PID control gains are adjusted by trial and error.

Fig. 10 shows the relationships between rotation speed and driving current (a) at room temperature and (b) in liquid nitrogen. The driving current means a total applied current to the motor. Fig. 10(a) shows that the rotation speed increases with increasing driving current. The relationship between rotation speed and driving current is almost linear. The slope in Fig. 10(a) is very large, because there is no mechanical friction for the rotor due to the AMB. Fig. 10(b) shows that the rotation speed increases with increasing driving current. The relationship between rotation speed and driving current is almost linear. However, the slope in Fig. 10(b) is smaller than that in Fig. 10(a). This is caused by the viscosity of liquid nitrogen.

4. Summary

This paper discusses the basic study on an AMB which works in liquid nitrogen (-200 C). The AMB is composed of a stator with four EMs, a rotor, two displacement sensors, a PM motor, etc. In this paper, two types of AMBs are discussed. The one AMB is made to study basic characteristics of the AMB in liquid nitrogen. From the result of impulse responses, it is found that the damping vibrations at room temperature and in liquid nitrogen are observed and that the vibrations disappear within 0.2 s. These show that the AMB works well in liquid nitrogen. The results of rotation tests show that the displacements in the x and y directions gradually increase with increasing rotation speed both at room temperature and in liquid nitrogen. However, the damping in liquid nitrogen is larger than that at room temperature. This is because the viscosity of liquid nitrogen is larger than that of air.

The pump is composed of the AMB, the PM motor, the displacement sensors and the rotor. The rotation speed for the pump increases with increasing driving current. The relationship between rotation speed and driving current is almost linear. Anyway, it is found that the pump succeeds to work well in liquid nitrogen.

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