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Active magnetic bearing for a liquid nitrogen pump

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Abstract. The development of a liquid nitrogen submerged pump for HTS applications is underway. A cryogenic active magnetic bearing is the main component of the pump. The bearing makes the maintenance interval of the pump longer than 3 years such interval is essential for the pump in commercial use of HTS applications such as long HTS cable. The bearing will be set in a HTS motor shaft of the pump. In experiments, a shaft without an HTS motor is used and the bearing was immersed in liquid nitrogen. The rotation of the shaft is made by a high-speed motor at room temperature. The bearing consists of two radial bearings and one axial bearing. The shaft was floating by the bearing and was rotated by the motor at room temperature. The steady rotation speed of 2,000, 3,000, 4,000 and 5,000 rpm were achieved, and the rotation speed satisfied the design speed of the pump which is 5,000rpm.

1. Introduction

A long length HTS power cable will be one of the main HTS applications for civil infrastructure. The main components of the cooling system for the cable are a refrigerator and a cryogen pump. The pump requires a long maintenance interval such as 3 years [1] and it should have 1-2 MPa pressure head [2][3] which is relatively high for a low flow rate of 50-100 L/min liquid nitrogen. There is no pump available which meets the specification above.

The purpose of this study is to develop the items below.

1. 3 years maintenance free cryogen pump for HTS applications.
2. The pump has 1 MPa pressure head and flow rate of 100L/min for LN.
3. A cryogenic active magnetic bearing for the pump.
4. An HTS motor for the pump.

In this paper, the study of a cryogenic active magnetic bearing for the pump is explained. The pump is required to have long maintenance interval such as more than 3 years and it is essential for real HTS applications. The long maintenance interval is a key point for the pump. The pump motor is HTS motor [4] and a bearing is cryogenic active magnetic bearing. With the cryogenic active magnetic bearing, the pump shaft can be short, then strong power is supplied to a pump impellor. Also, the pump can be submerged and the heat load to the cryogen will be low because of the small amount of heat generated in the HTS motor and the absence of a drive shaft..



2. Design of the submerged pump

A cryogenic active magnetic bearing is the key component of a submerged liquid nitrogen pump with an HTS motor. Newly designed liquid nitrogen pump is explained in this section.

2.1. The liquid nitrogen pump

The specification of the pump is shown in table 1. The pump flow rate of subcooled liquid nitrogen is 100L/min and the pressure head is 1MPa. This is typical flow rate for HTS cable [2]. The pressure head is enough for 5km length HTS cable. To reduce iron loss in a motor, the rotation speed is decided to be 5,000rpm which is relatively low value for a centrifugal pump. The maintenance interval is more than 30,000hrs. This specification is acceptable for the pump in a real grid HTS cable.

Table 1 LN pump specification

Fluid	Subcooled liquid nitrogen
Flow rate	100 L/min
Head	1.0MPa (2 stage)
Inlet pressure	0.5MPaG
Motor capacity	5kW, Water power 1.7kW, Shaft power 3.3kW
Motor voltage	3 ϕ , 200V
Rotation speed	5,000rpm
Maintenance Interval	more than 30,000hrs

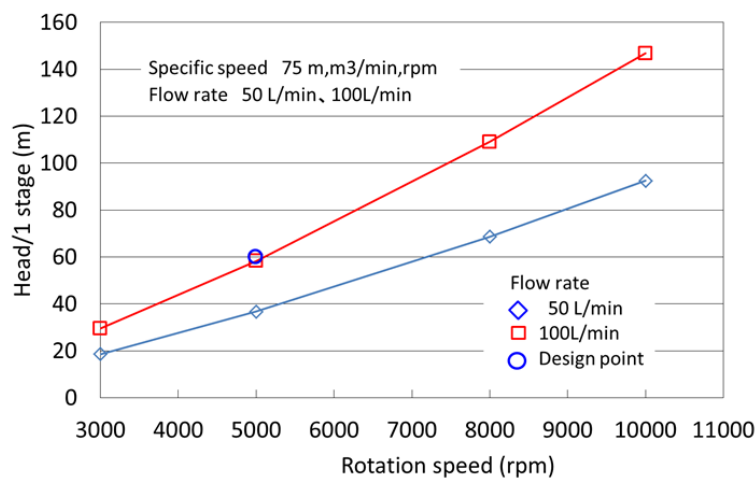


Fig. 1 Rotation speed and pressure head

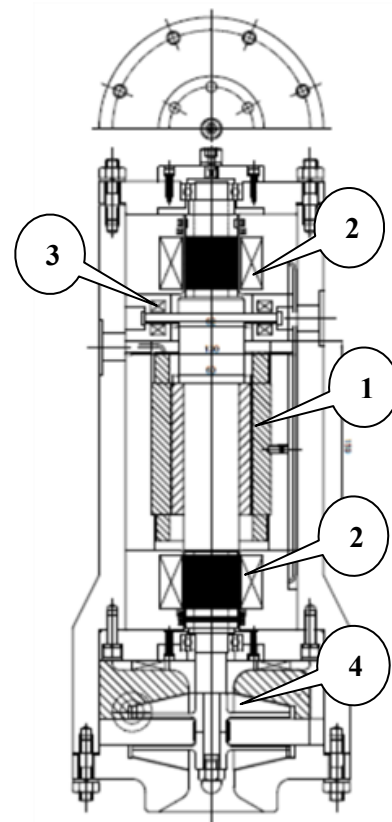


Fig.2 Drawing of the pump
1: HTS motor, 2: radial bearing,
3 : axial bearing, 4: pump impellor

The specific speed is important factor to design a centrifugal pump. In an engineering point of view, around 70 to 150 should be selected as specific speed for liquefied gas and 75 was selected in this study. The rotation speed is 5,000rpm, and the pressure head is 60m which is for 1 stage and the flow rate is 100L/min liquid nitrogen. This is the design point shown in figure 1. Since 60m pressure head is not enough for our purpose, a two-stage pump is designed for the pressure head of 120m which corresponds to 1MPa. The drawing of the pump is shown in figure 2. The impeller is at the bottom and an HTS motor is in the middle, the radial magnetic bearings are in both side of HTS motor. The axial magnetic bearing is set just above of the motor. The total height of the pump is about 500mm.

3. Cryogenic active magnetic bearing

An active magnetic bearing which is designed to be used at room temperature was immersed in liquid nitrogen and rotation test was carried out. During the cool down, the rotation shaft could not rotate, and the bearing did not work. Then new shaft was made for the improvement. The new shaft was run in liquid nitrogen and the rotation speed of 5,000rpm was achieved. Here basics of active magnetic bearing is explained and the rotation experiment of a shaft with the bearing in liquid nitrogen is described and discussed.

3.1. Basics of magnetic bearing

The shaft floats by magnetic force supplied by a coil and the force keeps the gap between the shaft and the bearing. The magnetic force is controlled by coil current which value is decided by gap sensor signal. The idea is described in following equations and figure 3. Where F_m is magnetic force, B : magnetic field, S : magnetic material cross section, N : coil turn, l : magnetic material length, h : gap, V : voltage, I : current. The gap is detected by coil inductance of sensor coil.

$$F_m = \frac{B^2 S}{2\mu_0} 2 = \frac{S(NI)^2}{\mu_0 \left(\frac{l}{\mu} + \frac{2h}{\mu_0}\right)^2}$$

Magnetic force: Gap control

$$L = \frac{N^2 S}{\frac{l}{\mu} + \frac{2h}{\mu_0}} \quad V = L \frac{\Delta I}{\Delta t}$$

Inductance: Gap detection

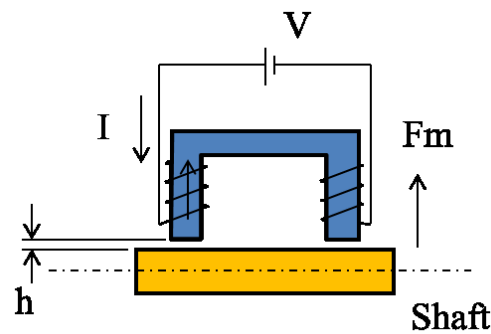


Fig. 3 Active magnetic bearing, gap control

3.2. Experiment

A copper coil motor with active magnetic bearing was immersed in liquid nitrogen and the motor shaft was rotated by a room temperature high speed motor. The motor and the shaft were connected with a long shaft. The drawing of experimental set up is shown in figure 4. The picture of experiment is shown in figure 5. The shaft with the bearings was in a cryostat. During cool down, the shaft floated and rotated in the beginning. At temperature around 180K the shaft was stacked and didn't rotate.

The bearing controller program was checked, and it is found that the gap sensor did not detect the gap. Because the shaft with an active magnetic bearing shrinks at 77K. After this experiment, a new motor shaft was fabricated with only stainless steel 304 in main structure. The material is the same as the pump casing and this idea avoids the problem caused by thermal contraction. Also, the inductance of the sensor coil was too small to control the gap at low temperature. The inductance of the sensor coil is decreased to almost half of the value at room temperature. It was caused by reduction of permeability at low temperature. Figure 6 shows the new shaft and bearings.

One way to get higher inductance, the sensor drive condition was optimized for low inductance sensor. In order that the bearing can be used without any tuning of the controller through room temperature to liquid nitrogen temperature, new controller program was arranged for this purpose, and the steady floating and rotation was achieved with this bearing. The bearings were the same as ordinary bearings, those were not changed.

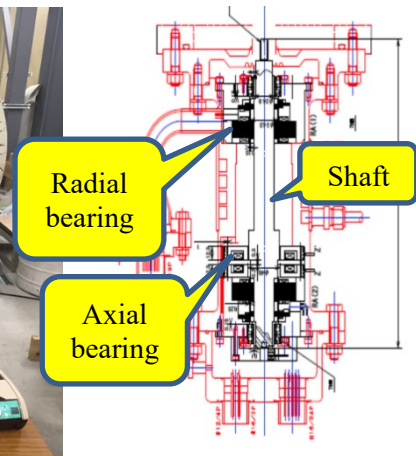
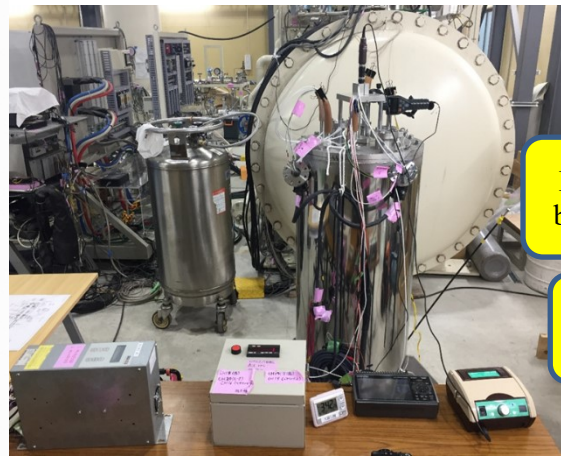
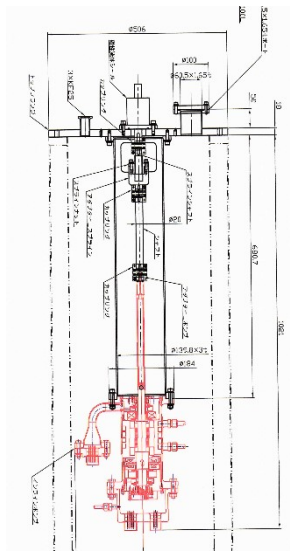


Fig.5 Picture of experiment

Fig.6 New shaft with the bearing

Fig. 4 Experimental set-up

3.3. Result

The bearings were immersed in liquid nitrogen without damage. The coils are moulded with plastic. The coil after immersing in liquid nitrogen is shown in figure 7. The Lissajous figures of shaft rotation is shown in figure 8. This figure shows the steady floating and rotation. The shaft was rotated in liquid nitrogen at 4,020rpm and 5,040rpm as shown in figure 8. Also the shaft was floated and rotated at room temperature and at 77K in liquid nitrogen.

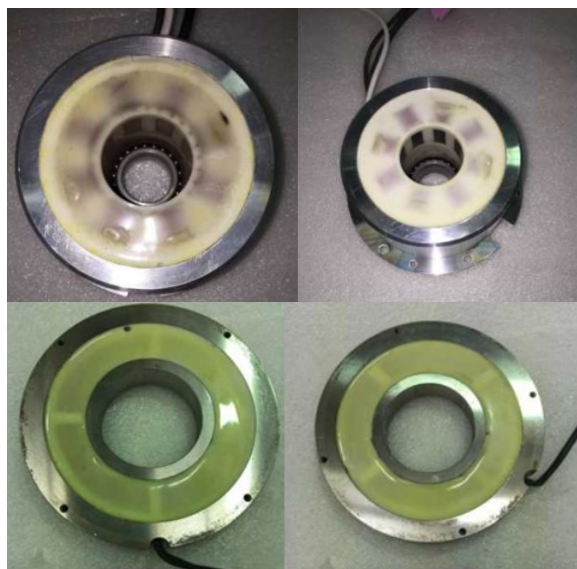


Fig.7 Radial bearing coils after LN dipping

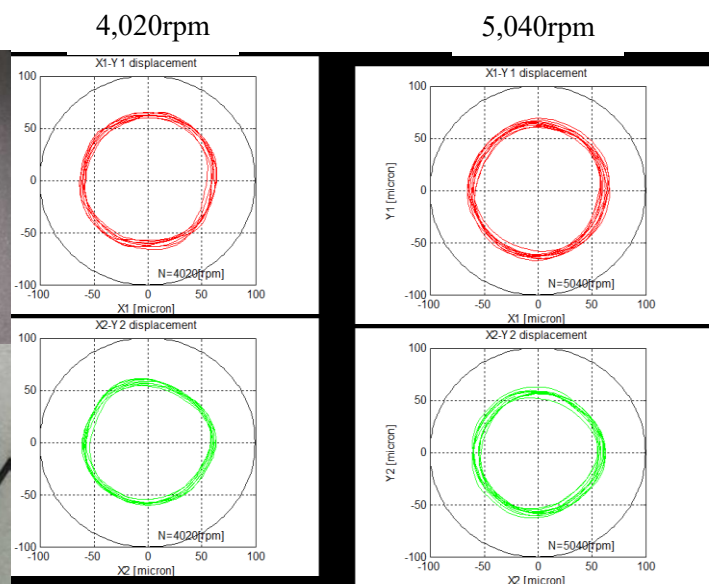


Fig. 8 Lissajous figures of shaft rotation

4. Conclusion

For a long length HTS power cable, a cryogen pump is required with long maintenance interval such as 3 years and it should have 1-2 MPa pressure head with a low flow rate of 50-100 L/min liquid nitrogen. In this study the cryogenic active magnetic bearing was developed for the pump. The 3 years

maintenance interval of the pump can be obtained with this bearing. The main results of this study are described below.

1. Operation of active magnetic bearing in liquid nitrogen was carried out and the steady rotation speed of 2,000, 3,000, 4,000 and 5,000 rpm were achieved.
2. Liquid nitrogen did not cause any damage to the bearing molding.
3. The new shaft was made of the same material as the casing and the program of the bearing controller was modified. Those solved the problems below.
 - a. The contraction of the bearing shaft and the casing caused the movement of shaft sensing target and sensor did not detect the target.
 - b. Inductance of the sensor coil was reduced by low temperature and the bearing could not be controlled.

As a result of above modification, the bearing can be steadily operated through room temperature to liquid nitrogen temperature.

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