MICRO MAGNETIC BEARING FOR AN AXIAL FLOW ARTIFICIAL HEART

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ABSTRACT

A miniaturized magnetic bearing with control in five degrees of freedom has been developed for a magnetically suspended axial flow pump in an implantable artificial heart. An impeller of the axial flow pump is suspended by a set of hybrid magnetic bearings at each side of the impeller. Permanent magnets produce bias magnetic flux for the magnetic bearings and the motor stator is set between the magnetic bearings. A three dimensional magnetic field analysis based on the finite element method was performed to design the magnetic bearings. Maximum rotating speed with complete levitation in the air was 12,000 rpm. Maximum oscillation amplitude in the radial and axial direction was 0.07 mm and 0.1 mm, respectively. The micro magnetic bearing performed well enough to act as a magnetic bearing for an axial flow artificial heart.

INTRODUCTION

Major design requirements in development of an artificial heart are high durability of the mechanics and small size for implantation. A turbo pump is an attractive candidate as a blood pump for the artificial heart to reduce the size of the device. However, the turbo pump has a bearing and seal, which determine the lifetime of the pump. Therefore, several groups in the world are trying to develop a magnetically suspended turbo pump to eliminate the mechanical bearing and seal [1]-[4]. We too have developed several types of magnetically suspended turbo pumps with self-bearing motors [4]-[8]. In the turbo pump, an axial flow arrangement has smallest volume and highest rotation speed. However, the size of the magnet bearing for an axial flow pump is too small to produce sufficient force to suspend an impeller, creating an engineering challenge. In this paper, a micro magnetic bearing which can be controlled over five degrees of freedom and a motor system for an axial flow artificial heart will be described.

METHOD

MAGNETICALLY SUSPENDED AXIAL FLOW PUMP

The basic concept for the magnetically suspended axial flow pump is shown in figure 1. A impeller for an axial flow pump is suspended by a set of magnetic bearings at both sides of the impeller and rotated by a motor stator at the center of it. The rotor impeller has impeller vanes and permanent magnets at it's center circumference. Blood will be pumped through the pump from an inlet port to the outlet port as the axial flow.

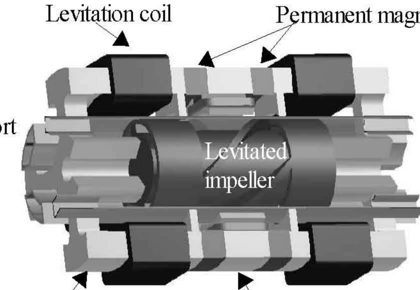

Figure 1 Basic concept for magnetically levitated axial flow pump

MAGNETIC SUSPENSION SYSTEM

Figure 2 shows a cross-sectional view of a miniaturized magnetic bearing with five degrees of freedom control. This bearing consists of two opposed hybrid magnetic bearings. Each magnetic bearing has four electromagnets to control it in five degrees of freedom. Bias magnetic flux, produced by permanent magnet set between the magnetic bearings, passes three -dimensionally through both the magnetic bearings and the impeller. The control magnetic flux generated by the electromagnets passes through the radial air gap of the impeller, the magnetic core of the impeller, and the axial air gap of the impeller. Five eddy current sensors

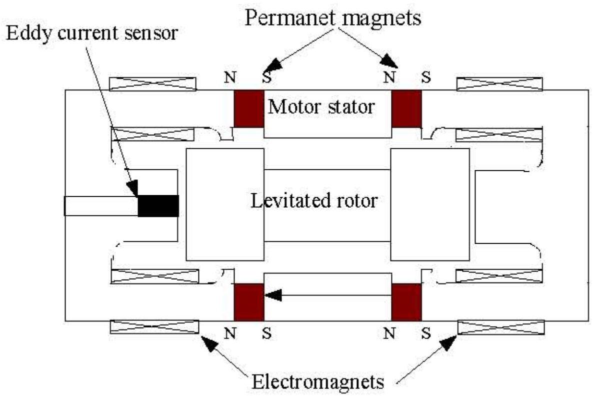

Figure 2 Cross-sectional view of a magnetic bearing

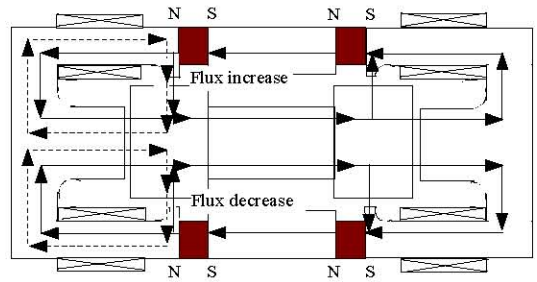

Figure 3 Magnetic flux pass way for radial position control

are used to measure the impeller position. One of the sensors is set in the center of the bearing to measure axial position of the impeller. Other sensors are set around the impeller to measure radial position and inclination of the impeller. Radial position and inclination of the impeller are controlled by regulating the magnetic flux of the electromagnets. Two opposite electromagnets are used in a push-pull manner to control radial position. Figure 3 shows the magnetic flux pass way in this case. Bias flux produced by the permanent magnet is shown as a solid line, electromagnet flux is shown as a dashed line. In this figure, magnet flux in the radial air gap of upper pole increases with the electromagnet flux to attract the levitated rotor upper side, but that of the other pole decreases. When the length difference of the radial air gap between opposite poles is very small, the force produced in the radial direction F_{radial}, will be as follows.

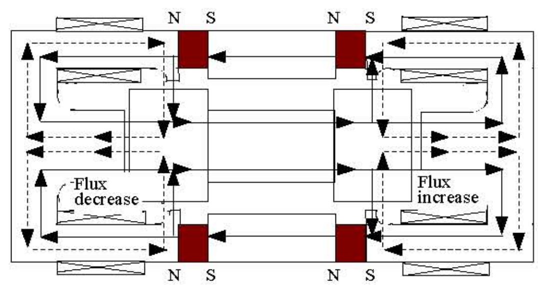

Figure 4 Magnetic flux pass way for axial position control

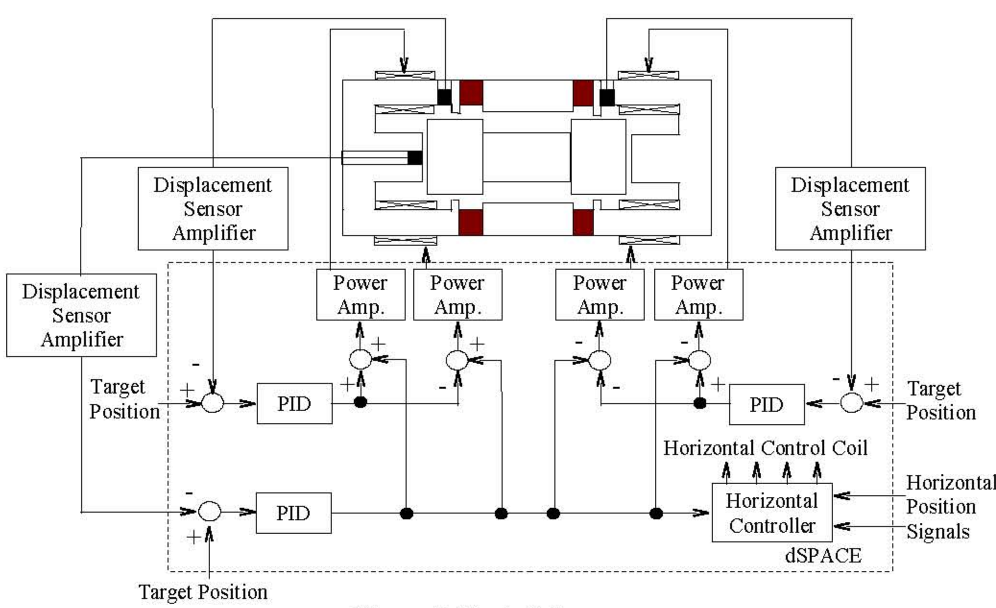

Figure 5 Control diagram

$$F_{radial} = F_{r1} - F_{r2} = (A/2\mu_0)\left((B_m + B_e)^2 - (B_m - B_e)^2\right) = 2(A/\mu_0)B_m \cdot B_e \quad (1)$$

where F_{r1} and F_{r2} are the radial force at each radial air gap, A is the cross-sectional area of the flux pass, μ_0 is the vacuum permeability, B_m is flux density produced by the bias permanent magnet at the air gap, and B_e is flux density produced by the electric magnet at the air gap. Then, radial position of the rotor can be controlled linearly because B_e is proportional to the current of the magnetic bearing. The axial position of the impeller is controlled in the same manner by regulating total magnetic flux of both bearings. Figure 4 shows the magnetic flux pass way for the axial position control to move the levitated rotor toward right on the figure. The opposite magnet bearing is used as a push-pull magnet and the total magnetic flux at the axial air gap is regulated by changing the electromagnet producing the flux. The control diagram for 5 DOF control is shown in figure 5. A digital PID controller was adopted for each control and a control system was constructed by using the dSPACE.

MAGNETIC BEARING DESIGN

A three dimensional magnetic field analysis based on the finite element method was performed to design the magnetic bearings. ANSYS, which is a commercial simulation program, was used for the analysis. A quarter simulation model for the magnetic field analysis is shown in figure 6. An important design criteria for a magnetic bearing in an artificial heart is small size. So, magnetic flux saturation will always be a problem in the device. We designed the magnetic bearing using

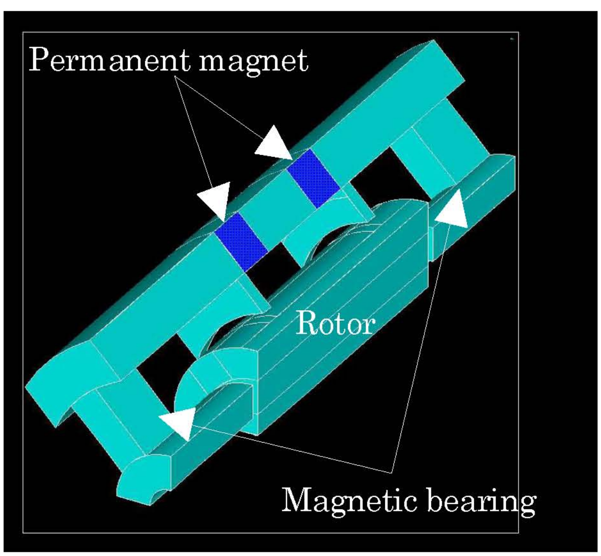

Figure 6 Quarter simulation model for the magnetic field analysis

magnetic field simulation to prevent flux saturation. The next design criteria for a magnetic bearing for an axial flow pump is sufficient axial force. Thrust hydraulic forth against the levitated impeller will be generated in an axial flow pump. Therefore, the magnetic bearing must produce a larger suspension force in the axial direction than the thrust hydraulic force to keep the impeller in position. The target force produced by the magnetic bearing in the axial direction is 8.4 N (calculated from an impeller diameter of 20mm and a pressure head of 200 mm Hg). The designed bearing core and rotor are shown in figure 7 and 8. The height and the diameter of the developed magnetic bearing are 26 mm and 38 mm, respectively. The diameter and the length of the impeller are 20 mm and

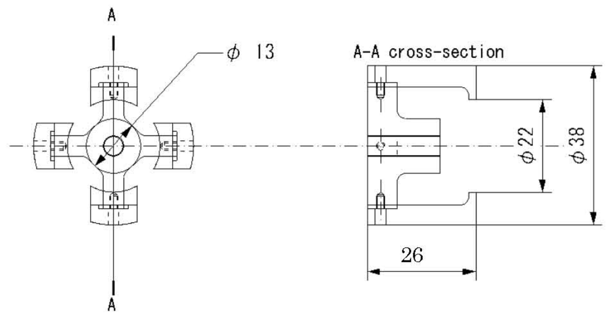

Figure 7 Core of magnetic bearing

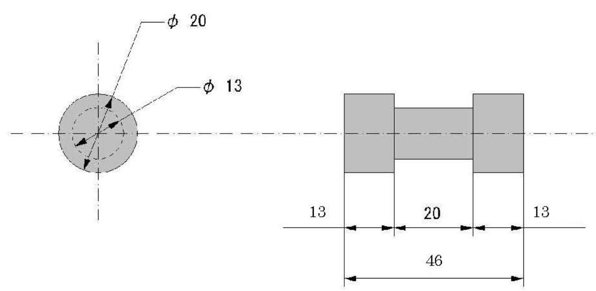

Figure 8 Rotor core

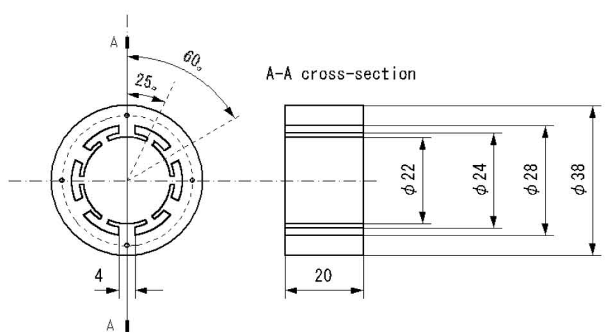

Figure 9 Motor stator

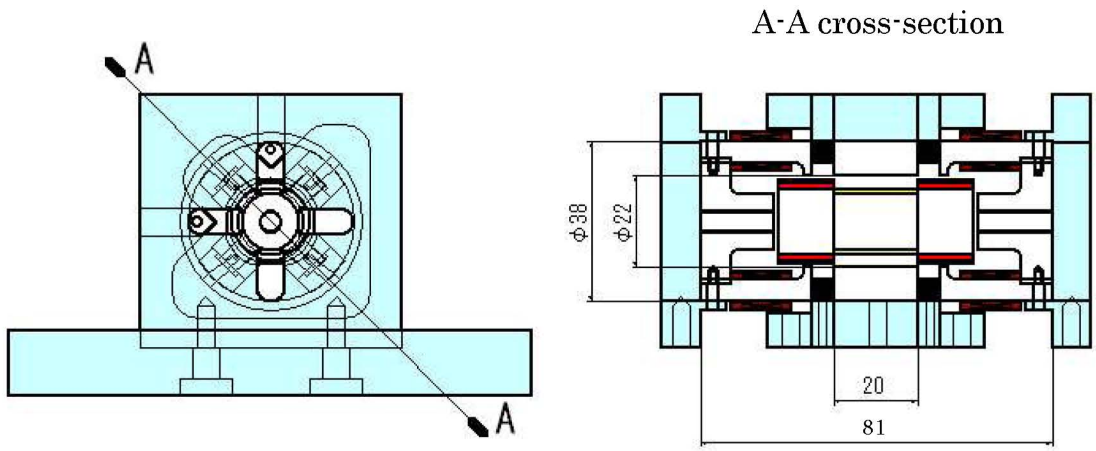

Figure 10 Magnetic bearing and motor system for maglev axial flow pump

46 mm, respectively. Each electromagnet has a 112 turn wound coil. Total length of the device is 81 mm.

MOTOR DESIGN

A synchronous motor was constructed at the center part of the pump. A motor stator which has six poles for three phases and a four pole rotating magnetic field is set between the magnetic bearings. Four thin permanent magnets are set on the surface of the levitated rotor. Each pole of the stator has a 22 turn coil. The designed motor stator is shown in figure 9. The outer and inner diameter, and length of the motor stator are 38 mm, 22 mm, and 20 mm, respectively. The air gap length between the stator and the rotor core is 4.5 mm. Motor attraction to the levitated rotor was measured and compared with the estimated bearing force by using finite element analysis.

EXPERIMENTS

The magnetic bearing and motor system was constructed and evaluated with following experiments. A schematic diagram of the experimental set up is shown in figure 10. The exterior view of the system is shown in figure 11. The axial force produced with the developed bearing was measured by using a force gauge. Also, the radial attraction generated between the motor stator and rotor was measured and compared with the estimated radial bearing force. Dynamic torque of the developed motor was measured by using a digital torque meter. The motor was supported by ball bearings and was not levitated in the torque measurement experiment. Finally, the levitation experiment was performed and levitation performance during rotation was evaluated in the air.

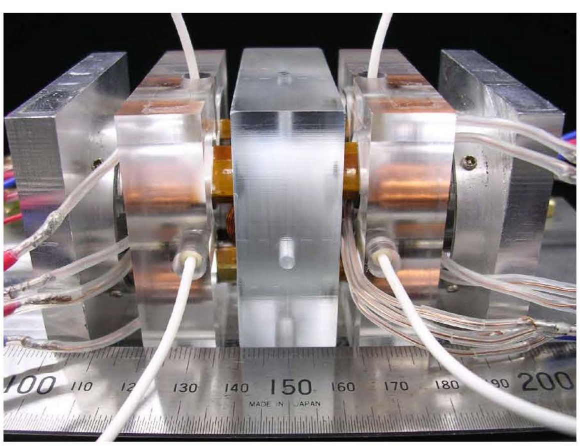

Figure 11 Exterior view of the experimental set up

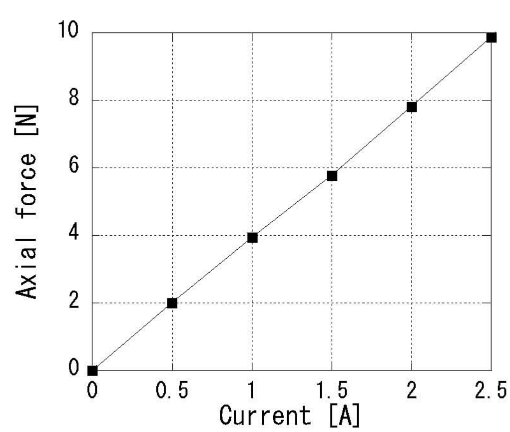

Figure 12 Measured axial force produced by the magnetic bearing

RESULTS

Figure 12 shows the force produced in the axial direction when the rotor was centered between the bearings. Maximum force was more than 10 N.

Figure 13 shows the relationship between the estimated attractive force produced by the magnetic bearing in the radial direction, the measured motor attraction, and the radial position of the rotor. The estimated radial force was from 2 N to 4 N and larger than the motor attraction in the whole range of the rotor positions.

The relationship between dynamic motor torque and rotating speed is shown in figure 14. The maximum torque at a rotation speed of 8000 rpm was 8 mNm. This torque value is enough to drive an artificial heart under a head pressure of 150 mm Hg and a flow rate of 5 l/min which is the usual operating range of the left ventricular assist system.

Figure 15 and 16 show the position control performance of the developed magnetic bearing during rotation in the air. The maximum rotating speed with complete levitation in the air was 12,000 rpm. Maximum oscillation amplitude in the radial direction was 0.07 mm at a rotating speed of 1,000 rpm and the oscillation amplitude was less than 0.04 mm when the rotating speed was higher than 6,000 rpm. The oscillation amplitude in the axial direction was less than 0.1 mm when the rotating speed was higher than 2000 rpm.

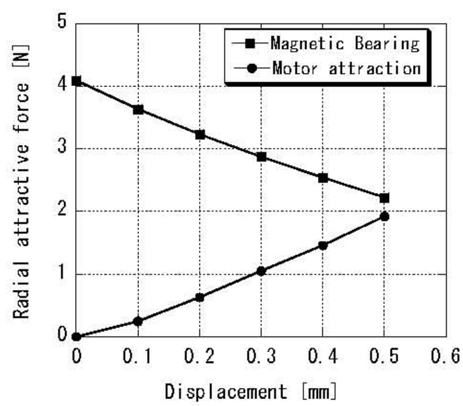

Figure 13 Radial bearing force and attraction between motor stator and rotor

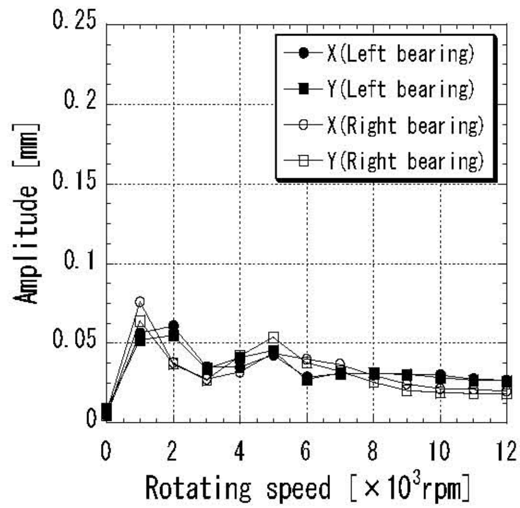

Figure 15 Maximum oscillation amplitude in the radial direction during rotation in the air

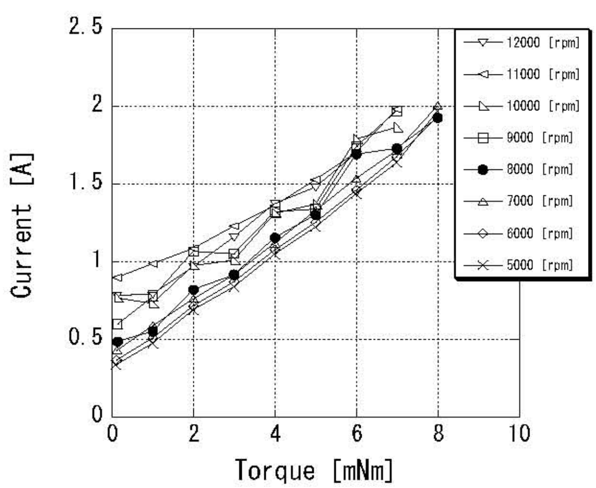

Figure 14 Relationship between dynamic motor torque and rotating number

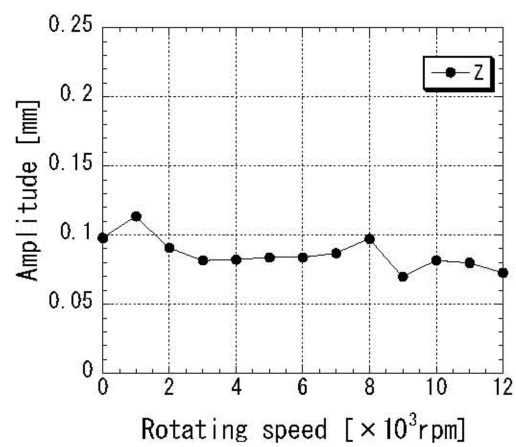

Figure 16 Maximum oscillation amplitude in the axial direction during rotation in the air

DISCUSSION

The micro magnetic bearing showed sufficient performance to act as a magnetic bearing in an axial flow artificial heart. The bearing could produce axial force greater than the design target force of 8.4 N required of a bearing of axial flow artificial heart. The radial bearing force of the magnetic bearing is greater than the radial force produced by the motor mechanism. The motor also provided sufficient torque for an artificial heart. The rotor could be levitated and rotated up to 12,000 rpm. An axial flow pump is usually driven in a rotation number range from several thousand rpm to 10,000 rpm. Developed system indicated sufficient suspension and rotation ability for an axial flow pump. The axial oscillation amplitude being larger than that in the radial direction is characteristic of the eddy current sensor used to measure axial rotor position. The sensor was embedded in the bearing core and affected by electromagnet flux change. The noise which has an amplitude of 0.1 mm was observed on the signal from the axial position sensor. The signal noise ratio of the sensor should be improved in the near future. Also, we are developing an axial flow pump to combine the micro bearing-motor system with. The pump performance of a maglev axial flow artificial heart will be reported in next several months.

CONCLUSION

Miniaturized magnetic bearing with five degrees of freedom control has been developed in a magnetically suspended axial flow pump in an implantable artificial heart. The bearing showed sufficient performance to act as a magnetic bearing in an axial flow artificial heart.

ACKNOWLEDGMENT

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