DESIGN OF A SELF-BEARING SLICE MOTOR FOR A CENTRIFUGAL BLOOD PUMP

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ABSTRACT

This paper introduces a radial type self-bearing slice motor. It has the capability of giving rotating torque and controlling radial gap magnetically. Other degrees of freedom are passively stable. This paper introduces the application of this motor to an artificial blood pump. The results of a simple experiment are described and passive stability is discussed. Finally a new design of self-bearing motor with a centrifugal pump is introduced which is under development.

INTRODUCTION

Recently, the centrifugal pump has attracted a lot of attention for application in artificial hearts (Taenaka et al., 1996; Akamatsu, Nakazeki and Itoh, 1992; Yamane et al., 1995; Allaire et al., 1996). It has the merits of compactness and high efficiency. Most of the designs require a contact supporting point. For long term application, the contact point should be removed to avoid blood thrombosis. Sometimes magnetic bearings are used to support the rotating parts (Akamatsu, Nakazeki and Itoh, 1992; Allaire et al., 1996). However, this requires a separate driving motor and a large number of control degrees of freedom.

This paper introduces a radial self-bearing slice motor that is a combination of a slice motor and a radial magnetic bearing (Okada, Dejima and Ohishi, 1995; Schöb and Barletta, 1996; Okada et al., 1997). Using this motor, a compact and high efficiency blood pump can be realized.

In this paper, a shaft supported self-bearing slice motor has been tested and results are reported. In addition, passive stability is also discussed. Finally a new design self-bearing motor with centrifugal pump is introduced which is under development. Rotating performance of this motor is shown to be suitable for the artificial heart applications.

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RADIAL SELF-BEARING SLICE MOTOR

Two types of radial self-bearing motors have been developed; permanent magnet (PM) synchronous and induction, both which have the capability of controlling the radial gap magnetically (Okada, Dejima and Ohishi, 1995; Okada et al., 1997). These self-bearing motors can support the rotor without physical contact, an attribute ideal for blood pump applications with the additional benefit of overall size reduction. But the induction motor is not applicable to the blood pump because the rotor generates heat from induction current. On the other hand, the PM type motor has merits of high efficiency and no generation of heat in the rotor, thus is ideally for suited artificial heart applications.

The principle of the self-bearing motor has been introduced in (Okada, Dejima and Ohishi, 1995; Schöb and Barletta, 1996; Okada et al., 1997). Rotational control is achieved by the rotating magnetic flux in the stator, which has the same pole number P as the rotor. In addition to the standard motoring P pole flux, the plus minus two ($P \pm 2$) pole flux of the motoring flux gives a pure translation force to the rotor. By changing the magnitude and phase of this $P \pm 2$ pole flux relative to the motoring flux, the radial force can be controlled. Figure 1 shows the schematic of the radial force control. The left side shows the plus two algorithm, while the right side shows the minus two algorithm. These pictures show that the radial force is generated independently of the rotor angular position.

The radial self-bearing motor has the capability of controlling 2 degrees of radial motion. Normally, the other degrees of freedom (axial and angular directions) of the rotor must be controlled using an additional magnetic bearing. With an increase in the number of control axes in a single unit, a complex construction becomes necessary and reliability of the system is lost. So fewer control degrees are preferable for applications in artificial organs. A slice rotor which has a shorter length than its diameter has improved passive stability in the axial and angular directions. Figure 2 shows the principle of the passive stability of the slice rotor.

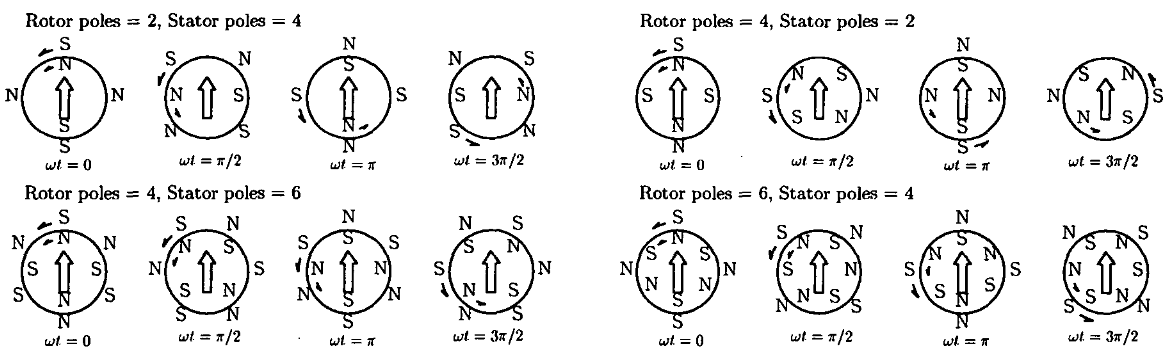


Figure 1: Radial force control of the self-bearing motor

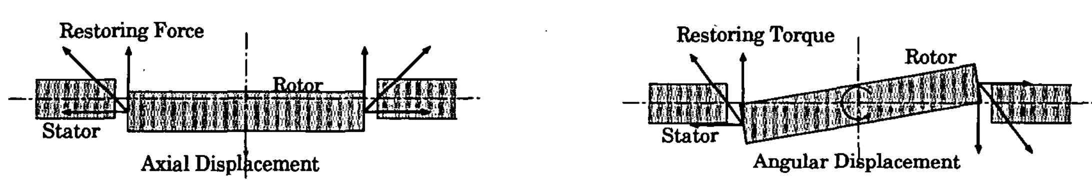


Figure 2: Passive stability of the axial and angular displacement of the self-bearing slice motor

The left side of the picture shows the axial direction. The displacement of the rotor produces magnetic force to restore its deflection, therefore the rotor is stable in the axial direction. The right side shows an angular direction. The rotor is also stable passively in this case. This construction has merits of compactness and simplification of the control system.

EXPERIMENTS OF SELF-BEARING SLICE MOTOR

In the slice motor, passive stability is improved by using a thinner rotor, but radial force and rotating torque will be decreased. Therefore, we need to confirm whether the slice motor has enough rotating torque and radial force experimentally.

The experimental setup is shown in figure 3. To simplify the experimental and control system, the rotor was attached to a shaft with a ball bearing in order to restrict the axial and angular motion. The test rotors are shown in figure 4. They have dimensions of 39 mm in diameter and 10 mm in thickness and are made of solid magnetic material (resistance: $95\mu\Omega$-cm, and relative permeability: 4160). Neodymium magnets (thickness 0.8 mm) are attached on the surface of the rotor.

The stator was built up using thin laminations to minimize eddy-current losses. The inner diameter of the stator is 41 mm, airgap between the rotor and stator is 1 mm. The stator has 12 concentrated wound poles, each of which has two coils; one generates the motoring flux and

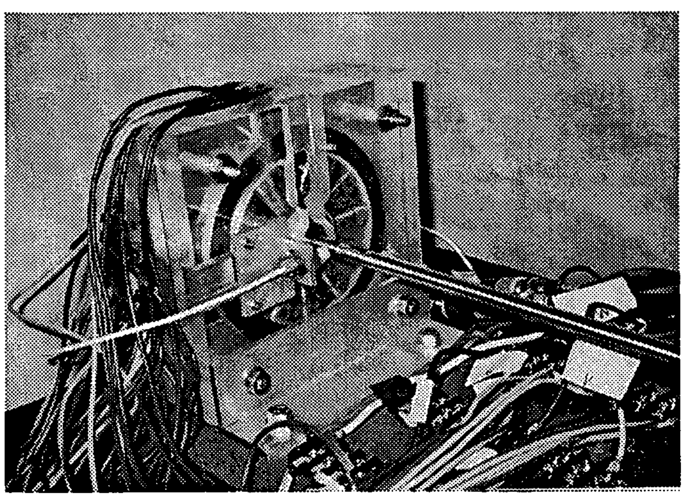
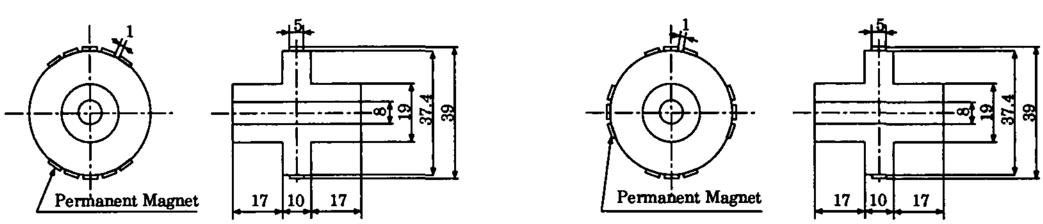


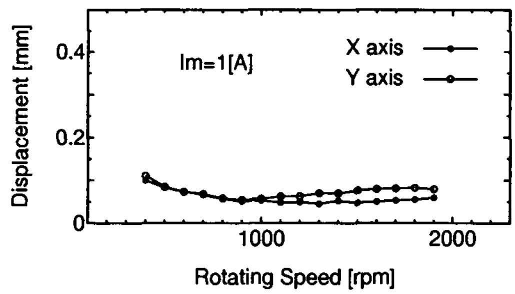
Figure 3: Experimental setup of the self-bearing motor



2 pole rotor

4 pole rotor

Figure 4: The shape of 2 pole and 4 pole rotor



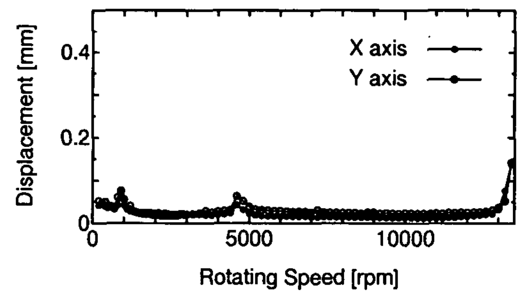


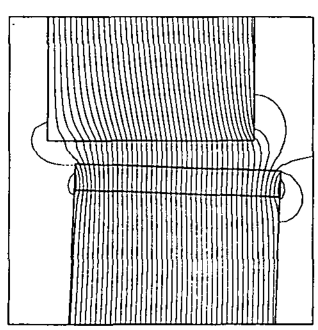
Figure 5: Unbalance response of 2 pole and 4 pole rotors (motoring current is 1[A])

the other generates the levitation control flux. In the case of a 2 pole rotor, motoring coils are connected to produce 2 pole, 3 phase flux and the radial force coils are connected to produce 4 pole, 3 phase flux. In the case of the 4 pole rotor, motoring coils are connected to produce 4 pole, 3 phase flux and radial force coils are connected to produce 6 pole, 2 phase flux. A PID feedback was used for the levitation control.

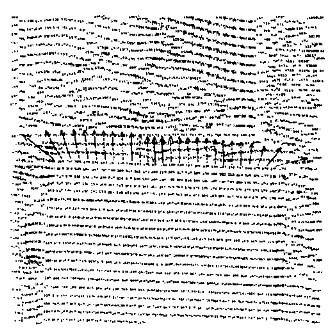
Unbalance responses are shown in figure 5. The left graph shows the results of the 2 pole rotor and the right graph shows the results of 4 pole rotor. In the case of the 2 pole rotor, the maximum rotating speed was limited about 2,000 rpm, while the 4 pole rotor could rotate at over 10,000 rpm. Vibration of the 2 pole rotor was larger than the 4 pole rotor. Generally, the motoring torque is proportional to the pole number. Hence the 2 pole rotor has larger phase difference between the rotor flux and the motoring flux than the 4 pole rotor. The radial position controller calculates the amplitude and phase of the levitation control flux using the angular position of the motoring flux in the stator. When there is the phase difference between the rotor flux and the radial force flux, the direction of the radial force is different from the desirable one. Hence, the 4 pole motor shows better results than the 2 pole motor.

PASSIVE STABILITY OF THE SLICE ROTOR

Passive stability of the slice rotor should be confirmed. The characteristic of the stability was calculated from magnetic field analysis using the 2 dimensional finite element method.



flux lines



attractive forces

Figure 6: Flux lines and attractive forces of the PM rotor (D=60, W=8, θ=2deg)

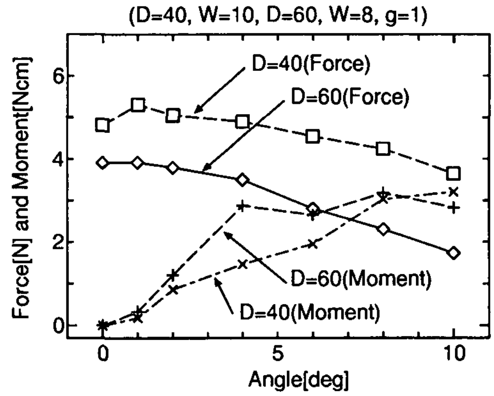


Figure 7: Attractive force and torque of the PM rotor

The flux lines and the attractive forces are shown in figure 6. This is a model of a part of the stator and rotor. The upper part shows the stator and lower shows the rotor with a permanent magnet. In this analysis, stator current is not included. The attractive force between the stator and rotor surface is calculated as shown in the right hand graph in figure 6.

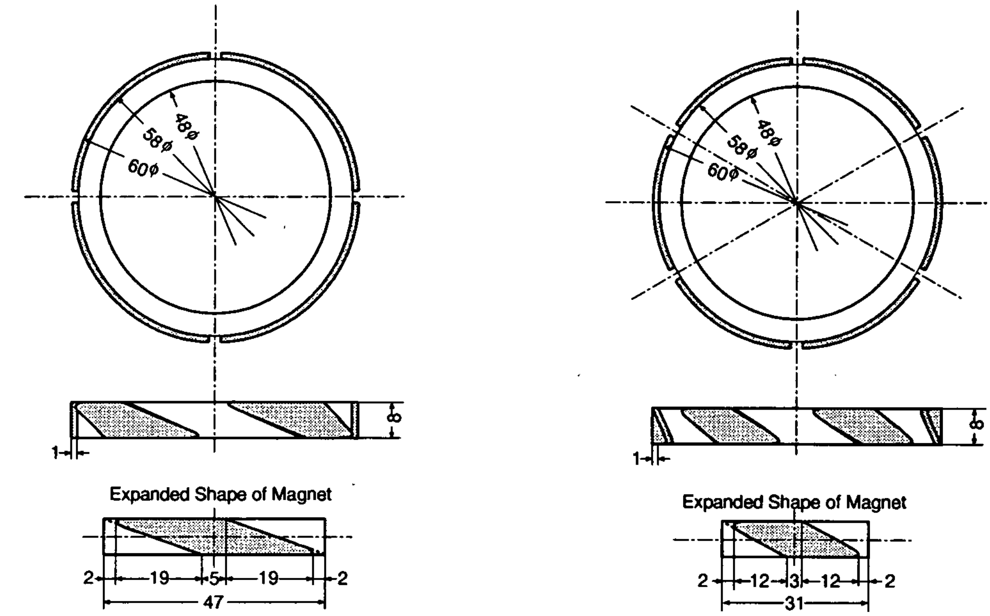
Figure 6 shows results of flux lines and attractive force distribution of a rotor with a 60 mm diameter and an 8 mm thickness (airgap between the stator and rotor is 1 mm). The rotor tilt is 2 degrees from the stator. Figure 7 shows the results of the attractive force and moment when the rotor tilts from 0 degrees to 10 degrees. The lines with □ and × show the results for a 40 mm diameter and 10 mm thickness rotor, while the lines with ◇ and + show results for a 60 mm diameter and 8 mm thickness rotor. The 60 mm rotor produces a smaller attractive force than the 40 mm rotor, but the moment is about 2 times greater than the 40 mm rotor. Therefore, the 60 mm rotor is said to be more stable than the 40 mm rotor.

Normally, passive magnetic bearings do not have enough damping. However, there is hydraulic damping when we apply it to the blood pump.

DESIGN OF PROTOTYPE BLOOD PUMP

Using the previous analytical and experimental results, we designed a prototype motor for the artificial heart. Figures 8 and 10 show the designed rotors and stators. The 4 pole and 6 pole rotors are designed to generate enough rotating torque and to avoid magnetic saturation. The dimensions are 60 mm in diameter and 8 mm in thickness to ensure passive stability. A ring type rotor is used in order to install colocated sensors inside and to reduce weight. Sensors are attached inside of the rotor, therefore it is possible to measure exact radial displacement of the rotor. Permanent magnets are designed to have special shape for sinusoidal flux distribution to reduce ripple torque. The thickness of the neodymium magnet is 1 mm. Figure 9 shows the magnetic flux density distributions in the free space of the 4 pole and 6 pole rotors. They are almost sinusoidal.

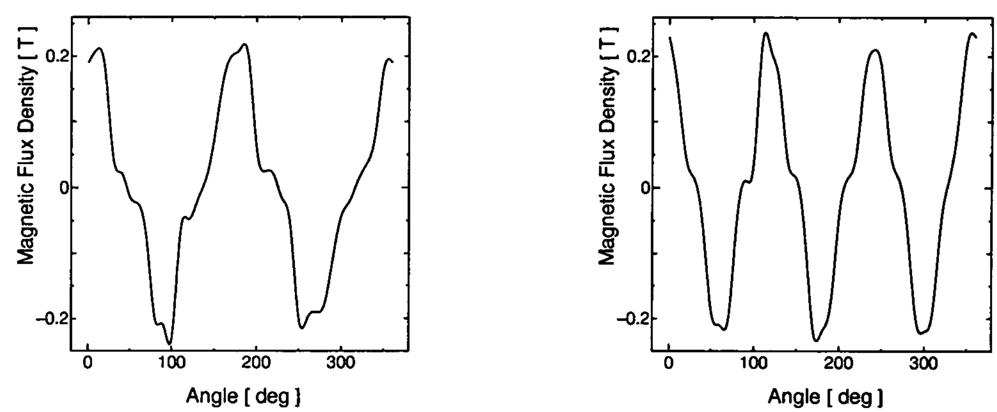
Figure 10 shows the two types of stators. The left one is a salient pole type stator and the right one is a closed slot stator. The closed one requires coil assembly before insertion into the back yoke. Both stators are made with thin laminations and the total thickness is 8 mm. The stator has 12 concentrated wound poles. Two coils are assembled to each pole. Coils are



4 pole rotor

6 pole rotor

Figure 8: 4 pole and 6 pole PM rotor for prototype motor

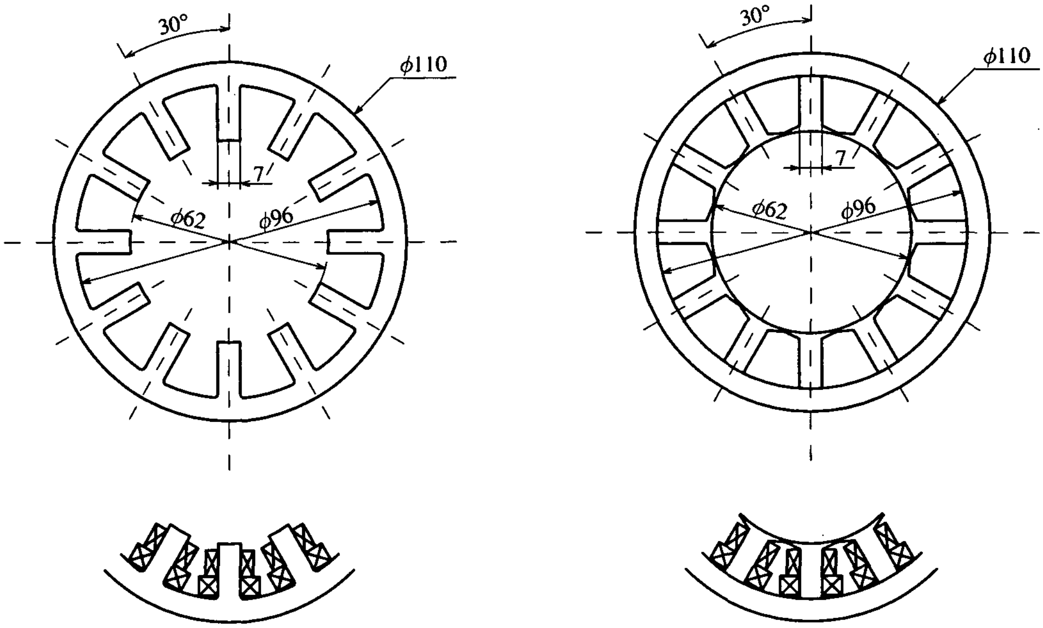


4 pole rotor

6 pole rotor

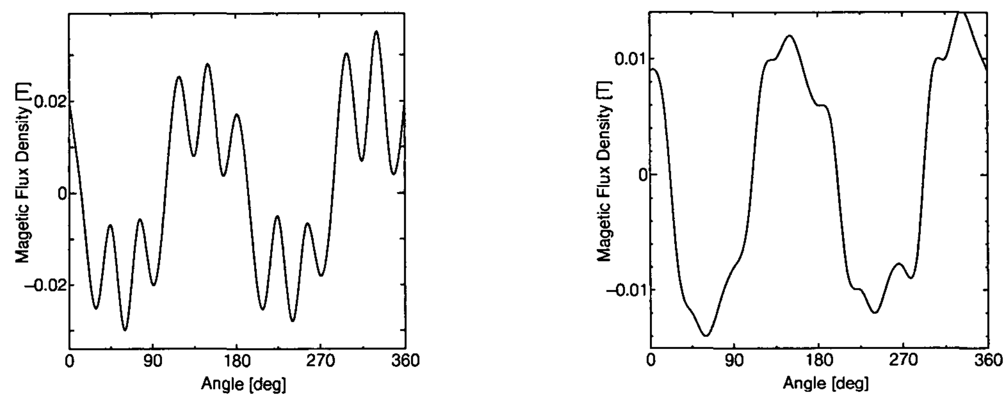
Figure 9: Flux density distribution of 4 pole and 6 pole rotor

connected to produce a 4 pole and a 6 pole flux. In the case of the 4 pole rotor, 4 pole flux is used for motoring and 6 pole flux is used for radial force control. In the case of the 6 pole rotor, 4 pole flux is used for radial force control and 6 pole flux is used for motoring. The salient pole stator is easier to assemble, but the magnetic flux distribution is not sinusoidal. Figure 11 shows the flux density distributions of the 2 stator types. The left graph shows the salient pole stator when the stator is generating a 4 pole flux, while right one shows the closed slot stator. The results show significantly more ripple with the salient pole design. The amplitude of the flux density of the salient pole stator is bigger than the closed pole stator. Therefore it is expected that the closed slot stator has better control capabilities, but efficiency is not as good as the salient pole stator.



salient pole type closed slot type

Figure 10: Salient pole type and closed slot type stator for prototype motor



salient pole type closed slot type

Figure 11: Magnetic flux density of salient pole type and closed slot type stator

Figure 12 shows the prototype motor which uses the 4 pole rotor and the closed slot stator. Unbalance response of this motor is shown in figure 13. The stator is installed horizontally. The rotor can rotate to enough rotating speed for the centrifugal blood pump, and the vibration is smaller than 0.1 mm until 3,000 rpm. The vibration level will be decreased when used in the blood. Because the passive and the active stability of the rotor will be improved by the hydraulic damping.

In this experiment, we could not confirm that the slice motor have enough torque to pump blood and the passive stability when it is pumping blood. Now, we are constructing the prototype blood pump which is shown in figure 14. Experimental investigations will be conducted to further confirm the application of this system for use as a blood pump.

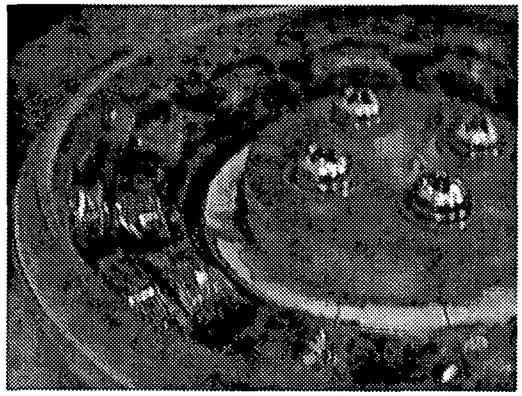


Figure 12: Prototype of the self-bearing slice motor

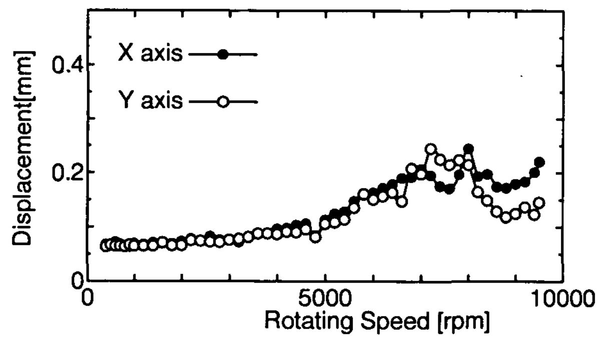


Figure 13: Unbalance response of the prototype motor (4 pole rotor and closed slot stator)

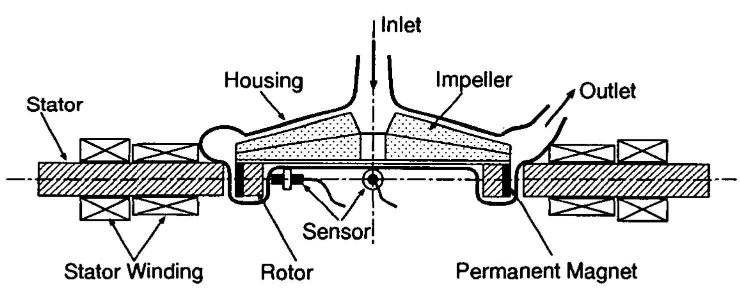


Figure 14: Prototype of artificial heart pump

CONCLUSIONS

This paper introduced the PM type self-bearing slice motor for an artificial heart. Experimental results shows that the self-bearing slice motor is well suited for the blood pump. FEM analysis shows that passive stability is ensured. Finally, a prototype design of slice motor and the construction of the blood pump were shown.

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