MIXED FLOW ARTIFICIAL HEART PUMP WITH AXIAL SELF-BEARING MOTOR

Yohji Okada, Naoto Yamashiro, Kunihiro Ohmori, Toru Masuzawa
Dept. of Mechanical Eng., Ibaraki University, Hitachi, Ibaraki-Pref., 316-8511 Japan
okada@mech.ibaraki.ac.jp

Takashi Yamane
AIST, Tsukuba, Ibaraki-Pref., 305-8564 Japan

Yoshiaki Konishi
Nikkiso Co., Higashi-Murayama, Tokyo, 150-8677 Japan

Satoshi Ueno
Dept. of Mechanical Eng., Ritsumeikan University, Kusatsu, Shiga-Pref., 525-8577 Japan

ABSTRACT

Aiming at a small blood pump with a levitated rotor, this paper introduces a design scheme for an axial-type self-bearing motor. The axial type, which is basically composed of a disc motor and an axial magnetic bearing, controls both the rotation and the axial translation of a rotor. The proposed motor is similar to the bi-directional disc motor except of changing the magnitudes of both side of flux to control the axial attractive force. However, the radial and tilt directions rely on passive stability and, therefore, has poor damping. The design involves the hydrodynamic bearing for improving the radial support property. Finally, the experimental setup is made to confirm the capability of the proposed motor and to apply to the mixed flow pump. The experimental results showed that the bi-directional axial-type self-bearing motor has high capability for a small continuous flow blood pump with enough flow rate and head.

INTRODUCTION

Several types of the artificial heart have been developed for long term ventricular assist systems. For the application to the artificial heart pump, major requirements are high durability, high reliability of the mechanics and compact size for implant. A continuous flow pump is able to reduce size of the device because pump volume is unnecessary(1). Therefore, several groups have developed a magnetically suspended continuous flow type blood pumps with a radial self-bearing motor. The axial type self-bearing motor, which is basically composed of a disc motor and an axial magnetic bearing, controls both the rotation and the axial translation of a rotor(2),(3). To stabilize the rotor completely, additive magnetic bearings are also needed. Such an axial type self-bearing motor has a simpler control mechanism as well as a smaller structure, than the radial type, since it treats only a single rotating magnetic flux.

Aiming at application to a small blood pump, axial type is smaller than centrifugal type (4)−(7). Hence we developed an axial pump with axial self-bearing motor (8),(9). However the flow rate was not enough. This paper introduces a design scheme of the axial type self-bearing motor for mixed flow blood pump. Since the main requirements for the blood pump are small size under 30 mm in diameter and high rotational speed over 5,000 rpm, the motor is designed to be a bi-directional type, which consists of two opposite stators and a rotor between them.

Finally the experimental device was improved to produce the higher torque and levitation force. The mixed flow pump is designed and tested to confirm its capability.

AXIAL SELF-BEARING MOTOR

The axial type self-bearing motor proposed in this paper is permanent magnet (PM) type.

Structure and Principle

Figure 1 shows the schematic structure. It consists of two opposite stators and a cylinder-type rotor between them, which is basically similar to a bi-directional disc motor, but the magnitude of driving current for each stator is controlled according to the

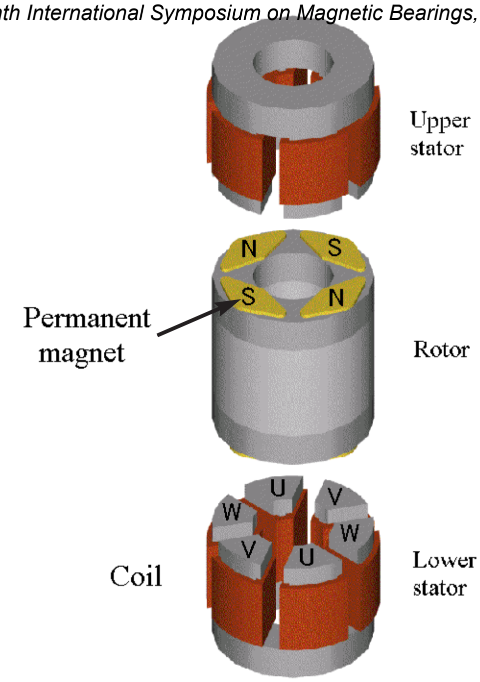

FIGURE 1: Schematic diagram of a bi-directional axial-type self-bearing motor

rotor position so as to levitate the rotor. Thus, the proposed self-bearing motor is a functional combination of bi-directional disc motor and conventional axial active magnetic bearing. On the upper and lower surfaces of the rotor, there are four PMs that are two N poles and two S poles by turns. While each stator has six cores with three-phase windings to generate four pole rotating magnetic flux in the air gap. The fluxes from the stator windings and the PMs produce the magnetic attractive force as well as motor torque. Note that in this motor, only the axial motion is actively controlled while the tilting and the radial transverse motions rely on passive stability.

Axial force and motoring torque

Assuming that the magnetic flux density B_r generated by permanent magnets of the rotor is sinusoidal, it is written as

$$B_r(\theta, t) = B_R \cos(\omega t - 2\theta) \quad (1)$$

Similarly, the magnetic flux density B_s generated by the stator windings is written as

$$B_s(\theta, t) = B_S \cos(\omega t - 2\theta - \psi) \quad (2)$$

Then, the single stator case leads to the simple expressions of the axial force F and the motoring torque T as[(2),(3)]

$$F = \frac{A_r}{4\mu_0}(B_R^2 + 2B_R B_S \cos\psi + B_S^2) \quad (3)$$

$$T = \frac{A_r g_0}{2\mu_0} B_R B_S \sin\psi \quad (4)$$

TABLE 1: Design parameters

parameter	value
outer diameter	$28[mm]$
inner diameter	$14[mm]$
rotor area	$462[mm^2]$
core area	$49[mm^2]$
No. of coil turns	50
thickness of P.M.	$0.7[mm]$
P.M. area	$70[mm^2]$
specific permeability of P.M.	1.05

The above relations denote that both axial force and motoring torque are controlled by changing the amplitude and the phase of the currents in the stator, even if not separately.

Now, let us expand the axial force of Eq. (3) and the motoring torque of Eq. (4) to the bi-directional case. The peak value B_S of Eq. (2) can be written about the upper and lower stators as

$$B_{S_{upper}} = B_M + B_C \quad (5)$$

$$B_{S_{lower}} = B_M - B_C \quad (6)$$

where $B_{S_{upper}}$ and $B_{S_{lower}}$ mean the magnetic flux densities of the upper and lower stators, respectively. B_M is a normal value of magnetic flux producing motoring torque, and B_C is a magnetic flux density for levitation control. Suppose that all conditions are the same in both stators, from the equations (3) and (4), we have,

$$F_{total} = \frac{A_r}{\mu_0}(B_R \cos\psi + B_M)B_C \quad (7)$$

$$T_{total} = \frac{A_r}{\mu_0} B_R B_M \sin\psi \quad (8)$$

Note that in this case, one can control the axial motion of the rotor, not affecting the motoring torque. Although these expressions may have some inaccuracy on account of heavy assumptions, they provide a good guideline on the design of control system.

Analysis and Design

Main requirements for the axial self-bearing motor are small diameter and enough torque. Since modeling error caused by leakage and nonlinear effect often increases in such a small system and the torque is in proportion to the cube of rotor diameter, it is necessary to carefully estimate the performance for design. For this purpose, we carried out finite element analysis of magnetic fields with the aid of ANSYS package. Figure 2 shows the created 3-D elements of the solid parts and Table 1 lists the design

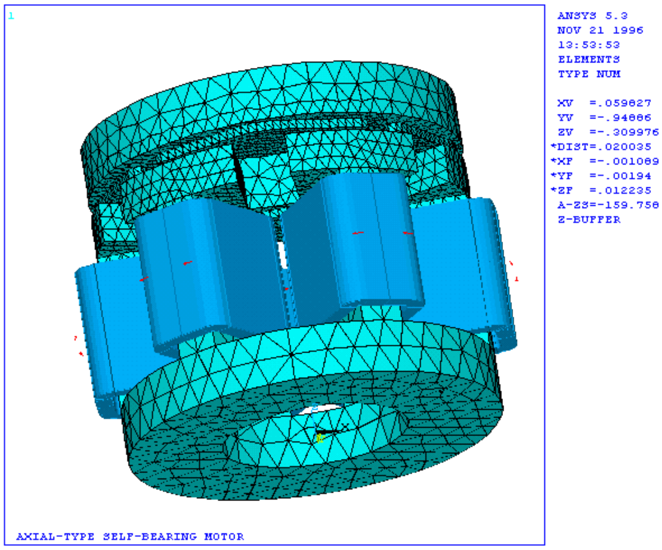

FIGURE 2: Solid elements created for the numerical analysis

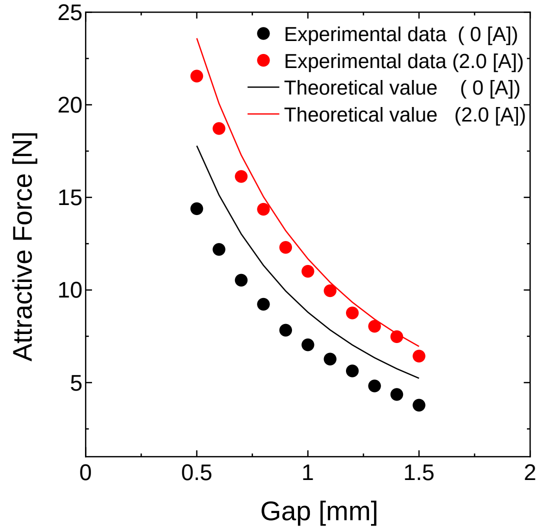

FIGURE 4: Attractive force versus gap

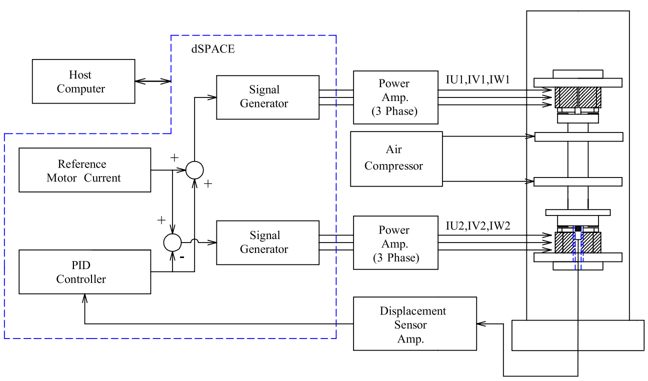

FIGURE 3: Control system

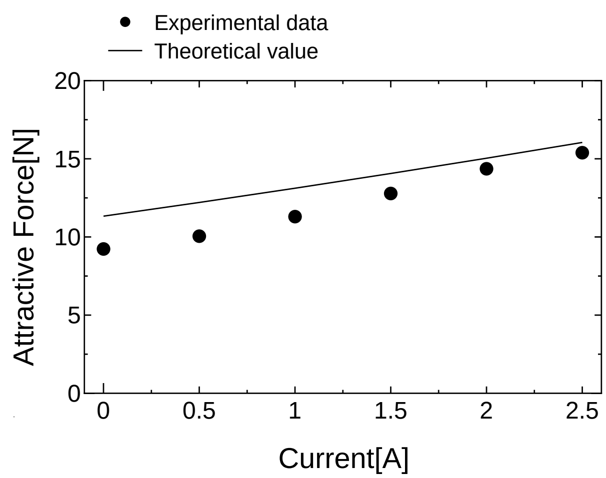

FIGURE 5: Attractive force versus current

parameters used for the analysis. The analyzed self-bearing motor was designed to have the maximum attractive force of 13.0 N and the maximum torque of 8.7 mNm. Here, note that the torque is of single case and it will be doubled in the bi-directional type.

EXPERIMENTAL RESULTS AND CONSIDERATIONS

To confirm the capability of the proposed theory, experimental apparatus was constructed. However the previous model was applied to the axial pump and did not produce enough flow rate(8),(9), we modified the motor and tested.

Modified Experimental Setup

The only modification we made is to increase the coil turn. The number of coil turn is increased from 50 to 83. With this modification we can expect the levitation force increase of 8% and the torque increase of 38%.

The control system is shown in Fig. 3. For levitation, the axial displacement of the rotor measured by a proximity probe is transformed into a DSP (dSPACE DS1103) and the calculated controller output is added to or subtracted from the amplitude of motor current. Then, two sets of three-phase currents are generated and fed to the stator coils through a six-channel power amplifier. The levitation control uses a standard PID controller. The parameters are; proportional gain $K_p = 17.5$ A/mm, derivative gain $K_d = 0.015$ As/mm, integral gain $K_i = 1.0$ A/smm, derivative time constant $T_d = 0.3$ msec, sampling interval $\tau = 0.1$ msec, and motoring current $I_m = 2.0$ A.

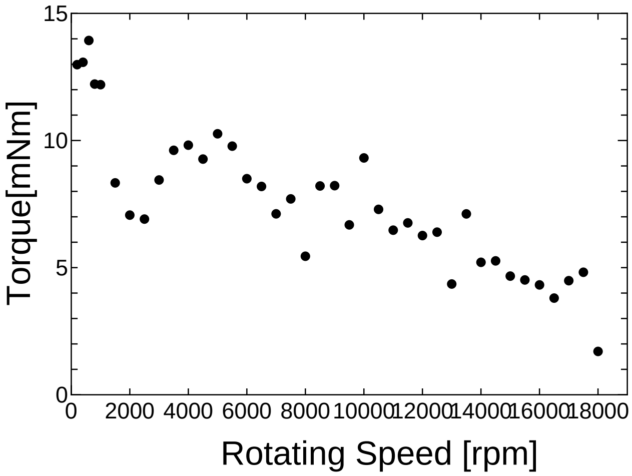

FIGURE 6: Dynamic torque

Force and Torque Characteristics

Prior to levitation test, the attractive force between the rotor and the stator was measured. Figure 4 shows the attractive force versus air gap for various non-rotating motor currents while Figure 5 is the attractive force versus coil current at the air gap of 0.8 [mm]. The former indicates the negative stiffness while the later is the current gain of the attractive force. Considering the air gap of 0.8 mm and the current of 2 A that will be used in the pump test, the measured results coincide well with the estimated ones. As expected the attractive force showed about 8% increase by increasing the number of the coil turn [(8),(9)].

The dynamic torque was also measured for the single stator and rotor as shown in Fig. 6. The torque is maximum at non-rotational (static) condition and decreases according to the rotational speed. That is a typical characteristics of PM synchronous motors. It can be noted that the maximum torque increased about 20% increase than the previous experiments [(8),(9)].

Levitated Rotation

The levitated rotating test was carried out for the bi-directional self-bearing motor in air. The step response in z-direction is shown in Fig. 7. The levitation is very stable. Then the levitated rotating test is carried out. The unbalance response in axial direction is shown in Fig. 8 and the one in radial direction is shown in Fig. 9. Here, one can see that the levitation is very stable up to the top speed of 7,600 rpm. In this case, an air bearing was used to improve the lateral stability, but it was replaced by a hydrodynamic blood bearing in the actual blood pump.

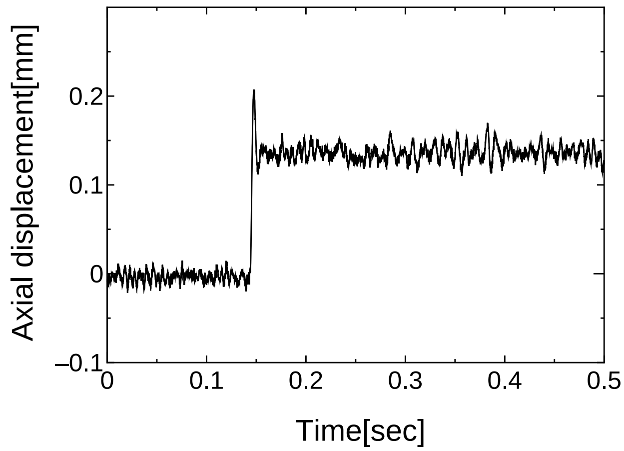

FIGURE 7: Step response in axial direction

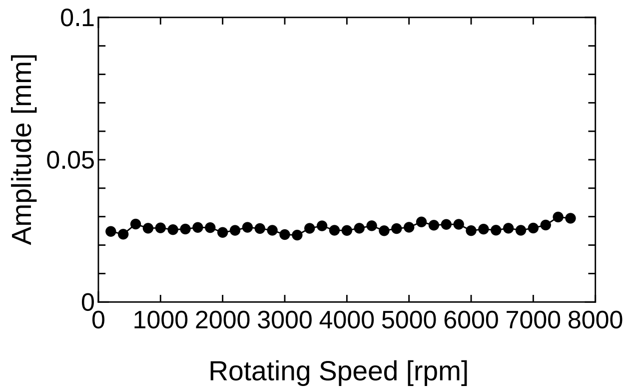

FIGURE 8: Maximum amplitude of axial displacement

Motor Efficiency

Motor efficiency is measured by measuring the output torque, speed and input power and calculating the output versus input power ratio. The motor efficiency is shown in Fig. 10. The maximum efficiency of 67.2 % was recorded at the speed of 10,000 [rpm] and the motor current of 2.0 [A]. The efficiency is quite good considering such small motor.

MIXED FLOW PUMP

A double mixed flow pump equipped with the proposed axial self-bearing motor was designed and fabricated, which is schematically shown in Fig. 11. In this pump, hydrodynamic blood bearings were used on the both sides of the pump. Assembled photo of the pump is shown in Fig. 12.

Pump Test

The rotor with impeller could be successfully levitated and rotated in the vertical rotor position.

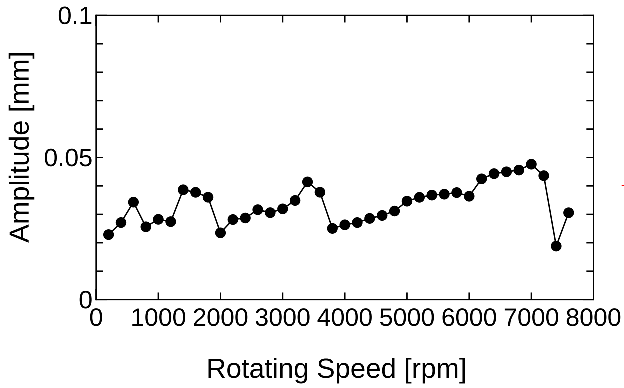

FIGURE 9: Maximum amplitude of radial displacement

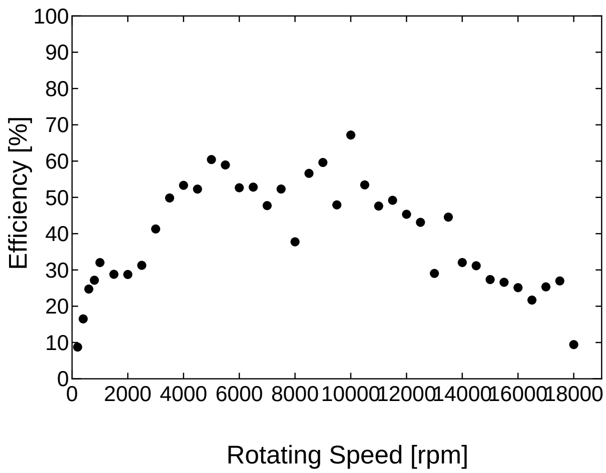

FIGURE 10: Motor efficiency

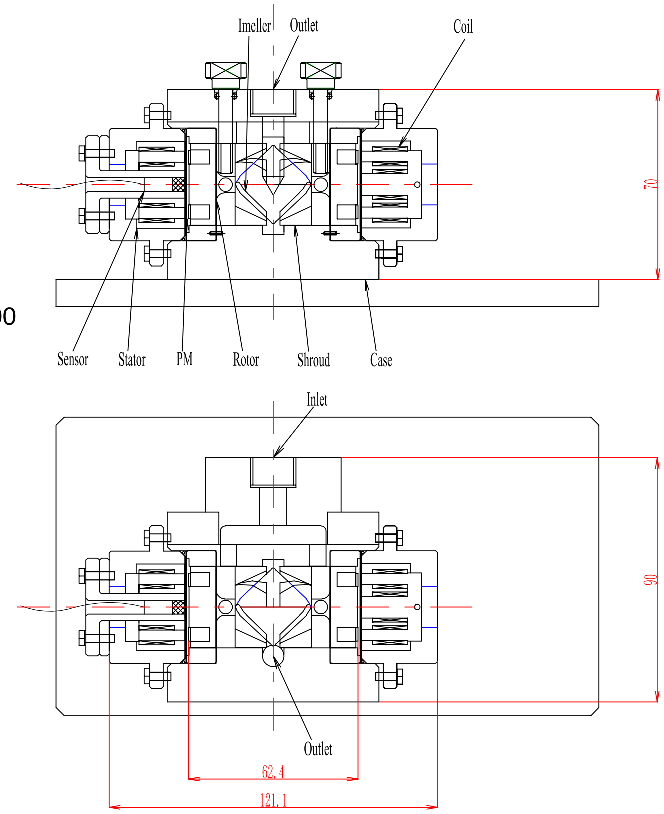

FIGURE 11: Mixed flow pump

The water pumping test was carried out. Figure 13 shows the measured pump head and flow rate characteristics. The pump test recorded the maximum head of 166 mmHg at the rotating speed of 5,200 rpm and the maximum flow rate of 5.86 L/min was recorded at the rotating speed of 5,000 rpm. The flow rate and the pressure recorded is considered enough for ventricular assist device. The input power was also measured using digital power meter (Yokogawa WT1600). The measured input power is shown in Fig. 14. The power consumption increases according to the rotating speed. The upper stator always requires bigger power due to supporting loss of the rotor. The total power is under 28.5 W which is recorded at 5,200 rpm.

Hemolysis Test

The developed pump has enough flow rate and head for heart pump. Hence the hemolysis test is carried out using cow's blood. The test condition is the followings; rotating speed is 3,100 rpm, flow rate is 4.08 − 4.20 L/min., pressure difference is 31 mmHg, and temperature is 44 deg C. The hemolysis result after 4 hours test was NIH=0.3858 g/100L which is 117 times larger compared with the BioPump BP-80. This is considered mainly due to the use of hydrodynamic blood bearing. The pump is under modification of reducing its size and replacing the hydrodynamic bearing with the PM type repulsive magnetic bearings.

CONCLUDING REMARKS

An axial self-bearing motor was developed for small mixed flow pump with magnetically suspended impeller. The motor could stably levitate and drive the rotor up to 7,600 rpm. This magnetically suspended motor is applied to the double mixed flow pump. The pump head of 166 mmHg and the flow rate of 5.86 L/min were recorded. However, the hemolysis test was bad mainly due to the hydrodynamic blood bearing. Further work is continuing to replace the hydrodynamic blood bearing with the PM type repulsive bearing. A new design is planned to use the single mixed flow pump for further miniaturlization.

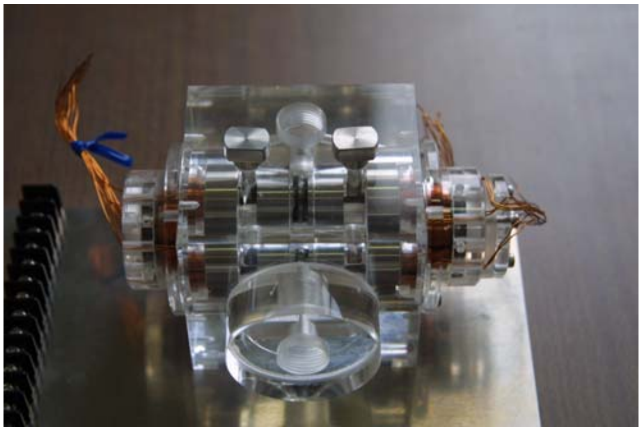

FIGURE 12: Photo of mixed flow pump

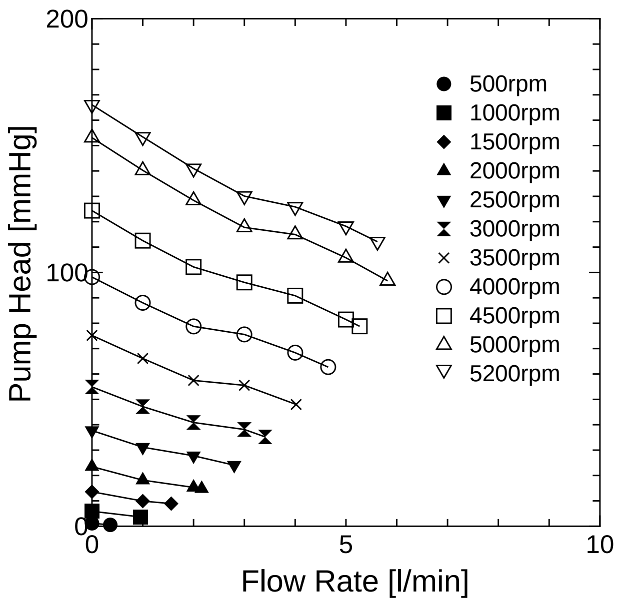

FIGURE 13: Flow rate and head of mixed flow pump

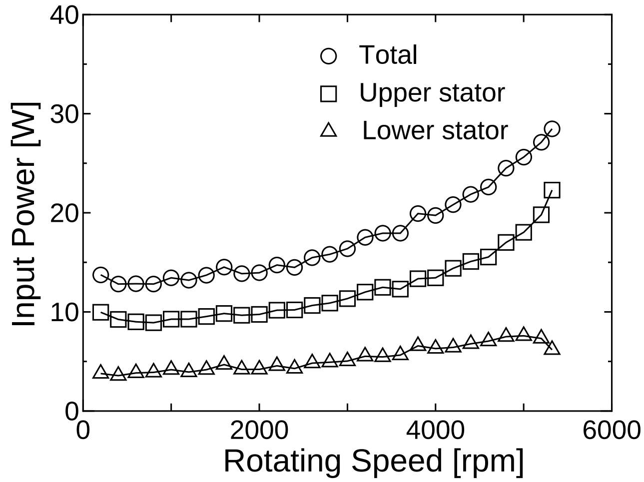

FIGURE 14: Input power of motor coils

References

1. Stepanoff, A., J., Centrifugal and Axial Flow Pumps, Kringer Publishing Co., Malabar, Florida, 1993
2. Ueno, S., et. al., Control of Axially Levitated Rotating Motor, Proc. of the 3rd Int'l Symposium on Motion and Vibration Control, Chiba, Japan, Vol. 1, 1996, pp. 94-99.
3. Ueno, S., and Okada, Y., Characteristics and Control of a Bidirectional Axial Gap Combined Motor-Bearing, IEEE/ASME Trans. on Mechatronics, Vol. 5, No. 3, September 2000, pp. 310-318
4. Mizuguchi, G., A., et. al., Development of the Baylor/NASA Axial Flow Ventricular Assist Device: In Vitro Performance and Systematic Hemolysis Test Results, Artificial Organs, 18(1), 1994, pp. 32-43
5. Joern Apel, Frank Neudel, Helnut Reul, Computational fluid dynamics and experimental validation of a microaxial blood pump, ASAIO Journal, No. 47, 2001, pp. 552-558
6. D. J. Buke, et. al., The HeartMate II: Design and Development of a Fully Sealed Axial Flow Left Ventricular Assist System, Artificial Organs, Vol. 25, No. 5, 2001, pp. 380-385
7. Siess T, Reul H, Rau G, Hydraulic refinement of an intraarterial microaxial blood pump, Artificial Organs, Vol. 18, 1995, pp. 273-285
8. Kunihiro Ohmori, Seung-Jong Kim, Toru Masuzawa, Yohji Okada, Design of an Axial-Type Self-Bearing Motor for Small Axial Pump, Proc. of 8th Int. Symp. on Magnetic Bearings, Mito, Japan, August 26-28, 2002, pp. 21-26
9. Yohji Okada, Toru Masuzawa, Ken-Ichi Matsuda, Kuniomi Ohmori, Takeshi Yamane, Yoshiaki Konishi, Shinya Fukahori, Satoshi Ueno, and Seoung-Jong Kim, Axial Type Self-Bearing Motor for Axial Flow Blood Pump, Artificial Organs, Vol. 27, 2003, pp. 887-891