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Development of radial type self-bearing motor for small centrifugal blood pump

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Abstract

A small magnetic levitated centrifugal blood pump using a radial type self-bearing motor has been developed for use as an implantable artificial heart. In order to realize an implantable small centrifugal blood pump for a small adult patient, miniaturization and high efficiency of the device are necessary. In this study, a radial type self-bearing motor which is small-diameter and thin was developed, and magnetic suspension characteristics were measured. And, a magnetic levitated centrifugal blood pump using the self-bearing motor was developed, and pump performance and levitation performance were measured. In the self-bearing motor, the plus minus two-pole algorithm is adopted to levitate and rotate the rotor. The plus two-pole algorithm type and the minus two-pole algorithm type were developed to compare the magnetic suspension force in the radial direction. The minus two-pole algorithm type had very good control ability in the radial direction. The passive stability performance in the axial direction was enough ability to suspend the rotor-impeller. The restoring force was possible to be varied by the rotation magnetic field. At the operating condition with a flow rate of 5 L/min against a pressure of 100 mm Hg, the oscillation amplitude in x, y, z direction were 0.014 mm, 0.014 mm and 0.039 mm, respectively. And, the total power consumption was 7.1 W. The developed small magnetic levitated centrifugal blood pump has demonstrated sufficient levitation performance and low total power consumption. The average displacement in z direction of the rotor-impeller was possible to change by changing the phase angle of the rotational magnetic field.

Keywords : Self-bearing motor, Plus minus two-pole algorithm, Magnetic levitated pump, Centrifugal blood pump, Ventricular assist device

1. Introduction

A heart transplant is one of a treatment for patient with severe heart failure. But, chronic donor shortage is serious problem. Most of the patients wait for a few years from a few months before receiving organ donation. Left ventricular assist devices (rotary blood pumps) that are mechanical devices for circulation have been researched and developed (Joyce, Joyce and Loebe, 2012). The mechanical life expectancy of a rotary blood pump is primarily determined by the durability of mechanical parts such as bearing and seals. Magnetic levitation technology is applied for durability enhancement of an artificial hearts (Merkel, et al., 2004, Murakami, et al., 2014, Nishinaka, et al., 2006, Onuma, et al., 2014 and Osa, et al., 2014). The non-contacting behavior of the artificial hearts using the magnetic levitation technology is good for high durability, lower hemolytic properties, and anti-thrombogenesity. Centrifugal blood pumps using a radial type self-bearing motor were previously developed for use as an implantable artificial heart (Onuma and Masuzawa, 2014). Since the radial type self-bearing motor (Murakami, et al., 2014, Onuma, et al., 2015, Onuma, et al., 2014, Onuma, et al., 2012, Reichert, et al., 2012 and Silber and Amrhein, 1998) is able to generate a magnetic suspension force and a torque by one stator, it is suitable for miniaturization of the device. In order to realize an implantable small centrifugal blood pump for a small adult patient, miniaturization and high efficiency of the device are necessary. In this study, a radial type self-bearing motor which is small-diameter and thin was developed, and magnetic suspension characteristics were measured. And, a magnetic levitated centrifugal blood pump using the self-bearing motor was developed, and pump performance and levitation performance were measured.

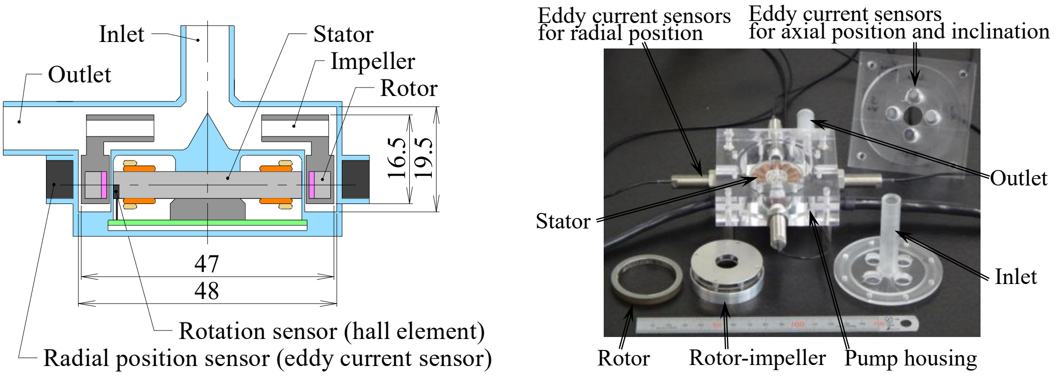
2. Methods

2.1 Magnetic levitated centrifugal blood pump

Fig. 1 shows the schematic of the magnetic levitated centrifugal blood pump. The magnetic levitated centrifugal blood pump using the radial type self-bearing motor, which has the pump housing's the inner diameter of 48 mm and the pump housing's the thickness of 19.5 mm, was developed. A closed type impeller with eight vanes was constructed on the top of the rotor. The outer diameter and the thickness of the rotor-impeller are 47 mm and 16.6 mm, respectively. The mass of the rotor-impeller is 33 g. Four eddy current sensors and three hall elements are used to control radial position and rotation speed of the rotor-impeller, respectively. Other four eddy current sensors are used to only measure the axial position and inclination of the rotor-impeller. Most narrow flow channel width in the radial direction and axial direction are 0.3 mm and 1.5 mm, respectively. And, the rotor-impeller can be tilted geometrically 2.8 degrees in flow channel.

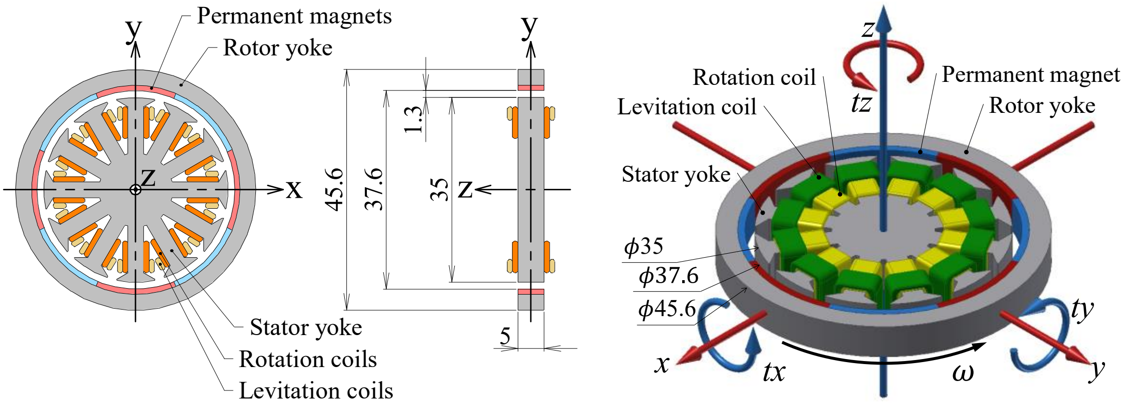
2.2 Radial type self-bearing motor

Fig. 2 shows the schematic illustration of the radial type self-bearing motor. The outer rotor structure, that a rotor is set around a stator, is adopted to miniaturize the device. The rotor has eight permanent magnets on inner circumferential surface. The stator set at the center of the pump has twelve teeth. The outer diameter of the stator is 35 mm. The outer diameter of the rotor is 45.6 mm. The thickness of the stator yoke and the rotor yoke is 5 mm. The air gap between the stator and the rotor is 1.3 mm. The rotor's mechanically suppressed range of movement is 0.3 mm. The radial position and rotation of the rotor-impeller are actively controlled through control of the magnetic field of the self-bearing motor. The axial position and inclination of the rotor-impeller are passively suspended by the strong magnetic attractive force in the radial direction between the stator and the rotor. The plus minus two-pole algorithm



(a) Schematic illustration (b) Photograph of component parts

Fig. 1 Schematic illustration of magnetic levitated centrifugal blood pump.



(a) Dimensional drawing (b) Oblique perspective figure

Fig. 2 Schematic illustration of radial type self-bearing motor.

(Okada, et al., 1995) is adopted to levitate and rotate the rotor. Rotation coils of 50 turns and levitation coils of 80 turns are separately constructed in the each tooth of the stator. Rotation coils produce 3-phase 8-pole magnetic field. 3-phase 10-pole levitation magnetic field type and 2-phase 6-pole levitation magnetic field type are developed to compare plus and minus of the plus minus two-pole algorithm.

2.3 Experiments

2.3.1 Measurement of attractive force in radial direction

The attractive force in the radial direction was measured using the load cell to evaluate the magnetic suspension force and negative spring force in the radial direction of 3-phase 10-pole levitation magnetic field type and 2-phase 6-pole levitation magnetic field type. The attractive force in radial direction measurement system is shown in Fig. 3. The rotor fixed to a linear slider connected with a load cell. The stator fixed to a holding fixture connected with a base. The amplitude of levitation current was changed from 0 A to 3 A. And, the displacement of the rotor from the center position was changed from 0 mm to 0.5 mm.

2.3.2 Measurement of Restoring Force in Axial Direction

The attractive force in the axial direction as a restoring force was measured using the load cell to evaluate the passive stability performance in the axial direction. Additionally, the interference to the restoring force by the rotational magnetic field was measured. The attractive force in axial direction measurement system is shown in Fig. 4. The rotor fixed to a linear slider connected with a load cell. The stator fixed to a holding fixture connected with a base. The axial displacement of the rotor was changed from 0 mm to 5 mm. The amplitude of rotation current was changed from 0 A to 3 A. And, the phase of current was changed from 0 degree to 180 degrees.

2.3.3 Measurement of pump performance and levitation performance

The magnetic levitated centrifugal blood pump using the 2-phase 6-pole levitation magnetic field type was connected to a closed mock circuit filled with water, and pump and levitation performances were examined. The closed mock circuit is composed of two pressure gauge sensors, a flow meter, a reservoir tank, and a gate valve. The magnetic levitated centrifugal blood pump and the closed mock circuit are shown in Fig. 5. The average position and the oscillation amplitude of the rotor-impeller were measured to evaluate the levitation performance during pumping. Then, the electrical input power to the maglev pump was measured with the power meter. Rotation and levitation of the rotor-impeller were controlled with a digital PID controller using a digital signal processor. The parameters of the

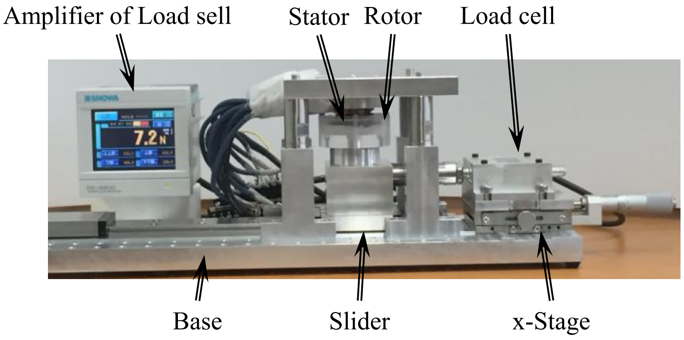


Fig. 3 Attractive force in radial direction measurement system

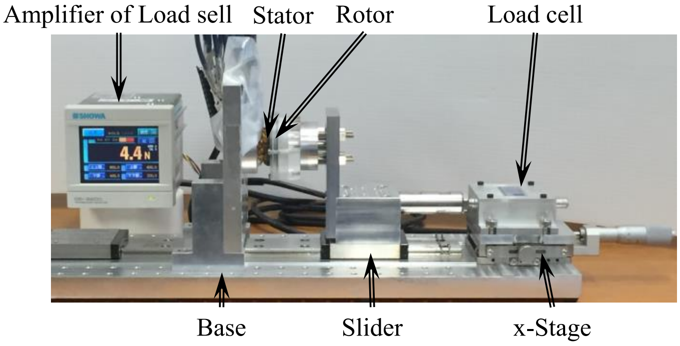
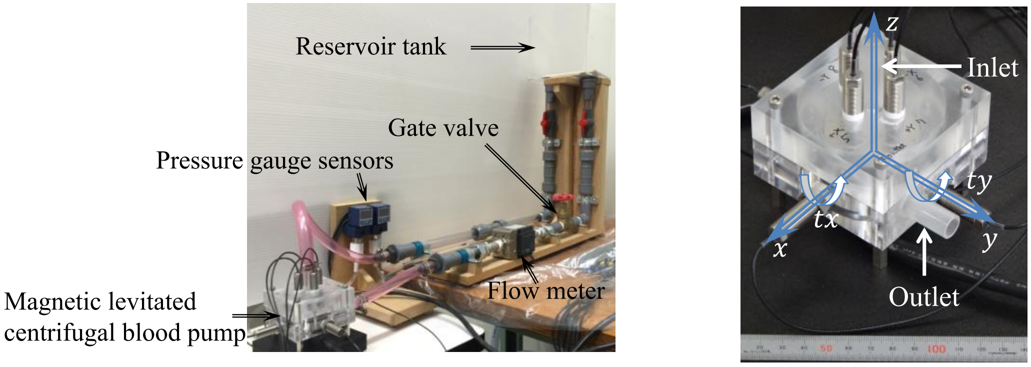


Fig. 4 Attractive force in axial direction measurement system



(a) Measurement system. (b) Magnetic levitated centrifugal blood pump.

Fig. 5 Measurement system of pump performance and levitation performance.

levitation PID controller were K_{lp} = 7 A/mm, K_{li} = 5 A/mm/s and K_{ld} = 0.016 A･s/mm respectively. The parameters of the rotation PI controller were K_{rp} = 0.003 A/rpm and K_{ri} = 0.7 A/rpm/s, respectively. The phase angle of rotational magnetic field and permanent magnet field was 90 degree.

2.3.4 Measurement of the axial position change caused by rotational magnetic field

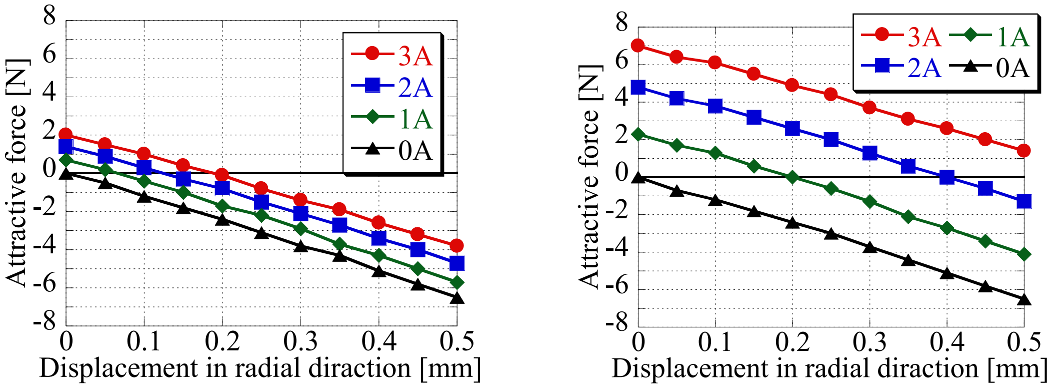
The effect to the axial position of the rotor-impeller by the rotational magnetic field was evaluated with the system of Fig. 5 which measured the pump performance and levitation performance. Rotational speed was set to 2300 rpm to achieve a flow rate of 5 L/min against a pressure of 100 mmHg. The phase of current was changed from 30 degree to 150 degrees. The average position and the oscillation amplitude of the rotor-impeller were measured to evaluate the levitation performance during pumping. Then, the electrical input power to the maglev pump was measured with the power meter.

3. Experimental results and discussion

3.1 Attractive Force in Radial Direction

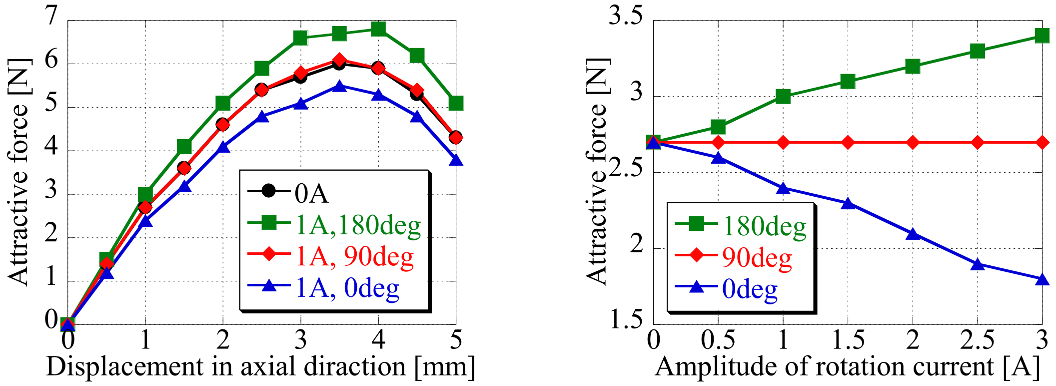
The measured attractive force in the radial direction is shown in Fig. 4. The magnetic suspension force of 3-phase 10-pole type and 2-phase 6-pole type generated by a current of 1 A at displacement of 0 mm (center position) were 0.7 N and 2.3 N, respectively. The negative spring force generated by displacement of 0.1 mm was 1.2 N.

Control ability of the 2-phase 6-pole levitation magnetic field type was much better than the 3-phase 10-pole levitation magnetic field type. It seems that the minus algorithm of the plus minus two-pole algorithm is suitable in the radial type self-bearing motor of the outer rotor structure. The 3-phase 10-pole type did not have enough control ability for the range of movement. Therefore, the measurement experiment of pump performance and levitation performance was performed only the magnetic levitated centrifugal blood pump using the 2-phase 6-pole levitation magnetic field type.



(a) 3-phase 10-pole type. (b) 2-phase 6-pole type.

Fig. 6 Attractive force in the radial direction.



(a) Current of 0 A and 1 A. (b) Displacement of 1 mm.

Fig. 7 Restoring force in axial direction.

3.2 Restoring Force in Axial Direction

The measured restoring force in the axial direction with respect to each displacement in the axial direction when was given a current of 0 A and a current of 1 A which changed a phase angle is shown in Fig. 5 (a). The measured restoring force in the axial direction at a displacement of 1 mm with respect to each current which changed a phase angle is shown in Fig. 5 (b). The restoring force at the current of 0 A and a displacement of 1 mm was 2.7 N. The maximum of the restoring force was 6.0 N at the displacement of 3.5 mm.

The passive stability performance in the axial direction was enough ability to suspend the rotor-impeller mass of 33 g. The restoring force of a phase of 90 degrees was the almost same as it at a current of 0 A. When the phase angle was larger than 90 degrees, the restoring force became stronger in proportion to the current than it at a current of 0 A. When the phase angle was less than 90 degrees, the restoring force became weaker in proportion to the current than it at a current of 0 A. It has been found to be varied a restoring force by the rotation magnetic field. When the permanent magnet’s field and the rotational magnetic field were facing at different magnetic poles, the restoring force was increased by increasing the magnetic flux density in the air gap. Conversely, when the permanent magnet’s field and the rotational magnetic field were facing at same magnetic poles, the restoring force was decreased by decreasing the magnetic flux density in the air gap.

3.3 Pump performance and levitation performance

Fig. 8 shows HQ characteristics. The pump was levitated and rotated up to a rotating speed of 3,000 rpm successfully. The maximum pressure and the maximum flow rate were approximately 203 mm Hg and 9.8 L/min, respectively. The target pump performance which is a flow rate of 5 L/min against a pressure of 100 mmHg is achieved with a rotating speed of 2,300 rpm. At a low flow rate, the bottom surface of the rotor-impeller was in contacted with the pump housing. At a rotating speed of 2,000 rpm, it was in contacted when a flow rate is 0 L/min. At a rotating speed of 2,300 rpm, it was in contacted when a flow rate is 1 L/min or less. At a rotating speed of 2,500 rpm, it was in contacted when a flow rate is 2 L/min or less. At a rotating speed of 3,000 rpm, it was in contacted when a flow rate is 4 L/min or less. Fig. 9 shows the relationship between the total power consumption and the flow rate. The maximum total power consumption was 21.5 W at a rotating speed of 3,000 rpm and a flow rate of 9.8 L/min. The total power consumption for the target pump performance was 7.1 W. Fig. 10 shows the average displacement and average tilt angle of the rotor-impeller which depend on each flow rate at a rotating speed of 2,300 rpm. At a flow rate of 5 L/min, average displacement in x, y and z direction were -0.0004 mm, 0.0006 mm and -0.49 mm, respectively. And, average tilt angle in tx and ty direction were -0.29 degree and 0.17 degree, respectively. Fig. 11 shows the oscillation amplitude in x, y, z direction and the oscillation amplitude in tx and ty direction of the rotor-impeller which depend on each flow rate at a rotational speed of 2300 rpm. At a flow rate of 5 L/min, oscillation amplitude in x, y and z direction were 0.014 mm, 0.014 mm and 0.039 mm, respectively. And, oscillation amplitude in tx and ty direction were 0.34 degree and 0.37degree, respectively.

The target pump performance is a flow rate of 5 L/min against a pressure of 100 mmHg. We believe that the total power consumption of a left ventricular assist device suitable for implantation should be less than 15 W with a flow rate of 5 L/min against a pressure of 100 mm Hg. At the operating condition to generate the target pump performance,

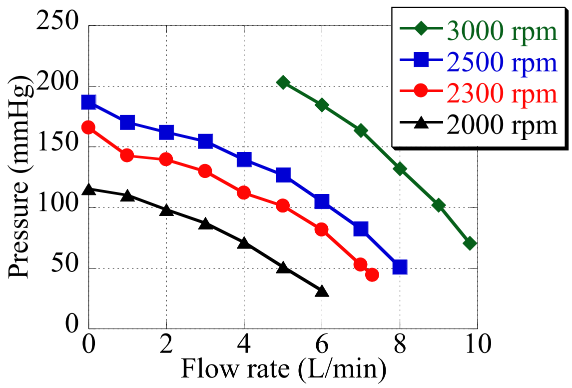


Fig. 8 HQ characteristics.

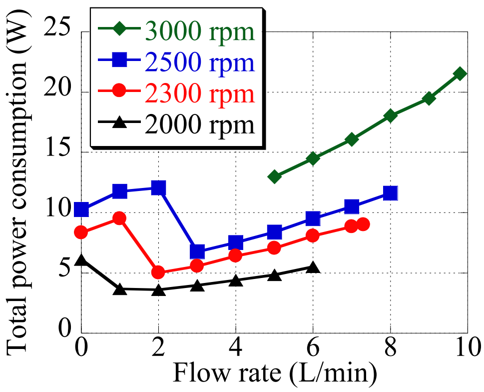


Fig. 9 Total power consumption versus flow rate.

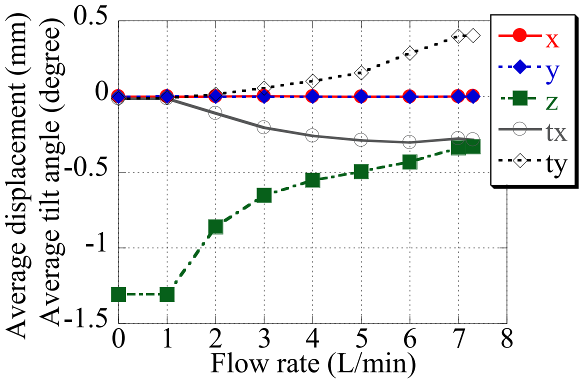


Fig. 10 Average displacement and average tilt angle versus flow rate.

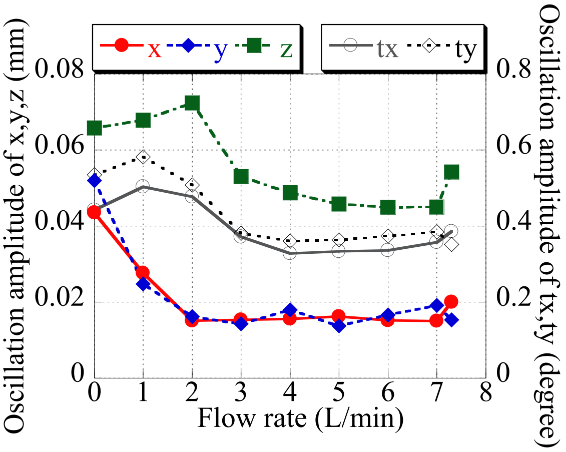


Fig. 11 Oscillation amplitude versus flow rate.

the developed magnetic levitated centrifugal blood pump has demonstrated sufficient levitation performance and low total power consumption. At a low flow rate, the average displacement in z direction and the oscillation amplitude were increased. Then, the bottom surface of the rotor-impeller was in contacted with the pump housing. The reason is that the thrust force in the axial direction increased with operating conditions approaching the shut off operation of the flow. It is possible to reduce the thrust force in the axial direction by boring the balance holes on the shroud of the impeller. When the rotor-impeller contacted with the pump housing, the total power consumption increased. It is because the power consumption for rotation was significantly increased by friction of the rotor-impeller's bottom surface and the pump housing.

3.4 The axial position change caused by rotational magnetic field

At a rotating speed of 2,300 rpm, the average displacement and the average tilt angle of the rotor-impeller which depend on the phase angle of the rotational magnetic field is shown in Fig. 12. The average displacement in x and y direction, and the average tilt angle in tx and ty direction caused little or no change by changing the phase angle. The average displacement in z direction increased downward with the increasing the phase angle. Fig. 13 shows the oscillation amplitude of the rotor-impeller which depend on the phase angle at a rotational speed of 2300 rpm. The oscillation amplitude in x and y direction caused little or no change by changing the phase angle. The oscillation amplitude in z, tx and ty direction increased with the increasing the phase angle. The power consumption for rotation and levitation at a rotational speed of 2300 rpm is shown in Fig. 14. When the phase angle was shifted from 90 degree, the power consumption for rotation increased. The power consumption for levitation increased with the increasing the phase angle.

The average displacement in z direction of the rotor-impeller was possible to change by changing the phase angle of the rotational magnetic field. When the phase angle was smaller than 90 degree, the average displacement in z direction and the oscillation amplitude in z direction were decreased. It is because the restoring force was increased.

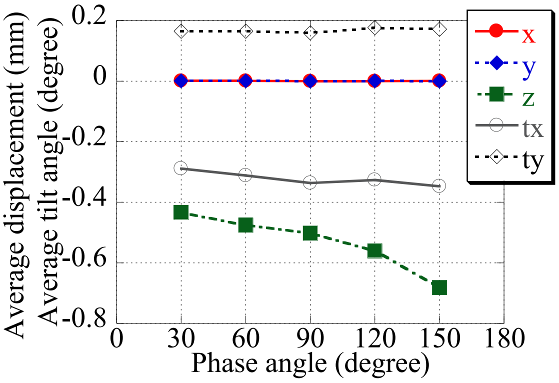


Fig. 12 Average displacement and average tilt angle versus phase angle.

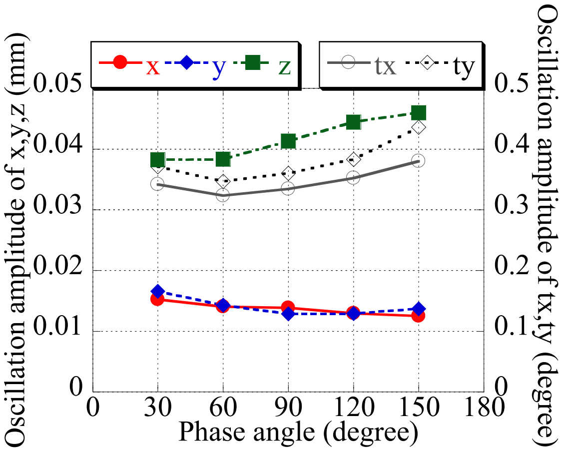


Fig. 13 Oscillation amplitude versus phase angle.

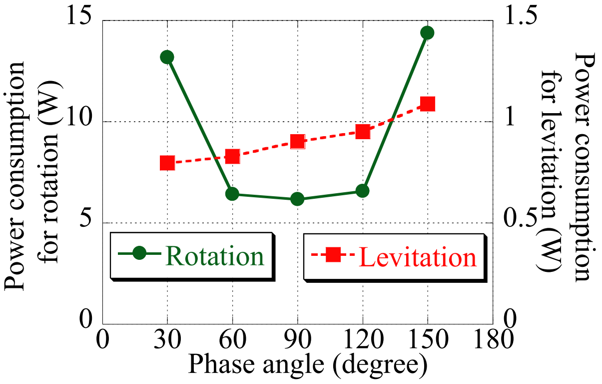


Fig. 14 Power consumption for rotation and levitation versus phase angle.

When the phase angle is smaller than 90 degree, the power consumption for rotation is increased. But, the power consumption for levitation is decreased. It seems that the axial displacement is affecting the generation efficiency of the magnetic suspension force in the radial direction. The generation efficiency of the magnetic suspension force in the radial direction was improved by reducing the axial displacement of the rotor and the stator. Therefore, the power consumption for levitation is decreased. In the phase angle range of from 60 degree to 90 degrees, by decreasing from 90 degree, it is possible to improve the levitation performance with just a little increases the total power consumption.

4. Conclusion

The small radial type self-bearing motor was developed, and magnetic suspension characteristics were measured. 2-phase 6-pole type had very good control ability in the radial direction. It seems that the minus two-pole algorithm is suitable in the radial type self-bearing motor of the outer rotor structure. The passive stability performance in the axial direction was enough ability to suspend the rotor-impeller. The restoring force was possible to be varied by the rotation magnetic field. The small magnetic levitated centrifugal blood pump using the self-bearing motor was developed. At the operating condition with a flow rate of 5 L/min against a pressure of 100 mm Hg, the developed small magnetic levitated centrifugal blood pump has demonstrated sufficient levitation performance and low total power consumption. The average displacement in z direction of the rotor-impeller was possible to change by changing the phase angle of the rotational magnetic field. By changing the phase angle of the rotational magnetic field, it is possible to improve the levitation performance with just a little increases the total power consumption.

Acknowledgment

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