Evaluation of Magnetic Suspension Characteristics and Levitation Performance of A Centrifugal Blood Pump Using Radial Type Self-Bearing Motor

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***Abstract*—Magnetic levitation technology is applied for durability enhancement of artificial hearts. A centrifugal blood pump using a self-bearing motor was previously developed for use as an implantable artificial heart. Rotors of three types which are different of magnetic suspension characteristics were fabricated. The magnetic suspension characteristics, the levitation and the pump performances of the Maglev pump were examined. If the negative spring force in the radial direction was weak, the restoring force in the axial direction and the restoring torque of the inclination were not always weak. It is possible to improve the motor performance by increasing the flux density of permanent magnet, even if the air gap is increased. It revealed that the levitation performance does not influence the pump performance. And then, it is possible to improve the levitation performance by reducing the negative spring force and improving the passive stability ability.**

I. Introduction

Magnetic levitation technology is applied for durability enhancement of an artificial hearts [1-8]. The non-contacting behavior of the artificial hearts using the magnetic levitation technology is good for high durability, lower hemolytic properties, and anti-thrombogenesity. A centrifugal blood pump using a self-bearing motor (Maglev pump) was previously developed for use as an implantable artificial heart [1-4]. In order to realize an implantable artificial heart for a small patient, miniaturization and high efficiency of the Maglev pump is necessary. To find ways of miniaturization and high efficiency, it is necessary to verify in greater detail the magnetic suspension characteristics, and to demonstrate the influence of the magnetic suspension characteristics on the levitation performance. In this study, rotors of three types which are different of magnetic suspension characteristics were fabricated, and the magnetic suspension characteristics of self-bearing motor of three type's rotor were measured. The levitation and the pump performances of the Maglev pump were examined.

II. Methods

A. *Centrifugal Blood Pump Using Self-Bearing Motor*

Fig. 1 shows the centrifugal blood pump using the self-bearing motor. The radial position and rotation of the rotor-impeller of the Maglev pump were actively controlled through control of the magnetic field of the self-bearing motor. The axial position and inclination of the rotor-impeller were passively suspended by the strong magnetic attractive force of permanent magnets positioned on the inner surface of the rotor-impeller. The Maglev pump's outer diameter and thickness were 78.5 mm and 41.5 mm, respectively. Fig. 2 shows the self-bearing motor. The outer rotor structure, that a rotor is set around a stator, is adopted to miniaturize the Maglev pump. The rotor, which is a yoke itself, has eight permanent magnets on inner circumferential surface. The stator set at the center of the pump has twelve poles. The plus minus two-pole algorithm [9] is adopted to levitate and rotate the rotor. The rotation coil to produce 3-phase 8-pole magnetic field and the levitation coil to produce 2-phase 6-pole magnetic field are separately constructed in the stator. Two eddy current sensors and three hall elements are used to measure rotor radial position and rotation speed respectively.

B. *Design of Rotor*

Rotors of three types which are different of magnetic suspension characteristics were fabricated. Parameters of created rotors are shown in Table I. Based on previous studies [1], rotors were designed. Type-A and Type-B are the same shape. And, Type-A was employed the permanent magnet's material with good ability than that of Type-B. The permanent magnet's material of Type-B and Type-C are same.

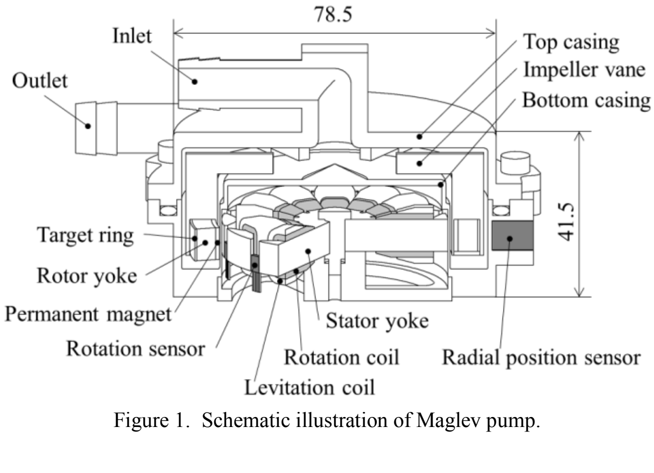

Figure 1. Schematic illustration of Maglev pump.

And, the thickness of the permanent magnet and the air gap length of Type-C are thicker and longer than those of Type-B. Therefore, the strength of the magnetic suspension force in the radial direction is Type-A, Type-B and Type-C, in that order.

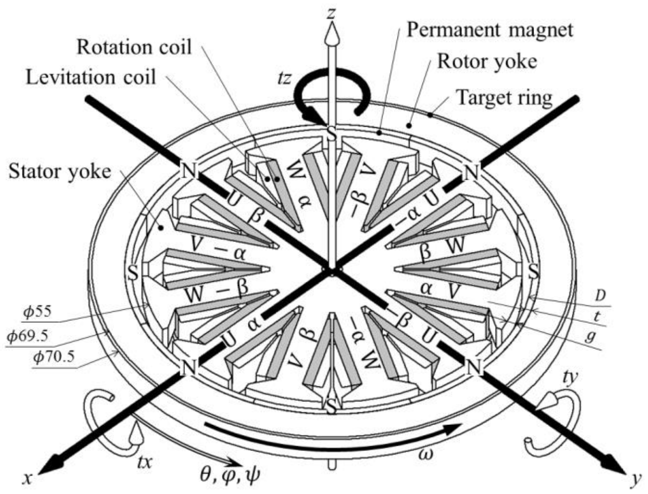

Figure 2. Cross-sectional perspective view of self-bearing motor.

TABLE I. PARAMETER OF DESIGNED ROTOR

Parameter		Type-A	Type-B	Type-C
Inner diameter of permanent magnet	D	58 mm	58 mm	59 mm
Air gap length between stator and rotor	g	1.5 mm	1.5 mm	2 mm
Thickness of permanent magnet	t	1 mm	1 mm	1.5 mm
Coercive force of permanent magnet		756 kA/m	692 kA/m	692 kA/m
Residual flux density of permanent magnet		1.03 T	0.95 T	0.95 T
Magnetic flux density in air gap generated by permanent magnets		0.392 T	0.360 T	0.387 T

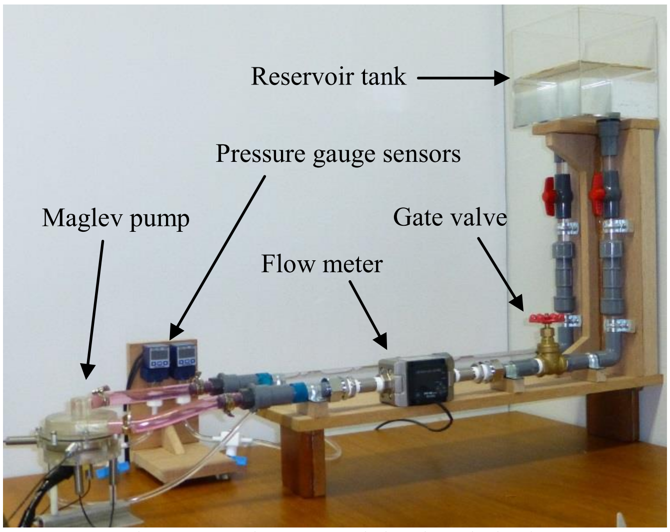

Figure 3. Maglev pump and closed mock circuit.

III. EXPERIMENTS

A. Measurement of Magnetic Suspension Characteristics

(1) Measurement of Attractive Force in Radial Direction

The attractive force in the radial direction was measured with the load cell to evaluate the magnetic suspension force and negative spring force in the radial direction. The rotor was fixed to the center position of Fig.1. To evaluate the magnetic suspension force, the excitation current was changed from 0 A to 3.0 A. To evaluate the negative spring force, the displacement of the rotor from the center position was changed from 0 mm to 0.5 mm.

(2) Measurement of Restoring Force in Axial Direction

The restoring force in the axial direction was measured with the load cell to evaluate the passive stability performance in the axial direction. The axial displacement of the rotor was changed from 0 mm to 8.0 mm.

(3) Measurement of Restoring Torque of Inclination

The restoring torque of the inclination was measured with the irrotational torque meter to evaluate the passive stability performance of the inclination. The inclination angle of the rotor was changed from 0 degrees to 5 degrees, at the axial position of 0 mm and 1 mm.

B. Measurement of Motor Performance

The motor power consumption to the load torque applied to the motor was measured to evaluate of the motor performance. And then, the motor efficiency was calculated from the shaft output of the motor and the motor power consumption. The rotor was attached to a shaft of the torque meter. The torque and electrical input power to the motor was measured with the torque meter and a power meter. The load torque to the motor was changed from 3 mNm to 50 mNm.

C. Measurement of Levitation and Pump Performances

The Maglev pump 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 Maglev pump and the closed mock circuit are shown in Fig. 3. The oscillation amplitude of the rotor-impeller was measured to evaluate the levitation performance during pumping. Then, the electrical input power to the maglev pump was measured with the power meter. In addition to two position sensors using to control the radial position of the rotor-impeller, four position sensors were placed on the bottom face of the Maglev pump to measure the axial displacement and the inclination of the rotor-impeller. Rotation and levitation of the rotor-impeller were controlled with a digital PID controller using a digital signal processor. The parameters of the PID controller were Kp = 5 A/mm, Ki = 5 A/mm/s, Kd = 0.02 A・s/mm respectively. The PID parameter of Type-A, the Type-B and Type-C is the same value. Rotational speed was set to 1500 rpm to achieve a flow rate of 5 L/min against a head pressure of 100 mmHg that is the pump condition of a ventricular assist device.

IV. RESULT

A. *Measurement of Magnetic Suspension Characteristics*

(1) Measurement of Attractive Force in Radial Direction

The measured magnetic suspension force in the radial direction is shown in Fig. 4. The magnetic attractive force of Type-A, Type-B and Type-C generated by a current of 1 A were 6.8 N, 6.2 N and 5.2 N, respectively. As designed, it was verified that the strength of the magnetic suspension force is Type-A, Type-B, and Type-C, in that order.

The measured negative spring force in the radial direction is shown in Fig. 5. The magnetic attractive force of Type-A, Type-B and Type-C generated by displacement of 0.1 mm were 2.1 N, 2.0 N and 1.2 N, respectively. Negative spring force was strong in the same order as the measurement of the magnetic suspension force.

(2) Measurement of Restoring Force in Axial Direction

The measured restoring force in the axial direction is shown in Fig. 6. The magnetic attractive force of Type-A, Type-B and Type-C generated by displacement of 1 mm were 3.3 N, 2.8 N and 3.0 N, respectively. The maximum of the magnetic attractive force of Type-A, Type-B, and Type-C were 13.5 N, 10.8 N and 12.6 N at 6 mm displacement, respectively. The strength of the restoring force in the axial direction is Type-A, Type-C, and Type-B, in that order.

(3) Measurement of Restoring Torque of Inclination

The measured restoring torque of inclination is shown in Fig. 7. The restoring torque of Type-A, Type-B and Type-C generated by inclination of 1 degree and axial displacement of 0 mm were 0.009 Nm, 0.006 Nm and 0.008 Nm, respectively. The restoring torque of Type-A, Type-B and Type-C generated by inclination of 1 degree and axial displacement of 1 mm were 0.013 Nm, 0.009 Nm and 0.011 Nm, respectively. The strength of the restoring torque of inclination is Type-A, Type-C, and Type-B, in that order. When the rotor 1mm displaced in the axial direction and the inclination angle of the rotor is the range of up to 3 degrees, the restoring torque is stronger than that in the case of no axial displacement. When the inclination angle of the rotor reaches 4 degrees or more, the restoring torque is weaker than that in the case of no axial displacement.

B. *Measurement of Motor Performance*

Fig. 8 shows the motor power consumption against each load torque at a rotational speed of 1400 rpm and 1600 rpm. When the load torque was 40 mNm at a rotational speed of 1400 rpm, motor power consumption of Type-A, Type-B and Type-C were 8.0 W, 8.6 W and 8.0 W respectively. When the load torque was 40 mNm at a rotational speed of 1600 rpm, motor power consumption of Type-A, Type-B and Type-C

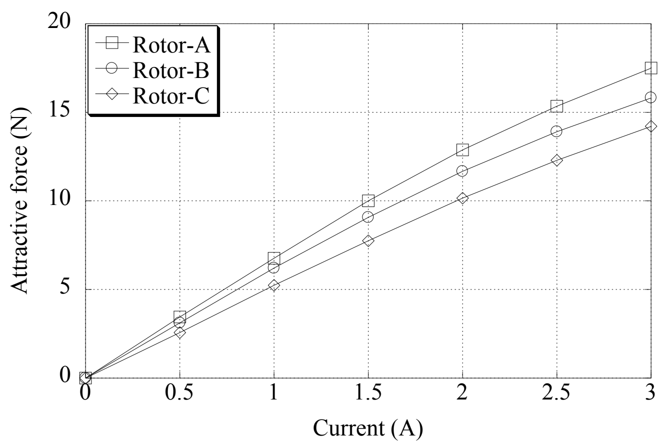

Figure 4. Magnetic suspension force in the radial direction.

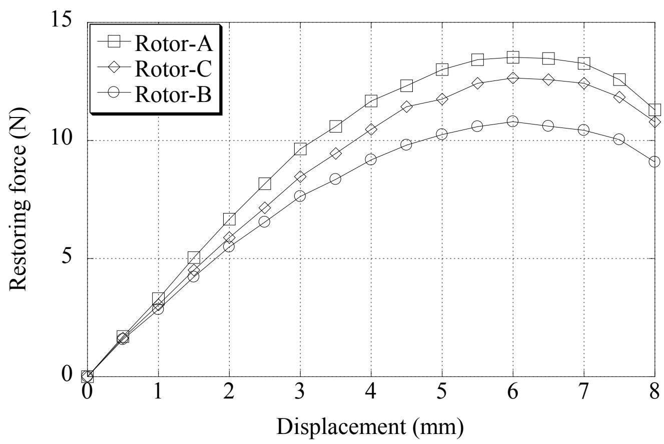

Figure 6. Restoring force in the axial direction.

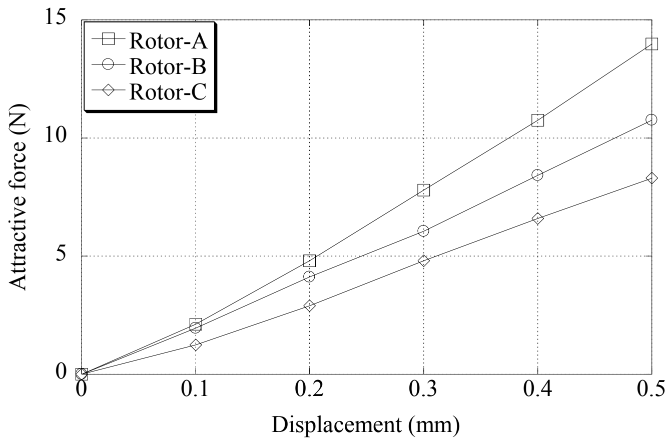

Figure 5. Negative spring force in the radial direction.

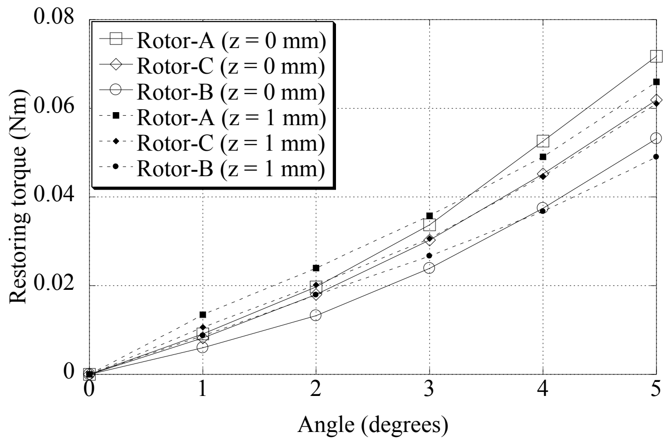

Figure 7. Restoring torque of inclination.

were 9.2 W, 9.7 W and 9.2 W respectively. Motor power consumption of Type-A and Type-C were approximately equal. And, these were lower than that of Type-B.

Fig. 9 shows the motor efficiency against each load torque at a rotational speed of 1400 rpm and 1600 rpm. At a load torque of 40 mNm, the motor efficiency was about maximum value. When the load torque was 40 mNm at a rotational speed of 1400 rpm, motor efficiency of Type-A, Type-B and Type-C were 73.7 %, 68.3 % and 73.1 % respectively. When the load torque was 40 mNm at a rotational speed of 1600 rpm, motor efficiency of Type-A, Type-B and Type-C were 72.7 %, 68.8 % and 73.0 % respectively. There is almost no difference between the motor efficiency of Type-A and Type-C at a torque load of 40 mNm. At a load torque is 30 mNm or less, the motor efficiency of Type-C was good compared to the other.

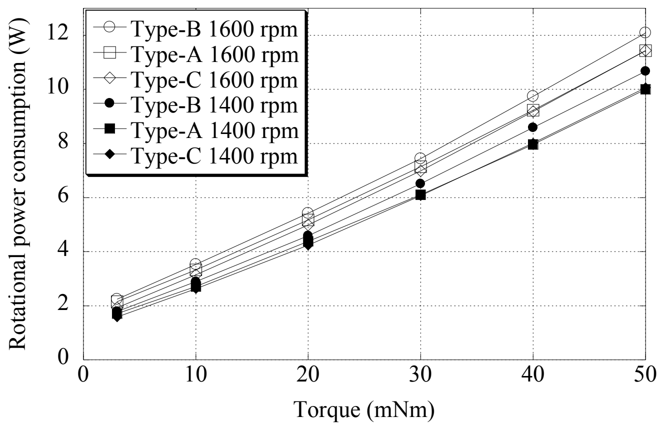

Figure 8. Rotational power consumption vs Motor torque.

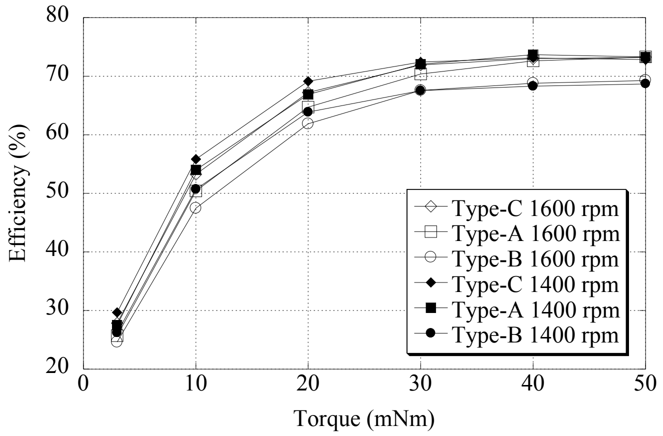

Figure 9. Motor efficiency vs Motor torque.

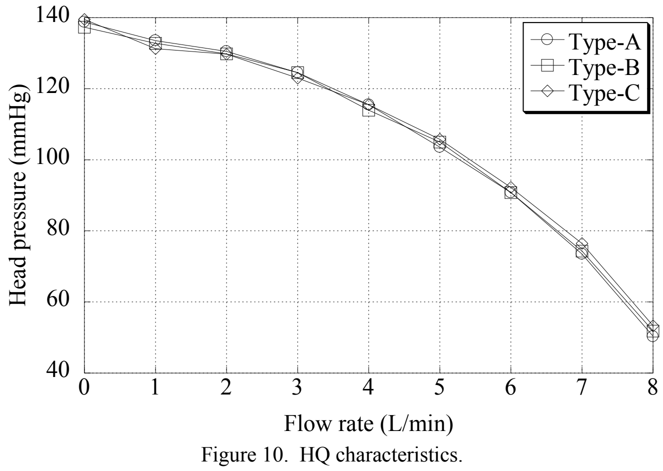

Figure 10. HQ characteristics.

C. *Measurement of Levitation and Pump Performances*

Fig. 10 shows HQ characteristics of Type-A, Type-B and Type-C with a rotational speed of 1500 rpm. At a flow rate of 5 L/min, head pressure of Type-A, Type-B and Type-C were 104 mmHg, 105 mmHg and 106 mmHg respectively. There was almost no difference in HQ characteristics. Maximum head pressure and flow rate were approximately 140 mm Hg and 8 L/min, respectively.

Fig. 11 shows oscillation amplitude in the radial direction (x, y) and axial direction (z) of the rotor-impeller against each flow rate at a rotational speed of 1500 rpm. At a flow rate of 5 L/min, oscillation amplitude in x, y and z direction of Type-A were 0.13 mm, 0.12 mm and 0.058 mm respectively. At a flow rate of 5 L/min, oscillation amplitude in x, y and z direction of Type-B were 0.15 mm, 0.13 mm and 0.036 mm respectively. At a flow rate of 5 L/min, oscillation amplitude in x, y and z direction of Type-C were 0.076 mm, 0.061 mm and 0.047 mm respectively. Fig. 12 shows oscillation amplitude in the inclination (tx, ty) of the rotor-impeller against each flow rate at a rotational speed of 1500 rpm. At a flow rate of 5 L/min, oscillation amplitude in tx and ty direction of Type-A were 0.65 degree and 0.73 degree, respectively. At a flow rate of 5 L/min, oscillation amplitude in tx and ty direction of Type-B were 0.33 degree and 0.38 degree, respectively. At a flow rate of 5 L/min, oscillation amplitude in tx and ty direction of Type-C were 0.35 degree and 0.39 degree, respectively. In all types, the rotor-impeller did not touch the casing during the experiment. The rotor-impeller of Type-C is most stable. Flow channel width in the radial direction and axial direction of Maglev pump are 0.5 mm and 1.5 mm, respectively. And, the rotor-impeller can be tilted geometrically 2 degrees in flow channel.

Fig. 13 shows the rotation, levitation and total power consumption against each flow rate with a rotational speed of 1500 rpm. Total power consumption is the sum of the rotation and levitation power consumption. At a flow rate of 5 L/min, rotation power consumption of Type-A, Type-B and Type-C were 8.6 W, 8.9 W and 8.6 W respectively. At a flow rate of 5 L/min, levitation power consumption of Type-A, Type-B and Type-C were 2.3 W, 4.9 W and 1.4 W respectively. At a flow rate of 5 L/min, total power consumption of Type-A, Type-B and Type-C were 10.9 W, 13.9 W and 10.0 W respectively. Levitation power consumption was substantially constant even if the flow rate changes. Levitation power consumption of Type-C was lower than that of the other. Levitation power consumption of the Type-B was higher most. Rotation power consumption was increased with an increase in the flow rate. There was no large difference in rotation power consumption of Type-A, Type-B and Type-C. Rotation power consumption of the Type-A and Type-C were approximately equal. And, these were slightly lower than that of Type-B. Therefore, total power consumption of Type-C was lower most.

V. DISCUSSION

Magnetic suspension characteristics depend on factors such as the magnetic flux density in air gap generated by permanent magnets and the stator coil, and the air gap length.

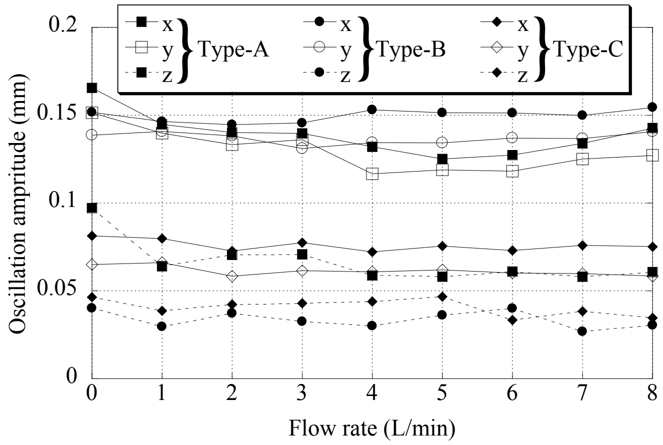

Figure 11. Oscillation amplitude of rotor-impeller in x, y, z direction.

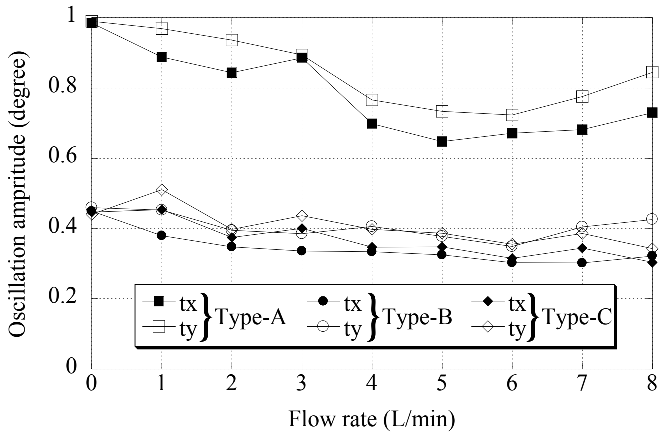

Figure 12. Oscillation amplitude of rotor-impeller in tx, ty direction.

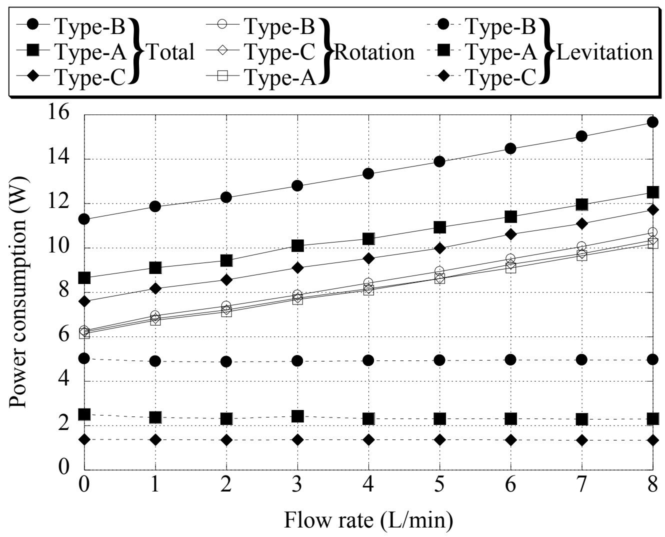

Figure 13. Power consumption in pumping.

The height of the magnetic flux density in air gap generated by permanent magnets is Type-A, Type-C and Type-B, in that order. However, Type-A and Type-C are similar in the height of the magnetic flux density in air gap generated by permanent magnets. The air gap length of Type-C is larger than the air gap of Type-A and Type-B. In the self-bearing motor of Type-A, Type-B and Type-C, the same stator was used. Therefore, it is conceivable that the air gap length have a large impact on determining the strength of the attractive force in the radial direction, whereas the air gap length has a small impact on determining the strength of the restoring force in the axial direction and the restoring torque of the inclination.

There was no difference of the motor performance of Type-C and Type-A at 40 mNm torque load. In load torque of 30 mNm or less, motor performance of Type-C was good compared to the other. The air gap length of Type-C is larger than the air gap of Type-A. But, the height of the magnetic flux density in air gap generated by permanent magnets of Type-A and Type-C are almost similar. Type-C has the most magnetic energy stored in the air gap. Therefore, motor performance of type C was good. The difference between the motor performance of Type-C and Type-A was reduced, probably due to the influence increase of magnetic saturation with an increase in the load torque. It is possible to improve the motor performance by increasing the flux density of permanent magnet, even if the air gap is increased.

There was almost no difference in HQ characteristics of Type-A, Type-B and Type-C. Therefore, it revealed that the levitation performance does not influence the pump performance.

Oscillation amplitude in the radial direction of the Type-C was lower most. It seems that this is because negative spring force was weaker most. Oscillation amplitude in the radial direction of the Type-B and Type-A were nearly equal value. However, oscillation amplitude in the inclination of the Type-A was large. In previous studies, it is clear that the force in the axial direction and the torque in the inclination are generated by generating a magnetic suspension force in the radial direction, in the case of the rotor-impeller is decentered [10]. If negative spring force is strong, it is possible that the interferential effect is stronger. The negative spring force of Type-A was the strongest. Consequently, the levitation performance of Type-C was the best. Total power consumption of Type-C that is the smallest oscillation amplitude in the radial direction was low. Levitation power consumption of Type-C that is the smallest oscillation amplitude in the radial direction was lower most. Oscillation amplitude have exert little influence on levitation power consumption. Consequently, it is possible to improve the levitation performance by reducing the negative spring force and improving the passive stability ability.

VI. CONCLUDION

Rotors of three types which are different of magnetic suspension characteristics were fabricated. The magnetic suspension characteristics of self-bearing motor of three type's rotor were measured. If the negative spring force in the radial direction was weak, the restoring force in the axial direction and the restoring torque of the inclination were not always weak. Magnetic suspension characteristics depend on factors such as the magnetic flux density in air gap generated by permanent magnets and the stator coil, and the air gap length. It is conceivable that the air gap length have a large impact on determining the strength of the attractive force in the radial direction, whereas the air gap length has a small impact on determining the strength of the restoring force in the axial direction and the restoring torque of the inclination. As a result of measurement of motor performance, it is possible to improve the motor performance by increasing the flux density of permanent magnet, even if the air gap is increased. As a result of measurement of levitation and pump performance, it revealed that the levitation performance does not influence the pump performance. And then, it is possible to improve the levitation performance by reducing the negative spring force and improving the passive stability ability.

ACKNOWLEDGMENT

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REFERENCES

[1] H. Onuma and T. Masuzawa, " Estimation of suspension characteristics of a radial type self-bearing motor using 12 slot stator," *Proc. 22th MAGDA Conference inMiyazaki*, pp.79-84, 2013.(in Japanese)

[2] H. Onuma, K. Ukita and T. Masuzawa, " Optimum pole number of a radial type self-bearing motor using 12 slots stator for artificial heart," *Journal of JSAEM*, vol. 20, no. 1, pp.59-65, 2012. (in Japanese)

[3] H. Onuma, T. Masuzawa, K. Matsuda and Y.Okada, " Magnetically levitated centrifugal blood pump with radially suspend self-bearing motor," *Proc. 8th International Symposium on Magnetic Bearings*, pp. 3-8, 2002.

[4] T. Masuzawa, H. Onuma,SJ Kim, Y. Okada, " Magnetically suspended centrifugal blood pump with a self-bearing motor," *ASAIO Journal*, vol. 48, no. 4, pp.437-442, 2002.

[5] K. Ukita, T. Masuzawa, H. Onuma, T. Nishimura and S. Kyo, " A Radial Type Self-Bearing Motor for Small Maglev Regenerative Blood Pump," *Journal of JSAEM*, vol. 20, no. 2, pp.312-318, 2012.

[6] T. Nishinaka, H. Schima, W. Roethy, A. Rajek, C. Nojiri, E. Wolner, and G M Wieselthaler," The DuraHeart VAD, a Magnetically Levitated Centrifugal pump: The University of Vienna Bridge-to-transplant Experience", *Circulation journal*, vol. 70, no. 11, pp.1421-1425, 2006.

[7] H. Onuma, M. Murakami and T. Masuzawa, " Novel Maglev pump with a combined magnetic bearing", *ASAIO Journal*, vol. 51, no. 1, pp.50-55, 2005.

[8] T. Merkel, A. Amdt, J. Hoffmann, P. Nusser, K. Graichen, W. Neumann and J. Muller, " Magnetic bearing in INCOR axial blood pump acts as multifunctional sensor", *Proc. 9th International Symposium on Magnetic Bearings*, #33 on CDROM, 2004.

[9] Y. Okada, T. Ohishi and K. Dejima, " General Solution of Levitation Control of a Permanent Magnet (PM) –Type Rotating Motor," *JSME International Journal Series C*, vol. 38, no. 3, pp.538-542, 1995.

[10] H. Onuma, K. Ukita and T. Masuzawa, " Effect of rotor displacement on a magnetically levitated motor for artificial heart", *The 54th Japan joint automatic control conference*, pp.1481-1482, 2011. (in Japanese)