Regular Paper

Characterizing A Compact 5-DOF controlled Self-Bearing Motor with Modified Magnetic Circuit to Improve Suspension Performance for Pediatric VAD

Masahiro OSA*1(Mem.), Toru MASUZAWA*1(Mem.), Ryoga ORIHARA*1 (Stu. Mem.) and Eisuke TATSUMI*2

Compact mechanical circulatory support (MCS) devices, such as continuous flow rotary blood pumps, have been clinically demanded for pediatric heart treatment. In this research, a miniaturized 5-degrees of freedom (DOF) controlled double stator maglev motor is undergoing development for use in pediatric MCS devices which have high durability and better blood compatibility. This paper reported improvement of the 5-DOF controlled maglev motor by modifying the magnetic circuit to enhance magnetic suspension performance and energy efficiency. The static suspension characteristics and energy efficiency of the developed motor with modified magnetic circuit were then investigated. The axial suspension force and the inclination torque were increased by more than 45%. The input power was reduced by 1-5 W, and the motor efficiency increased by 5-8%. The significantly improved suspension force and energy efficiency due to design refinement indicated feasibility of high performance next generation pediatric MCS device.

Keywords: self-bearing motor, 5-DOF control, double stator, axial gap, magnetic circuit, pediatric VAD.

(Received: 7 August 2018, Revised: 25 December 2018)

1. Introduction

Mechanical circulatory support (MCS) devices are widely used for heart disease treatment. Currently, a study of heart disease treatment in pediatric patients with MCS devices has strongly been demanded [1]. Development of MCS devices for pediatric circulation was supported as a national project in US since 2010. A significantly miniaturized rotary MCS device for pediatric is undergoing development by Jarvik Heart Inc [2,3]. However, the Jarvik device is facing technical difficulties such as deterioration of device lifetime, thrombosis and blood cell destruction, due to a mechanically contacting bearing to suspend a spinning rotor impeller. Hence, there have been increasing interest in next generation MCS devices which can completely levitate a rotating impeller due to high durability and better blood compatibility.

Magnetic suspension is one of the strongest technique to suspend the rotating impeller without mechanical contact. 2-degrees of freedom (DOF) controlled radial maglev motors and several 3-DOF controlled axial gap maglev motors have been developed [4-8]. The previously developed maglev motors are successfully applied to MCS devices for adult patients. In contrast, further miniaturization of the maglev motors has to be required for use in rotary pediatric MCS devices. In general, reduction of actively controlled axes is general strategy to miniaturize the magnetic suspension systems [9-11], however reduced actively positioned DOF causes instability of magnetic system due to deterioration of magnetic suspension force in ultra-compact maglev motor.

This study has been developed an ultra-compact pediatric MCS device with 5-DOF controlled axial gap type self-bearing motor. The developed device demonstrated noncontact suspension and a sufficient pump performance [12-14]. However, further improvement of magnetic suspension force and torque is needed to enhance higher mechanical reliability and energy efficiency to achieve clinically applicable MCS devices. In this study, a 5-DOF controlled self-bearing motor which has modified magnetic circuit to enhance the magnetic suspension performance and energy efficiency was developed. This paper is initial report of basic characteristics of the improved maglev motor; static suspension force characteristics and energy efficiency for motoring.

2. Materials and Methods

2.1 Structure of pediatric VAD with 5-DOF controlled maglev motor

The developing 5-DOF controlled self-bearing motor is an axial gap type surface permanent magnet synchronous motor. Fig. 1 shows a schematic diagram of the self-bearing motor. The motor consists of two identical motor stators and a levitated impeller. The levitated impeller is aligned between the both stators. The motor stators have 6-slots, and the levitated impeller has 4-pole permanent magnets on its surfaces. Combined windings for magnetic suspension and rotation control are wound on each tooth. The motor can produce torque and suspension force with double stator mechanism. An axial position (z) and rotating speed (ωz) of the levitated impeller are actively regulated with a 4-pole control rotating magnetic field. Radial positions (x and y) and tilting angles (θx and θy) of the levitated impeller are also actively regulated with another 2-pole control magnetic field. 5-DOF of impeller postures are independently positioned by overlapped two control magnetic fields in the air-gap.
2.2 Impeller suspension with 5-DOF active control

The axial flux motor can produce axial suspension force and rotating torque with a single rotating magnetic field which has common pole number to the rotor permanent magnets. The axial position ($z$) of the levitated impeller is actively positioned by utilizing field strengthening and field weakening as shown in Fig. 2. A rotating speed ($\omega_z$) of the impeller is controlled by conventional q-axis current regulation. The axial suspension force and the rotating torque are proportional to the d-axis current $i_d$ and the q-axis current $i_q$ based on vector control.

In the axial flux motor, the control magnetic field based on $p \pm 2$ pole algorithm can simultaneously produce inclination torque and radial suspension force. For example, inclination torque around y-axis and the radial suspension force in x direction are produced with a single stator. Hence, inclination angle ($\theta_y$) and radial position ($x$) of the levitated impeller can be controlled with the double stator mechanism as shown in Fig. 3. The inclination angle around x axis and the radial position in y axis can also be controlled in a similar manner. The magnitude and the direction of the inclination torque and the radial suspension force can be regulated with respect to excitation current supplied to the top stator and the bottom stator.

2.3 Design and development of ultra-compact 5-DOF controlled maglev motor

A magnetic circuit for the 5-DOF controlled self-bearing motor was modified by following design strategy to enhance the magnetic suspension performance and energy efficiency. 1) Keeping total device size: the motor outer diameter of 22 mm, the total height of 11.3 mm in a single motor stator, and the total volume of 13 cc in the previously developed prototype motor. 2) Maintaining the axial negative stiffness within +/- 10% of that produced by the previously developed prototype motor to prevent significant change of instability of the magnetic suspension system. 3) Maximizing the force coefficient in the axial direction defined as a slope of the suspension force with respect to excitation current change.

Variable geometric parameters characterizing the magnetic circuit of the self-bearing motor: pole surface area $A_p$, pole height $l_p$, back iron thickness $l_b$, permanent magnet thickness $l_m$, air-gap length $l_g$ and number of turns in windings $n$ are shown in Fig. 4. These variables summarized in Table 1 were numerically designed with theoretical calculation and determined by using 3-D finite element method (FEM) magnetic field analysis. The pole cross-sectional area and the back iron thickness were carefully reduced as small as possible to maximize the number of windings with no saturation. The decreased pole cross-sectional area of 17.0 mm$^2$ and the increased pole height of 9.3 mm drastically increase the number of turns in windings, and hence, force coefficient is effectively maximized with no significant change of the negative stiffness. The shortened air-gap length of 1.3 mm and thinner PM thickness of 0.8 mm were chosen by design optimization with theoretical calculation to...
achieve the maximum axial suspension force and also the equivalent axial stiffness of the prototype. The air-gap and PM thickness combination can efficiently produce the magnetic flux density produced by both electromagnet and permanent magnet in the air-gap due to reduced magnetic reluctance of the magnetic circuit, maintaining the axial negative stiffness.

3. Experiment

3.1 Measurement of magnetic flux density distribution in motor air-gap

Distribution of magnetic flux density in the motor air-gap, which is produced by rotor 4-pole permanent magnets, was measured with an experimental setup shown in Fig. 6. The motor stator and the rotor were fixed to center of the rotating stage. The Gauss meter (Model6010, F.W.BELL) was inserted in the air-gap of 1.3 mm between the motor stator and the rotor. The measurement angle was incremented 0-360 degrees by 2.5 degrees in mechanical angle. The stator windings were not excited in this experiment.

3.2 Static suspension force measurement

3.2.1 Axial suspension force and negative stiffness

The axial attractive force produced by the developed motor was measured to characterize the axial negative spring force with no excitation and the axial suspension force with excitation. The experimental setup is shown in Fig.7. The motor stator is fixed on the base. The rotor is connected to the load cell (NEC Avio) with the linear stage and can be displaced in only the axial direction. The motor stator and the rotor have coaxial configuration.

The axial negative spring force was firstly characterized by measuring the axial attractive force at different axial position in +/-0.3 mm from the axial magnetic center (air-gap length: 1.3 mm). The axial suspension force characteristic was then evaluated with the excitation current of 0-2.0 A at the air-gap length of 1.3 mm.
3.2.2 Radial suspension force and radial stiffness

The axial flux type maglev motor has a passive stability in radial direction due to the magnetic coupling force produced by the axial attractive force. The radial magnetic force produced by the developed motor was measured to evaluate radial restoring force with no excitation and the radial suspension force with excitation. The radial force measurement system is shown in Fig. 8. The motor stator is fixed on the base. The rotor can be moved with the linear stage and the linear slider in the radial direction. The radial force was measured by the load cell (T1-1000-240, Co., Ltd.).

The radial restoring force was measured by changing radial position of the rotor from the radial center to 1.0 mm. The radial suspension force characteristic was characterized with the excitation current of 0-2 A at the radial center position.

3.2.3 Inclination torque

The inclination torque measurement system is shown in Fig. 9. The motor stator is fixed on the base. The rotor is suspended with two ball-bearings, and can be rotated around y axis. The inclination torque produced by the developed motor was characterized as a product of the force measured with load cell and the length which defined as the distance between the rotor center and the force acting point. The excitation current was changed from 0 A to 2.0 A. The air-gap length is set to 1.3 mm.

3.3 Motor performance evaluation

The relationship between the rotating torque and the input power was evaluated. The motor efficiency was then characterized from the results of the ratio of the input power and the motor output work. The motor performance evaluation system is shown in Fig. 10. The motor stator is fixed on the base. The rotor is suspended with ball-bearing and can be rotated around z axis. The rotating torque produced by the developed motor was changed by hysteresis brake and measured with the torque meter (MD-502R, ONO SOKKI). The input power of the motor was measured with the power meter (WT1600, YOKOGAWA Co., Ltd.). The rotating speed was changed from 3000 rpm to 5000 rpm. The rotating torque was varied from 1 mNm to 5 mNm. The air-gap length was set to 1.3 mm.

![Fig. 9 Inclination torque measurement rig.](image1)

![Fig. 10 Rotating torque measurement rig.](image2)

![Fig. 11 Magnetic flux density distribution in motor air-gap in mechanical angle](image3)

![Fig. 12 Axial negative spring force at different axial displacements.](image4)

![Fig. 13 Axial suspension force with excitation current.](image5)
4. Results

4.1 Magnetic flux distribution in motor air-gap

The magnetic flux density distribution in the motor air-gap produced by the improved motor and the previously developed prototype is shown in Fig. 11. The improved motor was successfully able to maintain the magnetic flux density even though the geometric parameters of the motor were changed for suspension performance enhancement. The peak of the flux density produced by the improved motor was around 0.38.

4.2 Static suspension force characteristics

The axial negative spring force and the axial suspension force with excitation are shown in Fig. 12 and Fig. 13, respectively. The negative stiffness of the improved motor of 3.3 N/mm is slightly decreased from 4.0 N/mm. In contrast, the axial suspension force produced by the improved motor is successfully increased. The force coefficient of the axial suspension force is increased from 1.1 N/A to 1.5 N/A.

The radial restoring force and the radial suspension force with excitation current are shown in Fig. 14 and Fig. 15. The radial force characteristics do not have significant change according to the design refinement. The radial stiffness is 0.28 N/mm in single stator. The radial suspension force is 0.12 N/A.

The measured inclination torque is shown in Fig. 16. The improved motor achieves the enhanced inclination torque with the modified magnetic circuit. The torque constant in inclination torque is increased from 4.7 mNm/A to 8.6 mNm/A.

4.3 Rotating torque characteristics

The relationship between the rotating torque and the motor input power is shown in Fig. 17. The input power is increased as the increase in the rotating torque. The improved motor can reduce the input power to produce the required torque, in comparison with the previously developed prototype. The energy efficiency of the motor is shown in Fig. 18. The maximum energy efficiency of the improved motor is 23-26% over operational range of the pediatric VAD (The rotating torque of 1-3 mNm, and rotating speed of 3000-5000 rpm).

5. Discussion

Impeller suspension with magnetic levitation technique can lead better performance of device durability.
and blood compatibility of the rotary VADs than the conventional mechanical contacting bearing. The proposed 5-DOF controlled maglev motor can actively regulate the 5-DOF of impeller postures and rotating speed with two motor stators, and has significant advantages such as miniature device size, higher suspension stability, enhancement the motor torque. In next generation pediatric VADs development, the precise design of compact and high-performance maglev motor is much important.

The magnetic flux density distribution in the improved motor did not have significant change compare to the flux distribution of the previously developed prototype. The balance of the thickness of permanent magnets and the magnetic air-gap length was well designed to maintain the negative stiffness and reduce magnetic reluctance of the magnetic circuit. Refinement of the magnetic circuit sufficiently contributed to enhance the motor static suspension performance. Especially, the axial suspension force and the inclination torque were increased very well more than 45% from that of prototype motor. In contrast, the radial suspension characteristic was slightly deteriorated. The small reduction of the radial stiffness is caused due to the slightly decreased axial attractive force produced by the rotor permanent magnets. However, the stiffness is sufficient to sustain the levitated impeller during pump operation. Although the radial suspension force was also decreased a little, there is no problem because the axial flux motor is stable system in radial direction due to positive stiffness. The radial oscillation in resonance will be successfully suppressed with the obtained suspension force.

The gradient of the power consumption with respect to the rotating torque was decreased in the improved motor. The result indicates that the magnetic circuit refinement played a significant role in the enhancement of the rotating torque production. The power consumption of the improved motor at higher rotating torque was significantly reduced. This is because the copper loss was decreased due to enhanced torque constant. The input power of 1-5 W to produce required torque for pediatric circulation is small enough to achieve well pump operation. In contrast, the motor efficiency is slightly low due to small output required for pediatric circulatory support. The motor still has the space to reduce the iron loss by changing core material from balk iron to the powder magnetic core.

6. Conclusion

The static suspension characteristics and energy efficiency of the motor whose magnetic circuit has been modified to achieve the further improved ultra-compact maglev pediatric VAD was evaluated. The magnetic circuit refinement is much useful for enhancement of magnetic suspension and rotation performance of the maglev motor. The improved motor indicated potential of sufficient non-contact impeller suspension in pediatric VAD operation.

Acknowledgment

This work was supported by Japanese Society for the Promotion of Science (JSPS) KAKENHI Grant-in-Aid for Young Scientists (B) Grant Number 16K18036.

References

[1] J.Timothy Baldwin, Harvey S. Borovets, Brian W. Duncan, Mark J. Gartner, Robert K. Jarvik, William J. Weiss and Tracey R. Hoke, The National Heart, Lung, and Blood Institute Pediatric Circulatory Support, *Journal of the American heart association*, pp. 147-155, 2006.
[2] Marc Gibber, Zhongjun J. Wu, Won-Bae Chang, Giacomo Bianchi, Jingping Hu, Jose Garcia, Robert Jarvik, Bartley P. Griffith, In Vivo Experience of the Child-Size Pediatric Jarvik 2000 Heart: Update, *ASAIO Journal*, Vol. 56, No. 4, 2010.
[3] X. Wei, T. Li, S. Li, J. Sung, P. Sanchez, S. Niu, C. Watkins, C. DeFilippi, R. Jarvik, Z. J. Wu, B. P. Griffith, Preclinical evaluation of the infant Jarvik 2000 heart in a neonate piglet model, *The Journal of Heart and Lung Transplantation*, Vol. 32, No. 1, pp. 112-119, 2013.
[4] A. Yukawa, T. Shinshi, X.Zhang, H. Tachikawa and A.Shimokohbe, A One-DOF Controlled Magnetic Bearing for Compact Centrifugal Blood Pumps, Motion and Vibration Control, *Springer Science+Business Media B.V.*, pp. 357-366, 2009.
[5] Daniel L. Timms, Nobuyuki Kurita, Nicholas Greatrex, Toru Masuzawa, BiVACOR A Magnetically Levitated Biventricular Artificial Heart, Proc. of MAGDA conference in Pacific Asia, pp.482-487, 2011.
[6] M Osa, T. Masuzawa, E. Tatsumi, Miniaturized axial gap maglev motor with vector control for pediatric artificial heart, *Journal of JSAEM*, Vol.20, No. 2, pp.397-403, 2012.
[7] N. Kurita, T. Ishikawa, N. Saito, T. Masuzawa, Basic Design of the Maglev Pump for Total Artificial Heart by using Double Stator Type Axial Self-bearing Motor, *Proceedings of ISMB15*, pp. 509-514, 2016.
[8] Mandep R. Metha, Yoshifumi Naka, Nir Uriel, et al, A Fully Magnetically Levitated Circulatory Pump for Advanced Heart Failure, The *NEW ENGLAND JOURNAL of MEDICINE*, pp. 1-11, 2016.
[9] Quang Dich Nguyen, Satoshi Ueno, Analysis and Control of Nonsalient Permanent Magnet Axial Gap Self-Bearing Motor, *IEEE Transactions on Industrial Electronics*, Vol. 58, No. 7, pp. 2644-2652, 2011.
[10] Junichi Asama, Yuki Hamasaki, Takaka Kiwa, Akira Chiba, Proposal and Analysis of a Novel Single-Drive Bearingless Motor, *IEEE Transactions on Industrial Electronics*, Vol. 60, No. 1, pp. 129-138, 2013.
[11] R. Takeda, S. Ueno, C. Jiang, Development of a Centrifugal Cryogenic Fluid Pump using an Axial Self-bearing Motor, *Proceedings of ISMB15*, pp. 693-700, 2016.
[12] M Osa, T. Masuzawa, Tatsumi, 5-DOF control double stator motor for paediatric ventricular assist device, *Proceedings of ISMB13*, pp. paper 41 (9 pages), 2012.
[13] M Osa, T. Masuzawa, N. Omori, E. Tatsumi, Radial position active control of double stator axial gap self-bearing motor for pediatric VAD, *JSME Journal*, Vol.2, No. 4, pp. 1-12, 2015.
[14] M Osa, T. Masuzawa, T. Saito., E. Tatsumi, Miniaturizing 5-DOF fully controlled axial gap maglev motor for pediatric ventricular assist devices, *International Journal of AEM*, Vol.52, No. 1-2, pp. 191-198, 2016.