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Magnetic Suspension Stability of a Compact Axial Flux Self-Bearing Motor for Implantable Pediatric Rotary Blood Pumps

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Abstract

An Implantable rotary ventricular assist devices (VADs) development is strongly demanded for long-term circulatory support therapy in growing pediatric patients with heart failure. This paper proposes a double stator axial flux self-bearing motor for a rotary pediatric VAD with high mechanical durability and excellent hemocompatibility. A developed magnetically levitated pediatric VAD consists of a top motor stator and a bottom motor stator of the identical structure with six slots and four poles, and a levitated centrifugal impeller. The double stator mechanism achieves a smaller pump size and higher torque production. The maglev motor utilizes a 4-pole rotating magnetic field with vector control to regulate the axial position and rotation of the impeller, and a 2-pole rotating magnetic field with P+/−2 pole algorithm to control the radial position and inclination angle around the radial axis. In this paper, the maglev pediatric VAD was driven by 3 degrees of freedom control to simplify the control system and reduce power input. The developed pediatric VAD demonstrated non-contact impeller suspension and sufficient flow rate regulation from 0.5 to 2.5 L/min with a head pressure of 60-100 mmHg at the rotating speed of 3700-4600 rpm. The oscillation amplitude of the levitated impeller was also sufficiently suppressed in the dynamic suspension characteristics evaluation axially vibrating the pediatric VAD with vibration acceleration of 1.5 G and frequency of 10-120 Hz. The developed maglev blood pump demonstrated potential as an implantable pediatric circulatory support device with contactless operation.

Keywords: Axial flux, Self-bearing motor, Double stator, Ventricular assist device, Pediatric

1. Introduction

Mechanical circulatory support technology is strongly required for treatment of severe heart disease pediatric patients due to the significant shortage of donor hearts. However, the pediatric patients have to use only clinically available extracorporeal pulsatile flow blood pump (Lorts, et al., 2014, Miera, et al., 2014, Timothy, et al., 2006) which has high risk of adverse events such as blood clotting inside the pump and infection at percutaneous cannulation tubes. One of the most significant reasons above situation is that there are no implantable compact rotary blood pumps due to technical difficulty for miniaturization of impeller suspension technique with high durability and blood compatibility (Gibber, et al., 2010, Timothy, et al., 2017, Wearden, et al., 2006). Our research group has developed an ultra-compact magnetically levitated pediatric ventricular assist device (VAD) with double stator axial flux permanent magnet synchronous motor (Osa, et al., 2012, Osa, et al., 2021). Maglev VADs have significant advantages such as high durability, low hemolysis as well as less thrombosis compared to conventional blood pumps which use mechanically contacting bearings for impeller suspension (Emmanuel, et al., 2020, Farrar, et al., 2007, Wu, et al., 2019). The developed maglev pediatric VAD prototype indicated extracorporeal perfusion with non-contact impeller suspension for more than one month in chronic animal experiment. In this study, magnetic suspension performance of the developed ultra-compact maglev motor for pediatric VADs is investigated to demonstrate a guaranty of impeller suspension stability of the blood pump over operating conditions toward long term animal trial with device implanted.

2. Materials and methods

2.1 Structure of double stator axial flux self-bearing motor for compact maglev pediatric VAD

An overview of the magnetically levitated pediatric ventricular assist device (VAD) shown in Fig. 1 consists of a top stator and bottom stator which have same structure achieve contactless magnetic suspension of the levitating impeller. The double stator structure enables the construction of a magnetic suspension system with the minimum configuration and realizes not only compact device size but also high-torque production. The axial flux motor is a 6-slot and 4-pole permanent magnet synchronous motor. The axial position (Z) and rotating speed of the levitated impeller are regulated by the three-phase 4-pole magnetic field generated by the top and bottom motor stators. The radial position (X, Y) and inclination angle around the radial axis (θx, θy) of the levitated impeller are regulated by the three-phase 2-pole magnetic field. The five degrees of freedom (DOF) of the impeller postures and the rotating speed are actively controlled by integrating and distributing 4-pole and 2-pole control rotating magnetic fields in the air motor gap.
The axial position and rotating speed of the levitated impeller can be controlled by vector control. The axial attractive force can be generated by regulating the d-axis component of the three-phase alternating current that generates a four-pole rotating magnetic field as shown in Fig. 2. One of the top and bottom motors strengthen the magnetic field of the permanent magnet located on the levitated impeller, while the other weaken the magnetic field. The field strengthening and field weakening creates an imbalance in the magnetic attractive force between the top and bottom of the levitated impeller and can generate an axial suspension force. The rotating torque is regulated by the q-axis component of the three-phase alternating current to control the rotating speed of the levitated impeller.

The radial position and inclination angle around the radial axis of the levitated impeller are controlled independently using P±2 pole algorithm as shown in Fig. 3 and Fig. 4. The stator generates a 2-pole rotating magnetic field overlapping with the 4-pole rotating magnetic field produced by the permanent magnets of the levitated impeller. The inclination torque and radial magnetic force are generated simultaneously in this magnetic field distribution. When the top and bottom motors produce the inclination torque, the radial support force cancels out. In contrast, the inclination torque cancels out when both stators produce the radial suspension force. Consequently, the inclination angle and radial position of the levitated impeller can be independently controlled by regulating the inclination torque and radial suspension force in the top and bottom motors. Since the axial flux permanent magnet synchronous motor has passive stability in the radial direction, the motor can be driven as a 3-DOF controlled self-bearing motor with only inclination control is chosen.

![Figure 1](image1.png)  **Schematic view of the proposed maglev pediatric VAD.**

![Figure 2](image2.png)  **Axial position regulation with vector control.**

![Figure 3](image3.png)  **(a) Inclination torque production (b) Radial force production (c) Radial torque and force**

![Figure 4](image4.png)  **(a) Inclination control (b) Radial position control**

### 2.3 Fabrication of the compact self-bearing motor and centrifugal blood pump

A prototype of the pediatric VAD which consists of a self-bearing motor and a centrifugal blood pump shown in Fig. 5 and Fig. 6. The stator core is made of compressed magnetic powder (EU-69) to reduce eddy current loss in the core material. Concentrated windings of 123 turns using isolated copper wire of 0.3 mm in diameter are wound on each stator tooth which is 9.3 mm in height. The rotor is made of soft magnetic iron (SUS1-1). The permanent magnets placed on the rotor surface are made of neodymium iron boron (N-48H), which has residual magnetic flux density of 1.36 T and coercivity of 907 kA/m. The outer diameter and height of the self-bearing motor are 22 mm and 35 mm, respectively. When the centrifugal impeller is levitated at the axial magnetic center position, the air gap between the motor stator surface and the surface of the rotor permanent magnets is 1.3 mm. The prototype pump has a width and depth of 42 mm and a height of 45.3 mm. The centrifugal impeller has an outer diameter of 23.2 mm, a height of 10.8 mm, and a mass of 17.4 g. A double-volute geometry is used to mechanically suppress the radial hydraulic forces acting on the impeller. The range of motion of the axial, radial, and inclination angle around the radial axis in the pump casing is +/- 0.3 mm, +/- 0.7 mm, and +/- 1.5 deg, respectively.
2.4 Magnetic suspension and rotation control system of the developed maglev pediatric VAD

Fig. 7 shows an overview of the magnetic suspension and rotating speed control system in the maglev pediatric VAD. Three eddy current displacement sensors (PU-03A) placed at 90° intervals on the inside of the lower stator pole detect the axial position and the inclination angle around the radial axis of the levitated impeller. Two eddy current displacement sensors placed on the sides of the levitated impeller measure the radial position. Three Hall elements (HG-302C) placed at 60° intervals in the slot of the lower stator detect the rotating angle of the levitated impeller every 30° in electrical angle using the magnetic flux produced by the permanent magnets. Based on the levitated impeller postures measured by each sensor, a digital PID controller using dSPACE MicroLabBox and MATLAB Simlink determines the command of control current, and supplies each winding of the top and bottom stators using a single-phase PWM amplifier (JSP-090-10). The control currents of the three-phase 4-pole and 2-pole windings are added in the microprocessor and commanded to the single-phase PWM amplifiers to integrate rotating magnetic fields with different numbers of poles in the air gap. In this configuration, a total of 12 single-phase amplifiers are used in the top and bottom stators to supply control currents independently to each winding as shown in Fig. 8.

2.5 Basic pump performance and magnetic suspension performance evaluation

The developed prototype pediatric VAD was connected to a closed loop circulation circuit shown in Fig. 9 to characterize basic hydraulic and magnetic suspension performance at operating conditions for pediatric circulatory support. The circulation circuit filled with water consisted of a reservoir bag, an ultrasonic flowmeter (H12XL), a throttle valve, and a strain gage pressure gauge (9E02-P13). The pump was driven by 3-DOF control without radial position control to simplify the control system and avoid increasing the control current. Table 1 shows the control gains of the PID and PI controllers used for magnetic suspension and rotation. The blood pump was driven at 3700 rpm, 4000 rpm, 4300 rpm, and 4600 rpm based on the assumed operating speed, and the pump flow rate was adjusted by 0.5 L/min by changing the resistance of the circulation circuit with the throttle valve. The pressure difference between the pump inlet and outlet at each flow rate was measured as the head. The control frequency of the magnetic levitation system and the sampling frequency of the measurement system were set to 10 kHz. The average of the maximum and minimum values was calculated as the vibration amplitude from the measured axial position and inclination angle of the levitated impeller for 1 second. The total motor power consumption at each pump operating point was measured with a digital power meter (WT1800).
2.6 Dynamic suspension performance evaluation with shaking test

Dynamic response of the magnetic suspension system of the developed maglev pediatric VAD with respect to excitation disturbance was evaluated. The developed maglev pediatric VAD was placed on the axially vibrating shaker table shown in Fig. 10. The maglev pediatric VAD connected to the closed loop circulation circuit shown in Fig. 10 was driven as 3-DOF control, with a constant pump speed of 4000 rpm and produced flow rate of 1.5 L/min. Frequency of sinusoidal excitation disturbance and input acceleration were varied 10-120 Hz and 1-5 G. The PID gains of the magnetic suspension control system were the same values as in Table 1. The maximum axial vibration amplitude and maximum inclination amplitude of the levitated impeller for each input disturbance were calculated.

### Table 1 PID control gains for magnetic suspension and rotation

<table>
<thead>
<tr>
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<th>P</th>
<th>I</th>
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<tbody>
<tr>
<td>Axial position control</td>
<td>17 [A/mm]</td>
<td>0.1 [A/sec mm]</td>
<td>0.01 [A sec/mm]</td>
</tr>
<tr>
<td>Inclination angle control</td>
<td>2.4 [A/deg]</td>
<td>0.014 [A/sec deg]</td>
<td>0.004 [A sec/deg]</td>
</tr>
<tr>
<td>Rotating speed control</td>
<td>0.001 [A/rpm]</td>
<td>0.0036 [A/sec rpm]</td>
<td>0 [A sec/rpm]</td>
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3. Results

3.1 Basic pump performance and magnetic suspension performance evaluation

The hydraulic characteristic and total power input of the developed maglev pediatric VAD is shown in Fig. 11 and Fig. 12. The flow rate of the developed pump successfully regulated from 0.5 to 2.5 L/min against head pressure of 60-100 mmHg by changing pump speed from 3700 to 4600 rpm. The total power input to the maglev pump required to magnetic suspension and rotation during pumping increased with respect to increase in the flow rate and pump speed, and ranged from 1.5 to 3.8 W. The oscillation amplitude of the levitating impeller in each axis with pump operation is shown in Fig. 13. At all operating conditions, the levitated impeller was magnetically suspended without contact. The impeller oscillation amplitude of the actively regulated axial direction and inclination direction around the radial axes were less than 0.02 mm and 0.3 degrees at all operating points as shown in Fig. 13(a) and Fig. 13 (b). The passively stabilized impeller radial oscillation amplitude was less than 0.1 mm. A position eccentricity of the rotating center of the levitated impeller to the center of the pump base circle was increased as the flow rate increased as shown in Fig. 13 (c). The radial position eccentricity of the levitated impeller was less than 0.14 mm.
The dynamic suspension performance evaluation with shaking test

The axial oscillation amplitude of the levitated impeller when the maglev pediatric VAD was axially vibrated is shown in Fig. 14. Under all vibrating frequency and acceleration, the axial oscillation amplitude of the levitated impeller was successfully suppressed without mechanical contact. The magnitude of the impeller axial oscillation amplitude varied with respect to the excitation frequency change, and it also increased as the vibration acceleration increased from 1 G to 5 G at all frequencies. The axial oscillation amplitude was ranged from 0.04 mm to 0.09 mm at vibration frequencies of 10-40 Hz. The peak axial oscillation amplitudes 0.05-0.15 mm corresponded to accelerations of 1-5 G were observed at vibration frequency of 80 Hz. The impeller oscillation tended to decrease for frequencies above 80 Hz. The amplitude of the impeller inclination angle around x axis during axial vibration of the maglev pediatric VAD was representatively shown in Fig. 15. The impeller inclination angle was suppressed within the movable range. The amplitude of the impeller inclination angle of 0.67 degrees was relatively high at the condition that the maximum impeller axial oscillation amplitude was observed. However, the impeller inclination angle was remained constant around 0.5 degrees at the other operating points, that is indicating that the inclination angle was independent of the frequency and acceleration of the axial vibration acting on the maglev pediatric VAD.
4. Discussion

Magnetic suspension technology is one of the strongest strategies to significantly improve the durability and hemocompatibility of rotary VADs in long-term circulatory support. Especially in rotary pediatric VADs, non-contact impeller suspension with a compact actuator is essential to achieve flow regulation with changes in pump speed according to the pediatric patients growing up. The double stator axial flux self-bearing motor proposed in this paper is highly effective for the research and development of implantable rotary pediatric VADs, and could be a help to establish pediatric circulatory support.

The developed maglev pediatric VAD has the potential to provide the 0.5-2.5 L/min flow rate required for pediatric circulatory support in the pump speed range of 3700-4600 rpm. The power input of the maglev motor at the expected operating points is 1.5-3.1 W, which is small enough to avoid blood damage and thrombus due to device heat dissipation. The oscillation amplitude of the levitated impeller in actively controlled axes (≤ 0θ, ≤ 0y) were stably suppressed and contactless pumping was achieved at all operating points when the maglev pediatric VAD was statically placed. In addition, uniquely large vibration amplitudes of the levitated impeller were not observed under any operating conditions. The passively stabilized radial position of the levitated impeller was only slightly eccentric because the double volute structure was effective in suppressing the radial hydraulic thrust forces.

The position of the levitated impeller was well regulated and non-contact pump drive was achieved even when the maglev pediatric VAD was vibrated in the axial direction. The maximum oscillation amplitude of the levitating impeller was observed at a vibration frequency of 80 Hz. This is because the vibration frequency of 80 Hz was the resonance frequency of the magnetic suspension control system. However, the oscillation of the levitated impeller was sufficiently suppressed even at the resonance point, and the developed maglev motor indicated high magnetic suspension performance. The frequency of the acceleration disturbance acting on the VAD in the actual pump drive is assumed to be sufficiently small compared to the resonance frequency. Based on the increase in oscillation amplitude of the levitated impeller with respect to changes in vibration acceleration, the displacement of the levitated impeller response to the input disturbance acceleration can be approximated as 0.013 mm/G. This result implies well acceleration resistance of the developed maglev pediatric VAD that the magnetic suspension system can maintain contactless pumping against acceleration disturbances of higher than 10 G.

Conclusion
The ultra compact double stator axial flux type self-bearing motor has been developed for implantable rotary pediatric VAD. The developed maglev VAD indicated sufficient hydraulic performance for pediatric circulatory support according to patients growing up. The feasibility of non-contact impeller suspension of the developed pediatric VAD was indicated at all operating points and under axially vibrating conditions. The dynamic impeller suspension durability of the developed VAD radially vibrated or periodically inclined will be characterized. After the evaluation of the dynamic suspension performance, chronic animal experiment will be conducted.

References