

Magnetically Suspended Centrifugal Blood Pump with an Axially Levitated Motor

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Abstract: The longevity of a rotary blood pump is mainly determined by the durability of its wearing mechanical parts such as bearings and seals. Magnetic suspension techniques can be used to eliminate these mechanical parts altogether. This article describes a magnetically suspended centrifugal blood pump using an axially levitated motor. The motor comprises an upper stator, a bottom stator, and a levitated rotor-impeller between the stators. The upper stator has permanent magnets to generate an attractive axial bias force on the rotor and electric magnets to control the inclination of the rotor. The bottom stator has electric magnets to generate attractive forces and rotating torque to control the axial displacement and rotation of the rotor.

The radial displacement of the rotor is restricted by passive stability. A shrouded impeller is integrated within the rotor. The performance of the magnetic suspension and pump were evaluated in a closed mock loop circuit filled with water. The maximum amplitude of the rotor displacement in the axial direction was only 0.06 mm. The maximum possible rotational speed during levitation was 1,600 rpm. The maximum pressure head and flow rate were 120 mm Hg and 7 L/min, respectively. The pump shows promise as a ventricular assist device. **Key Words:** Rotary blood pump—Centrifugal pump—Magnetic suspension—Axially levitated motor—Ventricular assist system.

Magnetic suspension techniques have been used to eliminate the mechanical parts of centrifugal blood pumps (1–6). In particular, a group at Kyoto University introduced an axial-type magnetically suspended centrifugal pump as a ventricular assist device—the DuraHeart, currently developed by Terumo Corp.—and demonstrated survival of over 1 year in animal experiments. However, that device uses a magnetic coupling mechanism to rotate the levitated rotor. A motor with bearings, which limits the lifetime of the device, is used to rotate permanent magnets that transfer torque to the rotor. The HeartMate III developed by Thoratec Corp. uses a radially suspended self-bearing motor whose smaller diameter inner rotor helps to miniaturize the pump. Compared to the DuraHeart, the HeartMate III runs at a higher

rotational speed and has a smaller rotor surface area for magnetic suspension. Like the DuraHeart, the HeartQuest developed by MedQuest Products Inc. uses an axial suspension system. However, it has a linear actuator only in the axial direction; the inclination of the rotor is not controlled actively.

To eliminate additional moving parts in the artificial heart, we have investigated several magnetic suspension and rotation techniques that not only levitate the rotor but also rotate the rotor by using electromagnetic power. We have studied techniques using either active axial or active radial suspension. On the one hand, the radially suspended motor has an advantage in that it can be made thinner than the axially suspended motor because the magnetic mechanism can be constructed in the circumferential space of a levitated rotor. On the other hand, the magnetic suspension performance of the axially suspended system is better than the radial one, because the larger surface area of the rotor in the axial direction can be used for the magnetic suspension.

A maglev pump developed by our group with a radially suspended self-bearing motor has been reported in previous papers (5,6). In this article, a magnetically suspended centrifugal blood pump

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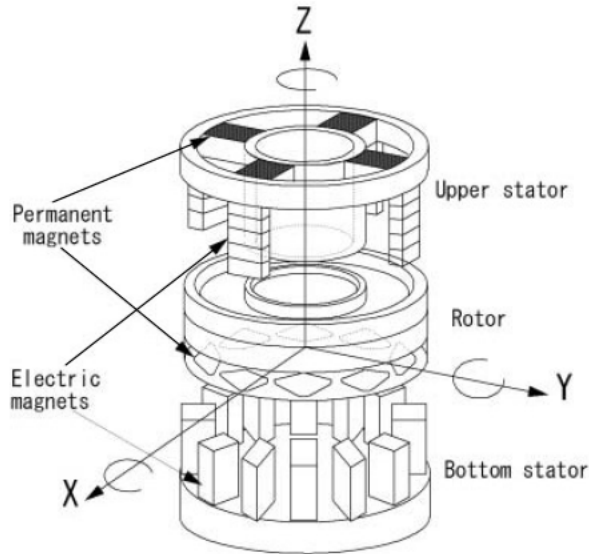


FIG. 1. Basic structure of the axially levitated motor is shown. The motor consists of an upper stator, a bottom stator, and a levitated rotor set between the stators.

using an axially levitated motor with active tilt control is described.

MATERIALS AND METHODS

Axially levitated motor

An axially levitated motor, with active levitation of the rotor in the axial direction, was developed and applied to a centrifugal blood pump. The basic structure of the levitated motor is shown in Fig. 1. The motor comprises an upper stator, a bottom stator, and a levitated rotor-impeller between the stators. The upper stator has four permanent magnets to generate the attractive bias force to the rotor against the attraction by the bottom stator. The upper stator also has four concentrated wound poles for electric magnets to control the inclination of the levitated rotor about the x and y axes (θ_x and θ_y). The bottom stator has 12 poles that concentrated coils of the electric magnets are wound on. The bottom stator produces the attraction and the rotating torque to control the axial displacement and the rotation of the levitated rotor. The rotor has eight permanent magnets on the surface facing the bottom stator and has a yoke on the upper stator side. Four eddy current sensors are used to measure the rotor positions and its inclination in the axial direction. The radial movement of the rotor is restricted by passive stability.

The stator and the permanent magnet of the rotor are assumed to produce the following magnetic flux density $B_s(\theta, t)$ and $B_r(\theta, t)$,

$$B_s(\theta, t) = B_s \cos(\omega t - M\theta) \quad (1)$$

$$B_r(\theta, t) = B_r \cos(\omega t - M\theta - \phi) \quad (2)$$

where B_s and B_r are the peak density of magnetic flux of the stator and the rotor, M is the pole pair number of the rotor, ω is the rotating speed of the rotor, θ is the angular coordinate, and ϕ is the phase difference. For simplicity, magnetic properties inside the rotor and stator are assumed to be homogenous and the reluctance is ignored when compared with that of the air gap. Then, the axial force f_z and the torque τ_z can be derived as follows (7,8),

$$f_z = \frac{(r_2^2 - r_1^2)\pi}{4\mu_0} [B_R^2 + 2B_R B_S \cos \phi + B_S^2] \quad (3)$$

$$\tau_z = \frac{zM(r_2^2 - r_1^2)\pi}{2\mu_0} B_R B_S \sin M\phi \quad (4)$$

where r_1 and r_2 are the inner and outer radii of the rotor, z is the equivalent distance of the air gap and the permanent magnet, and μ_0 is the permeability of vacuum. Therefore, the axial movement of the rotor can be controlled by changing the magnitude of magnetic flux of the motor stator B_s . The torque is also controlled by changing the phase difference ϕ . The rotor levitation and rotation is controlled with vector control techniques and a digital PID control algorithm using a digital signal processor.

The basic principle of the tilt control with the upper stator is shown in Fig. 2. The bias magnetic flux is produced by the four permanent magnets in the upper stator. A coil and an opposite coil are connected serially as a pair coil. Two pair coils are used to regulate the inclination of the levitated rotor in the x and y axes. When the levitated motor tilts, the magnetic flux in the side that the rotor approaches is decreased and the magnetic flux in the other side is

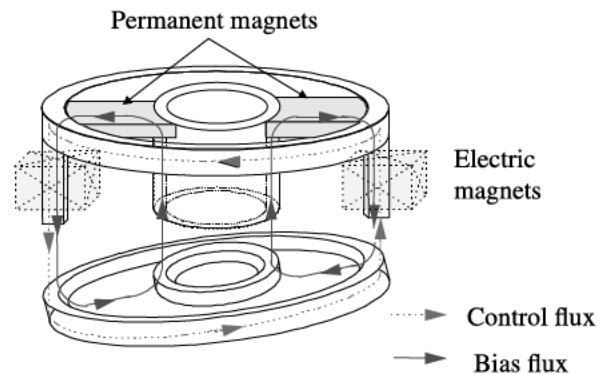


FIG. 2. Basic principle of the tilt control with the upper stator is shown. The bias magnetic flux produced by the four permanent magnets is regulated with the electric magnets.

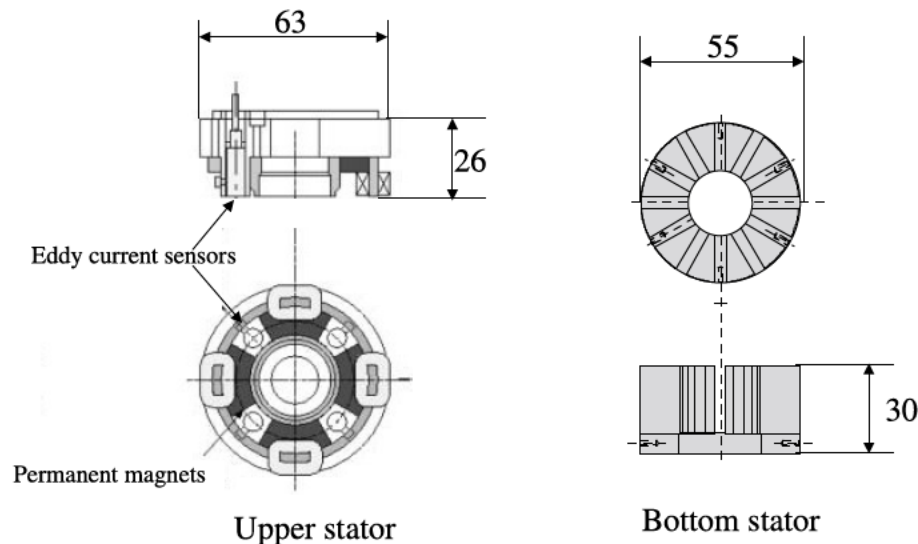


FIG. 3. Upper and bottom stators are shown.

increased, with the electric magnets to limit the inclination of the levitated rotor.

Motor design and experimental setup

When the pump, which has a hydraulic efficiency of 30%, is driven with a head of 150 mm Hg and a flow rate of 5 L/min, the motor must generate a power of 6 W. The rotational speed in this condition is assumed to be 2,000 rpm, at which the motor should generate a torque of 0.03 Nm. Therefore, the design specification for the levitated motor was to produce a torque of 0.03 Nm with a rotating speed of 2,000 rpm. The air gap between the rotor and the stator was set to 2 mm, with 20 N as the design point for the attractive force produced with the stator. The number of turns in the coils and the geometric parameters of the permanent magnets were determined with Eqs. 3 and 4.

Figure 3 shows the upper and bottom stators. The upper stator has a maximum diameter of 63 mm and a height of 26 mm. The weight of the upper stator is 250 g. Magnetic steel was used to make the core of the upper stator. Four permanent magnets made of Nd-Fe-B were set in the upper stator to produce the bias flux. The number of turns in a coil for the inclination control was 224. The diameter of the bottom stator core is 55 mm with a height of 30 mm. The weight of the bottom stator is 470 g. Thin laminated silicon steel was wound like a tree ring and poles were constructed by wire electron discharge to reduce the eddy current loss in the bottom stator. The number of turns in the motor coil was 100. The essential measurable characteristics of the axially levitated motor are the attractive forces produced by the top

and bottom stators, the torque produced by the bottom stator, the motor efficiency (motor torque times speed divided by the electric power input to the bottom stator), and the axial and radial displacements of the rotor.

Figure 4 shows the rotor construction. Eight permanent magnets were mounted on the surface facing the bottom stator. A yoke made of magnetic steel was set on the upper stator side to close a magnetic circuit for the upper stator. A hole with a diameter of 15 mm was constructed as an inlet eye at the center of the yoke. There is also a hole of the same size at

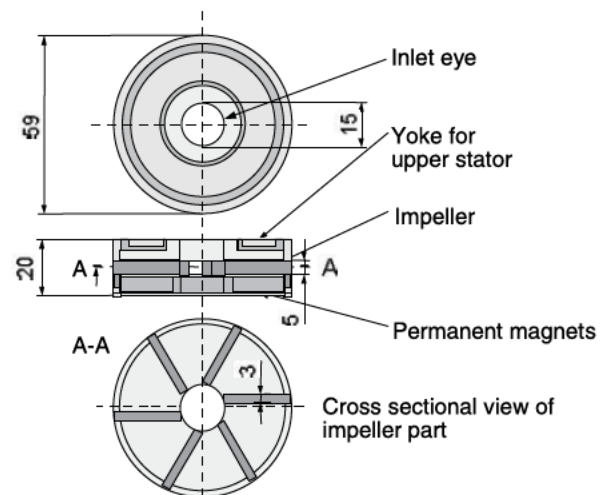


FIG. 4. Levitated rotor-impeller is shown. The rotor-impeller consists of a yoke for the upper stator, a closed impeller, and eight permanent magnets.

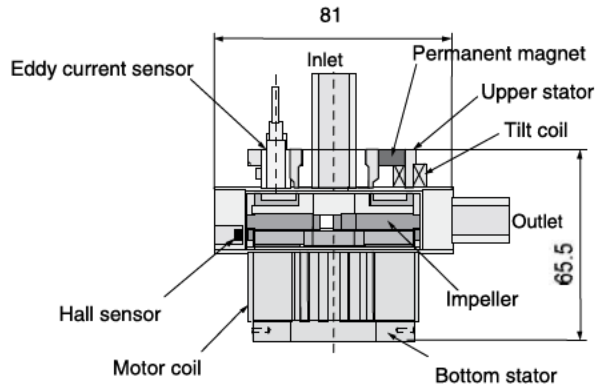


FIG. 5. Prototype pump with an axially levitated motor is shown.

the bottom side to provide washing behind the impeller. A closed impeller was constructed by sandwiching six impeller vanes made of acrylic resin between the permanent magnet and the yoke. The weight of the rotor-impeller is 180 g.

The prototype pump with the axially levitated motor is shown in Fig. 5. The rotor-impeller was encased in an acrylic resin casing. The upper and bottom stators were set on both sides of the casing. The height of the pump is 65.5 mm and its diameter is 81 mm. The axial distance between the rotor and the stators was set to 3 mm. The width of the axial gap between the rotor and the pump casing is 0.4 mm. The radial gap between the rotor and the casing is 1.5 mm. Four eddy current sensors were set in the upper stator to measure and control the axial rotor position. A Hall sensor-type rotary encoder was set at the circumference of the rotor to measure and control the rotating speed. The pump was connected

with a closed loop circuit filled with water and the magnetic suspension performance and pump performance were evaluated. The rotor displacement was measured with eddy current sensors to evaluate the suspension performance. The head pressure at the inlet and outlet was measured with pressure gauges (9E02-P13-2, NEC San-ei Instruments Co., Tokyo, Japan) and the flow rate of the pump was measured with a propeller flow meter (IR-OPFLOW-4, Beli Technics B.V., Wijchen, The Netherlands). Input energy into the upper and bottom stator was measured with a digital power meter (3192 AC/DC digital power meter, Hioki Co., Nagano, Japan).

RESULTS

Motor performance

Figure 6 shows the relationship between the attractive force produced by the stators and the air gap length. Figure 6a shows that the upper stator could produce a 20 N attractive force at the design point 2 mm air gap. Figure 6b shows the change in attraction as the air length and excitation current of the bottom stator were changed. The bottom stator could produce an attraction from 18 to 36 N with the 2 mm air gap. Figure 7 shows the performance of the levitated motor. Figure 7a shows that the motor rotating at 2000 rpm could generate a torque of more than 0.03 Nm when the phase difference was larger than 45 degrees. Figure 7b shows that the maximum efficiency of the motor was 70%.

Levitation performance

Figure 8 shows the axial average displacement and axial oscillation as a function of rotor speed. The four

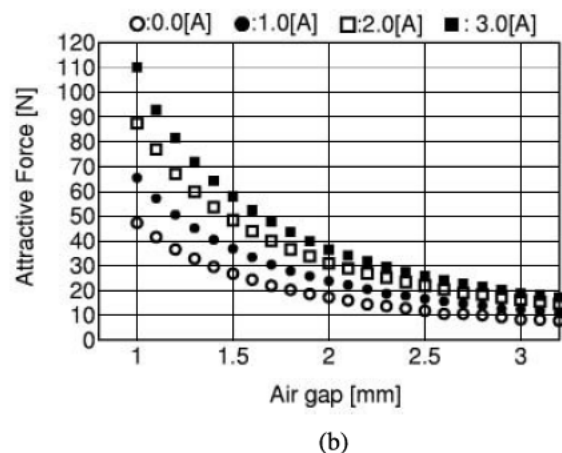
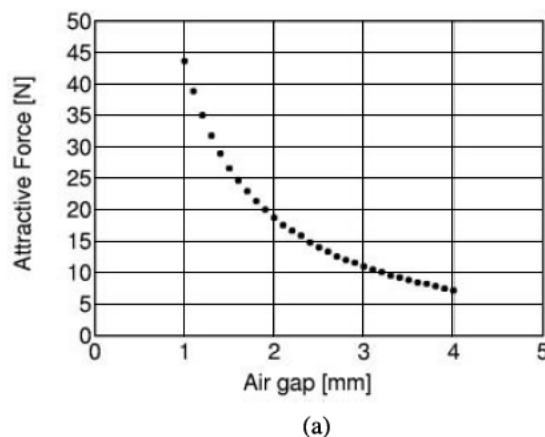


FIG. 6. Shown is the relationship between the attractive force produced by the stators and the air gap length. (a) Static attraction produced by the upper stator. (b) Attraction produced by the bottom stator. Relationship among attractive force, air gap length, and excitation current.

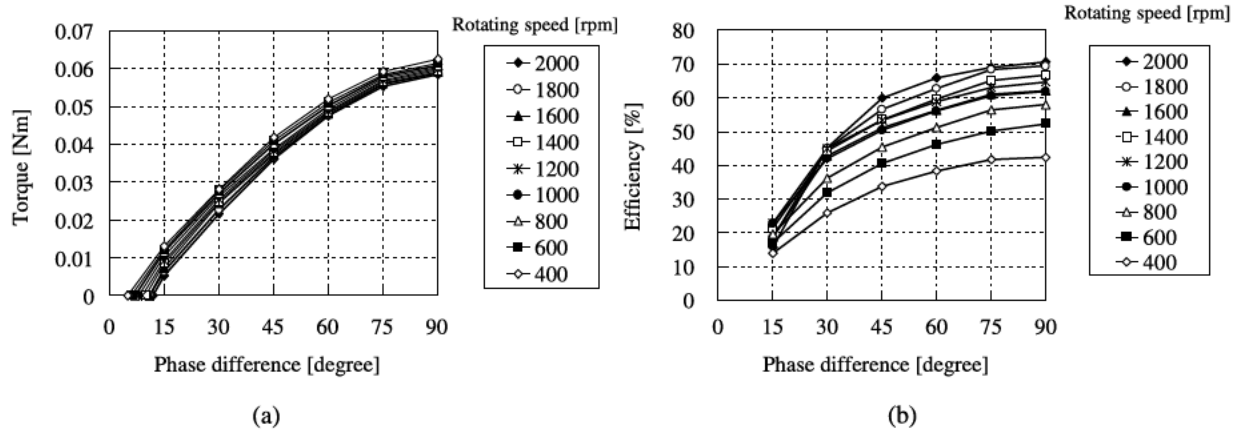


FIG. 7. Shown is the performance of the levitated motor. (a) Relationship between produced torque, phase difference, and rotating speed. (b) Relationship between power efficiency, phase difference, and rotating speed.

curves represent output from the four eddy current sensors. During pumping, the rotor could be rotated up to 1,600 rpm without touchdown, but touchdown on the lower pump casing always occurred beyond 1,700 rpm. Figure 8a shows that the maximum axial average displacement was 0.08 mm. Figure 8b shows that the maximum axial displacement oscillation amplitude was 0.06 mm.

The performance of the radial suspension as a function of rotor speed is shown in Fig. 9. Figure 9a shows a radial average displacement of 0.6 mm in the y direction and 0 mm in the x direction. Figure 9b shows that the maximum radial displacement oscillation amplitude was 0.35 mm.

The change in rotor inclination as a function of rotor speed is shown in Fig. 10. Figure 10a shows that

the maximum rotor inclination was less than 0.2 degrees during pumping. Figure 10b shows that the maximum rotor inclination oscillation amplitude was 0.15 degrees.

Pump performance

Figure 11 shows the pressure head and flow rate (HQ) characteristics of the maglev centrifugal pump. In this study, the maximum pressure head and flow rate were 120 mm Hg and 7 L/min, respectively. The input power, which is the sum of the input power into the upper and bottom stator, is shown in Fig. 12. The energy consumption with a head pressure of 100 mm Hg and a flow rate of 5 L/min was less than 8 W. The efficiency excluding the drive circuit was 15% under the same conditions.

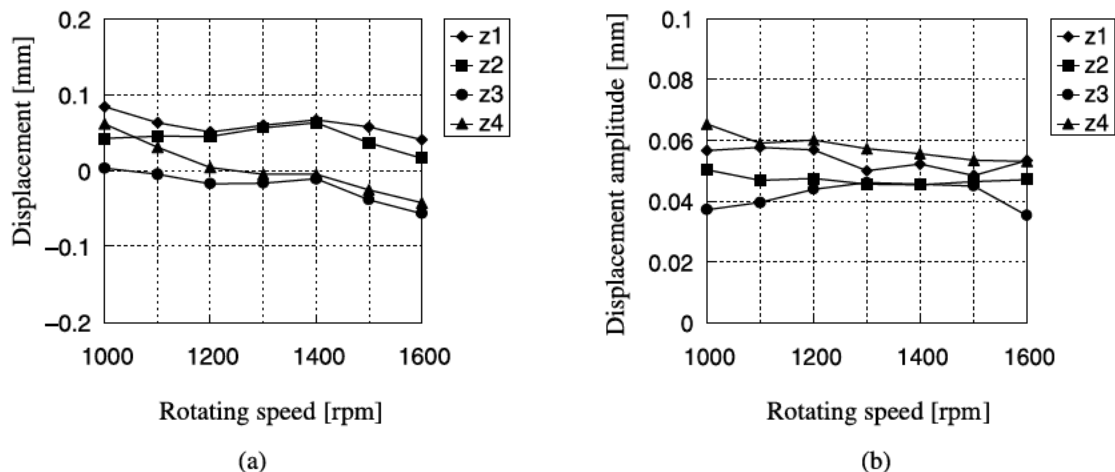


FIG. 8. Shown is the axial suspension performance with pumping, showing output of four eddy current sensors z1–z4. (a) Averaged displacement of the levitated rotor in the axial direction. (b) Oscillation amplitude of the levitated rotor in the axial direction.

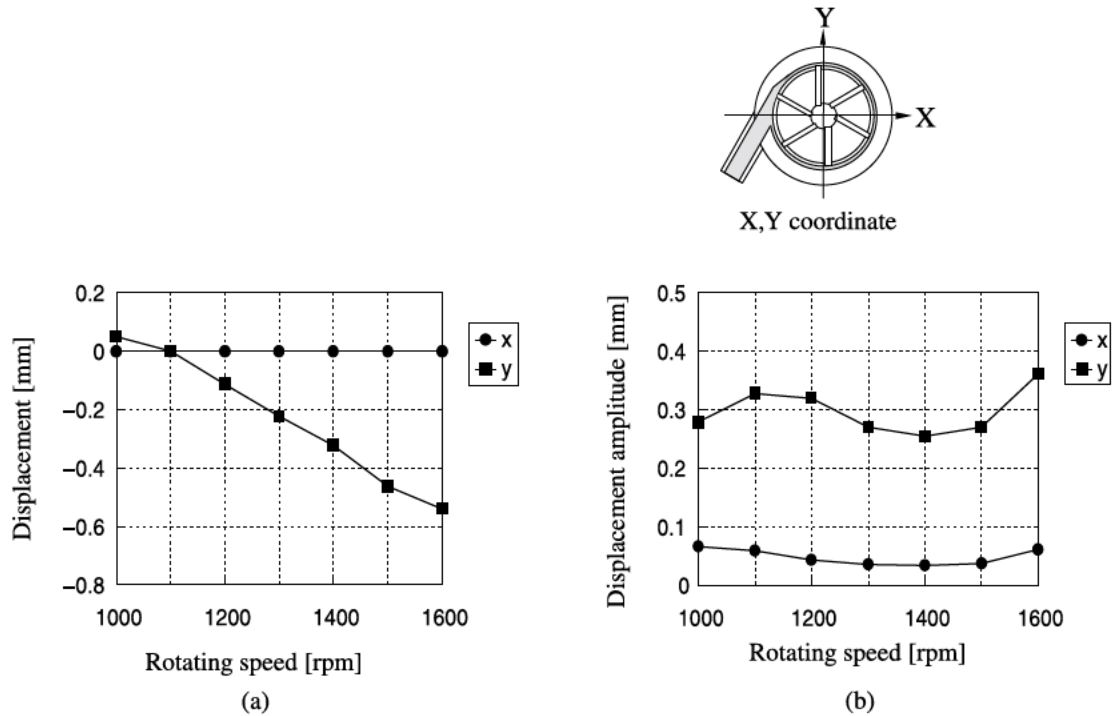


FIG. 9. Radial suspension performance with pumping is shown. (a) Averaged displacement of the levitated rotor in the radial direction. (b) Oscillation amplitude of the levitated rotor in the radial direction.

DISCUSSION

In these studies, the axially levitated motor was shown to be feasible for a blood pump. The stators could produce the design point 20 N attractive force and a torque well in excess of the 0.03 Nm design point. The performance of inclination control was

good. However, the touchdown of the rotor onto the lower pump casing for speeds greater than 1,700 rpm requires some explanation.

As shown in Fig. 13, the relationship between bias attraction (provided by the upper stator) and the produced force (provided by the bottom stator) determines the axial location of the rotor. The

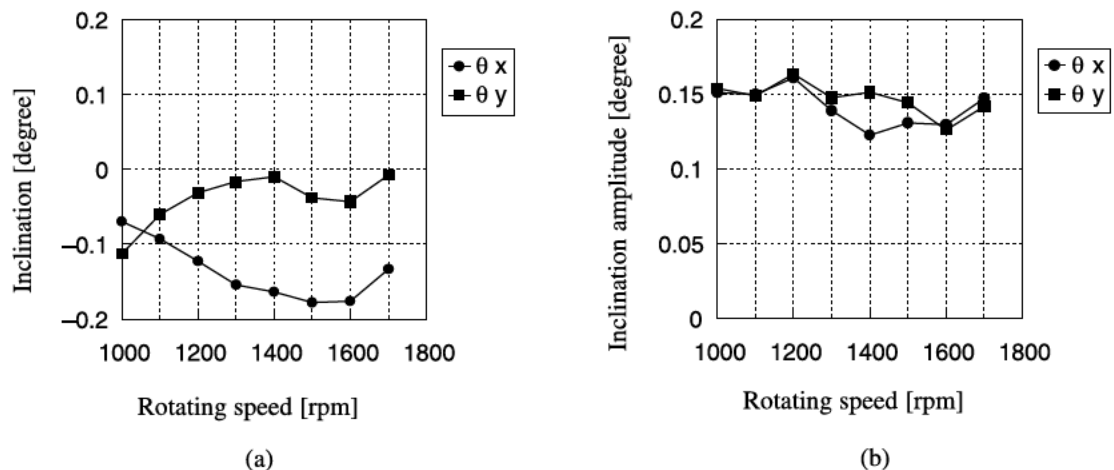


FIG. 10. Shown is rotor tilt control performance during pumping. (a) Averaged tilt angle of the levitated rotor. (b) Oscillation amplitude of the levitated rotor inclination.

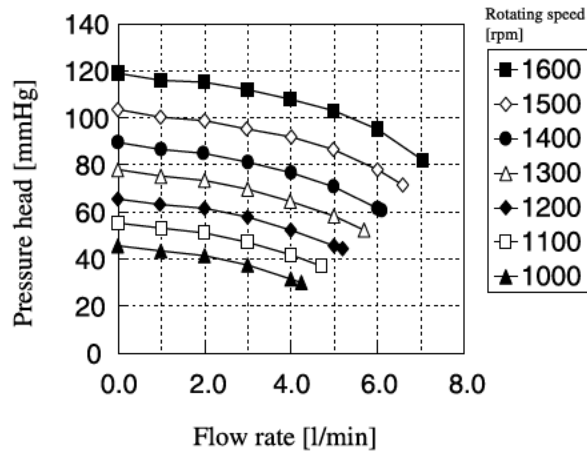


FIG. 11. Pressure head and flow rate (HQ) characteristics of the maglev centrifugal pump are shown.

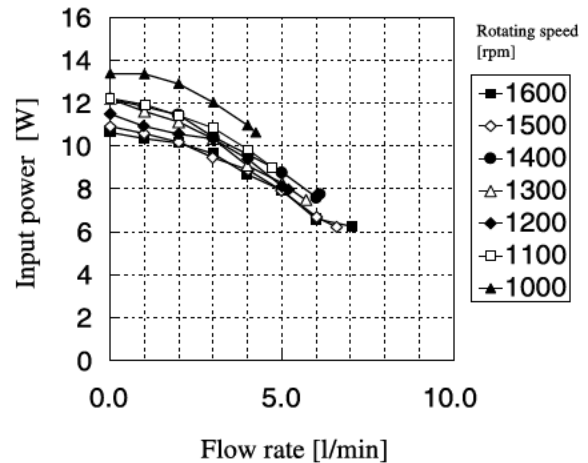


FIG. 12. Power consumption of the maglev centrifugal pump is shown, excluding controller and power stage.

produced force has two components: the controlled attraction and the torque building force. The control of the motor determines the angle between these components, which is generally maximized for greatest torque at the design point. At the “set point” or “balance point” (middle figure), the bias and controlled attractions are balanced. When the torque is decreased (left figure), the axial forces on the rotor remain in balance if the angle is decreased. When the torque is increased (right figure), the angle cannot be increased any further, so there are unbalanced axial forces that cause the rotor to accelerate downward into the pump casing.

The choice of the axial distance between the rotor and the stators embodies tradeoffs between axial levitation control stability and energy consumption. A smaller axial distance produces a larger attraction, but it causes a higher gain in levitation control. Conversely, a larger axial gap distance produces a more stable control but a decreased efficiency, as magnetic attraction drops off with distance. The 3 mm distance between the rotor and the bottom stator was chosen to minimize power consumption at the design point of 100 mm Hg pressure head and 5 L/min flow.

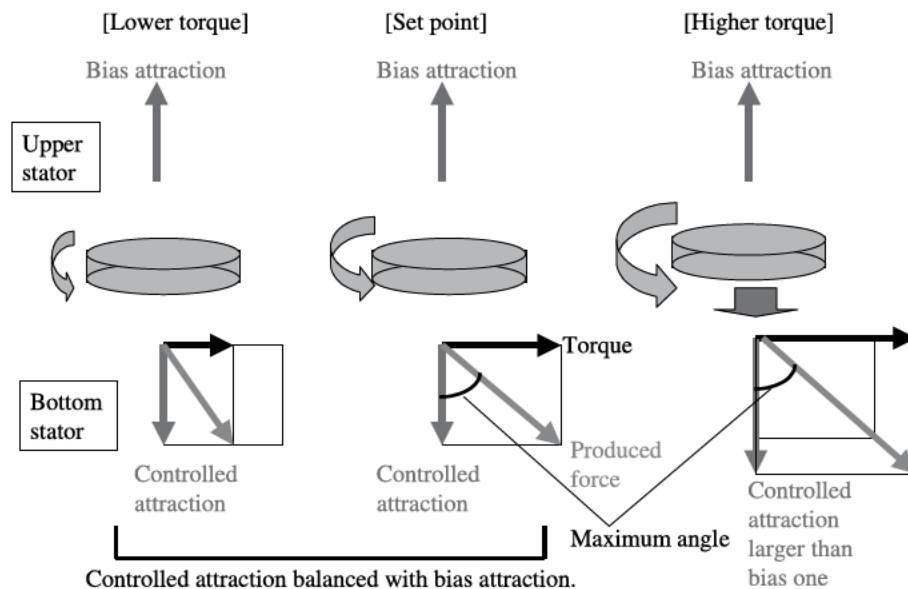


FIG. 13. Shown is relationship among controlled attraction, bias attraction, and torque.

We believe that the axially levitated motor could be optimized with respect to bias attraction and power consumption. The bias attraction is determined by the distance between the rotor and the upper stator, which is also set to 3 mm in the present device. If the bias attraction were increased by reducing this distance, then the balancing point could be moved to a higher torque. Consequently, the maximum torque before touchdown could be increased, albeit with an increased power consumption. A higher bias attraction is applied by tuning the controller gain, which would also increase power consumption. The present 8 W power consumption could probably be increased to as much as 15 W without ruling out implanted use of the device. Of course, a heat generation study should be performed in the future to confirm this opinion. Furthermore, we believe that a greater rotational speed and a pressure head more adequate for a ventricular assist device could be achieved by optimizing the bias attraction.

The radial movement of the levitated rotor was significant. However, passive stability was sufficient to ensure that the rotor did not touch the radial wall of the casing. If the bias attraction were increased, the passive stability would also be improved and the amplitude of the radial oscillation decreased. Because the results in Fig. 9 show a much greater rotor displacement amplitude in the y direction than in the x direction, we conjecture that unbalanced forces predominated in the y direction, perhaps due to the outlet port design. Further studies, such as measurement of the pressure distribution in the pump, should be performed to more fully investigate the passively levitated rotor axes.

The dimensions of the pump, while not too great for human implantation, could be reduced. The present 65.5 mm height results from the design of the active axial suspension. Although the design point torque target was 0.03 Nm, this motor produces a maximum torque of 0.06 Nm. By reducing the number of coil turns, a shorter bottom stator that has about 20 mm in height could provide adequate torque. The present 81 mm diameter results from the choice of acrylic for housing. The diameter of the pump could be reduced to 70 mm by using a titanium casing. The dimensions of the final pump will be 60 mm in height and 70 mm in diameter and the weight will be about 800 g with a titanium casing.

Besides the above changes, immediate development steps include development of displacement

sensors that can be used in the titanium casing and tests for hemolysis and thrombogenicity. Also, before in vivo studies, we must determine whether our device can be operated against a pulsatile pressure head. In the long term, the sophisticated control circuits must be miniaturized and optimized for reliability.

CONCLUSION

A magnetically suspended centrifugal blood pump has been designed and tested in vitro. The pump produced a maximum pressure head and flow rate of 120 mm Hg and 7 L/min, respectively. Further development of the magnetic circuits is needed to prevent axial rotor touchdown at speeds beyond 1,700 rpm and to reduce the overall height of the pump. The pump shows promise as a ventricular assist device and will be tested in vivo in the near future.

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