Cost-Effective Magnetic Bearing System using a Single-Use Magnet-Less Rotor for an Extracorporeal Centrifugal Blood Pump

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Abstract: In the field of rotary blood pumps, contactless support of an impeller by a magnetic bearing has been identified as a promising method to reduce blood damage and enhance the durability. We have developed a two-degrees-of-freedom controlled magnetic bearing system without any permanent magnet in the impeller, so that a single-use pump head of an extracorporeal centrifugal blood pump could be manufactured more easily at a low cost. A prototype blood pump with the magnetic bearing realized stable levitation and contactless rotation of the impeller. The run-out of the impeller position from 1,000 rpm to 3,000 rpm was less than 70 μm (3σ) in the radial controlled directions. The total power consumption of the magnetic bearing was less than 1 W at the same rotational speeds. The pump could yield a flow rate of 5 L/min against a head pressure of 590 mmHg (78.7 kPa) at the speed of 4,000 rpm, which provided sufficient performance for an extracorporeal circulation support.

Keywords: Cost-Effective Magnetic Bearing, Magnet-Less Rotor, Centrifugal Blood Pump, Single-Use Pump Head

Introduction

According to a report of the World Health Organization (WHO), heart failure is a leading cause of death in the world [1]. As a consequence, demands for extracorporeal blood circulation using a centrifugal blood pump (CBP), which yields blood flow by rotating an impeller, may be on upward trend. For ease of maintenance and cost-effective use, such a CBP usually utilizes a single-use pump head consisting of an impeller and a housing having an inlet and an outlet. Furthermore, middle-term circulation support with an extracorporeal CBP for bridge-to-transplant between a few weeks and a few months has been recently identified. The cost of the circulation support using the extracorporeal CBPs is a 1 % or less than that using implantable equipments. However, the mechanical bearing supporting the impeller limits the use of the pump to only a few days due to the wear of the bearing. Furthermore, the shear stress and stagnation of the blood flow around the bearing promote both blood destruction and blood clotting.

Levitating the impeller in a contactless manner with a magnetic bearing presents one of the solutions. CentriMag [2] (Levitronix GmbH), which utilizes a two degrees-of-freedom (DOF) controlled bearingless motor [3], is the only commercially available magnetically levitated (MagLev) CBP having a single-use pump head, where a permanent magnet ring is embedded in a plastic impeller in order to function as magnetic bearing and motor. Our group has also developed a MagLev CBP having a single-use pump head, including a neodymium ring magnet, which is under evaluation in animal experiments.

The levitation stability and the rotational accuracy of the MagLev CBP impeller depend on the precision of permanent magnet rings embedded in the impeller, so that the high manufacturing accuracy or the profile error compensation of the permanent magnet is required. Therefore, the single-use pump head with the permanent magnet tends to be expensive. To realize a cost-effective pump head in MagLev CBP, eliminating permanent magnets in the single-use rotor is of importance regarding cost, as well as simplifying its structure. Furthermore, the use of a rare metal, such as neodymium, included in some permanent magnets, should be avoided in a single-use pump head, due to the material rarity.

Therefore, in order to achieve the above mentioned requirements, including high durability, low blood damage, a cost-effective pump head and high reliability, a reduced controlled DOF magnetic bearing not requiring a permanent magnet in the rotor should be realized. Such a MagLev CBP has never been developed until now. In this study, we have developed a novel combined mechanism of a two-DOF magnetic bearing and a contactless torque transmission with a simply-structured magnet-less rotor for an extracorporeal CBP.

Principle of a Proposed Magnetic Bearing and Contactless Torque Transmission

Figure 1 shows the configuration of the combined mechanism of a magnetic bearing and a contactless torque transmission, which is designed for extracorporeal CBPs. Only an iron ring with eight slots on inner surface functions as a levitating rotor, which is embedded in the single-use plastic impeller. In order to reuse the electromagnets for magnetic levitation and a magnetic coupling disk for rotation, these components are separated from blood by walls of the housing. Around the rotor, there are four C-shaped electromagnet cores. One side of each of the electromagnet cores faces an outer surface of the rotor, and the other sides are connected with each other below the rotor.

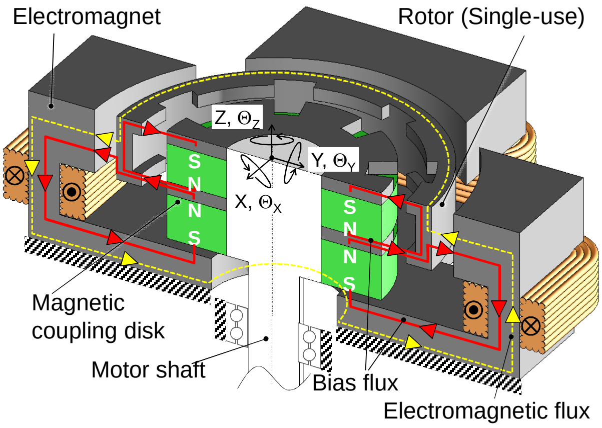

Fig. 1 Configuration of the magnetic bearing and torque transmission mechanism

Two iron rings with eight slots on an outer surface and two axially-magnetized permanent magnets are interlaminated. These parts compose the magnetic coupling disk, which is connected to a motor shaft. The permanent magnets generate a bias magnetic flux between the magnetic coupling disk, rotor, and electromagnet. Due to the negative stiffness, the rotor motion in the radial directions should be actively controlled to avoid contact. Figure 1 indicates that the electromagnetic flux generated by applying the coil current weakens the bias flux on the right-hand side, while the bias flux is strengthened on the opposite side. As a result, the electromagnet generates a driving force on the rotor. In order to convert the current to the electromagnetic force effectively, the path of the electromagnetic flux does not contain the permanent magnets, which have almost the same reluctance as the air. As shown in Fig. 2, restoring force and torque generated by the bias flux passively support the rotor motion in the axial and tilt directions.

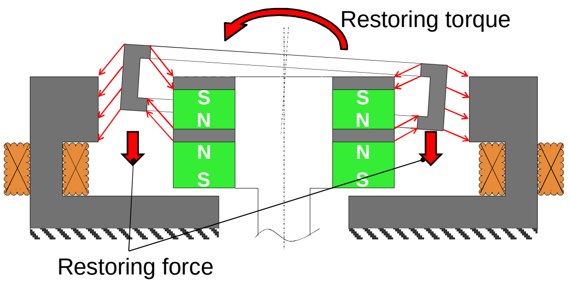

Fig. 2 Principle of the passive support

When the magnetic coupling disk is rotated by an external motor, misalignment between the slots of the rotor and magnetic coupling disk generate restoring torque on the rotor around the rotational axis. Consequently, the motor torque is transmitted to the rotor. This restoring torque is called the transmitted torque.

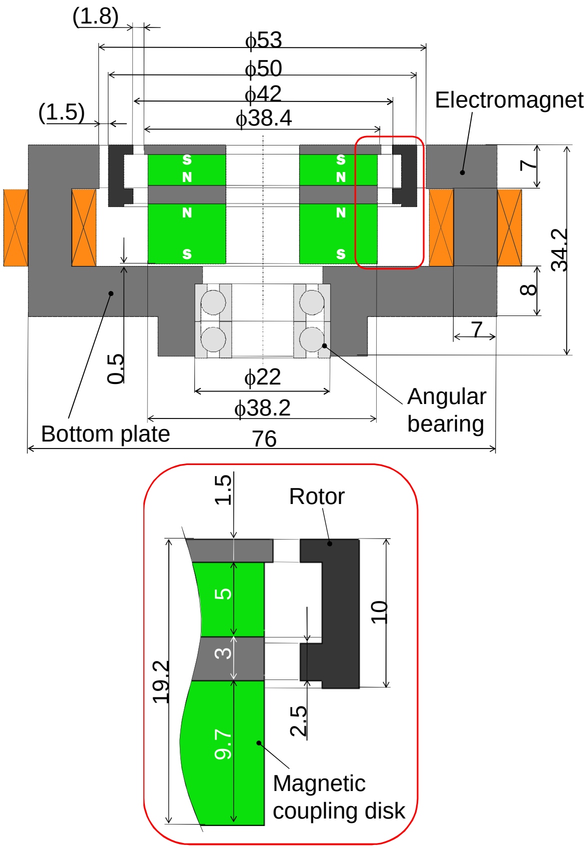

Fig. 3 Dimensions of the magnetic bearing

Design and Fabrication

Magnetic Bearing and Torque Transmission. In a previous study, we have developed another type of two-DOF controlled MagLev CBP [4,5] with a permanent magnet in the rotor. The passive stiffness of the magnetic bearing was 53.5 N/mm and 9.82 Nm/rad in the axial and tilt directions. Results of the excitation tests showed that the impeller could maintain contactless levitation against an impulse base excitation of 200 m/s^2, without filling fluid in the pump head. In the in vivo studies with calves, the impeller could levitate stably under the pulsation of the heart of the calves or disturbance force generated by the movement of the calves. Therefore, the stiffness of the previously proposed MagLev CBP with a permanent magnet in the rotor is sufficient for the extracorporeal circulation support. Hence, a proposed magnetic bearing without a permanent magnet in the rotor was designed so that the passive stiffness can attain almost the same level as that of the MagLev CBP with a permanent magnet in the rotor.

Figure 3 shows designed dimensions of the proposed magnetic bearing and the torque transmission mechanism. The gaps between the electromagnet and rotor and between the rotor and magnetic coupling disk were 1.5 mm and 1.8 mm, respectively. The gaps are required to accommodate a pump housing having wall thickness of the sufficient strength and to provide sufficient fluid clearances in order not to destroy blood cells. The gap between the magnetic coupling disk and a bottom plate of the electromagnet was 0.5 mm.

Since eliminating a permanent magnet in the rotor results in a decreased bias flux, an effort to maintain the bias flux is necessary. Therefore, by facing the same pole of the permanent magnets in the magnetic coupling disk, a strong magnetic coupling is generated in the gap between the bottom side of the rotor and the magnetic coupling disk. According to magnetic field FEM analysis, the simulated passive stiffness in the axial and tilt directions were 52.8 N/mm and 8.25 Nm/rad, respectively. The simulated maximum transmitted torque was 0.014 Nm. Even though the rotor does not include any permanent magnets, the stiffness achieved could attain almost the same value as those of previous MagLev CBP [4] devices due to its unique magnetic circuit.

Control System of the Magnetic Bearing. A pole placement compensator was utilized to control the radial motion of the rotor because the rotor motion was intrinsically unstable due to the negative stiffness. To compensate the imbalance of the bias flux or static external forces acting on the impeller, such as fluid force and gravity, the controller supplied a bias current to the electromagnet. The large bias current resulted in heat generation and the destruction of blood cells. In order to avoid this situation, a zero-power controller [6] was also used. The zero-power controller regulated the impeller position such that the attractive force by the bias flux and static external force were balanced. As a result, the bias current of the electromagnet was eliminated and the heat generation was decreased.

Extracorporeal MagLev CBP. As shown in Fig. 4, the proposed extracorporeal MagLev CBP was divided into a reusable unit and the single-use pump head. The reusable unit consisted of the electromagnet, magnetic coupling disk, eddy current displacement sensors for feedback control, and external motor (EC45flat50watt, maxson motor ag). Although the number of controlled DOF of the rotor was two (radial directions), differential output signals from the four displacement sensors were referred to reduce the effect of temperature drift and electromagnetic noise. The outer surface of the rotor functioned as a sensor target.

The single-use pump head with the impeller of 50.6 mm in diameter was easily inserted into the reusable unit. The shape and dimensions of the pump head were the same as those of the previously tested MagLev CBP presenting low blood damage [5]. The fluid clearance of 0.3 mm in width was the narrowest path through which blood flowed.

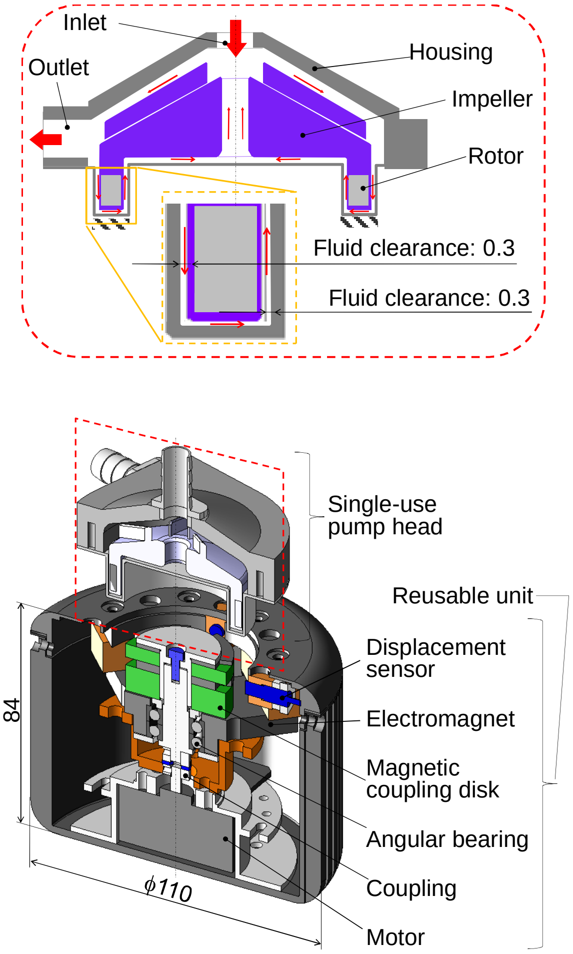

Fig. 4 Configuration of the proposed CBP

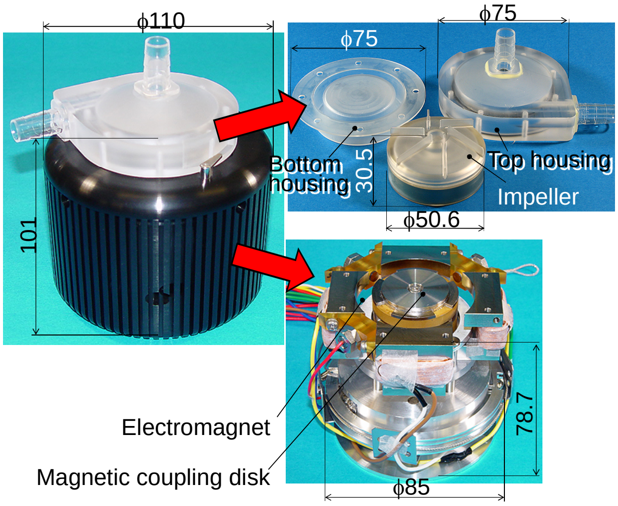

Fig. 5 Photographs of the prototype pump

Figure 5 shows photographs of a prototype MagLev CBP. Material of the impeller and pump head housings was

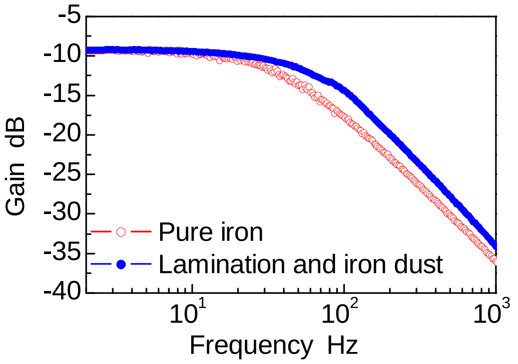

Fig. 6 Frequency response of the electromagnet from voltage to flux

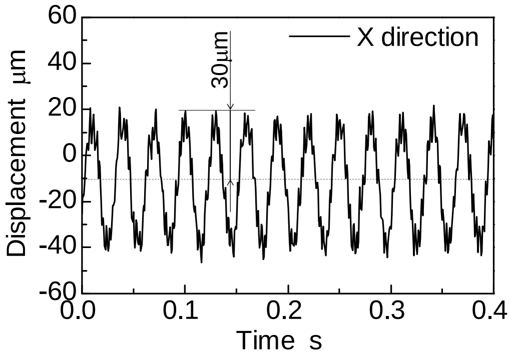

Fig. 7 Impeller displacement in 40 % glycerol water at 2000 rpm

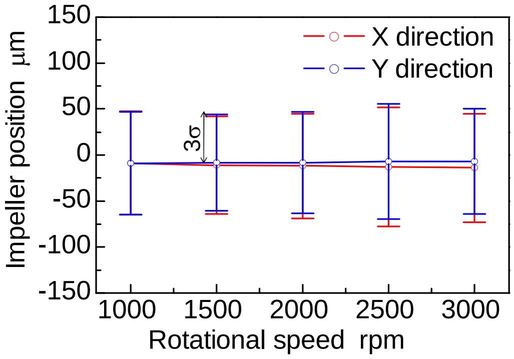

Fig. 8 Impeller position in 40 % glycerol water solution

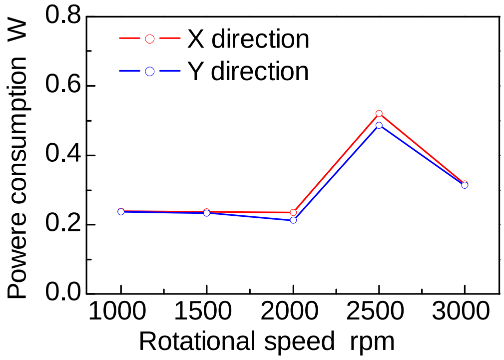

Fig. 9 Power consumption of the magnetic bearing

polycarbonate, being commonly used in medical products. The rotor and soft magnetic material of the magnetic coupling disk were made of pure iron. Two types of the electromagnet core were manufactured; one was made of pure iron and the other was made of laminated steel and iron powder [7] in order to compare the frequency characteristics.

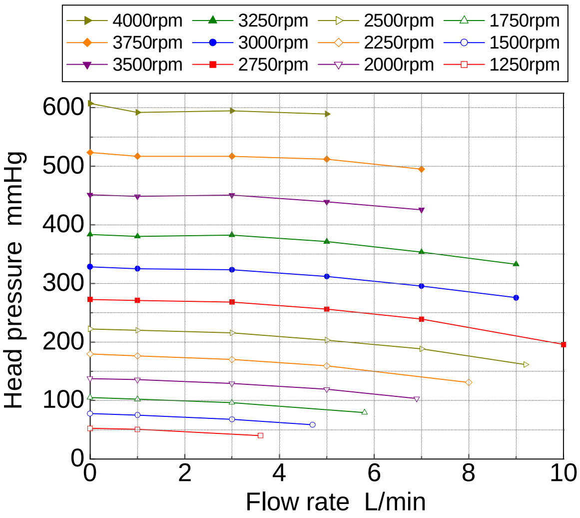

Fig. 10 Pressure flow characteristics

Results

Bandwidth of the Electromagnets. As shown in Fig. 6, the frequency responses of the two types of the electromagnets were measured with the impeller levitated. Note that the input signal of the response is voltage and the output is the electromagnetic flux, which was measured with a search coil wound around the electromagnetic core. The bandwidths of the electromagnet made of pure iron and that made of laminated steel and iron powder were 40 Hz and 62 Hz, respectively. Reducing the effects of the eddy current, the electromagnet made of laminated steel and iron powder achieved a 22 Hz higher bandwidth than that made of pure iron. Hence, in the following experiments, the electromagnet core made of laminated steel and iron powder was utilized.

Rotational Accuracy and Power Consumption of Magnetic Bearing. The rotational accuracy of the impeller and the power consumption of the magnetic bearing were measured. The working fluid filled in the pump head was 40 % glycerol water solution, the viscosity of which was the same as that of human blood. Figure 7 shows the impeller displacement at 2,000 rpm. The oscillation amplitude in the X direction was 30 μm, being adequately small, with respect to the fluid clearance of 300 μm. Figures 8 and 9 show the impeller position in the radial directions and power consumption of the magnetic bearing against rotational speeds. The impeller levitated stably and maintained contactless rotation through the measurement. The total power consumption was within 1 W, being superior to the previously tested MagLev CBP [4]. Precise assembly of the impeller due to elimination of a permanent magnet may contribute to reducing the unbalance force and the saving in power consumption.

Pressure Flow Characteristics. For extracorporeal blood pumps, pressure flow performance of a flow rate of 5 L/min against a head pressure of 250 mmHg (33.3 kPa) is commonly required in clinical uses. To evaluate the pressure flow characteristics, the prototype pump was connected to a simple mock circulatory loop consisting of a soft reservoir and a resistance element. The working fluid was 40 % glycerol water solution. Figure 10 shows the measured pressure flow characteristics. The prototype pump could yield a flow rate of 5 L/min against a head pressure of 590 mmHg (78.7 kPa), which was more than double the required performance.

Conclusion

In order to realize high durability, low blood damage, a cost-effective single-use pump head and high reliability, a magnetic bearing with a magnet-less rotor was proposed for an extracorporeal CBP. Even though a permanent magnet was not used in the levitating rotor, the magnetic bearing realized almost the same passive stiffness as previous models with a permanent magnet in the rotor. A prototype pump realized stable levitation of an impeller and sufficient pressure-flow characteristics for extracorporeal circulation support. Since a single-use pump head does not contain any permanent magnet, the proposed CBP offers a considerable advantage in low-cost mass production with high precision compared to conventional CBPs.

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