A Disposable Magnetic Bearing System for an Extracorporeal Centrifugal Blood Pump

Taichi Mamiya # 1*
Tokyo Institute of Technology
Yokohama, Japan

Wataru Hijikata #2
Tokyo Institute of Technology
Yokohama, Japan

Tadahiko Shinshi #3
Tokyo Institute of Technology
Yokohama, Japan

Abstract

In order to increase the design flexibility of the rotor/impeller in an extracorporeal maglev centrifugal blood pump and realize a magnet-less disposable pump head, a novel combination of a radial magnetic bearing and a magnetic coupling disk for transmitting the rotational torque from the motor, which surrounds the disposable magnet-less rotor/impeller, is proposed. The magnetic bearing system actively controls the radial motion of the rotor/impeller and passively controls motion in the other directions. Contactless stable levitation and rotation of the rotor at speeds from 0 to 3,200rpm were realized with a bearing system fabricated for a 50mm diameter rotor.

1 Introduction

Mechanical circulation support using a blood pump is the only means of survival for the most severe heart failure patients. For periods of up to a few days, an extracorporeal centrifugal blood pump (ECBP) is commonly used. An important feature of an ECBP is that its pump head, which consists of a rotor/impeller and a pump housing, is disposable, whereas other parts such as the 'motor and controller consoles' are designed to be reusable in order to achieve cost effective circulation support.

The requirements for next-generation disposable ECBPs, which can be used for "Bridge (ECBP) to Transplant", "Bridge to Recovery", or "Bridge to Bridge (Implantable ventricular assist device)" applications, are (1) sufficient durability of the disposable pump head for up to a few months, (2) lower thrombus formation and lower hemolysis than those of conventional short-term ECBPs, and (3) availability of a cost-effective disposable pump head.

Contactless support and rotation of the rotor/impeller using a magnetic bearing (MB) and a non-contact torque transmission mechanism (TTM) are key technologies needed to satisfy the requirements of durability of the disposable pump head and low blood damage[1]. Until now, the 'CentriMag' developed by Levitronix has been the only commercialized magnetically-levitated (MagLev) ECBP with a disposable pump head [2], and it has shown good clinical results [3]. However, an expensive rare earth magnet is invariably used in the disposable pump head. Apart from the CentriMag, our group has developed a disposable MagLev ECBP [4, 5], and this has exhibited good biocompatibility in both in-vitro and in-vivo animal experiments [6, 7]. Furthermore, a MagLev ECBP utilizing a magnet-free disposable impeller has also been developed [8].

The Maglev ECBP utilizing the magnet-free disposable impeller consists of a radial MB and a TTM. The radial MB, which is placed on the outer periphery of the impeller/rotor, actively controls the radial motion of the rotor/impeller and passively controls the motion in the other directions. The TTM, on the other hand, is on the inside of the rotor. Due to this configuration, shown in Fig. 1(a), the secondary blood flow from the outer gap between the rotor/impeller and the MB stator to the washout hole at the center of the impeller in the pump head is not smooth. This complex flow path might possibly give rise to thrombus formation and hemolysis. A solution that reduces this possibility is to arrange for both the MB stator and the TTM to be on the outer periphery of the rotor/impeller and thereby generate a smooth secondary flow as shown in Fig. 1(b).

1* Contact Author: shinshi@pi.titech.ac.jp, 4259 R2-38 Nagatsudacho, Midoriku, Yokohama, 226-8503 Japan

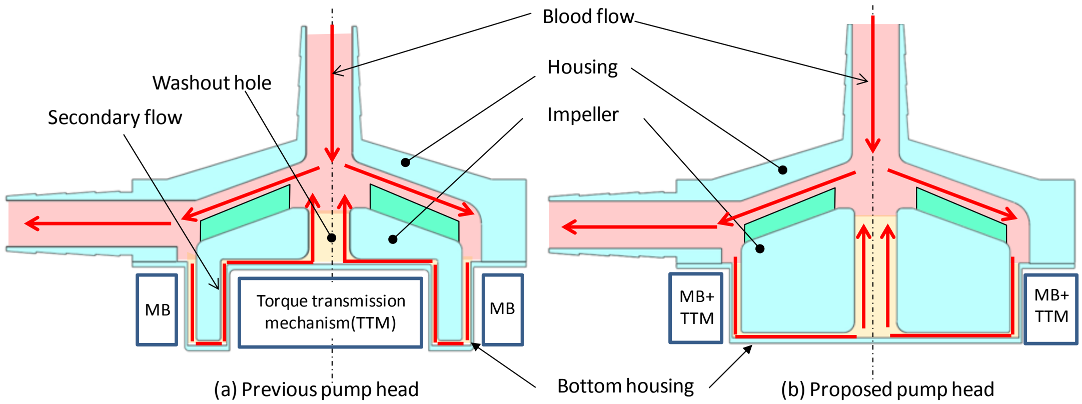

Figure 1: Disposable pump heads and the locations of the magnetic bearing and torque transmission mechanisms

The purpose of this study is to develop a novel combination of a radial MB and a TTM that can be placed outside the rotor/impeller to obviate the need for a permanent magnet.

2 Magnetic bearing using a disposable magnet-less rotor

2.1 Mechanism

Figure 2 shows the configuration of the proposed disposable maglev ECBP. The center part is a disposable pump head consisting of a magnet-less rotor/impeller, and the pump housing. The pump head can be detached for replacing it with new ones. The rotor/impeller is supported without contact by a magnetic coupling disk and is radially controlled by an electromagnet. The torque to rotate the rotor/impeller is transmitted from the motor to the magnetic coupling disk by spur gears.

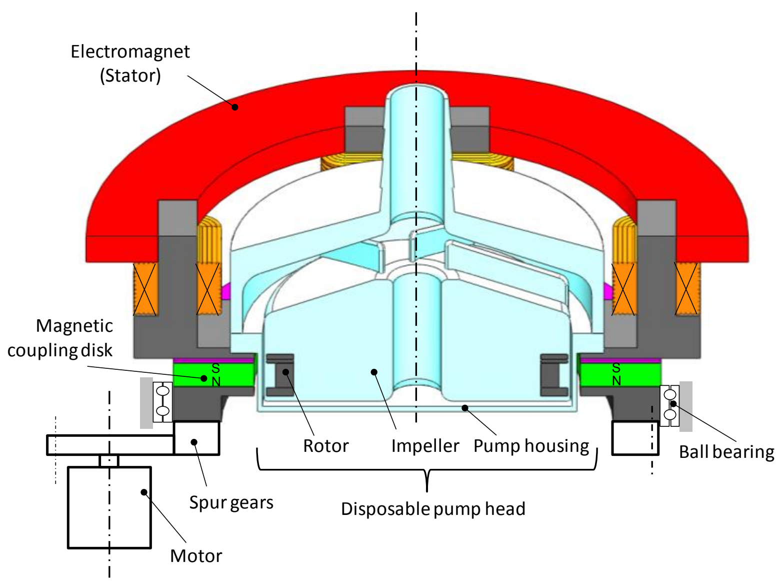

Figure 2: Proposed disposable maglev pump system

Figure 3 shows an exploded view of the proposed disposable maglev pump system without the impeller and the pump housing. The rotor has a four layer structure of iron rings, A to D. In the prototype rotor, the three rings A, B and C are machined as one part. The magnetic coupling disk, which is supported by a ball bearing and is driven by the motor, consists of a permanent magnet ring sandwiched between two iron rings with slots in them. Four L-shaped iron cores, each with a coil, are connected using an iron ring. These electromagnets form the stator of the MB.

2.2 Principle of levitation and rotation

The concept of this MB is to reduce the number of controlled DOFs in order to simplify the structure and to eliminate permanent magnets from the disposable parts so that a cost-effective solution for use with a disposable pump-head can be made feasible. However, since eliminating the permanent magnet from the impeller results in a decreased bias flux, it is necessary to maintain the bias magnetic flux for stable and robust magnetic levitation.

Between the magnetic coupling disk and the rotor, strong bias flux loops are generated. Theses bias magnetic fluxes passively support the axial and tilt motions of the rotor as shown in Fig. 4(a) and (b) as well as transmitting the motor torque to the rotor via the magnetic coupling disk as shown in Fig. 4 (d). The radial motion of the rotor/impeller should be positioned using feedback control because the magnetic coupling generates a negative stiffness in the radial direction. The upper bias flux loop between the magnetic coupling disk and the rotor are varied by a magnetic flux generated by the electromagnets as shown in Fig. 4 (c) and a radial force is generated due to the imbalance between the magnetic fluxes in the bearing clearances.

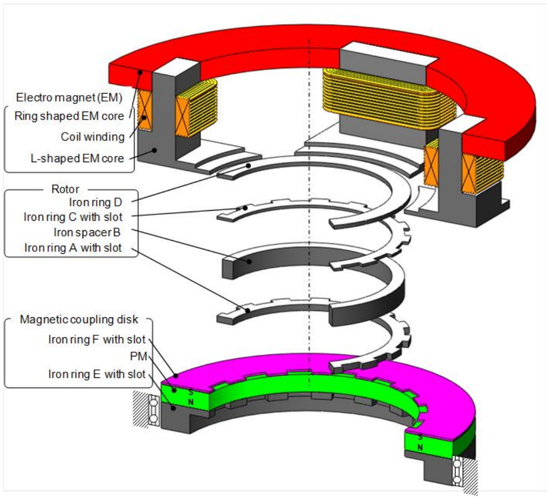

Figure 3: Configuration of the magnetic bearing and the torque transmission mechanism

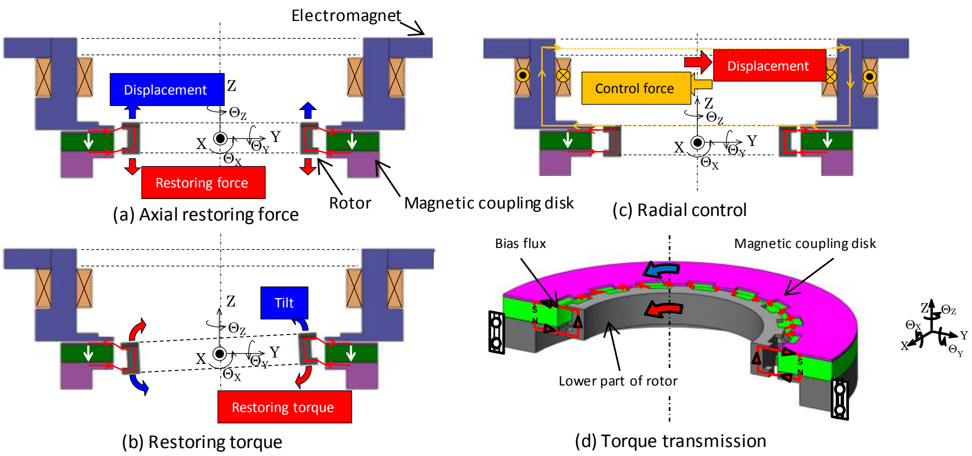

Figure 4: Principle of magnetic suspension and torque transmission

3 Design and Fabrication

The dimensions of the radial MB and the magnetic coupling disk were analyzed using magnetic analysis software (Maxwell 3D ver. 14.0, Ansys Inc.) to achieve the same levels of axial stiffness, tilt stiffness and maximum torque transmission obtained with previously designed maglev ECBPs that have been tested and found to be successful in animal tests[6,7]. The final dimensions and material of each mechanical part are summarized in Fig. 5. The simulated axial and tilt stiffnesses and the maximum torque transmission of the designed pump are 42.5N/mm, 10.6 Nm/rad and 0.097Nm, respectively, which are each more than 80% of those of previous ECBPs. These MB and TTM designs can also achieve the same fluid clearances as those of the previous maglev ECBP when they are applied to the new ECBP.

The fabricated test rig for the MB and TTM without the impeller and pump housing is shown in Figure 6. To evaluate the possibility of the noncontact levitation and the rotational accuracy of the rotor, its motion in six degrees of freedom were measured simultaneously using eddy current type displacement sensors.

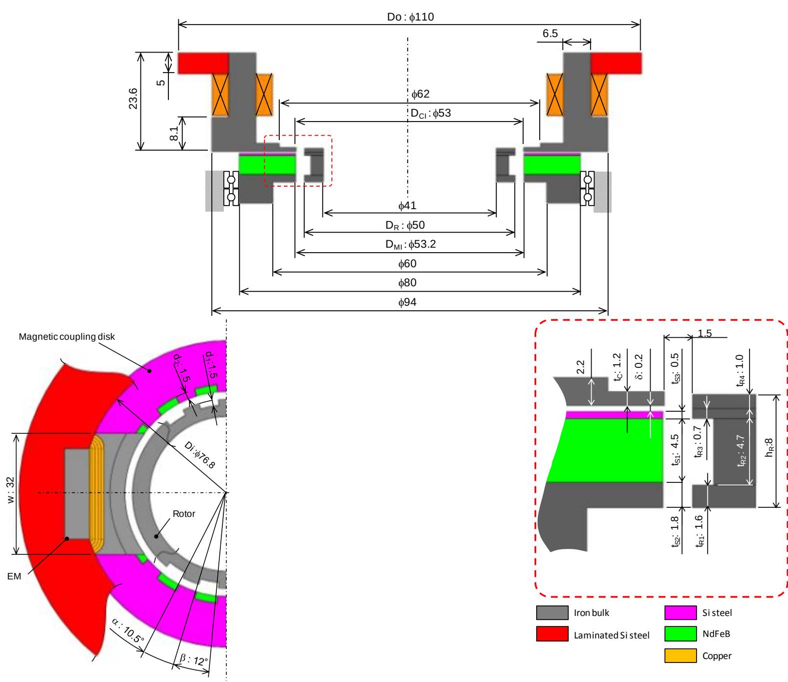

Figure 5: The dimensions of the designed magnetic bearing and the magnetic coupling disk

4 Experimental results

The performance of the MB was evaluated without blood or any liquid in the pump housing. In order to confirm contactless levitation of the rotor, the rotor position and rotational accuracy in all DOFs except the rotational direction were measured. Levitation of the experimental rotor was achieved utilizing radial motion feedback control.

The response of the rotor at startup is shown in Figure 7. Although the rotor was in contact with the housing wall before the control was initiated, it settled immediately and stabilized at the geometrical centre of the housing after the control was started. In the axial and tilt directions the rotor exhibits low damping characteristics compared with the transient responses in the radial directions due to the passive support utilizing the magnetic coupling alone. The damping usually improves when the pump housing is filled with blood or any liquid [9]. The measured stiffness from these damping oscillations and the simulated ones are compared in Table 1 and the errors between them are less than 10%. As shown in Figure 8, the vibration amplitude is sufficiently small compared with the designed radial and axial clearances of 0.3mm and 1.0mm, respectively.

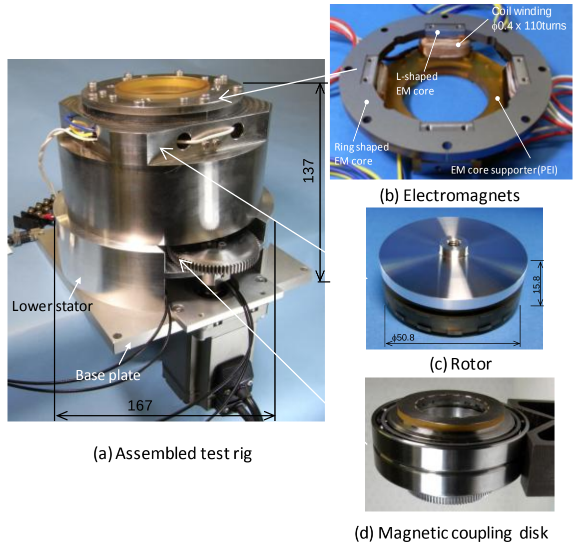

Figure 6: Photographs of the assembled test rig and its parts

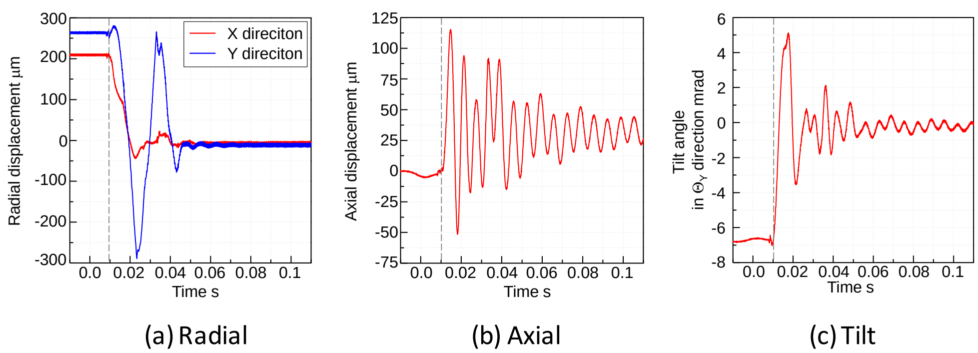

Figure 7: Rotor displacement at start up

Table 1:Passive stiffness of the magnetic bearing

	Simulated	Experimental
Stiffness in the axial direction K_z	42.4N/mm	45.1N/mm
Stiffness in the tilt direction K_θ	10.6Nm/rad	11.6Nm/rad

5 Conclusion

In order to increase the design flexibility of the rotor/impeller in an extracorporeal maglev centrifugal blood pump and realize a magnet-less disposable pump head, a novel combination of a radial magnetic bearing and a magnetic coupling disk for transmitting the rotational torque from the motor, which surrounds the disposable magnet-less rotor/impeller, is proposed. Even though a permanent magnet is not used in the levitated rotor, almost the same passive stiffness is realized for the MB as that observed in previous models using a permanent magnet in the rotor/impeller. The measured stiffness in each of the passively controlled directions is almost the same as in the simulated design. Stable levitation and rotation up to 3,200 rpm were achieved with the MB and the TTM. In future work, the combination of the MB and the TTM developed here will be applied to an ECBP.

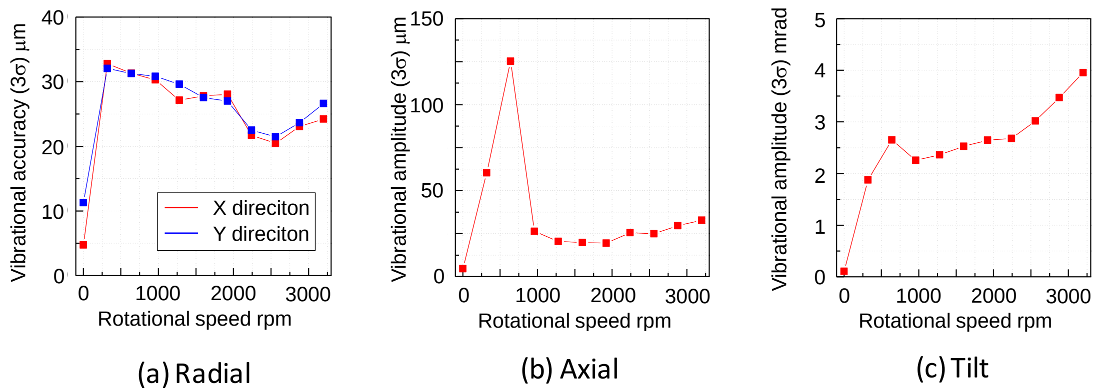

Figure 8: Rotational vibration

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