Fault-Tolerance for a Centrifugal Blood Pump using a Two-DOF Controlled Magnetic Bearing

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Abstract: In our laboratory, an implantable centrifugal blood pump (CBP) with a two degrees-of-freedom controlled magnetic bearing (MB) to support the impeller without contact has been developed to assist the pumping function of a weakened heart ventricle. In order to maintain the function of the CBP after damage to the electromagnets (EMs) of the MB, fault-tolerant strategies for the CBP are proposed in this study. Using a redundant design of the MB, the magnetic levitation of the impeller was maintained with damage to up to two out of a total four EMs of the MB. Furthermore, with damage to three EMs, contact-free support of the impeller was also achieved by using hydrodynamic and electromagnetic forces.

Keywords: Magnetic Bearing, Centrifugal Blood Pump, Fault-Tolerance

Introduction

Patients with severe heart failure need to have a heart transplant. However, due to the lack of heart donors, not all patients are able to have a transplant. To solve this problem, implantable ventricular assist systems comprising a centrifugal pump (CBP) with a magnetically levitated (maglev) impeller to pump the blood have been developed.

Because of the contact-free support of the impeller, maglev CBPs have a lower level of damage to blood cells, lower risk for blood clot formation and higher durability, compared with CBPs with contact bearings. However, a magnetic bearing (MB) is an unstable system, and damage to one of the components of the MB system, such as the coils of the EMs or the displacement sensors of the feedback systems, due to the shock and vibration during long-term implantable use, may lead to failure of the noncontact levitation and rotation of the impeller. Therefore, in order to maintain magnetic levitation where damage to the components of the MB system has occurred, fault-tolerant strategies for maglev CBPs are required. One of the possible strategies is redundancy design of the MB [1]. The other option is the use of a backup hydrodynamic suspension system for levitation of the impeller [2].

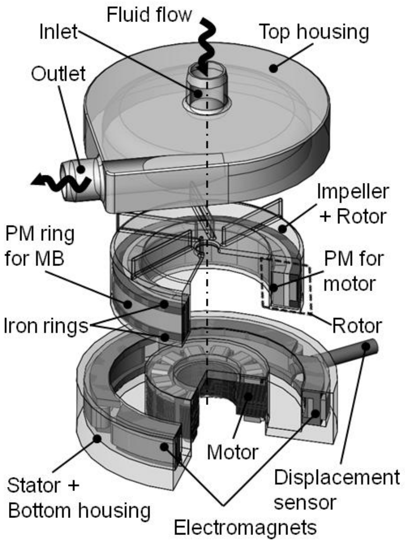
In our laboratory, an implantable CBP with a two degrees-of-freedom MB to support the impeller has been developed [4, 5], as shown in Fig. 1. In this study, we focused on the damages to the EMs of the MBs and fault-tolerant strategies for the implantable maglev CBP are proposed. The performance of the maglev CBP is evaluated experimentally.

MagLev CBP

The maglev CBP used in this study has a hybrid radial MB. Figures 1 and 2 show that the rotor of the MB is comprised of a sandwich of two iron rings and a permanent magnet (PM) ring, which is magnetized axially. The biased magnetic flux from the PM ring produces a closed magnetic coupling between the rotor and the four cores of the electromagnets surrounding the rotor, and the control magnetic flux is generated by regulating the current in each pair of EMs. The association of both magnetic fluxes is responsible for the generation of the radial magnetic push-pull force for controlling the radial motion of the impeller.

The control magnetic flux leaves the core of the EM on the left hand side, passes through the top iron ring, reaches the core of the EM on the right hand side, and returns to the core of the EM on the left hand side through the bottom iron ring. Since there are two coils that can generate the same magnetic flux, there is a redundancy in this design of MB.

The axial and angular motions of the rotor are passively supported by the magnetic coupling between the PM ring and the cores of the EMs. The built-in motor is comprised of a Halbach permanent magnet array attached to the inside surface of the rotor and a motor stator.



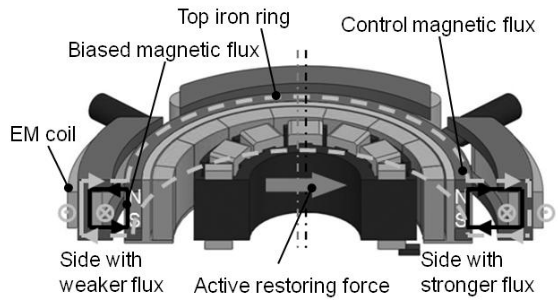


Fig. 1 *Configuration of the implantable Maglev CBP* ***Fig.2*** *Configuration of the MB and the motor*

Fault-Tolerant Strategy

Damage to the One EM in Each Pair of EMs. With damage to one EM in each pair of the EMs, magnetic levitation of the impeller is theoretically possible. The reason is that the same path for the control magnetic flux can be generated by the remaining EM. To achieve the fault-tolerance, each EM is powered by an independent power amplifier in Fig 3(b). Fig. 3(a) shows the conventional electrical connection of the maglev CBP which can't be used with damage to one EM in each pair of EMs.

Moreover, at a startup, a positioning controller in X direction is activated with a delay compared with the one in the Y direction. This is because the start-up instant is when the maximum current is required and the current is much larger than that without damage to the EM. By powering the EMs with a delay, the required current is decreased, which can be supplied by a conventional power source. This fault-tolerant method is evaluated measuring the currents of the EMs and the vibration of the impeller at a startup or during a rotation.

Damage to the One Pair of Active EMs. In a fluid environment, with rotation of the impeller, the radial stiffness is increased due to the presence of the wedge effect in the lateral fluid gap, caused by the whirling motion of the impeller, as in hydrodynamic bearings. Besides, the flow through the asymmetrical position of the pump outlet generates radial thrust acting on the maglev impeller. Therefore, by considering the relationship between the position of the pump outlet and the pair of active EMs, in order to generate an electromagnetic force to cancel the radial thrust, and by using the increased radial stiffness to cancel the negative stiffness of the MB, contact-free support of the impeller may be possible when there is damage to one pair of EMs.

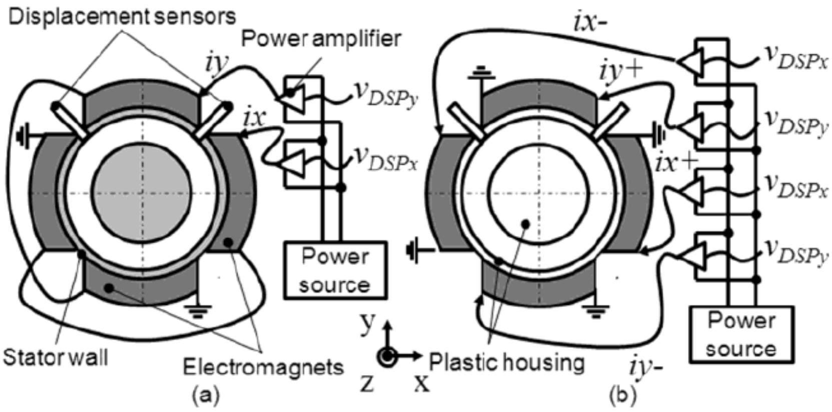


Fig. 3 Wirings among EMs, power amplifiers and power source

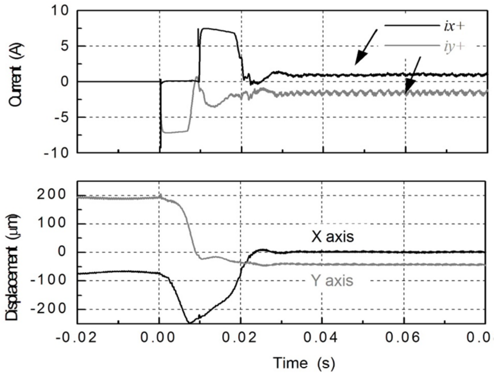
Experimental Setup

For experimental simplicity, this prototype was made of plastic housing: PEI plastic for the stator and acrylic plastic for the impeller and the top housing. The rotor comprises sixteen pieces of PMs in a Halbach array configuration, consisting of four N poles and four S poles pointing radially inward. The motor stator has twelve teeth with three phase winding. The impeller is 51 mm in diameter and 0.077 Kg in mass. The lateral fluid gap, between the impeller and the stator, is 0.25 mm. The maximum flow rate provided by the maglev CBP is 7.5 l/min, against a head pressure of 130 mmHg.

A simple mock circulatory loop comprising a reservoir, two pressure sensors, a flow meter and a screw clamp providing variable flow resistance, was used to evaluate the MB performance with rotation of the impeller. Pure water was used instead of blood. The rotational speed and the flow resistance were adjusted to achieve the pump operating point.

Experimental Results

Damage to the one EM in Each Pair of EMs. Figure 4 shows the displacements of the impeller and the currents of the coils at a startup, experimentally simulating the damage to one EM in each pair of EMs**.** A stable levitation was achieved, the peak currents are acceptable within the limitation of the power source and the amplitude of the residual vibration of the impeller (± 9 μm) is small, compared with a fluid gap of 250 μm. Figure 5 shows that the impeller was levitated without contact and rotated at 1700 rpm, achieving the pump operating point of 5 l/min against 100 mmHg, however, the vibration of the impeller and the current level of the EMs are higher than those without the damage.



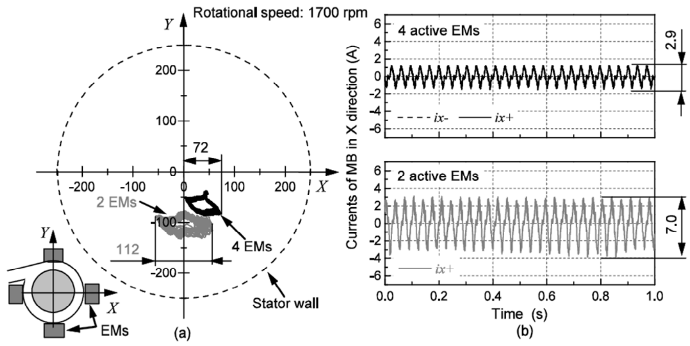


Fig. 4 *Startup characteristics of the impeller* ***Fig.5*** *Impeller trajectory* with damage to the one EM

Damage to the One Pair of Active EMs. For the initial condition, the impeller was levitated using one EM in each pair of EMs, as discussed in the previous experiment. During the rotation, one of the active EMs was deactivated. This experiment was repeated using one remaining active EM in the Y and then in the X direction. During these experiments, the positional relation between the pump outlet and the active EM is shown in Fig. 6. When the remaining active EM was located in the Y direction, touch-down of the impeller occurred, as shown in Fig. 6. However, when the remaining active EM was located in the X direction, levitation of the impeller was maintained.

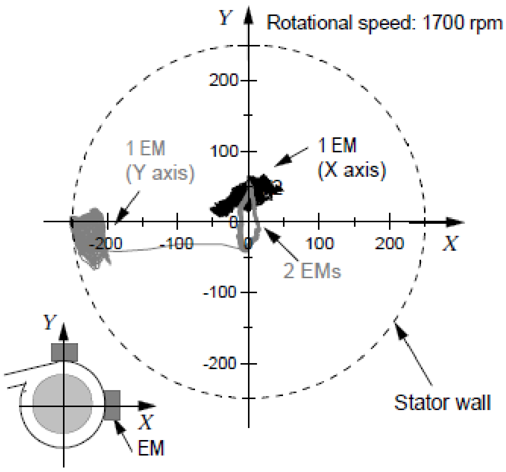


Fig.6 *Impeller trajectory before and after deactivation of one of two active EMs*

Discussion and Summary

Fault-tolerant strategies for using an implantable CBP with the two degrees-of freedom controlled MB, in case where there is damage to some of the EMs of the MB, were proposed. Where there is damage to one EM in each pair of EMs, the parallel redundancy design of the maglev CBP is able to maintain magnetic levitation of the impeller.

Non-contact support of the impeller using only one active EM, aligned with the direction of the pump outlet, was achieved. This is because of the presence of increased radial stiffness, due to the flow inside the pump, which canceled the negative stiffness of the MB.

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