Bearingless Slice Motors with PM-free Rotor for Disposable Centrifugal Blood Pumps

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Abstract

The principle, prototyping, and performance evaluation of two novel bearingless slice motors (BELSMs) designed for disposable centrifugal blood pumps are presented. Both BELSMs do not use permanent magnets in the rotor of the pump housing, thus reducing the cost of disposable components. One BELSM has twelve shared coils for rotation and magnetic levitation. The BELMS achieves passive stiffness in the axial and tilting directions using magnetic coupling generated in the axial direction. The stator structure is relatively simple but requires twelve amplifiers to drive the coils independently. The other BELSM has three-phase coils for rotation, two-phase coils for magnetic levitation, and magnetic couplings formed radially. The three-phase amplifier can drive the motor coils, and the two single-phase amplifiers can drive the suspension coils, simplifying the power circuit, but the stator structure is complex. A centrifugal pump was realized using the former BELSM. The maximum flow rate was 4.3 L/min, which was insufficient for the 5 L/min required for a blood pump. Due to the coil's large inductance and the amplifier performance limitation, it could not reach sufficient rotation. In the second BELSM, the pump's maximum torque and maximum speed have obtained the values required to achieve the target flow and pressure of the blood pump.

Keywords: *Bearingless motor, Centrifugal blood pump, Disposable rotor, Magnetic coupling*

1. Introduction

Centrifugal blood pumps are used in the treatment of acute heart failure and as a short- and mid-term bridge to heart transplantation or an implantable artificial heart. Recently, ECMO (Extracorporeal Membrane Oxygenation) systems consisting of an artificial lung and a centrifugal blood pump have been used to treat severe pneumonia caused by COVID-19. Centrifugal blood pumps with non-contact bearings have been developed to avoid hemolysis and thrombosis and improve durability for long-term use.

Centrimag^{TM} is the world's first extracorporeal centrifugal blood pump equipped with a bearingless slice motor (BELSM) (Gruber, et al., 2016). It is used for circulation support (John, et al., 2007) and ECMO therapy (Azziz, et al., 2010). The impeller of the Centrimag^{TM} is magnetically levitated and rotated with a slice rotor, featuring radial feedback control, passive support in the axial and tilt directions, and rotation by rotor-stator cores integrated with magnetic bearing and motor functions. The rotor, impeller, and pump housing are disposable for each patient in these centrifugal pumps for extracorporeal circulation. The rotor of Centrimag^{TM} is composed of a neodymium ring magnet.

A magnet-free rotor is required to reduce the cost of the disposable part. In the research on bearing slice motors, reluctance motor-type ones without a permanent magnet in the rotor have been studied (Gruber, et al., 2017) (Noh, et al., 2019). We are developing BELSMs for extracorporeal centrifugal blood pumps that do not use magnets in the rotor. The initial prototype was designed using a coil that generates a magnetic bias flux to cause tilting and passive axial stiffness. The power consumption for generating the magnetic bias flux was not acceptable for clinical use (Rao, et al., 2015).

We are developing two other BELSMs with permanent magnets on the stator side to reduce power consumption and form magnetic couplings. This paper presents the structure, magnetic levitation, and rotation performance of those BELSMs with a permanent magnet-free rotor and its pump performance when applied to a centrifugal pump.

2. Methods

Two types of BELSM structures (Type A and Type B) based on reluctance motors are proposed. Both rotors have central teeth and upper and lower flanges. These magnetic flux bias paths of the magnetic couplings that form the restoring force and restoring torque in the axial and tilting directions are different. In Type A of Fig. 1, permanent ring magnets magnetized in the thickness direction are placed on the upper and lower surfaces of the stator teeth tip, respectively. The magnets generate the axial magnetic flux flow. The principle of restoring torque generation is shown in Fig. 1. The radial bias flux is varied using coils wound on each tooth of the stator to provide radial force for stabilization. The torque to rotate the rotor is generated by changing the circumferential magnetic flux distribution by the coils.

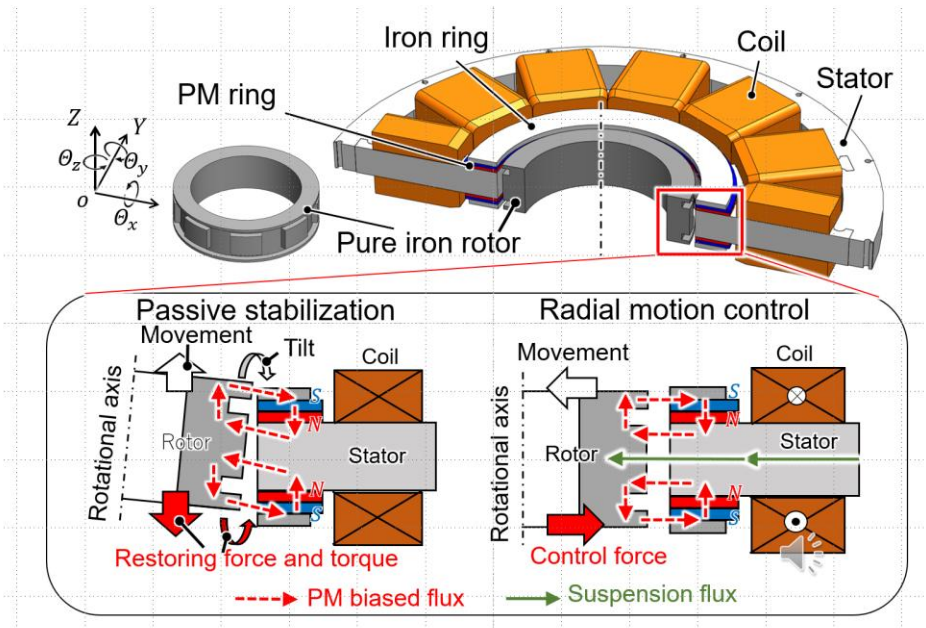

Figure 1 Type A BELSM having axial magnetic coupling and concentrated windings. The upper part is the configuration of the BELSM, lower part is passive and active suspensions (Shinshi, et al., 2018, Yang, et al. 2022)

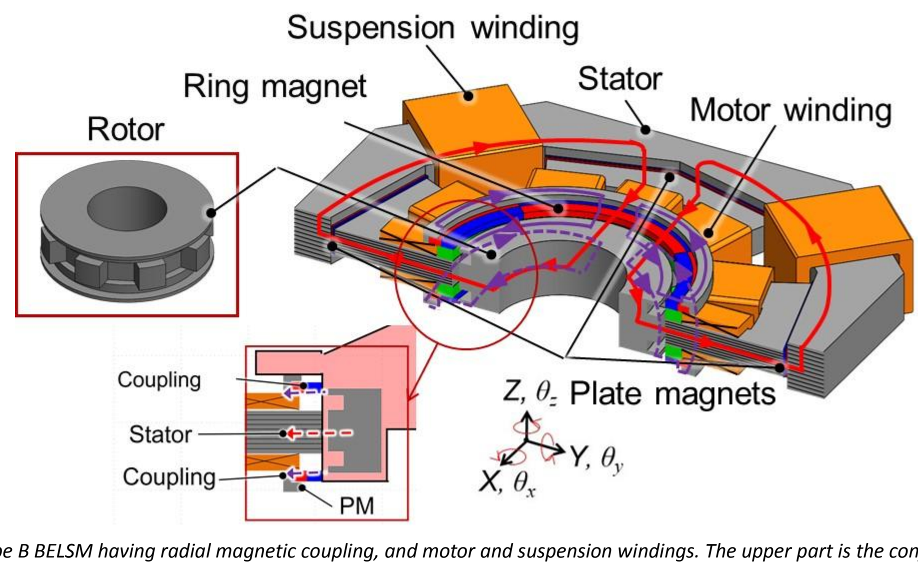

Figure 2 Type B BELSM having radial magnetic coupling, and motor and suspension windings. The upper part is the configuration of the BELSM, lower part is three-layered magnetic circuits (He, et al., 2022)

In Type B of Fig. 2, the magnetic coupling is formed in-plane by radially multipole magnetized ring magnets, generating restoring torque in the tilt direction and restoring force in the axial direction. To generate a magnetic bias flux in the magnetic motor circuit, plate magnets magnetized in the thickness direction are sandwiched between the inner and outer stator cores. Three layers of bias magnetic flux flow enhance the passive stiffness of the magnetic spring that supports the rotor.

Type B has advantages over Type A by separating the motor coils from the suspension coils. The inductance of one coil can be reduced, which lowers the drive output voltage of the amplifier. Another is that the number of amplifiers can be reduced. For example, if the stator has twelve teeth, Type A requires twelve independent single-phase amplifiers to apply independent currents to all coils. Type B also has twelve motor coils, but they are in sets of four and can be driven by a three-phase amplifier. The four coils for magnetic levitation can also be used in pairs, so only two single-phase amplifiers are required. The two types of BELSMs were designed using magnetic field analysis under the following requirements: rotor diameter of 50 mm, motor torque of 0.060 Nm or more, and bearing clearance of 1.5 mm. A centrifugal pump incorporating a Type A BELM is shown in Fig 3, and a Type B BELSM is shown in Fig. 4.

3. Results

Prototypes of Types A and B bearingless motors have been fabricated, and experiments on magnetic levitation and rotation have been successfully carried out, as shown in Figs. 3 and 4. The bearingless motor of Type A has already been integrated into a centrifugal pump, and measurements of flow rate and head pressure are in progress. The target rotation of 3000 rpm could not be reached, and the maximum flow rate was 4.3 L/min at 2300 rpm, which did not reach the minimum practical flow rate of 5 L/min. This is because the coil inductance is large, and the amplifier output voltage is insufficient to supply enough current to the coil at high-speed rotation.

Although the experiment was conducted outside the pump, a contactless rotation of 3000 rpm was successfully achieved for Type B. The experiment also confirmed that at 3000 rpm, a minimum of 0.06 Nm, which is the minimum required to drive the pump, can be generated. Type B BELSM will be integrated into centrifugal pumps and tested.

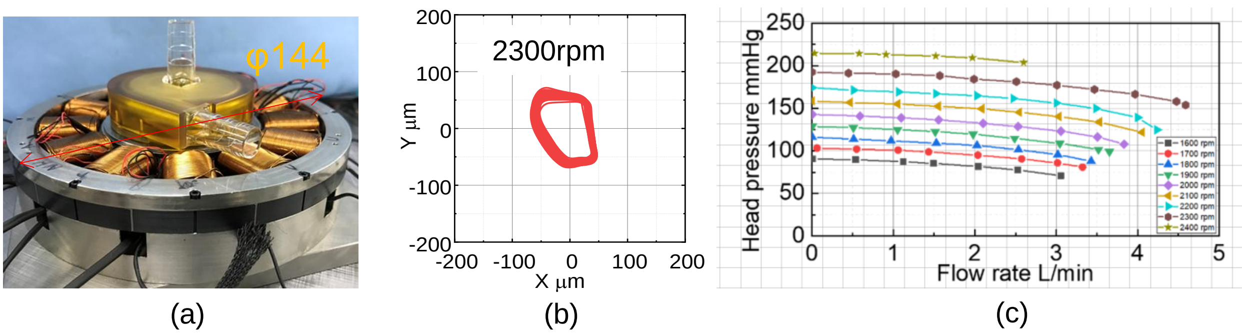

Figure 3 Fabricated Type A BELSM. (a) Prototype centrifugal pump incorporated with the BELSM, (b) Rotational accuracy at 2300rpm during a flow rate of 4.6 L/min, (c) HQ characteristics of the centrifugal blood pump.

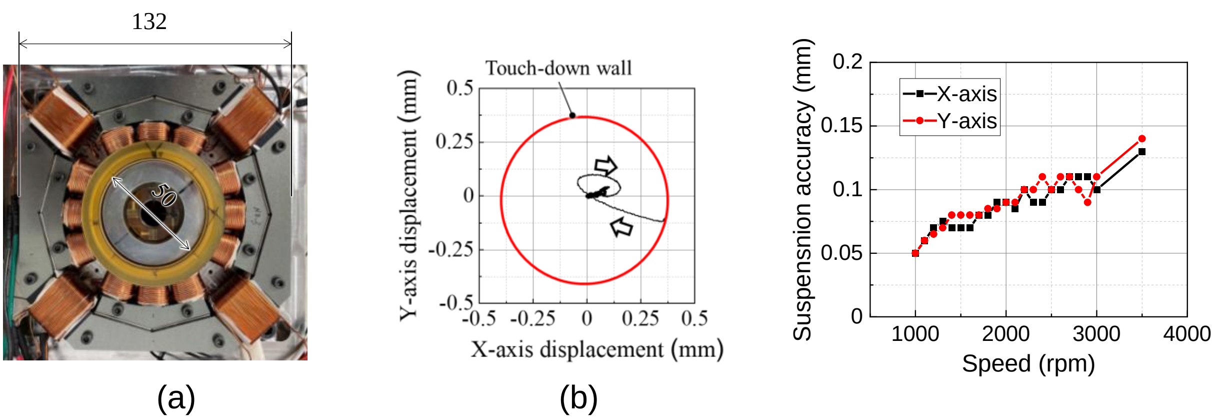

Figure 4 Fabricated Type B BELSM. (a) Prototype, (b)Start-up characteristics, and (c) Rotational accuracy levitating and rotating in the air.

4. Conclusion

The structures, prototypes, and performance of two BELSMs developed for disposable centrifugal blood pumps were presented. Both BELSMs used a rotor with only an iron core, without permanent magnets, to reduce the disposable part's cost. Both succeeded in magnetic levitation and rotation. However, the one with a simple stator structure, in which the suspension coil and motor coil were shared, had a large coil inductance, which caused problems in achieving high speed, and, when incorporated into a pump, did not achieve the pressure and flow rate requirements for a blood pump. The other type, in which the suspension and motor coils were separated, has a more complex stator structure, but the number of amplifiers for the drive can be reduced, and high-speed rotation can be achieved. In the future, the Type B BELSM is also aimed at being installed in centrifugal pumps and its evaluation.

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