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A Heteropolar Bearingless Slice Motor with PM-free Rotor for Disposable Centrifugal Blood Pump

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To achieve sufficient rotational torque and simple control of the levitated blood pump impeller, we develop a novel heteropolar 12/8 slot/pole bearingless slice motor with permanent magnets (PMs) free rotor. The bearingless motor adopts separated winding configurations, including three-phase motor windings (U, V, W) and two-phase suspension windings (a,b) in the heteropolar design. Due to the unique locations of the suspension windings on the yokes and the four-pole stationary biased flux, the radial force is produced regardless of the rotor angle, leading to a simple control diagram and the minimum number of amplifiers. Therefore, while being rotated, the rotor can be actively positioned in the radial directions with two independent controllers. We fabricate a prototype to prove the validity of the design. The bearingless slice motor reaches a rotational speed of 3,500 rpm without contact.

1. Introduction

Bearingless slice motors (BELSMs) are suitable for centrifugal blood pumps in extracorporeal circulation since BELSMs fulfill the demands of high biocompatibility and compactness. BELSMs integrate the functions of the motor and magnetic bearing into a single unit to obtain high compactness and non-contact support. During the rotation, the rotor of the BELSM is actively positioned at the radial center of the stator by magnetic force and supported by the passive stiffness in the tilting and axial directions via the restoring torque and restoring force. Therefore, the BELSMs are required to avoid damage to blood cells caused by local shear stress and frictional heat in the shaft, mechanical bearings, and mechanical sealing of conventional blood pumps.

However, the BELSMs always use more than five amplifiers to control suspension and rotation, and disposable rotors with permanent magnets (PMs), leading to high costs. Previously, a homopolar bearingless switched reluctance slice motor (BLSRM) with a PM-free rotor was proposed [1]. It achieves low disposable cost due to its pure-iron rotor. Nevertheless, the twelve combined windings of the motor and suspension with low current control bandwidth result in a high cost of twelve amplifiers and unstable suspension at speeds over 3000 rpm in the glycerin water.

This paper presents a novel heteropolar bearingless doubly salient slice motor with a PM-free rotor [2]. The 12/8 slot/pole motor adopts the separated windings and places the three-phase motor windings and two-phase suspension windings on the stator poles and yokes, respectively. The particular arrangement of suspension windings and 4-pole heteropolar field makes it possible to use only five amplifiers and enables a simple positioning control scheme. Suitable bandwidth of the motor and suspension windings are realized because of low inductance and separated PI controller for the motor and suspension windings.

2. Mechanical configurations of BELSM

Figure 1 shows the mechanical structure of the proposed BLDSPM with displacement and rotational sensors and touch-down jig. The motor consists of a disposable 8-pole rotor and a reusable 12-slot stator with motor and suspension windings. We use three eddy current displacement sensors. Two of them are fixed by the sensor holder at the center to measure the radial displacement of the rotor in the X and Y directions. One sensor is installed on the motor base plate to detect eight slots on the bottom surface of the rotor. The sensor output is used to measure the rotational angle. A touch-down spacer is inserted between the stator and rotor to limit the moving range of the rotor to ±0.4mm in the radial direction. The touch-down spacer suppresses the suspension current at touch-up and absorbs the shock at touch-down.

3. Control System

3.1 Electrical components

We build a control system running at a frequency of 20 kHz in MicroLabBox (dSPACE GmbH, Germany) for the closed-loop control of the rotational speed and radial displacement of the rotor. The three eddy current displacement sensors (probe, PU-05, converter, AEC-55, AEC Corp., Japan) are used with a measuring range of 2 mm. Five

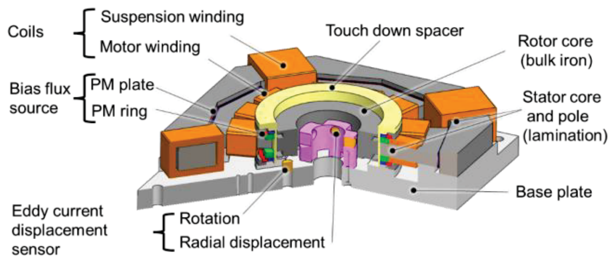


Fig. 1 Mechanical configurations of BELSM

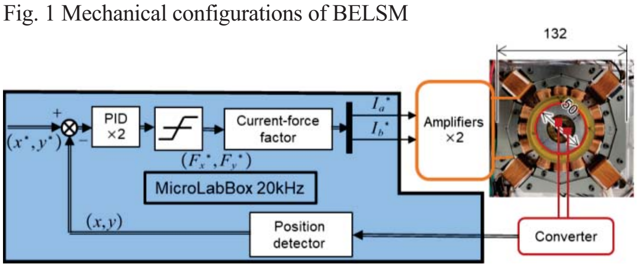


Fig. 2 Control schematic diagram of the radial displacement

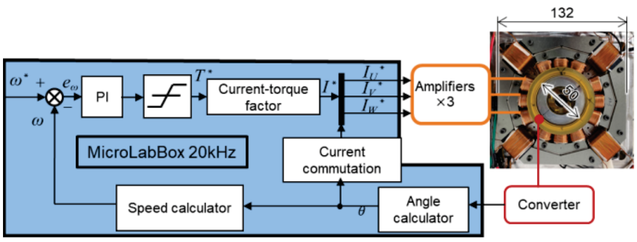


Fig. 3 Control schematic diagram of the rotational speed

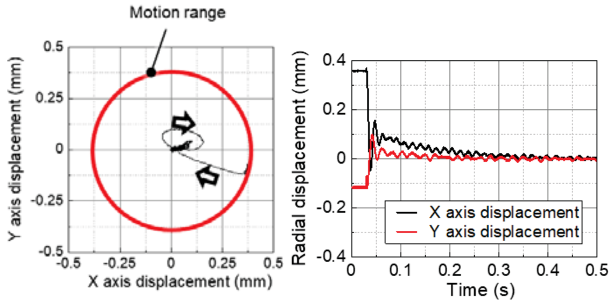
amplifiers (JSP-090-10, Junus, USA) use the pulse width modulation (PWM) method to drive the three-phase motor windings and two-phase suspension windings. Five current sensors (LA 25-NP, LEM Corp., Switzerland) are adopted to measure the currents in the windings.

3.2 Control diagram

Since the radial force generation is decoupled with the rotor angle, two simple and independent controller diagrams for the rotational speed and radial displacement are designed and implemented, as shown in Figs. 2 and 3. The connections from the eddy current displacement sensors and windings to the electrical components are shown in the system diagram and BELSM photograph. In the rotational controller, the angular position where the U phase pole is aligned to the rotor pole is defined as 0 electrical degrees, and a six-step commutation algorithm is employed to the three-phase windings to generate a continuous torque on the rotor, which is the same to brushless DC motors. The amplitude of the square-waveform current is derived by a PI controller. In the radial displacement controller, the reference is set to the geometrical center of the stator. A PID controller is employed to regulate the suspension current in *a* and *b*-phase windings.

4. Experimental Result

Based on the two independent controllers, suspension and rotational experiment in the air is first conducted. The startup response of the rotor is recorded and indicated in Figs. 4 (a) and (b). Only the suspension windings are energized during the startup. As shown in the figures, a stable suspension is achieved within 0.25 seconds after the



(a) (b)

Fig. 4 Measured startup responses (a) trajectory in the X and Y directions (b) transient responses in the X and Y directions

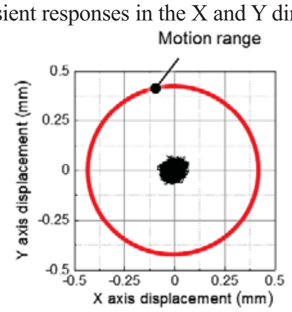


Fig. 5 Suspension accuracy at a rotational speed of 3500 rpm in the air

origin reference input. The overshot in the X and Y directions is less than one-third of the motion range, exhibiting a good vibrational convergence.

The rotor is then accelerated to 3500 rpm in the air. The trajectory of the rotor is shown in Fig. 5. The amplitude of the square-waveform current is about 2.5 A to sustain the rotational speed. The power consumption of the motor and suspension windings are 25 W and 2.2 W, respectively.

5. Conclusion

In this paper, a heteropolar bearingless slice motor is proposed. The motor realizes a simple control scheme by placing suspension windings on the stator yokes and employing a heteropolar design, requiring only five amplifiers in total. We fabricate a prototype and test its performance in the air. The BELSM succeeded in achieving a speed of 3500 rpm in the air. In the future, we will fabricate a disposable blood pump to suspend and rotate the rotor in the glycerin water. The hydraulic performance curve will be tested to verify the design as a blood pump.

ACKNOWLEDGEMENT

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