Design and Analysis of a Bearingless Permanent-Magnet Motor for Axial Blood Pump Applications

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ABSTRACT Because of their high power density and compact size, permanent-magnet (PM) motors have been commonly used to drive rotary blood pumps (RBPs), which are focused on the treatment of end-stage heart failure or as the bridge to a heart transplant. In this paper, a bearingless PM motor has been proposed for axial blood pump applications. The finite-element method (FEM) is used to predict the electromagnetic characteristics of the designed motor with improved performance. Two topologies are investigated, namely the integral-slot and distributed-windings method and the fractional-slot and double-layer concentrated windings method. Both motors are analyzed and optimized. FEM reveals that, compared with the integral-slot motor, the fractional-slot motor offers significantly enhanced performance, including reduced cogging torque, improved back electromotive force (back EMF), and decreased magnetic flux leakage. Finally, hydraulic experiments have been conducted in a mock-circulation loop to validate the feasibility of the designed motor for an axial blood pump. The results show that the fractional-slot bearingless PM motor can drive the RBP to produce physiological blood flow with reasonable efficiency.

INDEX TERMS Blood pump, cogging torque, finite-element analysis, fractional slot, permanent magnet motors.

I. INTRODUCTION
In the past few decades, rotary blood pumps (RBPs) have greatly improved the treatment of end-stage heart failure, either as the bridge to heart recovery or to a heart transplant. The increasing use of RBPs is related to multiple positive attributes, including reduced size, improved durability, and enhanced survival rate compared with volume-displacement pulsatile pumps [1]–[4]. Biocompatibility and durability are the two main concerns for the long-term or permanent use of RBPs. The former refers to controlling blood trauma to a permissible level, and the latter refers to solving the problem of life-limiting wear on mechanical bearings in the rotor. Blood trauma includes hemolysis and thrombosis. Hemolysis is defined as the hemoglobin disassociation into plasma for the break of membranes of red cells, while thrombosis refers to breaks [5], [6]. In order to reduce blood trauma, many new designs (e.g., streamlined design), as well as new structures for RBPs, have been put forward by researchers [1], [4], [7]. The bearing problem has been extensively investigated and non-contact bearing systems have been developed for long-term support of end-stage heart failure patients [7]–[11].

These non-contact bearing systems include an electromagnet / position-sensor bearing system, hydrodynamic bearing system, and a magnetically levitated bearing system. In an electromagnet system, such as HeartMate III and DuraHeart, the rotor is suspended using electronic position control and electromagnets. They offer the advantage of no life-limiting wear due to no contact between the bearing surfaces and low blood shear stress due to relatively large clearances between the rotating element and the housing. However, the complexity of the system increases instability and unreliability. For a hydrodynamic system, such as HeartWare HVAD, the rotor is suspended by fluid forces in thin blood films separating the rotor and pump housing based on the relative motion of surfaces. The hydrodynamic bearings are simple
and reliable, but the load–blood film is prone to high shear stress, which theoretically contributes to high hemolysis. In a magnetically levitated bearing system, the PMs are generally used in combination with hydrodynamic or electromagnetic bearing elements for stabilization in one or more directions of movement. For the complexity of this type of motor, it is difficult to obtain miniaturization for some special RBPs with the required overall size.

The purpose of this paper is to propose a new bearingless PM motor for an implantable axial blood pump with the overall size required (delivering the blood directly from the left ventricle to the aorta), in which both biocompatibility and durability are considered to provide long-term circulatory support for end-stage heart failure patients. The designed motor offers promising mechanical integrity and a compacted structure, which is described in Section II. In Section III, the finite element method (FEM) is used to analyze the electromagnetic characteristics and to reduce the cogging torque of the designed motor. In Section IV, hydraulic experiments are conducted to validate the feasibility of the motor in the axial blood pump.

II. PROPOSED MOTOR FOR AN AXIAL BLOOD PUMP

A. BEARINGLESS PM MOTOR

The axial blood pump using the proposed bearingless PM motor for an implantable axial blood pump with the overall size required (delivering the blood directly from the left ventricle to the aorta), in which both biocompatibility and durability are considered to provide long-term circulatory support for end-stage heart failure patients. The designed motor offers promising mechanical integrity and a compacted structure, which is described in Section II. In Section III, the finite element method (FEM) is used to analyze the electromagnetic characteristics and to reduce the cogging torque of the designed motor. In Section IV, hydraulic experiments are conducted to validate the feasibility of the motor in the axial blood pump.

B. REDUCTION OF COGGING TORQUE

High cogging torque always results in torque ripple, and thus decreases the stability of the motor [14], [15], [16]. Cogging torque is related to many motor parameters. In this section, two topologies are designed to analyze the influence of slots and windings on cogging torque [17], [18]. The topology with 12/4 integral slot and distributed windings has been shown in Fig. 2, and the new one with 6/4 fractional slot and concentrated windings is shown in Fig. 3. Their parameters are listed in Table 1. Model 1 represents the integral-slot motor and mode 2 represents the fractional-slot motor.

III. FINITE-ELEMENT ANALYSIS

FEM is used to investigate electromagnetic characteristics including the magnetic field distribution, back EMF, cogging
### TABLE 1. Design parameters.

| Parameters                      | Model 1 | Model 2 |
|---------------------------------|---------|---------|
| Number of phase                 | 3       | 3       |
| Number of turns                 | 32      | 40      |
| Number of slots                 | 12      | 6       |
| Stator outer diameter           | 33.3 mm | 31 mm   |
| Stator inner diameter           | 23.3 mm | 18.2 mm |
| Slot opening height             | 1 mm    | 1 mm    |
| Slot body height                | 2.55 mm | 2 mm    |
| Slot opening width              | 2 mm    | 0.8 mm  |
| Slot wedge maximum width        | 4.91 mm | 9 mm    |
| Slot body bottom width          | 5.1 mm  | 11 mm   |
| Number of winding layers        | 1       | 2       |
| Coil pitch measured in slots    | 3       | 1       |
| Number of poles                 | 4       | 4       |
| Pole embrace                    | 0.94    | 0.94    |
| Thickness of magnets            | 1.25 mm | 1.25 mm |
| Rotor outer diameter            | 20.8 mm | 16.8 mm |
| Rotor inner diameter            | 15.3 mm | 12.4 mm |

FIGURE 3. Proposed motor using 6/4 fractional slot and concentrated windings.

DC motor is driven by a square wave current. When the width of the flat top portion of back EMF is not enough, torque ripples, which eventually causes vibration and noise. The width of flat top in the back-EMF increases by nearly 30% in the fractional-slot motor will reduce torque ripple and make the motor more stable [15], [16].

The cogging torque of both motors is compared in Fig. 7. The maximum cogging torque of the fractional-slot model reaches 4 mN · qm, much lower than the maximum value of 28 mN · qm of the integral-slot motor. The fluctuation of the cogging torque in the fractional-slot motor decreases greatly, with an average of 10% that of the integral-slot motor. Cogging torque contributes to torque ripple in the motor, which causes mechanical vibrations of the motor. In the integral-slot motor, there are twelve slots and four poles. Therefore, three slots correspond to one pole, or six slots correspond to one pole-pair. The total cogging torque is the sum of cogging torque produced by each slot. In the integral-slot motor, the cogging torque waveform from every slot has the...
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A.

FIGURE 6. Back-EMF waveforms of both motors. (A) 12/4 integral slot and distributed windings. (B) 6/4 fractional slot and concentrated windings.

B.

FIGURE 7. Comparison of cogging torque.

same amplitude and phase with each other. However, in the fractional-slot motor, there are six slots and four poles. So the slots cannot distribute symmetrically in the magnet field, and thus the phase of cogging torque produced in each pole will vary. For cogging torque is vector, the sum of cogging torque produce in each slot decreases compared to the integral-slot motor.

Fig. 8 shows the fast Fourier transform (FFT) analysis of the cogging torque of the two models. The cogging torque of both models is much higher at the 3rd, 6th, and 9th harmonic orders than at others. Compared with the integral-slot model, the fractional-slot model has significantly reduced cogging torque, which verifies the decrease of cogging torque in the fractional-slot model.

IV. EXPERIMENTAL RESULTS

In order to validate the proposed motor for axial blood-pump applications, an experimental model has been built in this work. As shown in Fig. 9, the experimental mock circulation loop consists of an artificial atrium, HP/M1205A physiological monitor, axial blood pump using the proposed motor, Transonic T110 flow meter, and control system. The control system can regulate the rotating speed of the motor, which includes a drive, TMS320F2812 control chip, and filter. A water–glycerin mixture of 30% volume glycerin is used as the hydraulic test fluid with a viscosity of 0.00036 Pa·s (similar to human blood at 37 °C).

Fig. 10 shows the characteristic curves of the axial blood pump at different rotating speeds based on the hydraulic experiments in the mock circulation loop. In the characteristic curves, H represents the differential pressure and
Q represents the flow rate of the pump. The blood pump hydraulic performance reveals that the pump driven by both motors can produce physiological blood flow and pressure to assist a child patient or an adult patient with mild heart failure at a rotating speed of more than 7500 rpm [22]. The blood pump driven by the integral-slot motor or by the fractional-slot motor can produce a differential pressure of 51 mmHg or 57 mmHg, respectively, with the same flow rate of 2 L/min and rotating speed of 9500 rpm. Compared with the integral-slot motor, the average differential pressure of the blood pump with fractional-slot motor increases by nearly 7.2% at 9500 rpm and with a flow of 2 L/min.

Compared with the integral-slot motor, the average differential pressure of the fractional-slot motor blood pump increases by nearly 7.2% at 9500 rpm. However, the surface material of the non-contact bearing and stability at startup and shutdown of the motor are among the important issues to be solved in future work.

V. CONCLUSION
In this paper, a bearingless PM motor has been proposed for an axial blood pump with compact size. FEM is used to predict motor performance. Hydraulic experiments have been conducted to validate the feasibility of the motor for axial blood-pump applications. Both the numerical and experimental results verify that the fractional-slot topology can reduce the size of the pump, significantly decrease the cogging torque, and enhance the reliability. The proposed motor is feasible for the axial blood pump, offering the merits of a compact structure, high stability.

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