Study on Driving Motor for Magnetic Levitated Artificial Heart Pump

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ABSTRACT

A driving motor and its control system for magnetic levitated artificial heart pump are introduced. On the basis of traditional brushless DC motor, the stator removes slot and adopts coreless winding. The advantage of slotless stator and the design are introduced. The control system is designed based on back EMF method to control sensorless motor. IC ML4435 is used as the central control chip. The speed can be governed smoothly by adjusting the input voltage. The advantage is simple and has low power consumption.

KEYWORD

Magnetic bearing; Artificial heart pump; Slotless motor; ML4435

INTRODUCTION

In recent years, magnetic levitated heart pump has been developing rapidly. More and more evidences show that the third-generation heart pump has a better performance than the previous second-generation products. Maglev artificial heart pump has developed rapidly with its advantages of no contact support and long life. It has solved the problem of hemolysis and thrombosis leaded by the mechanical bearing. Driving problem is the key of the artificial heart pump. Performance and the size of a driven motor directly determines the performance and the size of a heart pump. Direct-drive pump has low power consumption and high energy conversion efficiency, so the application is mature and widely [1]. In terms of the choice of drive motor, DC motor and permanent magnet synchronous motor are used widely in domestic products. This type of motor has the advantages of high speed and simple structure, but there are some problems in the stability magnetic noise and torque ripple while the motor is in motion [2]. As a medical device, the heart pump motor should have optimization in the volume, stability, control and other aspects under the premise of meeting the basic requirements.

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In this paper, a kind of slotless brushless permanent magnet DC motor is put forward. The stator structure in the motor cancels the teeth and slots and coil windings are directly to the air gap. We use the ML4435 as main control chip and apply the back EMF rotor position detection method instead of the hall position sensor. We can realize the motor starting and control with these.

THE INTEGRAL STRUCTURE OF THE HEART PUMP

The structure of the magnetic levitated artificial heart pump is shown in Figure 1. It mainly contains the motor rotor, motor stator, radial permanent magnetic bearings, axial fluid-film bearings and front-back guide vanes. In normal operating conditions, the radial achieves balance through the Halbach permanent magnetic bearing and the axial achieves balance by fluid film bearings and blood reverse thrust. Finally the structure can achieve complete suspension. In the axial direction, a jewel thrust bearing is arranged to support and protect the structure when the flow is changed or in a static state.

![Figure 1. The structure of magnetic levitated artificial heart pump.](image)

The driving motor is located in the middle of the pump, and the motor rotor is coaxial with the magnetic bearing. Driven by the alternating magnetic field of the stator, the rotor drives the impeller to rotate to push the blood forward. Impeller and other parts contacted with blood are wrapped with medical titanium alloy.

MOTOR DESIGN

Motor Structure

Driving motor is composed of permanent magnet, shaft, coil winding and stator shown in Figure 2. On the basis of traditional DC motor, brushless, slotless, sensorless technology is applied to the new type motor and improves the operational stability and reliability. Motor rotor is circular NdFeB permanent magnet which is applies parallel magnetization.

Compared to the radial magnetization, airgap field and back EMF is closer to the sinusoidal waveform when surface magnet applies parallel magnetization. Parallel magnetization reduces the high harmonic content and increases the electromagnetic torque [3].

Slotless motor removes the teeth and slots on stator. In order to fix the coil, the coil windings require winding on a mold and solidify into a cup shape. Windings and stator are poured into a whole using epoxy resin. This structure makes the motor air gap much larger than the ordinary motor that expands the layout space of heart pump impeller. Large airgap increases the reluctance and contains the armature reaction. Windings can stand higher instant currents without being burned out. After canceling
the teeth and slots, the motor eliminates the noise caused by cogging torque and reduces the loss. The power consumption and weight of the motor are reduced and efficiency and operation stability are improved.

One-step forming slanting winding is applied to the slotless motor, which has much smaller inductance than ordinary winding. The slotless motor has small electric time constant and linearization output that speed is proportional to voltage and torque is proportional to the current. A, B and C three-phase symmetrical windings are evenly distributed into two layers. Each layer of each phase windings occupy 120 degrees and each coil is across a polar distance. Winding connection way is Wye-connection. The slotless coil winding is shown in Figure 3.

**Motors Size**

The main technical specifications of the heart pump drive motor are as follows: Rated voltage: \( UN=24V \); Rated speed: \( nN=12000\text{r/min} \); Rated power: \( PN=10W \); Rated output torque: \( T0=7.96 \times 10^{-3}\text{N*m} \).

Designers have more freedom and flexibility in the armature winding structure, electromagnetic load main and dimensions due to the cancellation of the teeth and slot. The main dimensions can be modeled with a slot motor in the design process. The main dimensions of the permanent magnet brushless DC motor can be determined according to the following formula:

\[
D_a = \sqrt[3]{\frac{6.1P'}{\alpha_i A B_\delta \lambda n_N}}
\]  

(1)

Where \( D_a \) is armature diameter, \( \alpha_i \) is calculating polar arc factor, \( A \) is line load(A/cm), \( B_\delta \) is air gap flux density(T), \( P' \) is calculating power(W), the motor works continuously, so \( P'=(1+2 \eta)/3 \eta \times PN \), \( \lambda \) is L/D ratio, \( \lambda = la/Da \).

Line load can be determined according to its operating mode and cooling conditions. The value of line load should be small because the motor operate in a continuous station and temperature rise of heart pump cannot be more than 2°C. The air gap flux density is determined according to the material and placement of permanent magnet. In this paper, NdFeB N50 is applied. Polar arc factor can be obtained by simulating using finite element software. For small power motors, the value of the L/D ratio is between 0.7 and 1.5.
DRIVE CONTROL SYSTEM DESIGN

Control circuit is the command center of BLDC motor to achieve normal operation and all kinds of speed regulating functions. According to the special requirements of the driving motor for heart pump, we can get the technical requirements of the controller as follows:

1) BLDC controller without position sensor;
2) The speed is tunable and the range is between 0 and 18000 rpm;
3) Start/stop of the motor is reliable and operation process is stable;
4) The power consumption of the controller should be low because heart pumps are powered by lithium batteries.

Motor Control Hardware Circuit

Drive control circuit mainly comprises a main control chip ml4435 (Fig.4), driving chip IR2130, inverter chip HCF4069, which form the square wave generating and switch transistors driving circuit. The diagram of the principle is shown in Figure 5.

Start of the motor is achieved by motor commutation. The motor produces a low speed in low frequency signal to generate a back EMF signal, which can lead the back EMF sampler circuit track motor position, and control commutation time through a phase-locked loop. Commutation control circuit can also produce a speed feedback signal for the speed control loop, which is composed of the error amplifier and PWM comparator. The speed control loop can produce a PWM duty-cycle for speed regulation control.

Phase Locked Loop (PLL) Control

The PLL of ML4435 is composed of back EMF sampler, commutation state machine and VCO as shown in Figure 6. The commutation clock follow the back EMF signal automatically and commutation function without sensor is realized finally [4].
In order to realize the correct commutation of the motor, the controller requires to control the on-off condition of 3-phase power switch according to certain rules. There are 7 phase-commutation logics which is programmed in commutation state machine. The 7 phase-commutation logics constitute a complete cycle. The VCO supplies correct clock to commutation state machine.

The input pin of back EMF obtain the signal from each phase of windings. This signal should be lower than the VCC of ML4435 (12V). If the rated voltage of motor is higher than 12V, it is necessary to connect a resistor RFB in series with the windings.

**PWM Speed Control**

The relationship between electromagnetic torque and speed of BLDC motor is shown in equation (2):

\[
T_e = K_T I_d = K_T \left( \frac{U_d}{R} - \frac{2K_T \Phi_m n}{R} \right)
\]

(2)

Where KT is a constant. The electromagnetic torque decreases linearly with the increase of speed.

From the above analysis, it can be known that the speed of the motor is related to the internal magnet flux \( \Phi_m \), the armature resistance R and the armature terminal voltage Ud. By regulating armature terminal voltage, the motor has large speed range, excellent static stability and achieves stepless speed regulation. Because of the immutable supply voltage, the average of motor input voltage is regulated by switch tube, while it is controlled by duty ratio of PWM signal. Then the motor speed can be controlled effectively.

When the motor is start normally and the speed reaches a certain degree, the back EMF can be detected in the winding. Then the control circuit enter the closed loop state. The speed control is achieved by setting a speed command at pin 5. The precision of the command is determined by RVCO and CVCO.

The concrete method is that a potentiometer is connected between the RT and the ground. At the speed boosting stage, the terminal voltage of SPEED SET (pin 5) rise by adjusting the potentiometer. Then the error of voltage between SPEED SET and speed feedback signal increase. The error signal is compared with PWM chopping signal through a comparator, then the output PWM duty increases and motor speed increases. At the same time, the speed feedback signal increases and approaches the output of speed error amplifier. Then the motor operate at a steady speed.
The deceleration process of the motor is adverse to the acceleration process. Speed loop compensation is placed at pin 5 (Fig.7) and its components are calculated as follows:

\[
C_{SC2} = \frac{1.44 \times N \times K_e \times V_{MOTOR} \times R_{VCO} \times C_{VCO}}{2 \pi \times J \times R_1 \times f^2} \tag{3}
\]

\[
R_{SC} = \frac{10}{2 \pi \times f \times C_{SC2}} \tag{4}
\]

\[
C_{SC1} = 10 \times C_{SC2} \tag{5}
\]

EXPERIMENTAL RESULTS AND ANALYSIS

The experimental use of the driving voltage $U_s$ adjustment range is from 3V to 24V. Turn on the motor controller and achieve closed-loop stable rotation of the motor. The voltage of the coil windings is changed in the driving voltage regulation range, and the speed of the motor can be adjusted smoothly. The back EMF signal and the rotating speed signal can be read by using an oscilloscope, then the rotor speed $n$ can be obtained. The back EMF signal of phase A and speed signal by experimental measurement is shown in Figure 8. 8-(a) and 8- (b) is the back EMF waveform and speed signal waveform under different speed. experimental data is shown in Table 1. Voltage-speed curve is shown in Figure 9.

![Figure 8. Back EMF of phase A and speed signal.](image)

(a)  (b)

Table 1. Experimental data.

| Voltage average of Phase A/V | Period of phase A back EMF signal /ms | Period of speed signal /ms | Speed/rpm |
|-----------------------------|--------------------------------------|---------------------------|-----------|
| 1.99                        | 13.8                                 | 4.6                       | 4347.8    |
| 2.76                        | 9.5                                  | 3.1                       | 6315.8    |
| 3.39                        | 7.4                                  | 2.6                       | 8008.1    |
| 4.13                        | 6.4                                  | 2.1                       | 9375.0    |
| 4.89                        | 5.7                                  | 1.8                       | 10526.3   |
| 5.75                        | 5                                    | 1.6                       | 12000.0   |
| 6.5                         | 4.5                                  | 1.5                       | 13333.1   |
| 6.98                        | 4.2                                  | 1.4                       | 14285.7   |
| 7.86                        | 3.6                                  | 1.2                       | 16666.7   |
| 8.75                        | 3.1                                  | 1                         | 19354.8   |
| 9.8                         | 2.76                                 | 0.88                      | 21739.1   |

The data is drawn into a line graph, and MATLAB is used for linear fitting. The relationship between speed and voltage can be approximated by a straight line.
The experimental results show that the system can achieve stable closed-loop operation, it also has the advantages of smooth rotation, low noise, and strong anti-jamming capability. According to the speed curve which is like a straight line, the system can meet the requirements of the performance index of heart pump.

This paper presents a kind of motor used in magnetic levitated heart pump. Experimental results show that the slotless motor has the advantages of excellent performance of speed regulation and the strong balance. The use of ML4435 controller based on the sensorless control method brings the advantages of simple structure, small volume and low power consumption. So from a certain extent, it can increase the use time of the battery to avoid replacing battery frequently.

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