Miniaturized Magnetically Levitated Motor for Pediatric Artificial Heart

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Abstract: An axially levitated motor has been developed for use in pediatric artificial hearts. The developed axially levitated motor consists of a top stator, bottom stator, and levitated rotor impeller. The developed motor has an outer diameter of 24 mm and a total length of 41 mm. The motor was designed based on three dimensional magnetic field analysis. The target axial attractive force of the levitated motor is 10 N, and a torque of 1 mNm at a rotational speed of 4000 rpm. The developed motor produces an axial attractive force of 10.6 N, and a torque of 5.8 mNm respectively. Experimental results display sufficient magnetic suspension capability and rotational performance of the levitation system for a pediatric ventricular assist device.

Keywords: Magnetic Bearing, Pediatric Artificial Heart, Infant

Introduction

Magnetic levitation technology offers longer device lifetime and better biocompatibility of the artificial heart by eliminating mechanical contacting components such as contact bearings and seals from the device [1]. The magnetically levitated artificial heart has been developed for use in infant patients. This requires the device to be smaller in size and has a longer life expectancy than adult artificial hearts. In this paper, a double stator self-bearing motor is presented and its levitation and motor performance is evaluated.

Methods

Principle of the double stator self-bearing motor. The basic structure of the double stator self-bearing motor is shown in Fig.1. A double stator mechanism is adopted to increase the motor torque while suspending the levitated rotor in the axial direction. The self bearing motor consists of a top stator, bottom stator and a levitated rotor set between the both stators. Both the top and bottom stators have 6 poles each. Two concentrated coils are wound on each pole. One of these coils is used to control the torque and axial position of the levitated rotor, while the second coil is used to regulate the tilt of the levitated rotor. Permanent magnets are used to create a single pole pair on the both the top and bottom of the rotor. The axial rotor position, rotor tilt and the rotating speed are controlled actively while the radial position of the rotor is restricted passively with magnetic stability.

Three-phase currents are fed into the motor coils to produce an attractive force and torque. The axial position and the torque will be regulated independently by changing the magnitude and the phase difference of the magnetic flux based on the vector control algorithm [2-3]. The stator and the permanent magnet of the rotor are assumed to produce the following magnet flux density $B_s(\theta, t)$ and $B_r(\theta, t)$,

$$B_s(\theta, t) = B_S \cos(\omega t - M\theta) \quad (1)$$

$$B_r(\theta, t) = B_R \cos(\omega t - M\theta - \psi) \quad (2)$$

Where B_S, B_R are peak density of magnetic flux produced by the stator electromagnet and the rotor permanent magnet, M is pole pair number of the rotor, ω is rotating speed of the rotor, θ is angular coordinate, and ψ is the phase difference. For simplicity, magnetic properties inside the rotor and the stator are assumed to be homogenous and the reluctance of the core is ignored when compared with that of the air gap. The magnetic stored energy can be expressed in terms of the energy density of the magnetic flux density integrated over the volume V of the magnetic field as follows,

$$W = \int_V \frac{B^2}{2\mu_0} dV \quad (3)$$

Then the axial force F_z and rotating torque τ_z can be derived as follows,

$$F_z = \frac{\partial W}{\partial z} = \frac{(r_2^2 - r_1^2)\pi}{4\mu_0}\{B_R^2 + B_R B_S \cos M\psi + B_S^2\} \quad (4)$$

$$\tau_z = \frac{\partial W}{\partial \psi} = \frac{zM(r_2^2 - r_1^2)\pi}{2\mu_0} B_R B_S \sin M\psi \quad (5)$$

Where r_1 and r_2 are the inner and outer radii of the rotor, z is the gap length which contains the thickness of the permanent magnets between the rotor and the stator, and μ_0 is the permeability of the air gap. To control the axial position and the torque of the rotor independently, the stator flux density B_s is divided into the direct axis component B_d and the quadrature axis component B_q corresponding to the flux components in the direction of the permanent magnet. The direct axis component B_d and the quadrature axis component B_q are defined as follows,

$$B_d = B_s \cos\psi = \frac{\mu_0 N I_s}{z}\cos\psi \quad (6)$$

$$B_q = B_s \sin\psi = \frac{\mu_0 N I_s}{z}\sin\psi \quad (7)$$

Where I_s is peak excitation current to produce the flux density B_S. Then Eq.4 and Eq.5 are redefined as follows.

$$F_z = \frac{\partial W}{\partial z} = \frac{(r_2^2 - r_1^2)\pi}{4\mu_0}\{(B_R + B_d)^2 + B_q^2\} \quad (8)$$

$$\tau_z = \frac{\partial W}{\partial \psi} = \frac{zM(r_2^2 - r_1^2)\pi}{2\mu_0} B_R B_q \quad (9)$$

The rotating torque is controlled with q-axis current of the motor and the attractive force is controlled with d-axis current independently.

Fig.2 shows the principle of the tilt control. The inclination of the levitated rotor is controlled by the tilt control coils which generate a uniform magnetic flux that interacts with the stator magnetic field. The interaction between the two magnetic fields produce an unbalanced magnetic flux density between the rotor and the stator surfaces. To illustrate this principal, consider only the top stator and permanent magnets of the top side of the rotor. The permanent magnet of the rotor is assumed to produce the following magnetic flux density $B_r(\theta, t)$.

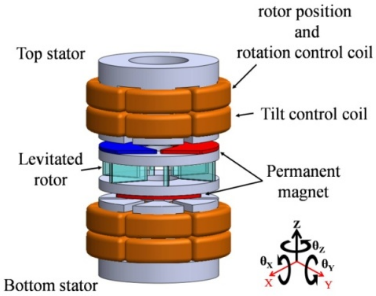


Fig.1 Double stator self-bearing motor

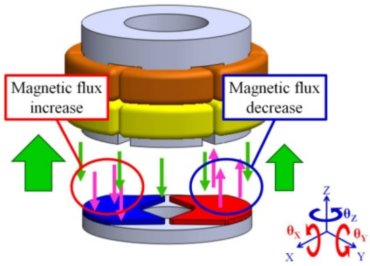


Fig.2 Tilt control principle

$$B_r(\theta, t) = B_R \cos(\omega t - \theta) \tag{10}$$

The tilt control coils produce a uniform flux that is defined as the magnetic flux density B_{tilt},

$$B_{tilt} = \frac{\mu_0 N I_{tilt}}{z} \tag{11}$$

where I_{tilt} is DC excitation current to produce the magnetic flux density B_{tilt}. The unbalanced axial attractive force of the N pole permanent magnet and S pole permanent magnet are described as F_N and F_S respectively.

$$F_N = \frac{(r_2^2 - r_1^2)}{4\mu_0}\{\frac{B_R^2}{2}\pi - 4B_R B_{tilt} + B_{tilt}^2\pi\} \tag{12}$$

$$F_S = \frac{(r_2^2 - r_1^2)}{4\mu_0}\{\frac{B_R^2}{2}\pi + 4B_R B_{tilt} + B_{tilt}^2\pi\} \tag{13}$$

A difference between these two attractive forces, F_N and F_S, produces a restoring torque τ_{tilt}.

$$\tau_{tilt} = L(F_S - F_N) = \frac{2L(r_2^2 - r_1^2)}{\mu_0} B_R B_{tilt} \tag{14}$$

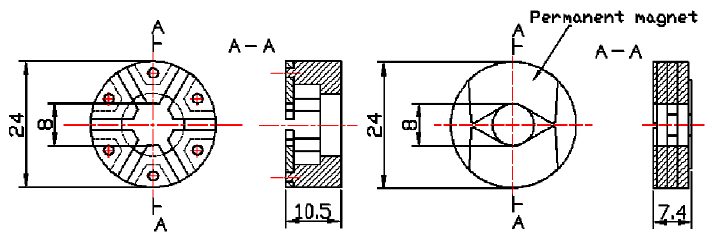
From the Eq.14, the restoring torque is proportional to the tilt control flux B_{tilt}. Therefore the inclination of the levitated rotor can be controlled by the excitation current I_{tilt}. Moreover, the inclination around x and y axes are controlled with the top and bottom stators independently, because the permanent magnets on the both rotor surfaces are set with a phase difference of 90 degrees.

Motor Design. Target pump performance of the pediatric artificial heart has a maximum flow rate of 1 L/min against a head pressure of 100 mmHg. The required torque for this performance is calculated to be 1 mNm with a rotor speed of 4000 rpm. Additionally, the target axial attractive force for the design of the self-bearing motor is 10 N when the air gap between the levitated rotor and the each stator is set to 1.5 mm. Parameters of the cross-sectional area of the magnetic cores and the size of permanent magnets are optimized using three dimensional magnetic field analysis. The number of coil turns and the geometric parameters of the permanent magnets are determined with Eq.4 and Eq.5.

Experimental Setup. Fig.3 and Fig.4 show the schematic and photographs of the stator made of magnetic steel and the rotor with two permanent magnets on the surface. The turn number for the axial position and torque coils is 70 turns/pole. The number for the tilt control coils is 70 turns/pole. The total height and diameter of the levitated rotor are 7.4 mm, and 24 mm, respectively. The rotor yoke was manufactured from magnetic steel. The weight of the rotor is 38 g. Two thin permanent magnets are mounted on both the top and bottom surfaces of the rotor. The Nd-F-B permanent magnets have a thickness of 0.7 mm.

Control system. Fig.5 shows the schematic of the levitation and motoring control system. Levitation and rotation of the rotor is controlled digitally by using a digital signal processor. Four eddy current sensors are used to measure the rotor position in the axial direction and its tilt angles. Small permanent magnets are set at the circumference of the rotor and a hall sensor is used to measure the rotating speed. Digital PID controllers are implemented on the digital signal processor with a control interval of 0.1 msec.

Experiments. The attractive force produced by the self bearing motor was measured. Fig.6 shows axial force measurement system. The measurement system consists of a load cell, micrometer slider, the motor stator held on the base and the rotor connected to the load cell. The air gap length was changed from 1.0 mm to 2.0 mm by using a micrometer slider. To determine their effect on the attractive force, the excitation current and phase difference between the rotor and stator magnetic fields were varied and the resulting force was measured. The excitation current was changed from 0 A to 2.5 A. The phase difference was changed from 0 degree to 90 degrees. In addition to the attractive force, the torque production characteristics were also measured. Fig.7 shows rotation torque measurement system which consists of a torque transducer, hysteresis brake, the motor stator set on the base and the rotor connected to a torque transducer with a shaft. The air gap length was set at 1.5 mm. The rotating speed was varied from 1000 rpm to 5000 rpm. The phase difference was changed from 40 degrees to 90 degrees at each rotating speed. Excitation current is regulated actively to achieve steady rotating speed during the torque measurement. The stators and rotor were combined with the digital control system. The feedback signal from the eddy current sensors is used to vary the attractive force of the top stator and balance the rotor against the bias force generated by the bottom stator. To determine the dynamic performance of this system the step response was measured when the axial position of the levitated rotor shifted by 0.25 mm. Frequency response of the position control was measured with the frequency sweeping method using an FFT analyzer. A sinusoidal disturbance was added to the levitation control current and the disturbance frequency was varied from 1 Hz to 1 kHz.



(a) Stator (b) Rotor

Fig.3 Size of the stator and the rotor

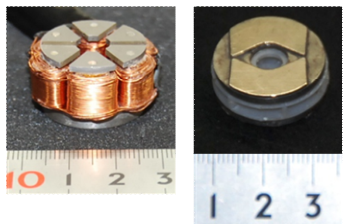


Fig.4 Photograph of the developed motor

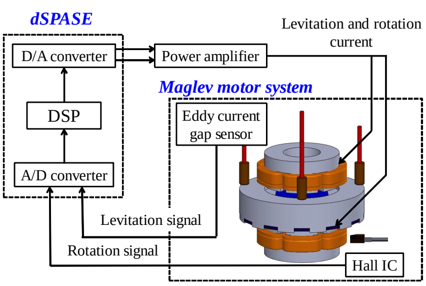


Fig.5 Control system

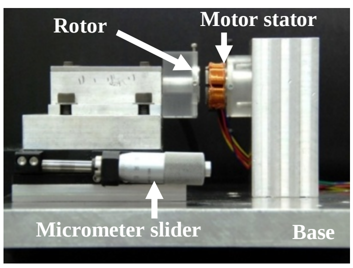


Fig.6 Axial force measurement system

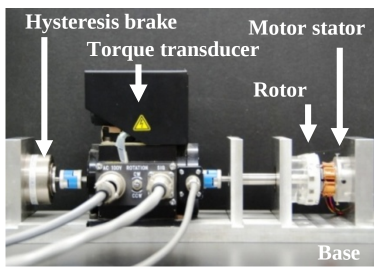


Fig.7 Torque measurement system

Results

Axial force. Fig.8 shows the relationship between attractive force and air gap length. The self bearing motor produces an axial attractive force of 10.6 N with an excitation current of 2.5 A, a phase difference of 0 degree and an air gap of 1.5 mm. The force to excitation current gradient of the developed by the motor is 1.5 N/A. The acceleration index is defined as a mass specific force index and indicates the dynamic suspension stability against acceleration, is 39.6 m/sec^{2}A for this device. Fig.9 shows the relationship between the attractive force and the phase difference with an air gap length of 1.5 mm. The motor produces the axial attractive force in the range from 6.7 N to 10.6 N by varying the phase difference from 90 degrees to 0 degree.

Rotational torque. Fig.10 shows the relationship between the motor torque and excitation current with a phase difference of 90 degrees and an air gap length of 1.5 mm. Fig.11 shows the relationship between the motor torque and the phase difference. The maximum torque at a rotational speed of 4000 rpm is 5.8 mNm with a phase difference is 90 degrees.

Levitation control ability. Fig.12 shows the system step response when the target axial rotor position is changed by 0.25 mm. The levitated rotor is stabilized within 100 msec. Fig.13 shows the frequency response of the motor in the axial direction and inclination. The first resonant peak is observed at approximately 100 Hz. The control system has reduced to amplitude of this resonant peak, however further suppression is required.

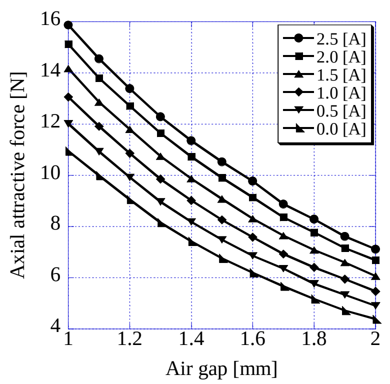


Fig.8 Axial force and air gap characteristic

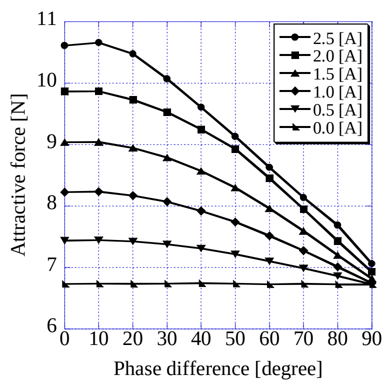


Fig.9 Axial force and phase difference characteristic

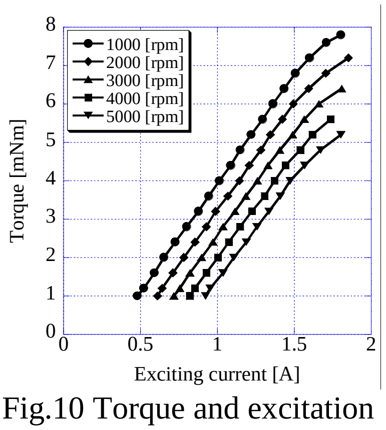


Fig.10 Torque and excitation current characteristic

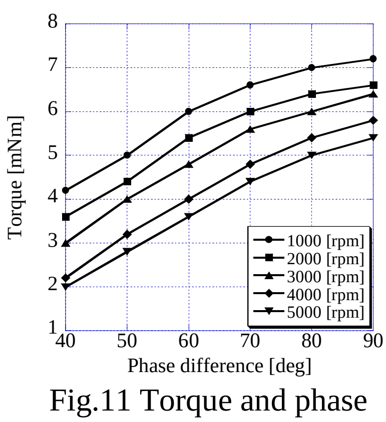


Fig.11 Torque and phase difference characteristic

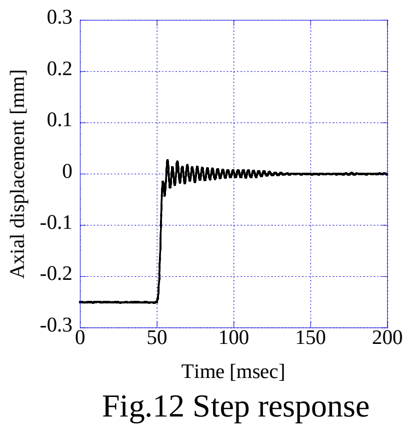
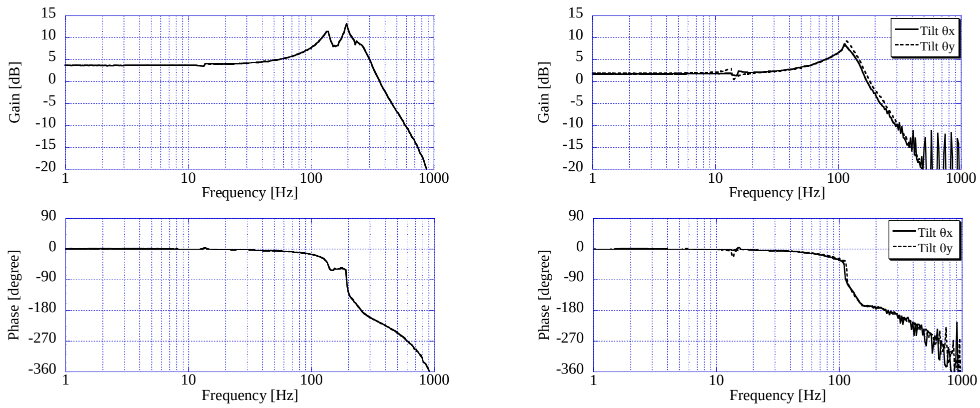


Fig.12 Step response



(a) Axial direction (b) Inclination (θ_x , θ_y)

Fig.13 Frequency response

Discussion

The developed motor displayed sufficient performance as an actuator for the pediatric artificial heart. The motor satisfies the design target for both the generated attractive force and torque. The acceleration index of 4 G with an excitation current of 1 A provides a suitable stiffness for the use in a pediatric artificial heart. The axial force and torque is controllable by changing the excitation current and the phase difference independently. Vector control is a candidate to control the self-bearing motor and implementation of this control strategy will be used in the next study to rotate the levitated rotor.

The vibration at a resonance frequency around 200 Hz could not be suppressed sufficiently. The control performance for the levitation system needs to be improved in future prototypes. Low suppression of this resonant frequency comes from the weak performance of the tilt control. The amplitude of the tilt restoring torque produced by tilt control electromagnet was small because the magnetic flux path for the tilt control is not closed to simplify the system. The force production mechanism for the tilt control should be improved to enhance the tilt control ability.

Conclusion

An axially levitated motor for use in a pediatric artificial heart was developed. The developed motor can produce an axial attractive force of 10.6 N and rotating torque 5.8 mNm which are above the target values of the pediatric artificial heart. These results show sufficient axial position controllability and rotational performance. This device shows it is possible to achieve a much smaller size and higher performance self-bearing motor. The developed self-bearing motor has the potential to work as a pediatric artificial heart.

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