A 5-DOF Active Controlled Disk Type PM Motor with Cylindrical Flux Paths

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***Abstract*—This paper proposes a novel disk type permanent magnet motor, which actively controls 5 degrees of freedom of a flat rotor without any contact. The proposed motor consists of an Axial Self-bearing Motor (ASBM) and additional cylindrical flux paths. The axial force and motor torque are controlled by the rotating flux with the same number of poles of the rotor, and the tilt control torque is produced by the rotating flux with the two plus or two minus poles of the rotor. The radial force is produced by supplying direct current to the stator windings. The direct current produces the flux through the stator and the cylindrical flux path, then the radial force can be generated by the interaction of the rotor poles and the edge of the cylindrical flux path. This paper introduces the structure and principle of the proposed motor, and shows the results of the magnetic forces calculated by the numerical electromagnet analysis.**

I. INTRODUCTION

An axial self-bearing motor (ASBM) is a combination of a disc motor and a thrust magnetic bearing, and can simultaneously produce rotating torque and control the axial position of the rotor[1]. Since the single rotating magnetic flux controls both the axial force and motor torque, the structure of the stator and control system is simple compared to other self-bearing motors. We are developing a miniaturized canned pump using the ASBM for a long lifetime[2].

However, the ASBM requires other radial magnetic bearings, such as permanent magnet repulsive type passive bearings and superconducting magnetic bearings[3] to support the radial directions of the rotor, then the overall structure tends to be complex and a lot of design effort is needed to meet specifications. Moreover, it is difficult to rotate over critical speed due to lack of the damping force by often-used passive magnetic bearings. In order to solve these problems, it is required to use the active control of 5 degrees of freedom with similar structure of the original ASBM.

This paper introduces a novel self-bearing motor, which actively controls 5-DOF of the flat rotor. Since only two stators can support the rotor, other radial bearings are unnecessary, and then the shaft of the rotor can be removed. This provides the flexibility of the overall design of the system such as canned pumps, vacuum pumps and so on.

In this paper, the structure of the proposed motor is introduced and the principles of the generation of the motor torque and bearing forces are shown. And the feasibility of the proposed motor is confirmed by finite element electromagnet analysis.

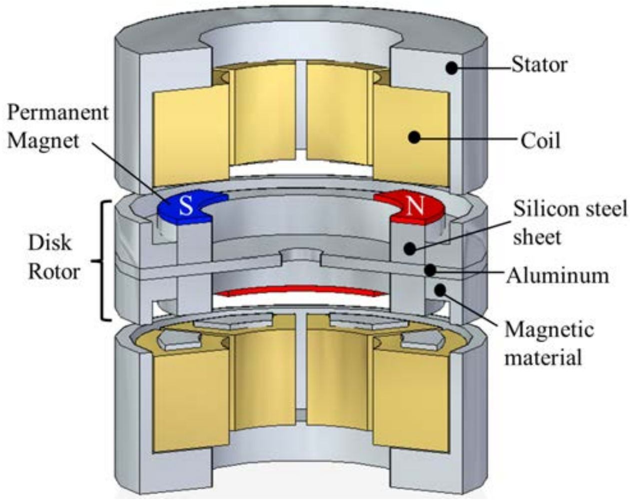


Figure 1. Structure of the disk motor.

II. STRUCTURE AND PRINCIPLE

A. Structure

The schematic structure of the proposed motor is shown in Fig. 1. The motor consists of one disc rotor and two stators placed on upper and lower side of the rotor. The cylindrical magnetic paths are attached on the outside of the stator and the rotor in order to generate uniform flux on the stator. The cylindrical flux paths are connected to the stator and rotor through back yoke. One stator has 6 concentrated coils and each coil is driven by a separate power amplifier. Two permanent magnets are attached on one side of the rotor surface to make 2-pole magnetic flux. The position of permanent magnet poles are shifted 90 degrees between upper and lower side of the rotor.

B. Motor Torque

The motor torque produced by the 2-pole rotating magnetic flux in upper and lower stator is out of phase with the rotor by 90 degrees. These fluxes do not flow in the cylindrical flux paths, and the motor works as a conventional one. The torque is controlled by the amplitude of the rotating fluxes. The rotating fluxes for the motor torque also produces the axial force. However, by using the same amplitude in both stators, the resultant axial force becomes zero.

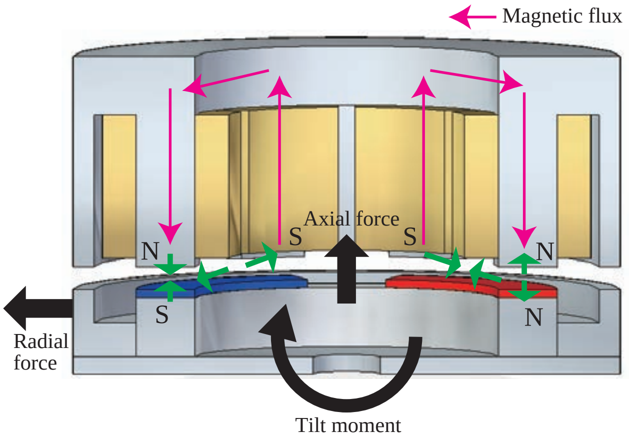


Figure 2. Tilt moment and radial force generation by 4-pole current.

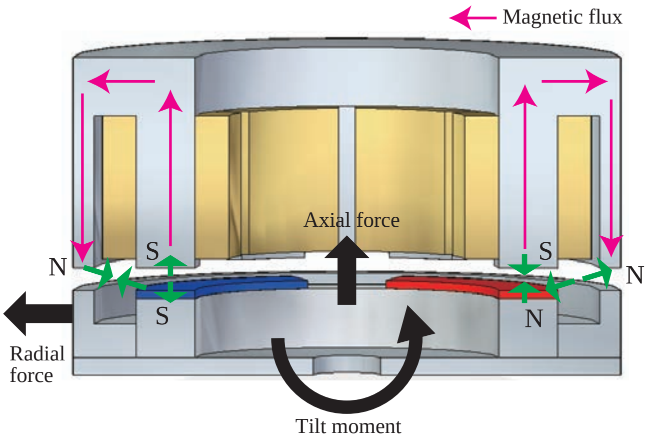


Figure 3. Tilt moment and radial force generation by direct current.

C. Axial Force

The 2-pole rotating magnetic flux with the same phase as the rotor, control the axial force. The axial force is generated by using the opposite amplitude in the upper and lower fluxes. The motor torque is not produced by these fluxes, and the axial force can control the amplitude of these fluxes.

D. Tilt Moment and Radial Force

The tilt moment and radial force are generated by 4-pole rotating magnetic flux and uniform flux. Fig. 2 shows the generation of tilt moment and radial force by 4-pole flux. The 4-pole flux unbalance the air gap flux density at right pole and left pole, and produce the difference of the attractive force. This imbalance produces the tilt moment around radial axis. The 4-pole flux also generate radial force due to south-poles of the stator and north- and south-poles of the rotor.

Fig. 3 shows the generation of tilt moment and radial force by uniform flux. Supplying direct current to all coils of the stator generates the magnetic flux flowing in the cylindrical magnetic path and makes uniform magnetic pole at the edge of the cylinder. The poles of the rotor and the cylinder edge

Table I. PARAMETERS OF THE ROTOR AND THE STATOR

Rotor and Stator	
Material	Silicon Steel
Rotor	$\phi 50 \times \phi 36 \times 7$ mm
Stator	$\phi 50 \times \phi 36 \times 25$ mm
Slot	10 wide $\times$ 18 deep mm
Coil Turns	200
Outer Cylinder	$\phi 65 \times \phi 60$ mm
Air Gap	2.7 mm
Rotor PM	
Material	NdFeB
Magnetization	Perpendicular
Shape	Segment
Size	r25 $\times$ r18 $\times$ 1 $\times 150^\circ$ mm

generate the attractive and repulsive force, and then the radial force can be obtained. In case of Fig. 3, north-pole is generated at the edge of stator by the direct current, and the attractive force acts on left side of the rotor and repulsive force acts on right side, then the left directional radial force is generated. At the permanent magnets on the rotor, the attractive force at the north-pole increases, and the south-pole force decreases, then the tilt moment is generated. The direction of the tilt moment is opposite to the moment by the 4-pole current. Hence, the tilt moment and radial force along the permanent magnet can be controlled by combining these two kinds of current.

By using two pairs of the stator and rotor, which has 90 degrees shifted permanent magnet, we can obtain the tilt moments and radial forces along two directions.

III. FEM ANALYSIS

In order to confirm the generation of tilt moment and radial force, three-dimensional finite element analyses was carried out by using JMAG. The radial force and tilt moment of a pair of 2-pole rotor and 6-slot stator are calculated by static magnetic analysis. The geometries of the rotor and stator are shown in table I.

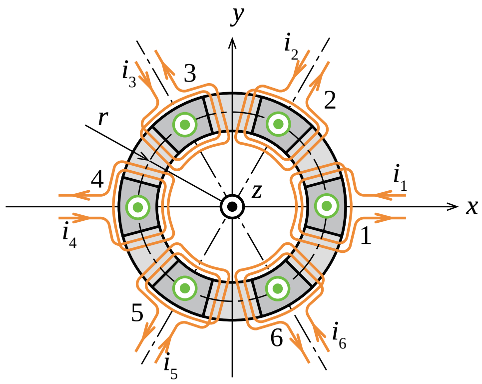
A coordinate system is defined as shown in Fig. 4. The direction of magnetization and the orthogonal direction of it are defined as a and b, respectively. The angle between x and a is defined as ψ. The rotation around each axis are represented by $\theta_z, \theta_x, \theta_y, \theta_a$ and θ_b.

The current of the stator coils is the summation of 2-pole current, 4-pole current and direct current;

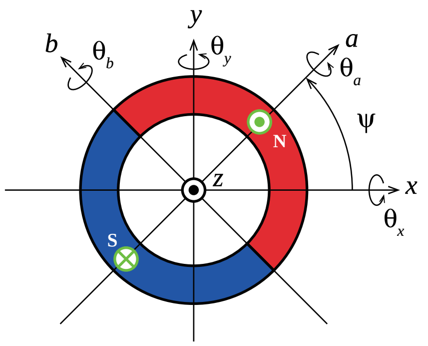
$$i_k = i_{2pk} + i_{4pk} + i_{dc} \quad (1)$$

$$i_{2pk} = i_z \cos\left\{\psi - \frac{(k-1)\pi}{3}\right\} + i_m \sin\left\{\psi - \frac{(k-1)\pi}{3}\right\} \quad (2)$$

$$i_{4pk} = i_{tx} \sin\left\{\psi - \frac{2(k-1)\pi}{3}\right\} + i_{ty} \cos\left\{\psi - \frac{2(k-1)\pi}{3}\right\} \quad (3)$$



(a) Top view of stator



(b) Top view of rotor

Figure 4. Coordinate System.

where $k = 1 \sim 6$ is a coil number. i_z is direct axis current and controls axial force. i_m is quadrature axis current and controls motor torque. i_{tx} and i_{ty} control tilt moment around x and y, respectively.

Fig. 5 shows the results of the radial force and tilt moment. Only the direct current is supplied to the stator, and the radial forces along a and b and tilt moment around a and b are calculated at $\psi = 0$. The radial force F_a and tilt moment M_b decrease in proportion to the direct current. F_b and M_a are not affected by the direct current.

Fig. 6 shows the radial force and tilt moment for 4-pole current at $\psi = 0$. The 4-pole current is supplied to produce only the moment around b-axis. That is

$$i_{tx} = -i_{tb} \sin \psi \tag{4}$$

$$i_{ty} = i_{tb} \cos \psi \tag{5}$$

F_a and M_b are linear with respect to i_{tb}. In this case, the slope of F_a is positive.

Fig. 7 and 8 shows the radial force and tilt moment with constant tilt current, $i_{tb} = 1$A and direct current, $i_{dc} = 1$A, respectively. In case of Fig. 7, the radial force produced by i_{tb} is canceled by i_{dc}. In case of Fig. 8, the tilt moment produced by i_{dc} is canceled by i_{tb}. These results confirm that the undesirable force and moment can be canceled by using both i_{dc} and i_{tb}, and just radial force or tilt moment can be obtained.

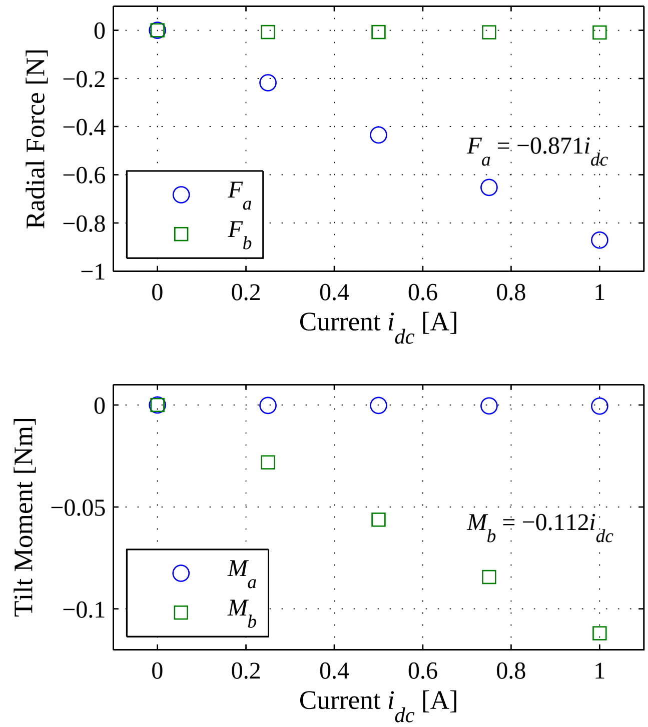


Figure 5. Radial force and tilt moment for direct current at $\psi = 0$.

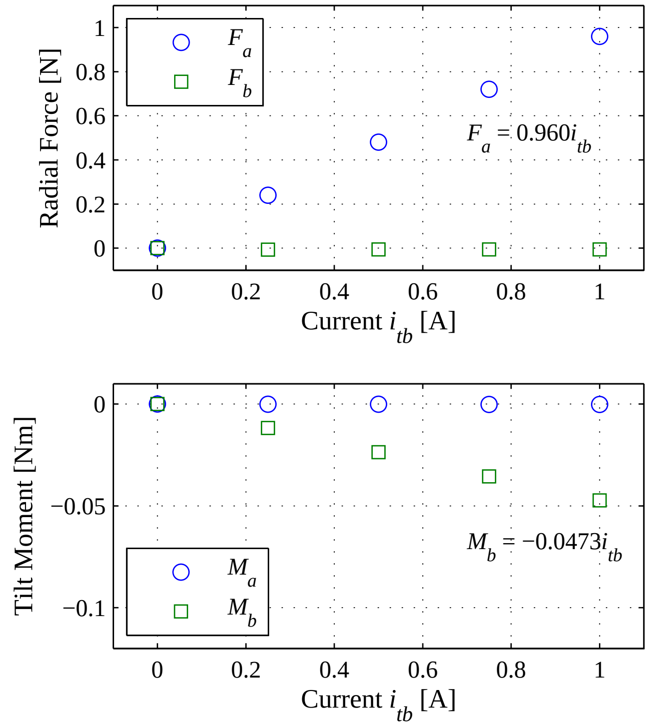


Figure 6. Radial force and tilt moment for 4-pole current at $\psi = 0$.

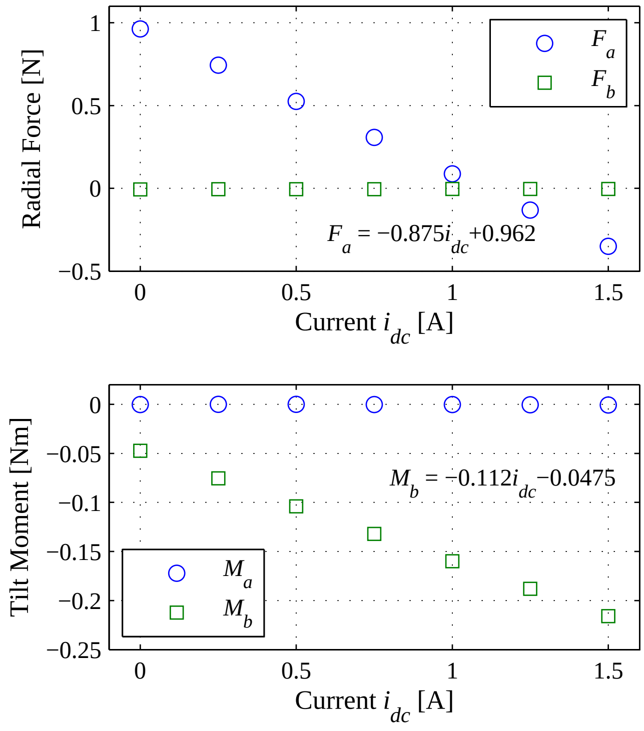


Figure 7. Radial force and tilt moment with $i_{tb} = 1$A at $\psi = 0$.

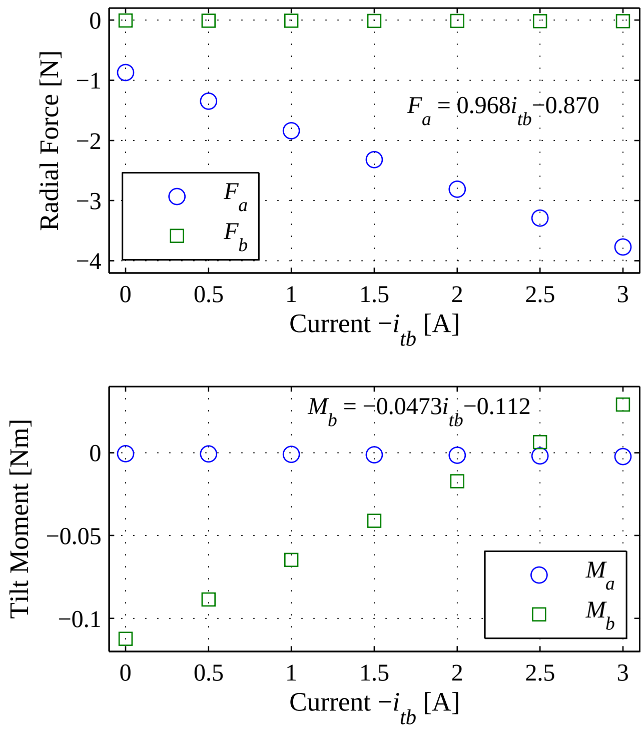


Figure 8. Radial force and tilt moment with $i_{dc} = 1$A at $\psi = 0$.

Moreover, the force gain and moment gain are almost same as the previous cases. Therefore, the radial force and tilt moment can be represented by

$$\begin{bmatrix} F_a \\ M_b \end{bmatrix} = -\begin{bmatrix} K_{fdc} & -K_{ftb} \\ K_{mdc} & K_{mtb} \end{bmatrix} \begin{bmatrix} i_{dc} \\ i_{tb} \end{bmatrix} \tag{6}$$

By solving the above equation, we have

$$\begin{bmatrix} i_{dc} \\ i_{tb} \end{bmatrix} = -\frac{1}{K_{fdc}K_{mtb} + K_{ftb}K_{mdc}} \begin{bmatrix} K_{mtb} & K_{ftb} \\ -K_{mdc} & K_{fdc} \end{bmatrix} \begin{bmatrix} F_a \\ M_b \end{bmatrix} \tag{7}$$

These current achieve decoupling control of radial force and tilt moment.

IV. Summary

This paper introduces a novel axial gap self-bearing motor, which has a capability of the 5-DOF active position control. The results of the FEM analysis show that the radial force and tilt moment can be controlled by combination of dc current and 4-pole current. We are making a prototype and the experimental results will be shown.

V. Acknowledgment

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