Numerical Calculation and Analysis of Suspension Force of Permanent Magnetic Bearing in Conical Spiral Blood Pump

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***Abstract*—The structure of conical blood pump is introduced, and a new hybrid-type permanent magnetic bearings(PMB) composed of axial and radial PMBs are presented. The hybrid-type PMBs can suspend the rotor in axial and radial directions by the magnetic force. The static magnetic field and the force of PMBs are also computed numerically with the software ANSYS. Study indicates that the radial magnetic suspension force created by the radial bearing is in proportional to the offset of the shaft in radial direction, while the axial magnetic suspension force produced by the radial magnetic bearing do harm to the stability of the bearing in axial direction. Such problem can be solved by reasonable design of the axial and radial magnetic bearings. The research work on PMB provides theoretical basis for the design, optimization and application of conical spiral blood pump.**

***Keywords*—blood pump, permanent magnetic bearing, suspension force, ANSYS**

I. INTRODUCTION

Heart disease has become the leading cause of human death. The blood pump, as the left ventricular assist device (LVAD), is studied to help treating the disease. For more than 50 years of efforts, the technology of blood pump has been greatly developed, some of the blood pumps have been in the period of animal tests or clinic use [1,2,3]. However, experiments and clinic applications indicate that, as the long-term running of the blood pump with high rotating speed inside human body, the heat produced by mechanical bearings because of the friction, may damage blood cells, cause thrombus and hemolysis, and even threat the patients' life. Also the mechanical bearings are easily damaged because of the friction. In order to minimize the damage of the blood cells while using blood pump, and make the blood pump in human body run a long time without mending, magnetic maglev technique can be used to levitate the rotor without friction.

At present, for most of the blood pump with magnetic bearings, the rotor is levitated by the mutual action of magnetic field produced by direct current(DC) coil bearings .Li X. J from Huazhong University of Science and Technology used driving coil to control the blood pump rotor to achieve radial and axial suspension, sliding model variable structure control method was applied to control the non-linear effect, such as quiver when rotation speed of the rotor is greater than 6000r/min [4]. Christoph H. Huber, Piergiorgio Tozzi from Service de Chirurgie Cardiovasculaire, Centre Hospitalier Universitaire Vaudois in Switzerland, designed a novel implantable axial flow pump with full magnetic suspension, the system further permanently consists of an inflow canella connected to the left ventricle, an angled connection to the outflow canella anastomosed onto the ascending aorta, a percutaneous pump cable connected to the control unit and a main as well as a backup battery. This axial pump was free of seals, bearings, mechanical friction and wear [5]. Roland Hetzer, Yuguo Weng from Department of Cardiothoracic and Vascular Surgery, Berlin, Germany, also designed an axial flow blood pump, they adopted magnetic suspension bearings to stabilize the impeller actively in the axial direction and passively in the radial direction. Thus, the impeller has no mechanical contact with the pump housing, and this renders the system completely wear-free and almost silent [6]. The pump has a controlling wire carrying DC through human body to supply power for the bearing, therefore, the patient may be easily infected by the wire, and complicated control devices are also needed to control the suspension of rotor. In recent years, with the fast development of fabricating technique of rare-earth permanent magnetic material, the rare-earth permanent magnetic bearing has been widely applied in many areas. PMB has found its way in blood pump. Qian K. X, from Jiangsu University applied a novel PMB to achieve the rotor's axial and radial suspension. Their PMB bearings are made up of two magnetic rings which were different in size but the same in magnetic direction, and has the function similar to that of axial springs and radial bearings [7]. A. Hamler, V. Gorican, B. Stumberger, M. Jesenik, M. Trlep, Faculty of Electrical Engineering and Computer Science, University of Maribor, Smetanova, presented a special design of a passive magnetic bearing with permanent magnets on the fixed and the rotating part of the bearing. Peculiarity of the presented passive magnetic bearing is its ability to take radial and axial loads in both directions by using axially magnetized permanent magnets [8].

In this paper, a new kind of hybrid-type PMBs composed of axial and radial PMB are introduced. The bearings can realize the rotor's suspension in axial and radial direction. It makes the whole blood pump simple in structure and small in size [9]. According to Earnshaw's theory [10], the PMBs are not suitable for suspension of the rotor independently. But a rotating rotor with high speed and large inertia can maintain its stability merely with PMB. In this article. So we only analyzed the static magnetic field generated by PMBs with ANSYS and calculate the force produced by the bearings. All the research work on PMB provides theoretical basis for the design, optimization and application of conical spiral blood pump.

II. INTRODUCTION OF THE BLOOD PUMP AND THE PRINCIPLE OF FINITE ELEMENT ANALYSIS

A. Structure of the conical spiral blood pump with PMB

The structure of the conical spiral blood pump with PMBs is shown in Fig. 1. It is composed of conical spiral rotor, housing, radial and axial PMBs. For the radial PMB, the inner magnetic rings are fixed at both end of the rotor, the outer magnetic rings are fixed in the flow-guide wheels. There is clearance between the outer and inner rings. For the axial PMB, two magnetic rings are mounted in the flow-guide wheel, the other two rings are fixed on both end of the rotor, which are the rings of the inner rings of the radial PMB. The flow-guide wheels are fixed on the housing, the rotor can rotate under the mutual support of the axial and radial PMB without mechanical contract. As is shown in Fig. 1, the blood flows from the left to the right. The PMB is made of Nd-Fe-B whose coercivity is $(12\text{-}16)\times10^3$A/m, and magnetic work product is $(382.08\text{-}1233.8)\times10^3$J/m^3. Since using the hybrid-type PMBs instead of traditional mechanical bearing or electromagnetic bearing, the blood pump is simpler in structure and lower in costs.

B. Virtual work principle in magnetic force calculation

The virtual work principle in calculating the magnetic force is to compute the moving (rotating) body's displacement under the magnetic work [10,11], and its calculation formula is as following

$$W_m = \iiint_V \left(\int_0^H B \cdot \mathrm{d}H \right) \mathrm{d}V \tag{1}$$

Where V——volume of the magnetic body
B——magnetic flux density
H——magnetic intensity

Then, the magnetic force along the l direction is

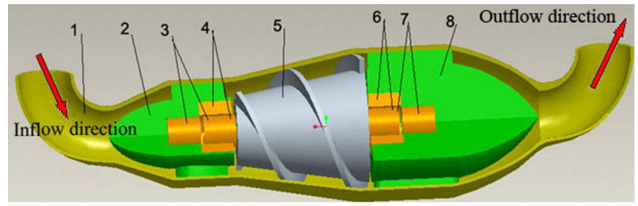
$$F_l = \frac{\partial w_m}{\partial l} = \iiint_V \left(B \cdot \frac{\partial H}{\partial l} \right) \mathrm{d}V + \iiint_V \left(\int_0^H B \cdot \frac{\partial H}{\partial l} \right) \frac{\partial}{\partial l} \mathrm{d}V \tag{2}$$

Since the difficulty of getting the analytic results from (2), the finite element method based on variable principle is usually used to solve the problem. If the solution area is divided into many small elements, according to the virtual work principle, equation (2) can be expressed as (3) when adopting the scalar magnetic potential method to compute the magnetic force.

$$F_l = \sum_e \left[\iiint_{Ve} \left(B \cdot \frac{\partial H}{\partial l} \right) \mathrm{d}V + \iiint_{Ve} \left(\int_0^H B \cdot \frac{\partial H}{\partial l} \right) \frac{\partial}{\partial l} \mathrm{d}V \right] \tag{3}$$

Choosing the field function φ as

$$\varphi = \sum_1^e N_i \varphi_i \tag{4}$$



1-housing 2,8-flow-guide wheel 3,7-axial PMB 4,6-radial PMB 5-rotor

Figure 1. The structure of the conical spiral magnetic blood pump.

Where, N_i is the shape function, φ_i is the scalar magnetic potential of the elements' point i, e is the total number of the elements. Then the magnetic intensity can be deduced as

$$H = -\nabla \varphi \tag{5}$$

When using local volume coordinate system, the followings expressions can be got

$$\frac{\partial}{\partial l}(\mathrm{d}V) = |J|^{-1} \cdot \frac{\partial |J|}{\partial l} \mathrm{d}V \tag{6}$$

$$\frac{\partial H}{\partial l} = J^{-1} \cdot \frac{\partial |J|}{\partial l} H \quad 7)$$

Where, J is the transformation Jacbian matrix of local volume coordinate system and global volume coordinate system. For the linear tetrahedron, the matrix is

$$J = \begin{bmatrix} x_1 - x_4 & y_1 - y_4 & z_1 - z_4 \\ x_2 - x_4 & y_2 - y_4 & z_2 - z_4 \\ x_3 - x_4 & y_3 - y_4 & z_3 - z_4 \end{bmatrix}$$

Where, x_i, y_i, z_i(i=1, 2, 3, 4) stands for the coordinate value of the point i. Substituting (4), (5), (6), (7) into (3), we can get the following expression

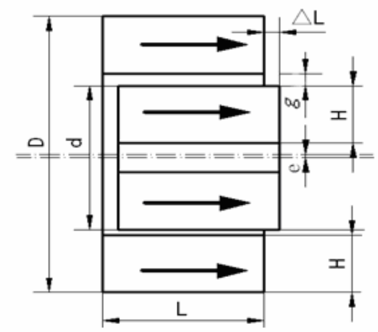
$$F_l = \sum_e \iiint_{Ve} \left[\left(-B \cdot J^{-1} \cdot \frac{\partial J}{\partial l} \right) \cdot H + |J|^{-1} \cdot \frac{\partial |J|}{\partial l} \int_0^H B \cdot \mathrm{d}H \right] \mathrm{d}V \tag{8}$$

In numerical simulation, by adding all elements together, the value of F_l can be got.

III. RESULTS AND ANALYSIS

A. Calculation model, material, structure, parameter and boundary conditions

In this paper, we simulate and analyze the magnetic field and suspension force of the PMB numerically with software ANSYS. As is shown in Fig. 2, the arrows indicate magnetizing direction. In simulation the remanence of the permanent magnet is B_r=1.08T, coercivity is H_c=981000A/m^3. The thickness of both the outer and inner magnet rings is H=2mm, the outer diameter of the outer magnet ring is D=9.5mm, the outer diameter of the inner magnet ring is d=5mm, the length of the magnet ring is L=5mm. The radial air clearance between the outer and inner rings is defined the average air clearance g_0 when offset e is zero(g_0=0). Average air clearance g_0 is an important parameter that has greater influence on the magnetic suspension force to the PMB.



D-diameter of outer ring *d*-diameter of inner ring *H*-thickness of the rings e-radial offset *L*-axial offset of the inner ring *g*-radial air clearance between inner and outer magnetic rings

Figure 2. Sketch of the radial PMB.

Since the structure of the magnetic rings is symmetrical, 2D model is applied in computing magnetic field. Under the same computation capacity, 2D model improves the accuracy because of denser meshes of the region, comparing with 3D model. In order to increase the simulation accuracy further, large air region outside the magnetic rings is modeled, the inner magnetic ring is regarded as module, magnetic flux parallel boundary conditions is utilized. An MVP/RSP resolver is adopted to compute the virtual work produced by the magnetic rings.

B. Analysis of the radial suspension force for radial PMB

The sketch of the radial PMB is shown in Fig2. When both the radial and axial offsets of the inner magnetic ring are zero (g_0=0, ΔL=0), the rotor is in equilibrium, otherwise, the rotor is in imbalance.

Fig. 3 shows the magnetic flux distributions of the radial PMB when the radial offset is *e*=0.1mm. Curves in Fig4 shows the relationship between the levitated force and the radial offsets when the axial offset is zero (ΔL=0). Fig. 3 clearly shows that all magnetic fluxes generated from both the inner and outer magnetic rings form a group of closed curves. The air clearance decreases gradually as the inner magnetic ring goes downwards, and the magnetic flux is getting thicker and thicker than that of opposite direction.

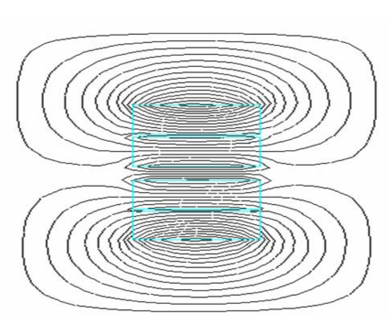


Figure 3. Magnetic flux of the radial PMB(*e*=0.05mm).

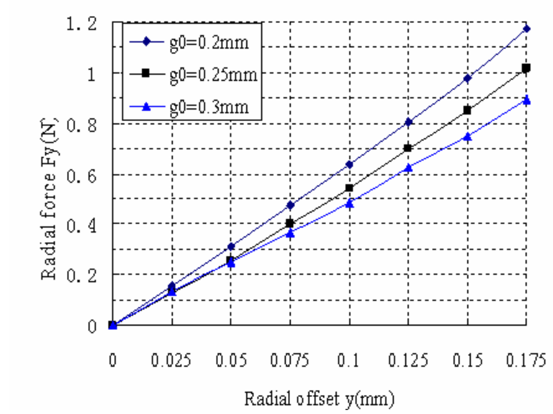


Figure 4. Relationship between the suspension force and the radical offsets with the axial offset ΔL =0.

Fig. 4 shows that the levitated force on the inner magnetic ring is in proportion to the radial offset of the magnetic ring. The greater the radial offset, the stronger the suspension forces. Fig. 4 also shows that the average air clearance g_0 has great influence on the suspension force. The greater of the air clearance is, the smaller the suspension force is. To get adequate suspension force is the key-point in designing PMB. Take the curve with air clearance g_0=0.2mm as an example, when radial offset is *e*=0.1mm, the suspension force produced by PMB is 0.65×2N=1.3N, the weight of the rotor is 0.3N approximately, there is still 1N force to overcome the radial disturbance to maintain the equilibrium of the rotor.

C. Analysis of the axial suspension forces produced by radial PMB

Because of the inherent instability of radial PMB, the inner and outer magnetic rings move along the axial easily, which is harmful to the stability of the rotor. Fig. 5 shows half of the magnetic flux distribution with radial offset *e*=0 and axial offset ΔL=0.05mm. Fig. 6 shows the relationship between the axial suspension forces and the axial offsets.

Fig. 5 shows that the magnetic fluxes in between the inner and outer magnetic rings form a closed curves, along the offset of the inner ring, the magnetic fluxes are denser than that of opposite direction.

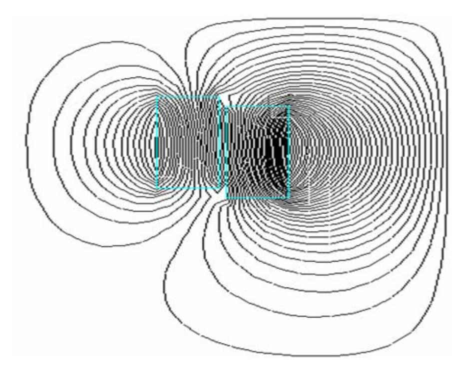


Figure 5. Magnetic flux when *e*=0 and ΔL =0.05mm.

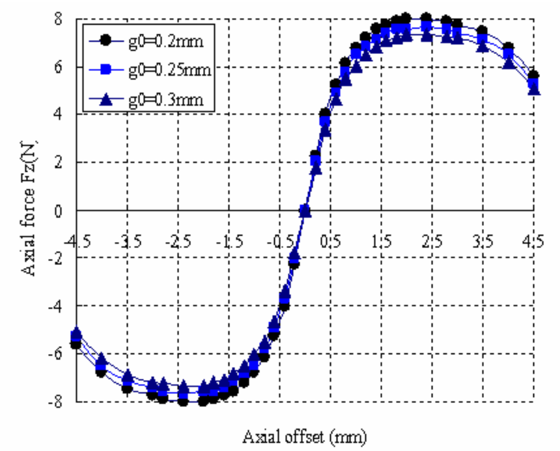
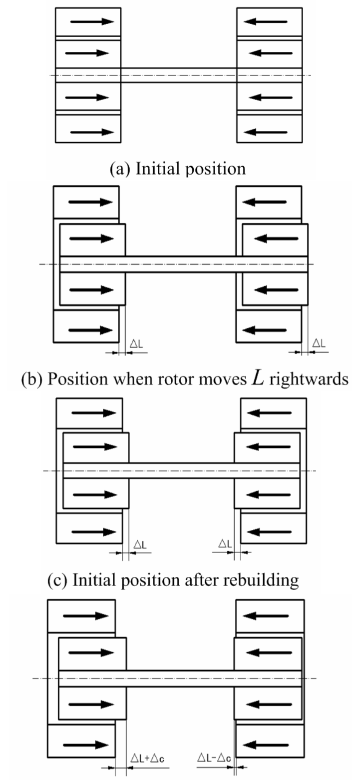


Figure 6. Relationship between the axial suspension forces and axial offsets.

Fig. 6 shows that the force direction acting on the inner ring is in the same direction of the offset of the inner ring, and has nothing to do with the magnetizing direction. The absolute value of the axial magnetic force increases quickly with the increasing of the axial offset within ΔL =±1.5mm. While axial offset changes from 1.5 to 2.5mm (or from -1.5 to -2.5mm), the magnetic force increases slowly. When axial offset is greater than ±2.5mm, the absolute value of the axial magnetic forces begins to drop. Moreover, the average air clearance g also has some effects on the axial forces. The smaller the g is, the greater the axial and radial forces are. The optimizing results can be obtained by reasonable design of the PMB.

D. Relationship between the axial suspension forces of the radial PMB and its structure

As is shown in Fig. 6, force direction on the inner magnetic ring is the same with the axial offset, the force increases greatly within ΔL =±1.5mm, which is danger to the stability of the individual PMB. Fig. 7(a) shows a pair of radial magnetic bearings with inner and outer rings being in its initial position without axial offset (ΔL = 0). Theoretically, in this condition, no axial forces produced, the rotor is in stability. When the rotor moves ΔL rightwards, as is shown in Fig. 7(b), according to the relationship between the axial suspension force and the axial offset shown in Fig. 6, the axial force acts on the inner rings on both sides, then the rotor will move rightwards, in this case, the rotor will be accelerated to move rightwards, and the stability of the rotor will be worsen. So it is necessary to rebuild the structure of the bearing. Fig. 7(c) shows the improving one, the inner rings on both sides move ΔL along their magnetizing directions. Since the axial offset direction of both rings is opposite, the moving distance is the same, the composite force on the rotor along the axial direction is zero, the rotor is in stability. If the rotor moves rightwards for a distance of Δc, as is shown in Fig. 7(d), the total offset of the left inner magnetic ring is $\Delta L+\Delta c$, and the right one is $\Delta L-\Delta c$. According to Fig. 6, the force on the left inner ring is rightwards, the force on the right one is leftwards, some of the force counterbalances each other. The force remained is toward left, which is opposite to rotor's moving direction, and is helpful to maintain the rotor being in stability.



(a) Initial position

(b) Position when rotor moves L rightwards

(c) Initial position after rebuilding

(d) Position when rotor moves c rightwards

Figure 7. Structure of the radial PMB.

E. Axial PMB

Because of axial instability of the radial PMB, a pair of axial PMB is necessary for the stability of the rotor in axial direction. The structure of the axial PMB is shown in Fig. 8, the bearing is composed of two magnetic rings, one is fixed in flow-guide wheel, the other is fixed on the end of the rotor, both the magnetic rings are the same in size, but different in magnetizing direction. According to the magnetic theory, both the magnetic rings form a repulsive axial PMB. From Fig. 1, we know that one of the axial magnetic rings and the outer magnetic rings of the radial magnetic bearing are mounted on the same flow-guide wheel. The forces produced by the two magnetic rings are internal forces, and couldn't affect the rotors' levitation. Fig. 9 shows the magnetic flux distribution for half model of the axial PMB with the axial air clearance z_0=0.5mm, Fig. 10 shows the relationship between the axial suspension force and the axial air clearance without radial offset.

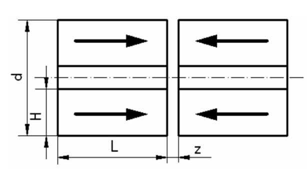


Figure 8. Axial PMB.

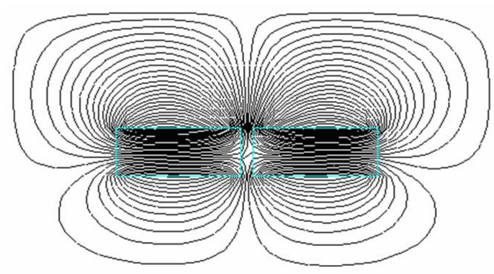


Figure 9. Magnetic flux distribution of half model of the axial PMB with the axial air clearance z_0=0.5mm.

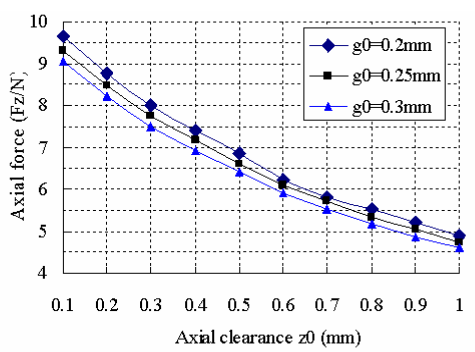


Figure 10. Relationship between the axial suspension force and the axial air clearance.

Fig. 9 shows that the magnetic fluxes are closed, the smaller the axial air clearance is, the denser of the magnetic fluxes are. Fig. 10 shows that with the increasing of the axial air clearance, the axial magnetic force decreases gradually. Meanwhile, the radial average air clearance g_0 also has some influence to the axial force. The greater the radial average air-clearance g_0 is, the weaker the axial force of the axial magnetic bearing is. In order to keep the rotor steady in the axial direction, the axial force produced by the axial magnetic bearing must be greater than that produced by the radial PMB. Take g_0=0.25mm, ΔL=0.5mm for example, assuming that no radial offset exists, from Fig. 6, Fig. 7(a) and Fig. 10, we know that when the rotor moves rightwards for a distance Δc = 0.2mm, forces towards the right acting on the left inner magnetic ring is (4.93+5.46)N, forces towards the left acting on the right inner ring is (7.85+3.42)N. Then the force towards left is greater than that of towards right, the rotor will moves towards left and back to its initial steady position.

IV. CONCLUSIONS

The numerical results with 2D model PMB show that the axial and radial levitated force produced by the PMB is influenced by many factors such as the structure of the PMB, radial average air clearance and axial offset. For radial PMB, the levitated force on the inner magnetic ring is in proportion to the radial offset of the magnetic ring. The greater the radial offset, the stronger the suspension force. The greater of the air clearance is, the smaller the suspension force is. For axial PMB, with the increasing of the axial air clearance, the axial magnetic force decreases gradually. The greater the radial average air clearance g_0 is, the weaker the axial force of the axial magnetic bearing is. In order to keep the rotor steady in the axial direction, the axial force produced by the axial magnetic bearing must be greater than that produced by the radial PMB.

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