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Study on Bearing Capacity Characteristics of an Axial Permanent Magnetic Bearing

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Abstract: An axial permanent magnetic bearing is designed by selecting the combination of type a1 of basic configurations of axial PMB. Considering that this bearing only produces axial displacement and has the axis-symmetry structure, so it could be simplified into an axis-symmetry 2-D plane model for studying. Then, using ANSYS to make magnetic force calculation about 1/2 model and the influence of the width, thickness, section area and gap of both stator magnetic ring and rotor magnetic ring on the axial bearing capacity and axial stiffness is acquired. In the end, through contrastive analysis, some useful conclusion are obtained which is the optimization basis for physical design of this type of axial PMB. It has certain guiding significance for engineering application.

Key words: Axial permanent magnetic bearing, ANSYS, bearing capacity characteristics, axial bearing capacity, axial stiffness

INTRODUCTION

Permanent Magnet Bearing (PMB) has the following advantages: micro friction, no attrition, high speed, low noise and power loss, no lubrication and sealing and a long life. According to Earnshaw (1842) law, PMB can't achieve stable suspension on all degrees of freedom. So some other active supporting schemes should be introduced on at least one degree of freedom in PM maglev system. More specifically, PMB combined with electromagnetic bearing and mechanical bearing can form hybrid MB system. In recent years, with the rapid development of NeFeB rare-earth permanent magnet material, many scholars, at home or abroad, have done a great deal of researches on PMB, especially the research of bearing capacity and stiffness. So far, the research method mainly focus on the Equivalent Magnetic Charge Method (EMCM) (Yonnet *et al.*, 1993; Tan *et al.*, 1994; Huang *et al.*, 2005), the Equivalent Surface Currents Method (ESCM) (Okuda *et al.*, 1984; Wang *et al.*, 2009), the Magnetic Vector Potential Method (MVPM) (Li *et al.*, 2006), the Virtual Displacement Method (VDM) (Marinescu and Marinescu, 1994; Tian *et al.*, 2007) and the Finite Element Method (FEM) (Yang *et al.*, 2001; Liu *et al.*, 2006), etc. And it is shown by previous experiments that the finite element solutions are consistent with experimental results when computing the bearing capacity and stiffness of PMB (Yao, 2004; Zhang *et al.*, 2012). Therefore, this thesis determines to research the bearing capacity characteristics of PMB to obtain the relation between bearing capacity, stiffness and structure parameters of magnet ring by using ANSYS so that some scientific basis can be provided for optimum structural design of PMB.

STRUCTURE OF AXIAL PMB

In 1981, Yonnet (1981) drew a conclusion that different basic configurations of axial PMB can be composed of permanent magnetic rings with axial and radial magnetization (Fig. 1).

In practical applications, magnetic ring with radial magnetization is difficult to realize while magnetic ring with axial magnetization is widely used. Hence, magnetic ring with axial magnetization should be selected to design PMB. Furthermore, in the ten basic configurations of axial PMB as shown in above, type a1 with simple structure and easy installation has the strongest axial force and tiny radial force for the vertical middle position which indicates that type a1 is suited for repulsive case of axial PMB. Therefore, this thesis takes type a1 as basis structure to compose an axial PMB which mainly applied for supporting axial load. The structure of this PMB is shown in Fig. 2.

Based on Earnshaw (1842) law, the axial PMB as shown in Fig. 2 has the radial instability so that some supplemental restraint devices need to be imposed on both ends of the shaft. Thanks to the exist of restraint

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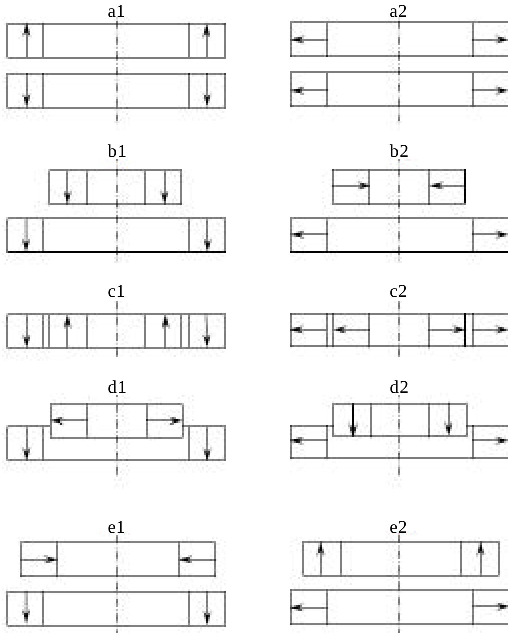

Fig. 1: Basic configurations of axial PMB

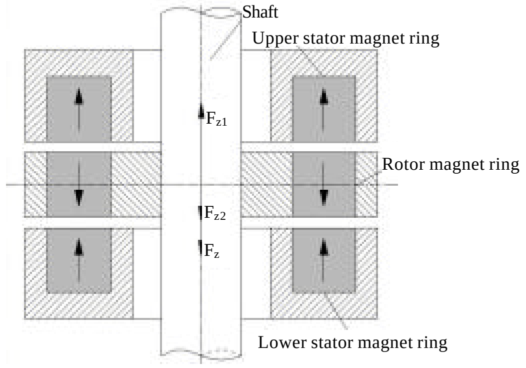

Fig. 2: Structure of axial PMB

device in radial direction, the PMB no longer produces radial displacement which shows that its radial force and stiffness don't have to be considered. As a result, this thesis only discusses the axial capacity and stiffness of the axial PMB.

The working principle of the axial PMB is described as follows. When the axial PMB working, its shaft will be acted by an external load F_z, then rotor magnetic ring along with shaft generates a downward displacement z which makes the gap between lower stator magnetic ring and rotor magnetic ring become smaller and the magnetic force F_{z1} (upward) on the shaft correspondingly increase while the gap between upper stator magnetic ring and rotor magnetic ring become bigger and the magnetic force F_{z2} (downward) on the shaft correspondingly decrease.

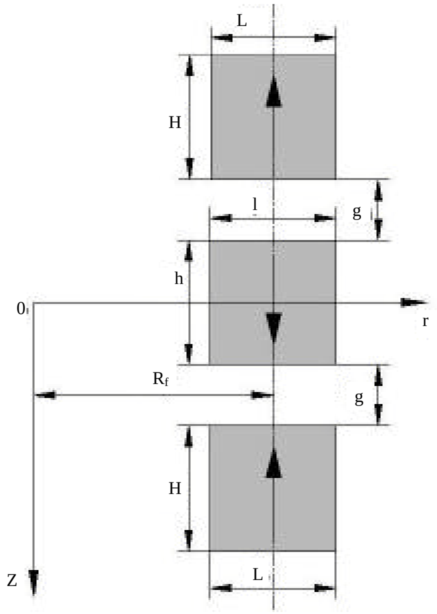

Fig. 3: A half of sectional model and structure size

With the axial displacement increasing, the resultant force will increase until its value equals to the external force, this moment both the shaft and rotor magnetic ring are in stable suspending state. So the axial external load F_z is:

$$F_z = F_{z1} - F_{z2} \tag{1}$$

The axial stiffness is defined as:

$$K_z = \frac{dF_z}{dz} \tag{2}$$

In order to analyze the PMB structure, this thesis adopts its a half of sectional model and that establishes r, z 2D coordinates, among which r axis represents radial direction and z axis represents axial direction. Specific structure size is shown in Fig. 3. As for the magnetic ring, its material is type N35 NdFeB. Moreover, by measuring the custom made magnetic ring in laboratory, its performance parameter is obtained in the following:

$$H_c = 922880\text{A/m},\ B_r = 1.2106\text{T}$$

Therefore, its relative permeability is:

$$\mu_r = \frac{B_r}{\mu_0 H_c} = \frac{1.2106}{4\pi \times 10^{-7} \times 922880} = 1.0443 \tag{3}$$

In Fig. 3, the meaning of each parameter is listed as follows: H is the thickness of stator magnetic ring, L is the width of stator magnetic ring, h is the thickness of rotor magnetic ring, l is the width of rotor magnetic ring, g is the average gap between stator and rotor magnetic ring, R_f is the average radius of magnetic ring (the average value between inside radius and outside radius of magnetic ring).

PROCESS OF SOLVING MAGNETIC FORCE

FEM is a practical method for computing magnetic force and now becomes a reference standard to measure whether right or wrong about magnetic analysis. With the help of ANSYS, this thesis mainly calculates the magnetic force of the axial PMB by using FEM, aiming at quickly and efficiently analyzing the effect of the size of magnetic ring toward magnetic force in the axial PMB. The following is the basis procedure of analyzing magnetic force based on ANSYS.

Building finite element model: The axial PMB is 3D, but just taking the fact that it only generates axial displacement and magnetic rings are symmetrical about center shaft into consideration, it could be reduced to 2D plane problem in the actual calculations which can obtain high precision while reducing computation. So, 2D model is built at xz plane and in view of the existence of leakage flux, building bigger air model is essential. To obtain more accurate magnetic force value, PLANE53 is selected for axial symmetry element to be used for internal air and magnet ring and INFIN10 is correspondingly selected to be used for outermost air in the distant field. Likewise, for the options of material, the relative permeability of air is μ_r =1 while magnet ring is μ_r = 1.0443, H_c = 922880A/m.

Meshing: Because of the big impact that grid precision is toward result, here uses free meshing and takes fine grade.

Loading and solution: This thesis makes an assumption that outward leakage flux is irrespective when studying the inner magnetic field distribution of the axial PMB. Therefore, zero magnetic potential boundary condition is applied on the outermost layer of model, that is to say A_Z=0. In addition, because the magnetic force applying rotor magnetic ring needs to be computed, rotor magnetic ring is defined as a component and then exerted force boundary conditions. Next, solver is picked out and analysis type is determined to static analysis, then the solver is started to solve.

Post-processing: The magnetic force analysis result of the axial PMB can be checked in POST1. For this example, Fig. 4 and 5 respectively shows magnetic field line distribution diagram and magnetic flux density contour diagram of a certain structure parameter axial PMB when its downward axial displacement is 0.8 mm.

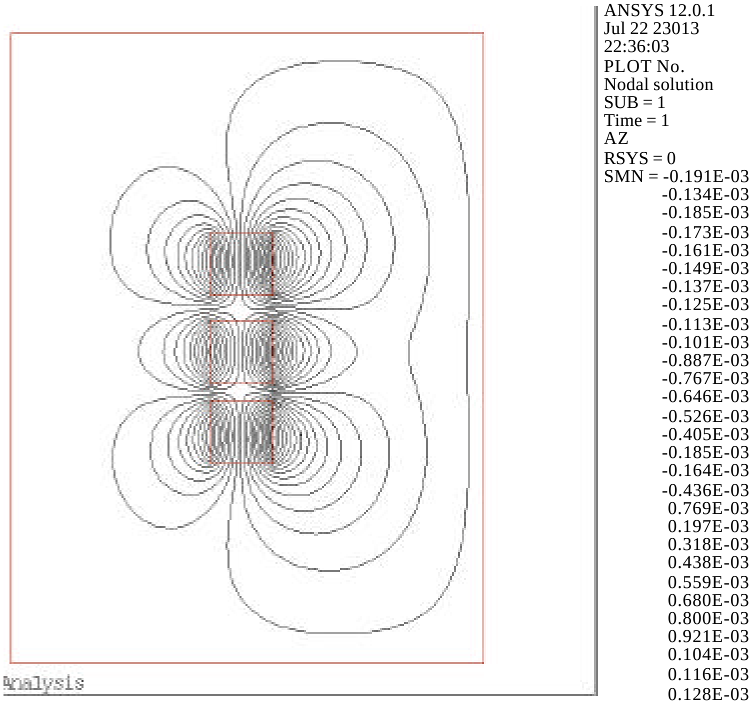

Fig. 4: Magnetic field line distribution diagram

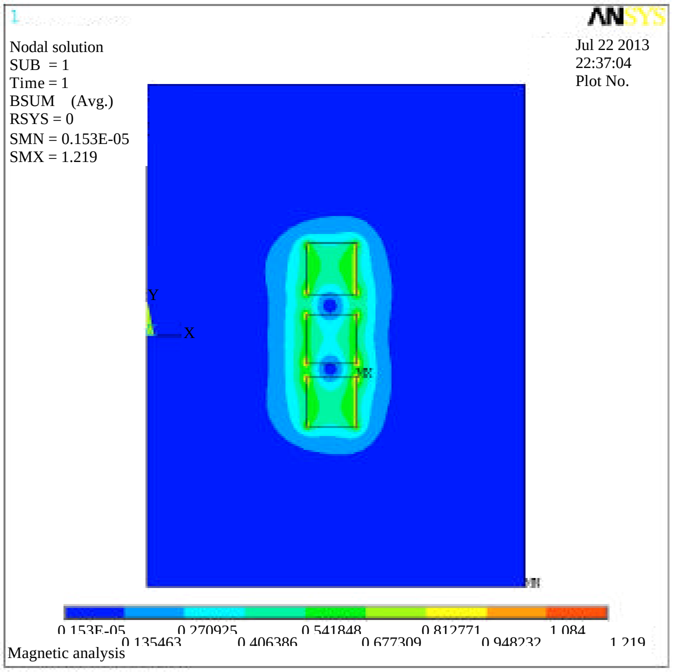

Fig. 5: Magnetic flux density contour diagram

Obviously, ANSYS computes magnetic force by VDM and MAXWELL and there are should be some minor differences between both. What calls for special attention here is that if the difference is bigger, modifying the precision and method of meshing ought to be considered.

ANALYSIS OF STRUCTURE SIZE

For the structure as shown in Fig. 2, so far, there has been less performance specification and lacking size design consideration at home or abroad. Besides, there has been little related data aim at optimum structural design of this type of PMB. Considering the above, here mainly performs a magnetic force analysis of the structure as Fig. 2, hoping to provide some references for the optimal design of PMB.

Considering service condition of magnet ring in the laboratory and overall size change of stator and rotor magnet ring, here takes R_f as constant, whose value is 44 mm. So the design consideration is mainly on basis of R_f. In addition, to make rotor magnetic ring always keep stable suspension under stationary state, the structural parameter's value of upper and lower stator magnetic rings must be identical. Specifically, the influence of the width, thickness, section area and gap of both stator magnetic ring and rotor magnetic ring on the axial bearing capacity and axial stiffness is shown in the following.

Influence of the width: At first, here presumes that g = 2 mm, H = h = 12 mm. Furthermore, in order to make rational analysis about the influence of the width of rotor and stator magnetic ring on axial bearing force and stiffness of PMB, this thesis decides to analyze both cases as $L \neq l$ and $L = l$. When $L \neq l$, l is taken as a constant of 12mm and the value of L successively takes 6, 9, 15 and 18 mm, that is $L/l \in \{0.5, 0.75, 1.25, 1.5\}$. At last, the above results are compared to the bearing force analysis of the case as $L/l = 1 (L = l = 12$ mm), then the curve of contrast analysis is obtained as shown in Fig. 6. While $L = l$, the value also successively takes 6, 9, 12, 15 and 18 mm, then the result of bearing force analysis is shown in Fig. 7.

It is shown in Fig.6 that the bearing stiffness of the axial PMB gradually increases as the both value tend to be equal in case of $L \neq l$ while L equals to l, the bearing stiffness attains its maximum. From Fig. 7, in case of $L = l$, the amplification of the bearing capacity and stiffness of the case of $L = H$ is more obvious than the case of $L<H$ while the case of $L>H$ compared to $L = H$ almost has no change. Therefore, when the width equals to the thickness, it hardly is an ideal result that improving bearing capacity and stiffness through increasing the width of magnetic ring.

Influence of the thickness: To analyze the influence of the thickness of the rotor and stator magnetic ring on the

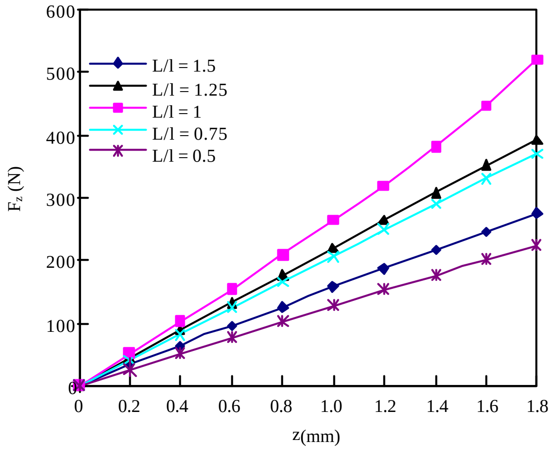

Fig. 6: Bearing capacity characteristics (L≠l)

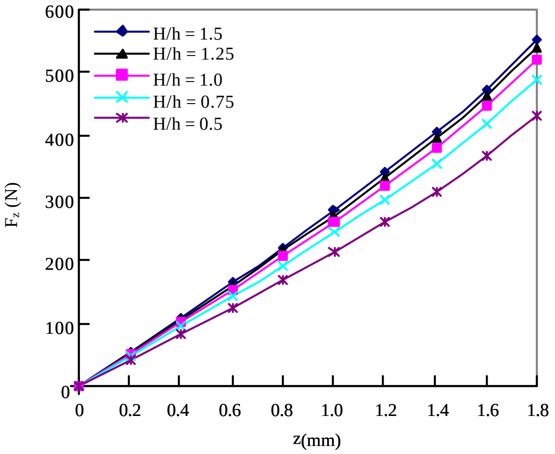

Fig. 8: Bearing capacity characteristics (H≠h)

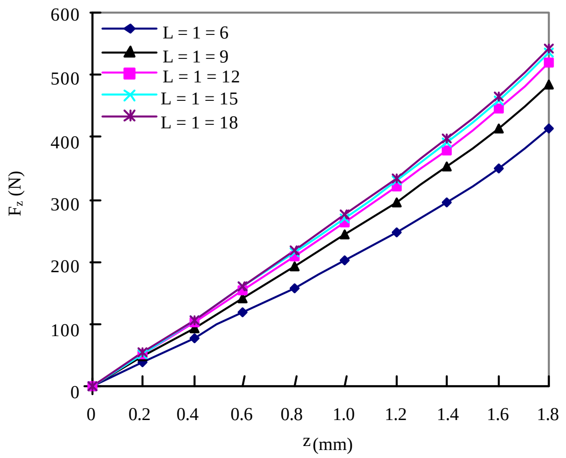

Fig. 7: Bearing capacity characteristics (L = l)

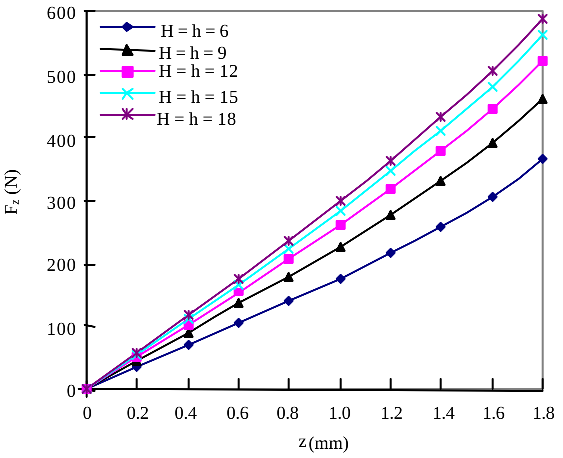

Fig. 9: Bearing capacity characteristics (H = h)

bearing capacity and stiffness of the axial PMB, here still divides the thickness into both cases as H = h and H≠h and presumes that g = 2 mm, L = l = 12 mm. When H≠h, h is taken as a constant of 12 mm and the value of H successively takes 6, 9, 15 and 18 mm, that is H/h∈{0.5, 0.75, 1.25, 1.5}. At last, the above results are compared to the bearing force analysis of the case as H/h = 1(H = h = 12 mm), then the curve of contrast analysis is obtained as shown in Fig. 8. While H = h, the value also successively takes 6, 9, 12, 15 and 18 mm, then the result of bearing force analysis is shown in Fig. 9.

It is shown in Fig.8 that the bearing stiffness of the axial PMB obviously increases as the increasing of H in the case of H<h, but when H>h, the increasing of H has almost no effect on the bearing stiffness of the axial PMB. So reasonably selecting the value of H appears especially essential. From Fig. 9, the bearing capacity and stiffness of the axial PMB increases radically as the increasing of H and h in the case of H<L while the growth trend markedly becomes slower and slower. Thus it can be seen that the influence of the selecting of H and h on the bearing capacity and stiffness of the axial PMB is significant.

Influence of the section area: In accordance with previous analysis, to make both magnetic rings generate ideal magnetic force, the width and the thickness are generally taken as equal in practical application. Here presumes that g = 2 mm and H = h = L = l which means that the section area is acted as a reference. So the section area of the magnetic ring is quadrate whose side length a successively takes 6, 9, 12, 15 and 18 mm. The result of bearing capacity analysis is shown in Fig. 10.

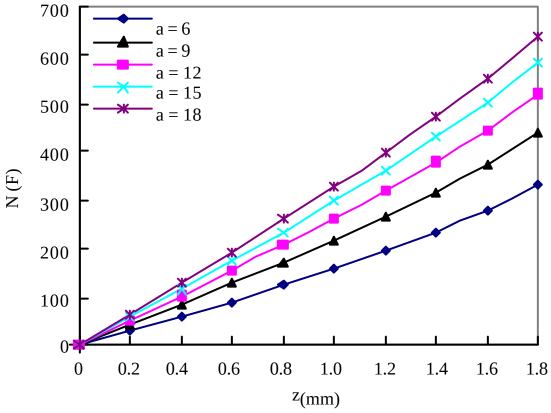

Fig. 10: Bearing capacity characteristics (a^2)

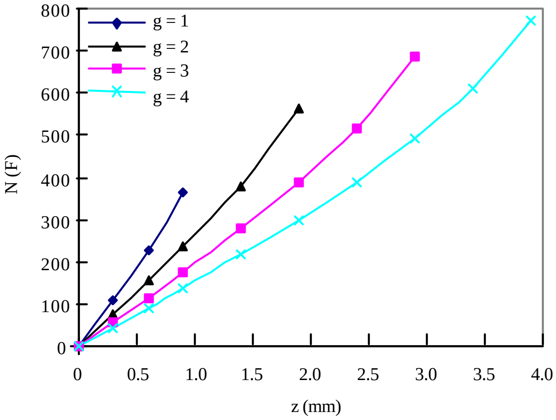

Fig. 11: Bearing capacity characteristics (g)

From Fig. 10, the axial bearing stiffness of the axial PMB increases and the increasing extent becomes slower and slower as the increasing of a. Besides, as the increasing of the axial displacement z, the axial bearing stiffness also has growing trend. So reasonably selecting the section area appears extremely essential.

Influence of the gap: Through referring to the above results and combining the actual conditions, here presumes that H = h = L = l = 12 mm and makes magnetic force analysis for the cases that g is successively assigned 1mm, 2mm, 3mm, 4mm. The analysis results are shown in Fig. 11.

It is shown in Fig. 11 that the axial bearing stiffness of the axial PMB gradually increases and the degree of linear fitting improves as the decreasing of the gap g. However the maximal axial bearing capacity sharply decreases. Therefore, when designing the gap of the axial PMB, we must consider dual influences of the maximal load and the bearing stiffness.

CONCLUSION

In case of taking definite R_f, in other words, in the case that the integral size of axial PMB is negligible, the design of this type of PMB mainly depends on H, h, L, l and g. From above analysis, we can draw four conclusions as follows:

- The rotor and the stator magnetic rings had better possess equal or close width, whose specific value should be on the basis of the average radius of magnet ring R_f to satisfy the axial bearing stiffness of axial PMB
- When the thickness of the rotor magnetic ring is less than the stator magnetic ring, increasing the thickness of the rotor magnetic ring can significantly upgrades the bearing capacity and stiffness. While when the thickness of the rotor magnetic ring is greater than the stator magnetic ring, increasing the thickness of the rotor magnetic ring has almost no help to upgrade the bearing capacity and stiffness. So taking equal or close thickness of the rotor and the stator magnetic ring is preferred and the value of the thickness had better be equal or close to the width
- When the axial PMB is being designed, the section of the magnetic ring had better be taken as quadrate or approximate quadrate. While when the section area reaches a certain extent, the axial bearing capacity and stiffness have less change. So as long as the section area only meets the bearing stiffness, the design is feasible
- The design of the gap of axial PMB depends on the working condition which mainly refers to the load and stiffness

All in all, the above conclusions have certain guiding significance for engineering application.

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