Analysis of Hybrid Magnetic Bearing for High Speed Spindle

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Abstract: High speed, precision, ultra-precise machining technology is an important trend of advanced manufacturing Engineering. The high-speed motorized spindle enable to attaining greater complexity and accuracy, which demands rotating machinery to be run at high speeds. Non contacting magnetic bearing are suitable for supporting the spindle and rotor in the rotating machinery because of the high temperatures generated by the contact between the spindle and bearing. The basics of Active Magnetic Bearing technology, material selection and working of hybrid active magnetic bearing of high speed spindle are well described. The analytical derivation of the forces in a Hybrid magnetic bearing is described and the initial parameter design is done with magnetic circuit. From the initial parameter the permanent magnet is designed through FEA using ANSYS workbench. Finally, simulation of the designed magnetic bearing for magnetic flux density and force dependency of current coil and rotor position are done. From the prediction of current stiffness and position stiffness we found that current stiffness provide more linearity than position stiffness.

Key words: High speed spindle; Hybrid magnetic bearing; Finite element method; ANSYS

1 Introduction

The High-speed machine tool is realizing high-speed machining, which is a promising advanced manufacturing technology for increasing productivity and reducing production costs. Motorized spindle is equipped with a built-in motor is of great significance to the research and development of high-speed machine tool. High temperature would be generated when ball bearing spindle system were operated at high speed which bring about the machining failure. Modern engineering technology, however attaining greater complexity and accuracy, demands rotating machinery to be run at high speeds. Magnetic bearings innovated the traditional supporting forms have many advantages, such as no friction and abrasions, no lubrication and no sealing, high speed, high precision and long life. They have a very good application future in high speed digital machine tools, robots, motors, energy storage systems of high speed flywheels, and so on. In machine tools, active magnetic bearings (AMB’s) have been applied in high speed spindles ranging from 1 kW (180 000 rpm) to 25 kW (30 000 rpm) to give a high metal removal rate and good accuracy. Active magnetic bearing that provides high rotational speed and high stiffness. Rotor systems supported by means of the radial AMB are complicated due to the composite action of the mechanical, the electrical and the electronic parts. The finite element method can be a powerful technique for magnetic field analysis. Most of papers use magnetic circuit model based on some assumptions, such as ignoring magnetic leakage and hysteresis, assuming the flux in the magnetic material is uniform, to simplify the
current-displacement-force relation as a linear one in the design. However, even the nonlinear current-force dependence can be efficiently linearized by bias and control current, while the position-force dependence and iron magnetization remain nonlinear. It is appeared that the magnetic circuit model is not effective enough to consider the complex nonlinear magnetic phenomenon of magnetic bearings. The magnetic field theory which essentially details the electromagnetic disciplines can predict the relationships between force and other electromagnetic properties of magnetic bearings. The Finite Element Analysis (FEA) based calculations may be very helpful for this purpose.

2. High Speed Spindle with Magnetic Bearing

2.1 Motorized Spindle

Motorized magnetic bearing spindle levitated with five axis controlled Hybrid active magnetic bearing. The spindle has two radial magnetic bearing and one axial bearing. When designing a spindle for high speed rotation several difficulties have to be overcome. Kimman has addressed these difficulties when building an active magnetic bearing system for high speed rotation. At high speed the rotor will rotate around its inertia axis. The magnetic bearings are not able to compensate for the eccentricity force. Here the spindle will not be laminated due to the high centrifugal stresses. The rotor is made of Sandvik 1802 stainless steel which has a high resistivity with respect to normal steel, and it is expected that the phase loss due to the eddy currents can be kept to a minimum. The rotor is equipped with a thrust disk as a body for the axial bearing. From the disturbances that are acting on the rotor system (Cutting force, Magnetic Unbalance, Rotor Unbalance) we find out the load capacity of magnetic bearing by balance of spindle with motor.

2.2 Magnetic Circuit Theory and Design

In the radial bearings, we apply a homo-polar bearing concept. In the homo-polar radial bearing configuration, one radial bearing consists of two four-pole stators. For the force analysis in the radial bearings, we determine the flux in the airgap caused by the permanent magnets and the flux generated by the control coils separately. The control flux can be added to the bias flux because of the superposition principle. The 3D section view of homo-polar type radial magnetic bearing with control flux and bias flux path is shown in Figure 1. The magnetic bearing stator is configured by two ferromagnetic material rings with stator poles were separated by permanent magnets.

![Figure 1: Homopolar active magnetic bearing](image)

On the rotor balance position, the rotor is suspended by the common effect of permanent magnet field and
electromagnetic field. If there is an external disturbance, which makes the rotor move down from the balance position. Then the upper airgap will become big, and the lower airgap will become small. The enlarged airgap will decrease the permanent magnetic field intensity and magnetic force, while the reduced airgap will increase the permanent magnet field intensity and magnetic force when there is only the permanent magnetic field, the rotor will continue to move down and will not come back to the balance position. If the control current is added into the control coils the upper air-gap field is the sum of electromagnetic field and permanent magnetic field, and the lower air-gap field is the difference of electromagnetic field and permanent magnetic field. So the upper magnetic force is larger than the lower magnetic force, and the rotor can come back to the balance position under the resultant force. On the other hand, if the rotor moves up from the balance position, it also can be balanced by changing the direction of the coils current. The force acting on the rotor are related to the flux density of the air gap. Consider the force in Y-direction \( F_y \), with a rotor displacement \( y \) and a current applied on the coils on the y-axis for both airgaps, results in the force in y-direction,

\[
F_y = \frac{B_1^2 A_g}{\mu_0} + \frac{B_2^2 A_g}{\mu_0}
\]

(1)

In which, \( B_1 \) is the upper air-gap magnetic field, \( B_2 \) is the lower air-gap magnetic field. According to the relationship between magnetic field intensity and magnetic force, the rotor’s resultant force equation becomes,

\[
F_y = \mu_0 \frac{H_c^2 L_m A_m^2}{4 A_g} \left[ \frac{1}{(g_0 + y)^2} + \frac{1}{(g_0 - y)^2} \right] + \mu_0 \frac{H_c^2 L_m A_m^2 N_i}{2(g_0^2 + y^2)}
\]

(2)

Where the coefficient \( \mu_0 \) is the vacuum magnetic conductivity, \( N \) is the turns of control coil, and the coefficient \( i \) is the working current of control coil. Magnetic flux density is depending upon the permanent magnet geometry, turns of coil and current passing through the coil. \( H_c \) represents the coercive force from the magnet, \( B_r \) is its remanence flux density, \( A_m \) is the cross-sectional magnet surface area, \( L_m \) the magnet thickness, and \( A_g \) the pole cross-sectional area of air-gap. By linear processing equation in the balance position, the magnetic force equation will be achieved as follows:

\[
F_y = K_y y + K_i i
\]

(3)

Where, \( K_y \) is the displacement stiffness coefficient, \( K_i \) is the current stiffness coefficient.

The material of stator taken as silicon steel iron core, which behaves linear property around 1.2tesla flux density. Maximum force capacity depends upon the area of pole \( A_g \) and maximum flux density \( B_s \). Form the above circuit theory the area of pole shoe area can calculated as below.

\[
A_g = \frac{F_{max} \mu_0}{2B_s^2}
\]

(4)

For front bearing the maximum force capacity \( F_{max} \) taken as 200N and the area \( A_g \) for front bearing as come 215 mm. In case of rear bearing the maximum force capacity \( F_{max} \) taken as 100N and the pole shoe area taken as 125 mm. We aim to set the flux density in the airgap at 0.5T - 0.6 T. The initial dimensions have been chosen using the analytical model described above section, the final dimensioning is done using the Finite Element Method (FEM) model. With the above considerations, the radial Active Magnetic
Bearings, including the permanent magnets can be dimensioned in an iterative fashion.

<table>
<thead>
<tr>
<th></th>
<th>Front bearing</th>
<th>Rear Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air gap length</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Magnet area</td>
<td>195 mm</td>
<td>110 mm</td>
</tr>
<tr>
<td>Magnet thickness</td>
<td>6 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>Stator ring thickness</td>
<td>12 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td>Stator ring Outer Diameter</td>
<td>80 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td>Stator ring inner Diameter</td>
<td>70 mm</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

3. Finite Element Analysis

The 3D finite element analysis of a radial hybrid magnetic bearing has been done with the ANSYS Workbench software which have computational environment of linear and nonlinear magneto static modelling of all parts including permanent magnet. The magnetostatic module enables to solve Maxwell’s equations with certain boundary conditions describing the electromagnetic problem on a macroscopic level. The task of modelling the magnetic field in a hybrid magnetic bearing requires significant geometric complexity. The hybrid magnetic bearing contain permanent magnet and active control coil in two parallel stators. Enclosure is used for creating enclosed air domain and converted into single solid multiple part geometry. The mesh density must also be great enough to achieve consistent results at the airgap. The tight clearance of rotor and stator at the MB also requires high mesh density at the rotor-stator interface. The mesh, generated automatically with aigap refining. The mesh is refined at the surface near the rotor-stator interface which is modelled as airgap sizing the element of stator, rotor and PM. The resulting FE model contains approximately 800,000 nodes and 600,000 elements.

![Figure 2: Enclosure Boundary condition and current direction of coil of the model](image)

The currents of each loop in coil are assigned at the beginning of each FE simulation. The geometry of the wire loops displayed on the right is an accurately representation of the wire coils in the HMB. The model also includes an enclosure that extends 20 mm in the radial direction beyond the MB stator. Parallel magnetic flux boundary conditions are applied the surfaces of the enclosure. Figure 2 shows the enclosure and current direction of coil of the model. The material properties, BH curve of the HMB stator models are
provided by ANSYS material library for silicon core iron steel and air of enclosure. The permanent magnet material chosen as NdFeB and their X coordinate change global Z axis, The HMB wires are modelled with the copper alloy.

4. Simulation Result Analysis

4.1 Permanent Magnet Design

The Permanent magnet is designed by FEA magnetic field analysis. Figure 3 is the simulation result of the initial simulation Hybrid magnetic bearing model with zero control current. The flux path shows that flux Permanent magnet bias flux flows into the near side stator pole. Then, the flux flows into the rotor via airgap. Afterward, the flux returns from rotor to the permanent magnet via the far side stator.

![Image](image1.png)

**Figure 3:** Vector plot of magnetic flux density without current

When there is no static load or external disturbance on the rotor, no current flows through the coils and only bias fluxes flow through the air gaps by permanent magnet. Therefore, the air gap flux densities are almost identical and equal. The magnetic flux density different will act force on the rotor. Rotor at centre position sum of force must be zero. The figure 4 shows without control current radial magnetic flux in the air gap has equal distribution in all direction, so that the total summation of magnetic force on the rotor is zero and it is levitated on the centre position.

![Image](image2.png)

**Figure 4:** Magnetic flux density in air gap for front and rear magnetic bearing.

Our aim to provide bias magnetic flux in air gap to 0.5T, different simulation takes place by changing the area of the permanent magnet. The maximum magnetic flux density distribution of the air gap front magnetic bearing 0.516T and in case of rear magnetic bearing it became 0.499 T.
4.2 Rotor Displacement

In fact, it is impossible to control the rotor being in the equilibrium state and the rotor displacement is usually controlled in a certain range according the requirement of precision. When rotor y=0.4mm, x=0, i=0, the air gap flux density distributions for only with permanent magnet are calculated and shown in Figure. 5, from which it can be seen that the air gap flux density distributions have variation compared with those in the equilibrium state. When the rotor move 0.4mm in y direction, Magnetic flux density is higher in upper air and less in lower air gap. It can be seen that the +y air gap flux densities are larger than the –y air gap flux densities because of the +y rotor displacement. Then a resultant force in the +y direction is produced by the bias fluxes.

![Figure 5: Flux density of air gap at 0.4 mm](image)

When x=0, I,=0, the relationships between radial magnetic force Fy for different displacements y (–0.4, to 0.4 mm) are shows on the graph. For front bearing position stiffness calculate as 0.436 N/µm and maximum force at 0.4 mm is 195 N. In case of rear bearing position stiffness calculate as 0.266 N/µm and maximum force at 0.4 mm is 110N.

![Figure 6: Forces for displacement of rotor](image)
4.3 Current through Coil

The resultant force generated by the bias fluxes on the rotor is in the y direction when the rotor offsets along the y direction is compensate by the control current given the coil in opposite sense. After a positive current $I_y$ is applied, the $+y$ air gap flux densities decrease while the $-y$ air gap flux densities increase, which decrease the resultant force and makes the rotor back to equilibrium. The analysis continue with rotor at centre position and current in coil will vary from +5A to -5A. The figure 7 show that the flux density in the magnetic bearing -4A current passing to coil. The flux density is higher in the upper pole and lower in the lower poles by cancelling control flux and permanent magnet flux.

![Figure 7: Vector plot of flux density when +4A and -4A current all coil](image)

The current stiffness is calculated by changing the coil current from 5A to -5A were rotor at centre position. Current v/s force relation of the front and rear magnetic bearing show on graph., the force is linear up to 4 A and 3.5A for front and rear magnetic bearing respectively. The stiffness calculate as 47.26 N/A front and 29.646N/A for rear magnetic bearing. For linear relation of current stiffness the maximum current that is design takes as 4A and 3.5A for at centre position with maximum force 180N and100N.

![Figure 8: Current v/s force relation of the magnetic bearing](image)

5. Conclusions

This paper proposed a Hybrid Active Magnetic Bearings for supporting motorized spindle. The magnetic field distributions and stiffness characteristics of Magnetic bearings are calculated by the FEA and some conclusions are obtained and summarized. Magnetic circuit solutions method used for fine out determine initial design parameters of Hybrid magnetic
bearing then, the detailed design considering saturation has been performed by nonlinear FEA software ANSYS Workbench. From the simulation the design will support the required force and it will possess linear relationship in current stiffness and position stiffness. As per the design the front bearing possess higher stiffness than rear bearing.

6. References


