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Simulation and Analysis of Hybrid Magnetic Bearing for High Speed Spindles

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ABSTRACT: 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 FEM method 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. The designed front bearing produce linearity up to a load of 180N for position stiffness and 195N for current stiffness, In case of rear bearing it can support 100N for current stiffness and 111N for position stiffness.

Keywords: Current stiffness, Finite element method, Magnetic bearing, Permanent magnet, Position stiffness, Rotor, Stator

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I. INTRODUCTION

The development of spindles with Active Magnetic Bearing (AMB) became very fast during the last ten years. In order to satisfy the need of industrial production, people require much higher accuracy of machine parts than before. Using magnetic bearing in high-precision lathe, milling and grinding machine tool could easily solve problems such as noise, heat, service life etc., which occurs in traditional bearing, and that show clearly the superiority of magnetic bearing. The first AMB spindle for application in milling was built by the company S2M in cooperation with Arnold in 1985. S2M, currently part of the SKF group, is still one of the world's largest suppliers of magnetic bearings. One of their products is a 30000 rpm 70 kW aluminium macro milling spindle. Auchet describes the use of bearing signals for cutting force estimation using an S2M spindle. An organization of German developed a motorized spindle of an internal grinder machine suspended by electromagnetic bearing, the rotational speed of which has achieved 120000 rpm; the rotation precision of 0.25μm has been achieved.

The spindle speed of a milling machine used for cutting the aluminium alloy could reach 30000 rpm, the maximum power of which is 35kW, the feed reach above 4.5m/min; when used in ultra-precision machining, the accuracy may reach to 0.1μm; the smooth finish may reach to 0.01μm. In order to investigate the use of AMBs in a motorized milling centre, a prototype radial AMB spindle has been designed and simulated. The miniature AMB spindle is a typical mechatronic system. The design and realization of a mechatronic system is an iterative process which starts with an assessment of the system requirements. Subsequently, the disturbances acting on the system are identified, followed by the mechanical design of the plant, and the simulation of the magnetic bearing.

II. FINITE ELEMENT DESIGN

The initial dimensions have been chosen using the analytical model and 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 2.1 lists the radial bearing dimensions. The considerations which have been made to determine the optimal bias flux level include avoiding saturation of parts of the flux path, not performing the reversing of the magnetic field in the air gap, operating in the linear range of the BH curve of the rotor and stator material and the force slew rate increases with increasing bias flux level.

Table-2.1: Dimension of Hybrid Magnetic Bearing

Parameters	Front Bearing	Rear Bearing	Unit
Stator Pole Surface area	218	125	mm^2
Air gap length	0.5	0.5	mm
Magnet area	195	110	mm^2
Magnet thickness	6	6	mm
Stator ring thickness	12	8	mm
Stator ring Outer Diameter	80	60	mm
Stator ring inner Diameter	70	50	mm
Number of coil Winding	72	72	turns

III. MATERIALS AND PROPERTIES

The rotor used here is sandvik1018 or ASTM S18235. Sandvik 1018 is ferritic stainless free-cutting steel, alloyed with titanium and sulphur. It is characterized by very good machinability, superior corrosion resistance and good magnetic properties. Sandvik 1802 is superior in all applications involving a sufficiently high cutting speed, preferably 200 - 300 m/min.

Table-3.1: Sandvik 1802 properties

Density	7700 Kg/m^3
Modulus of Elasticity	220x10^3 MPa
Resistivity	750 Ωm
Permeability	800
Saturation magnetization	1.4 T

Selection of proper material for bearing stator has a great influence on magnetic bearing load capacity and power requirement. Because of their magnetic properties soft magnetic materials (mainly iron-silicon alloys) are considered as the best for magnetic bearing design. Iron and low carbon iron have high magnetic saturation density and it is also cheaper. Silicon-Iron crystalline alloy has better electric resistivity and mechanical strength. The properties like saturation flux density, magnetic permeability, electrical resistivity, mechanical strength, machinability and cost of the soft magnetic alloys play important role in the selection process.

IV. RESULTS AND SIMULATIONS

The multi physics 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 modeling of all parts including permanent magnet. The presented numerical simulation was obtained using the application of nonlinear magneto static mode of the software ANSYS Magneto static. The magneto static module enables to solve Maxwell's equations with certain boundary conditions describing the electromagnetic problem on a macroscopic level.

4.1 Permanent Magnet Design

The Permanent magnet is designed by FEM magnetic field analysis. Figure 4.1 is the simulation result of the initial simulation Hybrid magnetic bearing model is with zero control current. The flux path shows that permanent magnet bias flux flows into the near side stator pole. Then, the flux flows into the rotor via air gap. Afterwards, the flux returns from rotor to the permanent magnet via the far side stator. Our aim is to provide bias magnetic flux in air gap to 0.5T, different simulations takes place by changing the area of the permanent magnet.

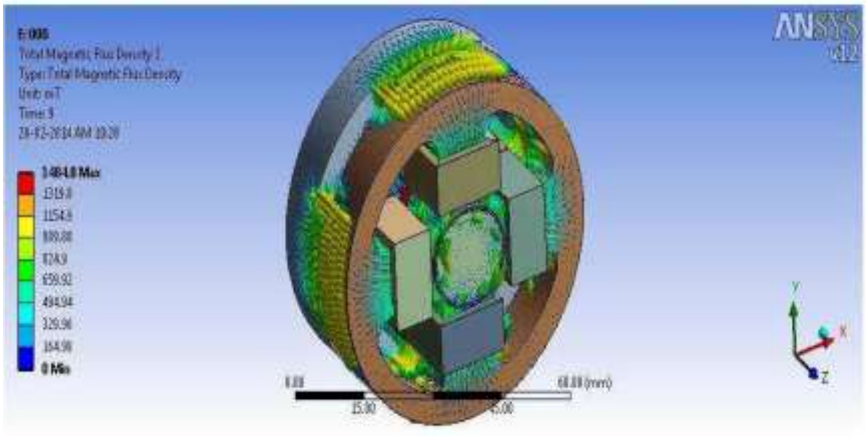

Fig-4.1: Vector Plot of Magnetic flux density without current

The maximum magnetic flux density distribution of the air gap for front magnetic bearing is 0.516T, shown in figure 4.2, and in case of rear magnetic bearing is 0.499 T, shown in figure 4.3.

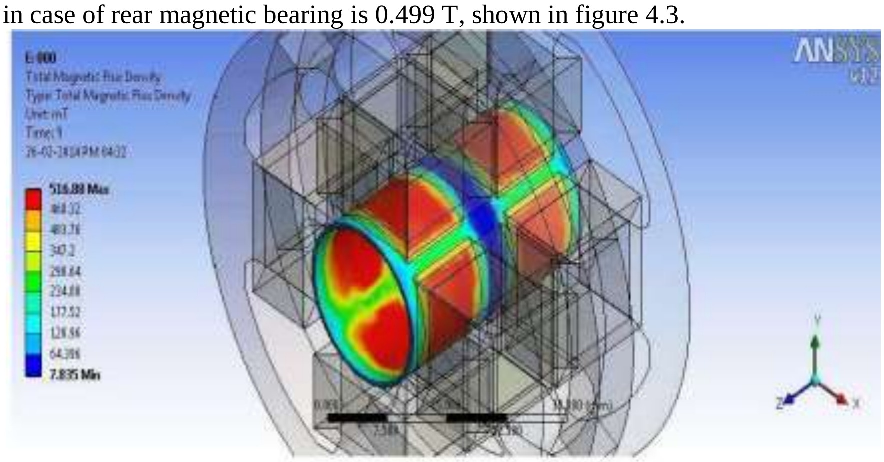

Fig-4.2: Magnetic flux density in air gap for front magnetic bearing

The magnetic flux density difference will generate force on the rotor. When the rotor is at center position, the sum of forces must be zero. The figure 4.2, 4.3 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 center position.

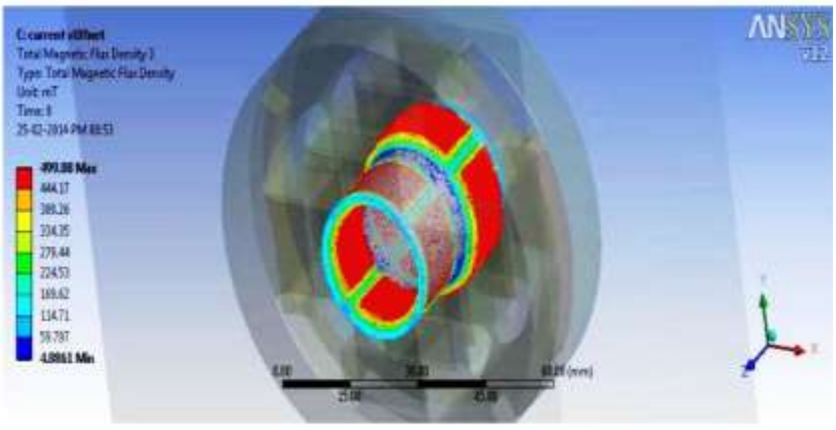

Fig-4.3: Vector plot of Magnetic flux density in air gap for rear magnetic bearing

4.2 Static Characteristics

Magnetic fields caused by rotor position and electric current can be analysed using 3D static magnetic analysis.

4.2.1 Rotor Displacement.

Magnetic flux density and rotor force are analysed by displacing from - 0.4 mm to 4 mm. Figure 4.4 shows flux density of air when the rotor move 0.4 mm in y direction. Magnetic flux density is higher in upper air and lesser in lower air gap. The difference in the magnetic flux density provides force in the rotor. The table 4.1 shows the different forces for displacement of rotor.

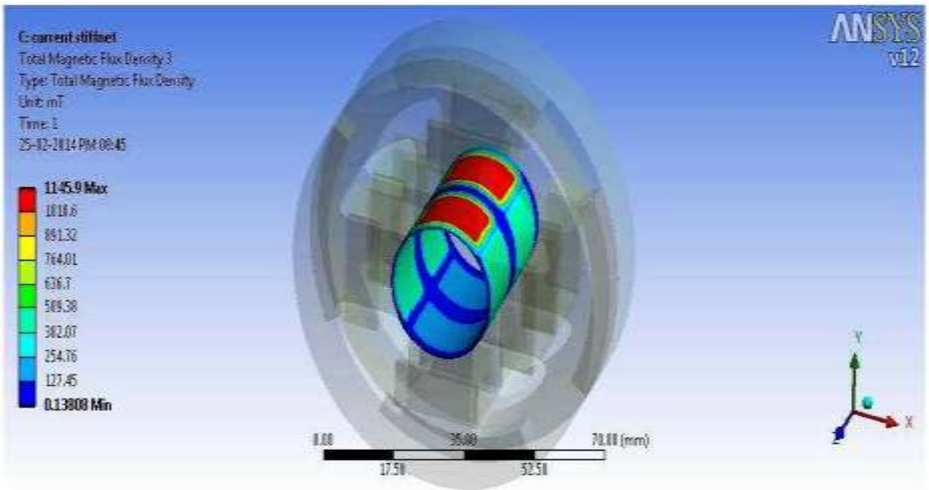

Fig-4.4: Flux density of air gap at 0.4 mm

Table-4.1: Forces for displacement of rotor

Rotor Position at Y axis	Force in Front Bearing N	Force in Rear Bearing N
0	0.255	0.342
0.1	29.93	20.27
0.2	65.58	48.152
0.3	118.09	80.989
0.4	195.07	111.88

4.2.2 Current on Coil

The analysis continue with rotor at center position and current in coil will vary from +5A to -5A. The figure 4.5 shows that the flux density in the magnetic bearing when -4A current passing to coil and the flux density is higher in the upper pole and lower in the lower poles by cancelling control flux and permanent magnet flux.

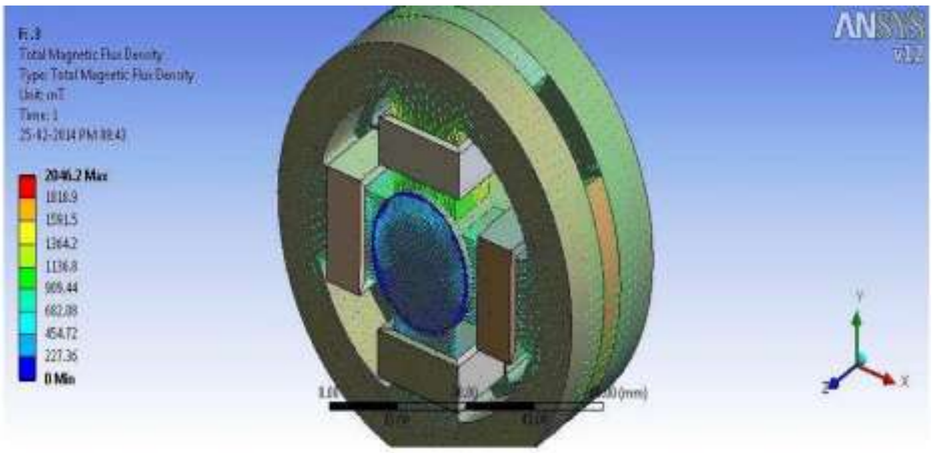

Fig-4.5: Vector plot of flux density when -4A current all coil

The figure 4.6 show that the flux density in the magnetic bearing when 4A current passing to coil and the flux density is high in the low pole and low in the upper poles by cancelling control flux and permanent magnet flux.

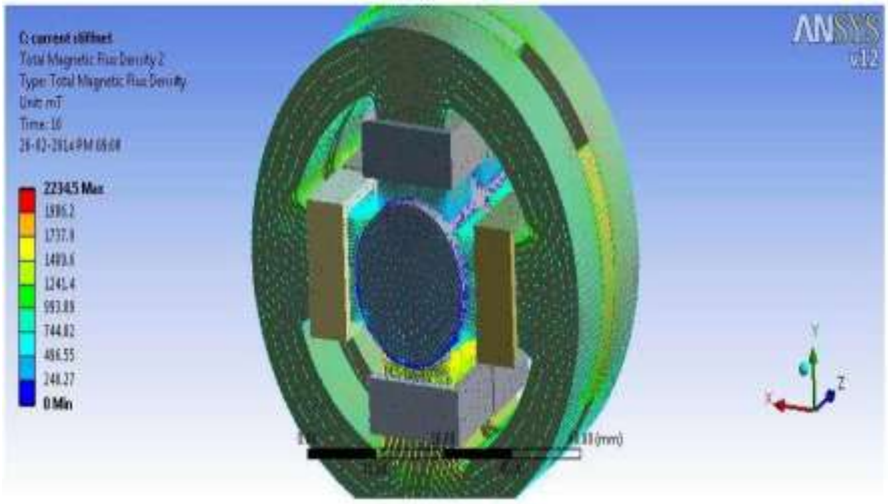

Fig-4.6: Vector plot of flux density when 4A current all coil

4.2.3 Current Stiffness and Position Stiffness.

The current stiffness is calculated by changing the coil current from 5A to -5A were rotor at center position. Current v/s force relations of the front magnetic bearing are shown in figure 4.7, the force is linear up to 4A and it becomes constant .The stiffness is calculated as 47.26 N/A. For linear relation of current stiffness the maximum current that design takes as 4A is at center position and the maximum force is 180N. After the maximum force, the force relation will act nonlinear.

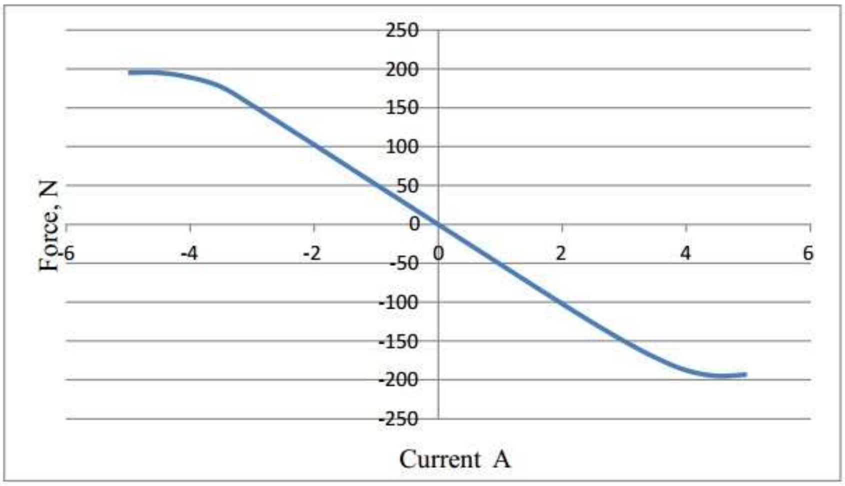

Fig-4.7: Current v/s force relations of the front magnetic bearing

Current v/s force relations of the rear magnetic bearing are shown in figure 4.8, the force variation is linear around up to 3.5A and it becomes constant. The stiffness is calculated as 29.646 N/A. For linear relation of current stiffness the maximum current that design takes as 3.5A is at center position and the maximum force is 100N. After the maximum force, the force relation will act nonlinear.

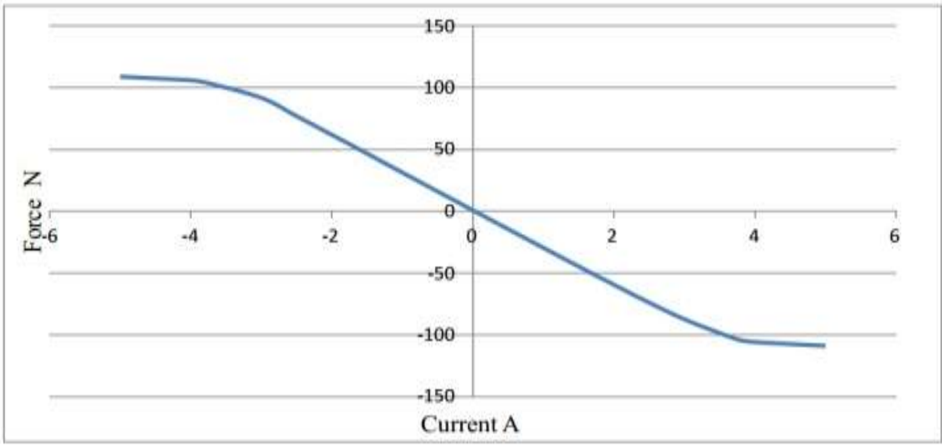

Fig- 4.8: Current v/s force relations of the rear magnetic bearing

The position stiffness is calculated by displacing rotor from -0.4mm to 0.4mm from its center position. Position v/s force relations of the front magnetic bearing are show in figure 4.9, the stiffness is calculated as 435520 N/m. The force is not linear to the position. The maximum force at 0.4 mm is 195 N.

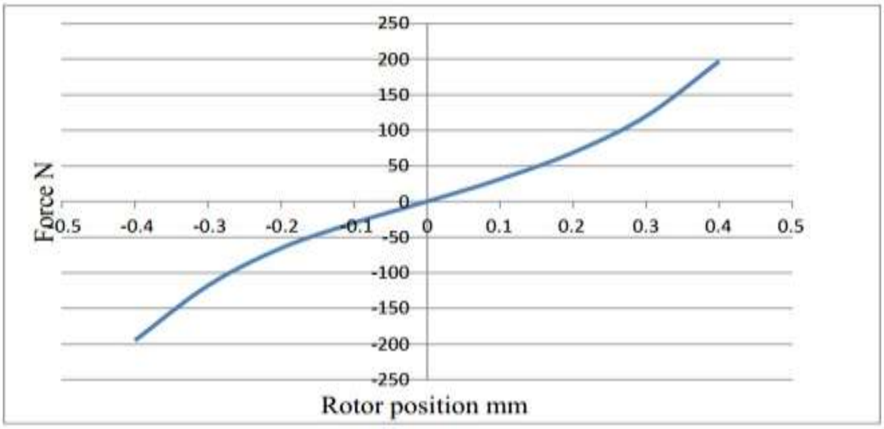

Fig- 4.9: Position v/s force relations of the front magnetic bearing

Position v/s force relations of the rear bearing are shown in figure 4.10.The stiffness is calculated as 266180 N/m. The force is not linear to the position. The maximum force at 0.4 mm is 110N.

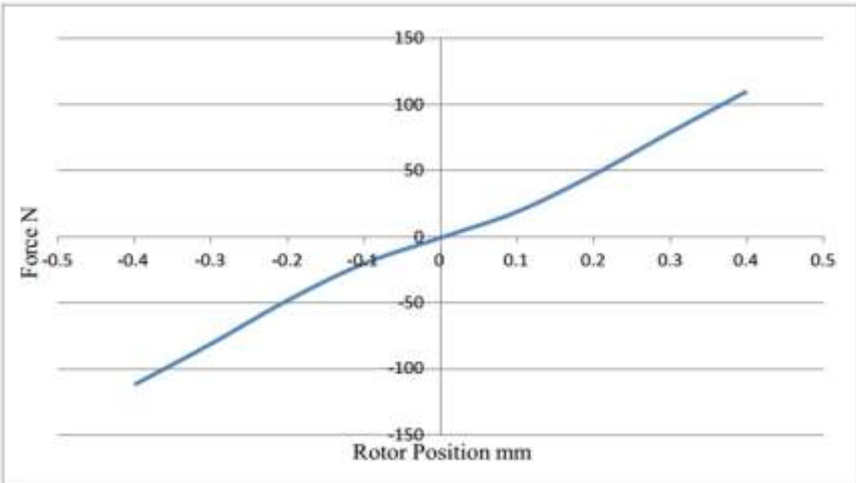

Fig- 4.10: Position v/s force relations of the front magnetic bearing

4.3 Result Summary

Table-4.2: Summary of FEA Simulation Result

Parameters	Front Magnetic Bearing	Rear Magnetic Bearing
PM Bias Flux	0.516T	0.499T
Maximum Position force	195	111N
Maximum Current force	180N	100N
Current stiffness	47.26 N/A	29.646N/A
Position stiffness	435520 N/m	266180 N/m

V. CONCLUSION

Magnetic circuit solutions method is used to determine initial design parameters of Hybrid magnetic bearing and 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. The flux density saturation will occurs at the root of the stator pole because of the curved shape on the top of stator pole. Permanent magnets provide the bias flux in the radial bearings. The flux densities in the bearings have been verified using Finite Element Modeling (FEM). Magnetic circuit method is not enough for magnetic bearing design. FEA method used to design Permanent magnet. Front bearing have higher position and current stiffness

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