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Design and Development of Passive Magnetic Bearing

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ABSTRACT: *Passive Magnetic Bearings (PMB) are known for their non-contact and negligible friction operations but these desirable characteristics of PMB can only be attained if proper designing of bearing is carried out based on the applied load. To aid to the design of PMB, 3D Coulombian model to estimate the load carrying capacity of magnetic bearings has been proposed. To exemplify the design procedure, analyses of various configurations of magnetic bearings have been presented. To economize the magnetic bearings, usage of easily available square magnets in stator made of aluminium has been proposed. Finally, a case study has been included to illustrate the design of magnetic bearing.*
Keywords: *Passive Magnetic Bearing, Coulombian model square magnets, Aluminium stator*

I. Introduction

Magnetic Bearings (MBs) have been used in various applications such as: molecular pump [1], flywheel energy storage system [2] and hybrid bearings [3, 4] due to their non-contact and low friction operations compared to the conventional bearings [5-8]. Moreover, MBs systems, can work in harsh environmental conditions such as extremely low temperatures, zero-gravity, and corrosive environments. The main advantages of MBs are "No lubricant, so no lubrication system" and "zero maintenance".

MBs are broadly classified as Active Magnetic Bearing (AMBs) and Passive Magnetic Bearing (PMBs). AMBs [8, 11] have built-in fault diagnostics and can work for wide range of speeds. Although the AMBs have these merits, requirement of complex controller, back-up bearing, high initial and running costs restrict wide usage AMBs in the common industrial applications. Shankar et al [12] concluded that it was hard to justify the usage of AMBs, which costs minimum of $1500 compared to similar sized greased lubricated rolling element and hydrodynamic bearings which cost lesser than $15. Further Shankar et al [12] compared the power losses due to these bearings and showed for a typical application, AMBs consumes 48W compared to 7W consumed by rolling element bearing.

PMBs [13-14] are economical compared to AMBs but due to its inherent brittle nature of magnetic materials [15-18] and moderate radial load carrying capacity [19] their applications are limited to low load application. However radial load carrying capacity of PMBs can be increased by seven times [15,19] times by reducing a full ring to half ring stator magnets [13, 20, 21]. For any PMB, the maximum load carrying capacity is achieved with half ring magnet at the bottom [20, 21], but when the applied load is lesser than load capacity of bearing made of half ring stator and full ring rotor magnets, the rotor will contact the top surface of the stator. In such a situation, the mechanical contact between stator and rotor results-in demagnetization of the rotor-magnet. To avoid this situation, a sector magnet is provided at the top side of the stator to apply a force in the direction opposite to the bottom magnet in order to reduce the total load by the PMBs [13, 20]. From the above discussion, it can be concluded that PMBs has to be designed based on the applied load.

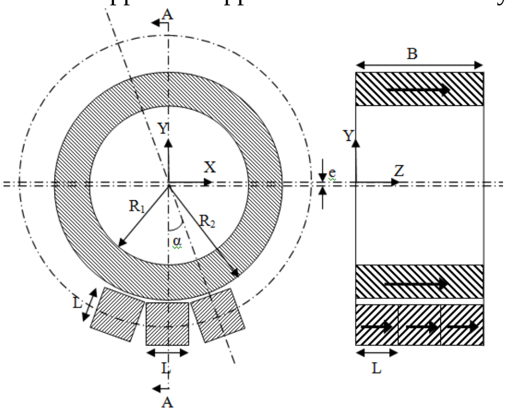
In the present research, instead of providing a half ring magnet at the bottom and reducing the load by providing a top sector magnet, design of sector magnets at the bottom side based upon the applied load has been proposed. This approach will reduce the volume of magnets, and so reduce the chances of breakage of magnets. To economize the PMBs, usage of easily available square has been suggested. In the present work, a methodology to form a sector shape using square magnets has been proposed.

The square magnets are accommodated in the aluminium stator [22], which will in-turn increase the damping property of the PMBs.

Systematic approach have been described to calculate the load carrying capacity of the proposed PMB. Different configurations of PMBs have been considered to illustrate the variation of load carrying capacity of the PMBs with different arc length of magnets. The theoretical load carrying capacity of PMBs is estimated using 3D Coulombian model [20, 22]. Finally, a case study has been included to illustrate the design of magnetic bearing.

II. Mathematical Model for Magnetic Bearing

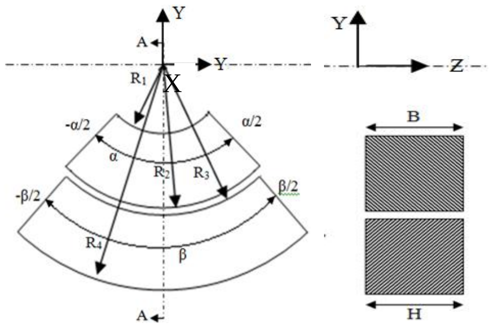
In the present work, PMB considered for mathematical modelling is shown in figure 1. Figures 1(a) and 1(b) shows the front and side views of a PMB. In this figure, rotor is a full ring magnet and stator consists of few numbers of square magnets (in this figure three square magnets are shown in figure 1(a)). The number of square magnets required for the PMB to support the applied load is estimated by using 3D Coulombian model.



(a) Front View (b) Side view

Fig.1: Cylindrical rotor and stator with square magnets

As per Coulombian model, the magnetic strength of a magnet depends on the charges distributed on both the surfaces of the magnets. Since it is difficult to represent a cuboidal part in cylindrical coordinates, an attempt is made to replace a cuboidal magnet by sector magnets of equal surface area. To validate the assumption, a comparison has been made between the vertical load carrying capacities of square and sector magnets. The vertical force using Coulombian model for the sector magnets and square magnets are given below.



(a)Front view (b) Sectional side view

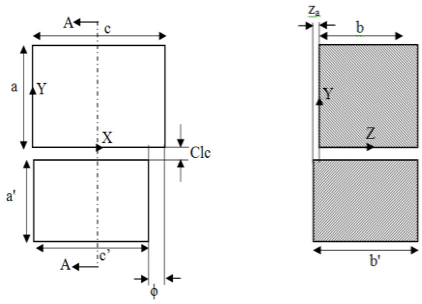
Fig. 2 Sector magnets

For estimating the force between two sector magnets in vertical (Y) direction ($F_{y,s}$) (as shown in figure 1) equation (1) is used. This equation is the modified equation of a full ring rotor and stator given by Hirani and Samanta [15]. The vertical force between two sector magnets ($F_{y,s}$) is given as:

$$F_{y,s} = \frac{\sigma_1 \sigma_2}{4\pi\mu_0}\left(R(z_a) + R(z_a + H - B) + R(z_a + H) + R(z_a - B)\right) \quad (1)$$

Where;

$$R(\alpha) = \int_{\frac{-\alpha}{2}}^{\frac{\alpha}{2}} \int_{\frac{-\beta}{2}}^{\frac{\beta}{2}} \int_{R_3}^{R_4} \int_{R_1}^{R_2} \frac{\left(e + r_{12}\cos(\theta) - r_{34}\cos(\theta')\right) r_{12} r_{34}}{\left(r_{12}^{\ 2} + r_{34}^{\ 2} + e^2 - 2r_{12}r_{34}\cos(\theta - \theta') + 2e\left(r_{12}\cos(\theta) - r_{34}\cos(\theta')\right) + (\alpha)^2\right)^{1.5}} dr_{12}\, dr_{34}\, d\theta\, d\theta'$$



(a)Front view (b) Sectional side view
Fig. 3 Cuboidal magnets

The vertical force ($F_{y,c}$) between two cubical magnets of sides a, b and c and a', b', and c' with an axial offset of 'z_a' (shown in figure 2) is estimated using Colombian equation provided by Akoun and Yonnet [22] and is represented in equation (A2).

$$F_{y,c} = \frac{\sigma_1\sigma_2}{4\pi\mu_0}\left(R(z_a)+R(z_a+b'-b)+R(z_a+b')+R(z_a-b)\right) \quad (2)$$

Where;

$$R(\alpha)=\int_0^c\int_0^a\int_0^{c'}\int_0^{a'}\frac{(\gamma+Y-y)}{\left((\phi+X-x)^2+(\gamma+Y-y)^2+(\alpha+Z-z)^2\right)^{1.5}}dXdYdxdy$$

Designing sector magnets equivalent to square magnets or vice versa for same load carrying capacity, the thickness and axial length of sector and cubical magnets were assumed to be equal i.e. (R_2-R_1)=a, (R_4-R_3)=a', B=c and H=c' (from figures 2 and 3). The angular length of the both sector magnets are kept equal (α=β= ψ) and estimated by equating the sum of the surface areas of the cubical magnet and sector magnets. The angle was calculated to be:

$$2L^2= \psi\,[(R^2_2-R^2_1) + (R^2_4-R^2_3)]/2$$
$$\psi=4L^2/[(R^2_2-R^2_1) + (R^2_4-R^2_3)] \quad (3)$$

The modified equation (2) is represented in equation (4)

$$R(\alpha)=\int_{\frac{-\Psi}{2}}^{\frac{\Psi}{2}}\int_{\frac{-\Psi}{2}}^{\frac{\Psi}{2}}\int_{R_3}^{R_4}\int_{R_1}^{R_2}\frac{(e+r_{12}\cos(\theta)-r_{34}\cos(\theta'))r_{12}r_{34}}{\left(r_{12}^2+r_{34}^2+e^2-2r_{12}r_{34}\cos(\theta-\theta')+2e(r_{12}\cos(\theta)-r_{34}\cos(\theta'))+(\alpha)^2\right)^{1.5}}dr_{12}dr_{34}d\theta d\theta' \quad (4)$$

Equation (1) can be extended for a magnetic bearing having a full ring rotor magnet and stator with 'n' number of square magnets as given equation (5):

$$F_{y,s} = \sum_{i=1}^{n} F_{y,s,i} \quad (5)$$

Where;

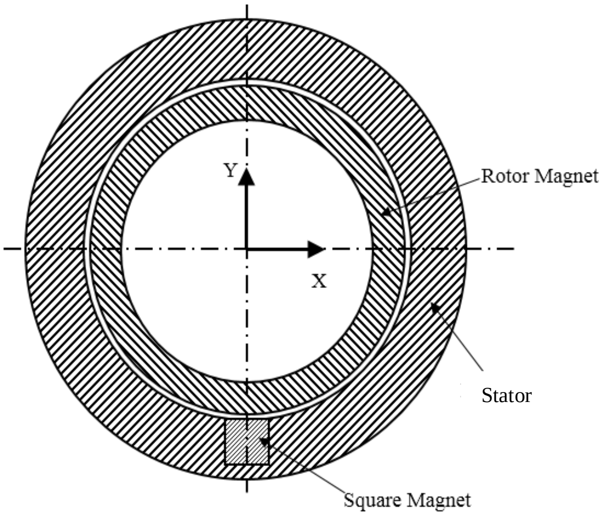
$$F_{y,s,i} = \frac{\sigma_1\sigma_2}{4\pi\mu_0}\left(R(z_a,i)+R(z_a+H-B,i)+R(z_a+H,i)+R(z_a-B,i)\right)$$

and

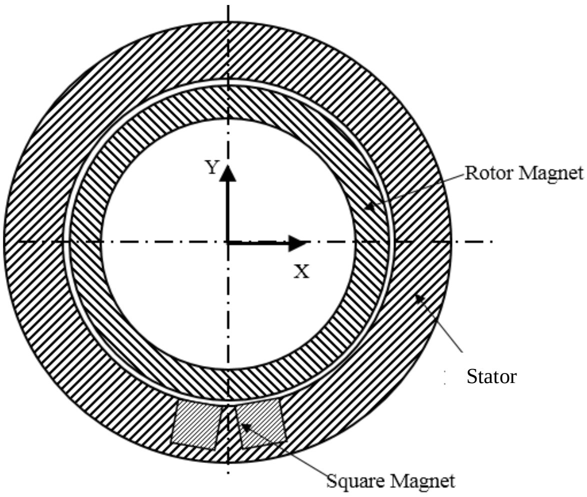
$$R(\alpha,i)=\int_{\frac{-\Psi}{2}+(i-1)\frac{2\pi}{n}}^{\frac{\Psi}{2}+(i-1)\frac{2\pi}{n}}\int_0^{2\pi}\int_{R_3}^{R_4}\int_{R_1}^{R_2}\frac{(e+r_{12}\cos(\theta)-r_{34}\cos(\theta'))r_{12}r_{34}}{\left(r_{12}^2+r_{34}^2+e^2-2r_{12}r_{34}\cos(\theta-\theta')+2e(r_{12}\cos(\theta)-r_{34}\cos(\theta'))+(\alpha)^2\right)^{1.5}}dr_{12}dr_{34}d\theta d\theta'$$

III. DESIGN AND DEVELOPMENT OF MAGNETIC BEARING

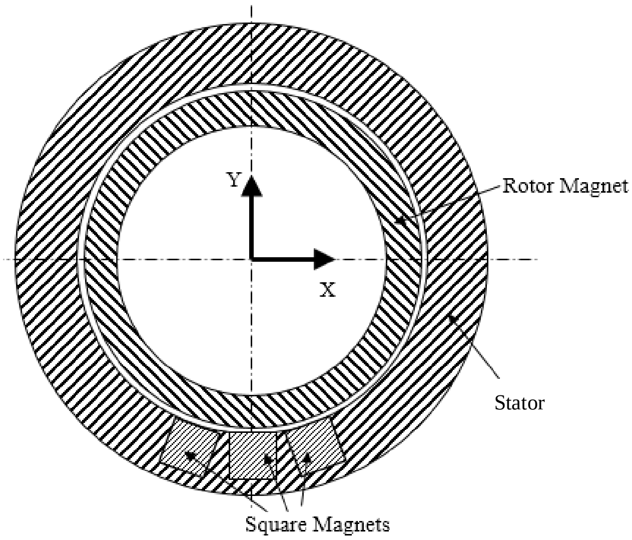
To estimate the load carried by the magnet bearing, mathematical modelling for magnetic bearing, discussed in section 2, was carried out. The magnetic-load capacities of four different configurations (shown in figure 4) were estimated. In these configurations, slots of cuboid shapes were made in the stator to accommodate the square magnets and provide support to the shaft.



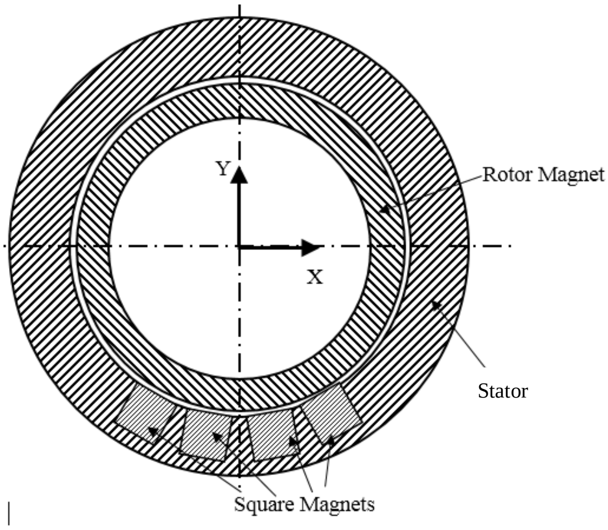
(a) Configuration 1



(b) Configuration 2



(c) Configuration 3



(d) Configuration 4

Fig. 4 Different configurations of magnetic bearing

1.1 Case study

To analyze the configurations depicted in figure 4, a case study is considered. The dimensions of magnetic bearing for the considered case study are: inner radius of rotor (R1)=0.005m, outer radius of rotor (R2)=0.024m, axial length of rotor (B)=0.03m, and stator-magnets of cuboid size (L)=0.01m were considered. The magnetic remanence of rotor (Br1)=1.1T and magnetic remanence of stator (Br2)=1.4T were accounted. The clearance between the rotor and stator magnet is kept as 1mm. The estimated load carrying capacities of different configurations at different eccentricities are shown in figure 5. From this figure, it can be inferred that, configuration 4 has the higher load carrying capacity and configuration 1 has the least load carrying capacity. It is worth noticing that the load carrying capacity is monotonically increases with increase in the number of square magnets but the increase is not proportional. The analysis was extended to the magnets with nine magnets and the load carrying capacity for different configurations at eccentricity ratio 0.99 is shown in figure 6. From this figure, it can be observed that, the increase in load is relatively insignificant if stator is made with more than five square magnets. In fact, the load carrying capacity reduces when the stator is made of more than seven square magnets.

IV. CONCLUSION

The procedure for designing Passive Magnetic Bearings (PMBs) using 3D Coulombian model has been described. Different configurations of PMB with different number of square magnets in the stator have been analyzed proposed. To exemplify the design procedure, a case-study was considered and upper limit on the magnet was decided. It was observed that increasing number of magnets do not increase the load carrying capacity proportionally. It can be concluded easily available economic square magnets can be replace with costly arc magnets.

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