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# DESIGN OF NON-CONTACT TYPE AXIAL BEARING USING CYLINDRICAL PERMANENT MAGNETS.

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***Abstract*:** Bearings have important function in support and guiding of a movable object with respect to some stationary structure. In case of conventional axial bearings, need of lubrication, wear and tear, friction, temperature rise due to friction plays important role in efficiency of system. Life of components reduces with wear and tear. Magnetic bearing system overcomes and focuses on reducing these factors so as to increase efficiency of system. Non-contact type axial bearing is designed which is non-contact type, tends to negligible frictional losses with increasing efficiency of system. Also wear and tear will be less which will increase life of components. Interaction of magnets is of main concern in designing such system. Feasible and easy to calculate solution is found and used while calculating magnetic force between magnets. Also considered using an electromagnetic radial bearing to sustain radial loads produced in system and to keep rotating component in line with axis without contact. Further MATLAB software is used for effective and accurate calculation. Experimental magnetic force calculation is carried out to validate the theoretical results. Further non-contact type axial bearing system is designed.

***Keywords*: Cylindrical Magnets , Magnetic Force, Axial Bearing, Contactless.**

## I. INTRODUCTION

Bearing has main purpose to support and guide the system of moving part with respect to some stationary parts. Conventional roller and slide bearings uses solid, fluid or gaseous lubricants at the mating surfaces of stationary and moveable bearing components. In contrast, magnetic bearings operate on the basis of electric or magnetic field forces without contact and lubricants. Magnetic bearings are advantageous, in particular, where conventional bearings reach to its limit because of lubrication issues. Lubricants, when environmental temperature increases and also when heat is induced because of friction, gets overheated thus losing their functionality. At low temperatures, fluid lubricants may get inoperable due to high viscosity. In certain applications it may also be desirable to avoid lubricants in view of physicochemical incompatibility with processes in vacuum, clean-room, chemical, food and medical applications. There are no such restrictions in a non-contacting support system as it operates free of wear, maintenance and frictional power loss.

A permanent-magnet bearing is a mechanical device which enables contactless relative motion between parts of the device with the help of attractive or repelling forces generated by magnets. Permanent magnets will be uniquely oriented to provide highly efficient rotational movement of first part relative to a second part about an axis. In high-speed applications, with non-contact type axial bearing vanishes need of lubrication, as contact is not present, frictional losses reduces tending to increase in efficiency of system. Life of parts also increases because of negligible frictional losses. If stated an example, a small wind turbine system is designed [5], where efficiency of the system is increased with the help of magnetic levitation.

Design of non-contact type axial bearing using permanent magnets mainly consists study of magnetostatic interaction between permanent magnets. Magnetic force between magnets is need to be known to design such system. There are various methods available [1][2][3][4][6] to calculate magnetic force but the complexity is very high. So, analytical approach has been found in this paper which is easy in view of calculation. Also, in construction of electromagnetic radial bearing, magnetic force between permanent magnet and an electromagnet is required. So, this analytical force calculation between a magnet and an electromagnet is given in this paper.

## II. DESIGN AND ANALYSIS

### 2.1 MAGNETIC FORCE ANALYSIS OF CYLINDRICAL MAGNETS.

When a single magnet is considered in external magnetic field, there are numerous methods available to calculate force. When the magnetization of magnet and external magnetic field are known, Kelvin's formula gives conceptually and computationally simple approach.[6]

From the Kelvin's formula external magnetic field $\vec{H}_{ext}$ is calculated using an equivalent magnetic current density and application of Biot-Savart's law.[6]

The gradual magnetic force $d\vec{F}$ is given by Kelvin's formula which have magnetization as $\vec{M}$ and external magnetic field as $\vec{H}_{ext}$ [6],

$$d\vec{F} = \mu_0 \nabla \left( \vec{M} . \vec{H}_{ext} \right) \tag{1}$$

$$\vec{F}_m = \int_V d\vec{F} dV \tag{2}$$

Let us consider, $\vec{M} = M\hat{z}$ . Equation (1) is simply giving the scalar product of $M$ and $H_Z$ (the z-component of H-field). According to equation 2, the gradient of the product $M \times H_Z$ is integrated with respect to volume of the magnet to obtain the vector force acting on the magnet. The axial component of the force is computed from the z-component of the gradient, and the lateral force components form the x and y components. The force expressions are given by [6],

$$\vec{F_Z} = \int_V d\vec{F}_Z = \mu_0 \int_V \frac{\partial}{\partial z} (M \times H_Z) \quad \text{(Axial Force)} \tag{3}$$

$$\vec{F_X} = \int_V d\vec{F}_X = \mu_0 \int_V \frac{\partial}{\partial x} (M \times H_Z) \quad \text{(Lateral Force)} \tag{4}$$

$$\vec{F_y} = \int_V d\vec{F}_y = \mu_0 \int_V \frac{\partial}{\partial y} (M \times H_Z) \quad \text{(Lateral Force)} \tag{5}$$

The overall attractive or repulsive force between magnets can be obtained from the magnetostatic interaction energy of the system E according to

$$\vec{F} = -grad(E) \tag{6}$$

And for this some assumptions are made like; cylindrical magnets are of same materials categorized by saturation magnetization M. The geometry of the two magnets is same and magnetization is uniform along the axial direction or axis of symmetry of cylindrical permanent magnets. [4]

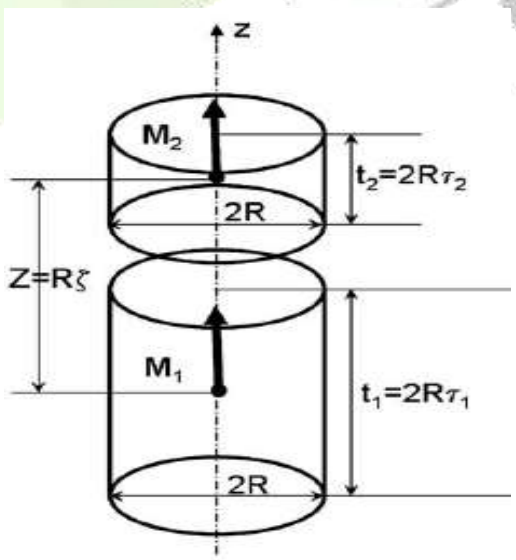


Fig. 1.1 Two Cylindrical Permanent Magnets with Common Axis [4]

From Fig. 3.1, where M1 and M2 are magnetization of magnets, 2R is dia of the magnet and t is thickness of the magnets. Here, two cylindrical magnets are interacting with each other. If the coordinate system with the z- axis along the cylinders axis is considered, then the attractive or repulsive force acts only in z-axis and can be expressed in the expression which consists $\mu_0$ as permeability constant, $J_d$ as Dipolar coupling integral,

$$F_z = -\frac{\partial E}{\partial Z} = 2\pi\mu_0 M^2 R^3 \frac{\partial J_d}{\partial Z} \tag{7}$$

$$J_d(\tau_1,\tau_2,\varsigma)=2\int_0^{+\infty}\frac{J_1^2(q)}{q^2}\sinh(q\times\tau_1)\sinh(q\times\tau_2)e^{-q\varsigma}dq \tag{8}$$

So, substituting equation 8 in to equation 7, equation of force will be [4],

$$F_z=-8\pi K_d R^2\int_0^{+\infty}\frac{J_1^2(q)}{q^2}\sinh(q\times\tau_1)\sinh(q\times\tau_2)e^{-q\zeta}dq \tag{9}$$

Where, $K_d$ is magnetostatic energy constant and expressed as $K_d=\mu_0 M_0^2/2$. Equation 9 is for the attractive or repulsive force acting in the axial direction, while there is no attractive or repulsive forces in x and y direction. The integral in equation 9 is somewhat complex for numerical valuation, so it is suitable to convert the integral to a more manageable form. The integral is of Lipschitz-Hankel type and may be expressed analytically in terms of a combination of complete elliptic integrals. [4]

So, equation after introducing elliptic integrals to calculate magnetic force between two cylindrical magnets can be expressed as [7],

$$F_z=\left(\frac{B_r^2}{2\mu_0}\right)A\times\{\sqrt{1+(a+b)^2}\left(\frac{8}{\pi}\right)(a+b)\left[K(q_1)-E(q_1)\right]$$

$$-\sqrt{1+(2a+b)^2}\left(\frac{4}{\pi}\right)(2a+b)\left[K(q_2)-E(q_2)\right]$$

$$-\sqrt{1+b^2}\left(\frac{4}{\pi}\right)(b)\left[K(q_3)-E(q_3)\right]\} \tag{10}$$

Where, h is thickness of permanent magnet, d is dia of magnet, s is separation between two magnets, K(q) and E(q) are the complete elliptic integrals of first and second kind resp., $a=h/d$ and $b=s/d$. For calculating complete elliptic integrals moduli q1, q2, q3 are [7],

$$q_1^2=\frac{1}{\left(1+(a+b)^2\right)}$$

$$q_2^2=\frac{1}{\left(1+(2a+b)^2\right)}$$

$$q_3^2=\frac{1}{\left(1+(b)^2\right)}$$

The first share of the equation 10 is the magnetic pressure and the terms inside brackets are dimensionless and justifies for the geometry of the system. In this, the magnitude of force is same, only the direction of the force changes and because of that sign changes from plus to minus or vice-versa in equation 10. [7]

MATLAB software is used with above equation to get generalized model, where magnetic force can be calculated for any radius and thickness of cylindrical magnets and with any value of its magnetization or coercive force.

### 2.2 MAGNETIC FORCE ANALYSIS FOR ELECTROMAGNETIC RADIAL BEARING.

For construction of electromagnetic radial bearing, first force interaction between magnet and an electromagnet must be calculated. By using magnetic scalar potential or magnetic vector potential, magnetic field of a cylindrical permanent magnet with height h and a radius r along the z-axis from the origin (z=0) can be given as [9],

$$\overrightarrow{B_m}=\frac{\mu M}{2}\left(\frac{z}{\sqrt{z^2+r^2}}-\frac{z+h}{\sqrt{(z+h)^2+r^2}}\right)\hat{z} \tag{11}$$

Where, $\mu$ is the permeability constant, $M$ is the magnetization of the magnet, h is height and z is the distance along axis from one end of the magnet (z>h).

If a magnet is viewed as a solenoid with N turns and height h through which current I flows, then a magnet with volume V and magnetic dipole moment m is,

$$M_0=\frac{m}{V}=\frac{\pi r^2 NI}{\pi r^2 h}=\frac{NI}{h}=nI$$

So, the magnetic field of a magnet can be expressed in terms of current I will be,

$$\overrightarrow{B_m} = \frac{\mu \times n \times I}{2}\left(\frac{z}{\sqrt{z^2+r^2}} - \frac{z+h}{\sqrt{(z+h)^2+r^2}}\right)\hat{z} \tag{12}$$

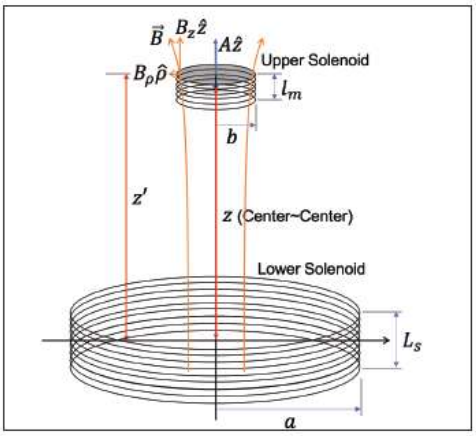


Fig. Arrangement of solenoids where upper solenoid is Magnet [9]

In above Figure, $l_m$ is length of upper solenoid, b is radius of upper solenoid, $l_s$ is length of lower solenoid, a is radius of lower solenoid, $N_m$ is number of turns (upper solenoid), $N_s$ is number of turns (lower solenoid), $I_m$ is current in the upper solenoid, $I_s$ is current in the lower solenoid.

From the above Figure, consider z as the distance between the centers of two solenoids and z' as field point, the magnetic flux can be expressed as,

$$\Phi = n_m \pi b^2 \int_{z-\frac{l_m}{2}}^{z+\frac{l_m}{2}} B_z(z')dz' \tag{13}$$

Where, $n_m = N_m / l_m$. If center of the magnet is considered as the origin of the coordinate in equation 12 of magnetic field, and substituted in the equation 13 of magnetic flux, we get,

$$\Phi = \frac{\mu_0 \pi b^2 n_m n_s I_s}{2}\left(\int_{z-\frac{l_m}{2}}^{z+\frac{l_m}{2}} \frac{(z'+L_s/2)dz'}{\sqrt{(z'+L_s/2)^2+a^2}} - \int_{z-\frac{l_m}{2}}^{z+\frac{l_m}{2}} \frac{(z'-L_s/2)dz'}{\sqrt{(z'-L_s/2)^2+a^2}}\right) \tag{14}$$

Considering their mutual inductance, force can be expressed as,

$$F = I_s I_m \frac{\partial m}{\partial z} = I_m \frac{\partial (I_s M)}{\partial z} = I_m \frac{\partial \Phi}{\partial z} \tag{15}$$

Substituting the required values in equation (15), Force can be expressed as [9],

$$F = \frac{\mu_0 n_s I_s n_m I_m \pi b^2}{2} \times \left( \frac{z+\frac{L_s}{2}+\frac{L_m}{2}}{\sqrt{\left(z+\frac{L_s}{2}+\frac{L_m}{2}\right)^2+a^2}} - \frac{z+\frac{L_s}{2}-\frac{L_m}{2}}{\sqrt{\left(z+\frac{L_s}{2}-\frac{L_m}{2}\right)^2+a^2}} - \frac{z-\frac{L_s}{2}+\frac{L_m}{2}}{\sqrt{\left(z-\frac{L_s}{2}+\frac{L_m}{2}\right)^2+a^2}} + \frac{z-\frac{L_s}{2}-\frac{L_m}{2}}{\sqrt{\left(z-\frac{L_s}{2}-\frac{L_m}{2}\right)^2+a^2}} \right) \tag{16}$$

Above equation gives the value of force between solenoid and a permanent magnet.

## III. RESULTS AND DISCUSSION

### 3.1 FORCES IN MAGNET

Calculation of force between two cylindrical permanent NdFeB N35 grade magnets, of diameter 25 mm and height 12 mm can be done with equation 10.

Repulsive magnetic force is calculated for separation of magnets from 1 mm to 50 mm. Below figure shows axial force variation with axial separation of NdFeB N35 magnets.

For calculating experimental force between coaxial cylindrical permnent magnets, micro-machining center is used. Micro machining center is having motion of spindle in z-axis. One magnet is fixed on dynamometer and other magnet is fixed at end of a spindle of micro machining center. The poles of the magnet are set similar, so that repulsive force of a magnet can be found.

Experimental magnetic repulsive force and theoretical magnetic repulsive force are plotted.

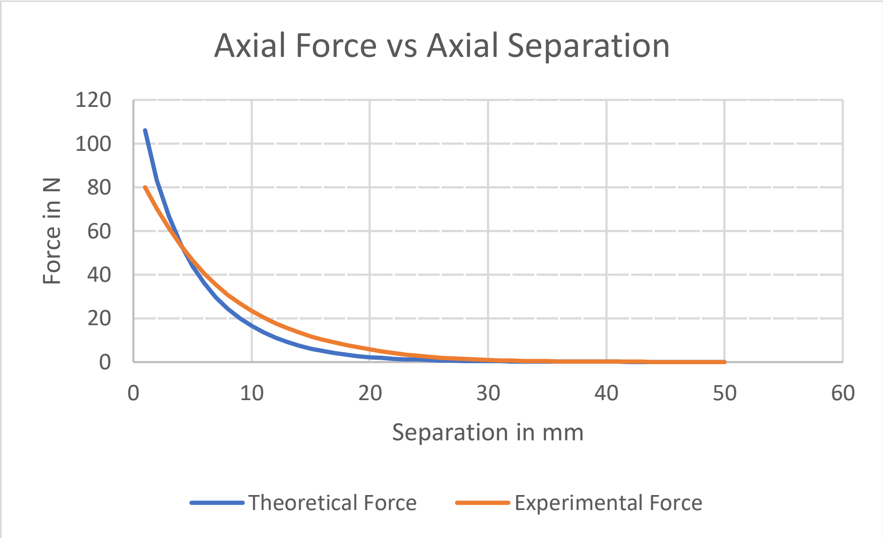


Fig: Axial Force vs Axial Separation

From above graph, is can be said that, both theoretical and experimental magnetic force are agreeing with each other. So, analytical approach used to calculate theoretical magnetic force between two coaxial cylindrical permanent magnets is easy, feasible and easy for computation.

For Electromagnetic Radial Bearing, magnetic force between a solenoid and a permanent magnet can be found from the Equation16.

Where, z= 0.031 m = center to center distance, $l_m$ = 0.006 m, b= 0.020 m, $l_s$ = 0.030 m, a = 0.015 m, $N_mI_m$=950000 A/m,

$N_sI_s$=950000 A/m

According to equation 16, after substituting the required values we get repulsive magnetic force as

F = 84.0512 N (For 5 mm separation)

F= 50.4076 N (For 10 mm separation)

### 3.2 PROTOTYPE (3D MODEL)

With the help of magnetic force calculated theoretically and experimentally, a non-contact type axial bearing system is designed, which is also supported by an electromagnetic radial bearing which absorbs radial loads produced inside the system and to keep rotating shaft in line with axis.

Material used are Magnets (NdFeB N35), Conventional radial bearing, Shaft of Stainless steel 304 grade, iron core, copper wire for winding, stainless steel 304 grade material for manufacturing casing.

Stainless steel 304 grade consists of chromium and nickel. It is considered as austnite steel. Nickel modifies physical structure of the steel and thus makes it non-magnetic.

From figure given below, When assembled, magnet 1 repels magnet 2 as their poles are kept same, thus lifting shaft attached to magnet 2. This arrangement works like an axial bearing. Another arrangement is made with an iron core, copper winding and magnet. Here, current is given to solenoid in particular way so that surface facing to magnet attains same pole as the surface of the magnet. This arrangement thus repels each other. This arrangement is made 3 times with equal gap in between them, so that they act like a radial bearing. The whole assembly can thus be called as electromagnetic radial bearing. Electromagnetic radial bearing supports the shaft radially. When given external rotational motion to shaft, like with motor, air jet, water jet or by any means, the shaft rotates without contact. As there is no frictional losses, shaft rotates at its maximum efficiency.

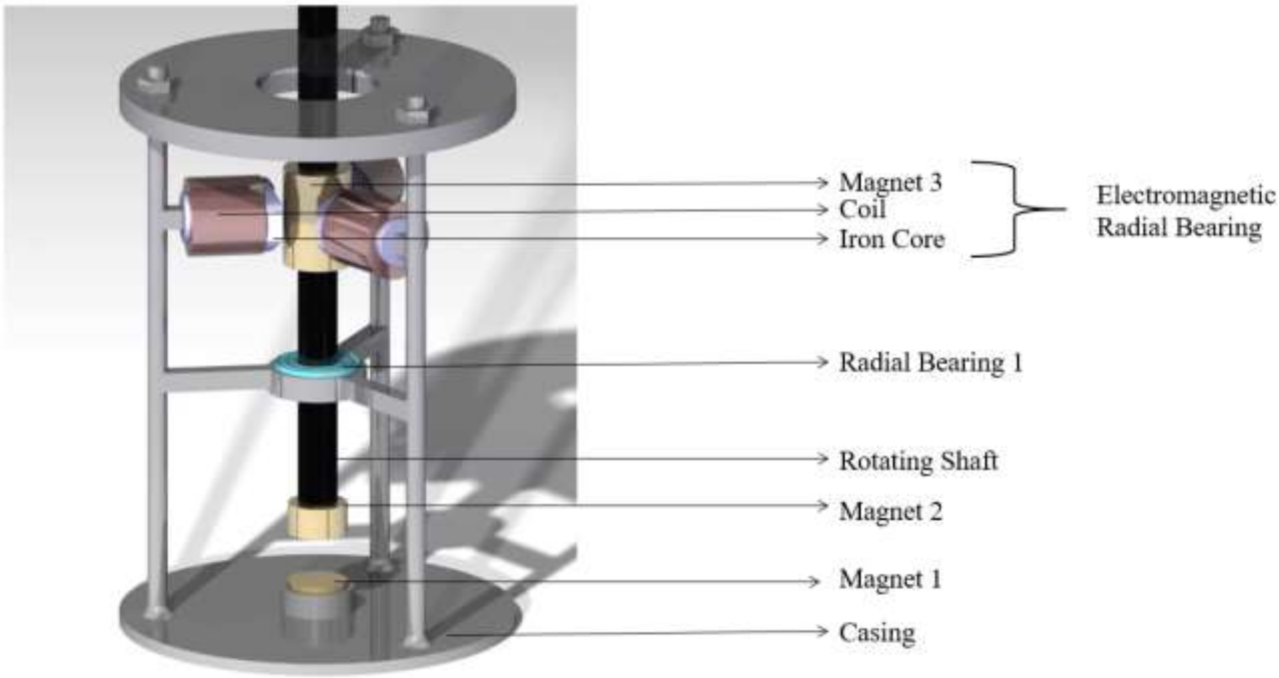


Fig. 3D Model of Prototype

## IV. CONCLUSION

Various theories regarding cylindrical permanent magnets were studied during this research. Various approaches to calculate magnetic forces between magnets are studied and presented a suitable, easy and feasible approach to calculate magnetic force between two coaxial cylindrical permanent magnets. The MATLAB software is used as mathematical tool to perform various calculations as it is efficient, easy and reliable. Experimental calculation of magnetic force is carried out and concluded that the theoretical and the experimental values of the force are agreeing with each other. So, the theoretical approach used to calculate magnetic force is validated. Conceptual prototype is built for a system of non-contact type axial bearing. Also, theoretical approach to calculate force between magnet and a solenoid is given which is used while designing electromagnetic radial bearing. This system will increase efficiency of the system as frictional losses are negligible. Wear and tear will be negligible tends to increase in life of parts of the system. No need of lubrication is there for designed system.

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