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Construction and Modelling of Horizontal Shaft Repulsive-Type Magnetic Bearing

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***Abstract*—This paper aims in modeling the performance of horizontal shaft repulsive type magnetic bearing. The model of the system is designed by using an industry level modelling software ANSYS Maxwell 16. The nature of the magnetic bearing designed is passive type and the bearing action takes place in accordance with the repulsive technology used in magnetic bearing assemblies. The model consists of two continuous shaped rotating bodies and two discontinuous shaped stator bodies with a certain amount of air gap clearance between the two distinct structures.**

Keywords*— *Magnetic Bearing; Horizontal Shaft; Repulsive Type

I. INTRODUCTION

Horizontal Shaft Repulsive-Type Magnetic Bearing (HRMB) is one of the most promising bearing due its low cost and simple construction. This bearing has low loss, low noise, require low lubrication and no hazards. This paper introduces a Horizontal Shaft HRMB, which consists of permanent magnets for radial stability and electromagnets for levitation & radial stability. Being a bearing HRMB is to serve two basic purposes, supporting of the rotor and minimizing of vibration of the rotor system. The rotor part is fixed with the horizontal axis of rotation known as the shaft and on the center of which a large circular disc is fixed known as Flywheel. In front of one face of the Flywheel, current controlled electromagnets are attached which along with the Flywheel plays an important role in maintaining the axial stability of the setup.

II. ABBREVIATIONS AND ACRONYMS

Horizontal Shaft Repulsive-Type Magnetic Bearing (HRMB)
Horizontal shaft Passive Magnetic Bearing (HPMB)

A. Horizontal shaft Passive Magnetic Bearing (HPMB)

A single-axis controlled repulsive-type magnetic bearing is a device which supports the rotor system by magnetic levitation and allows it to rotate freely with less vibration and low loss. Here two things are important; number one the rotor system should be levitated and number two the vibration of the rotor system should be less as much as possible at steady running condition as well as in different transient conditions like sudden change in load, on & off of the machine etc. For horizontal shaft magnetic bearing the levitation force can be achieved by the repulsive force between stator and rotor

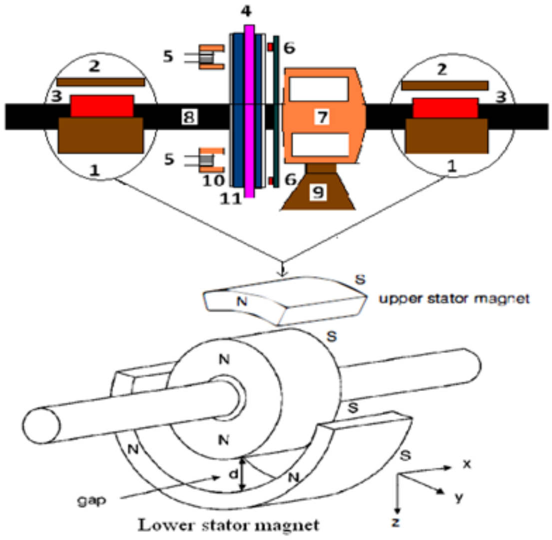

Fig. 1. Bearing Construction and configuration of the magnets for horizontal shaft magnetic bearing

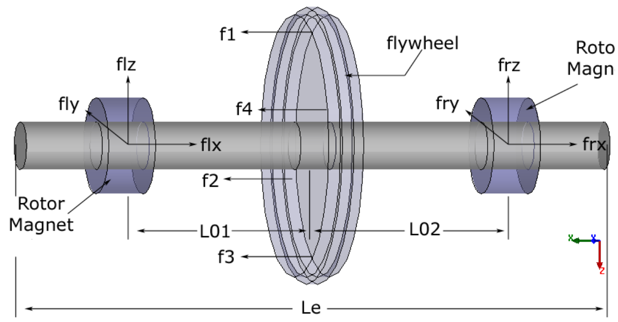

Fig. 2. Model of the rotor

The forces acting on the rotor are shown in the above figure. Here f_1, f_2, f_3, $f_4$are the forces acting on the rotor by electromagnet, f_{lx}, f_{ly} and f_{lz} are the forces on the left due to the permanent magnets and f_{rx}, f_{ry} and f_{rz} are the corresponding forces on the right as shown in the figure 2.

C. Forces due to permanent magnets

The forces flx, fly, flz, frx, fry and frz are a function of the displacements of the rotor along three directions measured from a predefined origin, usually the point of geometrical symmetry of the rotor. The following equation shows the dependence of these forces on rotor displacements.

$$\begin{bmatrix} f_c \\ f_b \\ f_a \end{bmatrix} = \begin{bmatrix} \frac{\delta f_c}{\delta g_c} & \frac{\delta f_c}{\delta g_b} & \frac{\delta f_c}{\delta g_a} \\ \frac{\delta f_b}{\delta g_c} & \frac{\delta f_b}{\delta g_b} & \frac{\delta f_b}{\delta g_a} \\ \frac{\delta f_a}{\delta g_c} & \frac{\delta f_a}{\delta g_b} & \frac{\delta f_a}{\delta g_a} \end{bmatrix} \begin{bmatrix} g_c - A_z \\ g_b \\ g_a - A_x \end{bmatrix} + \begin{bmatrix} Fc \\ Fb \\ Fa \end{bmatrix}$$

By Finite Element Analysis method, it can be shown that in the above equation, the following terms are negligibly small i.e.

$$\frac{\delta f_c}{\delta g_b} = \frac{\delta f_c}{\delta g_a} = \frac{\delta f_b}{\delta g_c} = \frac{\delta f_b}{\delta g_a} = \frac{\delta f_a}{\delta g_c} = \frac{\delta f_a}{\delta g_b} \cong 0$$

From this we can conclude that force developed on the rotor along any direction is hardly dependent on the displacement of the rotor along the other directions. Hence the simplified force equations acting on the rotor due to permanent magnets can be expressed as follows: -

$$f_a = -\left(\frac{\delta f_a}{\delta g_a}\right)(g_a - A_z) + F_a$$

$$f_b = -(R_b)g_b$$

Here c represents l_x and r_x, b represents l_y and r_y, a represents l_z and r_z

Let us Assume:-

$Q_a = \left(\frac{\delta f_a}{\delta g_a}\right)$ is the rotor stiffness along z direction

$S_c = \left(\frac{\delta f_c}{\delta g_c}\right)$ is the rotor stiffness along x direction

$R_b = \left(\frac{\delta f_b}{\delta g_b}\right)$ is the rotor stiffness along y direction

F_b and F_c is the steady state repulsive force acting on rotor along z and x direction. F_b=0 (approximately) A_z and A_x is the nominal displacement of rotor permanent magnets in steady state.

g_a, g_b, g_c are actual displacements of rotor permanent magnets.

D. Forces due to electromagnets

The expression of the force on the rotor due to electromagnets is based on following assumptions:

1. The force produced by the electromagnet is proportional to the square of the current and inversely proportional to the square of the gap distance.
2. Deviation around the nominal equilibrium operating point is small.

The equations of the electromagnets will be written as follows:

$$e = L\frac{di}{dt} + R$$

$$f = k\left(\frac{i}{g}\right)^2$$

L and R are the inductance and resistance of the electromagnet, e is the impressed voltage to the electromagnet and i is the current through the electromagnet, f is the electromagnetic force generated by the electromagnet and k is a constant used in the force expression which depends on the number of turns, surface area of the core of the electromagnet, permeability of free space etc.

Linearizing the operating characteristics of the electromagnet around the normal equilibrium operating point, expressing them by the deviated quantities from the steady state values, we get:

$$f' = 2F\left(\frac{i'}{I} - \frac{g'}{W}\right)$$

F, I and W are the generated force, current and gap at a steady state of the electromagnet. e', i' and f' are the incremental values of the impressed voltage, current and generated force respectively.

E. Forces acting on the rotor

F. Torques acting on the rotor

Along x-axis: $f_1 + f_2 + f_3 + f_4 - f_{lx} - f_{rx}$

Along y-axis: $f_{ly} + f_{ry}$

Along z-axis: $mg - f_{lz} - f_{rz}$

Here mg denotes the total weight of rotor.

Along x-axis: $T_m - p\rho - T_0$

Along y-axis: $f_{lz}L_{01} - f_{rz}L_{02} - f_1 l + f_3 l$

Along z-axis: $f_{ly}L_{01} - f_{ry}L_{02} - f_2 l + f_4 l$

Here mg denotes the total weight of rotor.

- T_m is electromagnetic torque of the motor
- T_0 is load torque acting on the shaft of the motor
- p is the angular velocity of the motor
- ρ is the coefficient of friction of the rotor.
- L_{01}, L_{02} are the distance of the centers of the two rotor permanent magnets from the center of the flywheel (usually L_1 and L_2)
- l is the distance of the center of the electromagnet from the center of the shaft.

Assuming $L01 = L02$ and $f1 = f2 = f3 = f4$ i.e. same force due to the four electromagnets, the expressions for torque around y and z axes are found to be dependent only upon the difference of force acting upon the two permanent magnets along z and y directions respectively. The smaller this difference, smaller will be the torques along these two directions.

G. Expressions for air gaps

$g_1 = W_1 - X_s + l\theta$	$g_3 = W_3 - X_s - l\theta$
$g_2 = W_2 - X_s + l\Psi$	$g_4 = W_4 - X_s - l\Psi$
$g_{lx} = A_x - X_s$	$g_{rx} = A_x - X_s$
$g_{ly} = y_s + L_{01}\Psi$	$g_{ry} = y_s + L_{02}\Psi$
$g_{lz} = A_z - Z_s + L_{01}\theta$	$g_{rz} = A_z - Z_s + L_{02}\theta$

Here:

- W1 to W4: nominal gaps of the electromagnets
- g1 to g4: actual gaps of the electromagnets
- xs, ys and zs: displacements of the rotor along the three axes
- θ: angle of pitch
- Ψ: angle of yaw

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H. Basic state equations

$$m\ddot{X}_s = f_1 + f_2 + f_3 + f_4 - f_{lx} - f_{rx}$$
$$m\ddot{Y}_s = f_{ly} + f_{ry}$$
$$m\ddot{Z}_s = mg - f_{lz} - f_{rz}$$
$$\ddot{\theta} = -\frac{PJ_x}{J_y}\dot{\Psi} + \frac{L_{01}}{J_y}f_{lz} - \frac{L_{02}}{J_y}f_{rz} + \frac{1}{J_y}(f_3 - f_1)$$
$$\ddot{\Psi} = -\frac{PJ_x}{J_y}\dot{\theta} + \frac{L_{01}}{J_y}f_{ly} - \frac{L_{02}}{J_y}f_{ry} + \frac{1}{J_y}(f_4 - f_2)$$

Here:

- Jx: moment of inertia of the rotor along x-direction
- Jy: moment of inertia of the rotor along y-direction

From the above state space equation for the current flowing in the electromagnets can be obtained. It is given as follows:

$$\frac{di_j}{dt} = -\frac{R_j}{L_j}i_j + \frac{e_j}{L_j} \qquad \text{(j=1 to 4)}$$

Gap sensors are used to measure the distance separating the electromagnets from the rotor. When for the *jth* electromagnet, the actual gap *gj* deviates from the nominal gap *Wj*; these gap sensors send a signal to the control circuit such that the disturbance is minimized. These gap sensors are scaled to give an output of 1V/mm.

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