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Modeling And Analysis of New Design Self Bearing Motor For Small And High Speed Applications

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Abstract : Self-bearing motors (SBMs) or Bearingless motors, are electric motors with a magnetically integrated bearing function. The main advantages are an increased power density and a reduced shaft length which softens the performance limitations imposed by rotor dynamics. Furthermore, SBMs extend the capability of active magnetic bearings (AMBs) by an extra degree-of-freedom (DOF), thus allowing for six DOF contactless positioning of rotors. In this work a practical model of the self-bearing motor is designed and constructed with mathematical model and the rotor is stabilized. The results are presented also analyzed.
Keywords : Active Magnetic Bearings, Self-bearing motors (SBMs).

1. INTRODUCTION

Self-bearing motor (SBM) or Bearingless motor, is a collection of electromagnets that enable the contact-less suspension of rotor and stabilization of the motor system is performed by feedback control. Two radial bearings and one axial bearing are used to control the five degrees of freedom of the rotor, while an independent driving motor is used to control the sixth degree of freedom. In comparison with mechanical and hydrostatic bearings the active magnetic bearings have many advantages and important are [1]:

- The rotor can be allowed to rotate at high speed, circumferential speeds about 350 m/s are achievable,
- The contact-less operation , the absence of lubrication and contaminating wear allow the use of magnetic bearings in vacuum , clean and sterile environments,
- The low bearing losses, at high operating speeds are 5 to 20 times less than in conventional bea ings, result in lower operating costs,
- Lower maintenance costs and higher life time due to the lack of mechanical wear,

The major drawbacks are the purchase price and not available necessary knowledge for the design and maintenance of magnetic bearings at the user side[2]. Due to many advantages, active magnetic bearings have found usage in many industrial applications, such as machine tools, energy storage flywheels, electric auxiliaries for aircraft, as well as high-speed turbines, centrifuges, compressors, etc. Active magnetic bearings constitute an inherently unstable system. Therefore, control is required to stabilize the shaft position and to ensure an appropriate damping and stiffness of the overall system. In most cases linear control methods are employed along with the differential driving mode. Here, the same bias current is supplied into the windings of all the electromagnets, while the position control is achieved in the *x* and

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y-axis, independently [3]-[5]. A quasi-linearization of the bearing force, as well as the required current gain and position stiffness are obtained in this way. The existence of the bias current, on the other hand, even under no load, leads to higher energy consumption and additional eddy current losses in the rotors [6]-[9].

2. MATHEMATICAL MODEL OF SELF- BEARING MOTOR

The simplified diagram of Active Magnetic Bearing system with four coils and rotating part is shown in figure 1.

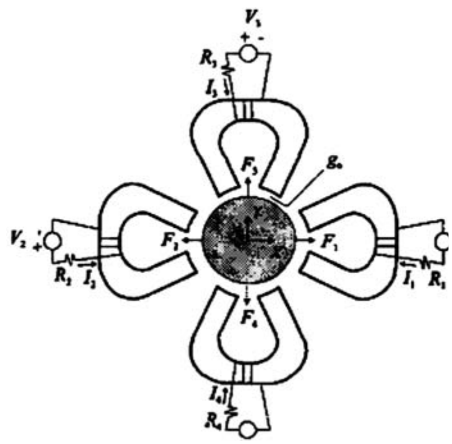

Fig. 1. Simplified Active Magnetic Bearing system

Let

F_x be the Radial forces in *x*-direction

F_y be the Radial forces in *y*-direction

F_1, F_2 be incremental forces in *x*-direction

F_3, F_4 be incremental forces in *y*- direction

The j^{th} incremental force is expressed as,

$$F_j = 2F\left[\frac{i'_j}{I_j} - \frac{g'_j}{W}\right] \tag{1}$$

Where

F_j is steady state force in jth direction

i'_j is incremental current

I_j is moment of inertia

g'_j is incremental gap length

W is equilibrium gap length

In steady state $F_1 = F_2$ and $F_3 = F_4$

Case 1: When rotor displaces in positive *x*-direction

Then to reach equilibrium F_1 should increase and F_2 should decrease.

Case 2: When rotor displaces in negative *x*-direction

Then to reach equilibrium F_1 should decrease and F_2 should increase.

Case 3: When rotor displaces in positive *y*-direction

Then to reach equilibrium F_3 should decrease and F_4 should increase.

Case 4 : When rotor displaces in negative *y*-direction

Then to reach equilibrium F_3 should increase and F_4 should decrease.

When there is a change from the equilibrium position x-axis sensors and y-axis sensors detect the disturbance and feedbacks in terms of changes the current in electromagnet which changes the electromagnetic force of the coil.

The change in force is given as $$F_j = 2F\left[\frac{i'}{I} - \frac{g}{W}\right] \quad (2)$$

Case 1: When rotor displaces in positive x-direction

Then the rotor to reach equilibrium F_1 should increase and F_2 should decrease.

Let x be incremental gap in x-direction

$$F_1 = 2F_x\left[\frac{i_1'}{I} - \frac{x}{W}\right] \quad (3)$$

$$F_2 = 2F_x\left[\frac{i_2'}{I} + \frac{x}{W}\right] \quad (4)$$

For F_1 to be more than F_2 then $i_1' \geq i_2'$ or i_2' should be negative

$$F_1 - F_2 = 2F_x\left[\frac{i_1'}{I} - \frac{x}{W} - \frac{i_2'}{I} - \frac{x}{W}\right] \quad (5)$$

$$F_1 - F_2 = 2F_x\left[\frac{i_1' - i_2'}{I} - \frac{2x}{W}\right] \quad (6)$$

$$F_1 - F_2 = -m\frac{d^2x}{dt^2} \quad (7)$$

$$-\frac{d^2x}{dt^2} = \frac{2F_x}{m}\left[\frac{i_1' - i_2'}{I} - \frac{2x}{W}\right] \quad (8)$$

Fixing current in coil 1

And sensors bring the change in coil 2

Therefore $i_1' = 0$ and $i_2' =$ negative value

$$\frac{d^2x}{dt^2} = \frac{2F_x}{m}\left[\frac{i_2'}{I} + \frac{2x}{W}\right] \quad (9)$$

Let $i_1' = 0$; where $i_2' =$ is positive quantity.

$$\frac{d^2x}{dt^2} = \frac{2F}{m}\left[\frac{i_2'}{I} + \frac{2x}{W}\right] \quad (10)$$

Case 2 : When rotor displaces in negative x-direction

Then the rotor to reach equilibrium F_1 should decrease and F_2 should increase.

Let x be incremental gap

$\therefore$ Change in gap for coil1 $= -x$

Change in gap for coil2 $= x$

$$F_1 = 2F_x\left[\frac{i_1'}{I} + \frac{x}{W}\right] \tag{11}$$

$$F_2 = 2F_x\left[\frac{i_2'}{I} - \frac{x}{W}\right] \tag{12}$$

$$F_1 - F_2 = m\frac{d^2x}{dt^2} \tag{13}$$

$$\frac{d^2x}{dt^2} = \frac{2F_x}{m}\left[\frac{i_2' - i_1'}{I} - \frac{2x}{W}\right] \tag{14}$$

We Know that $i' = 0$

$$\frac{d^2x}{dt^2} = \frac{2F_2}{m}\left[\frac{i_2'}{I} - \frac{2x}{W}\right] \tag{15}$$

Comparing equations (10) and (15). They are same but (10) = – (15) since acceleration in (10) is opposite to (15).

$$\frac{d^2x}{dt^2} = \frac{2F_x}{m}\left[\frac{i_2'}{I_x} - \frac{2x}{W}\right] \tag{16}$$

Similarly in Y direction we get the differential equation by solving case 3 and case 4, the equation is given below

$$\frac{d^2y}{dt^2} = \frac{2F_y}{m}\left[\frac{i_4'}{I_y} - \frac{2y}{W}\right] \tag{17}$$

Let $x_1 = x, x_2 = y, x_3 = \dot{x}, x_4 = \dot{y}, x_5 = i_2'$ and $x_6 = i_4'$ be the state variables and the state variable representation of the system is given by

$$\frac{d}{dt}\begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \\ i_2' \\ i_4' \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-4F_x}{mw} & 0 & 0 & 0 & \frac{2F_x}{mI_x} & 0 \\ 0 & \frac{-4F_y}{mw} & 0 & 0 & 0 & \frac{2F_y}{mI_y} \\ 0 & 0 & 0 & 0 & \frac{-R}{L} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-R}{L} \end{bmatrix}\begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \\ i_2' \\ i_4' \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{-1}{L} \\ \frac{-1}{L} \end{bmatrix} e \tag{18}$$

$$\frac{d}{dt}\begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \\ i_2' \\ i_4' \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-4F_x}{mw} & 0 & 0 & 0 & \frac{2F_x}{m I_x} & 0 \\ 0 & \frac{-4F_y}{mw} & 0 & 0 & 0 & \frac{2F_y}{m I_y} \\ 0 & 0 & 0 & 0 & \frac{-R}{L} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-R}{L} \end{bmatrix} \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \\ i_2' \\ i_4' \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{-1}{L} \\ \frac{-1}{L} \end{bmatrix} e \tag{19}$$

$$Y = \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \\ i_2' \\ i_4' \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} e \tag{19}$$

Table 1. Parameters of the self bearing motor system.

Symbol	***Optimum values***
F_x	11.76N
F_y	11.76N
m	8 kg
W	5 Cm
R	2.93Ω
L	0.0485H

Transfer function of the above state space equation using the parameters in table1

$$\frac{X(s)}{E(s)} = \frac{-[0.0003s^3 + 0.0154s^2 + 0.03s + 1.809]}{[0.0004s^4 + 0.0028s^3 + 0.0872s^2 + 0.1671s + 5.047]} \tag{21}$$

$$\frac{X(s)}{E(s)} = \frac{-[0.0001s^3 + 0.0044s^2 + 0.0025s + 0.5147]}{[0.0004s^4 + 0.0028s^3 + 0.08723s^2 + 0.1671s + 5.047]} \tag{22}$$

3. CONSTRUCTION DETAILS OF SELF BEARING MOTOR

The basic principle for levitating the rotor is the repulsion between the permanent magnets mounted on the rotor and the electromagnet on the stator. Lower the weight of the rotor lowers the power consumption by the electromagnet. The magnetic flux flows from North Pole to the South Pole and the flux path is closed inside the permanent magnet. Whichever the direction the rotor rotates the moment of the flux lines do not change. Hence repulsion can be continued even during the motoring operation. The fig 2 shows the rotor with the permanent magnets mounted on it.

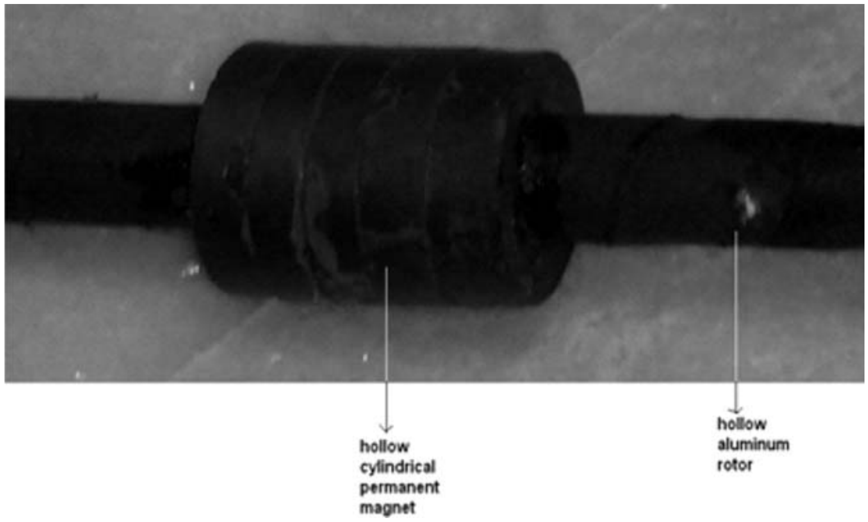

Fig. 2. Rotor with the permanent magnets.

The electromagnet in the stator which is used for levitation is shown in fig 3. It is made up of iron rod made into U shape and the pole shoe is made by slicing diagonally on the top. The winding or coil is wound on a hollow cylinder with the supports on the either side of the cylinder in order to protect the winding to fall off. The coils are varnished then dried and inserted into the iron core.

The windings are connected in series such that the induced flux aides each other and mutual inductance becomes positive. A dc voltage of 230*v* is applied to the poles through the diode bridge circuit with ratings of PIV = 230 volts and the maximum value of current is 6 Amperes

The voltage polarities are such that the North Pole is produced on the right leg and South Pole is produced on the left leg. The flux lines flow from north to South Pole and the flux path is closed internally. That is inside the material the flux flows from South Pole to North Pole. Hence due to the slicing of the core diagonally we do not get uniform flux distribution. Because of slicing the core diagonally the surface area is increased which decreases the reluctance of the flux path there by increasing the flux.

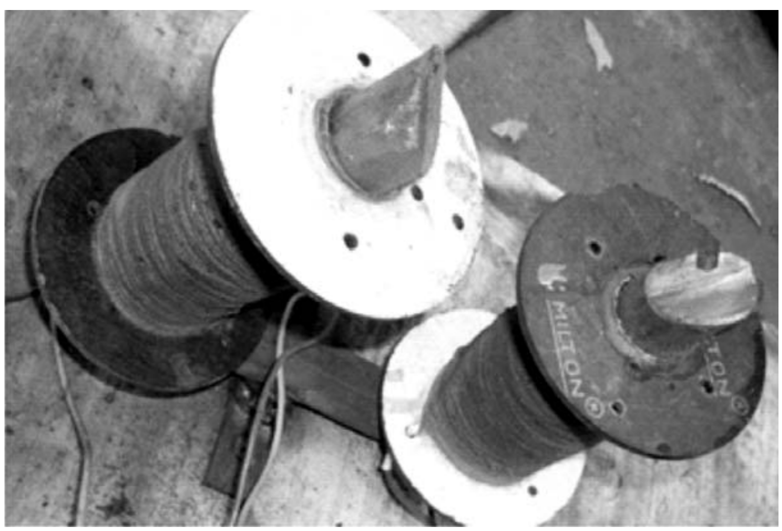

Fig. 3. The *x*-direction electromagnets in the stator

This interaction of fluxes produces upward force which counteracts the weight of the rotor. The electromagnet should be carefully designed so that the repelling force generated should be greater than the weight of the rotor. The rotor will not levitate by just giving the power supply to the electromagnet. The direction of the forces depends on the distance between the poles of opposite polarity on the magnet and electromagnet.

These forces cause instability to the rotor and thereby the rotor moves away from its ideal position. In order to lock the rotor in Y axis two electromagnets are placed on the either side of the rotor as shown in the figure 4. Two electromagnets placed are right and left so that the North poles of the rotor and the left and right electromagnets are in a same line. These electromagnets are kept on the wooden logs which is having a slot. These slots are used for varying the position of the electromagnets, since the height of levitation is difficult to determine. When the rotor due to some disturbances move towards left then the distance between the left electromagnet and the permanent magnet decreases and the distance between the right electromagnet and the permanent magnet increases.

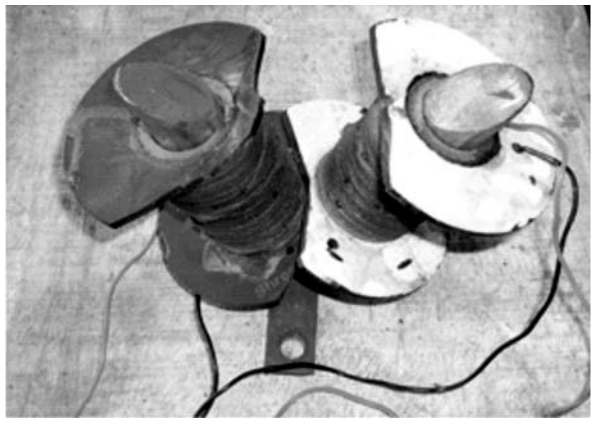

Fig 4. The Y-axis electromagnets.

Hence the force on the rotor from the left electromagnet increases whereas the force from the right electromagnet decreases thereby resulting in net force in the left direction. This force moves the rotor in the left direction. As the rotor moves Force from the left electromagnet decreases and the right electromagnet increases thereby the resulting force in the left direction decreases. The resultant force becomes zero at the stable operating point making the rotor fixed in the Y axis due to electromagnets at one particular point.

The stator electromagnets are placed on the either side of the rotor so that they both repel the rotor. When the rotor moves left the repelling force from the left side electromagnet will be more since due to reduction in the reluctance path which in turn increases the repelling force on the rotor. Also the force from the right side electromagnet will be lowered due to increase in the reluctance path. Hence there will be net force in the right direction thereby moving the rotor to left. This makes the rotor stable at one operating point in x axis direction. The combinations of all the three make the rotor stable at one operating point.

The figure 5. shows the combination of electromagnets in stator which make the rotor stable in x and y directions. Now the rotor is made stable in all the axes and it should be rotated. The stator for the motor is made up of circular iron and the poles are mounted on the stator.

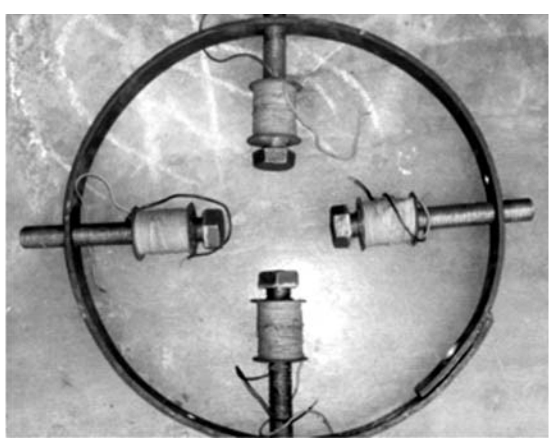

Fig. 5. Stator poles in *x* and *y* directions

The iron bolts used acts as poles when the coils are excited. Hence this is a four pole stator. It is placed on the both ends of the stator to produce the rotating torque. The complete stationary part structure of designed bearingless motor is shown in fig 6.

Fig. 6(*a*). The complete assembled stator part.

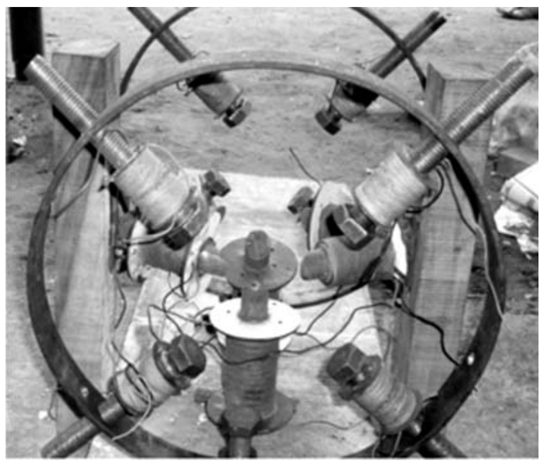

Fig. 6(*b*). The complete assembled stator part.

4. HARDWARE IMPLEMENTATION OF POSITION SENSORS AND CONTROL CIRCUIT

In order to control the permanent magnet rotating part position always at eccentric point the exciting current of stator poles is to be varied continuously. The instantaneous position of the rotor can be determined by planting infrared sensors in the stator as shown in fig 7.

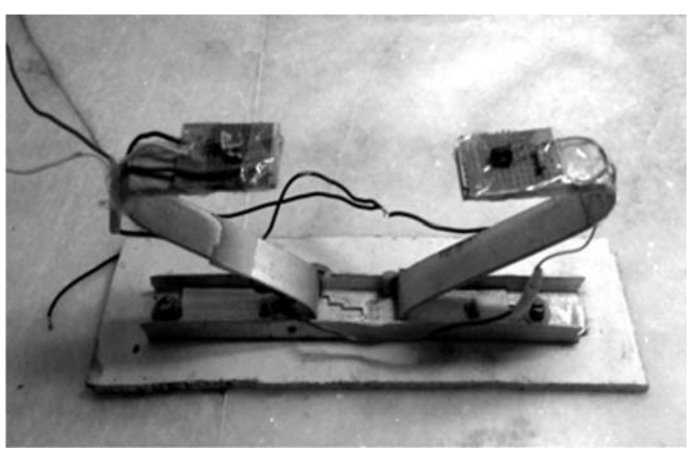

Fig. 7. Position sensors using infrared sensors.

The control circuit for regulating the current through the stator pole winding based on the feedback data generated from the infrared position sensors is shown in fig 8. A gate drive IC device is used to turn on and off the semiconductor switches. In the circuit for independent current control of each pole winding, a low-ohm sense resistor is placed between the source of the lv-side of the transformer.

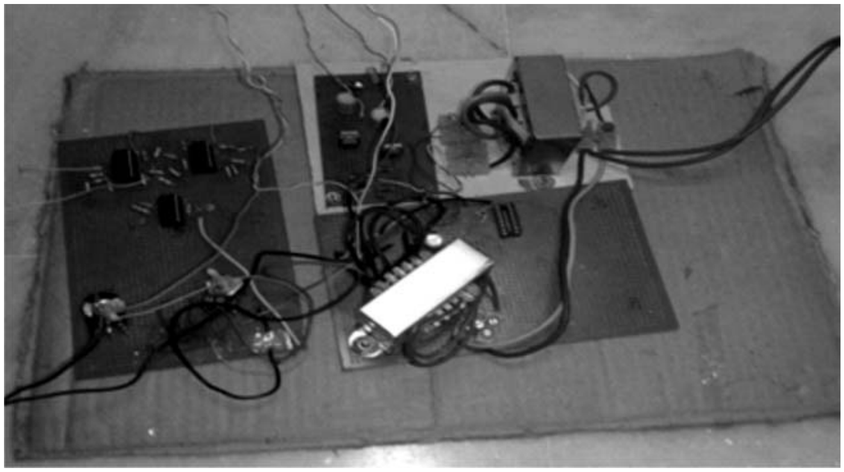

Fig. 8. Control circuit for regulating the current through electromagnets.

5. CONCLUSION

In this work the mathematical model of the self bearing motor is derived from the fundamentals principles. It can be observed from the mathematical model that the system is highly nonlinear and is open loop unstable. The prototype model of the self bearing motor with a new design procedure is realized and is made stable. It is found that repelling force of electromagnets is much better than the attracting force. A control circuit is designed for regulating the excitation current hence the attracting force based on the principles of PID controller.

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