MODELING OF A REPULSIVE TYPE MAGNETIC BEARING FOR FIVE AXIS CONTROL INCLUDING EDDY CURRENT EFFECT

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ABSTRACT - So far a single-axis controlled repulsive type magnetic bearing system have been designed and fabricated in our laboratory employing the repulsive forces operating between the stator and rotor permanent magnet for levitation. The radial axis is uncontrolled passive one. The higher speed of operation is limited due to the vibration along the uncontrolled axis and the increase of control current due to eddy current interference. This paper will discuss a detailed modeling of the repulsive type magnetic bearing system for five axis control including the eddy current effect and the method of reduction of eddy current effect. Simulation results using Matlab will be presented.

1. PURPOSE OF THE PAPER

Our objective is to develop low cost repulsive type magnetic bearing systems for industrial applications. Usually for stringent industrial applications active magnetic bearings are preferred for the adjustable damping and stiffness characteristics along all the axis of control. Earlier we have designed and developed a single axis controlled repulsive type magnetic bearing system[1]. But because of the vibration along the uncontrolled passive axis, the maximum speed of operation is limited and also the control current has a tendency to increase with speed due to the eddy current effect. This paper is an extension of our earlier work to make the system for five axis control and at the same time to develop some means to reduce the eddy current.

2. EARLIER SCHEME

The developed laboratory model of the repulsive type magnetic bearing system is shown in Fig.1. The rotor is levitated due to the repulsive force between the stator permanent magnet and rotor permanent magnet. Stator and rotor permanent magnets are placed at either end of the shaft. Four stationary electromagnets, a rotor flywheel with conducting surfaces on either side and a stator with windings are located at the middle of the shaft. The currents applied to the electromagnets are used to control the axial position, the pitch and the yaw of the rotor shaft. Gap sensors placed on the electromagnet assembly are used to measure the distance between the rotor and the electromagnet surfaces. The motor used here is an axial type induction motor. The advantages of using axial type induction motor are (1) a relatively large airgap between the stator and the rotor can be allowed, (2) the flywheel itself can be used as a rotor of the motor, (3) the diameter of the rotor can be bigger than the stator, and (4) the presence of the axial force will help to avoid the use of the controlled electromagnets in future. The mass of the rotor is 8kg, the length of the shaft is 510mm and the diameter of the fly-wheel is 220mm.

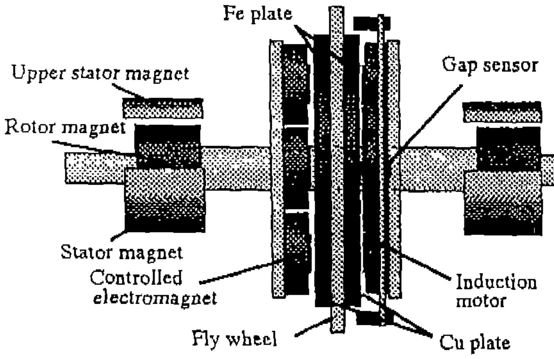

Fig. 1 Magnetic bearing configuration

3. EDDY CURRENT EFFECT AND ITS REDUCTION

Eddy current is generated in the flywheel of the rotor as it cuts the flux produced by the controlled electromagnet. The flux due to eddy current interacts with the main flux and consequently there is a reduction of flux in the airgap. In order to positioning the rotor at the same gap-distance the control current has to increase to maintain the flux density in the airgap. Since the generation of eddy current is dependent on speed, the control current has to increase at higher speed of operation. To reduce the effect of eddy current the method adopted here as follows.

(1) Material selection : By properly choosing the material of the rotor plate the increase of control current can be reduced as shown in Fig.2[2].

(2) Slit fabrication : By breaking the eddy current path with the help of fabricating slit in the rotor plate as shown in Fig.3 the generation of eddy current can be reduced. Since the slit reduces the mechanical strength of the rotor, the selection of the number of slits is critical. The variation of control current with speed for different number of slits is shown in Fig.4[3]. A trade-off between the mechanical strength and the reduction of eddy current is applied and 24 slits has been fabricated for the laboratory model.

4. MODELING FOR FIVE AXIS CONTROL INCLUDING EDDY CURRENT EFFECT

By controlling the current of the four electromagnets along the x-axis separately, three degrees of freedom, the x-axis displacement, x, the pitch, θ, and the yaw, ψ, can be controlled.

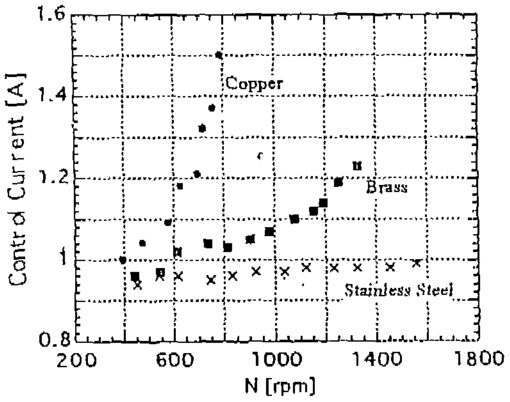

Fig. 2 Variation of control current for different materials

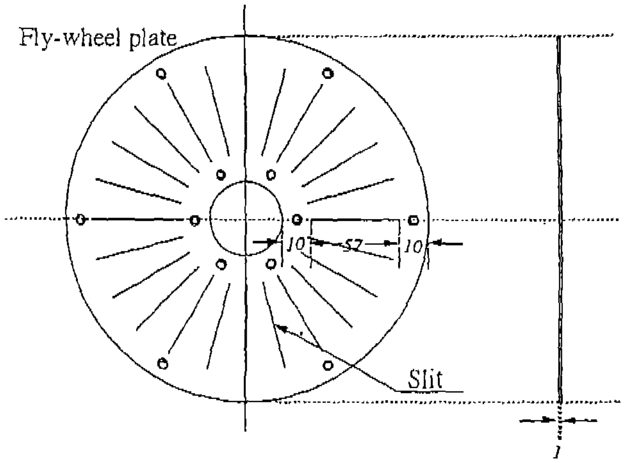

Fig. 3 Slit fabrication

For the y and z axis control we plan to add another two sets of electromagnets along y and z axis respectively. Controlling the currents of this electromagnets the stability along y and z axis can be achieved and the speed of operation can be increased to a higher value. The rotor modeling of the extended system is shown in Fig.5. To take into account the effect of eddy current in the modeling, the electromagnet and the rotor body acts like transformer with short circuited secondary.

The following equations are used for the modeling.

$$V = IR + L\frac{dI}{dt} + L_m\frac{dI_e}{dt} \qquad (1)$$

$$0 = L_m\frac{dI}{dt} + R_e I_e + L_e\frac{dI_e}{dt} \qquad (2)$$

where R and L are the resistance and inductance of the electromagnet, L_m is the mutual inductance between the electromagnet and the eddy current circuit. R_e and L_e are the resistance and inductance of the eddy current circuit. Experimentally measured values to be used to get the actual response.

Eqs(1) and (2) can be further expanded and is written into state-space forms as shown below.

$$\begin{bmatrix}\frac{dI}{dt}\\ \frac{dI_e}{dt}\end{bmatrix} = \begin{bmatrix} -R/K_1 & K_2/K_1 \\ L_m R/K_1 L_e & -(L_m K_2 + R_e K_1)/L_e K_1 \end{bmatrix}\begin{bmatrix} I \\ I_e \end{bmatrix} + \begin{bmatrix} 1/K_1 \\ -L_m/L_e K_1 \end{bmatrix}[V] \qquad (3)$$

where

$$K_1 = \frac{LL_m - L_m^2}{L_e} \quad \text{and} \quad K_2 = \frac{L_m R_e}{L_e}$$

For each electromagnet there are two state equations as discussed above. These equations are included in the modeling. The state equations of the detailed modeling has been listed in the appendix.

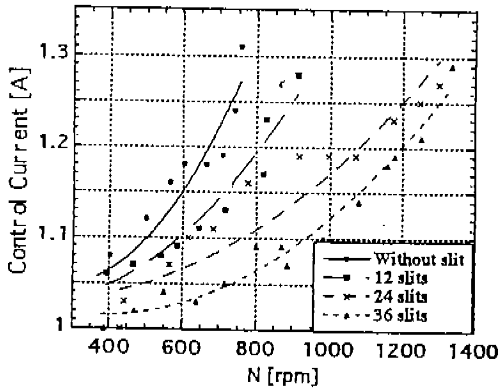

Fig. 4 Variation of control current for different slits

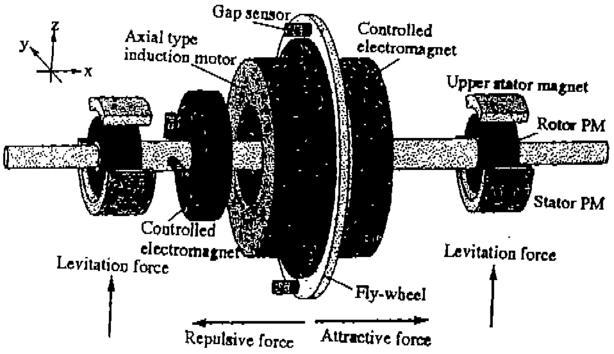

Fig. 5 Modeling of extended system

5. RESULTS AND DISCUSSION

Using Matlab the system performances are simulated for varying operating conditions. The most important one is the response to disturbance. Fig.6 and 7 show the responses of the rotor to disturbances along x-axis and z-axis respectively. Figs. 6a and 7a correspond to the modeling with uncontrolled y and z axis. Figs. 6b and 7b correspond to five axis controlled system but without including eddy current effect. Figs. 6c and 7c correspond to five axis controlled system including eddy current effect and a speed correspond to 60,000rpm.

It is seen that response along the x-axis doesn't change much where as the system goes to unstable state when the disturbance is created along z-axis while z-axis remains uncontrolled. The addition of control along y and z axis enhanced the operating speed to a very high value.

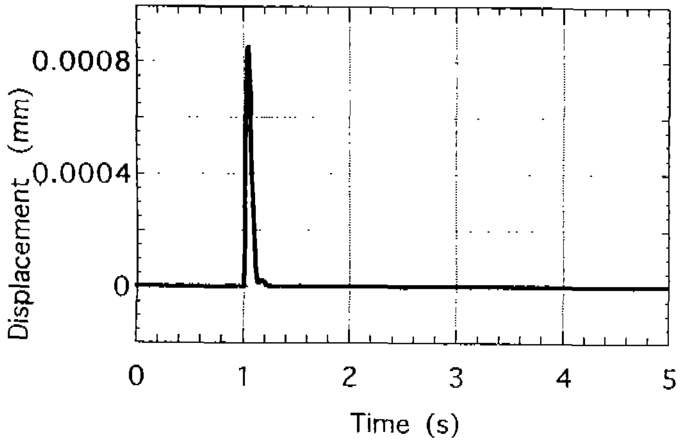

Fig. 6a Response along x-axis (y and z axis uncontrolled)

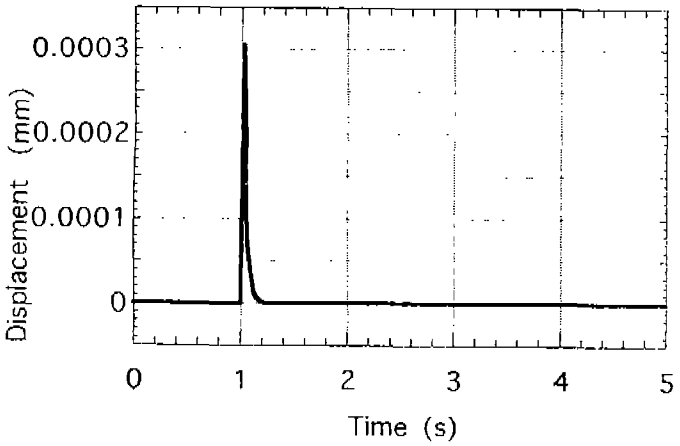

Fig. 7a Response along z-axis (y and z axis uncontrolled).

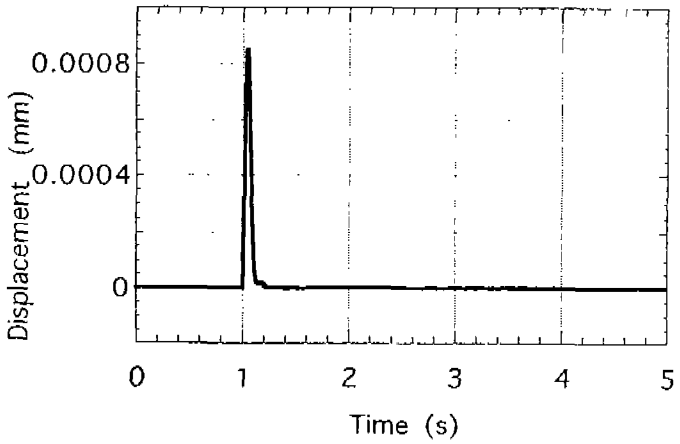

Fig. 6b Response along x-axis (y and z axis controlled but without eddy current effect).

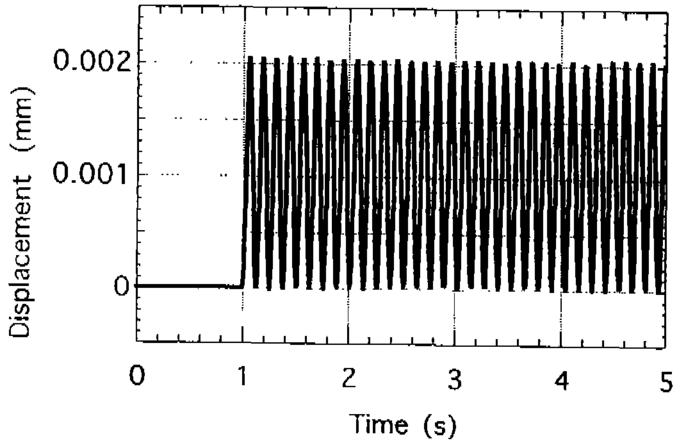

Fig. 7b Response along z-axis (y and z axis controlled but without eddy current effect).

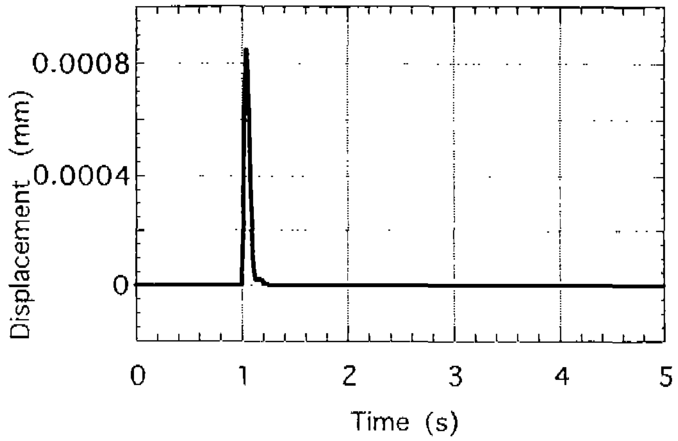

Fig. 6c Response along x-axis (y and z axis controlled but with eddy current effect).

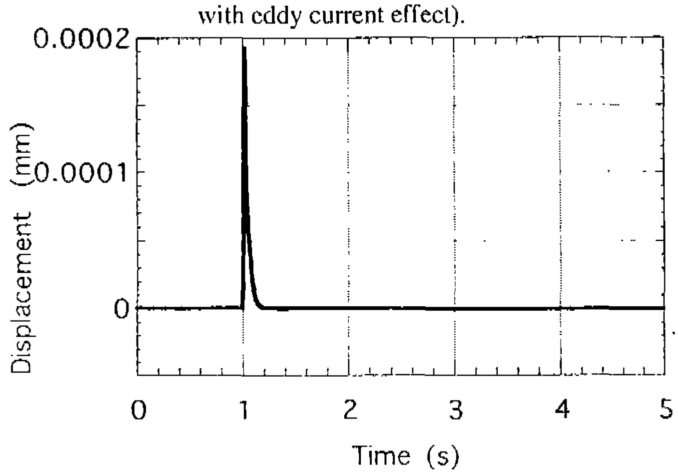

Fig. 7c Response along z-axis (y and z axis controlled but with eddy current effect).

6. CONCLUSIONS

This paper has described a detailed five axis modeling of a repulsive type magnetic bearing including the effect of eddy current. A single-axis controlled magnetic bearing system has already been fabricated and is extended for five axis control. System performances have been simulated for varying operating conditions which ensure the enhancement of the operating speed of the motor to a large value.

REFERENCES

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[2] T.Ohji, S.C.Mukhopadhyay, M.Iwahara and S.Yamada, "Control Current Minimization, Material Selection and Disturbance Attenuation for Flywheel Energy Storage System Employing Permanent Magnet Bearing", Proceeding of the international conference on Electrical Engineering, Vol.I, pp 303-306, July 21-25, Korea.

[3] T.Ohji, S.C.Mukhopadhyay, M.Iwahara, S.Yamada and F.matsumura, "Minimization of Control Current by Suitable Number of Slit Fabrication in the Plate for Flywheel Energy Storage System Employing Permanent Magnet Bearing", Proceeding of the international conference on Linear Drives in Industrial Applications, pp 315-318, April 8-10, 1998, Tokyo, Japan.

Appendix :

The system equations are represented in state space form. The detailed equations are listed in (4) to (16). The displacement along three axes x_s, y_s and z_s, the pitch and yaw and their derivatives, the incremental current of the electromagnets and the eddy current are the state vectors. The state space equations are solved using Matlab.

$$m\ddot{x}_s = f_1 + f_2 + f_3 + f_4 - f_{lx} - f_{rx} \quad (4)$$

$$m\ddot{y}_s = f_{ly} + f_{ry} + f_5 \quad (5)$$

$$m\ddot{z}_s = mg - f_{lz} - f_{rz} + f_6 \quad (6)$$

$$\ddot{\theta} = -\frac{pJ_x}{J_y}\dot{\psi} + \frac{L_{01}}{J_y} f_{lz} - \frac{L_{02}}{J_y} f_{rz} + \frac{l}{J_y}(f_3 - f_1) \quad (7)$$

$$\ddot{\psi} = \frac{pJ_x}{J_y}\dot{\theta} + \frac{L_{01}}{J_y} f_{ly} - \frac{L_{02}}{J_y} f_{ry} + \frac{l}{J_y}(f_4 - f_2) \quad (8)$$

$$\mathbf{x}_1 = [x_s \quad y_s \quad z_s \quad \theta \quad \psi]^T \quad (9)$$

$$\mathbf{z} = \dot{\mathbf{x}}_1 \quad (10)$$

$$\mathbf{i} = [i_1' \quad i_2' \quad i_3' \quad i_4' \quad i_5' \quad i_6']^T \quad (11)$$

$$\mathbf{e} = [e_1' \quad e_2' \quad e_3' \quad e_4' \quad e_5' \quad e_6']^T \quad (12)$$

$$e_j = Ri_j + L\frac{di_j}{dt} + L_m\frac{di_{e_j}}{dt} \quad (13)$$

$$f = k\left(\frac{i_j}{g_j}\right)^2 \quad (14)$$

$$e_j' = Ri_j' + L\frac{di_j'}{dt} + L_m\frac{di_{e_j}'}{dt} \quad (15)$$

$$f' = 2F_j\left(\frac{i_j'}{I_j} - \frac{g_j'}{W}\right) \quad (16)$$

where f_1 to f_6 are the forces due to electromagnets, f_{lx}, f_{ly} and f_{lz} are the repulsive forces due to left set of permanent magnet along the x, y and z direction, f_{rx}, f_{ry} and f_{rz} are the repulsive forces due to right set of permanent magnet along the x, y and z direction. i and e are the current and applied voltage of each electromagnet. i' and e' are the deviation of the current and applied voltage from the normal values. Ij and W are the staedy state current of the electromagnet and gap-distance between the electromagnet surface and the rotor. R is the resistance of the electromagnet coil, L is the self inductance and L_m is the mutual inductance between the coil and eddy current circuit.