https://doi.org/10.21289/KSIC.2023.26.2.231

A Six Pole Permanent Magnet Biased Homopolar Magnetic Bearing with Fault-Tolerant Capability

Uhn Joo Na*

〈Abstract〉

This paper develops the theory for a novel fault-tolerant, permanent magnet biased, 6-active-pole, homopolar magnetic bearing. The Lagrange Multiplier optimization with equality constraints is utilized to calculate the optimal distribution matrices for the failed bearing. some numerical examples of distribution matrices are provided to illustrate the new theory. Simulations show that very much the same dynamic responses (orbits or displacements) are maintained throughout failure events (up to any combination of 3 coils failed for the 6 pole magnetic bearing) while currents and fluxes change significantly. The overall load capacity of the bearing actuator is reduced as coils fail. The same magnetic forces are then preserved up to the load capacity of the failed bearing.

Keywords : Magnetic Bearing, Active Vibration Control, Hybrid Magnetic Bearing, Fault Tolerance, Permanent Magnet Device

* Corresponding Author, Professor, School of Mechanical Engineering Zip Code 51767
E-mail: uhnjoona@kyungnam.ac.kr

1. Introduction

Magnetic bearings have been investigated extensively for the last decades. Unlike heteropolar bearings [1-2], Homopolar magnetic bearings have a unique biasing scheme that directs the bias flux flow into the active pole plane where it energizes the working air gaps, and then returns through the dead pole plane and the shaft sleeve. Use of rare earth permanent magnets such as Samarium-Cobalt (Sm-Co) and Neodymium-Iron-Boron (Nd-Fe-B) yields a very high efficiency when the permanent magnets are used as the source of bias flux to energize the air gaps and electromagnets are used to supply control fluxes in the active plane. Unique flux paths of mixed axial/radial orientation in homopolar design help to lower eddy current power losses significantly [3].

Maslen and Meeker [4] introduced a fault-tolerant 8-pole heteropolar magnetic bearing actuator with independently controlled currents. Flux coupling in a heteropolar magnetic bearing allows the remaining coils to produce force resultants identical to the unfailed bearing, if the remaining coil currents are properly redistributed. Na and Palazzolo [5] also investigated the optimized realization of fault-tolerant magnetic bearing actuators and experimentally showed it on a flexible rotor such that rotor displacements after failure can be maintained close to the displacements before failure for up to all combinations of 4 coils failed and certain combinations of 5 coils failed out of 8 coils.

The present work describes the theory and following numerical analysis for the novel fault-tolerant homopolar magnetic bearing. Energy efficient homopolar magnetic bearings with fault tolerant capability may find great use in some applications such as flywheel energy storage systems and momentum wheels.

2. Bearing Model

The schematic drawing of a 6-active pole, double plane, permanent magnet biased homopolar magnetic bearing is shown in Fig. 1.

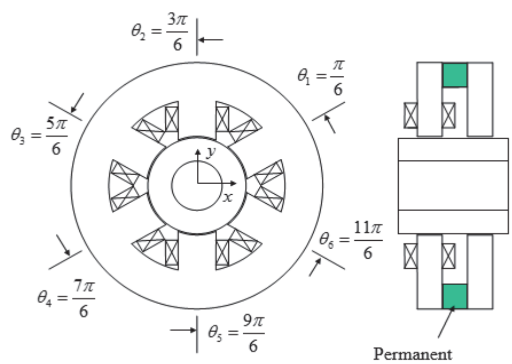

Fig. 1 Homopolar magnetic bearing

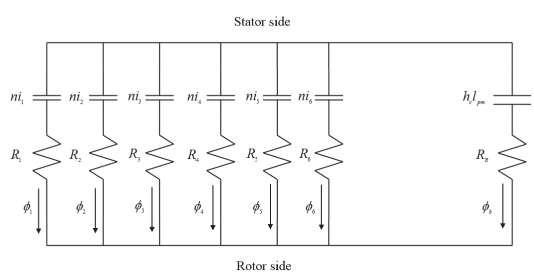

Fig. 2 Equivalent magnetic circuit for 6 pole homopolar magnetic bearing

Assuming that eddy current effects and material path reluctances are neglected, Maxwell's equations are reduced to the equivalent magnetic circuit for the homopolar magnetic bearing as shown in Fig. 2.

The reluctance in air gap j of the active pole plane is;

$$R_j = \frac{g_j}{\mu_0 a_0} \quad (1)$$

$$g_j = g_0 - x\cos\theta_j - y\sin\theta_j \quad (2)$$

The parameters μ_0, a_0, x, y, and g_0 represent the permeability of air, the pole face area of the active pole, the rotor positions, and nominal air gap, respectively. The permanent magnets are modeled as a source, $H_c L_{pm}$, and the return path reluctance R_R. Applying Ampere's loop law to the magnetic circuit results in a matrix equation.

$$\begin{bmatrix} R_1 & -R_2 & 0 & 0 & 0 & 0 \\ 0 & R_2 & -R_3 & 0 & 0 & 0 \\ 0 & 0 & R_3 & -R_4 & 0 & 0 \\ 0 & 0 & 0 & R_4 & -R_5 & 0 \\ 0 & 0 & 0 & 0 & R_5 & -R_6 \\ 1 & 1 & 1 & 1 & 1 & 1+\frac{R_6}{R_R} \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \\ \phi_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{h_c l_{pm}}{R_R} \end{bmatrix} + \begin{bmatrix} n & -n & 0 & 0 & 0 & 0 \\ 0 & n & -n & 0 & 0 & 0 \\ 0 & 0 & n & -n & 0 & 0 \\ 0 & 0 & 0 & n & -n & 0 \\ 0 & 0 & 0 & 0 & n & -n \\ 0 & 0 & 0 & 0 & 0 & \frac{n}{R_R} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{bmatrix} \quad (3)$$

or

$$R\Phi = H + NI \quad (4)$$

The magnetic circuit equation (4) for a homopolar magnetic bearing has a permanent magnet bias forcing term H that energize the working air gaps. The coil current vector I then provides only AC control currents. The fault tolerant, 6-active pole, homopolar magnetic bearing utilizes 6 independent coils each driven by its power amplifiers. The currents distributed to the 6-active-pole bearing are generally expressed as a 6×2 distribution matrix T and control voltage vector v_c. The current vector is;

$$I = T v_c \quad (5)$$

$$T = [T_x \; T_y],\; v_c = \begin{bmatrix} v_{cx} \\ v_{cy} \end{bmatrix}$$

The parameters v_{cx} and v_{cy} represent the x and y control voltages. A typical current distribution scheme (coil winding scheme) for a homopolar magnetic bearing is;

$$\tilde{T} = \begin{bmatrix} \sqrt{3}/2 & 1/2 \\ 0 & 1 \\ -\sqrt{3}/2 & 1/2 \\ -\sqrt{3}/2 & -1/2 \\ 0 & -1 \\ \sqrt{3}/2 & -1/2 \end{bmatrix} \quad (6)$$

The feedback control voltages v_{cx} and v_{cy}, determined with any type of control law and measured rotor motions, are distributed to each pole via $\tilde{T}$ in normal operation, and create effective stiffness and damping of the bearing to suspend the rotor around the bearing center position. If some coils fails, the full (6×1) current vector is related to the reduced current vector by introducing a failure map matrix W.

$$I = WI \quad (7)$$

For example the matrix for the 4th-6th coil failed bearing is described as;

$$W = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The reduced distribution matrix is defined as;

$$\hat{I} = \hat{T} v_c \quad (8)$$

$$\hat{T} = \left[\hat{T}_x \ \hat{T}_y \right] \quad (9)$$

$$\hat{T}_x = [t_1\, t_2\, t_3]^T, \hat{T}_y = [t_4\, t_5\, t_6]^T$$

The reduced distribution matrix is to be determined such that the magnetic forces should remain very much invariant before and after failure. The flux density vector can be determined from the magnetic circuit equation in Eq. (3). Leakage and fringing effects can be empirically determined and are simply derated by the fringing factor ζ . The flux density vector in the air gaps is described as;

$$B = \zeta A^{-1} R^{-1} (H + NI) \quad (10)$$

where the pole face area matrix is $A = diag([a_0, a_0, a_0, a_0])$. The flux density vector is then reformulated as;

$$B = Gv \quad (11)$$

$$G = \left[G_b H \ G_c \hat{T}_x \ G_c \hat{T}_y \right] . v = \left[1 \ v_{cx} \ v_{cy} \right]^T \quad (12)$$

$$G_b = \zeta A^{-1} R^{-1}, G_c = \zeta A^{-1} R^{-1} N W$$

Magnetic forces developed in the active pole plane are then described as;

$$f_x = v^T M_x v \quad (13)$$

$$f_y = v^T M_y v \quad (14)$$

$$M_x(\hat{T}) = -G^T \frac{\partial D}{\partial x} G, M_y(\hat{T}) = -G^T \frac{\partial D}{\partial y} G \quad (15)$$

and where the air gap energy matrix is;

$$D = diag([g_j a_0 / (2\mu_0)]) \quad (16)$$

Employing an optimal current distribution matrix T may decouple the linearized forces of the failed bearing, and even maintain the same decoupled magnetic forces as those of an unfailed magnetic bearing. The necessary conditions to yield the same decoupled magnetic control forces are;

$$M_x = k_v \begin{bmatrix} 0 & \frac{1}{2} & 0 \\ \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, M_y = k_v \begin{bmatrix} 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 \end{bmatrix} \quad (17)$$

If the distribution matrix $\tilde{T}$ is determined such that Eq. (15) satisfies Eq. (17), the nonlinear magnetic forces in Eqs. (13) and (14) become linearized at bearing center positions.

$$f_x = k_v v_{cx}, f_y = k_v v_{cy}, \tag{18}$$

Equations (15) and (17) can be written in 18 scalar forms, and then boils down to 10 algebraic equations if redundant terms are eliminated. The equality constraints to yield the same control forces before and after failure are;

$$\begin{aligned}
h_1(\hat{T}) &= \widehat{T}_x^T Q_{x0} \widehat{T}_x = 0 \\
h_2(\hat{T}) &= \widehat{T}_y^T Q_{x0} \widehat{T}_y = 0 \\
h_3(\hat{T}) &= H^T Q_{bx0} \widehat{T}_y = 0 \\
h_4(\hat{T}) &= \widehat{T}_x^T Q_{x0} \widehat{T}_y = 0 \\
h_5(\hat{T}) &= H^T Q_{bx0} \widehat{T}_y = k_v/2 \\
h_6(\hat{T}) &= \widehat{T}_x^T Q_{y0} \widehat{T}_x = 0 \\
h_7(\hat{T}) &= \widehat{T}_y^T Q_{y0} \widehat{T}_y = 0 \\
h_8(\hat{T}) &= H^T Q_{by0} \widehat{T}_x = 0 \\
h_9(\hat{T}) &= \widehat{T}_x^T Q_{y0} \widehat{T}_y = 0 \\
h_{10}(\hat{T}) &= H^T Q_{by0} \widehat{T}_y = k_v/2
\end{aligned} \tag{19}$$

where

$$Q_{\phi b0} = -G_b \frac{\partial D}{\partial \phi} G_b \Big|_{\substack{\phi=0 \\ \omega=0}}, Q_{\phi 0} = -G_c \frac{\partial D}{\partial \phi} G_c \Big|_{\substack{\phi=0 \\ \omega=0}}$$

The criterion for choosing the best candidate is the one that will yield the maximum load capacity prior to any saturation. To accomplish this a distribution matrix $\hat{T}$ can be determined by using the Lagrange Multiplier method to minimize the Euclidean norm of the flux density vector B. The cost function is defined as;

$$J = B(\hat{T})^T P B(\hat{T}) \tag{20}$$

where the diagonal weighting matrix P is also selected to maximize the load capacity. The Lagrange Multiplier method is then used to solve for $\hat{T}$ that satisfies Eq. (19). Define:

$$L(\hat{T}) = B(\hat{T})^T P B(\hat{T}) + \sum_{j=1}^{10} \lambda_j h_j(\hat{T}) \tag{21}$$

Partial differentiation of Eq. (21) with respect to t_i and λ_j leads to 16 nonlinear algebraic equations to solve for t_i and λ_j.

$$\Psi = \begin{bmatrix} \Psi_1(t,\lambda) \\ \Psi_2(t,\lambda) \\ \cdot \\ \cdot \\ \cdot \\ \Psi_{15}(t,\lambda) \\ \Psi_{16}(t,\lambda) \end{bmatrix} = 0 \tag{22}$$

$$\Psi_i = \frac{\partial L}{\partial t_i} = 0, i = 1,2,\ldots,6 \tag{23}$$

$$\Psi_{6+j} = h_j(\hat{T}) = 0, j = 1,2,\ldots,10 \tag{24}$$

3. Numerical Analysis

Various initial guesses are tested to find the solution of Eq.(22). Some examples of distribution matrices are calculated for the 6-pole homopolar magnetic bearing with the nominal air gap (0.508mm), pole face area

(602mm^2), number of coil turns (50turns). It is assumed that permanent magnets are selected to produce bias flux density of 0.8 Tesla in the air gaps of the active pole plane. A distribution matrix for an 6-pole homopolar bearing with the 5th-6th coils failed operation is calculated as;

$$T_{56} = \begin{bmatrix} 0.9669 & 1.6434 \\ -1.1149 & 1.3394 \\ -0.6164 & 1.6591 \\ -1.8801 & -0.0161 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{25}$$

A distribution matrix with the 4th-5th-6th coilsfailedoperationiscalculatedas;

$$T_{456} = \begin{bmatrix} 1.6776 & 1.0501 \\ 0.0003 & 1.9262 \\ -1.6781 & 1.0501 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{26}$$

Similarly, the distribution matrices can be calculated for a failed homopolar bearing up to any combinations of 3 coils failed out of 6 coils.

4. Control Simulations

The schematic of a fault-tolerant control scheme utilizing distribution matrices developed in the previous section is shown in Fig. 3. The controller consists of two independent parts, which are a feedback voltage control law and an adaptive current distribution mechanism. Though any control algorithm for magnetic bearing systems appearing in the literature can be utilized with the fault tolerant scheme, for sake of illustration, a simple PD feedback control law is used to stabilize the system. While the feedback control law remains unaltered during the failure the appropriate current distribution matrix can be continuously updated using an adaptive current distribution mechanism. The fault-tolerant control scheme can be easily implemented in a physical controller (DSP). The distribution matrix of $\tilde{T}$ is switched to

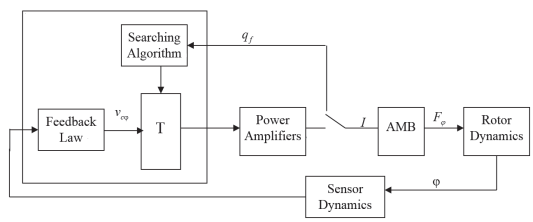

Fig. 3 Schematic of fault-tolerant control system

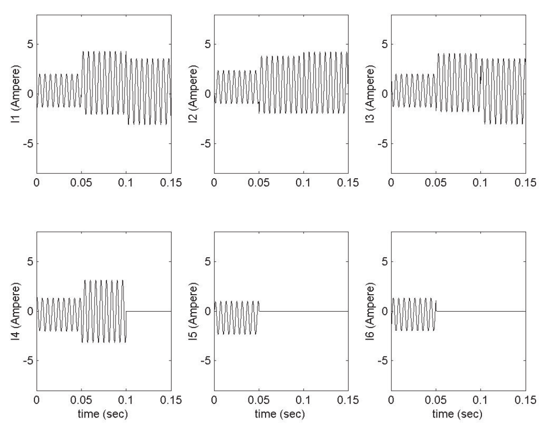

Fig. 4 Current plot for a series of failures

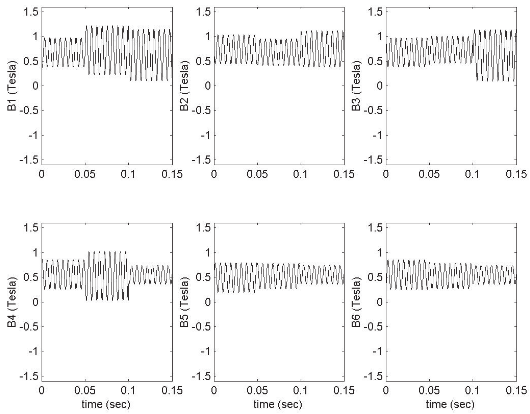

Fig. 5 Flux density plot for a series of failures

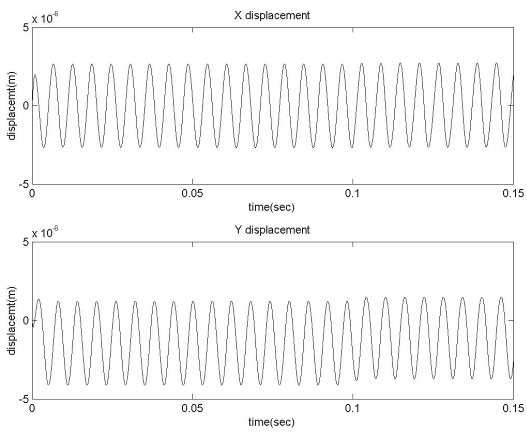

Fig. 6 Displacement plot for a series of failures

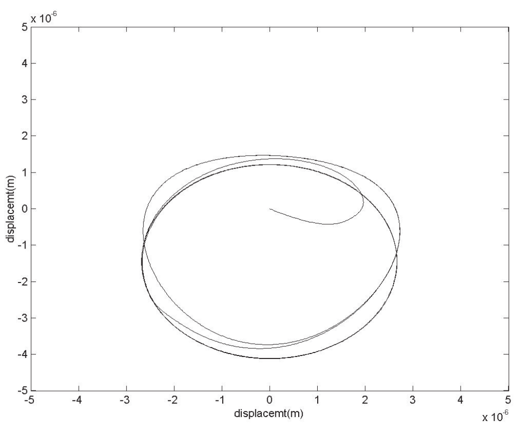

Fig. 7 Orbit plot for a series of failures

T_{56} and T_{456} when 2 adjacent coils failed at 0.05 seconds and then 3 adjacent coils failed at 0.1 seconds. The rotor speed is held constant at 10,000 RPM.

Fig. 4 shows transient response of the current inputs to the outboard bearing from the normal unfailed operation through the 5-6th coils and 4-5-6th coils of the outboard bearing failed at 0.05 seconds and 0.1 seconds, respectively. Fig. 5 shows the corresponding transient response of the flux densities in the outboard bearing for the 5-6th coils and 4-5-6th coils failed operation.

Fig. 6 and Fig. 7 show transient rotor displacements and orbits at the outboard bearing for the 5-6th coils and 4-5-6th coils failed operation respectively. Figs. 4-7 indicates that very much the same rotordynamic responses are maintained throughout the series of failure events, while currents and fluxes in the homopolar magnetic bearing change significantly.

5. Conclusion

A fault-tolerant control scheme is developed for the permanent magnet biased, 6-active-pole, homopolar magnetic bearings.

The homopolar bearing actuator using the fault tolerant control algorithm can preserve the same linearized magnetic forces by redistributing the remaining currents even if some components such as coils or power amplifiers suddenly fail. The distribution matrix

T of control voltages is determined by using the Lagrange Multiplier optimization with equality constraints for a failed bearing in a manner that the load capacity should be maximized. Simulations show that very much the same vibrations (orbits or displacements) are maintained throughout failure events while currents and fluxes change significantly with different distribution scheme. The distribution matrices can be calculated for a failed homopolar bearing up to all combinations of 3 coils failed out of 6 coils. The fault tolerance of homopolar magnetic bearings is achieved at the expense of additional hardware requirements such as independent coils (power amplifiers), fault detection system, additional DSP controller channels.

Acknowledgements

This paper was supported by Kyungnam University Research Fund.

References

[1] P. E. Allaire, D. W. Lewis, J. D. Knight, "Active Vibration Control of a Single Mass Rotor on Flexible Supports," Journal of the Franklin Institute vol. 315 pp. 211-222, (1983).

[2] J. Salm, G. Schweitzer, "Modeling and Control of a Flexible Rotor with Magnetic Bearing," Proceedings of the Third International Conference on Vibrations in Rotating Machinery pp. 553-561, (1984).

[3] Y. Fan, A. Lee, F. Hsiao, "Design of a Permanent/Electromagnetic Magnetic Bearing-Controlled Rotor System." Journal of the Franklin Institute, vol. 334B, pp. 337-356, (1997).

[4] E. H. Maslen, D. C. Meeker, "Fault Tolerance of Magnetic Bearings by Generalized Bias Current Linearization." IEEE Transactions on Magnetics, vol. 31, pp. 2304-2314, (1995).

[5] U. J., Na, A. B., Palazzolo, and A., Provenza, "Test and Theory Correlation Study for a Flexible Rotor on Fault-Tolerant Magnetic Bearings." ASME Journal of Vibration and Acoustics, vol. 124, pp. 359-366, (2002).

(Manuscript received March 1, 2023;
revised March 31, 2023; accepted April 10, 2023)