Fault Tolerant Control of Magnetic Actuators

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Abstract

This paper develops the theory for a fault-tolerant, permanent magnet biased, homopolar magnetic bearing. If some of the coils or power amplifiers suddenly fail, the remaining coil currents change via a novel distribution matrix such that the same magnetic forces are maintained before and after failure. Lagrange multiplier optimization with equality constraints is utilized to calculate the optimal distribution matrix that maximizes the load capacity of the failed bearing. The overall load capacity of the bearing actuator is reduced as coils fail.

1 Introduction

A magnetic bearing system is a mechatronics device consisting of a magnetic force actuator (an active magnetic bearing, or AMB), motion sensors, power amplifiers, and a feedback controller (DSP), that suspends the spinning rotor magnetically without physical contact, and suppresses vibrations. Magnetic bearings find greater use in high speed, high performance applications since they have many advantages over conventional fluid film or rolling element bearings, such as lower friction losses, lubrication free, temperature extremes, no wear, quiet, high speed operations, actively adjustable stiffness and damping, and dynamic force isolation. Though magnetic bearings find more applications in industry, reliability requirements limit magnetic bearings from being used in highly critical applications. Failure of components such as coils or power amplifiers in magnetic bearings may result in a failure of the entire system.

Fault tolerant control provides continued operation of magnetic bearing actuators even if its power amplifiers or coils suddenly fail. Much research has been devoted to fault-tolerant heteropolar magnetic bearings. Maslen and Meeker [1] introduced a fault-tolerant 8-pole heteropolar magnetic bearing actuator with independently controlled currents and experimentally verified it in [2]. 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 [3, 4] 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. Na and Palazzolo [5] introduced a fault-tolerant control scheme utilizing the grouping of currents to reduce the required number of controller outputs and to remove decoupling chokes.

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 an 8-active pole, permanent magnet biased homopolar magnetic bearing is shown in Fig. 1.

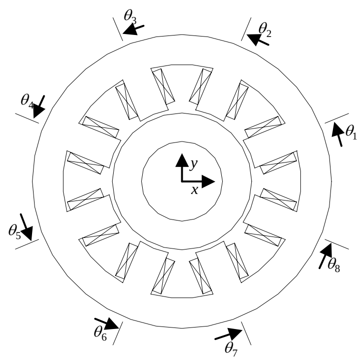

Figure 1. Schematic of an 8-Active Pole, Permanent Magnet Biased Magnetic Bearing

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. 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. With the uniform current distribution with $\tilde{T}$ as well as the symmetric bearing geometries, magnetic forces are (x , y) decoupled and vary linearly with respect to control currents and rotor displacements around the bearing center position. If symmetry is lost due to a coil failure, magnetic forces are no longer decoupled and linear with respect to control currents and rotor displacements, and even it may be difficult to maintain stable control. Reassigning the remaining currents with a redifined current distribution scheme may remedy this by providing the same decoupled magnetic forces as those before failure. Magnetic forces developed in the active pole plane are described as;

$$f_x = v^T M_x v \tag{1}$$

$$f_y = v^T M_y v \tag{2}$$

3 Bias Linearization

The magnetic forces in Eqs. (1) and (2) can be linearized about the bearing center position and the zero control voltages by using Taylor series expansion. The linearized magnetic forces are;

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = -\begin{bmatrix} k_{pxx} & k_{pxy} \\ k_{pyx} & k_{pyy} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} k_{vxx} & k_{vxy} \\ k_{vyx} & k_{vyy} \end{bmatrix}\begin{bmatrix} v_{cx} \\ v_{cy} \end{bmatrix} \tag{3}$$

The position stiffnesses are defined as;

$$k_{p\varphi\omega} = -H^T \left.\frac{\partial Q_{\varphi b}}{\partial \omega}\right|_{\substack{\varphi=0 \\ \omega=0}} H \tag{4}$$

where $$Q_{\varphi b} = -G_b \frac{\partial D}{\partial \varphi} G_b$$

The parameters φ and ω represent either x or y. The position stiffnesses of the homopolar bearing remain unchanged with a coil failure since the position stiffnesses are only influenced by the bias flux driven with permanent magnets. The voltage stiffnesses are defined as;

$$k_{v\varphi\omega} = 2H^T \left. Q_{b\varphi}\right|_{\substack{\varphi=0 \\ \omega=0}} \hat{T}_\omega \tag{5}$$

where $$Q_{b\varphi} = -G_b \frac{\partial D}{\partial \varphi} G_c$$

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. Maslen and Meeker [1] introduced a linearization method which effectively decouple the control forces for a failed bearing by choosing a proper distribution matrix. Though not identified in [1], the direct voltage stiffness k_v is used to yield the same linearized control forces as those of the unfailed bearing. The necessary conditions to yield the same decoupled magnetic control forces are;

$$M_x = k_v \begin{bmatrix} 0 & 1/2 & 0 \\ 1/2 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \; M_y = k_v \begin{bmatrix} 0 & 0 & 1/2 \\ 0 & 0 & 0 \\ 1/2 & 0 & 0 \end{bmatrix} \tag{6}$$

If the distribution matrix $\hat{T}$ is determined such that Eq. (20) should be met, the magnetic forces at bearing center position in Eqs. (12) and (13) lead to;

$$f_x = k_v v_{cx}, \quad f_y = k_v v_{cy} \tag{7}$$

Equations (6) 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;

$$\begin{aligned}
h_1(\hat{T}) &= \hat{T}_x{}^T Q_{x0} \hat{T}_x = 0 \\
h_2(\hat{T}) &= \hat{T}_y{}^T Q_{x0} \hat{T}_y = 0 \\
h_3(\hat{T}) &= H^T Q_{bx0} \hat{T}_y = 0 \\
h_4(\hat{T}) &= \hat{T}_x{}^T Q_{x0} \hat{T}_y = 0 \\
h_5(\hat{T}) &= H^T Q_{bx0} \hat{T}_y = k_v/2 \\
h_6(\hat{T}) &= \hat{T}_x{}^T Q_{y0} \hat{T}_x = 0 \\
h_7(\hat{T}) &= \hat{T}_y{}^T Q_{y0} \hat{T}_y = 0 \\
h_8(\hat{T}) &= H^T Q_{by0} \hat{T}_x = 0 \\
h_9(\hat{T}) &= \hat{T}_x{}^T Q_{y0} \hat{T}_y = 0 \\
h_{10}(\hat{T}) &= H^T Q_{by0} \hat{T}_y = k_v/2
\end{aligned} \qquad (8),$$

4 Optimal Distribution

Some examples of distribution matrices are calculated for the 8-pole homopolar magnetic bearing with the nominal air gap g_0 (0.508 mm), pole face area a_0 (602 mm^2), number of coil turns n (50 turns). It is assumed that permanent magnets are selected to produce bias flux density of 0.6 Tesla in the air gaps of the active pole plane. The design of the permanent magnets for a homopolar magnetic bearing is beyond the scope of this paper. The direct voltage stiffness k_v is then calculated as 106.651 N/volt. A distribution matrix for an 8-pole homopolar bearing with the 7th-8th coils failed operation is calculated as;

$$T_{78} = \begin{bmatrix} 1.9337 & -0.5171 \\ -0.7557 & 2.1604 \\ -0.2844 & 0.3313 \\ -0.3109 & 0.2836 \\ -2.1707 & 0.7506 \\ 0.5313 & -1.9159 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad (9)$$

A distribution matrix with the 6th-7th-8th coils failed operation is calculated as;

$$T_{678} = \begin{bmatrix} 1.5852 & 0.5941 \\ -0.9194 & 1.4034 \\ -0.5185 & 1.2468 \\ -0.3469 & 1.6607 \\ -2.2336 & -0.0018 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad (10)$$

A distribution matrix with the 5th-6th-7th-8th coils failed operation is calculated as;

$$T_{5678} = \begin{bmatrix} 1.8351 & 0.8207 \\ 0.2480 & 1.6421 \\ -0.2480 & 1.6422 \\ -1.8351 & 0.8206 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad (11)$$

Similarly, the distribution matrices can be calculated for a failed homopolar bearing up to all combinations of 5 coils failed out of 8 coils. In the previous fault tolerant scheme with heteropolar magnetic bearings [3, 4], distribution matrix solutions do not exist for a certain combination of 5 failed coils (for example, no solution exists for 5 adjacent coils failed heteropolar bearings).

The following system dynamics simulation illustrates the transient response of a rotor supported by magnetic bearings during a coil failure event. An unbalance force of $me\Omega^2$ with m (2.0 grams), e (0.01 m) and Ω (spinning speed) are applied at the two bearing locations. The distribution matrix of $\tilde{T}$ is switched to T_{5678} and T_{45678} when 4 adjacent coils failed at 0.02 seconds and then 5 adjacent coils failed at 0.04 seconds. The rotor speed is held constant at 20,000 RPM. Figures 2 shows transient response of the current inputs to the outboard bearing from the normal unfailed operation through the 5-6-7-8th coils and 4-5-6-7-8th coils of the outboard bearing failed at 0.02 seconds and 0.04 seconds, respectively. This 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.

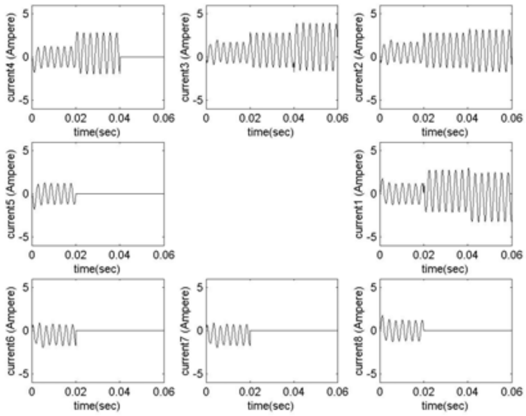

Figure 2. Current Plot for a Series of Failures

5 Conclusion

A fault tolerant control scheme is developed for an energy efficient homopolar magnetic bearing. 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. Only control currents as well as control fluxes are redistributed for the failed bearing while bias flux driven by permanent magnets remains constant. Less strict constraints of only 10 equations are required for the fault tolerant homopolar bearing to produce the same magnetic forces, while 12 constraint equations are required for the fault tolerant heteropolar bearing in [3]. This released conditions may give some benefits to the realization of fault tolerant homopolar bearings. The solution space of distribution matrices is extended for the homopolar bearing. The distribution matrices can be calculated for a failed homopolar bearing up to all combinations of 5 coils failed out of 8 coils. In the previous fault tolerant scheme with heteropolar magnetic bearings, no solutions exist for certain combinations of 5 failed coils. The load capacities of the failed homopolar magnetic bearings are greatly increased compared to those of heteropolar magnetic bearings.

Fault tolerance of the magnetic bearing actuator is achieved at the expense of additional hardware requirements and reduction of overall bearing load capacity. Therefore, the fault tolerant magnetic bearing should be designed enough to support loads even in case of a severe failure (5 coils failed out of 8 coils).

Otherwise, disturbances from unbalance, runouts, and sideloads should be maintained at low level to prevent saturation.

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