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ROTOR TRANSIENT RESPONSE WITH FAULT TOLERANT MAGNETIC BEARINGS

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ABSTRACT

The concept of fault-tolerant control was devised to increase the tolerance of active magnetic bearing to amplifier, coil, and electric cable failures (i.e. loss of magnetic poles). If some poles fail in operation, the bearing would remain functional. Special features of the self-healing magnetic bearing include:

- There is no need for off-line calculation and storage of control parameters associated with failed poles.
- There is no need for on-line monitoring of the failed pole patterns.

A computer program has been developed to increase understanding and facilitate the design of this type of fault-tolerant magnetic bearing. The details of transient simulation development are presented in this paper along with interesting numerical transient responses of a flywheel rotor system that employs a self-healing magnetic bearing.

INTRODUCTION

Magnetic bearings have gained popularity recently due to the oil free and efficiency requirements of turbomachinery. A conventional active magnetic bearing (AMB) as shown in Figure 1a has four quadrants of poles; two opposite quadrants are used to control rotor motions. There is usually one magnetizing coil per pole and the coils in the same quadrant are connected in series and driven by a dedicated power amplifier. The attractive magnetic forces in the conventional magnetic bearings make the rotor system inherently unstable and therefore require on-line servo control for stability. Any failure of the coils, amplifiers, or electric cables will cause the entire bearing to fail. Practitioners are continuously striving to design magnetic bearings with control redundancy especially for military and high-speed applications. Lyons et al [1] presented a paper in the design and control of a fault-tolerant active magnetic bearing system for aircraft engines. In their bearing design, one redundant control axis had been introduced by having three magnetically isolated control axes. Any two of these control axes are sufficient to maintain control of the rotor position.

Maslen and Meeker [2,3] presented a more generalized approach by controlling each pole of a magnetic bearing independently. The coil currents were determined by the required magnetic forces. The multi-pole force-to-current relationship required for designing the feedback control is difficult to identify and the mathematical solution is not unique due to the redundancy introduced by the additional control axis. In their work, the matrix relationship was computed numerically and stored digitally as look-up tables. This approach requires intensive computational time and computer memory to store the matrix parameters. In addition, on-line monitoring of coil failure pattern, such as measuring the coil currents, is required for servo control.

Recently, Chen [4] extended the previous work on independently controlling each pole or axis and summarized that there is no need to pre-calculate the force-to-current relationship. In his approach, each pole is controlled by a nominal set of bias currents and PID (proportional, integral, and derivative) gains, with consideration of possible current and flux saturation due to different pole failure patterns. This simple and straightforward control system presented by Chen [4] does not require any data storage or on-line current monitoring. The results have demonstrated that the new control system possesses a strong resilient nature to the pole failure characterized as *self-healing*. Chen has concluded that when some poles fail, the integral controls of the remaining poles work in unison and adjust current individually to regain control of the rotor. The difficult force-to-current relationships solved numerically in reference [2] appear to have been solved internally in a natural way by this control system.

Computer programs have been developed to design the magnetic actuator, predict the dynamic characteristics, and integrate this bearing characteristics into a flexible rotor system for a complete transient simulation to facilitate our understanding and design of this new type of fault tolerant magnetic bearing. Functions related to this fault tolerant magnetic bearing can be easily incorporated into an existing commercially available rotordynamics program, such as DyRoBeS© (Dynamics of Rotor Bearing Systems) [5].

MAGNETIC ACTUATOR DESIGN

In a conventional 8-pole magnetic bearing, as shown in Figure 1a, the flux path is designed with equal width and has alternative pole polarity, so that the flux flows locally in a quadrant. There is usually one coil per pole and the coils in the same quadrant are connected in series and driven by a dedicated power amplifier. For the same 8-pole self-healing magnetic bearing, as shown in Figure 1b, the rotor and stator cores are designed with the same uniform or identical poles. A minimum of three poles must be specified in the design. The selection of the number of poles depends on the redundancy requirement. Figure 2 shows the typical core configurations that range from six to eight poles. The cross-sectional areas of magnetic flux paths at the poles, rotor, and stator are the same values as one would design for the conventional AMBs. There are many ways to size the actuator cores and the process may involve many geometry, magnetic, and electrical parameters. The relationships among these parameters are not all well defined, therefore, the design is heavily dependent on the designer's experience. For the design purpose, some parameters are considered as inputs and the rest of the parameters can be calculated from these known parameters. Table 1 presents a typical sizing analysis result showing both the given and calculated parameter values.

The current stiffness and the position stiffness per pole are required to size the linearized control. However, their calculations are not as straightforward as in the conventional AMBs because the flux variation or re-distribution is no longer limited locally in a quadrant. The current or air gap variation of one pole not only changes the flux density of its own and opposite quadrants, but also affects all the quadrants. A detailed method on how to calculate these stiffness parameters has been presented in reference [4], and will not be elaborated here.

MAGNETIC FORCES

In the fault tolerant magnetic bearing, each pole has a single coil driven by a dedicated power amplifier. The current in each coil may vary from zero to the maximum amperage but it can never change sign. The air gap and coil current variations of one pole can not only change the flux density of its own and opposite quadrants but also the perpendicular quadrants. For generality, an pole magnetic bearing is employed in the formulation. Assuming that the reluctance of all metal components of the flux path is negligible and the only source of magnetic excitation in the bearing is due to the coil current, the current reluctance is solely due to the air gap (see Figure 3). From the Ampere's Law, the current and flux relationship [2,3] is:

$$\mathbf{R}\Phi = \mathbf{N}\mathbf{I} \qquad (1)$$

Where Φ is the flux vector, $\mathbf{I}$ is the coil current vector, is the reluctance matrix, and $\mathbf{N}$ is the coil winding influence matrix.

$$\mathbf{R} = \begin{bmatrix} R_1 & -R_2 & 0 & 0 & \cdot & \cdot \\ 0 & R_2 & -R_3 & 0 & \cdot & \cdot \\ 0 & 0 & R_3 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & R_{n-1} & -R_n \\ 1 & 1 & \cdot & \cdot & 1 & 1 \end{bmatrix}$$

$$\mathbf{N} = \begin{bmatrix} N_1 & -N_2 & 0 & 0 & \cdot & \cdot \\ 0 & N_2 & -N_3 & 0 & \cdot & \cdot \\ 0 & 0 & N_3 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & N_{n-1} & -N_n \\ 0 & 0 & \cdot & \cdot & 0 & 0 \end{bmatrix}$$

$R_i = g_i/\mu_o A$ = air gap reluctance at i^{th} pole
g_i = air gap at i^{th} pole
A = pole area
μ_o = air permeability
n = number of poles
N = number of coils per pole

Note that the coil winding influence matrix has of zeros and it indicates that one of the currents current vector is redundant. If one or more of the fail, the above equation is still valid. Once the flux is determined from equation (1), then flux density is calculated as:

$$\mathbf{B} = \mathbf{A}^{-1}\Phi \qquad (2)$$

[illegible] A is a diagonal matrix of the pole face area. The current for each pole includes the bias current and control current, which is governed by an independent controller as:

$$[illegible] = -C_p D - C_i \int D\, dt - C_d \frac{dD}{dt} \qquad (3)$$

[illegible] C_p, C_i, C_d are proportional, integral, derivative [illegible], D is displacement at each pole, and t is the [illegible]

[illegible] attractive force for each bearing is the summary of [illegible] forces from each pole:

$$[illegible] = \frac{AB^2}{2\mu_0} \qquad (4)$$

ROTOR TRANSIENT RESPONSE

The complete rotor bearing system equations of motion are of the form:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}(t) + \mathbf{F}_B(t) \qquad (5)$$

Where F_B is the magnetic bearing forces. The finite element formulations of the rotor systems presented by [illegible] [6] were employed in this paper, and are not repeated here.

There are several numerical tools readily available for solving a system of first order differential equations, such as the Runge-Kutta method. However, the excessive computational time and memory storage required in solving first order differential equations make these tools less attractive in dealing with large rotor bearing systems. The Newmark method is an unconditionally stable numerical integration scheme that has proven to be successful in solving the second order equations of motion for flexible rotor systems as shown by Chen [7].

EXAMPLES

A flywheel rotor demonstration rig is shown in Figure 4. The vertical rotor, weighing about 14 pounds and running at the maximum speed of 10,000 rpm, is supported by a ball bearing and a fault tolerant magnetic bearing. A deep groove ball bearing at the top also serves as a thrust bearing. It is supported at bottom by an 8 pole self-healing magnetic bearing.

An undamped critical speed map for this rotor is presented in Figure 5. With the fault tolerant magnetic bearing stiffness superimposed on the map, the undamped critical speed is found to be around 7600 rpm.

The mode shape of the first critical speed, as shown in Figure 6, has a pendulum shape while pivoting at top and swinging at bottom. To demonstrate the dynamic characteristics of the fault tolerant magnetic bearing, transient analysis has been performed with the following fault sequence:

- At time = 0.30 second, the #2 coil fails.
- At time = 0.50 second, the #3 coil fails.
- At time = 0.70 second, the #6 coil fails.

The first analysis was performed without any unbalance force. Figure 7 presents the transient displacements in the X and Y directions in the SHMB. The failure of the #2 coil has created large rotor excursions in both X and Y directions, because it is a 45° pole. Note that the displacements recover automatically within 0.2 seconds. The failure of coil #3 later creates the excursion mostly in the Y direction, because it is a 90° pole. When the #6 coil fails its effect is less in the X direction, because in handling the previous coil failures the self-healing control has smartly reduced the current in #6 as shown in the current plot of Figure 8. The Y excursion is larger, because the bearing has been significantly weakened in that direction by the failing #3 coil. It is amazing that the system knows how to adjust current naturally as shown in Figure 8. Adding a rotor unbalance response at 6000 rpm to the transient simulation, the rotor orbits at coil #2 failure are plotted in Figure 9. The top orbit is at the coupling end and the bottom orbit is at the SHMB. They are opposite in phase, as predicted by the mode shape plot of Figure 6.

SUMMARY AND CONCLUSION

The multi-axis, self-healing control scheme, which is tolerant to amplifier/cabling/coil faults will be popular for the next generation of magnetic bearings. To facilitate the rotor-bearing system design of the future, we have incorporated the self-healing design software into a commercially available rotor dynamic code – DyRoBeS©. Employing this combined code, one can:

1. Size the self-healing magnetic bearings needed for the rotor support.
2. Design the control parameters, such as feedback PID gains for each pole.
3. Perform nonlinear transient response simulating pole failures.

Using a vertical flywheel rotor as an example, we have analytically demonstrated the unique characteristics of the self-healing magnetic bearing, i.e.,

- When one or more poles fail, the remaining controlled poles can automatically re-arrange the currents and recover the magnetic levitation.

- The linear control law is very robust even when non-linearity, such as saturation of coil currents and magnetic flux is involved.
- There is no need to monitor pole failure patterns on-line, or store pre-calculated control parameters. This makes this control scheme elegantly simple and inexpensive to implement.

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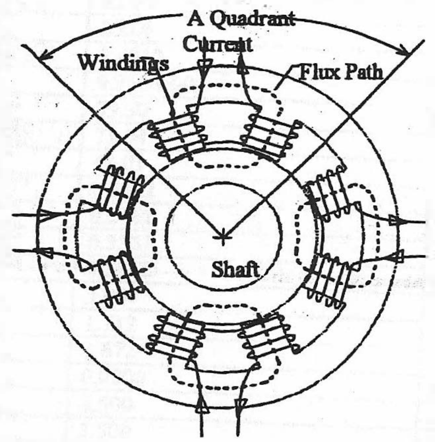

Figure 1a – Conventional Magnetic bearing

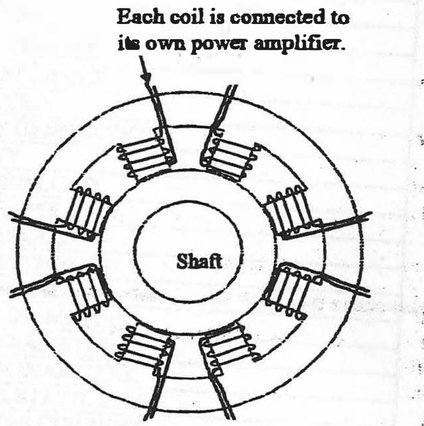

Figure 1b – Fault Tolerant Magnetic Bearing

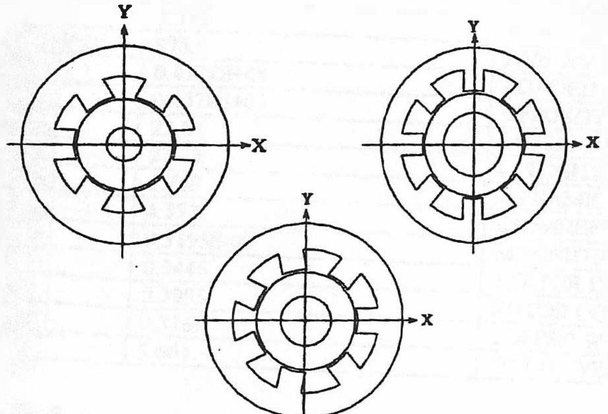

Figure 2 – A Typical Pole Arrangement

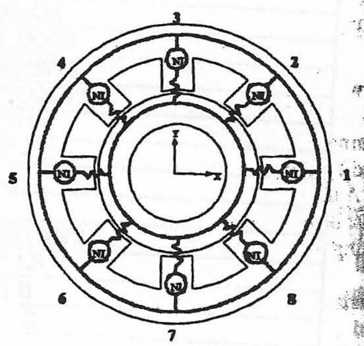

Figure 3 – Magnetic Circuit Model

TABLE 1 – SIZING ANALYSIS 8-POLE SHMB

INPUT

Value	Description
1.000	AXIAL LENGTH
8.000	NO. OF POLES
1.000	MAX. JOURNAL LAM. ID
0.5000	RATIO, WP/ (WP+S)
1.000	RATIO, T/S
0.8000E+05	SATURATION FLUX DENSITY
0.2000E-01	AIR GAP
0.2500E-01	BARE WIRE DIAMETER
0.2000E-02	WIRE INSULATION THICKNESS
0.7000	FILL FACTOR OF COIL IN SLOT
0.0000	STATIC LOAD
700.0	REFERENCE FREQUENCY
3000.	STIFFNESS AT OMREF
4.000	DAMPING AT OMREF
3.500	BIAS CURRENT

OUTPUT

500.8	MAX. AMPERE-TURNS
6.107	MAX. CURRENT
82.00	NO. OF TURNS/POLE
250.6	LENGTH OF WIRE/POLE
0.4010	WIRE RESISTANCE/POLE
0.3606E-02	INDUCTANCE/POLE
39.30	BEARING HEAT GENERATION
71.94	LOAD CAPACITY
43.01	EQUIV. PRESSURE LOAD
0.3362	CIRCUMF. WIDTH/POLE
0.3362	SURFACE AREA/POLE
0.3362	CIRCUMFER. WIDTH/SLOT
0.3362	SLOT RADIAL DEPTH
3.057	STATOR OUTER DIAMETER
1.712	STATOR INNER DIAMETER
1.672	JOURNAL OUTER DIAMETER
0.0000	EXTRA BIAS FOR STATIC LOAD
3.500	LOADED SIDE BIAS CURRENT
3.500	OPPOSITE SIDE BIAS CURRENT
711.5	OPEN-LOOP PROPORTION GAIN
6403.	OPEN-LOOP INTEGRAL GAIN
0.7153	OPEN-LOOP DERIVATIVE GAIN
5.592	AVE. CURRENT STIFF./AXIS
978.6	AVE. MAGNETIC STIFF./AXIS
0.4578E+05	LOADED SIDE FLUX DENSITY
0.4578E+05	OPPOSITE SIDE FLUX DENSITY
23.63	LOADED SIDE MAG. FORCE
23.63	OPPOSITE SIDE MAG. FORCE
1.740	DYNAMIC CURRENT
4.392	L*OMREF*DYNI
0.3195E-03	MAGNETIC FORCE CONSTANT
0.9446	STATOR CORE WEIGHT, LB
0.3995	ROTOR CORE WEIGHT, LB
0.3169	COPPER WIRE WEIGHT, LB
1.661	TOTAL WEIGHT, LB