KSTLE International Journal, Vol. 4, No. 2, December 2003, pp. 37-42

Design and Implementation of a Fault-Tolerant Magnetic Bearing System

B.C. Park, M.D. Noh*,†, S.K. Ro**, J.H. Kyung*** and J.K. Park****

Depaerment of Mechatronics Engineering, Chungnam National University, Daejeon, 305-764, Korea
**Department of Mechatronics Engineering, Chungnam National University, Daejeon, 305-764, Korea*
***Manufacturing Machinery Group, Korea Institute of Machinery and Materials, Daejeon, Korea*
****Manufacturing Machinery Group, Korea Institute of Machinery and Materials, Daejeon, Korea*
*****Manufacturing Machinery Group, Korea Institute of Machinery and Materials, Daejeon, Korea*

Abstract: One of the obstacles for a magnetic bearing to be used in the wide range of industrial applications is the failure modes associated with magnetic bearings, which we don't expect for conventional passive bearings. These failure modes include electric power outage, power amplifier faults, position sensor faults, and the malfunction of controllers. Fault-tolerant magnetic bearing systems have been proposed so that the system can operate in spite of some faults in the system. In this paper, we designed a fault-tolerant magnetic bearing system for a turbo-molecular vacuum pump. The system can cope with the actuator/amplifier faults which are the most common faults in a magnetic bearing system. We implemented the existing fault-tolerant algorithms to experimentally prove the adequacy of the algorithms for industrial applications. As it turns out, the system can operate even with three simultaneously failing poles out of eight actuator poles.

Keywords: Magnetic bearing, magnetic suspension, fault tolerance, magnetic circuit, active control

Introduction

One of the obstacles for a magnetic bearing to be used in the wide range of industrial applications is the failure modes associated with magnetic bearings, which we don't expect for conventional passive bearings. These failure modes include electric power outage, power amplifier faults, position sensor faults, and the malfunction of controllers. Fault-tolerant magnetic bearing systems have been proposed so that the system can operate in spite of some faults in the system [1,2,3]. For example, a backup battery can supply electricity when an electric power outage occurs. Better yet, rotational kinetic energy of the shaft can be converted into electric energy by reversing the power flow of the electric motor equipped in the system, thereby supplying electricity to the magnetic bearings while the shaft safely touches down to the backup bearings. A controller faults can be dealt with by using triple modular redundancy (TMR), where three identical controllers are employed to maintain system operation in spite of controller faults. For actuator/amplifier faults which are the most common faults in a magnetic bearing system, several researchers have proposed algorithms for fault tolerance by utilizing the pre-existing redundancy of the actuator [1,2]. It has been shown that an eight-pole magnetic bearing can sustain a fair amount of load capacity even with three poles failing to produce magnetic forces.

In this paper, we designed a fault-tolerant magnetic bearing system for a turbo-molecular vacuum pump. The system can cope with the actuator/amplifier faults. We implemented the existing fault-tolerant algorithms to experimentally prove the adequacy of the algorithms for industrial applications.

Theoretical Background

For the presentation of experimental results, it is necessary to briefly describe the actuator fault-tolerance algorithm. For details of the algorithms, interested readers are asked to review the references [1,2]. A schematic of an eight-pole radial magnetic bearing is shown in Fig. 1. If we ignore the path reluctances of the back iron and journal iron, we can set up a

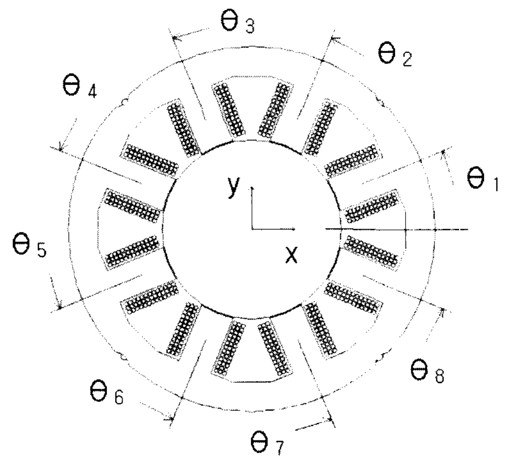

Fig. 1. 8-pole radial magnetic bearing.

†Corresponding author; Tel: +82-42-821-6877, Fax: +82-42-823-4919
E-mail: mnoh@cnu.ac.kr

simple magnetic circuit model consisting of the magnetomotive forces (mmf) and the air gap reluctances, as depicted in Fig. 2.

Recognizing the seven independent flux loops in Fig. 2, we can write Ampere's loop law as

$$R_j\phi_j - R_{j+1}\phi_{j+1} = Ni_j - Ni_{j+1}, \quad j = 1,\ldots,7 \tag{1}$$

where R_j is the reluctance of the j-th air gap defined as

$$R_j = \frac{g_j}{\mu_0 A} = \frac{g_0 - x\cos\theta_j - y\sin\theta_j}{\mu_0 A} \tag{2}$$

In (2), g_0 is the nominal air gap, A the pole face area, μ_0 the permeability of free space ($4\pi \times 10^{-7}$H/m), θ_j the angle of j-th pole, x and y the radial displacements.

The seven circuit laws of (1) plus the flux conservation law can be conveniently expressed in a matrix equation

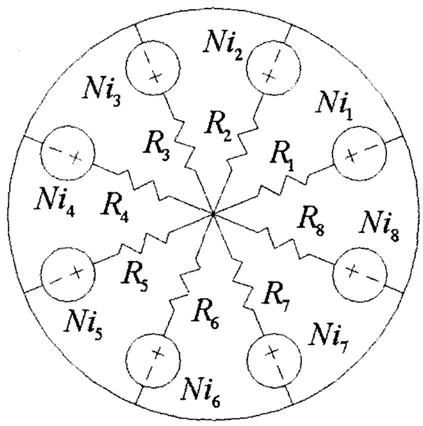

Fig. 2. Magnetic circuit model.

$$\begin{bmatrix} R_1 & -R_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_2 & -R_3 & 0 & 0 & 0 & 0 & 0 \\ & & & \vdots & & & & \\ 0 & 0 & 0 & 0 & 0 & 0 & R_7 & -R_8 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_7 \\ \phi_8 \end{bmatrix} = \begin{bmatrix} N & -N & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & N & -N & 0 & 0 & 0 & 0 & 0 \\ & & & \vdots & & & & \\ 0 & 0 & 0 & 0 & 0 & 0 & N & -N \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_7 \\ i_8 \end{bmatrix} \tag{3}$$

or

$$\mathbf{R\Phi} = \mathbf{NI} \tag{4}$$

Assuming uniform flux ϕ_j in the air gap, flux is related to flux density B_j by $\phi_j = B_j A$. In matrix form, this relationship is

$$\mathbf{\Phi} = \mathbf{BA}$$

where **A** is a diagonal matrix of pole face areas. Then, equation (4) can be written as

$$\mathbf{B} = \mathbf{A}^{-1}\mathbf{R}^{-1}\mathbf{NI} = \mathbf{VI} \tag{5}$$

Magnetic force can be expressed in terms of current vector as

$$F_x = -\mathbf{I}^T\mathbf{V}^T\mathbf{D}_x\mathbf{VI} \tag{6}$$

$$F_y = -\mathbf{I}^T\mathbf{V}^T\mathbf{D}_y\mathbf{VI} \tag{7}$$

where $\mathbf{D}_x$ and $\mathbf{D}_y$ are diagonal matrices defined as

$$\mathbf{D}_x = diag\left[\frac{A\cos\theta_j}{2\mu_0}\right], \quad \mathbf{D}_y = diag\left[\frac{A\sin\theta_j}{2\mu_0}\right] \tag{8}$$

As can be seen in (6) and (7), the magnetic force is quadratic to the coil currents. Furthermore, infinite number of coil currents can produce identical forces, since there is the redundancy of coil currents. One method of optimally solving this inverse problem is the bias linearization. The bias linearization gives us a current distribution matrix **W** which maps the control currents into the coil currents

$$\mathbf{I} = \mathbf{W}\begin{bmatrix} i_b \\ i_x \\ i_y \end{bmatrix} \tag{9}$$

such that the forces are linear to the control currents

$$F_x = C_x i_b i_x$$

$$F_y = C_y i_b i_y$$

For an eight-pole radial magnetic bearing, one example of this current distribution matrix is

$$\mathbf{W} = \begin{bmatrix} 0.5051 & 0.4572 & 0.1894 \\ -0.5051 & -0.1894 & -0.4572 \\ 0.5051 & -0.1894 & 0.4572 \\ -0.5051 & 0.4572 & -0.1894 \\ 0.5051 & -0.4572 & -0.1894 \\ -0.5051 & 0.1894 & 0.4572 \\ 0.5051 & 0.1894 & -0.4572 \\ -0.5051 & -0.4572 & 0.1894 \end{bmatrix} \tag{10}$$

Fault-tolerance algorithm utilize the bias linearization and the fact there is the redundancy of coil currents. When some of the poles fail, a new current distribution matrix can be used to relate the control currents with the force vector. For example, when the first pole fails, the following current distribution

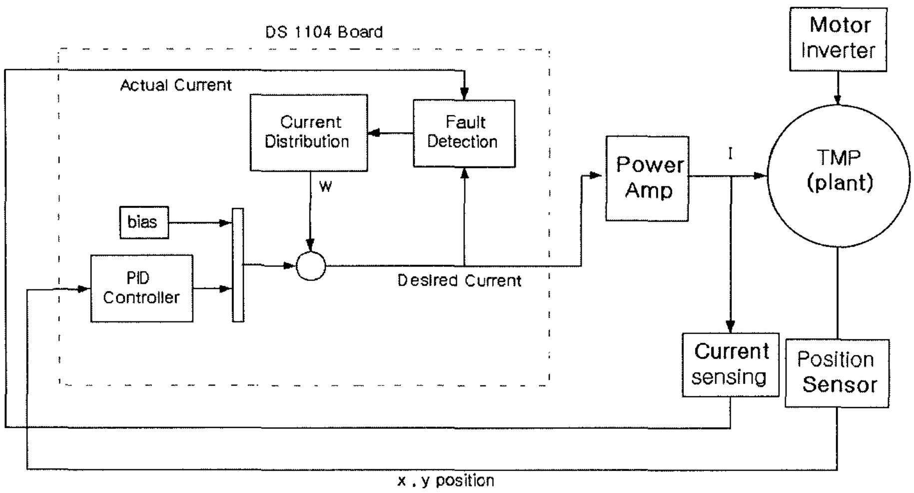

Fig. 3. System block diagram.

matrix enables the bearing to produce forces without any loss in load capacity.

$$\mathbf{W} = \begin{bmatrix} 0 & 0 & 0 \\ -1.01 & -0.6466 & -0.6466 \\ 0 & -0.6466 & 0.2678 \\ -0.01 & 0 & -0.3788 \\ 0 & -0.9145 & -0.3788 \\ -1.01 & -0.2678 & 0.2678 \\ 0 & -0.2678 & -0.6466 \\ -1.01 & -0.9145 & 0 \end{bmatrix} \tag{11}$$

Theory tells us that the bearing can produce the force vector in any direction even with three adjoining poles failing, when the coil selection matrix is

$$\mathbf{W} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -0.6667 & 0.4483 & -1.5307 \\ 0 & -0.9511 & -2.2961 \\ 0 & -0.9511 & -2.2961 \\ 0 & -0.9511 & -2.2961 \\ -0.6667 & -1.3994 & -0.7654 \end{bmatrix} \tag{12}$$

In case of three adjoining poles failing, however, the load capacity of the bearing is reduced to 14% of the no-fault case.

Experimental Setup

Fig. 3 illustrates the schematic of the fault-tolerant magnetic bearing system. The rotor of a prototype turbomolecular vacuum pump (TMP) is magnetically suspended by two radial magnetic bearings and one thrust magnetic bearing. One of radial magnetic bearings is fault-tolerant. A set of position sensors monitor the radial position of the rotor and produce the feedback signal for the controller. The controller generates command signal for the power amplifier to generate adequate coil currents in the bearing. For fault-detection, Hall-type current sensors (LEM HY-5p) monitor the coil currents.

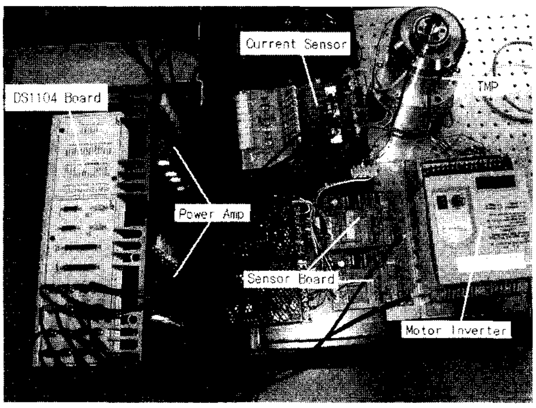

Fig. 4. Actual experimental setup.

A DSP controller (dSPACE DS1104) carries out the feedback control for the suspension, fault-detection, and the selection of the proper current distribution matrix **W** in case of faults. To reduce the computational burden of the DSP controller, the current distribution matrices for all fault conditions are pre-computed and stored in the onboard memory.

The power amplifiers are linear transconductance types, which means that the output current is proportional to the input command voltage. Inductive position sensors are employed, which has the position resolution of 0.43 μm and the bandwidth of 800 Hz [4]. Power amplifiers and position sensors are all made in-house. Fig. 4 shows the picture of the experimental setup.

The detection of actuator faults is accomplished by comparing the command current and the actual current. Considering the dynamic bandwidth of the current amplifiers and the accuracy of the current sensors, the fault signal is flagged when the error between the command and the actual current is greater than 100 mA for the duration of more than 4 ms.

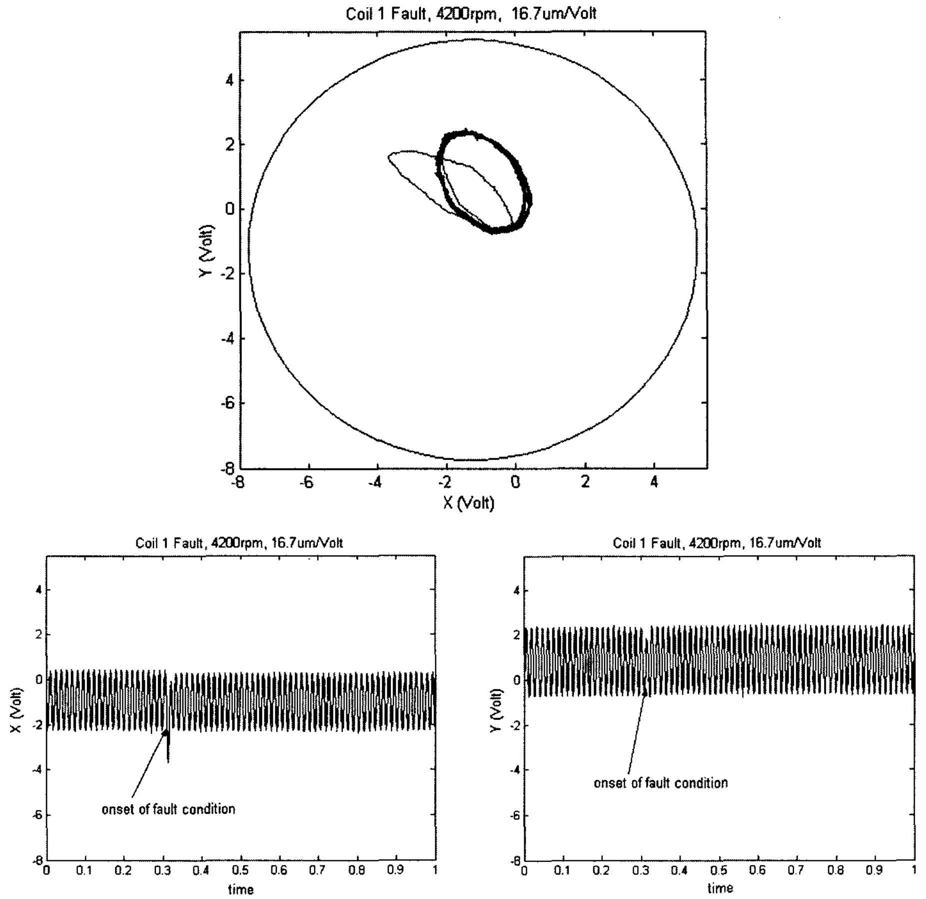

Fig. 5. Loci of the shaft movement before and after the one-pole failure.

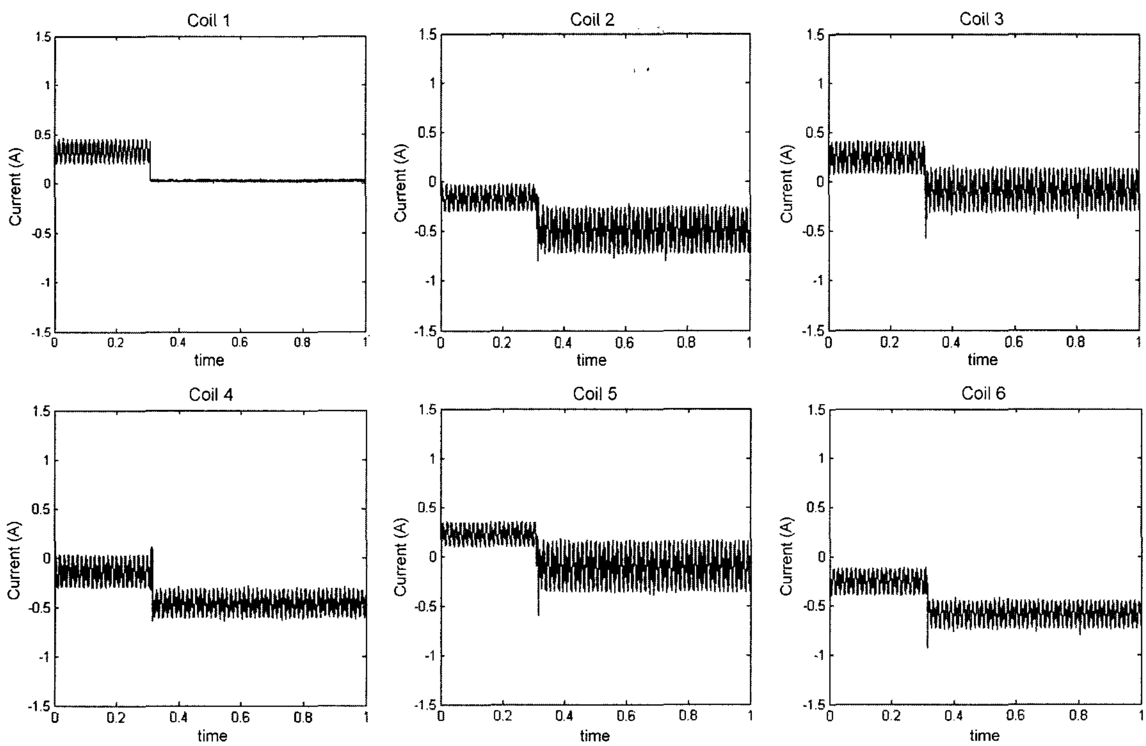

Fig. 6. Coil currents before and after the first pole fails.

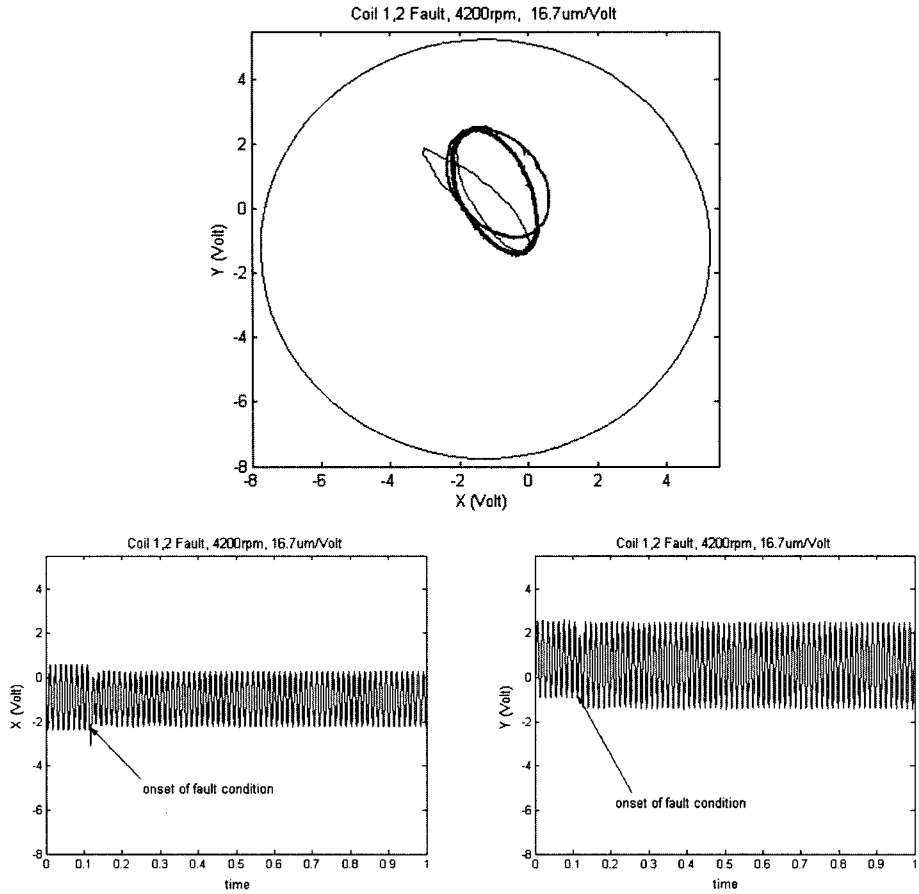

Fig. 7. Loci of the shaft movement before and after the two-pole failure.

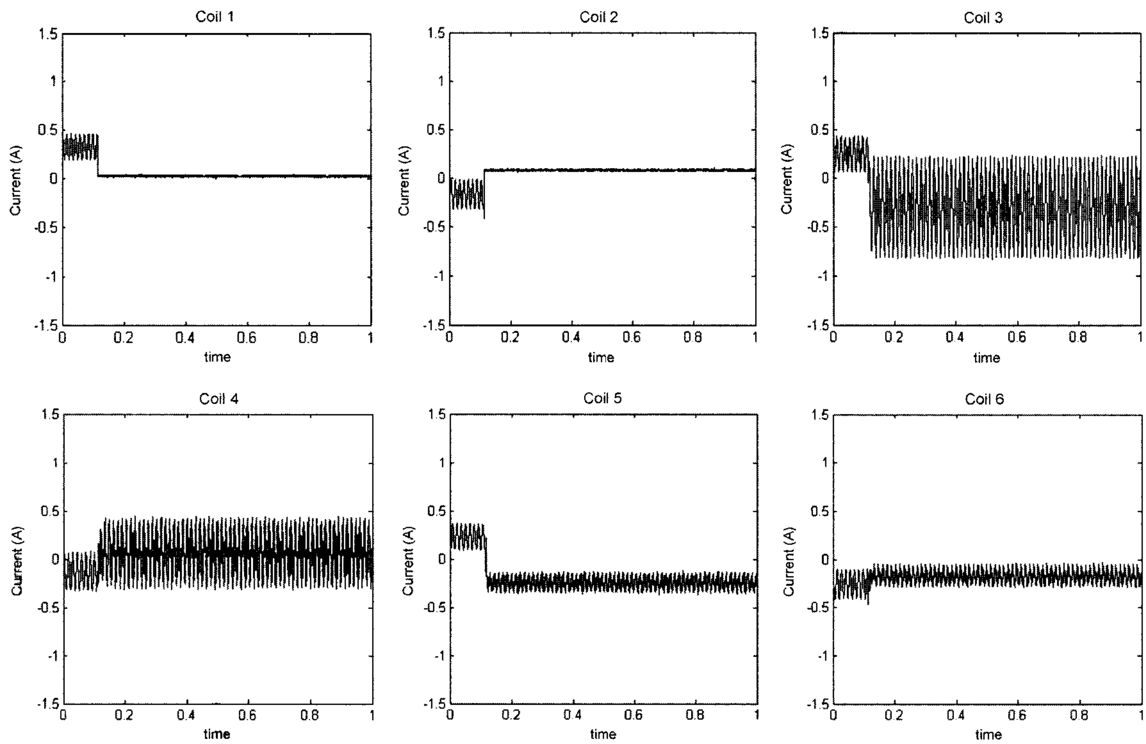

Fig. 8. Coil currents before and after pole 1 and 2 fail.

Experimental Results

Fig. 5 shows the loci of the rotational movement of the rotor, when one pole is made non-functioning. Except for a short transient, the loci after the fault overlaps with those before the fault, which makes virtually impossible to distinguish the fault condition from the no-fault condition. The large circle in Fig. 5 means the clearance space of the bearing. The fault condition becomes only noticeable when we take a look at the coil currents. Fig. 6. shows the measurements coil currents in several poles (pole number 1 to number 6). When the fault occurs in pole 1, the corresponding coil current becomes zero. Because of new current distribution matrix, the other coil currents slightly change and accommodate the fault-condition.

When two poles are failing simultaneously (pole 1 and 2), the results are not very different from the one-pole failure case. Fig. 7 shows the rotational loci of the rotor before and after the faults. The rotational movement of the rotor change little after the fault and is well within the clearance space of the bearing. Fig. 8 shows how the coil currents change when the fault occurs. The coil currents in pole 1 and 2 become zero after the fault. The peak-to-peak magnitudes of the coil currents in pole 3 and 4 increase, but those of pole 5 and 6 decrease.

Conclusions

In this paper we designed a fault-tolerant magnetic bearing system. We implemented an existing amplifier/actduator fault-tolerance algorithm and found that the experimental results support the theory. We hope that the results of this paper address some of the reliability issues that must be overcome for wide acceptance of magnetic bearing technology in industrial applications.

References

1. E. H. Maslen and D. C. Meeker, "Fault tolerance of magnetic bearings by generalized bias current linearization," IEEE Trans. Magn., vol. 31, pp. 2304-2314, 1995.
2. U. Na and A. B. Palazzolo, "Fault tolerance of magnetic bearings with material path reluctances and fringing factors" IEEE Trans. Magn., vol. 36, no. 6 pp. 3939-3946, 2000.
3. J. P. Lyons, M. A. Preston, R. Gurumoorthy, and P. M. Szczesny, "Design and control of a fault-tolerant active magnetic bearing system for aircraft engine," Proc. 4th Int. Symp. Magnetic Bearings, ETH Zurich, pp. 449-454,1994.
4. M. D. Noh, M. Jeong, B. Park, J. Park and S. Ro "Development of a low cost inductive sensor using switching noise demodulaton", Proc. 8th Int Symp. Magnetic Bearing, Mito, Japan, Aug 26-28, pp. 311-314, 2002.