DESIGN AND IMPLEMENTATION OF A FAULT-TOLERANT MAGNETIC BEARING SYSTEM FOR TURBO-MOLECULAR VACUUM PUMP

Myounggyu D. Noh, Seong-Rak Cho
Dept. Mechatronics Engineering, Chungnam National University, Daejon, Korea
mnoh@cnu.ac.kr

Jin-Ho, Kyung, Seung-kook Ro, Jong-Kweon Park
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 and implemented a fault-tolerant magnetic bearing system for a turbo-molecular vacuum pump. The system can cope with the actuator/amplifier faults as well as the faults in position sensors, which are the two major fault modes in a magnetic bearing system.

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 [4]. For actuator/amplifier faults, 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 as well as the malfunctioning of position sensors. In order to achieve actuator/amplifier fault tolerance, we used the bias linearization method suggested by Meeker and Maslen [1] in addition to the linear power amplifiers we built inhouse. For sensor fault-tolerance, we designed a ring-shaped inductive sensor described in the previous ISMB [5]. The multi-pole structure of the ring-shaped sensor made it easy to introduce the redundancy in sensing which we utilized for fault-tolerance by the method similar to [6].

We built a prototype turbo-molecular pump and tested the fault tolerance while running the pump up to 4200 rpm. The results shows that the magnetic bearing system can operate even with three simultaneously failing poles out of eight actuator poles in addition to some partial faults in the position sensor.

SYSTEM DESCRIPTION

The schematic diagram of the turbo-molecular vacuum pump is shown in Fig. 1. The rotor is driven by a brushless DC motor, and supported by the combination of two radial magnetic bearings and one thrust magnetic bearing. Each radial bearing has eight poles. For non-fault-tolerant operation, two adjacent poles are wired in series. Fault-tolerance requires that all eight poles are controlled separately. Although it is not shown in the diagram, the upper bearing is bigger than the lower bearing to counteract the heavy loading due to the pump blade. The thrust bearing consists of two actuator coils and one thrust plate. For startups and shutdowns, the rotor has two backup ball bearings which are not shown in the diagram. The air gap between the rotor and the radial magnetic bearings is 0.3 mm, whereas the radial clearance of the backup bearings is 0.1 mm.

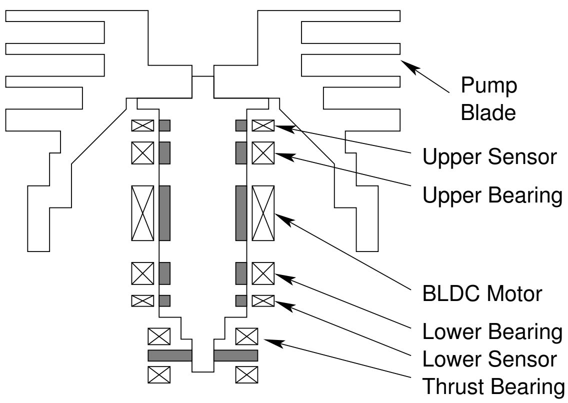

FIGURE 1: Schematic diagram of a magnetically levitated turbo-molecular pump

The currents in the bearing coils are generated by linear transconductance amplifier. The schematic of the amplifier is shown in Fig. 2. We used APEX PA21 dual power op amp for implementation. Since the power requirement is low (max. 1A), the inefficiency of the linear amplifier is not a big concern.

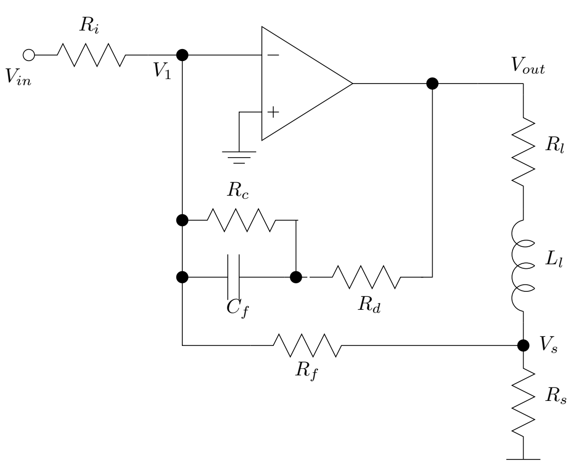

FIGURE 2: Schematic of linear transconductance power amplifier

The system is equipped with two sets of inductive sensors. Each set of the sensor is a multi-polar ring-shaped sensor which produces the radial position of the rotor [5]. For non-fault-tolerant operation, the 16 poles of the sensor are divided into four groups. Coils of the each group of four poles are wired in series. Two opposing groups differentially sense one axis of the rotor motion. The sensor coils are driven by a PWM switching power amplifier with 50% fixed duty cycle.

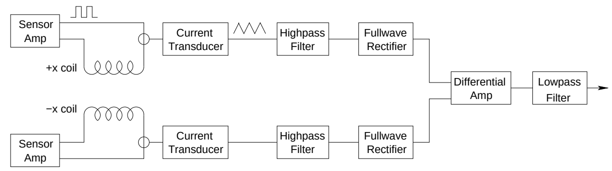

FIGURE 3: Block diagram of sensor signal processing circuit

The signal processing circuit is composed of the current transducers and the demodulation filter. The demodulation filter is basically a combination of a full-wave rectifier and a low-pass filter. A high-pass filter precedes the demodulation filter to remove any low frequency drift. The block diagram of the signal processing circuit is shown in Fig. 3

For fault-tolerant operation, the two adjacent poles of the sensor are wired in series so that one set of the sensor produces four channels. Since number of axes that one sensor needs to measure are two, the signals from these four channels are redundant. The fault-tolerance algorithm takes advantage of this redundancy.

ACTUATOR/AMPLIFIER FAULT TOLERANCE

If a fault occurs in the magnetic bearing or the power amplifier, the consequence of the fault is the same: the loss of coil currents. For fault-tolerant operation, we need to be able to use the functioning coils (or poles) to generate enough levitation force. In this paper, we used the bias linearization method [1]. For the presentation of the paper, we will briefly describe the bias linearzation algorithm.

In general, a radial magnetic bearing has more poles than the number of the force components that it needs to generate. For example, an eight-pole radial bearing typically generates two force components. Using the magnetic circuit theory, the magnetic force due to the coil currents can be expressed as

$$F_x = \mathbf{I}^T \mathbf{V}_x \mathbf{I} \qquad (1)$$

$$F_y = \mathbf{I}^T \mathbf{V}_y \mathbf{I} \qquad (2)$$

In (1) and (2), the current vector $\mathbf{I}$ contains the coil currents and the matrices $\mathbf{V}_x$ and $\mathbf{V}_y$ are the functions of air gaps, the number of turns per pole, pole face area, etc. With the given coil currents $\mathbf{I}$, the forces F_x and F_y are uniquely determined. However, the inverse relationship of the quadratic equations (1) and (2) is not unique. Bias linearization provides an optimal solution to this inverse problem [7]. If we choose an current distribution matrix **W** such that

$$\mathbf{I} = \mathbf{W}\begin{bmatrix} i_b \\ i_x \\ i_y \end{bmatrix} \tag{3}$$

the force becomes

$$F_x = C_x i_b i_x \tag{4}$$

$$F_y = C_y i_b i_y \tag{5}$$

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

$$\mathbf{W} = \begin{bmatrix} 0.5051 & 0.4572 & 0.1894 \\ -0.5051 & -0.1894 & -0.4572 \\ 0.5051 & -0.1894 & 0.4572 \\ -0.5051 & 0.4572 & -0.1894 \\ 0.5051 & -0.4572 & -0.1894 \\ -0.5051 & 0.1894 & 0.4572 \\ 0.5051 & 0.1894 & -0.4572 \\ -0.5051 & -0.4572 & 0.1894 \end{bmatrix} \tag{6}$$

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

$$\mathbf{W} = \begin{bmatrix} 0 & 0 & 0 \\ -1.01 & -0.6466 & -0.6466 \\ 0 & -0.6466 & 0.2678 \\ -1.01 & 0 & -0.3788 \\ 0 & -0.9145 & -0.3788 \\ -1.01 & -2678 & 0.2678 \\ 0 & -0.2678 & -0.6466 \\ -1.01 & -0.9145 & 0 \end{bmatrix} \tag{7}$$

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

$$\mathbf{W} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -0.6667 & 0.4483 & -1.5307 \\ 0 & -0.9511 & -2.2961 \\ 0 & -0.9511 & -2.2961 \\ 0 & -0.9511 & -2.2961 \\ -0.6667 & -1.3994 & -0.7654 \end{bmatrix} \tag{8}$$

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

SENSOR FAULT TOLERANCE

As in the case of actuator fault-tolerance, a simple way of achieving sensor fault-tolerance is by having redundancy. The muti-polar structure of the ring-shaped inductive sensor makes it easy to introduce reduandancy. As shown in Fig. 4, the coils of two adjacent poles are wired in series, for fault-tolerat operation. Two opposing sets of poles forms one sensing channel. Thus, there are four channels s_1, s_2, s_3, and s_4 in one ring-type inductive sensor. If the angles of each channel is θ_1 through θ_4, the outputs of the four channels are related to the displacement as

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & \sin\theta_1 \\ \cos\theta_2 & \sin\theta_2 \\ \cos\theta_3 & \sin\theta_3 \\ \cos\theta_4 & \sin\theta_4 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{9}$$

We can write (9) in a matrix form as

$$\mathbf{s} = \mathbf{A}\mathbf{x} \tag{10}$$

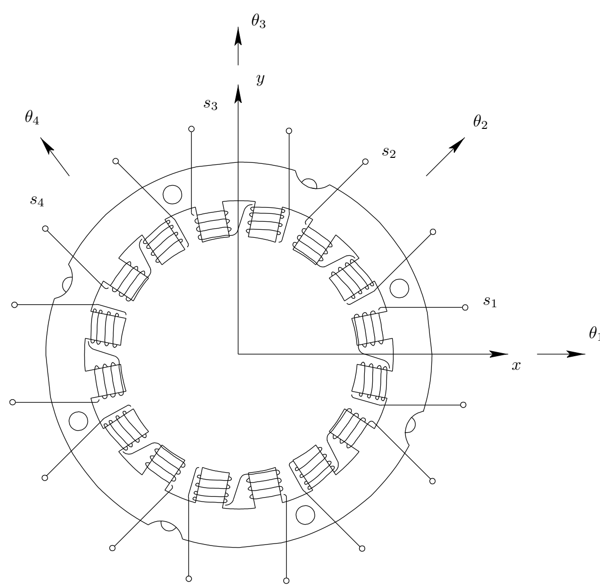

FIGURE 4: Fault-tolerant inductive sensor

The inverse of (10) is not unique. We can obtain an *optimal* solution by using the pseudo-inverse.

$$\mathbf{x} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{s} = \mathbf{G}_s\mathbf{s} \tag{11}$$

In case of faults in one channel, we can still obtain the sensor gain matrix $\mathbf{G}_s$ by eliminating the corresponding row in the matrix **A** [6]. We will call $\mathbf{G}_{s_i}$ as the sensor gain matrix when i-th channel is assumed to be malfunctioning and eliminated. In order to detect the sensor fault, we can compute the position estimates $\mathbf{x}_1$ through $\mathbf{x}_4$ using

$$\mathbf{x}_i = \mathbf{G}_{s_i}\mathbf{s} \tag{12}$$

Define the error residual as

$$e_i = ||\mathbf{s} - \mathbf{A}\mathbf{x}_i||_2 \tag{13}$$

Then, the error residuals should be equal to or very close to zero, if there is no fault. If one of the residuals is large compared to the other three, then the corresponding channel must be faulty. In that case, the position is computed by (12) rather than by (11).

EXPERIMENTAL SETUP

Fig. 5 shows the picture of the experimental setup. A DSP controller (dSPACE DS1104) carries out the feedback control for the suspension, and performs the fault-detection and fault-tolerance algorithms. The suspension controller is a simple PID (proportional-derivative-integral) type.

For actuator/amplifier fault-detection, Hall-type current sensors (LEM HY-5p) monitor the coil currents. The fault signal is flagged when the error between the current command signal and the actual current is greater than 100 mA for the duration of more than 4 ms, in consideration of the dynamic bandwidth of the current amplifiers and the accuracy of the current sensors. If the controller receives this fault signal, a new current distribution matrix is selected according to the fault condition.

The DSP controller also carries out the fault-detection algorithms for sensor, which is described in the previous section. If a sensor fault is detected, a new position estimates are computed from the remaining signals. Due to the limited number of analog-to-digital and digital-to-analog channels, only the upper radial bearing and upper radial sensor are fault-tolerant. The sampling rate of the controller is 20 kHz.

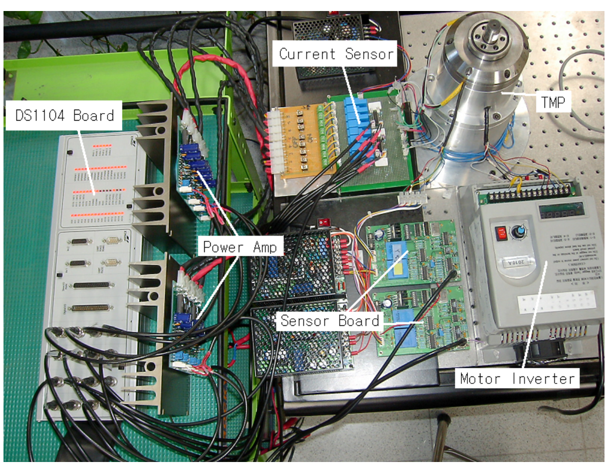

FIGURE 5: Experimental setup

EXPERIMENTAL RESULTS

Fig 6 shows the experimental results when three adjacent poles (coils 1, 2, and 3) in a eight-pole radial bearing are failing. The proportional gain is 2.4 and the derivative gain is 0.002. The integral gain is set to 0. The rotor is at standstill. Even with three poles failing, the suspension is maintained after a slight adjustment of the center position.

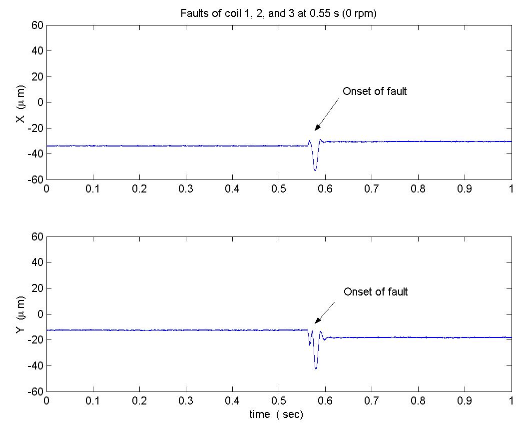

FIGURE 6: Rotor positions when the coil 1, 2, and 3 are disconnected

Sensor fault-tolerance is also tested. Fig. 7 shows the rotor positions when the actuator fault occurs while there is a sensor fault. One of four channels in one inductive sensor is disconnected, and coil 1 of the radial bearing is switched off. The results show that the faults does not seem to affect the operation, which demonstrate the adequacy of the fault-tolerance algorithms. The rotor is at standstill. The proportional gain is 2.5 and the derivative gain is 0.0065. The integral gain is 1 in this case.

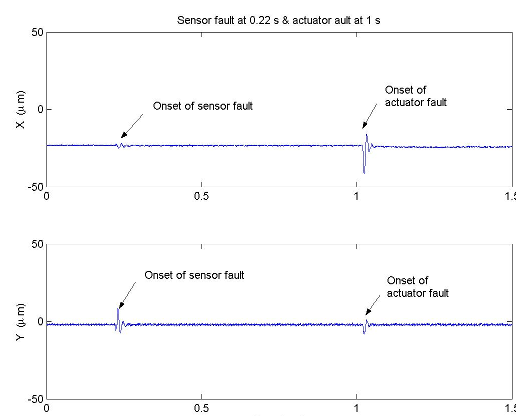

FIGURE 7: Rotor positions in case of simultaneous sensor and actuator faults

CONCLUSIONS

In this paper, we presented our experience of desiging and implementing s fault-tolerant magnetic bearing system for turbo-molecular vacuum pumps. The system can cope with actuator/amplifier faults as well as sensor faults. We took advantage of the pre-existing redundancy in the actuator and used bias linearization for fault-tolerance. We also used the redundancy in the sensor design after reconfiguring the mutipolar ring-shaped inductive sensor. Experimental results demonstrate the adequacy of the fault-tolerance algorithms. We are currently testing the fault-tolerant magnetically levitated turbo molecular pump running at 40,000 rpm with full loads.

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