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Fault-tolerant control of three-pole active magnetic bearing

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ABSTRACT

Active magnetic bearings have many advantages over conventional bearings due to contactless operation and adjustable force dynamics. However, one of the obstacles associated with these bearings is failure modes, which may result in destructive rotor dynamic behaviour. One of the important failure modes is electric power outage which may be due to failure of power amplifier, coil or electric wiring. In the present work, a fault tolerant controller has been designed for three-pole magnetic bearings to provide unaltered performance in the event of fault occurrence. The controller has been designed by incorporating the nonlinear fuzzy logic control. The present design of fuzzy logic controller is done by reducing the number of rules of its rule base. Simulations have been carried out to test the performance of the controller for different failure conditions. The designed controller is able to stabilize the rotor for large deviations from the origin even in the presence of failure. The controller is found to be robust as it provides satisfactory operation in the presence of uncertainties.

1. Introduction

Active magnetic bearings (AMBs) are considered to be superior over conventional bearings because the friction losses are reduced tremendously due to contactless operation. The bearings can also give high speed and are also able to eliminate lubrication and operation will be quiet. However, one of the obstacles associated with these bearings is failure modes. One of the important failure modes may be electric power outage which may be due to failure of power amplifier, coil or electric wiring. Such a failure may result in destructive rotor dynamic behaviour which will be enhanced in the absence of effective constraint by auxiliary bearings. Therefore, there is a need to design a fault tolerant magnetic bearing. Such a design can be achieved with the help of a fault-tolerant controller to allow the safe running of rotor in the event of fault occurrence.

In view of above, present work aims to design a fault-tolerant three-pole electromagnetic bearing. The stable operation of fault tolerant bearing can be achieved due to coupled nature of coils of the bearings. The change in current in any one coil affects the flux in all three air gaps. To design such a bearing, efforts are made to distribute the flux in such a way so that it becomes same as in good running three-pole bearing. For more than one coil failure in a multi-pole bearing like six or eight poles, Maslen and Meeker (1995) have proposed a current distribution matrix to find the currents in the remaining coils to provide the same linearized magnetic forces. Several researchers have used this approach for the fault-tolerant operation of the heteropolar (Na & Palazzolo, 2000; Noh, Cho, Kyung, Ro, & Park, 2005) and homopolar magnetic bearings (Li et al., 2004; Na, 2004). When only one coil has failed, the currents in remaining coils can be determined to provide the same load capacity. The same load capacity is obtained by maintaining the same flux in magnitude and direction in all the air gaps including the air gap of failed coil. Since present work is concerned to three-pole bearing and therefore this bearing can tolerate only one coil failure. Using Maslen and Meeker approach (Maslen & Meeker, 1995), the currents in remaining two coils are determined to maintain the same flux.

The fault-tolerant controller has been designed using the nonlinear fuzzy logic control because three-pole magnetic bearing is highly nonlinear. The fault-tolerant fuzzy controller for three-pole magnetic bearing is designed by first obtaining the required values of currents to be supplied to the coils assuming that all the coils are active. Then the currents for remaining two coils are determined when one coil failure has occurred. These currents will provide the required flux distribution in the three air gaps. The required values of currents for all the coils are determined by fuzzy logic control. Fuzzy logic control using linguistic information possesses several advantages such as robustness, model-free and rule-based algorithm. Several researchers have applied fuzzy logic control in magnetic bearings (Habib & Hussain, 2003; Hong & Langari, 2000; Hung, 1995; Minihan et al., 2003). Hung (1995) presented a fuzzy logic approach to adjust the linear (PID) controller signal to compensate the nonlinear effects. Habib and Hussain (2003) used the fuzzy logic control approach to tune the gains of the linear PD controller. Hong and Langari (2000) presented a fuzzy logic control strategy to overcome the inherent characteristics of displacement sensitivity and position-dependent nonlinearity of

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AMB. Minihan et al. (2003) presented a fuzzy controller design for a thrust magnetic bearing system. However, the huge amount of fuzzy rules for high-order systems makes the analysis complex. In the present design of fuzzy logic controller, the total number of rules has been minimized to reduce the complexity.

In the present work, initially magnetic bearing modelling is presented. Further, bias current modelling is also done. The fault-tolerant controller design has been presented to achieve the good performance of the bearing in normal operation and to ensure the same performance during the occurrence of failure of any one coil.

2. Magnetic bearing modelling

Basically, there are two types of electromagnetic bearings, named as Heteropolar magnetic bearings and Homopolar magnetic bearings. In heteropolar bearings, the flux is developed in perpendicular direction to the axis of rotor and in homopolar bearings, the same is developed along the axis (Schweitzer, Bleurer, & Traxler, 1994). Heteropolar bearings require less axial space along the shaft and they are much simpler in construction. The present work is mainly concerned to Heteropolar bearings.

Fig. 1 shows n-pole heteropolar magnetic bearing. Mostly the bearing and rotor are made either of steel or iron and both these have relative permeability greater than 1000 (Schweitzer et al., 1994). In view of this, the reluctances of all metal paths of the flux are neglected and reluctance only due to the air gap associated with each pole is considered. Further, it is also assumed that sources of excitation in magnetic bearing are only the coils wound on each pole. The equivalent magnetic circuit for n-pole heteropolar magnetic bearing is shown in Fig. 2.

To start the magnetic bearing modelling, initially Ampere's loop law (Maslen & Meeker, 1995) given by Eq. (1) is used:

$$R_j\phi_j - R_{j+1}\phi_{j+1} = N_jI_j - N_{j+1}I_{j+1}, \quad j = 1, 2, \ldots, n-1, \tag{1}$$

R_j is the reluctance of the jth air gap and is given by Eq. (2):

$$R_j = \frac{g_j}{\mu_0 A_j}, \tag{2}$$

where g_j is the jth air gap length, μ_0 is the magnetic permeability of free space, A_j is jth pole face area, ϕ_j is the magnetic flux in jth air gap, N_j is the number of coil turns of jth coil, I_j is the current in the jth coil and n is number of magnetic bearing poles. In Fig. 3, the equilibrium position of shaft centre is illustrated by O (0,0) and T (x, y) is its displaced position. 'P' is the position of jth pole face with the pole orientation θ_j ($\angle$POC). The nominal air gap length g_0 ('PO') and the modified air gap length g_j ('PZ') are related by Eqs. (3) and (4):

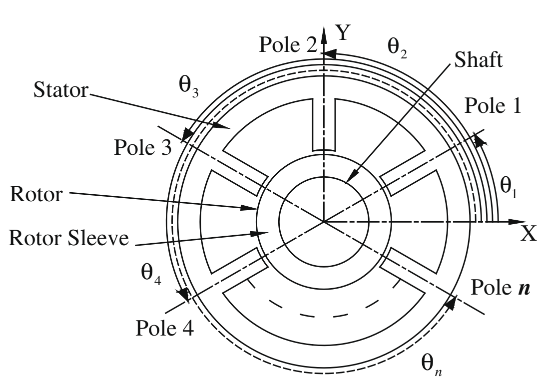

Fig. 1. Bearing geometry.

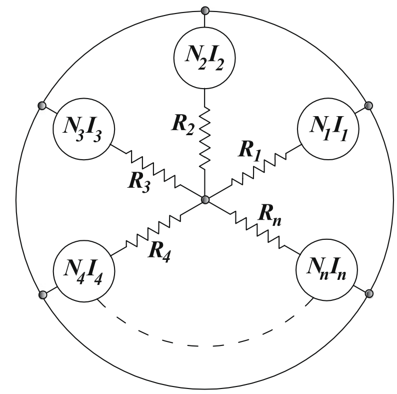

Fig. 2. Equivalent magnetic circuit for n-pole magnetic bearing.

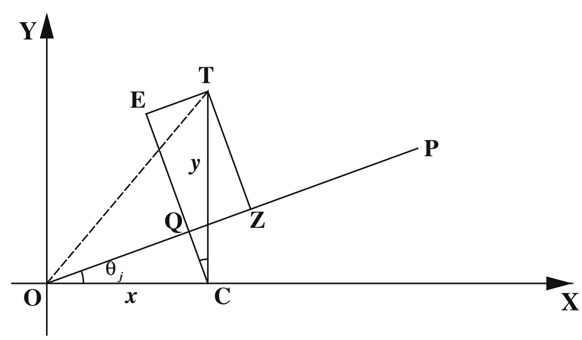

Fig. 3. Change in air gap length with shaft displacement.

$$\mathrm{PZ} = \mathrm{PO} - \mathrm{OQ} - \mathrm{QZ} = \mathrm{PO} - \mathrm{OQ} - \mathrm{ET}, \tag{3}$$

$$g_j = g_0 - x\cos\theta_j - y\sin\theta_j. \tag{4}$$

Application of conservation law of fluxes (Maslen & Meeker, 1995) of the magnetic circuit results in Eq. (5):

$$\sum_{j=1}^{n} \phi_j = 0. \tag{5}$$

Arranging Eqs. (1) and (5) in matrix form (Maslen & Meeker, 1995), we get Eq. (6)

$$\begin{bmatrix} R_1 & -R_2 & 0 & \cdots & 0 \\ 0 & R_2 & -R_3 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & R_{n-1} & -R_n \\ 1 & 1 & \cdots & 1 & 1 \end{bmatrix} \begin{Bmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_{n-1} \\ \phi_n \end{Bmatrix} = \begin{bmatrix} N_1 & -N_2 & 0 & \cdots & 0 \\ 0 & N_2 & -N_3 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & N_{n-1} & -N_n \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix} \begin{Bmatrix} I_1 \\ I_2 \\ \vdots \\ I_{n-1} \\ I_n \end{Bmatrix}. \tag{6}$$

This matrix relationship is represented more succinctly by Eqs. (7) and (8):

$$R\Phi = \mathbb{N}I, \tag{7}$$

$$\Phi = R^{-1}\mathbb{N}I, \tag{8}$$

where R is the reluctance matrix, Φ is the flux vector, $\mathbb{N}$ is the coil winding influence matrix and I is the coil current vector. Assuming uniform flux density in the air gap, flux ϕ_j is related to flux density B_j by $\phi_j = A_jB_j$. In matrix form, this relationship is given by Eq. (9):