Vibration Suppression for Asymmetric Rotor of Magnetic Suspended Flywheel Energy Storage System Using Cross-feedback-based Modal Decoupling Control

:Magnetic bearings have been used in flywheel energy storage systems for improving their performance due to the main advantage of contact-free operation. However, the gyroscopic coupling, parameter coupling and imbalance force affect the operating performance and stability of an magnetic suspended flywheel energy storage system with asymmetric rotor, therefore, a cross-feedback-based control method is proposed. Firstly, the dynamic model of a radial four-degree-of-freedom active magnetic bearing rotor system is derived. Next, a novel cross-feedback-based modal decoupling controller is designed for vibration suppression caused by gyroscopic coupling, parameter coupling and imbalance force. Better performance is obtained through comparing the decoupling performance, control performance and disturbance rejection performance with a traditional decentralized PID and a cross feedback controller via Adams-Matlab co-simulation technology.

Keywords: Flywheel energy storage, Magnetite bearings, Vibration suppression, Modal decoupling control

1 Introduction

Flywheel energy storage systems which are also called flywheel battery have been used more and more for energy harvesting and recycle in many situations, such as space satellites, renewable energy power generation systems, and electric vehicles, because of their cleanliness and high-density energy storage. The capacity of energy storage of them almost depends on the rotor velocity, however, in the traditional flywheel energy storage systems the mechanical friction resistance between the bearings and the rotor is too large. Hence, the recent flywheel energy storage technologies are limited.

Magnetic bearings have been used in flywheel energy storage systems for improving their performance due to the main advantage of contact-free operation. As the rotation is frictionless, there is no wear, no lubrication requirement, and very high rotation speeds are possible[1]. However, due to mass unbalance, the forced vibration in rotor system caused by the centrifugal force is the most general disturbance. Because the magnetic field distribution and the quality are not uniform, there is synchronous vibration in rotor system. Besides, the vibration caused by gyroscopic coupling effect and the high-order nonlinearity of the bearings also affect the operating performance and stability of flywheel energy storage systems. Moreover, magnetic suspended flywheel energy storage devices are complex and coupled system. Hence, the main purpose of this study is to propose a control method for achieving decoupling and stable operation of the aforementioned system.

To this end, various control schemes have been presented. These methods can be classified into two types: decentralized control which is a combination of several single degree of freedom controller[2]-[5]; centralized control which is a multiple degree of freedom controller[6]-[10]. Chen et. al presented a decentralized proportional–integral–derivative neural network (PIDNN) control scheme for regulating and stabilizing a 5-dof active magnetic bearings. Good control performance and robustness were verified experimentally[2]. Zhang et. al proposed a controller with local damping enhancement and cross feedback to suppress the gyroscopic effect and bending vibration in a flywheel energy storage system. The effectiveness of the proposed method demonstrated by experimental results[3]. Ouyang et. al proposed a double stage cross feedback controller for suppressing vibration caused by gyroscopic coupling effect and imbalance force in a wind power generator with magnetic bearings. Comparative simulations showed that the proposed method has steady accuracy and disturbance rejection performance[4]. Zhang Q et.el presented a modal decoupling controller for a magnetic bearing-supported flywheel rotor system. It is shown that the proposed control can separately regulate each modal stiffness and damping through decoupling between conical and parallel modes, and obviously improve the dynamic behaviors and anti-interference capacities of active magnetic bearing-supported flywheel rotor system with significant gyroscopic effect[5]. Schuhmann et.al proposed a linear quadratic Gaussian controller, consisting of an extended Kalman filter and an optimal state feedback regulator for a radial active magnetic bearing. It is shown that this controller yields improved rotor positioning accuracy, better system dynamics, higher bearing stiffness, and reduced control energy effort compared to the conventionally used PID control approaches[6]. Sung et.al proposed a robust digital control for active magnetic bearing (AMB) systems based on TS fuzzy model. The study results showed that even complex parametric uncertainty in the nonlinear system can also get good control effect[7]. Balini et. al presented a unstable H_∞ controller for an active magnetic bearing spindle with flexible dynamics. The effectiveness of the proposed method demonstrated by experimental results[8]. Kang et.al proposed an LMI-based H_∞ controller for a 4-axis unbalanced rigid asymmetric rotor supported by two active magnetic bearings. The effectiveness of the proposed method has demonstrated by comparing with a LQR controller[9]. Fang et.al proposed a m-synthesis control scheme for a magnetic bearings supported double-gimbal control moment gyro device. Good vibration suppression and robust performance were obtained by the proposed method via simulations and experiments[10].

Other methods have been also presented for active magnetic bearings control including sliding mode control[11]-[13], nonlinear smooth feedback control[14], adaptive control[15], and fuzzy logic control[16].

However, only symmetry rotor were considered in most existing literature. Due to the limitation of manufacturing process and the requirement of practical application, magnetic bearing systems usually are asymmetrical in size. In this situation, not only gyroscopic coupling but also parameter coupling could effect the stability and control performance significantly. Although centralized control method such as sliding mode control could be applied to solve the aforementioned problem, decentralized control method such as cross feedback controller has a simple structure, and can be achieved only by adding cross channels based on decentralized controllers. Furthermore, it has good compensating effect on the gyroscopic coupling[3]. However, the traditional cross feedback control method has terrible decoupling and robust performance. Hence, a cross-feedback-based controller that can solve the mentioned problem is proposed in this study. To this end, the dynamic model of a radial four-degree-of-freedom active magnetic bearing rotor system is derived. Next, a novel cross-feedback-based modal decoupling controller is designed for vibration suppression caused by gyroscopic coupling, parameter coupling and imbalance force Better performance is obtained through comparing the decoupling performance, control performance and disturbance rejection performance with a traditional decentralized PID and a cross feedback controller via Adams-Matlab co-simulation technology.

2 Rotor System Dynamics

This section describes the dynamics of a rotor system in a magnetic suspended flywheel energy storage, whose schematic model is shown in Fig.1

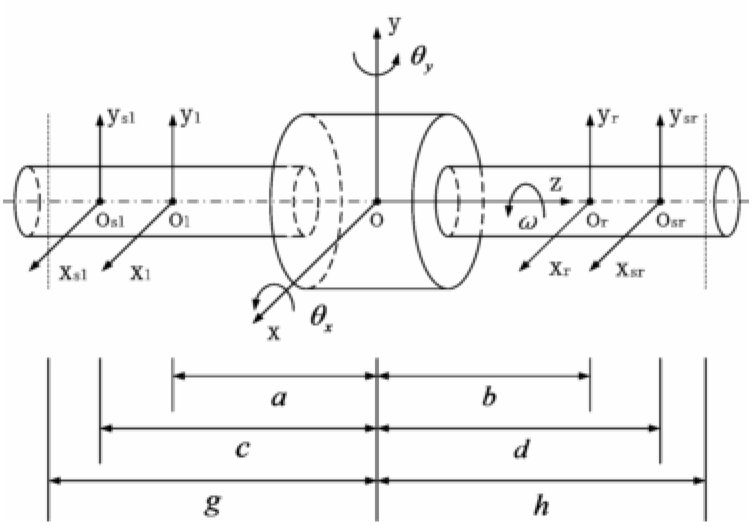

Fig.1. Schematic model of rotor

There are two radial active magnetic bearings and two position sensors implemented on both ends of the rotor, respectively. o-xyz, o_l-x_ly_l and o_r-x_ry_r, o_{sl}-$x_{sl}y_{sl}$ and o_{sr}-$x_{sr}y_{sr}$ denote the center of mass coordinate, left-side and right-side bearing coordinates, and left-side and right-side sensor coordinates, respectively. Parameters a and b denote the distance between center of mass of rotor and bearings, parameters c and d denote the distance between center of mass of rotor and sensors, and parameters g and h denote the distance between center of mass of rotor and loads, respectively.

It is assumed that the rotor system dynamics has the following characteristics:

The rotor can be considered as a rigid rotor.

The coupling between axial- and radial bearings can be neglected.

The dynamics of the sensors and amplifiers can be ignored because their time constants are very small comparing with the dynamics of rotor and controller.

The equations of translational- and rotational-motions for the rotor system are[4]:

$$\boldsymbol{M}\ddot{\boldsymbol{q}}_c + \boldsymbol{G}\dot{\boldsymbol{q}}_c = \boldsymbol{T}_L\boldsymbol{F}_U + \boldsymbol{P}_d + \boldsymbol{P}_{unb} \tag{1}$$

$$y = \boldsymbol{T}_s\boldsymbol{q}_c$$

$$\boldsymbol{M}=\begin{bmatrix} m & 0 & 0 & 0\\ 0 & m & 0 & 0\\ 0 & 0 & J_x & 0\\ 0 & 0 & 0 & J_y \end{bmatrix},\boldsymbol{G}=\begin{bmatrix} 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & J_z\omega\\ 0 & 0 & -J_z\omega & 0 \end{bmatrix},\boldsymbol{T}_L=\begin{bmatrix} 1 & 1 & 0 & 0\\ 0 & 0 & 1 & 1\\ 0 & 0 & a & -b\\ a & -b & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{T}_s=\begin{bmatrix} 1 & 0 & 0 & c\\ 1 & 0 & 0 & -d\\ 0 & 1 & c & 0\\ 0 & 1 & -d & 0 \end{bmatrix},\boldsymbol{T}_d=\begin{bmatrix} 1 & 1 & 0 & 0\\ 0 & 0 & 1 & 1\\ 0 & 0 & g & -h\\ g & -h & 0 & 0 \end{bmatrix},q_c=\begin{bmatrix} x_c\\ y_c\\ -\theta_x\\ \theta_y \end{bmatrix},F=\begin{bmatrix} F_{Lx}\\ F_{Rx}\\ F_{Ly}\\ F_{Ry} \end{bmatrix},$$

$$F_d=\begin{bmatrix} F_{dLx}\\ F_{dRx}\\ F_{dLy}\\ F_{dRy} \end{bmatrix},P_{unb}=\begin{bmatrix} me\omega^2\cos(\omega t+\theta_1)\\ me\omega^2\sin(\omega t+\theta_1)\\ (J_x-J_z)\varepsilon\omega^2\cos(\omega t+\theta_2)\\ (J_y-J_z)\varepsilon\omega^2\sin(\omega t+\theta_2) \end{bmatrix}$$

Where parameters x_c, y_c, θ_x and θ_y denote the center of mass of rotor position, the pitch angles around x and y axes in the generalized coordinate, respectively. Parameters ω,m, J_x, J_y, and J_z denote the angular speed, the rotor mass, the diametral moment of inertia in the x- and y-directions, and the polar moment of inertia, respectively. Parameters F_{Lx}, F_{Rx}, F_{Ly}, and F_{Ry} denote the radial bearing forces F which act on the rotor plane in the x- and y-directions, respectively. Parameters F_{dLx}, F_{dRx}, F_{dLy}, and F_{dRy} denote the load forces F_d which act on the rotor plane in the x- and y-directions, respectively. Vectors q_c and y are the rotor position variables within the center of mass of rotor and the output. Parameters e, ε, θ_1 and θ_2 are the eccentricity, the inclination of the principal axis, the static unbalance angular position and the dynamic unbalance angular position, respectively.

On the other hand, the linearized radial bearing forces F at equilibriums can be presented as follows[4]:

$$\boldsymbol{F}=\boldsymbol{K}_i\boldsymbol{i}-\boldsymbol{K}_s\boldsymbol{q}_L \tag{2}$$

$$K_i=\begin{bmatrix} k_{iLx} & 0 & 0 & 0\\ 0 & k_{iRx} & 0 & 0\\ 0 & 0 & k_{iLy} & 0\\ 0 & 0 & 0 & k_{iRy} \end{bmatrix},K_s=\begin{bmatrix} k_{sLx} & 0 & 0 & 0\\ 0 & k_{sRx} & 0 & 0\\ 0 & 0 & k_{sLy} & 0\\ 0 & 0 & 0 & k_{sRy} \end{bmatrix},i=\begin{bmatrix} i_{Lx}\\ i_{Rx}\\ i_{Ly}\\ i_{Ry} \end{bmatrix},q_L=\begin{bmatrix} x_l\\ x_r\\ y_l\\ y_r \end{bmatrix}$$

where K_i Ks, i and q_L denote the current stiffness matrix, the position stiffness matrix, the controlled current and the rotor position variables within the magnetic bearings.

The dynamic model of rotor-bearings system can be represented as follows by combining Eqs. (1) and (2):

$$\boldsymbol{M}\ddot{\boldsymbol{q}}_c + \boldsymbol{G}\dot{\boldsymbol{q}}_c + \boldsymbol{T}_L \boldsymbol{K}_s \boldsymbol{T}_L^T \boldsymbol{q}_c = \boldsymbol{T}_L \boldsymbol{K}_i \boldsymbol{i} + \boldsymbol{U}_d \tag{3}$$

where $U_d = T_d F_d + P_{unb}$, which can be considered as the disturbance of the system. The block diagram of the four-degree-of-freedom magnetic bearings is shown in Fig. 2.It is noted that the mathematical model of the rotor system is only used for controller design.

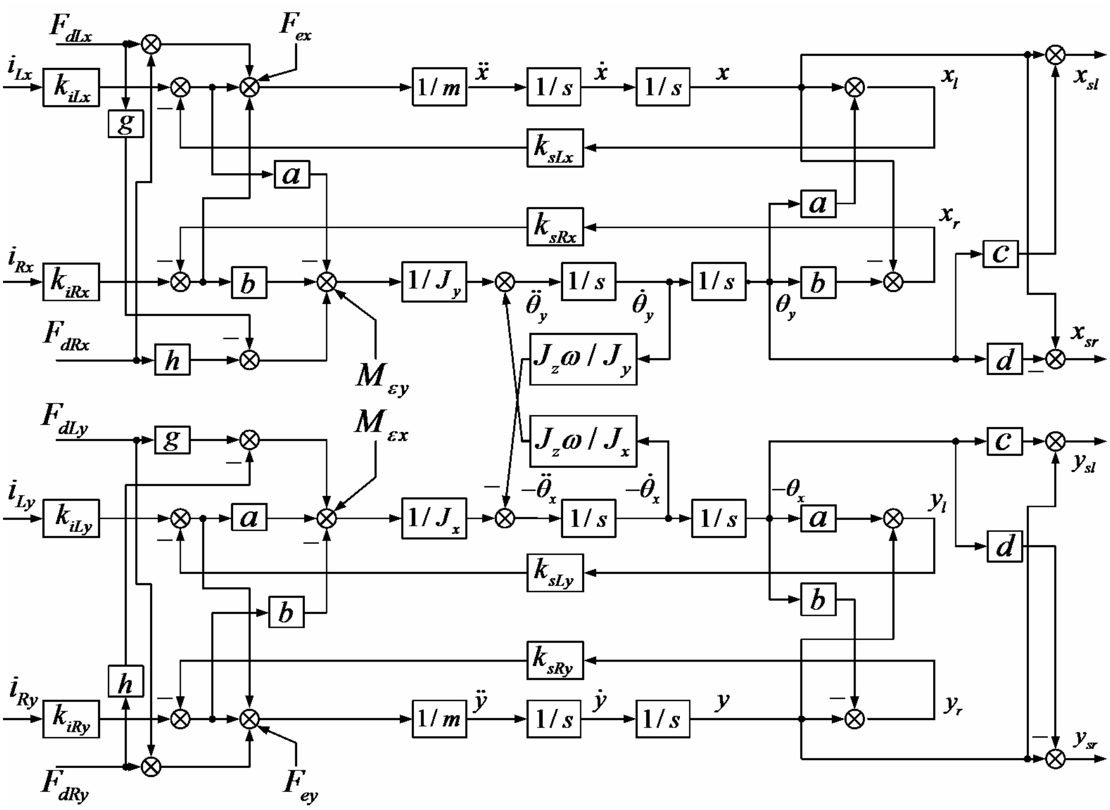

Fig.2. Four-degree-of-freedom magnetic bearings system

3 Cross Feedback Based Modal Decoupling Controller Design

As previously mentioned, the vibration in the asymmetric rotor system was caused by not only the gyroscopic coupling but also the modal coupling due to the asymmetric system parameters. Meanwhile, the mass unbalance and external loads are also the major reasons causing rotor vibration. Many methods have been proposed to solve the aforementioned problem. However, the traditional decentralized control and centralized control obtained bad control performance, especially the decoupling performance. Hence, this section presents a cross-feedback-based modal decoupling controller for vibration suppression of rotor system in the magnetic suspended flywheel energy storage.

The following PID controller is applied to each degree of freedom of the rotor system: