Research on Decoupling Active Disturbance Rejection Control Strategy for Active Radial Bearings Based on Kalman Filter

Kaiyu Shan, Ke Wang, Qiongxuan Ge，Liming Shi，Yaohua Li，Yuxiang Zhu
1.State Key Laboratory of High Density Electromagnetic Power and Systems, Institute of Electrical Engineering，Chinese Academy of Sciences，Haidian District, Beijing 100190, China;
2. University of Chinese Academy of Sciences, Shijingshan District, Beijing 100049, China

1. Introduction

Flywheel energy storage boasts advantages such as rapid response, high energy density, and long service life, rendering it with a broad application prospect in power grids with a high proportion of renewable energy generation. It is instrumental in grid frequency regulation and the smoothing of fluctuations in renewable energy generation [1].

Active Magnetic Bearings are deemed a crucial component of Flywheel Energy Storage Systems (FESS) due to their capability for contactless operation and ensuring optimal performance without the need for lubrication during high-speed rotation. However, the modeling and control of Active Magnetic Bearings remain challenging issues [2]. A typical FESS comprises five key components: the flywheel motor, flywheel rotor, bearings, vacuum chamber, and bi-directional converter [3], among which the active bearings are particularly critical. The modeling of active radial bearings involves unbalanced force terms, and the system is subject to disturbance forces. Moreover, the control precision requirements for active radial bearings are high, and the white noise in the system cannot be overlooked. Therefore, to ensure the stable operation of the flywheel energy storage system, this paper establishes a decoupling active disturbance rejection control strategy for Active Radial Bearings Based on Kalman Filter.

Compared to PID control, this method eliminates 98.5% of the white noise and low-frequency disturbances in the system, which is of significant importance for the stable operation of the flywheel energy storage system.

2. The dynamics model of Active Magnetic Bearings and Kalman Filter Design

The rotor mass is symbolized by m, the displacement stiffness of the magnetic bearing is denoted as k_x, J represents the equatorial moment of inertia, and the polar moment of inertia is represented by J_z. The displacements [x_a, x_b, y_a, y_b] in the X and Y directions are defined with respect to the equilibrium position. l_{mu} and l_{md} represent the distances from the upper and lower magnetic bearings to the centroidal plane ,respectively. The control currents i_1, i_2, i_3, and i_4 correspond to the four channels in the X and Y directions, referenced to the equilibrium position. The coupling between the four displacements and other branch displacements is regarded as disturbances, which are compensated for by an observer-based mechanism. The system dynamics are modeled as a double integrator system. Decoupling modeling is performed for the magnetic bearing main body to facilitate independent control and analysis[4].

$$\begin{cases}\ddot{x}_a=\frac{k_x}{m}(1+\frac{ml_{mu}^2}{J})x_a+[\frac{k_x}{m}(1-\frac{ml_{mu}l_{md}}{J})x_b-\frac{J_z wl_{mu}}{J(l_{mu}+l_{md})}\dot{y}_a+\frac{J_z wl_{mu}}{J(l_{mu}+l_{md})}\dot{y}_b]+i_1\\ \ddot{x}_b=\frac{k_x}{m}(1+\frac{ml_{md}^2}{J})x_b+[\frac{k_x}{m}(1-\frac{ml_{mu}l_{md}}{J})x_a+\frac{J_z wl_{md}}{J(l_{mu}+l_{md})}\dot{y}_a-\frac{J_z wl_{md}}{J(l_{mu}+l_{md})}\dot{y}_b]+i_2\\ \ddot{y}_a=\frac{k_x}{m}(1+\frac{ml_{mu}^2}{J})y_a+[\frac{k_x}{m}(1-\frac{ml_{mu}l_{md}}{J})y_b+\frac{J_z wl_{mu}}{J(l_{mu}+l_{md})}\dot{x}_a-\frac{J_z wl_{mu}}{J(l_{mu}+l_{md})}\dot{x}_b]+i_3\\ \ddot{y}_b=\frac{k_x}{m}(1+\frac{ml_{md}^2}{J})y_b+[\frac{k_x}{m}(1-\frac{ml_{mu}l_{md}}{J})y_a-\frac{J_z wl_{md}}{J(l_{mu}+l_{md})}\dot{x}_a+\frac{J_z wl_{md}}{J(l_{mu}+l_{md})}\dot{x}_b]+i_4\end{cases} \quad (1)$$

The Kalman filter is generally divided into two major parts:prediction and update.The core issue of the Kalman filtering method is:how to establish the state equations and measurement equations required for filtering.In the actual working process,the Kalman filter provides an optimal estimate for the system,provided that the system has a linear model.The use of the Kalman filtering method can simplify the computational load and save data storage.

3. Control Process

The overall control block diagram is shown in Figure 1. In the control process of the magnetic bearing, the reference displacement is first input to the LADRC controller of the displacement ring, and the reference current is output after processing. The reference current is further input to the P controller of the inner ring, which outputs the actual current through the H-bridge driving circuit, and finally drives the magnetic bearing body to generate a magnetic field to control the radial displacement of the rotor. At the same time, the actual displacement output from the magnetic bearing body is processed by the Kalman filter to eliminate noise and obtain the filtered displacement. The filtered displacement is input to the LESO expansion observer, which outputs the displacement, the first-order derivative of the displacement, and the perturbation information, and is fed back to the LADRC controller to complete the control closed-loop, thus realizing the precise control of the radial displacement of the rotor.

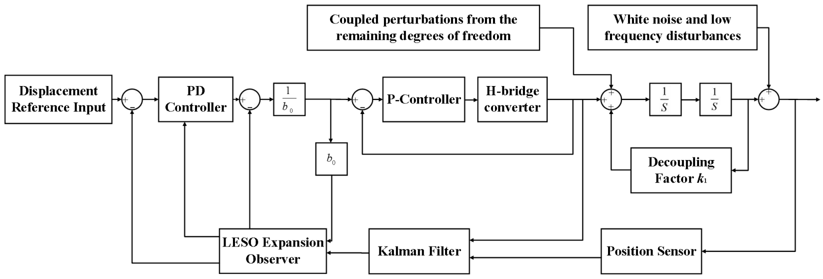
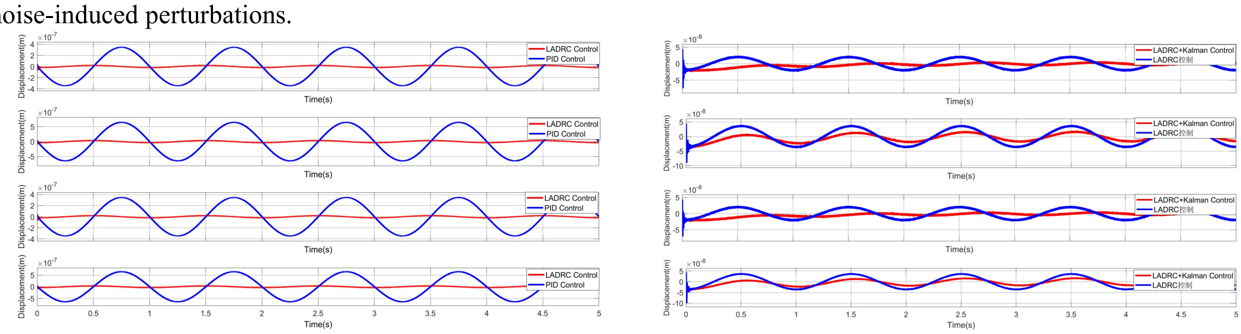


Fig. 1 decoupling active disturbance rejection control process for active radial bearings based on kalman filter

4. Analysis of Simulation Results

Figure 2(a) presents a comparative analysis of the four displacement channels under decoupled linear active disturbance rejection control (LADRC) and conventional proportional-integral-derivative (PID) control, displayed from top to bottom. The results demonstrate that the decoupled LADRC strategy achieves a significant suppression of disturbances, with an overall disturbance attenuation rate of approximately 95%. This indicates the superior performance of decoupled LADRC over traditional PID control in terms of disturbance rejection, thereby enhancing the operational stability of the flywheel energy storage system (FESS). Figure 2(b) compares the four displacement channels under decoupled LADRC and Kalman filter-augmented LADRC control. The integration of the Kalman filter with LADRC reduces system interference by 70% compared to the standard LADRC approach, effectively mitigating noise-induced perturbations.



(a)Comparison between LADRC and PID Control (b)Comparison between LADRC and Kalman+LADRC Control

Fig. 2 Comparison of Simulation Results

References

[1] Zhai D, Yao L, Liao S, et al. Modeling and Control of Flywheel Energy Storage System[C]//2023 6th International Conference on Electronics Technology (ICET). Chengdu, China: IEEE, 2023: 1289-1293.

[2] Tsai Y W, Phan V D, Duong V A. Sliding mode control for active magnetic bearings of a flywheel energy storage system[C]//2016 IEEE International Conference on Control and Robotics Engineering (ICCRE). Singapore: IEEE, 2016: 1-5.

[3] Qiunan Wang, Huawei Yuan, Xinjian Jiang, et al. A simple sensorless control strategy for IPMSM in 1 MW flywheel energy storage system[C]//2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia). Hefei, China: IEEE, 2016: 1923-1928.

[4] H. Q. Zhu, L. D. Zhu, X. J. Wu, and J. J. Chen, "The Active Disturbance Rejection Decoupling Control for Active Multivariable Magnetic Bearing System," Machine Design and Manufacturing Engineering , vol. 42, no. 12, pp. 1-5, Dec. 2013, DOI: 10.3969/j.issn.2095-509X.2013.12.001.