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Review:

Analysis of Control Method for Magnetic Bearing Systems

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Magnetic bearing systems have attracted extensive attention in the fields of high speed, spotless area, vacuum space, etc. System performance depends largely on the control link, and it has become a research focus to improve controller performance to ensure high precision stable suspension and high anti-interference capability. This paper considers optimized, sliding mode, robust, fuzzy, and neural network control systems and assesses their research status and limitations for magnetic bearing systems. Algorithms for proposed vibration and high speed flexible rotor controls are illustrated. Finally, development trends for control technology of magnetic bearing systems are discussed.

Keywords: magnetic bearing, vibration control, flexible rotor

1. Introduction

Magnetic bearings are new high performance non-contact levitation support bearings, widely used in high speed lathes, turbines, compressors, flywheel energy storage, turbo molecular pumps, artificial heart pumps, and other equipment due to superior qualities, such as high rotational speed, non-lubrication, wear free, easy maintenance, long life, low power consumption, and flexible control. These properties make magnetic bearings competitive in aeronautics, astronautics, transportation, nuclear energy, and life sciences applications where high speed drives are required [1–4]. The controller design for magnetic bearing systems is critical to realize these advantages and ensure high precision stable suspension of the rotor and high anti-interference capability. Thus, selection of suitable control methods becomes a core research problem for magnetic bearing systems.

Magnetic bearings are nonlinear systems and modelling accuracy will be decreased due to the cross coupling between magnetic poles, noise, data delay, and other factors. Therefore, it is difficult to design an optimal magnetic bearing controller. Shi et al. [5] summarized control method types, along with their applications and limitations. However, the summary only considers the control method, and ignores the research direction and control targets, so is of limited relevance. To better understand and promote development of magnetic bearing system control technology, this paper summarizes and classifies existing literature, providing an overview of control algorithm design, and vibration and high speed flexible rotor control.

2. The Design of Control Algorithm

The magnetic bearing system is a nonlinear and open loop unstable system, Thus, effectively improving controller performance and ensuring its stable operation is key to magnetic bearing control. Control algorithm design not only plays a key role in stabilizing the suspension of the rotor, but also has influences dynamic and static system performance. Traditional PID control, which is the earliest and most common control algorithm for magnetic bearing control systems, has advantages of easy parameter setting, good stability, and easy implementation [6–8]. However, traditional PID controllers are unable to achieve perfect control for high speed, high frequency, and high precision applications. To ensure magnetic bearing systems have better stability, robustness, and anti-jamming performance, more advanced control theories and algorithms have been applied, such as optimal, sliding mode, robust, fuzzy, neural network, etc. controllers.

2.1. Optimal Control

Optimal control is a strategy maximizing or minimizing a system performance index under constraints. Depending on the chosen performance index, optimal control is divided into frequency shaping and quadratic types [9]. For magnetic bearing control systems, optimal control is the only control algorithm that considers energy in the analysis and design phases [5].

For a radical four degree of freedom active magnetic bearing system, Zhu [10] used LQ optimal control theory to design a centralized and decentralized parameters control system. Simulation showed that the decentralized controller met system requirements at 60,000 rpm. Considered the gyroscopic effect, Barbaraci [11] utilized the minimum energy consumption condition to derive a speed varying optimal control for rotating active magnetic bearing systems. A second order polynomial matrix of the control matrix used the angular speed as a variable, which reduced the computational burden for controller implementation. For the magnetic bearing system of flywheel energy storage system, Zhu [12] proposed an LQG optimal control method based on minimizing a performance index that included synchronization errors in the radial direction. The proposed method was effective to suppress gyroscopic effort caused by disturbances and model uncertainties. Jastrzebski [13] discussed a centralized optimal position control for active magnetic bearing system, and proposed a genetic algorithm for different controller structures, the simulation and the experimental results are good agreement. Barbaraci [14] dealt with a comparison of three types of sub-optimal control law to use in speed-varying simulations in the angular speed of rigid shaft. Chen [15] used LQ method of optimal control theory to design a centralized and decentralized parameter controller for five degree of freedom AC hybrid magnetic bearing systems, the results have shown that the decentralized controller has better effect when the speed of the rotor runs under 30000 rpm.

Although the optimal control algorithm for magnetic bearing systems has been widely studied, it remains too sensitive to random disturbance and has poor robustness, which limits its application. The optimal control is based on a precise mathematical model, and the flexible rotor of a high speed magnetic bearing is difficult to fit into the model.

2.2. Sliding Mode Control

Sliding mode control is a special nonlinear control, with the nonlinearity mainly manifested in control discontinuity. The difference between sliding mode and other control methods is that the control system structure is not fixed, but changes dynamically according to the current system state, such as deviation and derivatives, etc., forcing the system to move according to a predetermined sliding mode trajectory. The sliding mode can be designed independently of the object parameters and external disturbances, providing the advantages of fast response speed, good robustness to system parameter perturbation and external disturbances, and simple physical implementation [16, 17]. Therefore, sliding mode control has become one of the most effective control methods for magnetic bearing systems.

For the uncertainty problem in the active magnetic bearing of a flywheel rotor system, Liu [18, 19] designed a sliding mode controller and fast terminal sliding mode controller separately, realizing robust system control. Under the condition of multiple disturbance sources, such as micro gravity and moving frames, Xu [20] designed an integral sliding mode controller based on exponential approximation, introduced an integral sliding mode plane relating to current and position, and adopted exponential approximation and saturation to suppress chattering. The method provided better control for dynamic performance and robustness. Shen [21] designed a backstepping controller for the mathematical model of an active magnetic bearing, and a sliding mode controller to compensate for uncertainty. The robust backstepping sliding mode control was realized, and effectively extended the stability region of the system. Chen [22] presented a robust nonsingular terminal sliding mode control method to achieve tracking control for the rotor position of a thrust active magnetic bearing, the method made it unnecessary to know the bound of the lumped uncertainty of the magnetic bearing in advance. Lin [23] used intelligent double integral sliding mode to design magnetic bearing control systems, and combined adaptive control method and neural network method, the control gains can be adjusted online and the uncertainty can also be observed simultaneously.

However, the disadvantage of this method is chattering when the state trajectory reaches the sliding surface. Chattering can be reduced, but only at the expense of system dynamic performance, and a single sliding mode control algorithm is difficult to achieve optimal system performance.

2.3. Robust Control

Robust control is a research method for magnetic bearing control systems. It can maintain system performance and enhance robustness in the presence of certain parameter perturbations, and the accuracy requirement of the controlled object mathematical model is low.

Meng [24] designed a robust decoupling controller for a radial 4 degree of freedom magnetic bearing based on an H_∞ loop shaping approach. System robustness and speed were achieved, and good control quality was obtained under perturbation. Liu [8] designed an H_∞ controller for a 5 degree of freedom hybrid magnetic bearing using a weighting function derived from the singular value graph, which had advantages in terms of stability and disturbance rejection. Noshadi [25] designed an H_∞ controller for an active magnetic bearing system, selecting weighting functions independent of the model order to reflect the tradeoff between robustness and performance.

However, robust control is not effective for vibration suppression at high speed and high frequency, and inertial coupling and gyroscopic effects are neglected when decoupling the model. Thus, the robust controller requires further improvement.

2.4. Fuzzy Control

Fuzzy control is a digital control technology based on fuzzy set theory, fuzzy linguistic variables, and fuzzy logic inference [26]. It has been widely studied for magnetic bearing systems because it does not require a precise mathematical model of the controlled object and provides strong control system robustness.

Hong [27] proposed a fuzzy model based on nonlinear fuzzy control. The model overcame position dependent nonlinearity of magnetic bearing systems, and stability analysis was performed using the LMI method. The proposed fuzzy controller yielded not only maximized stability boundary but also better performance. Hong [28] designed a fuzzy logic control strategy, to overcome displacement sensitivity and position dependent nonlinearity of an active magnetic bearing. The proposed controller provided robustness against uncertainties. Reddy [29] designed an optimized fuzzy logic controller for contactless active magnetic bearing systems, where the controller membership functions were tuned by a genetic algorithm based optimization process, achieving superior control effect. Chen [30] designed a fuzzy state feedback controller for magnetic bearing systems using the parallel distributed compensation principle and solved the convex optimization problem using the LMI method. The proposed controller improved system stability.

Although fuzzy control has been widely studied for magnetic bearing systems, the control accuracy remains relatively low, and it requires significant fuzzy processing experience. Therefore, fuzzy control needs to be combined with other control strategies.

2.5. Neural Network Control

Neural network is an intelligent control method to deal with multi-variable complex uncertain systems. It has strong adaptability, fault tolerance, and robustness; high parallel implementation ability; and can approximate any complicated nonlinear function. Therefore, it has good application prospects for magnetic bearing systems.

To solve the problem that the order of H_∞ controller is higher and practical implementation of the controller is difficult, Liu [31] designed a controller for the magnetic bearing of a high speed magnetic levitated switched reluctance motor using a BP neural network. The proposed controller had good disturbance rejection and robustness. Jeng [32] applied a Chebyshev polynomial based unified mode neural network to control a magnetic bearing system, and proposed an inverse system method incorporating offline and online structures. The proposed architecture provided superior flexibility and performance. Chen [33] proposed a hidden layer BP neural network controller for a flywheel magnetic bearing system. The back propagated algorithm for updating network weights was derived based on linear model and trained online. Stable flywheel suspension was achieved.

Although neural networks have been studied for magnetic bearing systems, they require significant data to support the neural network, and the information is easily lost. Therefore, neural networks require further study for application to magnetic bearing systems.

Other control strategies studied for magnetic bearing systems include feedback linearization [34, 35], adaptive methods [36, 37], and application of various control algorithms [38–40] aimed at improving stability, robustness, and anti-interference capability.

3. Vibration Control

The inertia center shaft of the magnetic bearing is not completely coincident with the geometric center axis. Therefore, vibrations are easily generated when the rotor rotates at high speed, which seriously affects stability and safety of the magnetic bearing system. As early as 1983, Burrows [41] studied reducing rotor vibration of magnetic bearing systems. Matsumura [42], Kang [43], and Long [44] studied vibration control based on the H_∞ robust controller, developing methods that effectively reduced rotor vibration amplitude and improved robustness. Durali [45] estimated system nonlinear coupled equations using sliding mode control and a neural network algorithm, and realized vibration control of the magnetic bearing rigid rotor. Han [46] proposed an active control method based on a sliding mode disturbance observer. The method could observe and compensate for unbalanced vibration, and effectively reduce vibration. Shi [47] and Huang [48] studied unbalanced vibration of magnetic bearings using fuzzy control, achieving satisfactory control. However, the common disadvantages of the these methods are that the algorithms are complex; difficult to implement; and have large computation cost, which delays calculation and affects system stability at high speed. Zheng [49] and Herzog [50] studied unbalanced synchronous and nonsynchronous vibration control for magnetic bearings based on the notch filter method, respectively. Although vibration suppression was significant, the main disadvantage of this method is that the closed loop transfer function is changed, and seriously affects system stability near the critical frequency. Knospe [51] effectively suppressed rotor unbalanced vibration based on the adaptive method, but the computational cost was significantly larger.

Michio Nakano proposed a repetitive control method that had good suppression for periodic disturbances [52, 53]. The method achieved high precision tracking control for periodic signals based on the internal model principle and reduced control difficulty. The core algorithm was simple and provided good performance stability. Zhang [54], Han [55], and Nakamura [56] introduced repetitive control methods to study vibration suppression of magnetic bearing systems, and achieved superior effects. However, aperiodic vibration usually contains different frequencies or the dynamic characteristics are unknown. Since the delay constant in the repetitive control is generally chosen to be the same as the period of the input signal, it is difficult to suppress aperiodic vibrations at the same time. The disturbance observer is a common vibration suppression method for repetitive control systems with uncertainties [57]. However, it needs to establish two sets of power systems (state and disturbance observers) to achieve the estimation of the disturbance, hence the design of the low-pass filter is complicated. The adaptive repetitive controller [58] also needs to design a frequency observer, making stability analysis of the control system significantly more complicated. Robust high order repetitive controllers [59] optimize the compromise index of periodic and aperiodic control performance, but sacrifice suppression one of the vibrations. Other models, such as sliding mode repetitive controller [60], etc., have also been studied. She [61] proposed a control method based on equivalent input disturbance compensation, with 2 degree of freedom. The proposed method can effectively reject periodic and aperiodic disturbances without requiring inverse dynamics of the plant or a priori information about the disturbances. This method exhibited high performance disturbance suppression for motor and power control systems, but it has not been applied to magnetic bearing systems.

4. High Speed Flexible Rotor Control

Active magnetic bearings can support high speed rotors, but cause the rotor to flex at high speeds, and produce multiple critical areas in the working speed range. When the flexible rotor encounters the critical speed, the bearing needs to provide sufficient support stiffness and damping, and treating the magnetic rotor as rigid inevitably produces large errors, which greatly increases the controller design difficulty.

Modern control theory to improve system dynamic performance has good flexibility, and many studies have investigated it use for control of flexible rotors. Gu [62] designed a controller for a magnetic bearing flexible rotor system based on linear quadratic Gaussian theory. The rotor passed through the first flexible critical rotational speed and rotated stably for a long period at this speed. Fujiwara [63] and Ito [64] realized smooth rotation of flexible rotors with magnetic bearing systems across the second and third order bending critical speed by modal control, respectively. Nonami [65, 66] solved the problem of modal spillover for flexible rotor control using robust H_∞ control strategy, and improved the stiffness of the flexible rotor by using μ controller. Xie [67] proposed a variable parameter PID control method based on rotation speed for a flexible rotor system. The proposed system stably passed the second order bending critical speed and provided good dynamic performance across the whole speed range. To satisfy the requirements for a system operating at low and high frequency, Zhuang [68] designed an adaptive PID controller based on a single neuron with varying learning rates. The method effectively reduced rotor vibration at critical speeds and helped the magnetic bearing system operate stably. Defoy [69] proposed a fuzzy controller based on inputs expressed in polar coordinates that effectively improved stability and robustness of the active magnetic bearing flexible rotor system. Liu [70] proposed a variable structure controller based on a reduced order model. The method was robust to error in the flexible rotor model and maintained good system dynamic performance with external disturbance.

5. Summary and Prospect

Magnetic bearings are typical nonlinear unstable systems, and are affected by noise, and periodic and aperiodic vibration in operation, as well as high speed rotor flexibility and other factors, which all reduce system control accuracy. Therefore, high performance controller design has become an important research direction for magnetic bearing systems. This paper describes magnetic bearing system control algorithms in detail, and introduces vibration and flexible control systems. Although magnetic bearing system control has made considerable progress in theory and application, many problems remain:

(1) Accurate mathematical models are required for high precision control. The influence of nonlinearity and coupling should be considered when the system is modeled and supplemented with model identification method, which will provide the basis for controller design. Therefore, we consider the adaptive state identification and multidimensional complex control technology, and introduce the optimal load distribution function and the optimal dispatching function of the control law to solve the problem of stiffness and damping identification of the magnetic rotor system.

(2) External uncertainties cause aperiodic vibrations in magnetic bearing systems. A single control algorithm for a given vibration cannot provide high precision control. Therefore, periodic vibration and aperiodic vibration should be considered simultaneously. To resolve the issue of eccentricity vibration, we focus on the eccentricity property which is periodic in the rotating angle, and introduce a transformation from time domain description of the control object to space domain description so as to do the eccentricity vibration compensation in the space domain via repetitive control method. Meanwhile, we are trying to compensate the nonlinear characteristics and system uncertainties by the equivalent input disturbance method into the system to guarantee the performance of the system transient process.

(3) High speed rotor control requires consideration of low and high frequency characteristics of the flexible rotor system. System stability should be considered when the rotor passes the critical bending speed range(s). A new and powerful robust control theory has recently been developed which uses the phase information of resonance modes. This theory will be applied to achieve high bandwidth and energy saving simultaneously. We intend to introduce this theory to expand

the bandwidth of the system to solve the problem.

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