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Precise control of a four degree-of-freedom permanent magnet biased active magnetic bearing system in a magnetically suspended direct-driven spindle using neural network inverse scheme

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ABSTRACT

The capacity of improving the control accuracy and dynamic performance of a four degree-of-freedom (DOF) permanent magnet biased active magnetic bearing (PMBAMB) system is critical to developing and maintaining a high precision application in a magnetically suspended direct-driven spindle system. The 4-DOF PMBAMB system, however, is a multivariable, strong coupled and nonlinear system with unavoidable and unmeasured external disturbances, in addition to having parameter variations. The satisfactory control performance cannot be obtained by using traditional strategies. Therefore, it is important to present a novel control scheme to construct a robust controller with good closed-loop capability. This paper proposes a new decoupling control scheme for a 4-DOF PMBAMB in a direct-driven spindle system based on the neural network inverse (NNI) and 2- degree-of-freedom (DOF) internal model control method. By combining the inversion of the 4-DOF PMBAMB system with its original system, a new pseudolinear system can be developed. In addition, by introducing the 2-DOF internal model controller into the pseudolinear system to design extra closed-loop controllers, we can effectively eliminate the influence of the unmodeled dynamics to the decoupling control accuracy, as well as adjust the properties of tracking and disturbance rejection independently. The experimental results demonstrate the effectiveness of the proposed control scheme.

1. Introduction

Compared with conventional mechanical bearings, magnetic bearings (MBs) possess several remarkable advantages, such as no friction and wear, no need of lubrication, long life span, high potential of high control precision, as well as the ability of long-term high speed running [1]. Therefore, MBs have been attracting considerable interests in various high-performance applications including flywheel energy and storage devices, bearingless motors, artificial heart pumps, vacuum pumps, numerical control machines, especially in special high-purity applications (e.g., pharmaceutical mixing, bioreactor mixing, etc.). Furthermore, in some special environments, such as at temperature extremes and in vacuum operations, MBs have the irreplaceable opportunity due to their obvious non-contact and frictionless characteristics [2–4].

Owing to the utilization of rare earth permanent magnet, permanent magnetic biased hybrid magnetic bearings (PMBAMBs) have characteristics of high efficiency, small size, and low running cost [5]. For these advantages, PMBAMBs have been widely

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adopted to take the place of the extra currents to produce the radial suspension forces. However, to design an available control scheme for a PMBAMB is still a challenging topic especially in a multi-DOF PMBAMB system due to its highly nonlinear, strong coupled, and open-loop unstable control characteristics. Thus, a sophisticated control scheme which is capable of regulating and stabilising the rotor of the PMBAMB system within a narrow airgap is of the essence in different operating environments [6].

As a traditional control scheme, the proportional plus integral plus differential (PID) control scheme has been already applied in the MB system in a general way owing to its simple realization [7,8]. However, the control performance of the MB system by using the conventional PID control scheme could not be very satisfied owe to the unmeasured parameters variations and unavoidable external disturbances. Therefore, with the development of modern control theories, all kinds of advanced control methods have been recently proposed for MB systems, such as fuzzy control [9], intelligent control [10], sliding mode control [11], predictive control [12], robust control [13], adaptive control [14,15], fractional order control [16], backstepping control [17], optimum control [18], etc. These advanced control methods not only enrich the control theory of MB systems, but also improve their performance in different aspects. The fuzzy control scheme can express a nonlinear magnetic levitation drive system by the time-varying convex combination of linear state space models utilizing nonlinear fuzzy membership functions so that it is possible to use other control technique. The sliding mode control scheme can guarantee asymptotic and finite-time tracking capabilities of the magnetic levitation drive system. The predictive control scheme can decrease the settling time remarkably and reduce oscillations in the lower part of operating range effectively. The adaptive control scheme can achieve simultaneous control of both rotor vibrations and transmitted forces in flexible magnetic suspension rotor systems. The backstepping control scheme uses the nonlinear observers to provide the estimate of the unmeasured state and can achieve high-quality control of the magnetic levitation drive system in the case of acceleration disturbances at different rotational speeds. The fractional order control scheme employs a new error criterion by combining the mean square error with a maximal phase error to find the optimal model with smaller phase errors.

Besides aforementioned nonlinear control methods, the linearization and decoupling control schemes have been widely employed for MB systems in recent years [19]. In general, the linearization and decoupling scheme can be divided into the differential geometry decoupling scheme and the inverse system scheme [20,21]. Since the differential geometry scheme is abstractive and needs to convert the control problem to the geometric domain, it is difficult to be popularized in practical applications. Additionally, the inverse system scheme is simple, intuitive, and relatively simple to carry out. In [22], the inverse system scheme is used for the radial position control of a magnetically suspended rotor system in a direct-driven spindle. However, attributed to the complexity of the magnetically suspended rotor system in a direct-driven spindle, its mathematical model will not be known precisely. So the motivation of linearization and decoupling is hard to achieve by only utilizing the inverse system scheme. The other approach is needed to combine with the inverse system method to realize the linearization and decoupling control.

On the other hand, the neural network is one of the intelligent control methods which does not need mathematical model of the controlled plant and can effectively approximate nonlinear systems [23–25]. With the well-developed on-line learning and self-adapting abilities, the neural networks are capable of dealing with highly nonlinear and time-varying systems with the unmeasured parameters variations, as well as the unavoidable external disturbances. Therefore, by using the neural network to construct inverse system, a new control method, the so called neural network inverse (NNI), is proposed [26].

Since the developed pseudo-linear system of 4-DOF PMBAMB system by using the NNI control scheme is not a simple linear system, the parameters variations may inevitably influence the properties of decoupling, tracking, and disturbance rejection performance. The traditional internal model control can obtain good performance for set point tracking, but gives the sluggish response for disturbance rejection problem. Thus, it is difficult for traditional internal model control to give consideration to both tracking and disturbance rejection properties. Therefore, for purpose of improving the static and dynamic properties of the whole 4-DOF PMBAMB system, and adjusting the tracking and disturbance rejection performances independently, the NNI control scheme plus 2- DOF internal model controllers are adopted in the paper.

The paper is organized as follows. First, in Section 2, we construct the model of the 4-DOF PMBAMB system in a magnetically suspended direct-driven spindle system and analyze its dynamic characteristics. After that, the NNI control scheme is adopted for decoupling control of the 4-DOF PMBAMB system in Section 3. Second, the internal model control theory is used to design the closed-loop controllers to improve system robustness in Section 4. Then, the comparative experimental researches between the proposed method and the traditional PID control scheme are carried out in Section 5. Finally, Section 6 concludes this paper.

2. 4-DOF PMBAMB system in a magnetically suspended direct-driven spindle system

2.1. System structure

The magnetically suspended direct-driven spindle system has 6-DOFs, i.e., a rotational DOF and 5 suspended DOFs. The fully suspended 5-DOF PMBAMB system in the magnetically suspended direct-driven spindle system includes four radial DOFs controlled by two 2-DOF radial PMBAMBs and one axial DOF controlled by a single-DOF axial MB. Since there is no coupling between the single-DOF axial MB and the 4-DOF radial PMBAMBs, we mainly focus on the nonlinear decoupling control of the 4-DOF PMBAMB system in this paper (the coupling characteristics of the 4-DOF PMBAMB will be analyzed in Section 2.3).

Fig. 1 illustrates the structure of the adopted magnetically suspended direct-driven spindle system. A single-DOF axial MB and two 2-DOF radial PMBAMBs are used to suspend and regulate the rotor in the axial and radial DOFs, respectively. Two pairs of the perpendicular eddy-current displacement sensors (i.e. gap sensors) are installed closely to respective 2-DOF radial PMBAMBs to measure the respective radial displacements in perpendicular directions. Additionally, an eddy-current displacement sensor is installed closely to the single-DOF axial MB to measure the axial displacement in axial direction. After the rotor displacements in five