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Hybrid control of a three-pole active magnetic bearing

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ABSTRACT

The design and implementation of the hybrid control method for a three-pole active magnetic bearing (AMB) is proposed in this paper. The system is inherently nonlinear and conventional nonlinear controllers are a little complicated while the proposed hybrid controller has a piecewise linear form, i.e., linear in each sub-region. A state-feedback hybrid controller is designed in this study and the unmeasurable states are estimated by an observer. The gains of the hybrid controller are obtained by the LQR method in each sub-region. To evaluate the performance, the designed controller is implemented on an experimental setup. The experimental results show that the proposed method can efficiently stabilize the three-pole AMB system. The simplicity of design, domain of attraction, uncomplicated control law and computational time are advantages of this method over other nonlinear control strategies in AMB systems.

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1. Introduction

Nowadays, two parameters are important in manufacturing of rotating machinery such as machine tools, turbines and compressors, namely, speed and accuracy. In these systems, the AMB is being used to achieve high rotational speeds instead of conventional bearings. AMBs have advantages such as noncontact load carrying, long life duty, no need to lubrication, ability to work in vacuum and high temperature environments, high efficiency, high speed, and etc.

The AMB system has almost a nonlinear behavior. Hence, a control technique that can stabilize the system in a large domain of attraction is the best solution for this application. Linear controllers have been extensively used by many researchers in this area. However, this type of controller can stabilize the AMB system only in a small region near the linearization point. To solve this problem, it is better that a nonlinear control method to be used. The three-pole configuration of AMB has a strongly nonlinear dynamics, so a nonlinear controller is expected to have the best performance for such a system. The hybrid configuration is a conventional method to control nonlinear systems, in which some linear controllers are matched to each other by a switching logic. In this method, the whole domain is divided into small zones and the system is controlled by designing linear controllers for these zones. The main benefits of this method are simplicity and coverage of the total domain.

The hybrid control method has been widely used by researchers. Fierro [1] used this technique to control a group of nonholonomic mobile robots with range sensors. The stability of the hybrid system that he developed is studied by using the Lyapunov theory. Karimoddini [2] presented a bumpless hybrid supervisory control scheme to stabilize an unmanned helicopter. The proposed method is based on polar partitioning of the workspace. Lin-Shi [3] used a hybrid control strategy to control motor drives on a permanent-magnet synchronous motor. Han et al. [4] used a hybrid feedback control to stabilize a spring-loaded inverted pendulum system. The results of this paper show that this approach has good performance on different conditions of a nonlinear system. Liu and Stechlinski [5] investigated the stabilization of a class of nonlinear systems with distributed delays using impulsive and switching control. Their criteria are based on a special type of state dependent switching law which partitions the state space into stabilizing sub-regions. A common Lyaponuv function is used to prove stability. Yuan and Wu [6] investigated the stability and L_2-gain problems for a type of linear hybrid control system by utilizing ELF[1] technique. A hybrid conditions are expressed in LMIs.[2] They used the proposed method to control an inverted pendulum example.

To control a three-pole AMB two kinds of controller can be designed, the first one is current-control method and the 2nd is voltage-control approach. Classical linear control techniques are

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[1] Extended Lyaponuv-like function.
[2] Linear Matrix Inequalities.

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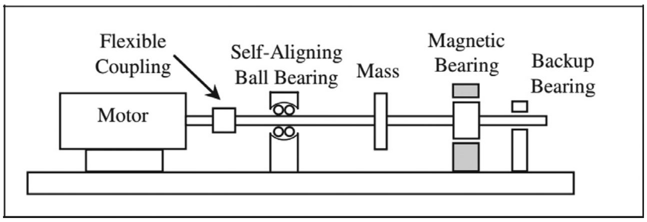

Fig. 1. Schematic of a single magnetic bearing [12].

rarely used to control and stabilize a three-pole AMB. Darbandi [7] proposed linear and nonlinear output feedback controllers to stabilize a three-pole AMB system. Although the system is inherently nonlinear, Darbandi showed that the system nearly have linear behavior on small displacement. Hsu [8] used the feedback linearization method to stabilize the three-pole AMB and obtained admissible domain in state space by the Lyapunov approach. Later, Chen [9] presented a new current-control approach based on sliding mode method for a three-pole AMB system. The experimental results of this paper show that the rotor can be levitated to the stator axis and its settling time is about 0.4 s. Later, Chen [10] proposed a voltage-controlled integral sliding mode controller. In his study, the settling time is 0.5 s and experimental results and simulations are nearly the same. Chen [11] implemented linear controller, feedback linearization and integral sliding mode method on a three-pole AMB experimentally. Finally, he concluded that the linear controller is more sensitive to system parameter uncertainties and unmodeled dynamics than the sliding mode technique.

In this study, the main goal is to propose a pseudo-linear controller to stabilize a three-pole AMB system. To this end, a hybrid control method is suggested which is based on some conjunct linear controllers. The proposed technique is inherently nonlinear but linear control methods are used to design the controller and obtain the controller gains. After that the designed controller is implemented on a three-pole AMB experimental setup in dynamic and static modes. Finally the simulation and experimental results are presented to illustrate the performance and applicability of the proposed controller.

One of the targets of this paper is proposing a simple and practical control method for using in the three-pole active magnetic bearings. Darbandi implemented a linear controller and also an integral sliding mode (as a nonlinear approach) on this experimental setup [7]. The integral sliding mode is the only nonlinear controller that is designed and applied for this setup. Darbandi concluded that since the integral sliding mode is a model based technique the unmatched uncertainties and un-modeled dynamics can significantly affect its performance, and the computation time increases in this method comparing to simple well-tuned linear techniques [7]. As a result the linear control is more applicable than integral sliding mode (as a nonlinear well-known controller). In this paper the stability of the closed-loop system has been proven however in [7] the stability of the proposed linear controller has not been proved.

The power consumption is an important parameter in AMBs. In this paper, it is shown that the power usage has been decreased in the hybrid control method comparing to a simple linear control.

2. Modeling

2.1. Three-pole active magnetic bearing

Fig. 1 shows schematic of the three-pole AMB that is used in this paper. The rotor is supported with a self-aligning ball bearing and the three-pole AMB. The self-aligning ball bearing allows the end of rotor can move freely in radial direction. The other end of rotor is levitated by the three-pole AMB and the AMB is supported by a backup bearing. A flexible coupling is used to decrease the transmitted forces and moments according to misalignment. The rotor is supposed to be rigid and its dynamic can be modeled by 2-DOF rotating disk. According to the configuration of setup, the gyroscopic effect can be neglected [12].

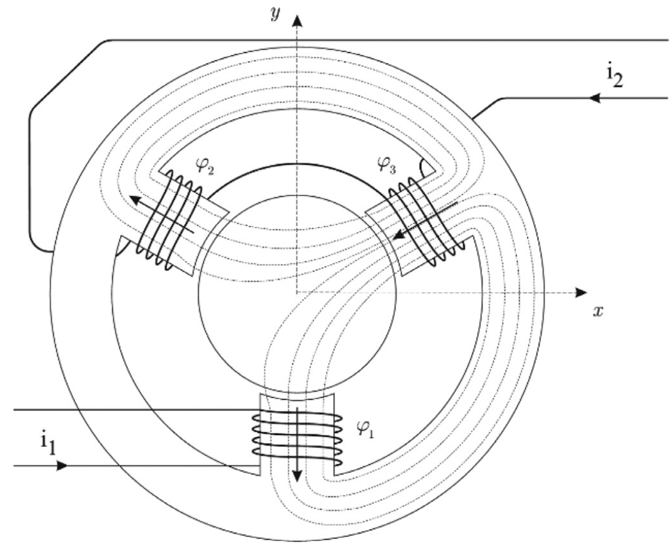

Fig. 2. three-pole Active Magnetic Bearing with 2 coil currents [5].

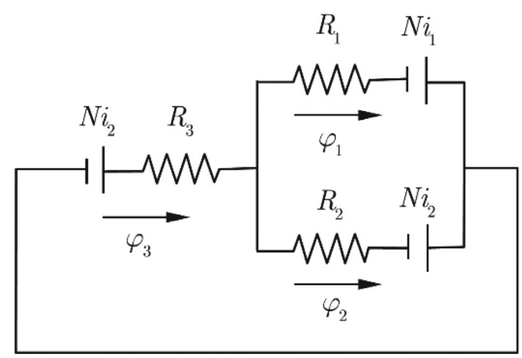

Fig. 3. Magnetic circuit of three-pole AMB [5].

In Fig. 2 schematic of a three-pole AMB configuration proposed by Chen and Hsu [13] in 2002 is shown. In [14] Bouaziz et al. studied the angular misalignment and flexibility of coupling in an AMB but in the present case, according to the above mentioned explanation, the angular misalignment between shaft and coupling and its flexibility are not considered.

The poles radially stand with an angle of 120° from each other. Each pole with the surface area A is made of copper wires and has one coil with N turns. The magnetic flux of pole j is depicted by φ_j. According to Fig. 2 the current that passes through coils 2 and 3 is the same, but this current makes opposite magnetic fluxes in their corresponding poles. When the system is in equilibrium position, the shaft axis and axis of the stator are coincident using a bias current in the upper coils which counter-balances the weight. It should be mentioned that in this case two power sources are needed to produce the currents of coils and only one of them has a bias current, so this formation results in an optimum situation [7].

Assuming no flux leakage, no saturation and no reluctance of core (core is made of iron), the magnetic circuit diagram of the AMB is shown in Fig. 3.

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