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Adaptive control of an active magnetic bearing with external disturbance

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ABSTRACT

Adaptive back stepping control (ABC) is originally applied to a linearized model of an active magnetic bearing (AMB) system. Our control goal is to regulate the deviation of the magnetic bearing from its equilibrium position in the presence of an external disturbance and system uncertainties. Two types of ABC methods are developed on the AMB system. One is based on full state feedback, for which displacement, velocity, and current states are assumed available. The other one is adaptive observer based back stepping controller (AOBC) where only displacement output is measurable. An observer is designed for AOBC to estimate velocity and current states of AMB. Lyapunov approach proves the stabilities of both regular ABC and AOBC. Simulation results demonstrate the effectiveness and robustness of two controllers.

1. Introduction

A magnetic bearing is a bearing which supports a load (such as a rotor) using magnetic levitation [1]. Magnetic bearings are classified into two categories: passive and active ones. A passive magnetic bearing is composed of permanent magnets and its output flux cannot be controlled. An active magnetic bearing (AMB) is made of electromagnets and its output flux can be adjusted by changing the current on the coil. Therefore, AMB is more popular in practice than passive magnetic bearings due to its controllable output flux.

AMB has been broadly used in flywheel energy storage systems, turbo compressors, vacuum pumps, vehicle gyroscopes, and so on. AMB has several advantages over conventional ball or journal bearings. The most significant advantage is that since the AMB suspends rotor in a magnetic field, the rotor can spin at a high speed (up to 60,000 rpm) without contacting any mechanical part. The only friction in AMB is windage, which can be removed when AMB is operated in vacuum enclosure. This frictionless feature also leads to low energy loss and the elimination of extra lubricating system [2]. In addition, AMB has a long life span due to its low equipment wear and its insensitivity to pressure and temperature changes. Nevertheless, an external disturbance can cause a large deviation of a rotor from its equilibrium position. Then the rotor would touch a stator, resulting in the failure of operation. Therefore the control of the rotor position becomes a crucial problem for AMB systems. A controller that is robust against external disturbance is ideal for the AMB.

Different control approaches have been reported for regulating the rotor position of AMB systems. PID control in [3–5] is a typical and efficient method to stabilize the rotor. A proportional gain controller is reported in [4]. The PID controller is simple to implement and easy to tune. However, it is not robust against disturbances and system uncertainties. Other than PID, Least Quadratic Regulator (LQR) control is designed and realized in a small size prototype AMB [6]. The performances of a PID controller, a cascaded PI/PD controller, and a LQR based control method are compared with each other in [7,8] for AMB systems. It is discovered in [7,8] that the LQR based controller has better performance than PID or PI/PD controller. However, the design and tuning of LQR based controller is time consuming and computationally complex [7]. Self sensing control of AMB is introduced in [9–12]. Self sensing refers to the controller design in the absence of an extra position sensor. The position information thus needs to be obtained by measuring the bearing coil current. A novel approach called Active Disturbance Rejection Control (ADRC) developed in recent years is simulated on a self sensing AMB system in [2,12]. The ADRC demonstrates an excellent disturbance rejection capability through combining a PD controller with a linear extended state observer [12]. However, there is a steady state error in the position response for the ADRC controlled AMB system [12].

In this paper, an adaptive back stepping control (ABC) method is originally applied to a linearized model of the AMB. The ABC

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developed in recent decades [13–22] is an advanced control approach including recursive feedback control, Lyapunov stability and adaptive law. In [19,20], the ABC is also combined with neural and fuzzy integral action. It is shown in [18] that the ABC is superior to PI/PD or PID controller in its robustness against system uncertainties. Therefore ABC has been successfully applied to inverted pendulum, robot manipulator, jet engine, helicopter, and induction motor drive [13–21]. In this paper, a regular ABC and a novel adaptive observer based back stepping controller (AOBC) are developed on the AMB system respectively. While the regular ABC is based on the feedback information of three states (displacement, velocity, and current) from AMB, the AOBC is constructed on only one state (displacement). In [23], some preliminary results are reported about the application of a regular ABC to the AMB. The AOBC is an alternative solution to the control problem of the AMBs where current and velocity are not measurable. It is demonstrated in this paper that ABC and AOBC are robust against both external disturbance and parameter variations. But the ABC in [13–21] only compensates the variations of system parameters. Moreover, in this paper, the ABC is constructed based on position feedback. So a steady state error would be eliminated in the displacement of the rotor. The control systems' stability is verified by Lyapunov's direct method.

The rest of this paper is organized as follows. The dynamic modeling of the AMB system is given in Section 2. The design of ABC is presented in Section 3. The stability and robustness analyses for ABC are demonstrated in Section 3 as well. The development of AOBC is presented in Section 4. The simulation results are shown in Section 5. Concluding remarks and future research are given in Section 6.

2. Dynamic modeling of an AMB system

In a typical stable AMB model, the rotor is levitated at its equilibrium point which is positioned right in the middle of two magnets. The two opposite electro magnets are trying to pull the rotor on each side in the absence of any external force. When an external force causes a displacement of the rotor from its equilibrium position, the displacement will be sensed by a position sensor. Position sensor outputs the position information to an electronic control system, which increases the current in one direction and decreases the current in another direction through the respective electro magnets. This produces a differential force to push the rotor to its original position. The signal from the electronic controller continuously updates the differential force to stabilize the rotor till no position error (between rotor's position and equilibrium position) is sensed.

Fig. 1 shows a simple magnetic actuator model. In this figure, I is the coil current, g is air gap, N is the number of coil rounds on the core, A_g represents the cross section area and g is the air gap, l is the length of the path enclosing a surface through which the current flows. The magnetic field generated by the current will create an upward force.

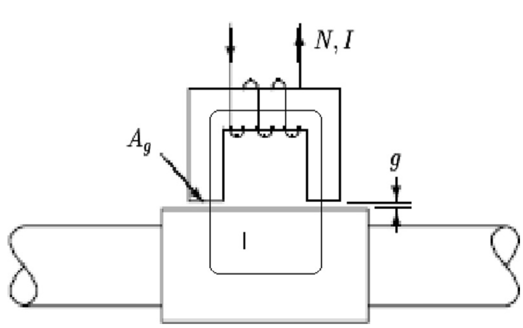

Fig. 1. Magnetic actuator.

According to Ampere's loop law, we have (1), where H is the magnetic field, n_s is the number of the segments through the path l, and n_c is the number of different coils.

$$\sum_{i=1}^{n_s} H_i l_i = \sum_{i=1}^{n_c} N_i I_i \tag{1}$$

Assuming that the permeability of the mediums μ is constant in each segment, we will have the magnetic flux density B_i given by

$$B_i = \mu_i H_i \tag{2}$$

Combining (1) and (2) yields

$$\sum_{i=1}^{n_s} \frac{B_i l_i}{\mu_i} = \sum_{i=1}^{n_c} N_i I_i \tag{3}$$

For the system in Fig. 1, there are two air gaps and the permeability of air (μ_g) is much less than that of iron (μ_0). Then from (3), we will have

$$2\frac{Bg}{\mu_g} = NI \Rightarrow B = \frac{\mu_g NI}{2g} \tag{4}$$

The energy E stored in the air gaps is represented by

$$E = A_g g \int H dB = A_g g H B \tag{5}$$

where H is constant. The electromagnetic force (F) is the derivative of the energy E with respect to air gap. Considering (5) and (2), we can calculate the electromagnetic force F as

$$F = \frac{dE}{dg} = BHA_g = \frac{1}{\mu_g} B^2 A_g \tag{6}$$

With the equation of flux density in (4), we can rewrite (6) as

$$F = \frac{\mu_g N^2 I^2 A_g}{4g^2} \tag{7}$$

In this paper, we use a one degree of freedom (DOF) AMB model as shown in Fig. 2.

In Fig. 2, F_d is a disturbance force on the rotor, and F_1 and F_2 are two opposite electromagnetic forces, whose values are calculated through (7). The rotor in the middle of two cores is levitated and rotates in a plane perpendicular to the figure. We can adjust the input voltage u_1 and u_2 to control the two currents i_1 and i_2 so as to determine the resultant force. In Fig. 2, the displacement of rotor from nominal position x_0 is x, and m is the rotor's mass. According to Newton's law, we have

$$m\ddot{x} = F_1 + F_d - F_2 \tag{8}$$

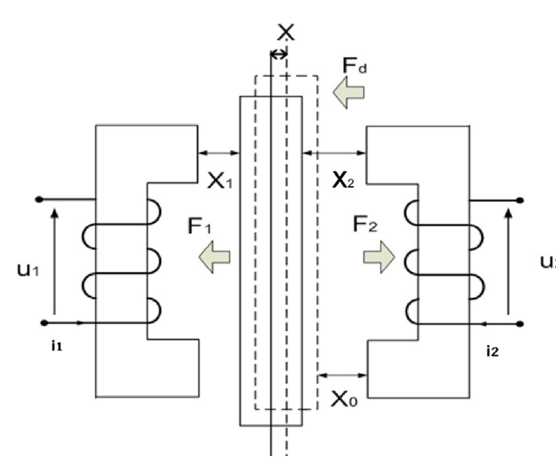

Fig. 2. AMB model.