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Nonlinear Control Type Magnetic Bearing for Adding Damping Force to Existing Rotor

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Abstract

This paper proposes a nonlinear control method of magnetic bearings for adding the desired damping force to an existing rotor supported by passive magnetic bearings (PMBs) or gas bearings. PMBs composed only of permanent magnets do not require a control circuit. Therefore, PMBs can be economically manufactured. However, the vibrations cannot be suppressed because PMBs cannot generate damping force. Therefore, studies have been conducted on hybridized magnetic bearings. However, hybridized magnetic bearings have a disadvantage in that they are complicated and expensive. Gas bearings can generate excellent support force and damping force during high-speed rotation. However, it is difficult to dampen certain vibrations such as whirl vibration. Therefore, a method combining gas bearings and active magnetic bearings (AMBs) was considered in order to dampen such vibrations. Because the support rigidity of the AMBs are applied, the dynamics is significantly changed as compared with rotors supported only by the gas bearings. Moreover, because sufficient stiffness can be obtained from the gas bearings, it is useless to add stiffness through the magnetic bearings. To solve the above problems, we propose the use of the AMBs only for the generation of damping force. When using a general linear control, it is necessary to supply the bias current to the AMBs. However, it adversely affects the support stiffness of the rotor because a negative stiffness is generated by the bias current. We have previously proposed a control method with unnecessary bias current through nonlinear control of the AMB, and applied this method to actual equipment. However, this method involved the generation of both support force and damping force. Here, we focus on generating only damping force. This method is verified through the simulation.

Keywords : Nonlinear control, Active magnetic bearing, Passive magnetic bearing, Vibration control, Damping force, Switching low.

1. Introduction

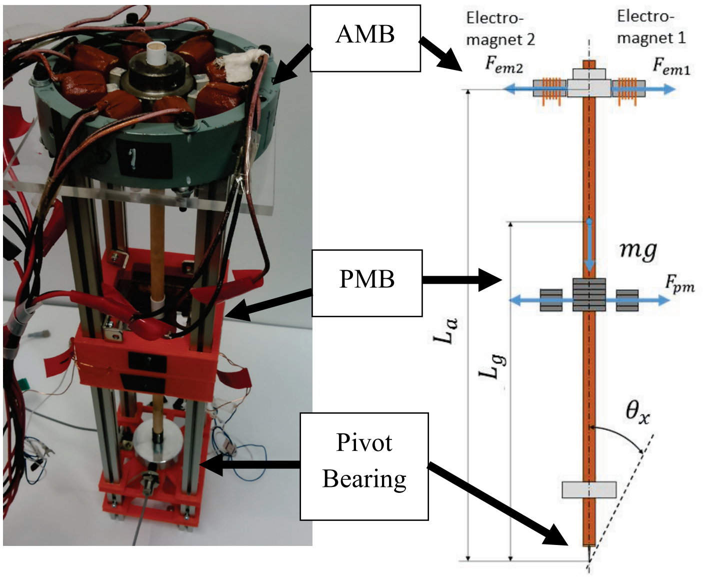
This paper proposes a nonlinear control method of magnetic bearings for adding the desired damping force to an existing rotor supported by passive magnetic bearings (PMBs) or gas bearings. If the only one degree of freedom is controlled, PMBs composed only of permanent magnets do not require a control circuit (Schweizer and Maslen, 2009). Therefore, PMBs can be economically manufactured. However, the vibrations cannot be suppressed because PMBs cannot generate damping force. Therefore, studies have been conducted on hybridized magnetic bearings (Cheng and Day, 2010). However, hybridized magnetic bearings have a disadvantage in that they are complicated and expensive. Gas bearings can generate excellent support force and damping force during high-speed rotation (Belforte, et al.). However, it is difficult to dampen certain vibrations such as whirl vibration. Therefore, a method combining gas bearings and active magnetic bearings (AMBs) was considered in order to dampen such vibrations (Knopf and Nordmann, 1998). Because the support rigidity of the AMBs is applied, the dynamics is significantly changed as compared with rotors supported only by the gas bearings. Moreover, because sufficient stiffness can be obtained from the gas bearings, it is useless to add stiffness through the magnetic bearings. To solve the above problems, we propose the use of the AMBs only for the generation of damping force. When using a general linear control, it is necessary to supply the bias current to the AMBs. However, it adversely affects the support stiffness of the rotor because a negative stiffness is generated by the bias current. We have previously proposed a control method with unnecessary bias current through nonlinear control of the AMB (Ariga, et al., 2000), and applied this method to actual equipment (Nonami, et al.). However, this method involved the generation of both support force and damping force.

Here, we focus on generating only damping force. Based on the mathematical model of the controlled object, a control algorithm for switching the electromagnets depending on the speed of the rotor is derived. To assume that the bias current is not supplied, nonlinear control algorithms are derived.

Paper is organized as follows. First, outline of the control object and the mathematical model is shown. Then, the non-linear control algorithms and their stability of proof are shown. This method is verified through the simulation. After showing the simulation results, conclusions are set forth.

2. Control object

In this study, the control target is an upright rotor, whose appearance and schematic diagram are shown in Fig. 1. The parameters used in this study are defined in Table 1. The PMB supports the rotor and enables it to stand stably. A pivot bearing is used as a thrust bearing. However, if vibration occurs due to a disturbance, the vibration can't be attenuated without control. To quickly attenuate this vibration, the AMB is placed on top. Displacement of the rotor by eddy current sensor installed at the bottom is measured. Then, the rotor of the Inclination θ_x and the angular velocity $\dot{\theta}_x$ can be obtained by calculation.



(a) Appearnace (b) Configuration diagram

Fig. 1 The control target is an upright rotor. The PMB supports the rotor and enables it to stand stably. A pivot bearing is used as a thrust bearing. To quickly attenuate this vibration, the AMB is placed on top. Displacement of the rotor by eddy current sensor installed at the bottom is measured.

Table 1 Table 1 Definition of parameters

I	Moment of inertia
θ_x	Inclination
M	Mass
g	Gravitational acceleration
$i_1,\ i_2$	Coil current 1and 2
d_0	Air gap
L_g	Position of the center of gravity
L_a	Position of AMB
c	Attenuation coefficient
K_P	Sprig force of PMB
k_e	Attractive force constant of electromagnet
α	Design parameters of nonlinear control

Each gap between electromagnets and the rotor are expressed by the following equation.

$$\begin{cases} d_1 = d_0 - L_a \sin\theta_x \cong d_0 - L_a\theta_x \\ d_2 = d_0 + L_a \sin\theta_x \cong d_0 + L_a\theta_x \end{cases} \tag{1}$$

In this case, the equation of motion of the control object is obtained by the following equation. Attractive forces of e two electromagnets have a nonlinear characteristic.

$$I\ddot{\theta}_x = \left(MgL_g - K_p\right)\theta_x - c\dot{\theta}_x + L_a k_e \left\{ \left(\frac{i_1}{d_1}\right)^2 - \left(\frac{i_2}{d_2}\right)^2 \right\} \tag{2}$$

When controlling, only either electromagnet is used. Therefore, it is treated as one input system.

3. Nonlinear control algorithm

Control currents are supplied to the electromagnets that are disposed opposite to each other on either side of the rotor. They are determined by the following control algorithm in accordance with the angular velocity of the inclination of the rotor, where α is greater than 1.

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**** Control Algorithm *****
 IF $\dot{\theta}_x \geq 0$ THEN
    $\begin{cases} i_1 = 0 \\ i_2 = d_2\sqrt{c(\alpha-1)\dot{\theta}_x/(L_a k_e)} \end{cases}$    (3)
 ELSE
    $\begin{cases} i_1 = d_1\sqrt{c(1-\alpha)\dot{\theta}_x/(L_a k_e)} \\ i_2 = 0 \end{cases}$    (4)
 END
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The stability when using above algorithm, is proved as follows.

Proof

If $\dot{\theta}_x \geq 0$, Equation (3) is substituted for Eq. (2).

$$\begin{aligned} I\ddot{\theta}_x &= \left(MgL_g - K_p\right)\theta_x - c\dot{\theta}_x + L_a k_e \left\{ -\left(\frac{i_2}{d_2}\right)^2 \right\} \\ &= \left(MgL_g - K_p\right)\theta_x - c\dot{\theta}_x + L_a k_e \left\{ -\left(\frac{d_2\sqrt{c(\alpha-1)\dot{\theta}_x/(L_a k_e)}}{d_2}\right)^2 \right\} \\ &= \left(MgL_g - K_p\right)\theta_x - c\dot{\theta}_x - L_a k_e \frac{c(\alpha-1)\dot{\theta}_x}{L_a k_e} \\ &= \left(MgL_g - K_p\right)\theta_x - c\alpha\dot{\theta}_x \end{aligned} \tag{5}$$

If the spring force of the PMB is greater than the overturning moment due to gravity, $K_p > MgL_g$ is satisfied. So the following equation is stable.

$$I\ddot{\theta}_x + c\alpha\dot{\theta}_x + \left(K_p - MgL_g\right)\theta_x = 0 \tag{6}$$

In case of $\dot{\theta}_x < 0$, The same procedure gives us Eq. (6). Therefore, the control system in the proposed algorithm is stable. ■

4. Simulation results

By controlling The AMB according to the above algorithm, the damping ratio of the rotor will be α times the value of that without control. Figure 2 shows the simulation results of control for the damping ratio for 10 times ($\alpha = 10$). Compared to the vibration without control, good damping is obtained. Control currents are switched in accordance with the sign of the angular velocity.

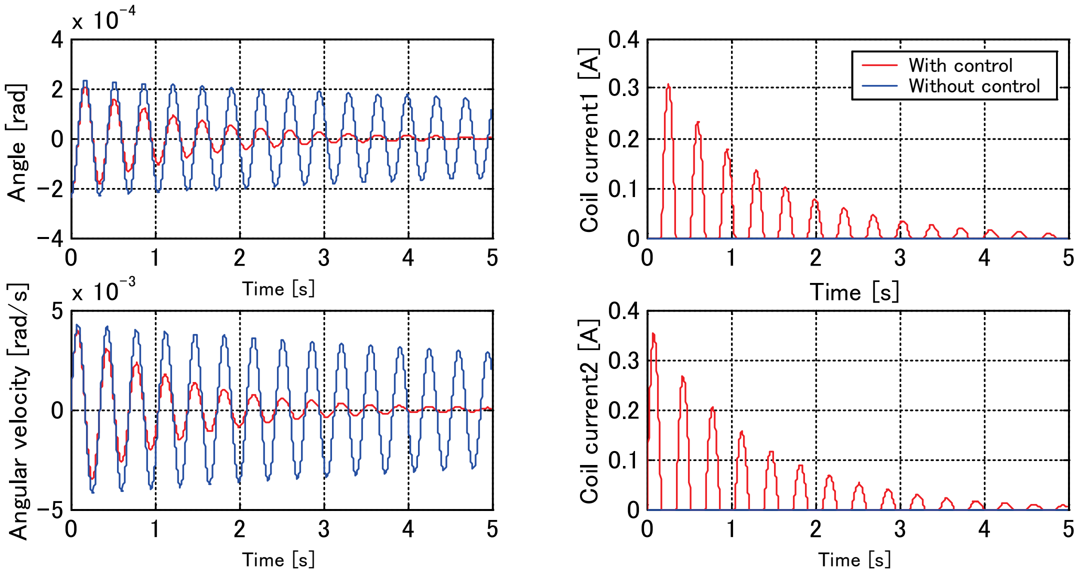

Fig. 2 The simulation results of control for the damping ratio for 10 times ($\alpha = 10$) are shown. The responses without control are indicated by blue lines. Since the coil currents (i_1, i_2) are not supplied, the rotor oscillates continuously. On the other hand, the responses with control are indicated by red lines. The results have shown that good damping is obtained. Control currents (i_1, i_2) are switched in accordance with the sign of the angular velocity. Compared to the vibration without control, both eigenfrequency are the same. Therefore, it's indicated that nonlinear controller doesn't generate the spring force.

5. Summary

This paper proposes a nonlinear control method of magnetic bearings for adding the desired damping force to an existing rotor, which is supported with passive magnetic bearings or gas bearings. Effectiveness of the proposed method was confirmed through simulations. The future challenge is to demonstrate the effectiveness of the proposed method through experiments.

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