A study on zero-bias simple adaptive control AMB system

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Abstract

For further evaluation of the zero-bias SAC method, we built a rotor AMB experiment system of which the ratio of the moment of inertia I_z/I_r is almost 1. Zero-bias SAC was introduced to control the attitude/position of rotor and compensate gyro effect. It is difficult to control since the second rigid mode (2R) forward natural vibration frequency grows parallel with the rotation frequency which means that 2R natural vibration will keep influencing the rotor during rotation. With conventional PID method, orbits of rotor became unstable when rotation frequency increased to about 100Hz. In comparison, with SAC method we rotated up to 225Hz perform without any gyro effect and the orbits of rotor were considerably stable.

Keywords : Zero bias, Simple adaptive control, Active magnetic bearings, Gyro effect, Forward natural vibration

1. Introduction

For AMB system, the magnetic force for levitating the rotor has strong nonlinearity. It is common to linearize the non-linearity by supplying bias current on the electromagnet additionally, which however, may increase power consumption and eddy current losses. We proposed a zero-bias control method without using permanent magnet and verified its power-saving potential[1][2][3]. To stabilize disturbance, we introduced simple adaptive control (SAC[4]) to our zero-bias system and achieved good performance on flywheel AMB system mounted on a electric vehicle [5]. In this study, for further evaluation of the zero-bias SAC method, we built a rotor AMB experiment system of which the ratio of the moment of inertia I_z/I_r is almost 1. It is much more difficult to control because of the severe variation of forward/backward natural vibration frequency due to gyro effect. The experimental result will be reported in the paper.

2. Rotor AMB Experiment System

The rotor AMB experiment system consists of rotor AMB and AMB controller. Fig. 1 shows the system block diagram and Fig.2(a) shows the cross sectional view of the rotor AMB system. We utilized an arbor design for supporting axial load and transiting rotational torque so axial AMB and motor were eliminated and only radial AMBs were left. Consequently, the rotor shaft become shorter, and the ratio of the moment of inertia I_z/I_r become almost 1. It is believed that rotors with $I_z/I_r \approx 1$ is difficult to control since the second rigid mode(2R) forward natural vibration frequency grows parallel with the rotation frequency as showed in Fig.2(b), which means that 2R natural vibration will keep influencing the rotor during rotation.

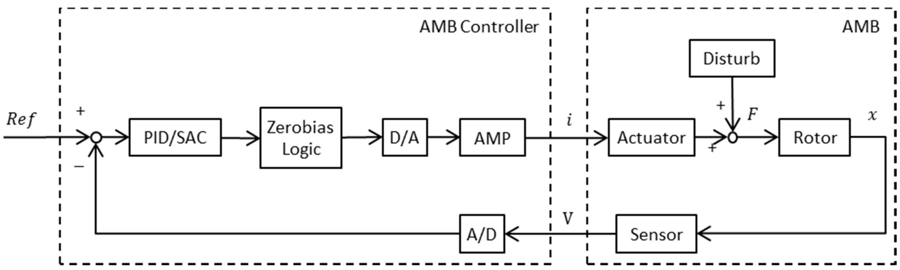
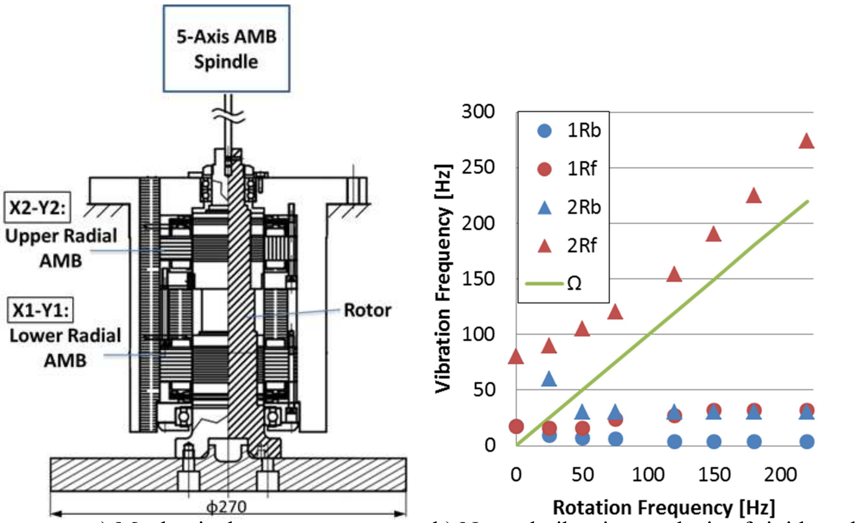


Fig. 1 Block diagram of zero-bias AMB system



a) Mechanical structure b) Natural vibration analysis of rigid mode

Fig.2 Rotor AMB experiment system

Table 1 Rotor AMB system details.

Parameter	Value
Mass of Rotor shaft	3.64 [kg]
Mass of Rotor disk	11.59 [kg]
Moment of ineria about z axis (I_z)	0.111 [kgm^2]
Moment of ineria about $x\&y$ axis (I_r)	0.105 [kgm^2]
Radial touchdown gap	100 [μm]
Bias current	0 [A]

3. Zero-bias SAC

3.1 SAC algorithm

SAC using output feedback is a simple yet robust adaptive control algorithm. A controllable and observable plant model with order n_p is described as:

$$\dot{x}_p(t) = A_p x_p(t) + B_p u_p(t)$$

$$y_p(t) = C_p x_p(t) \tag{1}$$

where x_p is the n_pth-order plant state vector, u_p is the system input vector, y_p is the system output vector. We consider this plant satisfy the Almost Strictly Positive Real (ASPR) condition and describe a reference model as:

$$\dot{x}_m(t) = A_m x_m(t) + B_m u_m(t)$$

$$y_m(t) = C_m x_m(t) \tag{2}$$

For SAC, based on the ASPR condition, even the actual parameter $\mathrm{A_p}, \mathrm{B_p}$ and $\mathrm{C_p}$ of the plant model are unknown, the system input $\mathrm{u_p}(\mathrm{t})$ can be adjusted to make the plant model output $\mathrm{y_p}(\mathrm{t})$ track the reference model output $\mathrm{y_m}(\mathrm{t})$ asymptotically. Let the tracking error $\mathrm{e_y}(\mathrm{t}) = \mathrm{y_p}(\mathrm{t}) - \mathrm{y_m}(\mathrm{t})$, the SAC controller can be designed as follow:

$$u_p(t) = K(t)z(t) \tag{3}$$

$$z(t) = [e_y(t)^T,\ x_m(t)^T,\ u_m(t)^T]^T \tag{4}$$

$$K(t) = [K_e(t), K_x(t), K_u(t)] \tag{5}$$

Further, the gain parameter vector $\mathrm{K}(\mathrm{t})$ is automatically tuned by the following PI adaptive laws:

$$K(t) = K_P(t) + K_I(t) \tag{6}$$

$$K_P(t) = -e_y(t)z(t)^T \Gamma_P \tag{7}$$

$$\dot{K}_I(t) = -e_y(t)z(t)^T \Gamma_I - \sigma K_I(t), \quad \sigma > 0 \tag{8}$$

where Γ_P *and* Γ_I are positive-definite symmetric adjusting gain matrices.

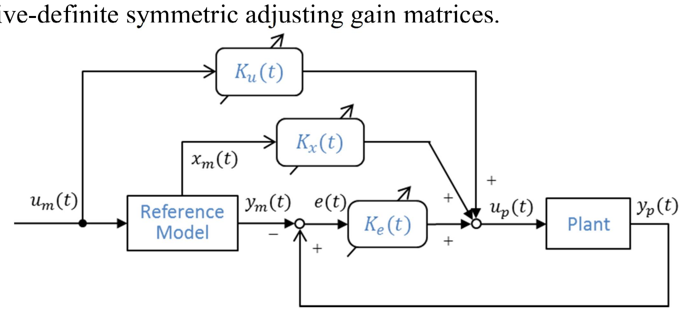


Fig.3 Block diagram of SAC scheme

3.2 SAC for Zero-bias AMB

We introduced SAC to our zero-bias AMB to stabilize rotor attitude, as shown in Fig.4. For zero-bias AMB, controller work near zero point which means the control input u(t) become zero when the plant output y(t) is near the target position 0um. As a result, there is no need to tune the gain parameter for target output and state output of the reference model, so here reference model is not necessary. For a quicker response and stronger adaptability and robustness, we chose the PID adaptive law. SAC controller for zero-bias AMB can be designed as follows.

$$u_p(t) = K(t)z(t) \tag{9}$$

$$z(t) = e_y(t) \tag{10}$$

$$K(t) = K_e(t) = K_P(t) + K_I(t) + K_D(t) \tag{11}$$

$$K_P(t) = -e_y(t)z(t)^T \Gamma_P \tag{12}$$

$$\dot{K}_I(t) = -e_y(t)z(t)^T \Gamma_I - \sigma_I(t)K_I(t) \tag{13}$$

$$K_D(t) = -\dot{e_y}(t)z(t)^T \Gamma_D \tag{14}$$

$$\sigma_I(t) = \sigma_1 \frac{e_y(t)^T e_y(t)}{1+e_y(t)^T e_y(t)} + \sigma_2, \quad \sigma_1, \sigma_2 > 0$$

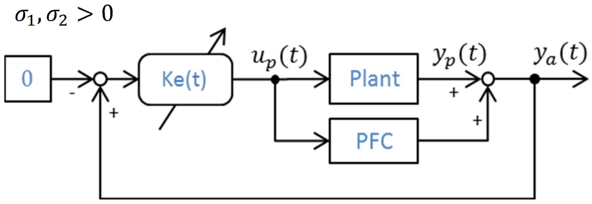
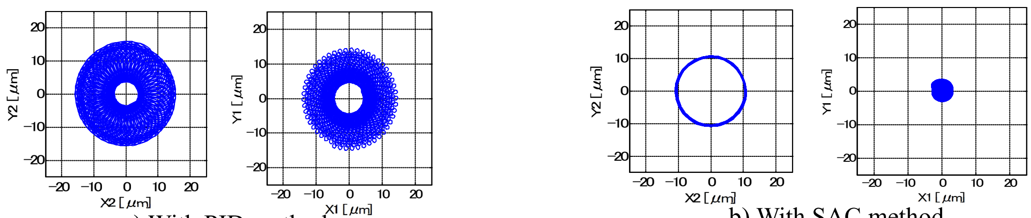


Fig. 4 Block diagram of SAC scheme for zero-bias AMBs. We add a Parallel Feedforward Configuration (PFC) and then construct an augmented plant model to satisfy the ASPR condition. Thus, the feed-back gain $K_e(t)$ is guaranteed to be adaptively adjusted to achieve $\lim_{t\to\infty} e_y(t) = 0$.

4.Simulation and Experiment

Fig. 5 shows the simulation results at 200Hz(12,000rpm). Orbits of the rotor controlled by SAC method and PID method are showed respectively.

We could see orbits of rotor are unstable in PID method, which suggest that with constant feedback gain, the stability of the system get worse when dynamics of the plant model change due to the gryo effect during rotation. In comparison, SAC method adjust the feedback gain $K_e(t)$ adaptively to suppress the gyro effect, so orbits of rotor are comparatively stable.



a) With PID method b) With SAC method

Fig.5 Simulation result of orbits of rotor at speed of 200Hz

We also performed rotational tests for evaluation. Orbits of rotor controlled by PID method, showed in Fig. 6, became unstable after speeding up to 100Hz (6,000rpm), which show the same tendency comparing to the result of simulation described above.

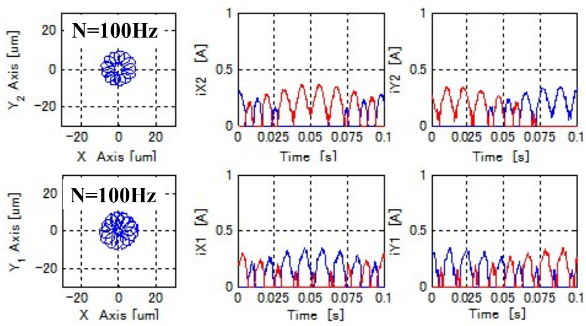


Fig.6 Experiment result with PID controller at speed of 100Hz

Fig. 7 shows orbits of rotor controlled by SAC method at the speed of 100Hz (6,000rpm), 150Hz (9,000rpm), 200Hz (12,000rpm) and 225Hz (13,500rpm). It appeared during speeding up process, even the 2R forward natural vibration frequency grows parallel with the rotation frequency, the rotor rotated up to 225Hz without any gyro effect and the orbits are considerably stable. The average value of the total control current supplied to the radial AMBs was lower than 0.8A. It is suggested that zero-bias SAC adaptively adjust the feedback gain $K_e(t)$ to compensate gyro effect and control the 2R forward natural with least power.

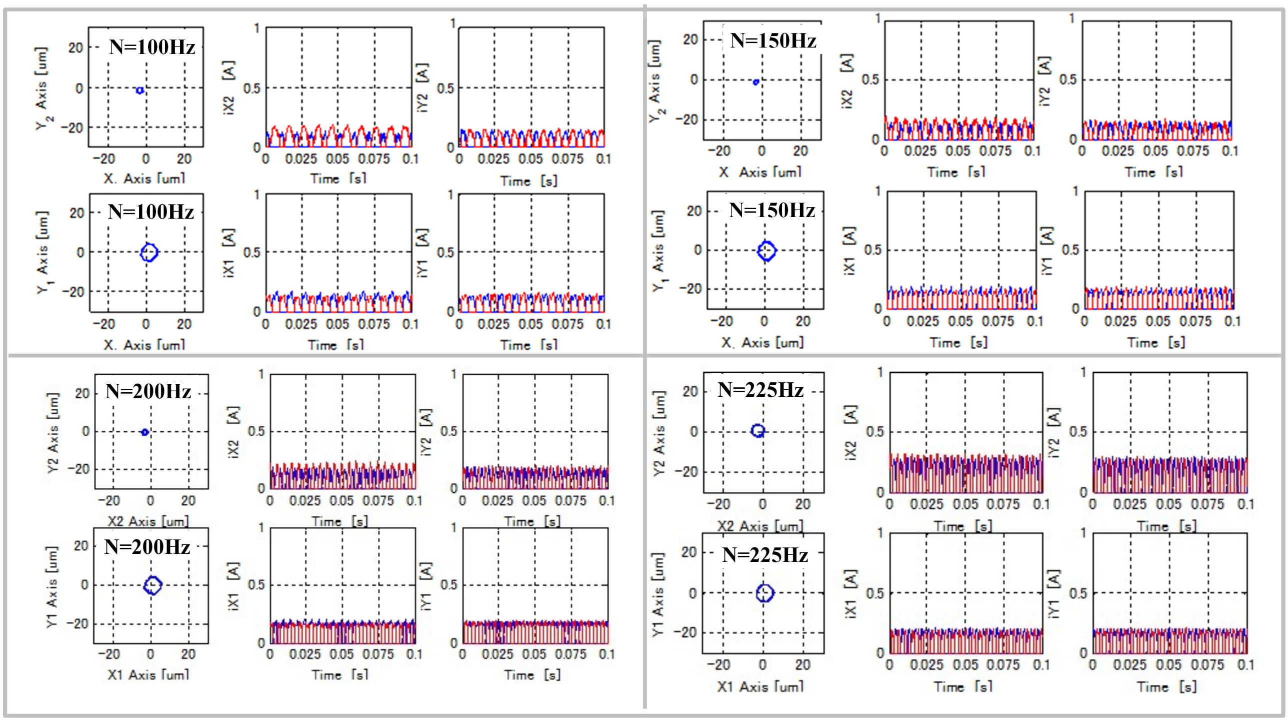


Fig.7 Experiment result with SAC controller at speed of 100Hz~225Hz

5. Conclusion

For further evaluation of Zero-bias SAC, we designed and built a rotor AMB experiment system of which the ratio of the moment of inertia I_z/I_r is almost 1. Zero-bias SAC was introduced to control the attitude/position of rotor and compensate gyro effect. According to the experimental results, the rotor rotated up to 225Hz without any gyro effect and the rotations was considerably stable. It can be concluded that with zero-bias SAC control scheme, gyro effect and the 2R forward natural vibration were adaptively controlled with low power consumption. We will perform rotation test up to 300Hz for future research.

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