A Method of Simple Adaptive Control for MIMO Nonlinear AMB-flywheel Levitation System

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Abstract—**In this paper, AMB-flywheel is desirable to minimize the energy required for its stabilization control. We propose a design method for performing SAC control for a MIMO AMB-flywheel system with five degrees of freedom; The SAC controller was proposed for application to an AMB-flywheel system and control performance was improved by combining SAC with PID controller. The PID based SAC controller is evaluated via experiments. We present the analysis results of the influence of external disturbances from the EV driving on the road and high-speed rotation experimental results about the AMB-flywheel system. The results demonstrate that the SAC controller is feasible and effective.**

I. INTRODUCTION

In recent years, energy consumption certainly increases year by year, but the fossil fuels, such as petroleum, coal and natural gas, is limited, and will dry up in the future. The renewable natural energy resources (Wind, solar, wave, and geothermal energies) are considered replaces the major role of fossil energy. In this new energy field, the current energy storage system is used chemical batteries, which are still not fully satisfying the requirement. The flywheel energy storage system to store electricity is one solution for energy optimal utilization[1], [2].

Most of studies about active magnetic bearing flywheel energy storage system is fixed on the ground, as used in wind-power plant or UPS systems; we developed electrical vehicle with AMB-flywheel as shown in Fig 1. In this paper, we are focusing on the use of AMB-flywheel energy storage system on electric vehicle. An AMB-flywheel system is a replacement of conventional chemical battery for electric vehicle.

II. MODELING OF AMB-FLYWHEEL

Accurate mathematical description of the physical system is the important part of effective controller design. Building a mathematical mode of the system to represent the actual physical system can be used to verify the performance of system through digital simulation work. It is also providing a structural form for new control algorithms[3]. Stable operation of flywheel, which consists of active magnetic bearings, is achieved through appropriate magnetic forces generated by the magnetic bearing actuator. The physical properties of the active magnetic bearing have been presented in Table I This AMB-flywheel was designed as a vertical structure. In this research, it will be installed on the electrical vehicle (EV) as the vertical direction, so we should defined z-axis as the gravity direction in the modeling of it in Fig 2.

Figure 1. Overview of over of AMB-flywheel powered EV

As covered in last section, the linearization model could provide satisfactory system response at approximately close to the linearized region, but nonlinear control techniques developed based on nonlinear AMB model can be achieved at wider range of system operations. Let us consider the rotor of the AMB system as a rigid rotor. The fundamental equations of motion of a rigid rotor-active magnetic bearing system in horizontal direction is derived as (1)

$$\begin{cases} m\ddot{x} = F_x + m\delta\omega^2\cos(\omega t) \\ I_r\ddot{\theta_y} - I_z\omega\dot{\theta_x} = N_y + ml_c\delta\omega^2\cos(\omega t) \\ m\ddot{y} = F_y + m\delta\omega^2\sin(\omega t) \\ I_r\ddot{\theta_x} + I_z\omega\dot{\theta_y} = N_x + ml_c\delta\omega^2\sin(\omega t) \end{cases} \quad (1)$$

Where x and y denote the linear displacement of the rotors

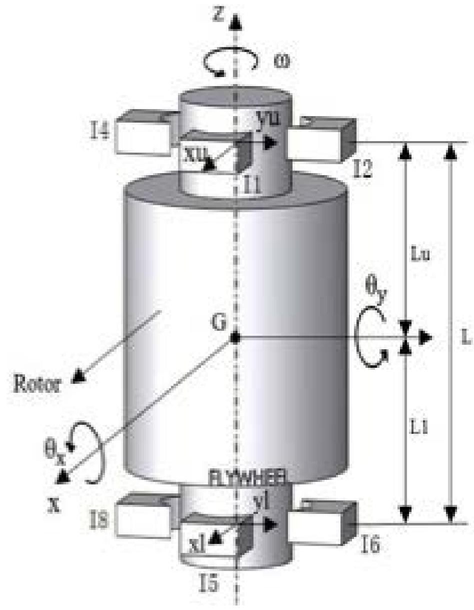

Figure 2. Overview of over of AMB-flywheel powered EV

Table I
PARAMETERS OF THE AMB-FLYWHEEL

Item	Value	Unit
m	Rotor mass	$100\,\mathrm{kg}$
I_z	Polar moment of interia	$1.114\,\mathrm{kg.m}^2$
I_r	Other moment of interia	$2.610\,\mathrm{kg.m}^2$
L_u	Distance of upper AMB from center of gravity	$1.815e-4\,\mathrm{m}$
L_l	Distance of lower AMB from center of gravity	$3.086e-4\,\mathrm{m}$
X_0	Nominal air gap in radial direction	$0.5e-3\,\mathrm{m}$
Z_u	Nominal air gap in axial direction	$0.4e-3\,\mathrm{m}$
I	Allowable current	$6\,\mathrm{A}$

center of mass along the x and y axes, respectively. Similarly, θ_y and θ_x denote the angular displacements of the rotor around the x and y axes, respectively. F_x and F_y denote the electromagnetic forces acting on the bearing in the x and y directions, respectively. ω denotes the flywheel rotation speed; δ , the eccentricity; m , the mass of the rotor; I_z , the moment of inertia about the z axis; and I_r , the moment of inertia about the x and y axes. N_x and N_y denote the moment of force about the x and y axes, respectively. F_x , F_y , N_x , and N_y can be expressed as(2)

$$\begin{cases} F_x = f_{xu} + f_{xl}, F_y = f_{yu} + f_{yl} \\ N_x = f_{yl}L_l - f_{yu}L_u, N_y = f_{xu}L_u - f_{xl}L_l \end{cases} \tag{2}$$

III. ANALYSIS AND DESIGN SAC FOR AMB-FLYWHEEL

The operating environment of the automotive is complex. The road conditions impacts the AMB-flywheel when vehicle is driving, such as different vibration, acceleration, deceleration, steering and so on. Therefore, it is necessary to design a strong stiffness active magnetic bearing controller for suitable the vehicle dynamic specific. There are two key techniques for development of AMB-flywheel powered Electric Vehicle (EV):
1. AMB stable suspension control under driving disturbances.
2. Reducing the energy consumption.

An electrical vehicle with a flywheel energy storage system using a five-degree-of-freedom magnetic bearing has been carrying out as shown in Fig 1. Simple adaptive control is a simple and robustness algortithm, which could be apply to AMB flywheel system[4], [5]. According to the work condition of controlled object AMB-flywheel powered EV, We apply a PID based simple adaptive control scheme designs combined with zero-bias control rule for the AMB-flywheel energy storage system.

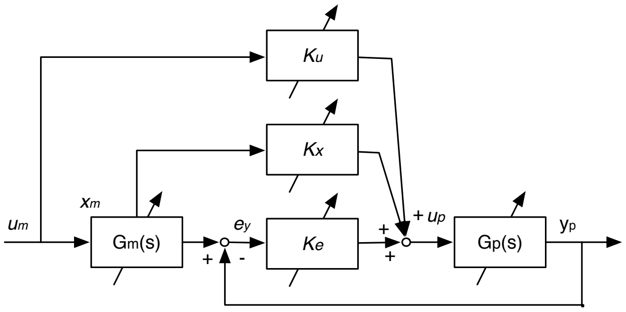

Figure 3. Block diagram of the SAC scheme

The SAC algorithm structure and overview of control object AMB-flywheel are shown as Fig.3. The system was simulated, and the final result shows the control method is feasible and effective. SAC is a simple yet robust algorithm for unmodeled dynamics [6]. In this algorithm, a plant model of order n_p is described as

$$\begin{cases} \dot{x}_p = A_p x_p(t) + B_p u(t) \\ y_p(t) = C_p x_p(t) \end{cases} \tag{3}$$

where $x_p(t)$ is the n_p th-order plant state vector, $u(t) \in R^{nj\times 1}$ is the system input vector,$y_p(t) \in R^{nj\times 1}$is the system output vector, and observable but unknown parameter plant model of order. The plant output $y_p(t)$ is required to asymptotically track the output of the following model, y_m.

$$\begin{cases} \dot{x}_m = A_m x_m(t) + B_m u_m(t) \\ y_m(t) = C_m x_m(t) \end{cases} \tag{4}$$

If we let tracking errore$_y(t) = y_m(t) - y_p(t)$, the SAC controller can be defined as

$$k(t) = k_I(t) + k_p(t) \tag{5}$$

$$\dot{k}_I(t) = \Gamma_I z(t) e_y(t) - \delta(t) k_I(t) \tag{6}$$

$$k_p(t) = \Gamma_p z(t) e_y(t) \tag{7}$$

$$\delta(t) = \frac{\delta_1 e_y(t)^2}{\delta_3 + e_y(t)^2} + \delta_2 \tag{8}$$

where δ_1, δ_2 and δ_3 are small positive constants and Γ_I and Γ_p are constant matrices. $\Gamma_I = \Gamma_I^T > 0$ and $\Gamma_p = \Gamma_p^T > 0$.

We need to tune parameters of Γ_I and Γ_p for SAC controller by ourselves in the simulation and the experiment for AMB-flywheel system.

In order to prove the stability of the closed-loop system, the controlled plant is required to be SPR or ASPR. The ASPR conditions are as follows:

A. The system plant is strictly proper or proper
B. $G_p(s)$ is the minimum-phase
C. $G_p(s)$ has the minimal realization A, B, C, where $CB > 0$.

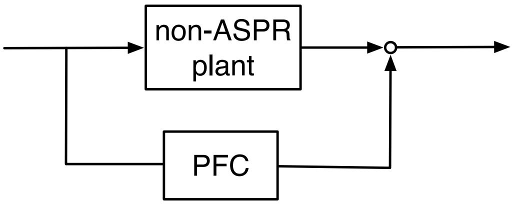

Figure 4. Parallel feedforward compensator for non-ASPR plant

However, since most practical systems do not satisfy the ASPR condition, the ASPR conditions are the fundamental restrictions for practical applications of the output-feedback-based adaptive control.A PFC should be developed to make the augmented system a minimum-phase system and ensure that it has a relative degree one.

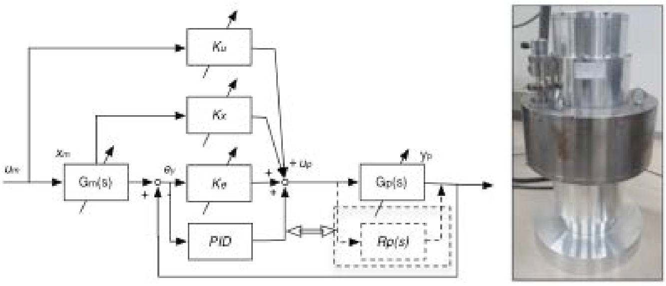

Figure 5. Block diagram of SAC-PID double controller

In this case, the design of a PFC for AMB-flywheel system consists of two steps. We first design the PID Controller that stabilizes the model of the AMB flywheel at the center position. Then inverse transfer function of the stabilizing PID controller is used for the PFC. The PFC renders the augmented system to be almost strictly positive real (ASPR)[7]. We have to design the PFC such that it renders the augmented system to be ASPR. The first step designs a PID controller for without SAC controller. This PID controller can stabilize the flywheel rotor at the operating point. Inverse transfer function of the obtained PID controller is used for the PFC in Fig 2. The air gap is very small between the rotor of flywheel and touchdown bearing, so AMB controller require high response speed and small overshoot. In SAC, auto-adjustment of the gain parameters is originally based on the PI adaptive. Here, for a quicker response, a PID rule is added. This PID-SAC combined with PID and SAC controller, which has advantages of quicker response and stronger adaptability and robustness characteristics for AMB-flywheel system. SAC with PID rule is shown in Fig 5, and the reference model is set as zero. In this double controller system, PID is defined as the PFC for AMB-flywheel plant. Hence, the SAC controller can be defined as achieve $\lim_{t\to\infty} e_y(t)$. Hence, the controller can be defined as

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

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

$$k(t) = k_I(t) + k_p(t) + k_{PID} \tag{11}$$

$$k_p(t) = \Gamma_p z(t) e_y(t) \tag{12}$$

$$\dot{k}_I(t) = \Gamma_I z(t) e_y - \sigma(t) k_I(t) \tag{13}$$

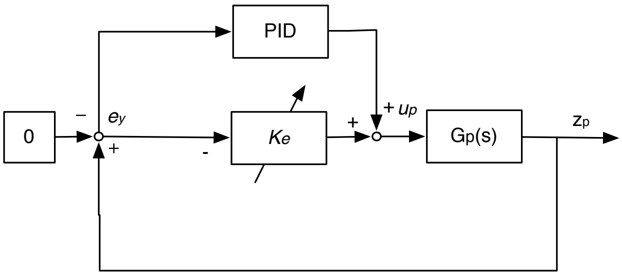

Figure 6. Simplified block diagram of SAC with PID

IV. ZERO-BIAS CURRENT MAGNETIC BEARING

Since the AMB-flywheel system is used as a storage device for electrical energy, it is desirable to minimize the energy required for its stabilization control. Zero-bias current magnetic bearings have the potential to reduce power losses because only a single electromagnet of the pair is operational at any time. The switching rule of zero-bias control is defined as

$$f = f_1 + f_2 \tag{14}$$

$$f = \begin{cases} f_1 & (f_2 = 0), \quad if x \geq 0 \\ f_2 & (f_1 = 0), \quad other \end{cases} \tag{15}$$

The SAC control input $U = (f_{xu}, f_{xl}, f_{yu}, f_{yl})$ is provided in the form of an attractive force between the electromagnets, but it should be converted into electric current.The zero-bias modes of other electromagnet pairs follow the same form.

V. EXPERIMENTAL RESULTS

Experiments were performed on the PID based SAC with the zero-bias modes. The orbit of 120Hz CFRP rotor flywheel rotation is shown in Fig.7. The displacement of charging and discharging experiment is shown as Fig.8 from 0Hz to 100Hz and 100Hz to 0Hz.

The control currents in the direction of the upper electromagnets during the rotation experiment are shown in Fig.5. As seen in the Fig.9, the maximum current is less than 1A, when the flywheel rotated from 0HZ to 100Hz.

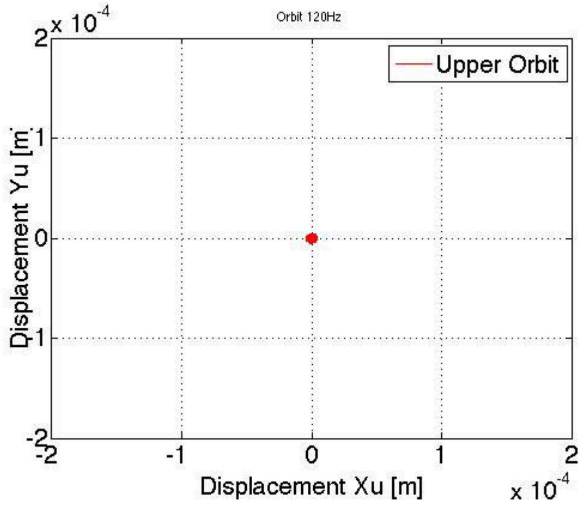

Figure 7. The orbit of 120Hz flywheel rotation

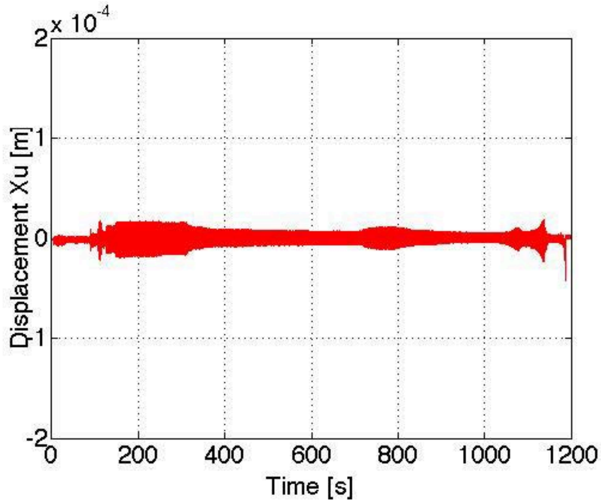

Figure 8. Displacement Xu from 0Hz-100Hz-0Hz rotations

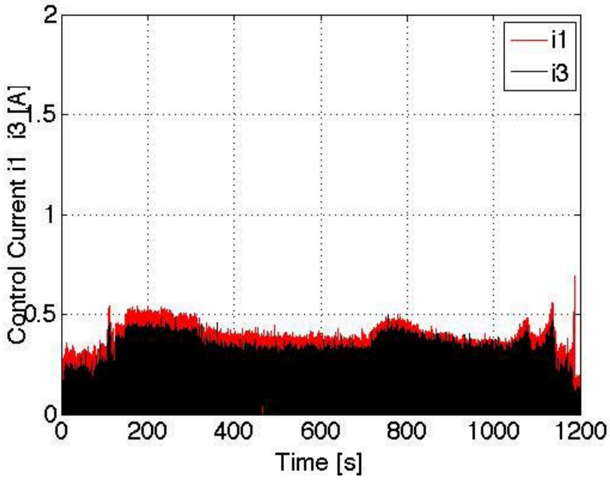

Figure 9. The orbit of 120Hz flywheel rotation

VI. CONCLUSION

This paper is concerned with the design of a simple adaptive control (SAC) technique and application into AMB-flywheel system, and effort provided an analysis of SAC with a focus on operating with minimal power, and showed that it worked. The results of the analysis of the simple adaptive zero bias control data has been presented. The analytical results were based on nonlinear model, and the experimental results indicate how a magnetic bearing operates using the SAC method. PFC cause the offset problem of levitating of flywheel rotor, it effects the rotation of flywheel rotor on radial direction offset. Then, we modified the basic SAC scheme with PID based SAC. The control performance was improved by combining SAC with PID controller. In the proposed approach, SAC was successfully applied to vertically design five-axis controlled AMB-flywheel systems. The experimental results were found to satisfy the requirements of the AMB-flywheel system. Low-loss operation is very important in AMB system applications, especially in high speed energy flywheel energy storage system. Since eddy current losses are propositional to the flux, zero-bias control scheme for AMB are advantageous for low-loss operation of AMBs. The zero-bias mode did not deteriorate the stability of the control system; further, energy consumption in this mode was low.

The AMB system that means low power and low loss without bias currents has been proposed using SAC design of nonlinear control theory with zero-bias current control for a AMB system. In this study, SAC controller was successfully applied to a vertical designed five-axis AMB-flywheel system. The high-speed rotation experimental results have presented in this shaft paper. Using PID based SAC controller can suspended the flywheel rotor rapidly and stably.

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