Benchmark and Verification of Control Algorithm for Flywheel with Active Magnetic Bearing on Electric Vehicle and Proposal of New SAC Algorithm (ε_1 modification and bias variable Γ_p approach)

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Abstract— **This paper presents the requirements which a good rotor controller of flywheel energy storage system (FESS) with Active Magnetic Bearing (AMB) on Electric Vehicle (EV) should satisfy. AMB-FESS is used for energy regeneration. The dynamics of the flywheel rotor on EV is very complex and to compare various features a benchmark is necessary. Controllers are evaluated according to certain criteria as used by many motor companies. Controllers are selected to satisfy the design requirements prescribed by many motor companies. Thus the robust adaptive controllers were chosen and benchmarked using simulations and experiments. The investigation revealed that a controller with high rigidity gain and a reference model can not only suppress disturbance effects but also lower power consumption. Therefore Simple Adaptive Control with epsilon1 modification and bias variable gamma P approach is proposed. The utility of the new controller experimentally was proven.**

Keywords— Flywheel Energy Storage System, Active Magnetic Bearing, Electric Vehicle, epsilon1 modification approach, bias variable gamma P approach

I. INTRODUCTION

Recently, it is becoming popular applying flywheel to vehicles for energy regeneration. Otaki and Kosuda had revealed that gyroscopic precession of flywheel does not affect the drivability and stability of the vehicle in theory and experiments. [1] Saito showed that Flywheel Energy Storage Systems (FESS) are superior to capacitor or Li-ion batteries when used for the regeneration systems and power sources. [2] Yokota reported that hybrid system which consists of hydraulic drive flywheel and gasoline engine is effective for decreasing fuel consumption. [3] Moreover, Jens has investigated the control method for flywheel and CVT. He revealed that the system can increase drivability and decrease power consumption. [4] In industry, flywheels are widely used. TOROTRAK, RICARDO, Optare and Allison Transmission developed flywheel bus. [5]

However, the research used mechanical bearing flywheels. Because of the friction heat, energy efficiency is low. Therefore we propose Active Magnetic Bearing (AMB) - FESS. Recent research has been focused on AMB-FESS mounted on vehicles. The University of Texas, Center for Electro Mechanics (UT-CEM) and Department of Defense has been developing an AMB-FESS combat vehicle. [6] However this system uses permanent magnets and needs big control inputs. Moreover, UT-CEM had developed a flywheel bus. [7], [8], [9], [10], [11] In this research, flywheel design, control design of magnetic bearing, design of gimbals for sustaining flywheel and its efficiency are described.

Though resent research or applications of AMB-FESS has been focused on large vehicles, very few research focused on AMB-FESS for consumer vehicles. It is more difficult to reduce power consumption, miniaturize and make flywheel robust. This system requires a high positioning accuracy. Therefore, it is necessary to compare and develop a good control algorithm for AMB-FESS on Electric Vehicle (EV). The Uppsala University has been focused on the control algorithm for the inverter/converter, analysis of the magnetic bearing, and design of the driveline [12], [13], [14], [15]. However, recent research hasn't been focused on the control algorithm for AMB flywheel rotor on EV.

The objective of this research is to compare several control methods and grasp the features which control algorithm is good for AMB-FESS on EV. We compare several methods by evaluating criteria as used in many motor companies (-difficulty of design, power consumption, and external disturbance suppression) and propose the best controller for AMB-FESS on EV. In this investigation, we focused on robust adaptive control algorithms and its features. The algorithms can tune gains and change controllers adaptively and continuously so designers can design controllers easily and improve their quality. Moreover, these methods are robust. Therefore they can compensate for variable external disturbance. Furthermore, they can lower power consumption because of adaptive gain tuning.

In this investigation, several robust adaptive control algorithms were benchmarked using simulations and experiments. Generalized Minimum Variance Control (GMVC) (One of the Self Tuning Regulators), Model Reference Adaptive Control (MRAC), and Simple Adaptive Control (SAC) are simulated and experimentally evaluated. These controllers use sigma-modification approach or epsilon 1 modification algorithm and/or bias variable gamma P approach. These algorithms were compared with Linear Quadratic Gaussian (LQG) algorithm and PID algorithm which are widely used in industry.

Thorough this research, we found the features which a good performance controller for AMB-FESS on EV should have. The feature is that the controller with high rigidity and a reference model, can suppress disturbance effects, lower power consumption and improve positioning accuracy. Therefore we improved the SAC algorithm and named it SAC with epsilon 1 modification and bias variable gamma P approach.

In this paper, we also examine the performance of a new SAC algorithm by simulation and experiment. We also showed that the new algorithm is the best robust adaptive controller for AMB-FESS on EV.

II. CONTROL SYSTEM DESIGN

A. Equations of Motion

To apply robust adaptive control algorithms, AMB-FESS on EV must be described by equations of motion. Our system satisfies the following 4 assumptions.

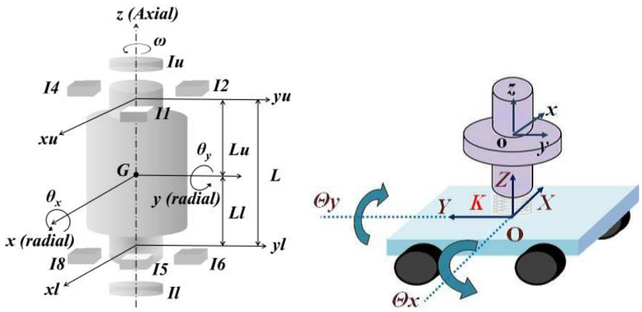
- Vehicle cannot move in yaw direction
- Flywheel rotor rotates at constant speed
- Flywheel is fixed in the center of gravity of the vehicle
- Flywheel rotor and vehicle move or incline slightly

Based on these assumptions, AMB-FESS on EV is described by the equations of motion. Coordinate system of AMB-FESS on EV is set as shown in Fig.Ⅱ. In Fig.Ⅱ (a), x_u, y_u, x_l and y_l are axes of upper and lower radial direction of flywheel. I_1 to I_8, I_u and I_l are the input currents to each electric magnet. G is the position of center of gravity. X and Y are axes of radial direction of EV. θ_x and θ_y are tilting angles of flywheel. L_u and L_l are the distances between center of gravity and x_u-y_u/x_l-y_l plane. L is the distance between x_u-y_u plane and x_l-y_l plane. ω is rotation speed. In Fig.Ⅱ (b), x-y-z and X-Y-Z are the coordinate axes of flywheel/ vehicle. Origin is located of the center of gravity. δ is the mass eccentricity, and l_c is the distance between the origin of the coordinate system and the geometric origin. Generally, l_c is unknown. Θ_x and Θ_y are tilting angles of EV. K is the spring constant of EV and the anti-vibration rubber. Details of the other parameters are as described in Table.Ⅱ.

Derivation of the equations of motion [16] is very complex, and its summary is described below. Models are described in moving coordinate system. Considering roll-pitch motion, our models derive from law of conservation of momentum and law of conservation of angular momentum. These models are shown as equation (1) and (2). Equation (1) is the model of the EV while equation (2) is the model of the flywheel. This model was calculated in respect to the center of gravity. The model can be transformed to sensor coordinates (X_u, Y_u, X_l, and Y_l) by using simple transforming matrixes.

(a) Flywheel (b) Fly-car

Figure Ⅰ. Overview of flywheel and Overview of fly-car



(a) Coordinate system of flywheel (b) Coordinate system of vehicle

Figure Ⅱ. Coordinate system

TABLE I. SPECIFICATION OF FLYWHEEL SYSTEM

Parameter	Value
Rotor mass	100 Kg
Flywheel diameter	0.4 m
Flywheel thickness	0.04 m
Polar moment of inertia	0.877 Kg・m^2
Tilting moment of inertia	2.438 Kg・m^2
Constant of radial AMB	25.196 N・mm^2/A^2
Constant of axial AMB	70.568 N・mm^2/A^2
Upper distance from center of gravity	0.186 m
Lower distance from center of gravity	0.304 m
Radial nominal air gap	0.5 mm
Axial upper nominal air gap	0.33 mm
Axial lower nominal air gap	0.6 mm
Radial nominal touch-down gap	0.2 mm
Axial nominal touch-down gap	0.4 mm
Allowable current	6 A

$$\begin{cases} I_{VX}\ddot{\Theta}_X = -N_x + N_X \\ I_{VY}\ddot{\Theta}_Y = -N_y + N_Y \\ M\left(\ddot{X} + \ddot{Y}\Theta_X - \ddot{Z}\Theta_Y\right) = -(F_x + mg\Theta_Y) + \\ \qquad \{F_X - (F_Z - \mathrm{Mg})\Theta_Y + K_X\mathrm{X} - K_Z\mathrm{Z}\Theta_Y\} \\ M\left(\ddot{Y} + \ddot{Z}\Theta_X\right) = -\left(F_y - mg\Theta_X\right) + \\ \qquad \{F_Y + (F_Z - \mathrm{Mg})\Theta_X + K_Y\mathrm{Y} - K_Z\mathrm{Z}\Theta_X\} \\ M\left(\ddot{Z} + \ddot{X}\Theta_Y - \ddot{Y}\Theta_X\right) = -(F_z - mg) + \{F_X\Theta_Y \\ \qquad -F_Y\Theta_X + (F_Z - \mathrm{Mg}) + K_X\mathrm{X}\Theta_X + K_Z\mathrm{Z}\} \end{cases} \tag{1}$$

$$\begin{cases} I_r(\ddot{\Theta}_X - \omega\dot{\Theta}_Y - \omega\dot{\theta}_y + \ddot{\theta}_x) + I_z\omega(\dot{\Theta}_Y + \dot{\theta}_y) \\ \qquad = N_x + ml_c\delta\omega^2 \sin\omega t \\ I_r(\ddot{\Theta}_Y + \omega\dot{\Theta}_X + \omega\dot{\theta}_x + \ddot{\theta}_y) - I_z\omega(\dot{\Theta}_X + \dot{\theta}_x) \\ \qquad = N_y + ml_c\delta\omega^2 \cos\omega t \\ m(\ddot{x} + \ddot{X}) = F_x - mg\Theta_Y - K_X X + K_Z Z\Theta_Y \\ \qquad + m\delta\omega^2 \cos\omega t \\ m(\ddot{y} + \ddot{Y}) = F_y + mg\Theta_X - K_Y Y - K_Z Z\Theta_X \\ \qquad + m\delta\omega^2 \sin\omega t \\ m(\ddot{z} + \ddot{Z}) = F_z - mg - K_X X\Theta_X - K_Z Z \end{cases} \quad (2)$$

TABLE II. PARAMETERS IN THE EQUATION OF MOTION

Parameter	vehicle	Flywheel
Mass	M	m
Moment of inertia	I_X, I_Y, I_Z	I_r, I_p
Center of gravity	X, Y, Z	x, y, z
Tiliting angle	Θ_X, Θ_Y	θ_x, θ_y
Disturbance force	F_X, F_Y, F_Z	
Disturbance moment	N_X, N_Y	
Control force		F_x, F_y, F_z
Control moment		N_x, N_y
Spring constant	K_X, K_Y, K_Z	

B. *Control algorithms*

Adaptive control method can be designed by using implicit or explicit methods. Considering difficulties of design, this research adopts implicit methods.

[Model Reference Adaptive Control System (MRACS)]

MRACS is one of model following control systems. MRACS defines control input as denoted by equation (3) [17].

$$u(t) = \theta(t)^T z(t) \quad (3)$$

Here, $z(t)$ is the data vector. This term consists of output of the reference model, output of the plant and input to the plant. $\theta(t)$ is the state value vector. This term is defined as follows.

$$\dot{\theta}(t) = -\Gamma(t)z(t)\varepsilon_1(t) \quad (4)$$

Here, $\Gamma(\Gamma = \Gamma^T > 0)$ is the weight matrix and $\varepsilon_1(t)$ is the augmented error.

[Simple Adaptive Control System (SACS)]

SACS is a simplified MRACS. SACS makes control input as in equation (5).

$$u(t) = K(t)z(t) \quad (5)$$

Here, $z(t)$ is same as in equation (3). $K(t)$ is the adaptive gain vector. This term is defined in equations (6) to (8). [18], [19]

$$K(t) = K_P(t) + K_I(t) \quad (6)$$

$$K_P(t) = -\Gamma_P(t)z(t)e(t) \quad (7)$$

$$\dot{K}_I(t) = -\Gamma_I(t)z(t)e(t) - \sigma_I K_I(t) \quad (8)$$

Here, weight matrix Γ_P, Γ_I and σ_I have the following properties - $\Gamma_P = {\Gamma_P}^T > 0, \Gamma_I = {\Gamma_I}^T > 0, \sigma_I > 0$. The term $e(t)$ is the residual tracking error. Equations (6) to (8) are proportion + integral adjustment rule. σ_I is sigma-modification approach. Details are described below.

[Generalized Minimum Variance Control System (GMVCS)]

GMVCS is the well known self tuning control system. GMVCS uses an evaluation function. The plant is described as follows.

$$A(z^{-1})y(t) = z^{-1}B(z^{-1})u(t) + C(z^{-1})w(t) \quad (9)$$

Here, $y(t)$ is the output of the plant, $u(t)$ is the input to the plant and $w(t)$ is white noise. A, B and C are some polynomials. Evaluation function is described in equation (10).

$$J = \bar{E}[\{P(z^{-1})y(t+\tau) + Q(z^{-1})u(t) - R(z^{-1})r(t)\}^2] \quad (10)$$

Here, $\bar{E}$ [ ] means expectation (spatial averaging). τ is a constant value. P, Q and R are polynomials and these terms satisfy equation (11) - Diophantine equation.

$$P(z^{-1})C(z^{-1}) = A(z^{-1})E(z^{-1}) + z^{-1}F(z^{-1}) \quad (11)$$

Here, E and F are polynomials. Control input: $u(t)$ is defined equation (12).

$$u(t) = {[C(z^{-1})R(z^{-1})r(t) - F(z^{-1})y(t) + G(z^{-1})u(t)]} / {[b_0 + q_0]} \quad (12)$$

Here, b_0 and q_0 is the first term of B or Q, respectively, and $G(z^{-1})$ satisfy equation (13).

$$G(z^{-1}) = E(z^{-1})B(z^{-1}) + C(z^{-1})Q(z^{-1}) - (b_0 + q_0) \quad (13)$$

[Sigma-Modification Approach]

Sigma-Modification Approach is often used in SACS algorithms. This approach increases robustness of adaptive control [20], [21], [22]. However, this method can't decrease residual tracking error. Our group defines σ as follows.

$$\sigma(t) = \sigma_1 + {\sigma_2 e(t)^2} / {[\sigma_3 + e(t)^2]} \quad (14)$$

Here, σ_1 to σ_3 are tuning parameters.

[Epsilon1 Modification Approach]

The epsilon1 Modification Approach uses equation (14) instead of equation (15). [23] Using this approach the reference value can be reached.

$$\sigma(t) = \gamma_I \|\varepsilon_1(t)\| \quad (15)$$

Here, $\gamma(\gamma_I = {\gamma_I}^T > 0)$ is the weight matrix. This approach and sigma-modification approach can be applied to MRACS, SACS and GMVCS.

[Bias Variable gamma P Approach]

If SACS with epsilon1 modification approach is used, residual tracking error goes to zero, but at the same time, it loses its rigidity. From equation (7), it is obvious that rigidity gain goes to zero when residual tracking error goes to zero. If AMB-FESS doesn't have rigidity, it cannot suppress external disturbance. Therefore, Bias Variable gamma P approach is proposed to avoid this problem.

In this research, Γ_P (in equation (7)) is defined as

$$\Gamma_P = c_1 + \frac{c_2}{\delta + z(t)e(t)} \tag{16}$$

This is the bias variable gamma P method. c_1 and c_2 are constant values. δ is a very small constant value. δ is introduced to prevent division by zero and smoothing of the gain changing. Using equation (16), if residual tracking error goes to zero, the system keeps its rigidity. The method described above revealed to be very useful for the system which needs high rigidity gains.

III. BENCHMARK

In this investigation, at first, several control algorithms designed for axial direction are benchmarked in simulations. The model of axial direction is very simple. Moreover, the axial direction controller and the radial direction controllers should have same structures to make the design process easier.

Therefore, we simulated and compared controllers using the axial direction model. We selected controllers that gave good simulation results and then investigated their efficiency experimentally.

We compared control algorithms based on 3 criteria common in industry – external disturbance suppression, power consumption, and difficulty of design [24].

External disturbance suppression is evaluated by 2 norm the displacement and infinity norm the displacement. The 2-norm of displacement evaluates controller's robustness against external impulse disturbances. Infinity norm the displacement evaluates a controller's robustness against persistent external disturbances. Power consumption is evaluated by the power consumption evaluation function denoted as follows.

$$J_P \overset{\text{def}}{=} \frac{1}{\tau}\int_0^{\tau} I(t)^2 \, d\tau \tag{17}$$

"I" is the control currents and τ is driving time. Because AMB has magnetic flux leakage, it is impossible to know the real resistance value. However, currents are measured by sensors. Therefore the criterion is introduced. Difficulty of design is evaluated by the number of tuning parameters.

A. Similation

Simulation model considers white noise and disturbances measured in a driving experiment. The maximum disturbance in axial direction is almost 1[G]. The MRACS's reference model is a 2nd order system. The damping ratio is 0.8 and the setting time is 0.2 second. The SACS'S reference model is the 1st order system and the other terms are the same as MRACS. Moreover, all algorithms use the bias control method. Results are shown in Table.Ⅲ.

Accordingly to Table. Ⅲ, MRACS with epsilon1 modification and bias variable gamma P approach is the best controller in respect to 2norm, infinity norm, and power consumption.

TABLE III. CONTROLLER EVALUATION

Controller	2norm	∞ norm	P.C.E.V.	N. T.P.
MRACS + ε +Γ	7.8×10^{-5}	4.4×10^{-6}	0.89	22
SACS + σ	9.3×10^{-4}	2.7×10^{-5}	1.83	8
SACS + ε +Γ	3.7×10^{-4}	1.4×10^{-5}	1.02	8
GMVCS	Failed to Stabilize			10
LQG	7.1×10^{-3}	3.2×10^{-4}	2.07	8
PID	1.3×10^{-3}	2.2×10^{-5}	1.85	3

*$\varepsilon+\Gamma$: epsilon1 modification and bias variable gamma P approach
*σ: sigma modification approach
*P.C.E.V.: Power Consumption Evaluation Value
*N.T.P.: the Number of Tuning Parameters

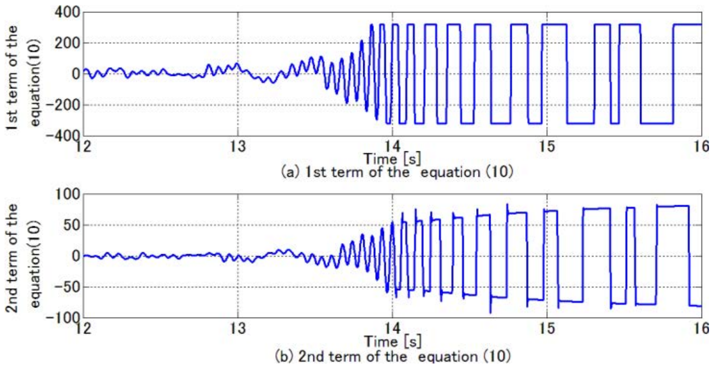


Figure Ⅲ. Each term value of equation (10)

However, the controller is not good in terms of difficulty of design. If MRACS is mounted on radial direction controllers, the designer has to tune (at least) 88 parameters. As a whole, SACS with epsilon1 modification and bias variable gamma P approach is a good performance controller.

Additionally, SACS with epsilon1 modification and bias variable gamma P approach is better than SACS with sigma modification approach. Sigma modification cannot decrease a residual tracking error. Therefore, the controller needs much power consumption. Moreover, the norm values are higher than SACS with epsilon1 modification and bias variable gamma P approach

GMVCS cannot suppress disturbances. Fig.Ⅲ shows each term value in the equation (10). Because reference value is zero, the third term of the equation (10) is omitted. According to the equation (10) and/or Fig.Ⅲ, the controller provides appropriate input after flywheel moves extremely. Therefore, GMVCS cannot suppress disturbances. Moreover, the PID controller is superior to the LQG controller for the same as GMVCS.

On the other hand, MARCS and SACS controllers can suppress impulse/persistent external disturbance compared with the other controllers. These controllers have the reference models. Controllers force the flywheel to follow the reference model if flywheel moves extremely. Therefore these controllers are robust against large disturbances.

Furthermore, the performances of SACS with sigma modification approach are similar to PID controllers. This result proves that the performance of epsilon1 modification and bias variable gamma P approach is superior to sigma modification approach.

TABLE IV. CONTROLLER EVALUATION

Controller	2norm/ M.D. [G]	∞ norm/ M.D. [G]	P.C.E.V. / A.D. [G]	N.T.P.
SACS +ε +Γ	5.1 × 10^{-4}	2.6 × 10^{-5}	0.71	8
LQG	6.4 × 10^{-3}	2.6 × 10^{-4}	2.23	8
PID	9.1 × 10^{-4}	1.3 × 10^{-4}	1.18	3

*M.D.: maximum disturbance
*A.D.: average disturbance
*$\varepsilon+\Gamma$: epsilon1 modification and variable gamma P approach
*P.C.E.V.: Power Consumption Evaluation Value
*N.T.P.: the Number of Tuning Parameters

In this investigation, we also simulated the adaptive controllers without the robust structures or zero bias controllers. However these controllers couldn't suppress disturbances and white noise. We conclude that adaptive controllers need robust structures.

As a matter of course, these results depend on gain tuning. However it can be said with high possibility that the number of tuning parameters and the features which good performance controllers have doesn't change.

B. Experiments

According to simulation results, SACS with epsilon1 modification and bias variable gamma P approach is a good performance controller for AMB-FESS on EV. To verify its performance, we compared it with LQG controller and PID controller by a driving experiment.

These controllers were compared while the flywheel rotor rotated at 100 Hz. The model of AMB-FESS (equation (1) and (2)) doesn't have coupled terms between axial and radial direction. However, the real plant has coupled affects. Therefore, performance of axial direction controllers must be investigated while the flywheel rotor rotates.

Experiment results are shown in Table.Ⅳ and Fig. Ⅳ to Fig. Ⅶ. According to Table.Ⅳ, 2 norm and infinity norm of the displacement are divided by the maximum disturbance. Moreover, the power consumption evaluation value is divided by the average disturbance.

The disturbance values are different from each experiment. Therefore, these criteria must be evaluated by the same condition.

According to Table. Ⅳ, the features of the controller's performances are similar to TableⅢ. SACS with epsilon1 modification and bias variable gamma P approach is good performance controller for AMB-FESS on EV in respects to external disturbance suppression and power consumption.

Fig.Ⅳ to Fig.Ⅵ show the each experiment data. According to these data, SACS with epsilon1 modification and bias variable gamma P approach received the largest disturbance (almost 2.5[G]). This controller can suppress external disturbance, in contrast to the LQG and PID controllers which cannot. The flywheel was almost touched-down.

Fig.Ⅶ shows the disturbance and gains of SACS with epsilon1 modification and bias variable gamma P approach

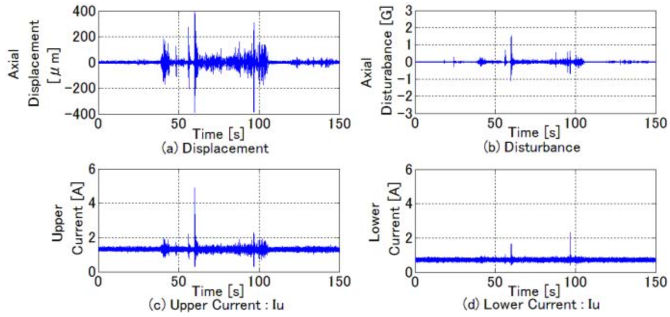


Figure Ⅳ. Displacement, disturbance and input current (LQG)

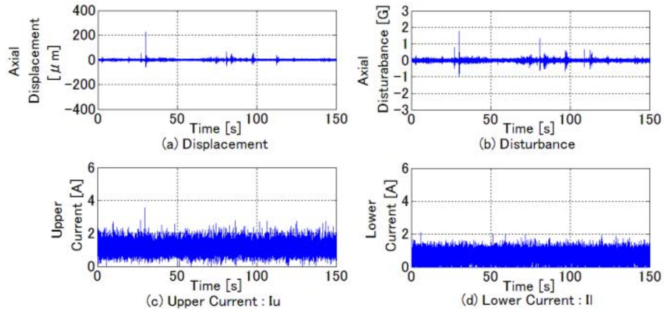


Figure Ⅴ. Displacement, disturbance and input current (PID)

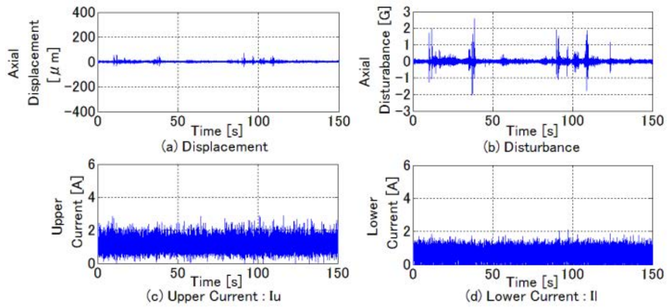


Figure Ⅳ. Displacement, disturbance and input current (SACS)

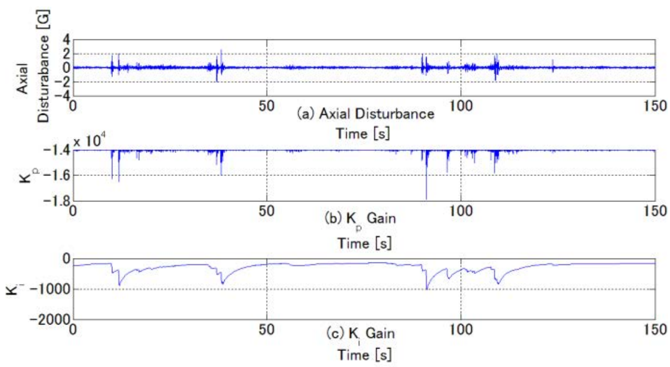


Figure Ⅶ. Disturbance and Kp, Ki gain (SACS)

during experiment. When the flywheel rotor vibrates on a large scale, K_p gain increases instantly. A few sampling steps after that, K_i gain increases to follow the reference value. Therefore the controller can suppress external disturbance well.

IV. CONCLUSIONS

In this investigation, several robust adaptive controllers for AMB-FESS on EV were benchmarked. We compared the controllers by 3 criteria – external disturbance suppression, power consumption, and difficulty of design. External disturbance suppression is evaluated by 2 norm and infinity norm of the displacement. Power consumption is evaluated by input currents. Difficulty of design is evaluated by the number of tuning parameters.

Through this investigation, it is clarified that good performance controllers for AMB-FESS on EV have following 7 features.

Good performance controllers …

- don't evaluate control inputs
- tune gains adaptively
- have a robust structures
- have a reference model.
- have the structure which decrease a residual tracking error
- doesn't have zero rigidity gain at the same time reference values are reached
- have appropriate bias rigidity gains

As a matter of course, the results depend on gain tuning. However, it can be said with high probability that the features which good performance controllers have don't change.

Moreover, in this investigation, we proposed Simple Adaptive Control System with epsilon1 modification and bias variable gamma P approach. This controller is easy to design and shows good performance.

Hereafter, Simple Adaptive Control System with epsilon1 modification and bias variable gamma P approach will be mounted to radial direction's controllers. Moreover, the features which are found in this investigation are evaluated quantitatively. Furthermore, our group will make energy regeneration structure and investigate the utility of AMB-FESS EV.

REFERENCES

[1] H. Otaki, M.Kosuda, 'Some Analysys and Development of Flywheel Powered Vehicle', *JSME Transactions*, Series C, Vol 46, No. 411, pp.1375, 1980

[2] T.Saito, H.Ogasawara, N. Yamada, 'Study of Flywheel Energy Storage System and Application to Electric Vehicle', *JSME Transactions*, Series B, Vol 70, No. 697, pp.2482-2489, 2004

[3] S.Yokota, 'A Flywheel Hybrid Vehicle Making Use of Constant Pressure System : Fabrication of Stationary Test Facility and Experiment of Urban Driving Schedule', *JSME Transactions*, Series C, Vol 68, No. 671, pp.2127-2132, 2002

[4] Jens Schlurmann and Dierk Schroder, 'Compensation of Dynamic Torques and Flywheel Start in a CVT Based Hybrid Powertrain', *Proceeding of the 2006 IEEE International Conference on Control Application*, FrA06.4

[5] TOROTRAK plc. (online), available from < http://www.torotrak.com/>, (accessed on 10th June, 2014)

[6] M.A.Pichot, J.P.Kajs, B.R.Murphy, A.Ouroua, B.M.Rech, R.J.Hayes, J.H.Beno, G.D.Buckner, and A.B.Palazzolo, "Active Magnetic Bearing for Energy Storage System for Combat Vehicles", *IEEE Transactions on magnetics*, Vol 37, No.1, pp.318- 323,2001

[7] B.T.Murphy, D.A.Bresie, H.H.Beno, "BEARING LOADS IN A VEHICULAR FLYWHEEL BATTERY", *SAE Technical Paper* 970213, 1997

[8] Lawrence A.Hawkins, Brian T.Murphy, "APPLICATION OF PERMANENT MAGNET BIAS MAGNETIC BEARINGS TO AN ENERGY FLYWHEEL", *Fifth Symposium on Magnetic Suspension Technology* 1999

[9] Lawrence A.Hawkins, Brian T.Murphy, John Kajs, "ANALYSYS AND TESTING OF A MAGNETIC BEARING ENERGY STORAGE FLYWHEEL WITH GAIN-SCHEDULED MIMO CONTROL", *Proceedings of ASME TURBOEXPO 2000, Munich, Germany*, ASME 2000-GT-405, 2000

[10] Lawrence HAWKINS, Brian MUROHY, Joseph ZIERER, Richard HAYES, "Shock and Vibration Testing of an AMB Supported Energy Storage Flywheel", *JSME international journal* Series *C*, Vol.46, No.2 pp.429-435, 2003

[11] R.J.Hayes, J.P.Kajs, R.C.Thompson, "J.H.Beno, Design and Testing of a Flywheel Battery for a Transit Bus", *SAE Technical Paper* 1990-01-1159, 1999

[12] Johan Abrahamsson, Magnus Hedlund, Tobias Kamf, Hans Bernhoff, "High-Speed Kinetic Energy Buffer: Optimization of Composite Shell and Magnetic Bearings", *IEEE Transaction,* Vol.61, No.6 pp.3012-3021, 2014

[13] Johan Abrahamsson, Janaina Goncalves de Oliveira, Juan de Santiago, Johan Lundin, Hans Bernhoff, "On the Effeciency of a Two-Power-Level Flywheel-Based All-Electric Driveline", *Energies,* ISSN 1996-1073, pp.2794-2817, 2012

[14] Janaina G. Oliveira, Hans Bernhoff, "Power electronics and control of two-voltage-level flywheel based all-electric driveline", *ISIE IEEE international symposium,* pp.1659-1665, 2011

[15] Janaina Goncalves de Oliveira, Hans Bernhoff, "Battery Recharging Issue for a Two-Power-Level Flywheel System", *Journal of Electric and Computer Engineering*, Vol. 2010, No.37, 2010

[16] Fumiya Shimizu, "Development of Simulator for AMB-Flywheel Energy Storage System", *JSME Transaction MOVIC2013*, B05, 2013

[17] R.V. Monopoli, 'Model Reference Adaptive Control with an Augmented Error Signal', *IEEE Transaction*, AC-19-5, pp.474-484, 1974

[18] J. Broussard and M.J. O'Brien, 'Feedforward Control to Track the Output of a Forced Model', *IEEE Transaction,* AC-25-4, 851-853, 1980

[19] H. Kaufman, I. Bar-Kana, K. Sobel, 'Direct Adaptive Control Algorithms', *Theory and Applications* ,2nd Ed., Springer-Verlag ,1998

[20] P.A.Ioannou and P.V.Kokotovic, "Robust Redesign of Adaptive Control", *IEEE Trans,* AC-29-3, pp.202-211, 1984

[21] I. Mizumoto, Z. Iwai, "Recent trend of SAC", *JSIE transaction*, Vol.40, No.10, pp.723-728, 2001

[22] P.A.Ioannou, 'Robust Adaptive Controller with Zero Residual Tracking Errors', *IEEE Transaction,* AC-31-8, pp.773-776 , 1986

[23] K.S.Narendra and A.M. Annaswamy, "Robust Adaptive Control in the Presence of Bounded Disturbance", *IEEE Trans*, AC-31-4, pp.306-315, 1986

[24] Yuji Yasui, Ikue Kawasumi, Kousuke Higashitani, 'The Adaptive Air-Fuel Ratio Control for High-Efficiency and Low-Emission Engines', *SICE Transaction on Industrial Application*, Vol.9 No.3 pp.11-16 , 2010