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ZERO POWER CONTROL OF 0.5KWh CLASS FLYWHEEL SYSTEM USING MAGNETIC BEARING WITH GYROSCOPIC EFFECT

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ABSTRACT

This paper proposes a new method how to construct the reduced-order model of rotor system with gyroscopic effect used for control system design of closed loop system. In order to demonstrate the validity of this method, the controlled model and zero power control of a 0.5KWh class flywheel system using magnetic bearing with gyroscopic effect are given in this paper. In this paper, the zero power control means not only the zero bias current but also the zero control current.

INTRODUCTION

It is very difficult to construct a reduced-order model for control system design of rotor system with gyroscopic effect because gyroscopic matrix is a symmetric matrix. So the reduced-order model of rotor system without gyroscopic effect is used to construct the controller and the controller used in closed loop system with gyroscopic effect is desired to get good control performance. But sometimes good control performance is not able to obtain for rotor system with strong gyroscopic effect. So, in this paper cholesky decomposition has been used to construct the reduced order model for control. In order to demonstrate the validity of this method, the controlled model and zero power control of a 0.5KWh class flywheel system using magnetic bearing with gyroscopic effect are given in this paper. In this paper, the zero power control means not only the zero bias current but also the zero control current. Only electromagnetic bearings are used in system and permanent magnetic bearing is not used. When the magnetic bearing is generating control input, the opposite magnetic bearing does not generate any control input. When the rotor keep it's equilibrium, the magnetic bearings do not use any energy or current at this time. The magnetic bearing system is different from a conventional magnetic bearing system[1].

In order to clarify the validity of this method, the controlled model by cholesky decomposition of a 0.5KWh class flywheel system using magnetic bearing is derived and the zero power control system is designed in this paper. Firstly, the one-dimensional FEM model and the reduced-order FEM model with gyroscopic effect of a 0.5KWh class flywheel system used for control are introduced. Secondly, the zero power controller and the low-pass filter are designed by using the reduced-order FEM model. Here, the low-pass filter is used to avoid spillover of higher order vibration modes. Thirdly, the validity of the controller and the low-pass filter are verified by simulation and experiment. From simulation and experiment, it seems the proposed method is useful for control system design taking into account a strong gyroscopic effect.

VIBRATION ANALYSIS

The 0.5KWh class flywheel system using magnetic bearing is shown in FIGURE 1. FIGURE 1(a) is flywheel rotor and FIGURE 1(b) is an overview of the test rig.

(a) (b)
FIGURE 1: Flywheel rotor
(a) Flywheel rotor (b) Overview of test rig

We carried out the vibration analysis of 0.5KWh class flywheel system by ANSYS which is a kind of CAE software based on finite element method. After constructing the three dimensional model of 0.5KWh class flywheel system with gyroscopic effect, the eigenvaule and eigenvector were computed by ANSYS. The detailed vibration analysis was done with gyroscopic effect. But the influences of AMB are ignored.

The relation between rotation speed and natural frequency with gyroscopic effect is given in FIGURE 2.

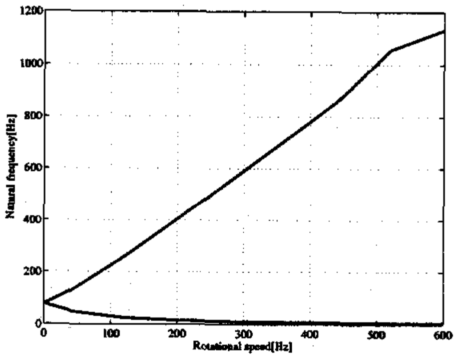

FIGURE.2: Relation between rotional speed and natural frequency

From the result of ANSYS, it is clarified there is the first flexible mode in the range of control(within 500Hz) with gyroscopic effect. The result is close to that of vibration analysis by MATLAB.

ONE DIMENSIONAL FEM MODEL WITH GYROSCOPIC EFFECT

There are two AMB in the system to control the system against a sudden disturbance and to pass it's critical speeds. In order to construct the model of system with the effects of AMB and flywheel, the system is divided into six parts. The one-dimensional FEM model is given in FIGURE 3.

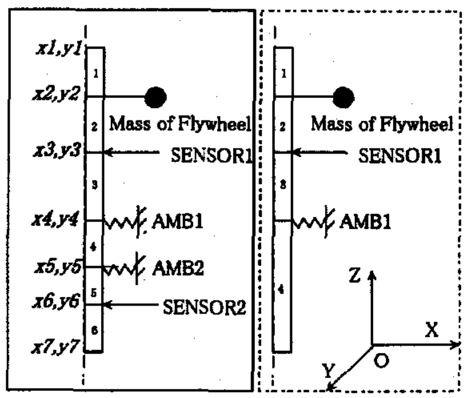

FIGURE.3: One dimensional finite element model(FEM)0cm

The positions of AMB1, AMB2, sensor and flywheel are shown in Figure 3. x_1,y_1,x_2, y_2,x_3,...,x_7,y_7 are the displacements of each position in X and Y directions. AMB1 and AMB2 are used for the control of the radial direction.

Based on Figure 3, the condition and output equation of the 0.5KWh class flywheel system are computed. We can get one-dimens ional FEM model by free-free flywheel system with gyroscopic effect and damp as follows:

$$M\ddot{Q} + (G + C)\dot{Q} + KQ = BU + EN \qquad (1)$$

Here,$Q = [x_1, \theta_{x_1}, y_1, \theta_{y_1}, \Gamma, \theta_{x_7}, y_7, \theta_{y_7}]^T$, M is mass matrix($M \in R^{28\times28}$), K is stiffness matrix($K \in R^{28\times28}$), G is gyroscopic matrix($G \in R^{28\times28}$), C is damp matrix($C \in R^{28\times28}$). B is the matrix used for control input($B \in R^{28\times4}$). E is used for disturbance($E \in R^{28\times1}$). U is control input($U \in R^{4\times1}$). N is disturbance($N \in R^{1\times1}$). Q is vector($Q \in R^{28\times1}$).

MODE DECOMPOSITION WITH GYROSCOPIC EFFECT

The strict method can't be used to construct a reduced-order model for control system design of rotor system with gyroscopic effect by mode decomposition because gyroscopic matrix is anti-symmetric matrix and the model separation must be done in plural domain. In this paper, the cholesky decomposition is used to construct a reduced-order model for AMB control system design of rotor system with gyroscopic effect.

A general equation of motion of rotor system with gyroscopic effect can be written as follows:

$$M_g\ddot{q} + G_g\dot{q} + K_gq = Tf \qquad (2)$$

Form dynamic characterization of rotor system, M_g and K_g are symmetrical matrix and G_g is a anti-symmetric matrix. From Eq.2 we can get:

$$M^*\dot{x} + G^*x = T^*f \qquad (3)$$

where,

$$x = \begin{pmatrix} q \\ \dot{q} \end{pmatrix} M^* = \begin{pmatrix} K_g & 0 \\ 0 & M_g \end{pmatrix}$$

$$G^* = \begin{pmatrix} 0 & -K_g \\ K_g & G_g \end{pmatrix} T^* = \begin{pmatrix} 0 \\ T \end{pmatrix}$$

From characterization of M_g and K_g, M^* is a symmetric matrix. The Eq.4 can be got by cholesky decomposition.

$$M^* = LL^T \qquad (4)$$

Consider Eq.4, the Eq.3 can be rewritten as:

$$LL^T\dot{x} + G^*x = T^*f \tag{5}$$

Λ is defined as:

$$\Lambda = L^{-1}G^*L^{-T} \tag{6}$$

Then,

$$\Lambda^T = -\Lambda \tag{7}$$

And Φ is:

$$\Phi = \Lambda^T\Lambda \tag{8}$$

So, the eigenvectors of Φ is P. Because Λ is a anti-symmetric matrix, Φ has two same eigenvectors λ_i. The eigenvalues of u_i and v_i are λ_i. So, P is obtained as:

$$P = \begin{pmatrix} u & v \end{pmatrix} \tag{9}$$

x can be defined as

$$x = L^{-T}P\xi \tag{10}$$

This leads to Eq.11 from Eq.5.

$$\dot{\xi} = \Theta\xi + \psi f \tag{11}$$

Where,

$$\Theta = -P^{-1}\Lambda P\Gamma\Gamma\psi = P^{-1}L^{-1}T^*$$

And then from relation of physical coordinate and mode coordinate, the Eq.12 can be got.

$$x = L^{-T}P\xi = L^{-T}[u\Gamma v]\begin{pmatrix} \eta \\ \zeta \end{pmatrix} \tag{12}$$

Here, mode vector η and ζ are correspond to u and v. From characterization of P and Λ, Θ is a anti-symmetric matrix and the mode separation as below is possible.

$$\Theta = -\begin{pmatrix} 0 & \omega \\ -\omega^T & 0 \end{pmatrix} \tag{13}$$

ω is a diagonal matrix. The elements of ω are natural frequencies. After Eq.12 and Eq.13 are applied to Eq.11, the follows equation is got.

$$\frac{d}{dt}\begin{pmatrix} \eta_1 \\ \Gamma \\ \eta_n \\ - \\ \zeta_1 \\ \Gamma \\ \zeta_n \end{pmatrix} = -\begin{pmatrix} 0 & 0 & 0 & \omega_1 & 0 & 0 \\ 0 & \Gamma & 0 & 0 & \Gamma & 0 \\ 0 & 0 & 0 & 0 & 0 & \omega_n \\ -\omega_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Gamma & 0 & 0 & \Gamma & 0 \\ 0 & 0 & -\omega_n & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} \eta_1 \\ \Gamma \\ \eta_n \\ \zeta_1 \\ \Gamma \\ \zeta_n \end{pmatrix} + P^{-1}L^{-1}T^*f \tag{14}$$

Where $\omega_1, ..., \omega_n$ are eigenvalues. From Eq.14 we see the mode separation is possibility by the upper method. By the way, Meirovitch [7] did not use cholesky decomposition and the Eq.15 is got from Eq.3.

$$\lambda_g M^* x_g + G^* x_g = 0 \tag{15}$$

Here, λ_g is fixed scalar and x_g is vector. Then Meirovitch proposed mode separation method and this method only can used for eigenvalues are plural number. This paper proposed a new mode separation method by cholesky decomposition which can used for eigenvalues are general values. This method is more useful than the method proposed by Meirovitch.

ZERO POWER CONTROLLER DESIGN

We apply zero power control method to 0.5KWh class magnetic bearing flywheel system. Because the zero power nonlinear control is a nonlinear control method, the stability of closed-loop system can't verify by eigenvalues. In order to verify the validity of a servo system zero power controller, the controller should be used to full-order model with gyroscopic effect of Eq.(1) and examine the stabilization of closed loop system. But the degree of closed loop system with gyroscopic effect is very high and the numerical computation is impossible. So, the system which has same eigenvalues as that of six divisions FEM model in the range of 10^3 is used in closed-loop simulation. The dimension of control input and output is same to that of the six divisions FEM model. In order to estimate the state of mode coordinate, the indentity observer is used for closed loop simulation. The low-pass filter is used to avoid spillover of higher vibration modes. The outputs of system are used to design the zero power controller. The augmented plant is shown in FIGURE 4.

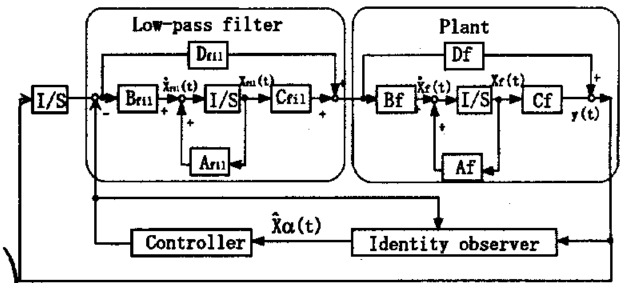

FIGURE 4: Block diagram of backstepping control with indentity observer and low-pass filter

The eight dimensional low pass filter is designed and state-space description is shown in Eq.4.

$$\begin{cases} \dot{x}_{fil} = A_{fil}x_{fil} + B_{fil}u_{fil} \\ y_{fil} = C_{fil}x_{fil} + D_{fil}u_{fil} \end{cases} \tag{16}$$

Where, $A_{fil} \in R^{8\times8}, B_{fil} \in R^{8\times4}, C_{fil} \in R^{4\times8}, D_{fil} \in R^{4\times4}, x_{fil} \in R^{8\times1}, y_{fil} \in R^{4\times1}, u_{fil} \in R^{4\times1}$. After add the eight dimensional low pass filter to the reduced-order model with gyroscopic effect, the augmented plant is obtained as:

$$\begin{cases} \dot{x_a} = A_a x_a + B_a u_{fil} \\ y_a = C_a x_a + D_a u_{fil} \end{cases} \tag{17}$$

Where, $A_a \in R^{20\times20}, B_a \in R^{20\times4}, C_a \in R^{4\times20}, D_a \in R^{4\times4}, x_a \in R^{20\times1}, y_a \in R^{4\times1}, u_{fil} \in R^{4\times1}$.

The zero power controller designed by Eq.17. To design a servo system zero power controller, Eq.17 is changed to Eq.18.

$$\begin{bmatrix} \dot{y}_a \\ \dot{x}_a \end{bmatrix} = \begin{bmatrix} 0 & C_a \\ 0 & A_a \end{bmatrix} \begin{bmatrix} y_a \\ x_a \end{bmatrix} + \begin{bmatrix} 0 \\ B_a \end{bmatrix} u_{fil} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} y_a \tag{18}$$

Eq.18 can be re-written as:

$$\dot{x}_{rs} = A_{rs}x_{rs} + B_{rs}u_{fil} + E_{rs}y_a \tag{19}$$

Where, $A_{rs} \in R^{24\times24}\Gamma B_{rs} \in R^{24\times4}\Gamma E_{rs} \in R^{24\times4}\Gamma x_{rs} \in R^{24\times1}, u_r \in R^{4\times1}, y_a \in R^{4\times1}$. The follows equation can be got from Eq.7.

$$\begin{cases} \dot{x}_{rsp} = A_{11}x_{rsp} + A_{12}\dot{x}_{rsp} + B_{rsp1}u \\ \ddot{x}_{rsp} = A_{21}x_{rsp} + A_{22}\dot{x}_{rsp} + B_{rsp2}u \end{cases} \tag{20}$$

From Eq.(20), $\dot{x}_{B1}$ and $\dot{x}_{B2}$ can be defined as:

$$\begin{cases} \dot{x}_{B1} = x_{B2} = \dot{x}_{rsp} \\ \dot{x}_{B2} = \ddot{x}_{rsp} = \overline{M}x_{rsp} + \overline{N}u \end{cases} \tag{21}$$

Where:

$$\begin{cases} \overline{M} = A_{21}A_{21}^{-1}[I - A_{12}] + A_{22} \\ \overline{N} = -A_{21}A_{21}^{-1}B_{rsp1} + B_{rsp2} \end{cases}$$

The closed-loop system can desired as:

$$x_{B2des} = -\overline{C}_1 x_{B1} \tag{22}$$

the state variable and deviation of stability can defined as $Z_B(x_{B2} - x_{B2des})$. So, the lyapunov function of the whole system with deviation Z_B can be written as:

$$v = \frac{1}{2}(x_{B1}^T \overline{P} x_{B1} + Z_B^T \overline{Q} Z_B) \tag{23}$$

Then

$$\dot{v} = \frac{1}{2}(\dot{x}_{B1}^T \overline{P} x_{B1} + x_{B1}^T \overline{P} \dot{x}_{B1} + \dot{Z}_B^T \overline{Q} Z_B + Z_B^T \overline{Q} \dot{Z}_B) \tag{24}$$

However,

$$\overline{P} = \overline{P}^T > 0\Gamma\overline{Q} = \overline{Q}^T > 0$$

If the control input use

$$u = \overline{N}^{-1}[-inv(\overline{Q}) \times \overline{P}x_{B1} - \overline{C}_2\overline{C}_1x_{B1} - (\overline{M} + \overline{C}_1 + \overline{C}_2)x_{B2}] \tag{25}$$

the follows equation can be got from Eq.24

$$\dot{v} = -x_{B1}\overline{P} \times \overline{C}_1 x_{B1}^T - Z_B\overline{Q}C_2Z_B^T \tag{26}$$

From Eq.26, we can see the negative definite condition is satisfied.

SIMULATION RESULTS

The bode plot of designed low pass filter is shown in FIGURE 5.

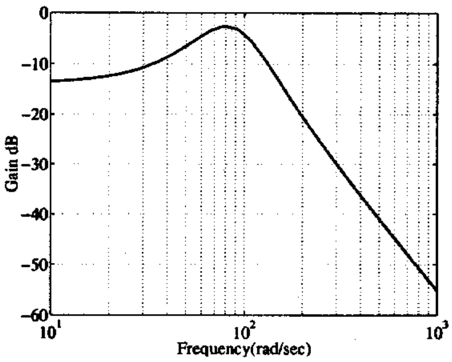

FIGURE 5: Bode plot of low-pass filter

The parameter of zero power controller is given as follows:

$$C_1 : 47.5$$
$$C_2 : 4.0$$

At the same time the observer is shown as follows:

$$Q_{ob} : 90000 \times [eye(12)]$$
$$R_{ob} : 2.1 \times 10^{-10} \times eye(4)$$

The closed-loop system simulation has been done by the upper low pass filter, observer, zero power controller. The rotational speed of system is a parameter and set as 60Hz used for controller design. In order to verify the stability of closed-loop system with gyroscopic effect, the simulation of closed-loop system has been done when rotational speed of system is changed from 0Hz to 120Hz and impulse input is set to 10N. The impulse disturbances responses, control input and lyapunov function are given in FIGURE 6 to FIGURE 11 respectively. The same controller is also used to closed-loop system with rotational speed from 0Hz to 120Hz and the stability of closed-loop system is verfied. From upper to bottom, the FIGURE 6 given the output of X direction of sensor1, the output of Y direction of sensor1, the output of X direction of sensor2 and the output of Y direction of sensor2. At the same time, the control inputs and lyapunov function are shown in FIGURE 7 and FIGURE 8.

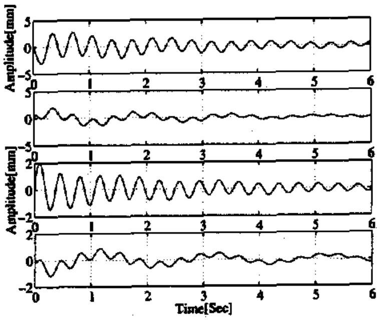

FIGURE 6: Impluse disturbances responses(Displacement, without rotational speed)

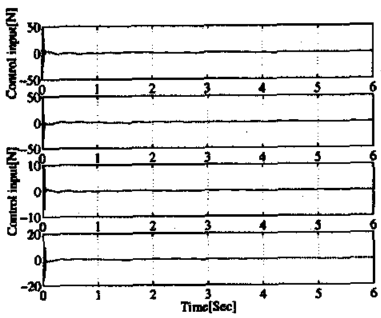

FIGURE 7: Impluse disturbances responses(Control input, without rotational speed)

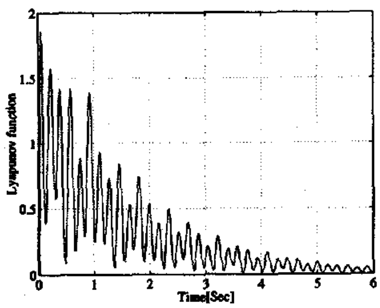

FIGURE 8: Impluse disturbances responses(Lyapunov function, without rotational speed)

From FIGURE 6 to FIGURE 11, we see the control input of closed-loop system with gyroscopic effect had become zero at last. The real zero power controller has been designed for 0.5KWh class flywheel system using magnetic bearing with gyroscopic effect.

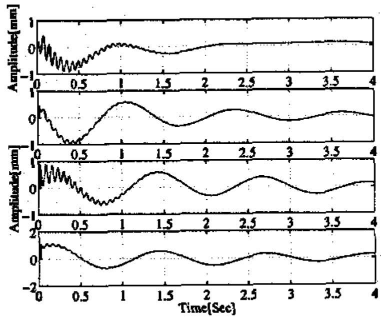

FIGURE 9: Impluse disturbances responses(Displacement,rotational speed is 120Hz)

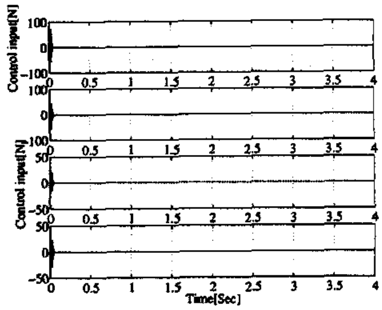

FIGURE 10: Impluse disturbances responses(Control input,rotational speed is 120Hz)

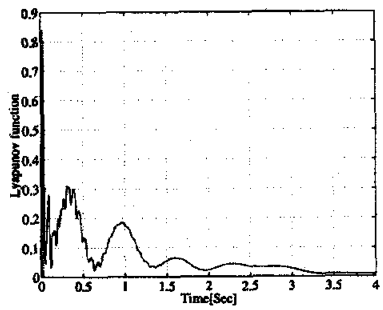

FIGURE 11: Impluse disturbances responses(Lyapunov function,rotational speed is 120Hz)

EXPERIMENT RESULTS

We applied the method to 0.5KWh class magnetic bearing flywheel system experiment. Because the computational speed of DSP is very slow, the one dimensional FEM model which designed only with the upper AMB(AMB1) and sensor(sensor1) is used to experiment. The model with the upper AMB and sensor is shown in FIGURE 3 as dotted line. The dimension of the model is same to that of one-dimensional FEM model with AMB1, AMB2, sensor1 and sensor2. The number of control input and output is 2. The experimental setup is given in FIGURE 12. The responses and control currents with initial value are shown in FIGURE 13 and FIGURE 14. From the figures, we see the rotor is stablity in a fixed point. But the rotor is not approaches the equilibrium point for we not use the servo system in experiment. We are improving the controller for better performance of closed-loop system when rotor is rotating and then we will design the controller used for one-dimensional FEM model with AMB1, AMB2, sensor1 and sensor2 by a new DSP later.

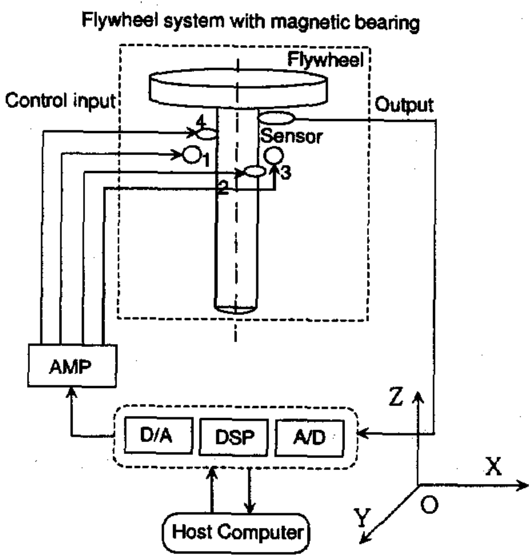

FIGURE 12: Expermental Setup

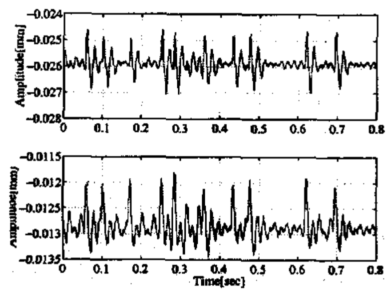

FIGURE 13: Responses with initial value (Displacement[mm])

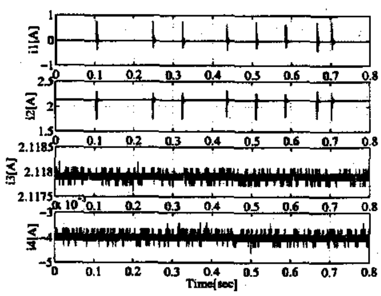

FIGURE 14: Responses with initial value (Control input[A])

CONCLUSIONS

This paper has designed zero power controller for 0.5KWh class flywheel system using magnetic bearing with gyroscopic effect. The one dimensional FEM model of flywheel system with gyroscopic, the reduced-order model with gyroscopic effect and servo system zero power controller were discussed in this paper. From simulation and experiment, the following conclusions can be obtained.

(1) In order to improve the consuming electric power of energy storage flywheel system, the zero power nonlinear control had been done.

(2) Using the reduced-order model with gyroscopic effect, servo zero power controller had been designed. The servo zero power controller not only useful for reduced-order model but also useful for full order model. However the zero power nonlinear control is a nonlinear control method, the stability of closed-loop system can't verify by eigenvalues.

(3) This paper had verified the possibility of zero power control method for 0.5KWh class flywheel system using magnetic bearing. From simulation and experiment, it seems the proposed method is useful for control system design taking into account a strong gyroscopic effect. We are improving the zero power controller for better performance when rotor is rotating

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