Plane Stabilization of the Electron Storage Ring Using Automatic 3-DOF Girder System

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Abstract—The plane stabilization of 1.2 GeV electron storage ring of the Siam Photon Source has changed one millimeter per year resulted from the occurrences of floor subsidence. The alignment takes approximately three months which requires a lot of manpower. This paper presents the new technique of the control system design and mathematical model of the automatic 3-DOF girder system for aligning the magnets in the electron storage ring. The girder system is designed based on three eccentric circle cam actuators with DC motor which are translation along the y-axis (heave), rotation around the x-axis (pitch) and the z-axis (roll). The control system consists of two control loops: a) the inner control loop which is composed of three actuators used the angular position control with pole-placement through the state feedback with full-order state observer and b) the outer control loop which tracks control of the girder system with proportional-integral controller tuning using the optimization method based on the simplex search method. The performance of the automatic 3-DOF girder system is supported by simulation and experimental results. Therefore, the experimental results show that it exactly and quickly tracks the reference input and robustly regulates the output response which has the external disturbances. This prototype is appropriate for the development of the magnet girder system for the electron storage ring.

Index Term—angular position control, observer-based state feedback controller, tracking control and output regulation, PI-controller, 3-DOF girder system, eccentric circle cam actuator

I. INTRODUCTION

The 1.2 GeV electron storage ring of the Siam Photon Source (SPS) at the Synchrotron Light Research Institute (SLRI) has produced the synchrotron light using the magnetic field to change the electron directions, emit light, and store the electrons. The synchrotron light is provided to scientists for their various research [1]-[3]. The occurrences of floor subsidence cause the plane stabilization of the electron storage ring with a circumference is 81.3 meters have been changing by one millimeter per year. The magnet girder system of the SPS electron storage ring is shown in Fig. 1. The alignment process of all magnets in the electron storage ring takes approximately three months and requires a lot of manpower [4], [5]. Consequently, the solution to this problem is to apply the automatic girder system in which the alignment is precisely and quickly with less manpower [6], [7]. Their use of iterative techniques for the control of the girder system. This paper presents the new technique of the control system design, the mathematical model of the automatic three degrees of freedom (3-DOF) girder system, and the experimental results. The automatic 3-DOF girder system driven by three eccentric circle cam actuators which are translated in the y-axis (heave), rotated around the x-axis (pitch), and the z-axis (roll). The experimental setup for evaluating the performance of the girder system to demonstrate the effectiveness: the mathematical model, angular position control of the actuator system, tracking control, and output regulation of the girder system. The control system is composed of two control loops: a) the inner control loop which consists of three eccentric circle cam actuators used the angular position control with pole-placement through the state feedback with the full-order state observer and b) the outer control loop which tracking control and output regulation of the girder system with proportional-integral (PI) controller tuning using the optimization method based on the simplex search method. The structure of this paper as follows: the next section explains the mathematical model of the 3-DOF girder system, section 3 presents the control system design, section 4 demonstrates the experimental results, and finally, is the conclusion.

II. MATHEMATICAL MODEL OF 3-DOF GIRDER SYSTEM

The 3-DOF girder system is placed on three eccentric circle cam actuators which are translation along the y-axis within ±5 mm range, rotation around the x-axis within ±20 mrad range and the z-axis within ±20 mrad range. The translation along the x-axis (sway), the z-axis (surge), and rotation around the y-axis (yaw) are approximately zero.
The 3D model of the automatic 3-DOF girder system is shown in Fig. 2. An actuator system is made up of the permanent magnet (PM) DC motor, worm gearbox, planetary gearbox, eccentric circle cam [8], [9], and the rotary encoder. Planetary gearbox can reduce the speed and increase the torque of the PM DC motor [10]. The locked position of the eccentric circle cam is applied by the worm gearbox [11]. In addition, the external disturbances were built by adjusting Bolt-1 and Bolt-2.

\[ T_m(t) = J_i \dot{\theta}_i(t) + b_i \dot{\theta}_i(t) + T_L(t) \]  
\[ J_e \dot{\theta}_m(t) + b_e \dot{\theta}_m(t) + T_L(t) = T_m(t) \]

The ratio of gears of worm gearbox and planetary gearbox are \( N_w = N_{w1}/N_{w1} \), \( N_p = N_{p1}/N_{p1} \), and \( N_l = N_{l1}N_{l1} \). The angular position of shafts are \( \alpha_1 = N_{a1} \), \( \alpha_2 = N_{a2} \), and \( \alpha_3 = \alpha_L \). The torques transmitted on gears are \( T_l = N_p T_1 \) and \( T_i = N_p T_3 \).

\[ T_m(t) = J_i \dot{\theta}_i(t) + b_i \dot{\theta}_i(t) + T_L(t) \]  
\[ T_3(t) = N_p J_2 \dot{\alpha}_3(t) - N_p b_2 \dot{\alpha}_3(t) \]  
\[ T_2(t) = J_2 \dot{\alpha}_2(t) + b_2 \dot{\alpha}_2(t) + T_L(t) \]

Referring to (6), it can be written as

\[ T_3(t) = N_p T_1(t) - N_p J_2 \dot{\alpha}_3(t) - N_p b_2 \dot{\alpha}_3(t) \]

Substituting (8) into (7)

\[ N_p T_1(t) - (N_p)^2 J_2 \dot{\alpha}_3(t) - b_2 \dot{\alpha}_3 = J_3 \dot{\alpha}_3 + b_3 \dot{\alpha}_3 + T_L(t) \]

Substituting (5) into (9)

\[ J_{eq} \dot{\alpha}_3(t) + b_{eq} \dot{\alpha}_3(t) + T_L(t) = N_l T_m(t) \]

This \( \omega_{eq} \) is the actuator system velocity (rad/s), \( \alpha_m \) is the angular position of the motor (rad), and \( \alpha_L \) is the angular position of the actuator system (rad). Refer to (1), (10) it can be written as

\[ V_m(t) = R_s \dot{i}_a(t) + L_s \dot{i}_a(t) + N_l K_i \dot{\omega}_L(t) \]

\[ J_{eq} \dot{\theta}_L(t) + b_{eq} \dot{\theta}_L(t) + T_L(t) = N_l K_i \dot{i}_a(t) \]

B. Model of the 3-DOF girder system

The coordinate system used to describe the girder movement is shown in Fig. 4. The movement in three-dimensional space are translations along the x-axis (sway, u), y-axis (heave, v), and z-axis (surge, w) and rotations around the x-axis (pitch, \( \theta \)), y-axis (yaw, \( \psi \)), and z-axis (roll, \( \phi \)).

The three rotation matrices around the x-axis, the y-axis, and z-axis are given by

\[ \mathbf{S}_s \text{ (sway)} = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \]

\[ \mathbf{S}_h \text{ (heave)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \psi & \sin \psi \\ 0 & -\sin \psi & \cos \psi \end{bmatrix} \]

\[ \mathbf{S}_r \text{ (surge)} = \begin{bmatrix} \cos \phi & \sin \phi & 0 \\ -\sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \]
\[
R_z(\theta) = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & -\sin \theta \\
0 & \sin \theta & \cos \theta
\end{bmatrix}
\]

(13)

\[
R_y(\varphi) = \begin{bmatrix}
\cos \varphi & 0 & \sin \varphi \\
0 & 1 & 0 \\
-\sin \varphi & 0 & \cos \varphi
\end{bmatrix}
\]

(14)

\[
R_x(\psi) = \begin{bmatrix}
\cos \psi & -\sin \psi & 0 \\
\sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

(15)

Therefore, the rotation matrix of the girder system is

\[
R = R_x(\psi)R_y(\varphi)R_z(\theta)
\]

and defined as \(\cos \theta = \cos \theta, \sin \theta = \sin \theta, \cos \psi = \cos \psi, \sin \psi = \sin \psi, \cos \varphi = \cos \varphi, \) and \(\sin \varphi = \sin \varphi\) is given by

\[
R = \begin{bmatrix}
c \varphi c \psi & c \varphi s \psi & -c \psi s \varphi \\
c \varphi s \psi & c \varphi s \psi & -c \psi s \varphi \\
-c \psi s \varphi & c \psi s \varphi & c \varphi c \psi
\end{bmatrix}
\]

(16)

Drawing of the 3-DOF girder system is shown in Fig. 5. The three actuators will be rotating in the x-y plane and the angle of rotation of the Actuator-1, Actuator-2, and Actuator-3 are \(\alpha_1, \alpha_2,\) and \(\alpha_3\) within \(\pm 90^\circ\) range, respectively. Point A is the rotation axis, point B is the center of the eccentric circle cam, and point C is the contact point between the eccentric circle cam and the girder. The angle \(\beta_1, \beta_2,\) and \(\beta_3\) are \(135^\circ, 135^\circ,\) and \(45^\circ,\) respectively. The diameter of the eccentric circle cam is 100 mm and the eccentricity \((e)\) is 5 mm. Vector \(\vec{m}\) is the vector from point O (center of the girder) to point A. Vector \(\vec{v}\) is the vector from point A to point B. And vector \(\vec{n}\) is the vector from point B to point C.

\[
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix} = \begin{bmatrix}
1 & -\phi & 0 \\
\phi & 1 & -\theta \\
0 & \theta & 1
\end{bmatrix}
\]

(17)

When the girder system is moving from the ideal vector \(\vec{x}_0\) to the new vector \(\vec{x}\). Therefore, the transformation matrix consists of the rotation matrix first, followed by the translation matrix. The transformation matrix is given by

\[
\begin{bmatrix}
x \\
y - y_o + v \\
z - z_o
\end{bmatrix} = \begin{bmatrix}
\cos \alpha - \phi \sin \alpha \\
\phi \cos \alpha + \sin \alpha \\
\sin \alpha
\end{bmatrix}
\]

(21)

Substituting (19) and (21) into (20), the result as

\[
\begin{bmatrix}
\vec{v}_i \\
\vec{n}
\end{bmatrix} = \begin{bmatrix}
x - \vec{n} \vec{m} - \vec{n} - r
\end{bmatrix}
\]

(22)

The experimental results of a 3-DOF girder system [12] it can be seen that the angle of pitch and roll are small in radians \(\theta, \phi \ll 1\). Therefore, we obtain the small angle approximation are \(\cos \theta \approx 1, \sin \theta \approx \theta, \cos \varphi \approx 1,\) and \(\sin \varphi \approx \varphi\). Refer to (16), the rotation matrix of a 3-DOF girder system can be written as

\[
\begin{bmatrix}
\cos \alpha - \phi \sin \alpha \\
\phi \cos \alpha + \sin \alpha \\
\sin \alpha
\end{bmatrix}
\]

(23)

The ideal angle of rotation \(\alpha\) is perpendicular to the \(\beta\), then \(e \cos(\alpha - \beta) = 0\). Refer to (22), the result as (23) it is the forward kinematics equation. Therefore, the forward kinematics equation of 3-DOF girder system is given by (24).
\[
\begin{align*}
&\left( \sin \beta_{ao} \right) v - \left( m_{ao} \sin \beta_{ao} \right) \theta + \\
&\left( m_{ao} \sin \beta_{ao} - m_{ao} \cos \beta_{ao} + e \sin(\alpha_i - \beta_{ao}) \right) \phi \\
&= e \cos(\alpha_i - \beta_{ao}) \\
&= s_1 \beta_{o1} - m_{s1} \beta_{o1} \ g1) \hspace{1cm} v \\
&= s_2 \beta_{o2} - m_{s2} \beta_{o2} \ g2 \hspace{1cm} \theta \\
&= s_3 \beta_{o3} - m_{s3} \beta_{o3} \ g3 \hspace{1cm} \phi \\
&\begin{bmatrix}
  v \\
  \theta \\
  \phi
\end{bmatrix} = \\
&\begin{bmatrix}
  e \cos(\alpha_i - \beta_{ao}) \\
  e \cos(\alpha_i - \beta_{ao}) \\
  e \cos(\alpha_i - \beta_{ao})
\end{bmatrix}
\end{align*}
\] (23)

Therefore, the inverse kinematics equation of a 3-DOF girder system is given by

\[
\begin{align*}
\alpha_1 &= \beta_1 - \phi \cos \alpha_i - m_{s1} \cos \beta_{o1} + (\phi m_{s1} - \theta m_{s1} + v) \sin \beta_{o1} \\
&= e \cos(\alpha_i - \beta_{ao}) \\
\alpha_2 &= \beta_2 - \phi \cos \alpha_i - m_{s2} \cos \beta_{o2} + (\phi m_{s2} - \theta m_{s2} + v) \sin \beta_{o2} \\
&= e \cos(\alpha_i - \beta_{ao}) \\
\alpha_3 &= \beta_3 - \phi \cos \alpha_i - m_{s3} \cos \beta_{o3} + (\phi m_{s3} - \theta m_{s3} + v) \sin \beta_{o3} \\
&= e \cos(\alpha_i - \beta_{ao})
\end{align*}
\] (27)

III. THE CONTROL SYSTEM DESIGN

The new technique of the control system design of the automatic 3-DOF girder system consists of two control loops: a) the inner control loop which is composed of three actuator systems and b) the outer control loop which tracks the reference input and regulates the output response of the heave, pitch, and roll of the girder system. Block diagram of the control system of the automatic 3-DOF girder system is shown in Fig. 6. The reference input are the heave \( v_h \), pitch \( \theta_d \), and roll \( \phi_d \). The angular position input of three actuator systems are \( \alpha_{d1} \), \( \alpha_{d2} \), and \( \alpha_{d3} \) which calculated by the inverse kinematics equation and the angular position output are \( \alpha_L \), \( \alpha_L2 \), and \( \alpha_L3 \). The output response are heave \( \alpha_L \), pitch \( \theta_L \), and roll \( \phi_L \). The external disturbances of the 3-DOF girder system are \( D_v \), \( D_\theta \), and \( D_\phi \).

A. The angular position control of the actuator system

The angular position control of the eccentric circle cam actuator system is actuated by a PM DC motor, worm gearbox, and planetary gearbox. Measured the angular position by the rotary encoder. The control system uses the state feedback control with the full-order state observer based on the pole placement method [14], [15]. Therefore, the control system design as follows:

\[
\dot{x}(t) = Ax(t) + Bu(t)
\]
\[
y(t) = Cx(t)
\]

Where \( x(t) \) is the state vector and define the state variables are \( x_1 = \alpha_L(t) \), \( x_2 = \omega_L(t) \), and \( x_3 = i_a(t) \). \( A \), \( B \), and \( C \) are constant matrices. \( u(t) \) is the control signal equal to \( V_a(t) \). \( y(t) \) is the output signal equal to \( \alpha_L(t) \). Refer to (11), (12), we obtain the state equation is given by

\[
\begin{align*}
\dot{\alpha}_L(t) &= \omega_L(t) \\
\dot{\omega}_L(t) &= \frac{b_eq_\omega \omega_L(t) + N_I K_i \alpha_d(t)}{J_{eq}} \\
\dot{i}_a(t) &= \frac{N_I K_h \omega_L(t) - R_a i_a(t)}{L_a} + \frac{V_a(t)}{L_a}
\end{align*}
\] (29)

The state space equations can be written by

\[
\begin{bmatrix}
\alpha_L \\
\omega_L \\
i_a
\end{bmatrix} = \\
\begin{bmatrix}
0 & 1 & 0 \\
-\frac{b_eq_\omega}{J_{eq}} & N_I K_i & 0 \\
0 & 0 & \frac{R_a}{L_a}
\end{bmatrix} \\
\begin{bmatrix}
0 & 0 \\
1 & \frac{1}{L_a}
\end{bmatrix}
\begin{bmatrix}
\alpha_L \\
\omega_L \\
i_a
\end{bmatrix}
\]
\] (30)

A prototype of the actuator system is shown in Fig. 7. The prototype consists of a PM DC motor, worm gearbox with gear ratio 15:1, eccentric circle cam, and the rotary encoder which has 2,500 pulses per revolution. We use the multi-meter and LCR meter to measure the resistance and inductance of the motor winding \( R_e = 3.2715 \ \Omega \) and \( L_a = 2.0487 \times 10^{-3} \ \text{H} \). And estimating the value of parameters are \( K_h \), \( K_r \), \( J_{eq} \), and \( b_eq \) is based on measuring the output velocity of the eccentric circle cam. The parameter estimation of the actuator system using MATLAB-Simulink based on the simplex search method [16] \( K_h = 7.0103 \times 10^{-2} \ \text{V/s/rad} \), \( K_r = 9.5361 \times 10^{-3} \ \text{N/m/A} \), \( J_{eq} = 14.7729 \ \text{kg.m}^2 \), and \( b_eq = 5.8634 \ \text{N.m.s/rad} \).
Refer to (30), it can be rewritten as
\[
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3
\end{bmatrix} =
\begin{bmatrix}
  0 & 1 & 0 \\
  0 & -0.3969 & 0.4841 \\
  0 & -25,663.7135 & -1,596.8663
\end{bmatrix}
\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3
\end{bmatrix} +
\begin{bmatrix}
  0 \\
  488.1144
\end{bmatrix}
\]

Hence, the transfer function of the actuator system
\[
\frac{\alpha_d(s)}{V_d(s)} = \frac{236.2961}{s(1+589.0453)(s+8.2178)}
\]

Then the system is type 1 with involves the integral. Block diagram of the state feedback control is shown in Fig. 8.

The control signal is determined by
\[
u = -Kx
\]
\[
u = \begin{bmatrix}
  k_2 \\
  k_3
\end{bmatrix}
\begin{bmatrix}
  x_2 \\
  x_3
\end{bmatrix} + k_1 \left( \alpha_d - x_1 \right)
= -\left( k_1 x_1 + k_2 x_2 + k_3 x_3 \right) + k_1 \alpha_d = -Kx + k_1 \alpha_d
\]

**K** is the state feedback gain matrix. And the controllability matrix of the actuator system is given by
\[
M = \begin{bmatrix} B & AB & A^2B \end{bmatrix}
\]

The determinant of matrix **M** is \(-2.7258 \times 10^7\), so the rank of the controllability matrix is equal to the rank of the system. Therefore, the actuator system completely states controllable.

The desired of the closed-loop poles of the angular position control at \( p_1 = -4 + 3j \), \( p_2 = -4 - 3j \), and \( p_3 = -2,000 \). Then the damping ratio of the actuator system is \( \zeta \approx 0.8 \) and undamped natural frequency is \( \omega_n \approx 5 \text{ rad/s}. \) Characteristic equation is \( s^3 + 2,008s^2 + 16,025s + 50,000 \). The Ackermann's formula [14] for determining the state feedback gain matrix is given by
\[
K = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} B & AB & A^2B \end{bmatrix}^{-1} \phi(A)
\]

Since \( \phi(A) = A^3 + 2,008A^2 + 16,025A + 50,000I \). Therefore, the state feedback gains are \( k_1 = 211.5988 \), \( k_2 = 11.8681 \), and \( k_3 = 0.8415 \).

The control system uses the state feedback control with full-order state observer and block diagram of the observer-based state feedback control is shown in Fig. 9.
The full-order state observer equation is given by
\[ \dot{x}(t) = Ax(t) + Bu(t) + L(y(t) - Cx(t)) \]
\[ u(t) = -K\dot{x}(t) \]  \hspace{1cm} (35)

\( x(t) \) is the estimated state vector, \( C\dot{x}(t) \) is the estimated output signal. The output signal and the control signal are input to the observer. Matrix \( L \) is the observer gain matrix that correcting disparity between the measured output signal and estimated output signal.

Refer to (35), the Laplace transform is given by
\[ \hat{x}(s) = (sI - A + LC + BK)^{-1}LY(s) \]
\[ U(s) = -K\hat{x}(s) \]  \hspace{1cm} (36)

The transfer function of the observer-based state feedback control is given by
\[ \frac{U(s)}{-Y(s)} = K(sI - A + LC + BK)^{-1}L \]  \hspace{1cm} (37)

The observability matrix of the actuator system is given by
\[ O = \begin{bmatrix} C \\ CA \\ CA^2 \end{bmatrix} \]  \hspace{1cm} (38)

The determinant of matrix \( O \) is 0.4814, so the rank of the observability matrix is equal to the rank of the system. Therefore, the actuator system completely states observable.

The desired of the closed-loop poles of the observer at \( p_1 = -500 + 500i \), \( p_2 = -500 - 500i \), and \( p_3 = -2,000 \). Then the damping ratio of the observer system is \( \zeta = 0.7 \) and undamped natural frequency is \( \omega_n \approx 707 \) rad/s. The characteristic equation of the observer system is
\[ s^3 + 3 \times 10^4 s^2 + 2.5 \times 10^6 s + 1 \times 10^9 \].

The Ackermann’s formula [14] for the state observer gain matrix is given by
\[ L = \phi(A) \begin{bmatrix} C \\ CA \\ CA^2 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \]  \hspace{1cm} (39)

Since \( \phi(A) = A^3 + 3 \times 10^3 A^2 + 2.5 \times 10^6 A + 1 \times 10^9 I \).

Therefore, the state observer gains are \( l_1 = 1,402.7368 \), \( l_2 = 246,402.5301 \), and \( l_3 = 1,214,975,450.6596 \). Refer to (37), the transfer function of the observer-based state feedback control is given by
\[ \frac{U(s)}{-Y(s)} = \frac{1.03 \times 10^9 s^2 + 7.27 \times 10^9 s + 2.12 \times 10^{11}}{s^3 + 3.41 \times 10^8 s^2 + 3.08 \times 10^6 s + 1.11 \times 10^9} \]

See Fig. 7 and Fig. 9, \( \alpha_d \) is the angular position input (reference input) and \( \alpha_L \) is the angular position output (output response). Therefore, the experimental results of the angular position control of the actuator system are shown in Fig. 10. Fig. 10(a) shows the angle of rotation with +90° and Fig. 10(b) illustrates the angle of rotation within +90° range. We can see the errors between the reference input and the output response is very small within the ±0.20° range.

![Block diagram of the observer-based state feedback control](image)

**Fig. 9.** Block diagram of the observer-based state feedback control

\[ \text{Full-order state observer} \]

**B. The motion control of the 3-DOF girder system**

The inner control loops use the angular position controls of three actuator systems with the observer-based state feedback control. The outer control loops consist of the tracking control and output regulation of the heave, pitch, and roll of the girder system with the PI controller 1, PI controller 2, and PI controller 3 [17] (see Fig. 6). In this situation, the tuning of the PI controller gains using the optimization method with MATLAB-Simulink based on the simplex search method [18], [19]. Flowchart of the optimization method for the PI controller gains is shown in Fig. 11.
The optimization method for the PI controller gains $K_p$ and $K_i$ is presented as follows:

**Step-1** ($K_{p1}$ and $K_{i1}$ gains): Given the initial conditions of $K_{p1}, K_{i1}, K_{p2}, K_{i2}, K_{p3}$ and $K_{i3}$ gains of the PI controller 1, PI controller 2, and PI controller 3. Setting the bounds of the output response for the heave (pitch and roll equal to zero), the final value $+5$ mm, rise time $5$ sec, overshoot $5\%$, settling time $8$ sec, and steady-state error $\pm 0.2\%$. Simulation of the automatic 3-DOF girder system (see Fig. 6). Check the output response of the heave (the error between the setting bounds and the output response). Therefore, the PI controller gains are $K_{p1} = 0.1654$ and $K_{i1} = 0.4603$.

**Step-2** ($K_{p2}$ and $K_{i2}$ gains): Given the initial conditions of $K_{p2}, K_{i2}, K_{p3}$, and $K_{i3}$ gains of the PI controller 2 and PI controller 3. Setting the bounds of the output response for the pitch (heave and roll equal to zero), the final value $+20$ mrad, rise time $5$ sec, overshoot $5\%$, settling time $8$ sec, and steady-state error $\pm 0.2\%$. Simulation and checked the output response of the pitch. Therefore, the PI controller gains are $K_{p2} = 0.1809$ and $K_{i2} = 0.5223$.

**Step-3** ($K_{p3}$ and $K_{i3}$ gains): Given the initial conditions of $K_{p3}$ and $K_{i3}$ of the PI controller 3. Setting the bounds of the output response for the roll (heave and pitch equal to zero), the final value $+20$ mrad, rise time $5$ sec, overshoot $5\%$, settling time $8$ sec, and steady-state error $\pm 0.2\%$. Simulation and checked the output response of the roll. Therefore, the PI controller gains are $K_{p3} = 0.2223$ and $K_{i3} = 0.7689$.

**IV. THE EXPERIMENTAL RESULTS**

In-house fabricated prototype and the experimental setup of the automatic 3-DOF girder system is shown in Fig. 12 (see Fig 2). The girder system is based on three eccentric circle cam actuators are Actuator-1, Actuator-2, and Actuator-3 and the weight of the girder about 100 kg. The translation along the y-axis (heave) is measured by a displacement sensor which has an accuracy of 0.005 mm. The rotation around the x-axis (pitch) and the z-axis (roll) are measured by an inclination sensor which has an accuracy of 0.6 mrad. The sensors are installed at the center of the girder. The automatic 3-DOF girder system has been tested by the RAPCON platform [20], [21] with MATLAB-Simulink. The inner control loops use three actuator systems with the observer-based state feedback control. The outer control loops use the tracking control and output regulation with the PI controller 1, PI controller 2, and PI controller 3 which use $K_p$ and $K_i$ values derived from the optimization.

**A. The tracking control**

See Fig. 2, Fig. 6, and Fig. 12, the experiment results of the tracking control are shown in Fig. 13 - Fig. 15 without the external disturbances ($D_x$, $D_y$, and $D_y$). In Fig. 13(a) - Fig. 15(a) shows the step reference input and the output response of the heave is $+5$ mm, of the pitch is $+20$ mrad and of the roll is $+20$ mrad, respectively. In Fig. 13(b) - Fig. 15(b) shows the angle of rotation of three actuator systems (see Fig. 9, Alpha-d = $\alpha_d$ and Alpha-L = $\alpha_L$). We can see the settling times within 8 sec and steady-state errors between the step reference input and the output response of the translation along the y-axis (heave) within $\pm 0.01$ mm, the rotation around the x-axis (pitch) within $\pm 0.6$ mrad, and rotation around the z-axis (roll) within $\pm 0.6$ mrad.
See Fig. 2, Fig. 6, and Fig. 12, the experiment results of the tracking control are shown in Fig. 16 - Fig. 18 without the external disturbances. In Fig. 16(a) - Fig. 18(a) shows the girder system can track the step reference input of the heave within ±5 mm range, of the pitch and roll within ±20 mrad range, respectively. In Fig. 16(b) - Fig. 18(b) shows the angle of rotation of three actuator systems. We can see the 3-DOF girder system can exactly and quickly tracks the reference input of the heave, of the pitch, and roll.

Fig. 15. The rotation around the z-axis (roll) with +20 mrad

Fig. 16. Tracking control of the translation along the y-axis (heave) within ±5 mm range

(a) Translation along the y-axis (+5 mm)
(b) Angle of rotation of three actuator system

(a) Rotation around the x-axis (+20 mrad)
(b) Angle of rotation of three actuator system

(a) Translation along the y-axis (±5 mm)
(b) Angle of rotation of three actuator system

Fig. 13. The translation along the y-axis (heave) with +5 mm

Fig. 14. The rotation around the x-axis (pitch) with +20 mrad
The experiment results of the output regulation are shown in Fig. 21 and Fig. 22 with the external disturbances signals were built by adjusting Bolt-1 (see Fig. 19) and adjusting Bolt-2 (see Fig. 20). In Fig. 21(a) and Fig. 22(a), shows the output response of the heave, the pitch, and roll with setting the reference input of the heave, the pitch, and roll to zero with adjusted Bolt-1 and adjusted Bolt-2. In Fig. 21(b) and Fig. 22(b), shows the angle of rotation of three actuator systems. We can see the 3-DOF girder system can robustly regulate the output response of the heave, the pitch, and roll to zero.

**B. The output regulation**

The prototype of a 3-DOF girder system can exactly track the reference input of the heave, pitch, and roll without the external disturbances. See Fig. 2, Fig. 6, and Fig. 12, the external disturbance signals ($D_h$, $D_p$, and $D_\phi$) were built by adjusting Bolt-1 and Bolt-2 (the control system do not use). Therefore, the external disturbance signals were built by adjusting Bolt-1 and Bolt-2 is shown in Fig. 19 and Fig. 20.
his work was ‘‘...’’ developing ...regulate the output response which has the external disturbances. In addition, the girder system can successfully perform the design values of the heave with an accuracy ±0.01 mm, the pitch and roll with an accuracy ±0.6 mrad and can robustly regulate the output response which has the external disturbances. In addition, the girder system can successfully perform the design values of the heave with an accuracy ±5 mm range, the pitch and roll within ±20 mrad range. Therefore, this prototype is appropriate for developing the magnet girder system for plane stabilization of the electron storage ring. For future research, the automatic girder system with higher degrees of freedom and higher precision will be designed.

V. CONCLUSION

This paper presents the new technique of the control system design of the automatic 3-DOF girder system for aligning the magnets in the electron storage ring. The prototype of the girder system has been built to demonstrate the effectiveness of the mathematical models, angular position control of the actuator system, tracking control and output regulation of the girder system. The experimental results reveal that the actuator system can precisely track the reference input with an accuracy ±0.20°, the girder system can exactly and quickly track the reference input of the heave with an accuracy ±0.01 mm, the pitch and roll with an accuracy ±0.6 mrad and can robustly regulate the output response which has the external disturbances. In addition, the girder system can successfully perform the design values of the heave within ±5 mm range, the pitch and roll within ±20 mrad range. Therefore, this prototype is appropriate for developing the magnet girder system for plane stabilization of the electron storage ring. For future research, the automatic girder system with higher degrees of freedom and higher precision will be designed.

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