논 문
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평판 모터 상태 관측을 위한 비선형 관측기

A Nonlinear Observer for the Estimation of the Full State of a Sawyer Motor

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Abstract - To improve the performances of Sawyer motors and to regulate yaw rotation, various feedback control methods have been developed. Almost all of these methods require information on the position, velocity or full state of the motor. Therefore, in this paper, a nonlinear observer is designed to estimate the full state of the four forcers in a Sawyer motor. The proposed method estimates the full state using only positional feedback. Generally, Sawyer motors are operated within a yaw magnitude of several degrees; outside of this range, Sawyer motors step out. Therefore, this observer design assumes that the yaw is within ±90º. The convergence of the estimation error is proven using the Lyapunov method. The proposed observer guarantees that the estimation error globally exponentially converges to zero for all arbitrary initial conditions. Furthermore, since the proposed observer does not require any transformation, it may result in a reduction in the commutation delay. The simulation results show the performance of the proposed observer.

Key Words : Sawyer motor, Nonlinear observer, Lyapunov method

1. Introduction

Sawyer motors are widely used not only in semiconductor manufacturing systems and precision machine tools but also in automated assembly. A Sawyer motor is a dual-axis linear motion motor that consists of four forcers symmetrically mounted onto a puck, as depicted in Fig. 1. These motors are capable of high position resolution (2μm) and high speed motion (1m/sec) using open-loop microstepping. However, during this open-loop microstepping, Sawyer motors may miss steps, have long settle times, or fail to reject disturbances. Furthermore, the undesired rotation (yaw) due to asynchronous mounted forcers at the center of mass and the occurrence of disturbances cannot be regulated during open-loop microstepping.

Various feedback control methods have been developed to control Sawyer motors [1], [2], [3], [4]. A robust adaptive control was developed to achieve good tracking performance and to regulate the yaw rotation [1], and anadaptive variable structure controller was proposed to guarantee global asymptotic tracking of a reference trajectory [2]. Robust backstepping was developed to

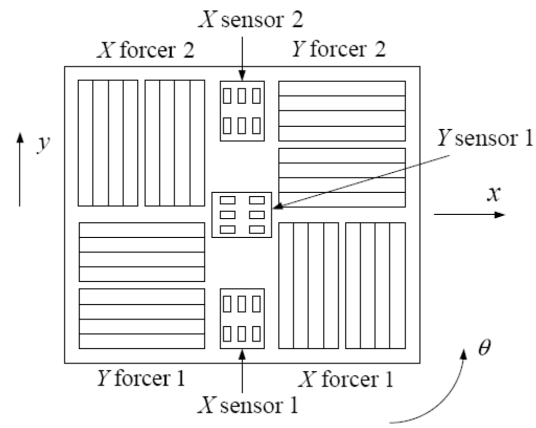

Fig. 1 Bottom view of a Sawyer motor

control Sawyer motors without the need for parameter information or current measurements [3]. To further improve the performance of a Sawyer motor, a feedback controller which accounts for the electrical dynamics should be used. Therefore, a robust adaptive control including the electrical dynamics was proposed to improve the performance of a Sawyer motor without any knowledge of electromechanical system parameters [4]. All of these methods require information on the position and the velocity of the motor component, otherwise known as the full state. Therefore, the control methods require an observer to estimate the full state. Several observer designs have been proposed to estimate the states of permanent magnet stepper motors (PMSMs)

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whose principles are similar to those of Sawyer motors [5], [6], [7]. A reduced order observer was developed for the estimation of the velocity using phase currents and position [5]. In [6], a sliding mode observer was studied to estimate the velocity using only position feedback, and a nonlinear velocity observer was proposed using the phase currents and position [7]. In [4], since the robust adaptive control requires knowledge of the currents, an observer was proposed to estimate the currents of Sawyer motors. These methods require state or output transformation in order to obtain linear error dynamics; however, problems may occur because of the imprecision of the commutation due to the time delay between the current measurements and the position encoder feedback. It was reported that the commutation delay may cause striking qualitative changes in the behavior of the motor [8], [9]. Furthermore, all of these methods used a reduced observer. Recently, a nonlinear observer with no coordinate transformation was proposed to estimate the full state of a PMSM using the Lyapunov method [10]. The nonlinear observer guarantees that the origin of the estimation error dynamics is globally exponentially stable.

In this paper, a nonlinear observer is designed to estimate the full state of a Sawyer motor. The proposed method estimates the full state using only positional feedback. Generally, Sawyer motors are operated within a limited yaw magnitude of several degrees. If the magnitude of the yaw exceeds this limit, Sawyer motors step out. Therefore, the yaw in this study is assumed to be within $\pm 90^o$. The convergence of the estimation error is analyzed using the Lyapunov method. The proposed observer guarantees that the estimation error exponentially converges to zero. Furthermore, since the proposed observer does not require any transformation, the commutation delay may be reduced. The simulation results illustrate the performance of the proposed observer.

This paper is organized as follows. In Section II, a mathematical model is presented. A nonlinear observer is developed in Section III, and the simulation is presented in Section IV. Finally conclusions are made in Section V.

2. Model

A Sawyer motor consists of four forcers (X_1, X_2, Y_1, and Y_2) symmetrically mounted onto a puck. All principles of each forcer are similar to those of the PMSM. The electrical dynamics of forcer X_1 is given [3] by

$$\begin{aligned} \dot{i}_{x_{1a}} &= \frac{1}{L}[v_{x_{1a}} - Ri_{x_{1a}} - \kappa \dot{x}_1 \cos(\gamma x_1)] \\ \dot{i}_{x_{1b}} &= \frac{1}{L}[v_{x_{1b}} - Ri_{x_{1b}} - \kappa \dot{x}_1 \sin(\gamma x_1)] \end{aligned} \tag{1}$$

where x_1 is the position of forcer X_1, $i_{x_{1a}}$ and $i_{x_{1b}}$ are the currents in forcer X_1, $v_{x_{1a}}$ and $v_{x_{1b}}$ are the voltage inputs in the forcer X_1, κ is the force constant, R is the winding resistance, L is the inductance, and $\gamma = 2\pi/p$ where p is the toothpitch, respectively. The electrical dynamics of the other forcers X_2, Y_1 and Y_2 are the same as those of X_1. The forces generated by the forcers X_1, X_2, Y_1, and Y_2 are defined as F_{x_1}, F_{x_2}, F_{y_1}, and F_{y_2}, respectively. The total forces in the x and y directions and the torque are given by

$$\begin{aligned} F_x &= F_{x_1} + F_{x_2} \\ &= \kappa(i_{x_{1a}} \cos(\gamma x_1) + i_{x_{1b}} \sin(\gamma x_1) \\ &\quad + \kappa(i_{x_{2a}} \cos(\gamma x_2) + i_{x_{2b}} \sin(\gamma x_2)) \\ F_y &= F_{y_1} + F_{y_2} \\ &= \kappa(i_{y_{1a}} \cos(\gamma y_1) + i_{y_{1b}} \sin(\gamma y_1) \\ &\quad + \kappa(i_{y_{2a}} \cos(\gamma y_2) + i_{y_{2b}} \sin(\gamma y_2)) \\ \tau &= (F_{x_1} - F_{x_2})r + (F_{y_1} - F_{y_2})r \\ &= [\kappa(i_{y_{1a}} \cos(\gamma y_1) + i_{y_{1b}} \sin(\gamma y_1) \\ &\quad - \kappa(i_{y_{2a}} \cos(\gamma y_2) + i_{y_{2b}} \sin(\gamma y_2))] \\ &\quad + [\kappa(i_{x_{1a}} \cos(\gamma x_1) + i_{x_{1b}} \sin(\gamma x_1) \\ &\quad - \kappa(i_{x_{2a}} \cos(\gamma x_2) + i_{x_{2b}} \sin(\gamma x_2))] \end{aligned} \tag{2}$$

where r is the distance from the center of the motor to the forcer. Therefore, the dynamics of a Sawyer motor may be put in the form of

$$\begin{aligned} \dot{x} &= x_v \\ \dot{x}_v &= \frac{1}{M}[F_x - \eta_x x_v] \\ \dot{y} &= y_v \\ \dot{y}_v &= \frac{1}{M}[F_y - \eta_y y_v] \\ \dot{\theta} &= \theta_v \\ \dot{\theta}_v &= \frac{1}{I}[\tau - \eta_\theta \theta_v] \\ \dot{i}_{x_{1a}} &= \frac{1}{L}[v_{x_{1a}} - Ri_{x_{1a}} - \kappa x_{1_v} \cos(\gamma x_1)] \\ \dot{i}_{x_{1b}} &= \frac{1}{L}[v_{x_{1b}} - Ri_{x_{1b}} - \kappa x_{1_v} \sin(\gamma x_1)] \\ \dot{i}_{x_{2a}} &= \frac{1}{L}[v_{x_{2a}} - Ri_{x_{2a}} - \kappa x_{2_v} \cos(\gamma x_2)] \\ \dot{i}_{x_{2b}} &= \frac{1}{L}[v_{x_{2b}} - Ri_{x_{2b}} - \kappa x_{2_v} \sin(\gamma x_2)] \\ \dot{i}_{y_{1a}} &= \frac{1}{L}[v_{y_{1a}} - Ri_{y_{1a}} - \kappa y_{1_v} \cos(\gamma y_1)] \\ \dot{i}_{y_{1b}} &= \frac{1}{L}[v_{y_{1b}} - Ri_{y_{1b}} - \kappa y_{1_v} \sin(\gamma y_1)] \\ \dot{i}_{y_{2a}} &= \frac{1}{L}[v_{y_{2a}} - Ri_{y_{2a}} - \kappa y_{2_v} \cos(\gamma y_2)] \\ \dot{i}_{y_{2b}} &= \frac{1}{L}[v_{y_{2b}} - Ri_{y_{2b}} - \kappa y_{2_v} \sin(\gamma y_2)] \end{aligned} \tag{3}$$

where x is the X-axis position of the center of the puck, y is the Y-axis position of the center of the puck, θ is the yaw rotation, and $x_1 = x + r\sin(\theta)$, $x_2 = x - r\sin(\theta)$, $y_1 = y + r\sin(\theta)$, and $y_2 = y - r\sin(\theta)$ are the positions of force X_1, X_2, Y_1, and Y_2 respectively. x_{1_v}, x_{2_v}, y_{1_v}, and y_{1_v} are the linear velocities of the forcers, θ_v is the angular velocity of the yaw rotation. The i_i's are the currents in the forcers, the v_i's are the voltage inputs in the forcers, and, η_x, η_y, and η_θ are the coefficients of viscous friction, respectively.

3. Observer Design

The nonlinear observer is proposed such that

$$
\begin{aligned}
&\dot{\hat{x}} = \hat{x}_v + l_x(x-\hat{x})\\
&\dot{\hat{x}}_v = \frac{1}{M}[\kappa(\hat{i}_{x_{1a}}\cos(\gamma x_1) + \hat{i}_{x_{1b}}\sin(\gamma x_1)\\
&\qquad + \kappa(\hat{i}_{x_{2a}}\cos(\gamma x_2) + \hat{i}_{x_{2b}}\sin(\gamma x_2)) - \eta_x\hat{x}_v] + l_{x_v}(x-\hat{x})\\
&\dot{\hat{y}} = \hat{y}_v + l_y(y-\hat{y})\\
&\dot{\hat{y}}_v = \frac{1}{M}[\kappa(\hat{i}_{y_{1a}}\cos(\gamma y_1) + \hat{i}_{y_{1b}}\sin(\gamma y_1)\\
&\qquad + \kappa(\hat{i}_{y_{2a}}\cos(\gamma y_2) + \hat{i}_{y_{2b}}\sin(\gamma y_2)) - \eta_y\hat{y}_v] + l_{y_v}(y-\hat{y})\\
&\dot{\hat{\theta}} = \hat{\theta}_v + l_\theta(\theta-\hat{\theta})\\
&\dot{\hat{\theta}}_v = \frac{1}{I}[\kappa(\hat{i}_{x_{1a}}\cos(\gamma x_1) + \hat{i}_{x_{1b}}\sin(\gamma x_1)\\
&\qquad - \kappa(\hat{i}_{x_{2a}}\cos(\gamma x_2) + \hat{i}_{x_{2b}}\sin(\gamma x_2))\\
&\qquad + \kappa(\hat{i}_{y_{1a}}\cos(\gamma y_1) + \hat{i}_{y_{1b}}\sin(\gamma y_1)\\
&\qquad - \kappa(\hat{i}_{y_{2a}}\cos(\gamma y_2) + \hat{i}_{y_{2b}}\sin(\gamma y_2)) - \eta_\theta\hat{\theta}_v] + l_{\theta_v}(\theta-\hat{\theta})\\
&\dot{\hat{i}}_{x_{1a}} = \frac{1}{L}[v_{x_{1a}} - R\hat{i}_{x_{1a}} - \kappa\hat{x}_{1_v}\cos(\gamma x_1)] + l_{x_{1a}}(x-\hat{x})\\
&\dot{\hat{i}}_{x_{1b}} = \frac{1}{L}[v_{x_{1b}} - R\hat{i}_{x_{1b}} - \kappa\hat{x}_{1_v}\sin(\gamma x_1)] + l_{x_{1b}}(x-\hat{x})\\
&\dot{\hat{i}}_{x_{2a}} = \frac{1}{L}[v_{x_{2a}} - R\hat{i}_{x_{2a}} - \kappa\hat{x}_{2_v}\cos(\gamma x_2)] + l_{x_{2a}}(x-\hat{x})\\
&\dot{\hat{i}}_{x_{2b}} = \frac{1}{L}[v_{x_{2b}} - R\hat{i}_{x_{2b}} - \kappa\hat{x}_{2_v}\sin(\gamma x_2)] + l_{x_{2b}}(x-\hat{x})\\
&\dot{\hat{i}}_{y_{1a}} = \frac{1}{L}[v_{y_{1a}} - R\hat{i}_{y_{1a}} - \kappa\hat{y}_{1_v}\cos(\gamma y_1)] + l_{y_{1a}}(y-\hat{y})\\
&\dot{\hat{i}}_{y_{1b}} = \frac{1}{L}[v_{y_{1b}} - R\hat{i}_{y_{1b}} - \kappa\hat{y}_{1_v}\sin(\gamma y_1)] + l_{y_{1b}}(y-\hat{y})\\
&\dot{\hat{i}}_{y_{2a}} = \frac{1}{L}[v_{y_{2a}} - R\hat{i}_{y_{2a}} - \kappa\hat{y}_{2_v}\cos(\gamma y_2)] + l_{y_{2a}}(y-\hat{y})\\
&\dot{\hat{i}}_{y_{2b}} = \frac{1}{L}[v_{y_{2b}} - R\hat{i}_{y_{2b}} - \kappa\hat{y}_{2_v}\sin(\gamma y_2)] + l_{y_{2b}}(y-\hat{y})
\end{aligned}
\tag{4}
$$

where $\hat{x}$ is the estimation of the X position of Sawyer motor, $\hat{x}_1$ is the estimation of the X position of forcer X_1, $\hat{x}_2$ is the where $\hat{x}$ is the estimation of the X position of Sawyer motor, $\hat{x}_1$ is the estimation of the X position of forcer X_1, $\hat{x}_2$ is the estimation of the X position of forcer X_2, $\hat{y}$ is the estimation of the Y position of Sawyer motor, $\hat{y}_1$ is the estimation of the Y position of forcer Y_1, $\hat{y}_2$ is the estimation of the Y position of forcer Y_2, and $\hat{\theta}$ is the estimation of yaw, respectively. The velocity estimations are represented by $\hat{x}_v$, $\hat{y}_v$, $\hat{x}_{1_v}$, $\hat{x}_{2_v}$, $\hat{y}_{1_v}$, $\hat{y}_{2_v}$, and $\hat{\theta}_v$. the $\hat{i}'_i$s are the estimations of the phase currents and the l_i's are the observer gains, respectively. We define the estimation errors such that

$$
\begin{aligned}
&\tilde{x} = x - \hat{x},\ \tilde{y} = y - \hat{y},\ \tilde{\theta} = \theta - \hat{\theta},\\
&\tilde{x}_v = x_v - \hat{x}_v,\ \tilde{y}_v = y_v - \hat{y}_v,\\
&\tilde{x}_{1_v} = x_{1_v} - \hat{x}_{1_v},\ \tilde{y}_{1_v} = y_{1_v} - \hat{y}_{1_v},\\
&\tilde{x}_{2_v} = x_{2_v} - \hat{x}_{2_v},\ \tilde{y}_{2_v} = y_{2_v} - \hat{y}_{2_v},\\
&\tilde{\theta}_v = \theta_v - \hat{\theta}_v.\ \tilde{i}_i = i_i - \hat{i}_i.
\end{aligned}
\tag{5}
$$

Then the error dynamics becomes

$$
\begin{aligned}
&\dot{\tilde{x}} = -l_x\tilde{x} + \tilde{x}_v\\
&\dot{\tilde{x}}_v = -l_{x_v}\tilde{x} + \frac{1}{M}[\kappa(\tilde{i}_{x_{1a}}\cos(\gamma x_1) + \tilde{i}_{x_{1b}}\sin(\gamma x_1)\\
&\qquad + \kappa(\tilde{i}_{x_{2a}}\cos(\gamma x_2) + \tilde{i}_{x_{2b}}\sin(\gamma x_2))\\
&\qquad - \eta_x\tilde{x}_v]\\
&\dot{\tilde{y}} = -l_y\tilde{y} + \tilde{y}_v\\
&\dot{\tilde{y}}_v = -l_{y_v}\tilde{y} + \frac{1}{M}[\kappa(\tilde{i}_{y_{1a}}\cos(\gamma y_1) + \tilde{i}_{y_{1b}}\sin(\gamma y_1)\\
&\qquad + \kappa(\tilde{i}_{y_{2a}}\cos(\gamma y_2) + \tilde{i}_{y_{2b}}\sin(\gamma y_2))\\
&\qquad - \eta_y\tilde{y}_v\\
&\dot{\tilde{\theta}} = -l_\theta\tilde{\theta} + \tilde{\theta}_v\\
&\dot{\tilde{\theta}}_v = -l_{\theta_v}\tilde{\theta} + \frac{1}{I}[\kappa(\tilde{i}_{x_{1a}}\cos(\gamma x_1) + \tilde{i}_{x_{1b}}\sin(\gamma x_1)\\
&\qquad - \kappa(\tilde{i}_{x_{2a}}\cos(\gamma x_2) + \tilde{i}_{x_{2b}}\sin(\gamma x_2))\\
&\qquad + \kappa(\tilde{i}_{y_{1a}}\cos(\gamma y_1) + \tilde{i}_{y_{1b}}\sin(\gamma y_1)\\
&\qquad - \kappa(\tilde{i}_{y_{2a}}\cos(\gamma y_2) + \tilde{i}_{y_{2b}}\sin(\gamma y_2)) - \eta_\theta\tilde{\theta}_v]\\
&\dot{\tilde{i}}_{x_{1a}} = -l_{x_{1a}}\tilde{x} + \frac{1}{L}[-R\tilde{i}_{x_{1a}} - \kappa\tilde{x}_{1_v}\cos(\gamma x_1)]\\
&\dot{\tilde{i}}_{x_{1b}} = -l_{x_{1b}}\tilde{x} + \frac{1}{L}[-R\tilde{i}_{x_{1b}} - \kappa\tilde{x}_{1_v}\sin(\gamma x_1)]\\
&\dot{\tilde{i}}_{x_{2a}} = -l_{x_{2a}}\tilde{x} + \frac{1}{L}[-R\tilde{i}_{x_{2a}} - \kappa\tilde{x}_{2_v}\cos(\gamma x_2)]\\
&\dot{\tilde{i}}_{x_{2b}} = -l_{x_{2b}}\tilde{x} + \frac{1}{L}[-R\tilde{i}_{x_{2b}} - \kappa\tilde{x}_{2_v}\sin(\gamma x_2)]\\
&\dot{\tilde{i}}_{y_{1a}} = -l_{y_{1a}}\tilde{y} + \frac{1}{L}[-R\tilde{i}_{y_{1a}} - \kappa\tilde{y}_{1_v}\cos(\gamma y_1)]\\
&\dot{\tilde{i}}_{y_{1b}} = -l_{y_{1b}}\tilde{y} + \frac{1}{L}[-R\tilde{i}_{y_{1b}} - \kappa\tilde{y}_{1_v}\sin(\gamma y_1)]\\
&\dot{\tilde{i}}_{y_{2a}} = -l_{y_{2a}}\tilde{y} + \frac{1}{L}[-R\tilde{i}_{y_{2a}} - \kappa\tilde{y}_{2_v}\cos(\gamma y_2)]\\
&\dot{\tilde{i}}_{y_{2b}} = -l_{y_{2b}}\tilde{y} + \frac{1}{L}[-R\tilde{i}_{y_{2b}} - \kappa\tilde{y}_{2_v}\sin(\gamma y_2)].
\end{aligned}
\tag{6}
$$

For the proof of the stability of the error dynamics (6), the Lyapunov candidate function is defined as

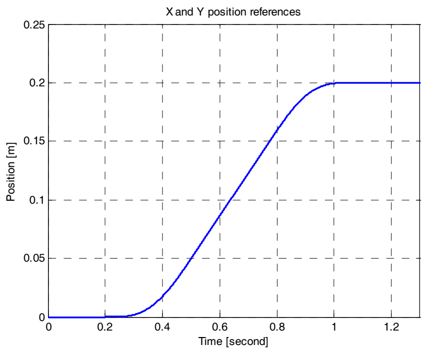

Fig. 2 Position references of *x* and *y*

$$V=\frac{1}{2}\Big(\tilde{x}^2+\frac{M}{L}\tilde{x}_v^2+\tilde{y}^2+\frac{M}{L}\tilde{y}_v^2+\tilde{\theta}^2+\frac{I\cos(\theta)}{L}\tilde{\theta}_v^2 + \tilde{i}_{x_{1a}}^2+\tilde{i}_{x_{1b}}^2+\tilde{i}_{x_{2a}}^2+\tilde{i}_{x_{2b}}^2+\tilde{i}_{y_{1a}}^2+\tilde{i}_{y_{1b}}^2+\tilde{i}_{y_{2a}}^2+\tilde{i}_{y_{2b}}^2\Big). \tag{7}$$

We assume that the yaw is within $\pm 90^o$ so that V is always positive definite. If l_x, l_y, l_θ are positive, l_{x_v} and l_{y_v} are L_0/M, l_{θ_v} is L_0/I, and the other observer gains are zeros, the derivative of V becomes the negative definite function

$$\dot{V}=-l_x\tilde{x}^2-\frac{\eta_x}{L}\tilde{x}_v^2-l_y\tilde{y}^2-\frac{\eta_y}{L}\tilde{y}_v^2-l_\theta\tilde{\theta}^2-\frac{\eta_\theta}{L}\tilde{\theta}_v^2 -\frac{R}{L}\big(\tilde{i}_{x_{1a}}^2+\tilde{i}_{x_{1b}}^2+\tilde{i}_{x_{2a}}^2+\tilde{i}_{x_{2b}}^2+\tilde{i}_{y_{1a}}^2+\tilde{i}_{y_{1b}}^2+\tilde{i}_{y_{2a}}^2+\tilde{i}_{y_{2b}}^2\big). \tag{8}$$

Therefore, the estimation error exponentially converges to zero for all arbitrary initial conditions. In (8) we see that the convergence rate of the estimation error depends on l_x, l_y, l_θ, η_x, η_y, η_θ, L, and R.

4. Simulation Results

Simulations were executed to evaluate the performance of the proposed control using Matlab/Simulink. A Sawyer motor was operated using open-loop microstepping. In simulations, it was assumed that there are no disturbance and parameter uncertainties; therefore, the yaw was zero due to the synchronization of the forcers. The parameters of the Sawyer motor used in simulations are $M=1.35$kg, $I=0.004$kg/m^2, $r=0.0485$m, $p=1.016$mm, $\gamma=2\pi/p$, $\kappa=17$ N/A, $L=0.7$mH, $R=2\Omega$, η_x = 0.4, η_y = 0.4, and η_θ = 0.4 , respectively. And the observer gains are $l_x=1000$, $l_y=1000$, $l_\theta=1000$, $l_{x_v}=5.1852\times10^{-4}$, $l_{y_v}=5.1852\times10^{-4}$, $l_{\theta_v}=0.175$, $l_{x_{1a}}=0$, $l_{x_{1b}}=0$, $l_{x_{2a}}=0$, $l_{x_{2b}}=0$, $l_{y_{1a}}=0$, $l_{y_{1b}}=0$, $l_{y_{2a}}=0$, and $l_{y_{2b}}=0$, respectively. Figure 2 shows the references for x and y. The estimation results of the positions and velocities are shown in Figs. 3, 4, 5, and 6. We see that the estimated states agreed well with the actual states. And the current estimation results of x_1 are depicted in Figs. 7, and 8. Figures 9 and 10 are magnified images of the estimation results in order to show them in more

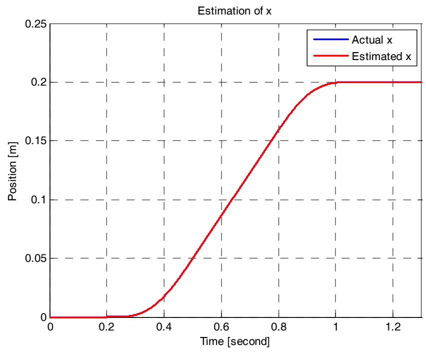

Fig. 3 The estimation of x

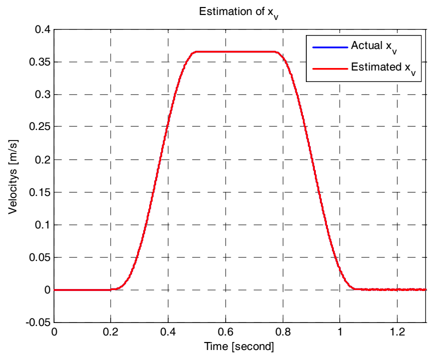

Fig. 4 The estimation of x_v

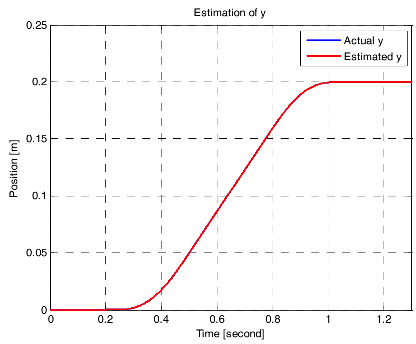

Fig. 5 The estimation of y

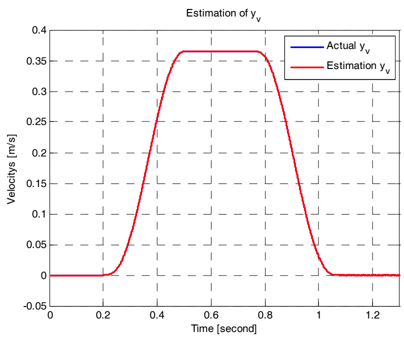

Fig. 6 The estimation of y_v

detail. It is shown that the actual currents and the estimates had the same responses.

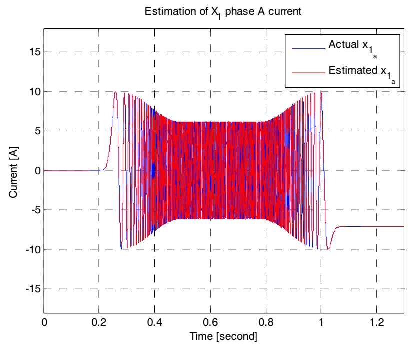

Fig. 7 The estimation of phase A current of Forcer X_1

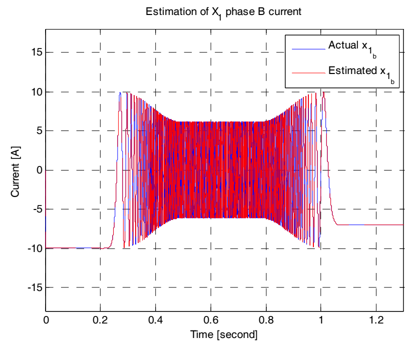

Fig. 8 The estimation of phase B current of Forcer X_1

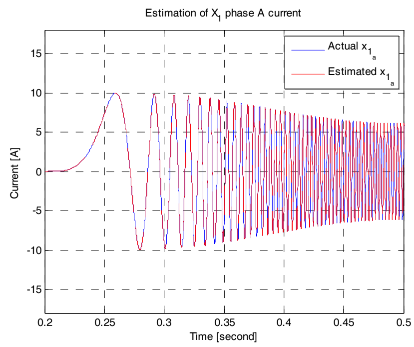

Fig. 9 The zoom plot of estimation of phase A current of Forcer X_1

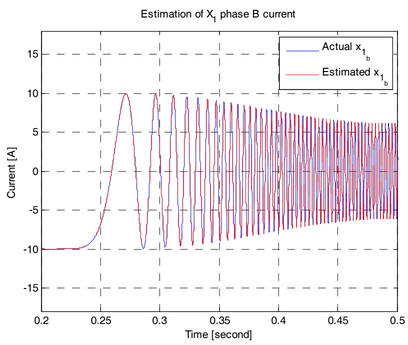

Fig. 10 The zoom plot of estimation of phase B current of Forcer X_1

Figures 11, 12, 13, and 14 are the estimation results with the mechanical disturbances; $f_{dx} = 0.14(1+0.5\cos(3t))\dot{x} + 2\sin(4\gamma x)$

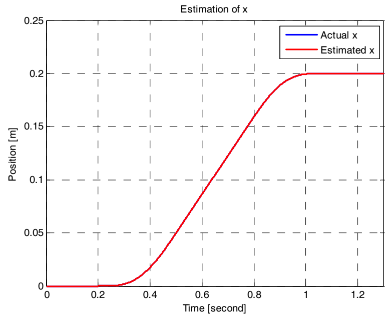

Fig. 11 The estimation of x with disturbances

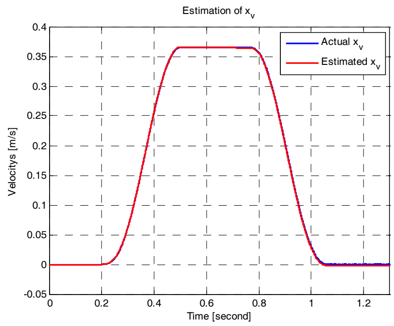

Fig. 12 The estimation of x_v with disturbances

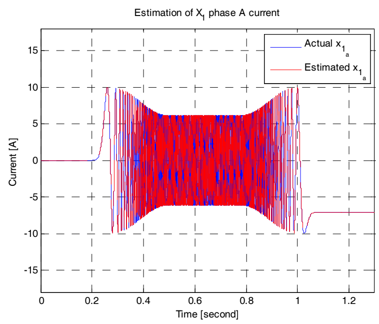

Fig. 13 The estimation of phase A current of Forcer X_1 with disturbances

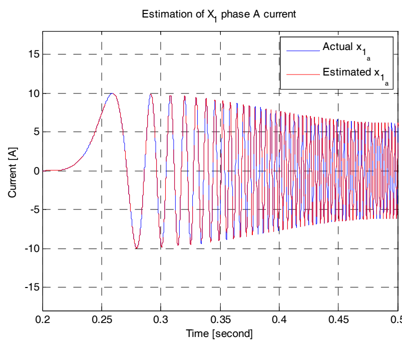

Fig. 14 The zoom plot of estimation of phase A current of Forcer X_1 with disturbances

$f_{dy} = 0.14(1+0.5\cos(5t))\dot{y} + 2\sin(4\gamma y)$, $\tau_l = 0.5(1+0.5\cos(2t))\dot{\theta}$. Although mechanical disturbances existed in Sawyer motors, we see that the estimated states agreed well with the actual states.

4. Conclusion

In this paper, a nonlinear observer was proposed to estimate the phase currents and velocities of four forcers in a Sawyer motor. The proposed method estimates the full states using only positional feedback. The convergence of the estimation error was proven using the Lyapunov method. The proposed observer guarantees that the estimation error globally exponentially converges to zero. Furthermore, since the proposed observer does not require any transformation, the commutation delay may be reduced. The simulation results showed the estimated states agreed well with the actual states although there exist the mechanical disturbances.

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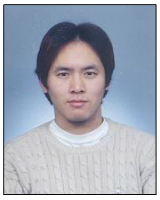

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