International Journal of Innovative Computing, Information and Control
Volume **16**, Number **5**, October **2020**

ICIC International ©2020 ISSN 1349-4198
pp. 1811–1820

A NOVEL FINITE-TIME EXTENDED STATE OBSERVER FOR A CLASS OF NONLINEAR SYSTEM WITH EXTERNAL DISTURBANCE

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Received May 2020; revised August 2020

Abstract. *In this paper, a novel finite-time extended state observer is proposed for a class of nonlinear systems with external disturbance. Considering external disturbance as an additional state, disturbance observer design is transformed into state observer design. The newly developed extended state observer adopts fractional power and switching term that are related to output estimation error to achieve finite time convergence for all error states. A numerical simulation is implemented to verify the performance of the proposed novel finite-time extended state observer.*
Keywords: Extended state observer, Finite time convergence, Disturbance observer, Switching term, Fractional power

1. **Introduction.** In engineering, model of some systems is expressed as integral-chain system, such as position servo control system. Integral-chain systems are widely studied in literature. Most systems can also be converted into integral-chain nonlinear systems. Significant uncertainties and external disturbances widely exist in various practical systems [8,11,13,27]. They significantly degrade the performance of control systems and even affect the stability of control systems [2]. Therefore, integral-chain nonlinear systems with uncertainties and external disturbances have a wide range of application significance. For this kind of system, it has been widely recognized that uncertainty and disturbance rejection are important in the field of control. If a disturbance is known or measurable, then the disturbance can be attenuated or eliminated by feedforward [7,15]. However, quite often, uncertainty and disturbance are unknown or directly measured. Uncertainty and disturbance estimation has attracted a great deal of attention in the last few decades [2]. There exist various disturbance observers such as unknown input observer [17,19], uncertainty and disturbance estimator [35], iterative learning observer [3], perturbation observer [14] and the disturbance observer [28,29]. However, these disturbance estimating methods usually require all system states [4,9,10]. In practice, many advanced control strategies also need full-state information. For most of practical systems, it is hard to obtain all system states. Even if these states can be measured, heavy measurement noise may also deteriorate the performance of control system [31]. Extended state observer (ESO) can not only observe the system states, but also estimate the disturbances. And ESO is a promising observer since it does not require accurate mathematical model [30].

DOI: 10.24507/ijicic.16.05.1811

Therefore, ESO has been applied into many engineering practices, such as load simulator [16], quad-rotor vehicle [33], vehicle active suspensions [22], guidance law design [37], DC-DC buck power converter systems [24], electro-hydraulic actuator [5] and robot control [32].

In ESO design, the internal uncertainty and external disturbance are lumped as total disturbance. The total disturbance is augmented as a new state. Hence, disturbance observer design is transformed into state observer design. If the lumped disturbance is a constant (or changes slowly), i.e., the first time derivative of the lumped disturbance is zero, then traditional linear ESO (LESO) can guarantee the asymptotic stability [6]. If the first time derivative of lumped disturbance is bound, then traditional linear ESO only guarantees boundedness of the estimation error [6]. Compared with LESO, nonlinear ESO adopts a kind of saturation function to increase convergence rate and avoid chattering [34]. However, the rate of convergence far away from the equilibrium point is slow. A novel extended state observer was presented in [25]. The designed extended state observer used both nonlinear and switching terms related to the output estimation error. So it possesses faster convergence rate and smaller estimation error. However, the estimation errors still converge to a residual set when the first time derivative of lumped disturbance is bound.

Compared with asymptotic convergence, finite time convergence can provide a faster convergence rate and better disturbance rejection [12]. Finite time state observers are investigated in [1,18,20,21,23,26]. Inspired by these references, a novel finite-time extended state observer is proposed for a class of nonlinear systems with external disturbance in this paper. First, external disturbance is extended as an additional state. Then, based on the super-twisting algorithm, the novel finite-time extended state observer is designed. Finally, finite-time stability is proved by Lyapunov stability theory.

This paper is organized as follows. Section 2 presents problem statement and preliminaries and the observer design and the proof of stability are given in Section 3. Section 4 shows an illustrative example and Section 5 gives the conclusions.

2. **Problem Statement and Preliminaries.**

Let us consider a second order nonlinear dynamical system with single-input and single-output

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2) + bu + \omega(t) \end{cases} \tag{1}$$

where x_i $(i = 1, 2)$ denote the system states, $f(x_1, x_2)$ is a known function which belongs to C^2 and is considered as Lipschitz function with respect to state variables x_i $(i = 1, 2)$, $\omega(t)$ is the lumped disturbance including uncertainties and external disturbances, b is control gain, and u is the control input.

Remark 2.1. *For system (1), $f(x_1, x_2)$ is the known function. If $f(x_1, x_2)$ is unknown, then it can be treated as the part of the lumped disturbance.*

Assumption 2.1. *The lumped disturbance $\omega(t)$ in system is continuous and satisfies $|\omega(t)| \le d_1$ and $|\dot{\omega}(t)| \le d_2$, where the positive scalars d_1 and d_2 are finite and known.*

Lemma 2.1. [36]. *Suppose that $V(x)$ is a smooth positive definite function on $U \subset R^n$ and satisfies the differential inequality*

$$\dot{V}(x) + \beta_1 V(x) + \beta_2 V^{\chi}(x) \le 0 \tag{2}$$

where $\beta_1 > 0$, $\beta_2 > 0$ and $0 < \chi < 1$ are constants. Then, for any given t_0, there exists an area $U_0 \subset R^n$ such that any $V(x)$ which starts from U_0 can reach at $V(x) \equiv 0$ in finite *time and the settling time t_r satisfies*

$$t_r = t_0 + \frac{1}{\beta_1(1-\chi)} \ln\left(\frac{\beta_1 V^{1-\chi}(x_0) + \beta_2}{\beta_2}\right) \tag{3}$$

For nonlinear system (1), disturbance estimation requires all system states x_1 and x_2, even their derivative. In practice, the output x_1 can be measured. However, quite often, the state x_2 is unknown or directly measured. The ESO is an effective means to tackle this problem. The common extended state observer can only guarantee that the estimation error converges to a very small range centered on zero. A finite time extended state observer will be developed in the next section, which guarantees that the estimation error converges to zero.

3. **FTESO Design and Analysis.** The lumped disturbance $\omega(t)$ can be extended as an additional state variable, i.e., $x_3 = \omega(t)$. And the system state x is now extended to $x = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T$. Let $h(t)$ represent the time derivative of x_3, and then the system (1) can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2) + bu + x_3 \\ \dot{x}_3 = h(t) \end{cases} \tag{4}$$

A novel finite-time extended state observer for system (4) is designed as

$$\begin{cases} \dot{\hat{x}}_1 = k_1\phi(\tilde{x}_1) + \hat{x}_2 \\ \dot{\hat{x}}_2 = k_2\vartheta(\tilde{x}_1)\phi(\tilde{x}_1) + f(\hat{x}_1, \hat{x}_2) + \hat{x}_3 + bu \\ \dot{\hat{x}}_3 = k_3\vartheta(\tilde{x}_1)\phi(\tilde{x}_1) \end{cases} \tag{5}$$

where $\phi(\tilde{x}_1) = sig^{\frac{1}{2}}(\tilde{x}_1) + \lambda sig^{\alpha}(\tilde{x}_1)$, $\vartheta(\tilde{x}_1) = \frac{1}{2}|\tilde{x}_1|^{-\frac{1}{2}} + \alpha\lambda|\tilde{x}_1|^{\alpha-1}$, $\hat{x}_1$, $\hat{x}_2$ and $\hat{x}_3$ are estimations of states x_1, x_2 and x_3, respectively, $\alpha > 1$ and $\lambda > 0$ are adjustable coefficients of observer, and k_1, k_2 and k_3 are observer gains.

Estimation error dynamics of observer can be written as

$$\begin{cases} \dot{\tilde{x}}_1 = -k_1\phi(\tilde{x}_1) + \tilde{x}_2 \\ \dot{\tilde{x}}_2 = -k_2\vartheta(\tilde{x}_1)\phi(\tilde{x}_1) + \tilde{f} + \tilde{x}_3 \\ \dot{\tilde{x}}_3 = -k_3\vartheta(\tilde{x}_1)\phi(\tilde{x}_1) \end{cases} \tag{6}$$

where $\tilde{f} = f(x_1, x_2) - f(\hat{x}_1, \hat{x}_2)$.

Remark 3.1. *There is no published literature applying the super-twisting algorithm into the design of third-order ESO. Compared with the LESO [6], the proposed scheme can guarantee finite time convergence. Compared with finite-time ESO [20,25], the proposed scheme feeds back the output estimation error via both nonlinear and switching terms, not only to guarantee fast convergence and robustness, but also make the estimate error converge to zero.*

To analyze stability of observer, a new vector is defined as

$$\varsigma = \begin{bmatrix} \varsigma_1 & \varsigma_2 & \varsigma_3 \end{bmatrix}^T = \begin{bmatrix} \phi(\tilde{x}_1) & \tilde{x}_2 & \tilde{x}_3 \end{bmatrix}^T \tag{7}$$

According to the equality $\varsigma_1 = \phi(\tilde{x}_1)$, the derivative of ς_1 can be deducted as

$$\dot{\varsigma}_1 = \dot{\phi}(\tilde{x}_1) = \left(\frac{1}{2}|\tilde{x}_1|^{-\frac{1}{2}} + \alpha\lambda_1|\tilde{x}_1|^{\alpha-1}\right)\dot{\tilde{x}}_1 = \vartheta(\tilde{x}_1)\dot{\tilde{x}}_1 \tag{8}$$

According to Equation (6), Equation (7) and Equation (8), it follows that

$$\dot{\varsigma} = \vartheta(\tilde{x}_1)\left(A\varsigma + B\bar{h}\right) + F \tag{9}$$

where

$$A = \begin{bmatrix} -k_1 & 1 & 0 \\ -k_2 & 0 & 1 \\ -k_3 & 0 & 0 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},\ F = \begin{bmatrix} 0 \\ \tilde{f} \\ (\varepsilon(\tilde{x}_1) - 1)\tilde{x}_3 \end{bmatrix},\ \bar{h} = \frac{h(t)}{\vartheta(\tilde{x}_1)},\ \varepsilon(\tilde{x}_1) = \frac{1}{\vartheta(\tilde{x}_1)}.$$

Note that

$$\varepsilon(\tilde{x}_1) = \frac{1}{\vartheta(\tilde{x}_1)} = \frac{1}{\frac{1}{2}|\tilde{x}_1|^{-\frac{1}{2}} + \alpha\lambda|\tilde{x}_1|^{\alpha-1}} \tag{10}$$

Using the derivative and the second derivative of $\varepsilon(\tilde{x}_1)$, it can be easily proved that $\varepsilon(\tilde{x}_1)$ is bound. That is to say, the term $\varepsilon(\tilde{x}_1)$ satisfies the constraint $0 < \varepsilon(\tilde{x}_1) < \sigma$, where σ is a constant value related to the constant coefficients α and λ.

Proposition 3.1. *For the system (1), the finite-time extended observer is designed as Equation (5). Estimation errors $\tilde{x}_1$, $\tilde{x}_2$ and $\tilde{x}_3$ will converge to zero in finite time if the gains k_1, k_2 and k_3 are chosen so that there exists a suitable matrix $P = P^T$ such that*

$$A^TP + PA + PBB^TP + 4C^TC + \delta I = 0 \tag{11}$$

where δ is a positive constant, $C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$.

Proof: A Lyapunov function can be written as

$$V = \varsigma^T P\varsigma \tag{12}$$

Obviously, the following inequality is established:

$$|\vartheta(\tilde{x}_1)\varsigma_1| = \frac{1}{2} + \left(\frac{1}{2} + \alpha\right)\lambda|\tilde{x}_1|^{\alpha-\frac{1}{2}} + \alpha\lambda^2|\tilde{x}_1|^{2\alpha-1} \geq \frac{1}{2} \tag{13}$$

Considering Inequality (13), it follows that

$$\bar{h} = \frac{h(t)}{\vartheta(\tilde{x}_1)} \leq \frac{h(t)}{\vartheta(\tilde{x}_1)\varsigma_1}|\varsigma_1| \leq 2|\varsigma_1| = 2|C\varsigma| \tag{14}$$

According to the definition of Euclidean norm, it follows that

$$\|\varsigma\|^2 = [\phi(\tilde{x}_1)]^2 + \tilde{x}_2^2 + \tilde{x}_3^2 \geq c_\lambda^2|\tilde{x}_1|^2 + \tilde{x}_2^2 + \tilde{x}_3^2 \tag{15}$$

where $c_\lambda = \min\{1, \lambda_1\}$, $\|\bullet\|$ is the Euclidean norm of $\bullet$.

Since the function $f(x_1, x_2)$ is Lipschitz, a group of known positive constants c_i $(i = 1, 2)$ exist to satisfy the Lipschitz conditions

$$\left|\tilde{f}\right| \leq c_1|\tilde{x}_1| + c_2|\tilde{x}_2| \tag{16}$$

According to Inequalities (15) and (16), there exists a positive constant c_ς such that

$$\|F\|^2 = \left\|\begin{bmatrix} 0 & \tilde{f} & (\varepsilon(\tilde{x}_1) - 1)\tilde{x}_3 \end{bmatrix}^T\right\|^2 \leq 2c_1^2|\tilde{x}_1|^2 + 2c_2^2|\tilde{x}_2|^2 + c_\varepsilon^2|\tilde{x}_3|^2 \leq c_\varsigma^2\|\varsigma\|^2 \tag{17}$$

where $c_\varepsilon = \max\{|\varepsilon(\tilde{x}_1) - 1|\}$, $c_\varsigma = \max\left\{\frac{\sqrt{2}c_1}{c_\lambda}, \sqrt{2}c_2, c_\varepsilon\right\}$.

Using Equations (9), (12), (14) and (17), the time derivative of V is given by

$$\begin{aligned} \dot{V} &= \dot{\varsigma}^T P\varsigma + \varsigma^T P\dot{\varsigma} \\ &= \vartheta(\tilde{x}_1)\left[\varsigma^T\left(A^T P + PA\right)\varsigma + 2\varsigma^T PB\bar{h} + 2\varsigma^T PF\right] \\ &\le \vartheta(\tilde{x}_1)\left[\varsigma^T\left(A^T P + PA\right)\varsigma + \varsigma^T PB^T BP\varsigma + \left|\bar{h}\right|^2 + 2c_\varsigma \|P\| \|\varsigma\|^2\right] \\ &\le \vartheta(\tilde{x}_1)\left[\varsigma^T\left(A^T P + PA + PB^T BP + 4C^T C\right)\varsigma + 2c_\varsigma \|P\| \|\varsigma\|^2\right] \end{aligned} \tag{18}$$

The following inequality for quadratic forms holds

$$\lambda_{\min}(P)\|\varsigma\|^2 \le \varsigma^T P\varsigma \le \lambda_{\max}(P)\|\varsigma\|^2 \tag{19}$$

According to the definition of Euclidean norm, it follows that

$$\|\varsigma\|^2 = [\phi(\tilde{x}_1)]^2 + \tilde{x}_2^2 + \tilde{x}_3^2 \ge \lambda_1^2 |\tilde{x}_1|^{2\alpha} \tag{20}$$

According to Inequality (19) and Inequality (20), the following inequality holds

$$\lambda_1^2 |\tilde{x}_1|^{2\alpha} \le \|\varsigma\|^2 \le \frac{V}{\lambda_{\min}(P)} \tag{21}$$

From Inequality (21), one obtains

$$|\tilde{x}_1| \le \left(\frac{V}{\lambda_1^2\lambda_{\min}(P)}\right)^{\frac{1}{2\alpha}} \tag{22}$$

$$|\tilde{x}_1|^{-\frac{1}{2}} \ge \left(\frac{V}{\lambda_1^2\lambda_{\min}(P)}\right)^{-\frac{1}{4\alpha}} \tag{23}$$

Substituting the equality $\vartheta(\tilde{x}_1) = \frac{1}{2}|\tilde{x}_1|^{-\frac{1}{2}} + \alpha\lambda_1|\tilde{x}_1|^{\alpha-1}$ into Inequality (18), and considering Inequalities (19) and (23), Inequality (18) can be rewritten as

$$\begin{aligned} \dot{V} &\le -\left(\delta - 2c_\varsigma\|P\|\right)\vartheta(\tilde{x}_1)\|\varsigma\|^2 \\ &\le -\left(\delta - 2c_\varsigma\|P\|\right)\left(\frac{1}{2}|\tilde{x}_1|^{-\frac{1}{2}} + \alpha\lambda_1|\tilde{x}_1|^{\alpha-1}\right)\frac{V}{\lambda_{\max}(P)} \\ &\le \left(\delta - 2c_\varsigma\|P\|\right)\left(-\chi_1 V^{\frac{4\alpha-1}{4\alpha}} - \chi_2 V\right) \end{aligned} \tag{24}$$

where $\chi_1 = \frac{\lambda_1^{\frac{1}{2\alpha}}[\lambda_{\min}(P)]^{\frac{1}{4\alpha}}}{2\lambda_{\max}(P)}$, $\chi_2 = \frac{\alpha\lambda_1|\tilde{x}_1|^{\alpha-1}}{\lambda_{\max}(P)}$.

Consequently, according to Lemma 2.1, if the coefficients are properly chosen so that the condition $\delta > 2c_\varsigma\|P\|$ is satisfied, estimation errors will then converge to the zero in finite time. This completes the proof.

Remark 3.2. *Notice that V in (12) is continuous and differentiable everywhere except when $\tilde{x}_1 = 0$. It is obvious that V is positive definite and radially unbounded. It is proved that $\dot{V}$ is negative definite except when $\tilde{x}_1 = 0$. Before arriving at the equilibrium point $(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3) = (0,0,0)$, the trajectories of system (1) cannot stay on the plane $\tilde{x}_1 = 0$. And it will intersect the plane $\tilde{x}_1 = 0$ when $(\tilde{x}_2, \tilde{x}_3) \ne (0,0)$ before reaching the origin. This means that $\dot{V}$ exists almost everywhere and V decreases until the system reaches the equilibrium. If the origin is reached at some time T, then the trajectory will stay there.*

Although the proposed novel extended state observer is designed for a second order system, we can conveniently extend this result to the high order systems.

Considering the following n-dimensional nonlinear system

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \vdots \\ \dot{x}_{n-1} = x_n \\ \dot{x}_n = f(x_1, \dots, x_n) + \omega(t) + bu \end{cases} \tag{25}$$

where x_i $(i = 1, 2, \dots, n)$ are the system states, $f(x_1, \dots, x_n)$ is the known function which is considered as Lipschitz function with respect to state variables x_i $(i = 1, 2, \dots, n)$.

The lumped disturbance $\omega(t)$ is considered as a new state variable. System (25) can be then rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \vdots \\ \dot{x}_n = x_{n+1} + f(x_1, \dots, x_n) + bu \\ \dot{x}_{n+1} = h(t) \end{cases} \tag{26}$$

A novel finite-time extended state observer for system (26) is designed as

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + k_1\phi\left(\tilde{x}_1\right) \\ \dot{\hat{x}}_2 = \hat{x}_3 + k_2\vartheta\left(\tilde{x}_1\right)\phi\left(\tilde{x}_1\right) \\ \vdots \\ \dot{\hat{x}}_n = \hat{x}_{n+1} + bu + k_n\vartheta\left(\tilde{x}_1\right)\phi\left(\tilde{x}_1\right) \\ \dot{\hat{x}}_{n+1} = k_{n+1}\vartheta\left(\tilde{x}_1\right)\phi\left(\tilde{x}_1\right) \end{cases} \tag{27}$$

where $\hat{x}_i$ $(i = 1, 2, \dots, n)$ are estimations of system states x_i $(i = 1, 2, \dots, n)$, k_i $(i = 1, 2, \dots, n)$ are observer gains.

By borrowing the primary analysis utilized in the proof of Proposition 3.1, estimation errors $\tilde{x}_i$ $(i = 1, 2, \dots, n)$ will converge to the origin in finite time if the gains k_i $(i = 1, 2, \dots, n)$ are chosen.

4. **Simulation Results.** To investigate the performance of the proposed method, simulation based on MATLAB/Simulink was conducted.

Consider the following second order nonlinear plant

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \omega(t) + 133\sin(0.2\pi t) \end{cases} \tag{28}$$

where $\omega(t)$ denotes the lumped uncertainty, and $133\sin(0.2\pi t)$ represents the system input.

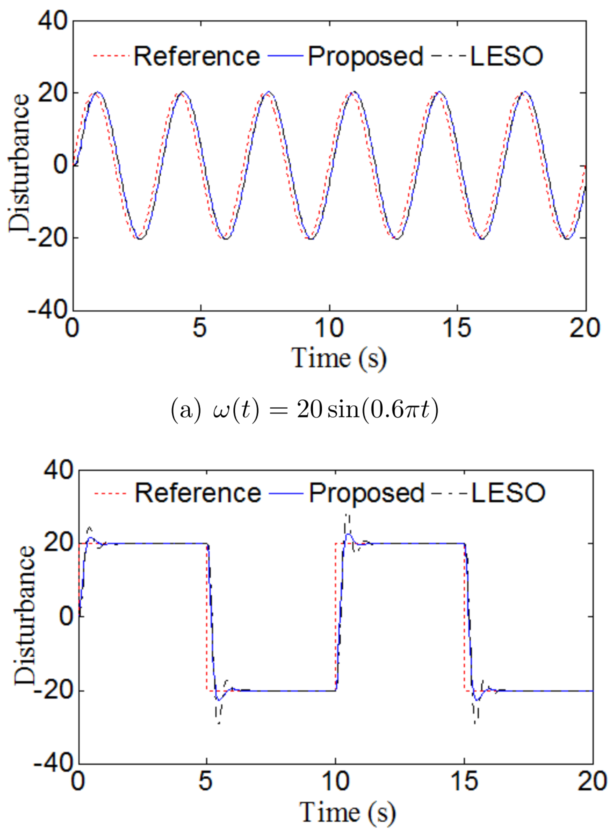
The FTESO for system (28) is designed as

$$\begin{cases} \dot{\hat{x}}_1 = k_1\phi\left(\tilde{x}_1\right) + \hat{x}_2 \\ \dot{\hat{x}}_2 = k_2\vartheta\left(\tilde{x}_1\right)\phi\left(\tilde{x}_1\right) + \hat{x}_3 + 133\sin(0.2\pi t) \\ \dot{\hat{x}}_3 = k_3\vartheta\left(\tilde{x}_1\right)\phi\left(\tilde{x}_1\right) \end{cases} \tag{29}$$

In order to show the performance of the proposed observer, the LESO is used as a comparison. In this simulation, the parameters in observer (29) are designed as $k_1 = 20$,

$k_2 = 180$, $k_3 = 1200$, $\alpha = 1.05$ and $\lambda = 1$. The first order Euler algorithm with a sample time of 0.001s is adopted in the simulation.

First, the square disturbance $\omega(t) = 20sign(\sin(0.2\pi t))$ and the sinusoidal disturbance $\omega(t) = 20\sin(0.6\pi t)$ are employed to investigate the performance of the proposed method. Figure 1(a) shows the estimation results for sinusoidal disturbances. It can be indicated that the proposed observer and LESO have the same bandwidth and are able to accurately estimate the time-varying disturbances. Figure 1(b) shows the estimation result of the square disturbance. The square disturbance is unchanged in most of the time except for some isolated points. It can be seen clearly from Figure 1(b) that the estimate of disturbance converges faster to the true value.



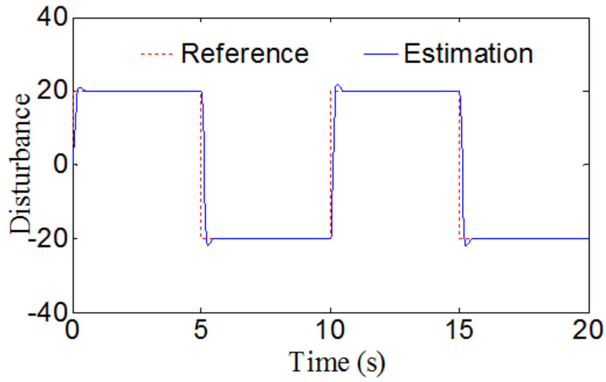
(a) $\omega(t) = 20\sin(0.6\pi t)$

(b) $\omega(t) = 20sign(\sin(0.2\pi t))$

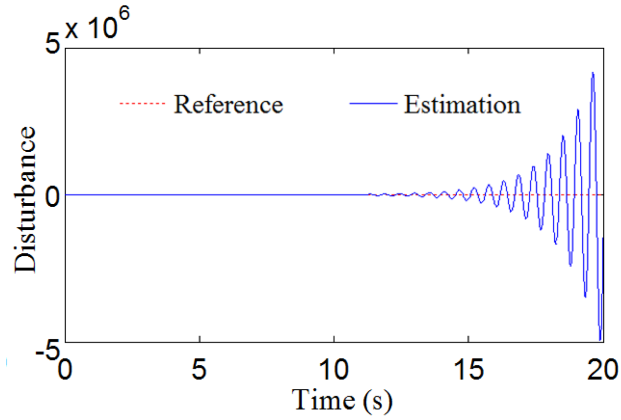
FIGURE 1. Performance comparison of disturbance estimation

To further verify performance of observer, the gains are changed as $k_1 = 8$, $k_2 = 120$, $k_3 = 1200$. Figure 2 shows the estimation results of square disturbance. It can be indicated that the proposed method has stronger robustness against variation of gains.

5. **Conclusion.** In this paper, a novel finite-time extended state observer is proposed for a class of nonlinear systems with external disturbance. The fractional power and switching term related to output estimation error is adopted in the developed extended state observer. The fractional power term of the output estimation error could make the observer have a faster convergence rate. The switching term could counteract the adverse effect of external disturbance. It is proved that the novel finite-time extended state observer achieves finite time convergence for all error states. This method is conveniently extended into the high order systems. A simulation example verifies the effectiveness of



(a) The proposed observer



(b) LESO

FIGURE 2. Disturbance estimation of square disturbance

the developed observer. However, it is difficult to adjust the parameters of the proposed method. In the future, the adaptive scheme will be introduced into the proposed extended state observer.

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