A Cascade Finite-Time Nonlinear Extended State Observer for Active Disturbance Rejection Control

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Abstract. Extended state observer(ESO) is a class of high-gain observers and plays a significant role in output feedback control theory for uncertain nonlinear systems. However, it faces a challenge in industrial applications when the output is corrupted by high-frequency measurement noise, which means the core parameter, referred to as bandwidth, cannot be too large. It faces a trade-off between convergence rate and noise suppression. In this paper, A new cascade finite-time nonlinear ESO(FTNESO) combining cascade structure and finite-time nonlinear observer, which provides extra degree of freedom to design the controller, is proposed to improve the estimation performance in the presence of measurement noise. Based on the proposed cascade FTESO, an active disturbance rejection control scheme(ADRC) is established, and the controller is applied to the nonlinear gas turbine model to show its effectiveness.

Keywords: cascade · finite-time · nonlinear ESO · measurement noise · load varying

1 Introduction

Gas turbines play a significant role in the industrial field and are used on many occasions. However, in recent years, the structure of gas turbines has become more complicated, and they always work under complex conditions, so the controllers are challenging to design [1]. The traditional controller applied in the gas turbine system is a proportional integral derivative (PID) controller. It is a classical control structure and easy to design but leads to poor control accuracy or robustness.

Due to its simple structure and model-independent characteristics, ADRC is becoming popular in the gas turbine control field. In [2], Jiang et al. adopted

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ADRC in gas turbine control systems, compared ADRC with PID, and concluded that ADRC is superior to classical PID for its inherent robustness. Sun et al. proposed an increment cascade ADRC structure that could deal with gas turbine speed and power turbine speed simultaneously [3]. Du et al. [4] combined an ADRC with a bumpless transfer controller and improved control quality in the natural gas supply system of the gas turbine.

ADRC was proposed naturally from PID by Han [5]. Furthermore, Gao put forward linear ADRC (LADRC), using the method of pole assignment, introducing the parameter called "bandwidth" to simplify parameters adjusting [6]. To a considerable extent, the core component of ADRC is the extended state observer (ESO); the performance of ADRC depends on the accuracy and speed of ESO. However, the observer theory has its drawbacks which means it faces a trade-off between tracking speed and measurement noise suppression [7]. In [8] Łakomy K et al. proposed a new paradigm called cascade ESO, which is composed of several simple ESOs, to improve the observer's performance considering the existence of measurement noise; each level can filter part of the noise with a relatively small bandwidth. Moreover, the total result is a combination of each level. However, with extra cascade levels, the phase lag becomes more pronounced and deteriorates the accuracy of the controller.

One of the most direct ways to deal with this drawback is to improve the convergence rate of ESO. Dai et al. replaced traditional ESO with high-order sliding mode observer (HOSMO) in a class of nonlinear systems and proved the stability of the closed-loop system [9]. Humaidi et al. in [10] used another finite-time nonlinear ESO, depending on a particular nonlinear function, and came to similar effects. Another approach proposed by Wei et al. is adding a phase-leading network to a classical ESO [11], called phase-leading ESO (PESO). They provided an effective way to estimate dynamic responses without introducing extra nonlinearities or increasing the order.

This paper proposes a new ADRC based on a cascade finite-time nonlinear extended state observer. First, an FTNESO is designed to guarantee finite-time convergence of the state observers. Then, it is combined with a cascade structure to filter measurement noise. At last, the proposed controller is verified by two examples and applied to a gas turbine. The main contributions of this paper are summarized below:

1) A cascade FTNESO-based ADRC structure was introduced to improve dynamic performance.
2) A classical system example was considered, and the advantages of the proposed controller were verified by comparison.
3) An nonlinear model of a gas turbine was established and controlled by the proposed controller.

2 Preliminaries

Before the proposed cascade finite-time nolinear extend state observer based ADRC is explained, we first recall some existing preliminary results.

2.1 Standard ESO and Cascade ESO

First, the algorithm of standard ESO is established for a nonlinear dynamical system. The dynamical system is described by the following state-space model:

$$\begin{cases} \dot{x}(t) = A_n x(t) + B_n[bu(t) + f(x,t) + d(t)], \\ y(t) = C_n^T x(t) + w(t), \end{cases} \tag{1}$$

where $x = [x_1, x_2, \cdots, x_n]^T \in \mathbb{R}^n$ is the state, $d \in \mathbb{R}$ is an external disturbance, $u \in \mathbb{R}$ is the control input, $y \in \mathbb{R}$ is the measured output, $w \in \mathbb{R}$ denotes the measurement noise, $f \in \mathbb{R}$ represents lumped dynamics of the controlled system, b is the bounded uncertain nonzero control gain, and matrices A_n, B_n and C_n are given by

$$A_n = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \end{bmatrix} \in \mathbb{R}^{n\times n}, B_n = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \in \mathbb{R}^{n\times 1},$$

$$C_n = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}^T \in \mathbb{R}^{n\times 1}.$$

Based on the standard ESO method, let $F(t) \triangleq f(x,t) + d(t) + (b - b_0)u$, which is also called total disturbance, be the extended state x_{n+1}, where b_0 is the nonzero nominal value of the control gain b, we can expand the n order system to $n+1$ order, with its state called z. Assume that the total disturbance $F(t)$ and its derivative $\dot{F}(t)$ are bounded, then the standard ESO design is expressed by the dynamics of the extended state estimate $z := \xi \in \mathbb{R}^{n+1}$, i.e.,

$$\dot{\xi} = A_{n+1}\xi + d_{n+1}b_0 u + L_{n+1}(y - C_{n+1}^T \xi), \tag{2}$$

where $d_{n+1} \triangleq [0, \cdots, 1, 0]^T \in \mathbb{R}^{n+1}$, and $L_{n+1} \triangleq [k_1\omega_1, k_2\omega_1^2, \cdots, k_{n+1}\omega_1^{n+1}]^T \in \mathbb{R}^{n+1}$ is the observer gain vector determined by parameter $\omega_1 \in \mathbb{R}_+$ and coefficients $k_i \in \mathbb{R}_+$ for $i \in \{1, 2, \cdots, n+1\}$. Moreover, the coefficient $k_i, i = 1, 2, \cdots, n+1$, is selected such that the following polynomial is Hurwitz:

$$\lambda^{n+1} + k_1\lambda^n + \cdots + k_n\lambda + k_{n+1}.$$

The observation error can be defined as $\tilde{\xi} \triangleq z - \xi$, while its dynamics can be calculated as

$$\dot{\tilde{\xi}} = (A_{n+1} - L_{n+1}C_{n+1}^T)\tilde{\xi} + B_{n+1}\dot{F} - L_{n+1}w. \tag{3}$$

However, the standard ESO suffers a trade-off between the speed of state reconstruction and the suppression of noise. Specifically, as is discussed in [12], we can select a large ω_1 to guarantee a fast convergence speed, while the impact of noise $w(t)$ is also amplified, and on the contrary, the smaller the parameter ω_1, the slower the convergence, and the less sensitive to noise.

In order to deal with the problem, a cascade ESO is proposed in [8], which decomposes the unknown total disturbance into a predefined number of parts based on certain frequency, and using a series of cascaded observers to reconstruct them respectively. In detail, the first level of cascade ESO uses a relatively low ω_1 to ensure only the precise estimation of the first element of state, i.e., $C_{n+1}^T z$. Following elements of the extended state, depending on further derivatives of the first one, usually are more dynamic, thus are not estimated precisely by the first level of ESO. So, the estimated state z_{n+1} will not correctly represent the total disturbance, denoting residual total disturbance as $\tilde{F} = F - z_{n+1}$, which could cause a poor control precision. Then next level observer is proposed with a larger ω_1 to guarantee a more accurate evaluation of the remaining elements of state. So by increasing the level of cascade ESO to arbitrary value p, such that $p \geq 2$, we could get a precise estimation of all the elements of state.

Based on the method proposed in [8], a cascade ESO with p level is described as

$$
\begin{aligned}
\dot{\xi}_1 &= A_{n+1}\xi_1 + d_{n+1}b_0 u + L_{1,n+1}(y - C_{n+1}^T \xi_1), \\
\dot{\xi}_i &= A_{n+1}\xi_i + d_{n+1}(b_0 u + B_{n+1}^T \sum_{j=1}^{i-1} \xi_j) \\
&\quad + L_{i,n+1} C_{n+1}^T (\xi_{i-1} - \xi_i),
\end{aligned}
\tag{4}
$$

for $i \in \{2, \cdots, p\}$, $L_{i,n+1} = [k_1\omega_i, k_2\omega_i^2, \cdots, k_{n+1}\omega_i^{n+1}]^T$, where $\omega_i = \alpha\omega_{i-1}$ for $\alpha > 1$. So we only need to determine the first parameter ω_1. Finally, the extend state estimate should be expressed as

$$
\hat{z} := \xi_i + B_{n+1} B_{n+1}^T \sum_{j=1}^{i-1} \xi_j. \tag{5}
$$

The core idea of the cascade ESO is summarized as: observering the total disturbance with several levels, each level employs a larger bandwidth to estimate residual total disturbance left from the previous level, and get the precise estimation by combining all levels.

2.2 Nonlinear ESO

Compared with the linear ESO, the nonlinear ESO (NESO) has many advantages, such as guarantees fast-convergence, more robust to noise etc., for NESO always employs nonlinear function, which can ensure "big error, small gain or small error, big gain". As is proposed in [13], using an appropriate nonlinear function $f_{ci}(e)$ to construct NESO and choosing the parameter correctly, we could prove that the observation error dynamic has the following characteristics:

(1) converges to zero in finite-time if the derivative of the total disturbance F equals to zero, i.e., $\dot{F}(t) = 0$;
(2) can be bounded by a close region G_0, if $\dot{F}(t)$ is bounded, i.e., $|\dot{F}(t)| \leq W$.

The most commonly used nonlinear function in NESO is $fal(\cdot)$, given as

$$
fal(e, \alpha, \delta) = \begin{cases} \dfrac{e}{\delta^{1-\alpha}} & |e| \leq \delta, \\ |e|^{\alpha} sgn(e) & |e| > \delta, \end{cases} \tag{6}
$$

where δ is a small number which aims to express the length of the linear part. Based on $fal(\cdot)$ function, a classical nonlinear ESO is given by Han [14].

3 Main Results

In this section, inspired by [8,10], we will propose a new ESO algorithm combining a finite-time NESO and cascade ESO. And based on the proposed ESO, an improved ADRC algorithm is established.

3.1 New Finite-Time NESO

As is discussed above, a new finite-time NESO (FTNESO) is proposed here. The FTNESO has the following advantages when compared to standard ESO:

(1) ensure finite time convergence;
(2) are more flexible to deal with the peaking phenomenon;
(3) has a saturation-like profile.

For ninlinear dynamical system (1), the proposed new FTNESO is designed as

$$\begin{aligned} e &= y - C_{n+1}^T \xi \\ \dot{\xi} &= A_{n+1}\xi + d_{n+1} b_0 u + \mathcal{C} L_{n+1} \mathcal{G}(\omega_1 e) e, \end{aligned} \tag{7}$$

where $L_{n+1} = [k_1\omega_1, k_2\omega_1^2, \cdots, k_{n+1}\omega_1^{n+1}]^T \in \mathbb{R}^{n+1}$ is the same as a standard ESO, $\mathcal{C} = diag\{c_1, c_2, \cdots, c_{n+1}\} \in \mathbb{R}^{n+1 \times n+1}$ is a diagonal matrix, which is used to help further suppress peaking phenomenon of ESO, and the parameters $c_i, i = 1, 2, \cdots, n+1$ are chosen such that $c_1 > c_2 > \cdots > c_{n+1} > 0$. The nonlinear function $\mathcal{G}(\cdot) : \mathbb{R} \rightarrow \mathbb{R}$ is defined as

$$\mathcal{G}(\omega_1 e) = K_\alpha |\omega_1 e|^{\alpha - 1} + K_\beta |\omega_1 e|^\beta, \tag{8}$$

where $K_\alpha, K_\beta, \alpha$ and β are the positive design parameters among 0 and 1. Similar to $fal(\cdot)$ function (6), the proposed nonlinear function $\mathcal{G}(\cdot)$ also has a saturation-like profile that ensure the feature of "small error, large gain, and large error, small gain", and it is an odd function in terms of the error e, while e is closer to zero, the value of $\mathcal{G}(\cdot)$ is larger, i.e., $\mathcal{G}_{min} < \mathcal{G}(\omega_1 e) < \infty$.

Based on the new FTNESO (7), the observation error $\tilde{\xi}$ is given by:

$$\dot{\tilde{\xi}} = A_{n+1}\tilde{\xi} + B_{n+1}\dot{F} - \mathcal{C} L_{n+1} \mathcal{G}(\omega_1 e)(C_{n+1}^T \tilde{\xi} + w). \tag{9}$$

Particularly, if we select $\mathcal{C}$ as a $n+1$-order identity matrix, and assume $\mathcal{G}(\cdot)$ degenerate to a constant, i.e., $\mathcal{G}(\omega_1 e) \equiv 1$, which means the parameters in (8) are chosen as $\alpha = 1; \beta = 0; K_\alpha + K_\beta = 1$, then the NESO (7) is deteriorated to standard ESO (2).

As is shown in [13], using Filippov sense and self-stable region approach, we can prove that the new NESO is globally asymptotically stable, and converge to the extend state of system (1) in finite time if the measurement noise $w(t)$ can be ignored, i.e., $\tilde{\xi} = 0$ for all $t > t_f$.

3.2 New Cascade Finite-Time NESO for ADRC

A classical ADRC diagram is composed of three modules: a tracking differentiator (TD), a linear extend state observer (LESO), and a state error feedback (SEF). In brief, TD is a relatively independent part, and is employed to track the reference input and get its derivative, which will be used in SEF module. SEF is designed to provide a stable and effective output signal based on state error feedback control and total disturbance feedforward cancelling. The SEF commonly adopted is:

$$\begin{aligned} u &= u_0 - \frac{\hat{z}_{n+1}}{b_0}, \\ u_0 &= \sum_{i=1}^{n}(v_i - \hat{z}_i), \end{aligned} \tag{10}$$

where $v_i, i \in \{1, 2, \cdots, n\}$ are the derivatives of reference signal given by TD, i.e., $v_1 \to r, v_2 \to \dot{r}, \cdots, v_n \to r^{n-1}$, and r is the reference. Apparently, the first part of control signal u is given by state error feedback and the latter comes from total disturbance feedforward.

It is analyzed and verified in [10] that the observation errors of classical cascade ESO is bounded under non-zero measurement noise. Here, for the sake of fast convergence and peaking phenomenon suppression, in this section, FTNESO (7) is used as a component in cascade ESO, i.e., taking place of standard ESO in each level of cascade ESO. So the proposed p-level cascade FTNESO is expressed as:

$$\begin{aligned} e_1 &= y - C_{n+1}^T \xi \\ \dot{\xi}_1 &= A_{n+1}\xi_1 + d_{n+1} b_0 u + \mathcal{C} L_{n+1} \mathcal{G}(\omega_1 e_1) e_1, \\ \\ e_i &= C_{n+1}^T(\xi_{i-1} - \xi_i) \\ \dot{\xi}_i &= A_{n+1}\xi_i + d_{n+1}(b_0 u + B_{n+1}^T \sum_{j=1}^{i-1} \xi_j) \\ &\quad + \mathcal{C} L_{i,n+1} \mathcal{G}(\omega_i e_i) e_i, \end{aligned} \tag{11}$$

for $i \in \{2, \cdots, p\}$, and the matrices $L_{i,n+1}$ are the same as (4). The description of extend state estimate is consistent with (5). The matrix $\mathcal{C}$ in each level, used to weaken peaking phenomenon, could be selected as a constant matrix to reduce parameters' adjusting. Also, if $\mathcal{C}$ is degenerate to identity matrix and $\mathcal{G}(\omega_1 e) \equiv 1$, cascade FTESO is deteriorated to cascade ESO.

Ignoring the measurement noise $w(t)$, we could prove, using the method given by [8], that each level of the cascade ESO is globally asymptotically stable and converge to state z in finite time, which means each level of cascade structure converges fast and ensures rapid response to various fluctuation. A block diagram of ADRC control structure with the proposed cascade FTNESO is shown in Fig. 1.

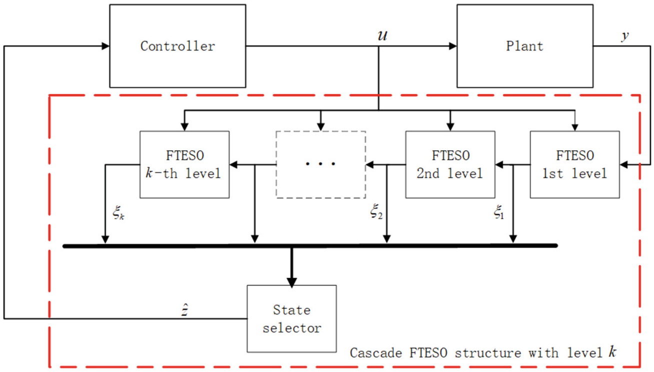

Fig. 1. the proposed cascade FTNESO

3.3 Simulation and Verification

In order to verify the effectiveness of proposed cascade FTNESO based ARDC in terms of control precision and measurement noise attenuation, its result is compared with a standard ESO based ADRC and a classical cascade ESO based ADRC. The following motion control test bed system, i.e., second order time-varying single-input single-output system is considered:

$$\ddot{y} = (-1.41\dot{y} + 23.2T_d) + 23.2u, \tag{12}$$

and torque disturbance is set as $T_d = 5sin(t) + 1$, or written in state-space form:

$$\begin{cases} \dot{x}(t) = A_2 x(t) + B_2[bu + f(x) + d(t)], \\ \quad y = C_2^T x(t) + w(t), \end{cases} \tag{13}$$

with system state $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, where $b = 23.2$, $f(x) = -1.41x_1$, $d(t) = 23.2T_d$, and $w(t)$ is band-limited white noise caused by sensors with power $1e^{-6}$. The sampling frequency is set to 1000 HzHz. For comparison, the cascade level p is set as 3.

Sim1. Firstly, we assume the control gain b is accurately known, then $b_0 = b = 23.2$, and total disturbance is generalized as $F(t) = -1.41x_1 + 23.2T_d$. The total disturbance estimation, controller output and system output controlled by these three controller (i.e., standard ESO based ADRC, classical cascade ESO based ADRC and FTNESO based ARDC) is given in Fig. 2. The parameters are summarized in Table 1. The coefficient $k_i, i = 1, 2, 3$ in observer gain matrix L_3 is selected as $k_1 = 3, k_2 = 3, k_3 = 1$ by pole placement technique, i.e., assigning all observer eigenvalues at $-\omega_1$.

Considering the system output, the control signal and reconstructed total disturbance, we can find that, the standard ESO with parameter $\omega_1 = 150$, which

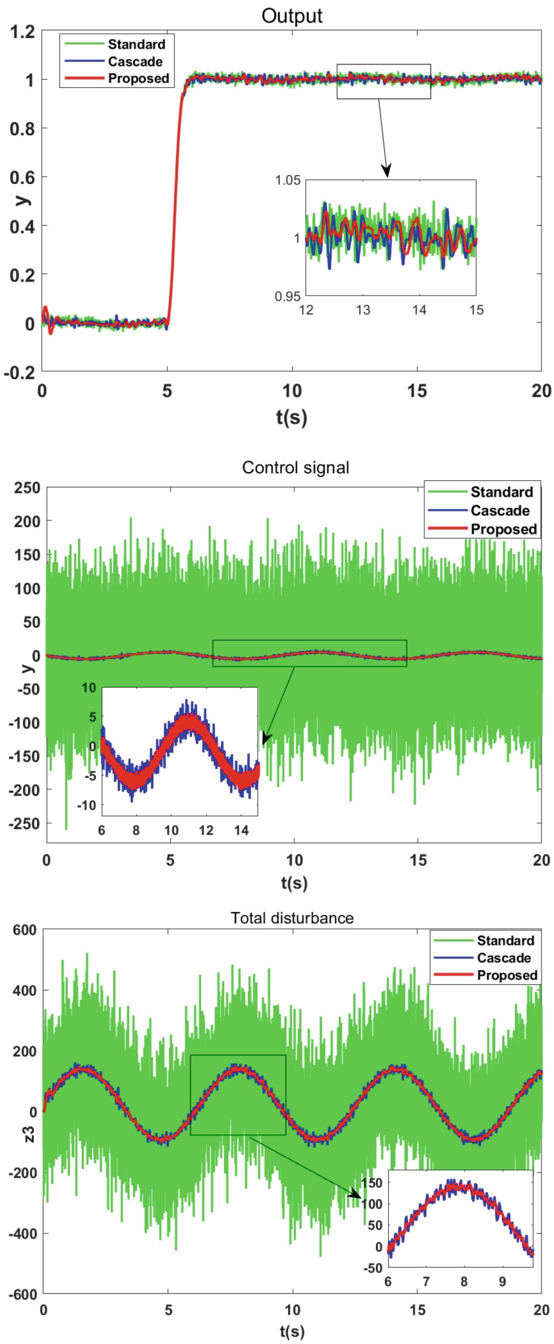

Fig. 2. performance comparison between three controllers with given $b_0 = b = 23.2$

Table 1. Observer structures and parameters used in the comparison

	ω_1	ω_2	ω_3
Standard ESO	150		
Cascaded ESO	35	$1.1\omega_1$	$1.1^2\omega_1$
Proposed FTESO	60	$1.1\omega_1$	$1.1 * 1.2\omega_1$
	$K_\alpha = 0.999; \alpha = 0.3013; k_\beta = 0.38; \beta = 0.305$		

is also known as observer bandwidth, is severely polluted by measurement noise, i.e., its observed total disturbance varying rapidly, and consumes more control energy to obtain similarly output results. It is not difficult to understand, as is analyzed in [7], with a large observer bandwidth, the tracking speed is accelerated, means the observer error declines rapidly, while the noise is amplified simultaneously, and the higher order of state to be estimate, the amplification effect is more obvious. While the rest two cascade methods show better tracking performance and smaller oscillation frequency, additionally,the FTESO has better noise suppression ability. To compare the advantages and disadvantages of the two cascade methods, we consider two internal criteria given in [11], which can represent tracking accuracy and energy consuming, i.e., $\int_0^T t|r - y(t)|\, dt$ and $\int_0^T u(t)^2\, dt$, and simulation time is set as $T = 5s$. The results are shown in Table 2.

Table 2. Assessment based on selected integral quality criteria in $Sim1$

Criterion	$\int_0^T t\|r - y(t)\|\, dt$	$\int_0^T u(t)^2\, dt$
Standard ESO	3.689	50041.1
Cascaded ESO	3.470	308.6
Proposed FTESO	3.222	283.7

Hence, from Table 2, compared to classical cascade ESO based ADRC, the proposed FTNESO based ADRC are more precise in reference signal tracking and more energy saving, which means also more friendly to actuators and dynamical system.

Sim2. Consider SISO system (12) again, for in many cases the control gain b is probably time-varying or not precisely known, but based on prior knowledge we assume that the nominal value b_0 is 15. Then the total disturbance can be summarized as $F(t) = -1.41x_1 + 23.2T_d + (b - b_0)u$. If we don't adjust the controller structure and control parameters, this is reasonable for the controller should be robust against various working condition changes in practical application, then the advantages of proposed cascade FTNESO based ADRC are more apparent. The responses and state estimations are shown in Fig. 3. Same as before, the internal criteria,i.e., tracking accuracy and energy consuming are exhibited in Table 3.

Table 3. Assessment based on selected integral quality criteria in $Sim2$

Criterion	$\int_0^T t\lvert r-y(t)\rvert\,dt$	$\int_0^T u(t)^2\,dt$
Standard ESO	4.612	83969.5
Cascaded ESO	4.022	535.9
Proposed FTESO	3.157	300.4

From the results we see obviously that the effect of classical cascade ESO based ADRC deteriorated rapidly, the tracking performance even worse than standard ESO based ADRC. Whereas the proposed cascade FTNESO still observer system state and total disturbance effectively with previous bandwidth for its fast convergence merit. In fact in this simulation, if the parameter b_0 is selected as 12 or smaller, which is quiet possible in practical application, for the control gain might affected by external interference and vary in a large region, the classical cascade ESO based ADRC even cannot ensure state convergence. While on the other hand, the proposed cascade FTNESO based ADRC also show great performance.

4 Application in Gas Turbine

Gas turbine has a complicated structure and composes of many thermodynamic models, turbomachinery models, sensor models, actuator models and heat exchange models. Recently years, ADRC is applied in gas turbine to achieve better dynamical performance and disturbance rejection ability.

In classical ADRC controller, while considering measurement noise, with a large observer bandwidth to observe system states and total disturbance rapidly, the control signal will therefore fluctuate violently. In this section, we will apply the new proposed cascade FTNESO based ADRC into the gas turbine model to filter measurement noise as much as possible and retain its disturbance rejection ability. For comparison, a classical ADRC controller is also established.

In order to verify the disturbance rejection ability and noise suppression ability of cascade FTNESO based ADRC adopted in gas turbine. in this paper, gas turbine component-level model built with T-MATS toolbox and controller simulations is set up in MATLAB. The reference speed is set to 6400 r/min, the load varies in the form of sine wave between 100% and 40% at 10s on the gas turbine. A band-limited white noise with power $4.5e^{-4}$ is used to simulate the measurement noise.

The performance of classical ADRC and cascade FTNESO based ADRC are compared and the results are shown in Fig. 4. Two criteria discussed above, tracking accuracy and energy consuming are compared in Table 4. To distinguish

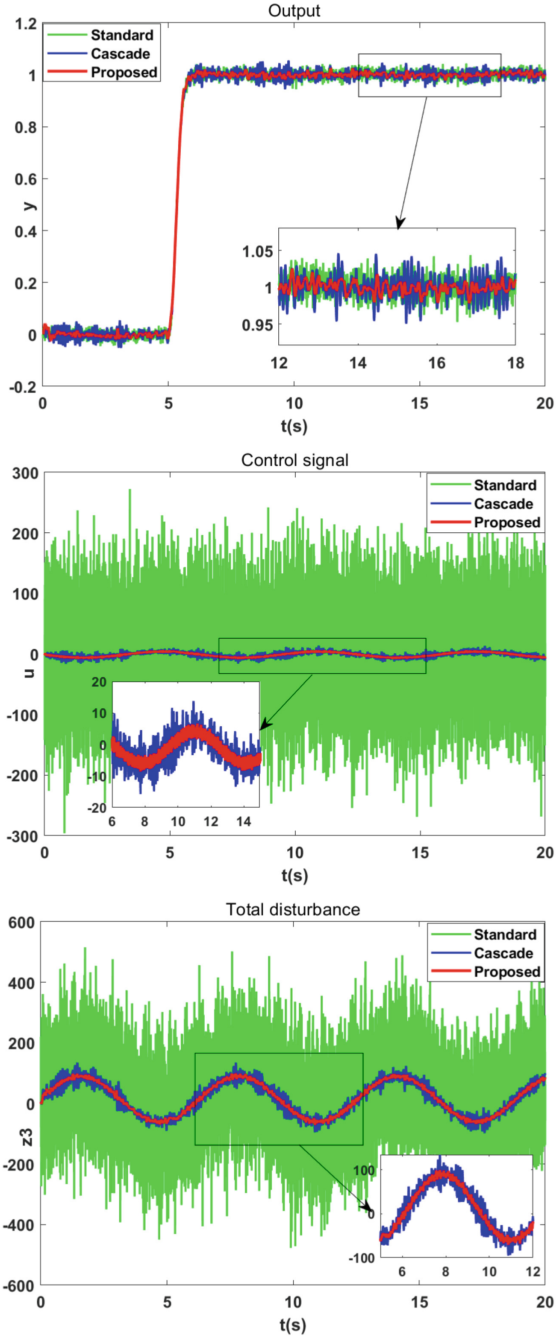

Fig. 3. performance comparison between three controllers with unknown $b = 23.2$ and nominal $b_0 = 15$

these two controllers, here we introduce another criterion [14], i.e., vibration amplitude of control input(($\int_0^T |\dot{u}(t)|\, dt$)).

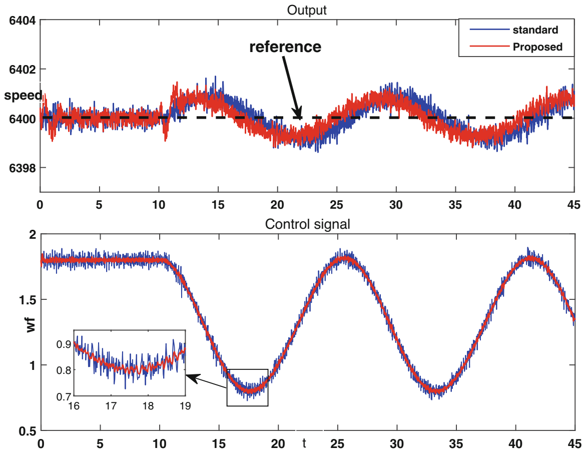

Fig. 4. performance comparison in gas turbine model

Table 4. Assessment based on selected criteria in gas turbine

Criterion	$\int_0^T t\lvert r - y(t)\rvert\, dt$	$\int_0^T u(t)^2\, dt$	$\int_0^T \lvert\dot{u}(t)\rvert\, dt$
Standard ADRC	545.1	99.50	127.4
Proposed ADRC	515.0	99.44	26.3

We could find clearly that our proposed cascade FTNESO based ADRC shows better dynamic performance and with less fluctuations.

5 Conclusion

This paper proposes a new active disturbance rejection controller based on cascade finite-time nonlinear extended state observer for a kind of nonlinear system with uncertainty both from measurement noise and inner load fluctuation. The new FTNESO-based ADRC has a faster response to handle the uncertainties caused by the load varying and a more substantial inhibition effect on measurement noise. A SISO model is established to verify the superiority of the proposed controller compared to the other two classical controllers. Then, the controller is used in a strongly nonlinear gas turbine model and proved to work effectively. Further work includes simplifying parameter adjustment.

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