

Terminal Sliding Mode Control for Cyber Physical System Based on Filtering Backstepping

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Abstract: Based on a nonlinear flight dynamic model with aerodynamic coefficients and external disturbance uncertainties, which is a typical cyber physical system, a filtering backstepping terminal sliding mode control method is proposed for a robust controller. The tracking differentiator can provide the capability of solving the problem of "complexity explosion" in backstepping controllers to simplify the backstepping implementation. Nonlinear disturbance observers are used to observe the uncertainties of the nonlinear flight dynamic system. The terminal sliding mode controller is designed to improve its convergence rate and the tracking accuracy. Finally, nonlinear 6-degree-of-freedom simulation results for an F-16 aircraft model elaborate the effectiveness of the proposed control system.

Keywords: Cyber-physical system (CPS), disturbance uncertainties, filtering backstepping, nonlinear disturbance observer (NDO), terminal sliding mode control.

1 Introduction

In recent years, cyber-physical systems, which consist of physical and computational components, have drawn considerable attention^[1]. The fact that computation, communication and control (3C) are now highly integrated in the concept of cyber-physical system (CPS). A typical CPS has the capabilities of sensing, controlling and communication, which can reflect the interaction and coordination between the physical and computational elements. Therefore, the design of control strategy in CPS is of crucial importance for stabilization and efficiency of system dynamics. CPS can be found in aerospace, automotive, transportation, infrastructure management and environmental monitoring^[2, 3]. An important application of CPS is the flight control system^[4]. And the efficacy of the control law will decide whether the CPS can bring its predominance into play or not^[5].

Due to the unmodeled dynamics and external disturbances, the flight control system is a typical uncertain nonlinear system. Recently, adaptive backstepping design method has become an important method for the research of dealing with uncertainties^[6-8]. A drawback of the conventional backstepping method may cause the problem of complexity resulting from the repeated differentiations^[9]. Dynamic surface control (DSC) technique could solve the complexity problem in backstepping design method by introducing a first-order filter of the synthetic input at each step of the traditional backstepping design procedure^[10]. Sliding mode control (SMC) has better robustness against

the parameter uncertainties^[11-13]. In [11, 12], SMC was proposed for the full envelop of the aircraft model with parameter uncertainties. The combination of SMC and adaptive backstepping control benefits from both approaches. The role of SMC is to achieve more robustness to disturbances and uncertainties^[14]. However, unwanted chattering in the conventional sliding surface makes adaptive backstepping SMC unsuitable for high accuracy requirement. There are many methods which can be employed to reduce chattering such as integral sliding surface^[15], high-order SMC^[16] and dynamic SMC^[17]. High-order sliding mode controllers can also be used to improve the system responses.

In this paper, the flight control CPS with aerodynamic coefficients and external disturbances is studied by adaptive backstepping SMC. The tracking differentiator is used to reduce the complexity of the computation. Nonlinear disturbance observer (NDO) is used to observe the uncertainties to compensate the control inputs^[18, 19]. The high-order sliding mode control law is designed to eliminate the chattering and improve the system response time. Simulation examples are given to illustrate the effectiveness of the proposed methods.

Nomenclature.

F : Aerodynamic forces about the body-fixed frame

L, M, N : Aerodynamic rolling, pitching, yawing moments

I : Moment of inertia

p, q, r : Roll, pitch, yaw rates about the body-fixed frame

\bar{q} : Dynamic pressure

m : Aircraft mass

T : Thrust

S : Reference wing area

C_* : Non-dimensional aerodynamic coefficient

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V : Velocity
 α, β : Angle of attack, sideslip angle
 $\delta_e, \delta_a, \delta_r$: Elevator, aileron, rudder angles
 ϕ, θ, ψ : Roll, pitch, yaw angles

2 Problem statement

The body-fixed nonlinear equations of motion for an F-16 aircraft with external uncertainties and aerodynamic coefficients can be written as^[20]

$$\begin{cases} \dot{x}_1 = f_1(x_1, x_3) + g_1(x_1, x_3)x_2 + M_1 \\ \dot{x}_2 = f_2(x_1, x_2) + g_2(x_1)u + M_2 \\ \dot{x}_3 = f_3(x_1, x_2) \\ M_1 = \Delta f_1(x_1) + \Delta g_1(x_1)x_2 + [h(x_1) + \Delta h(x_1)]u \\ M_2 = \Delta f_2(x_1, x_2) + \Delta g_2(x_1)u + d(t) \end{cases} \quad (1)$$

$$x_1 = [\alpha, \beta, \phi]^T, x_2 = [p, q, r]^T, x_3 = [\theta, \psi]^T, u = [\delta_e, \delta_a, \delta_r]^T.$$

And the expressions of $f_1, g_1, f_2, g_2, f_3, h$ are the same as given in [20].

M_i represents the compound uncertainties in the model. $\Delta f, \Delta g$ and Δh represent the aerodynamic coefficients, $d(t)$ is the external uncertainty. h represents the aerodynamic force component caused by the control surface deflection. It is seen as one part of the model uncertainties M_1 . The task of the controller to be designed is to track the commands of α, β and ϕ . Assumption 1 is used in the design and analysis process.

Assumption 1. The desired trajectory $y_c = [\alpha_c, \beta_c, \phi_c]^T$ is bounded, namely

$$\| [y_c, \dot{y}_c, \ddot{y}_c] \| \leq c_0$$

where $c_0 \in \mathbf{R}$ is a known positive constant and $\| \cdot \|$ denotes the 2-norm of a vector or a matrix.

Lemmas 1 and 2 are used in the design and analysis process.

Lemma 1. There exist positive constants α_m, β_m and $\theta_m \in \mathbf{R}$ such that the magnitudes and derivatives of f_1, f_2, g_1 and g_2 are bounded for all α, β and $\theta \in \mathbf{R}$ satisfying $|\alpha| \leq \alpha_m$ and $|\beta| \leq \beta_m$. Furthermore, there exist g_{i0} and g_{i1} such that $0 < g_{i0} \leq \|g_i\| \leq g_{i1}, i = 1, 2$.

Lemma 2. There exist two arbitrary vectors $x, y \in \mathbf{R}^n$ satisfying

$$x^T y \leq \frac{\varepsilon^p}{p} \|x\|^p + \frac{1}{q\varepsilon^q} \|y\|^q$$

$\varepsilon > 0, p > 1, q > 1$ and $(p - 1)(q - 1) = 1$. When $p = q = 2$ and $\varepsilon^2 = 2$, there exist $x, y \in \mathbf{R}^n$ such that $x^T y \leq \|x\|^2 + \|y\|^2$.

3 Controller design and stability analysis

3.1 Tracking differential filter

The derivative of the virtual control signal obtained through the filter can effectively reduce the amount of calculation in the backstepping control. The classical differential

filter has amplification effect on noises. Nonlinear tracking differentiator (NTD) can overcome the drawback when it is used to simplify the calculation. Its expression is written as^[21]

$$\begin{cases} \dot{y}_1 = y_2 \\ \dot{y}_2 = \gamma \text{sat}(y_1 - v_0(t) + \frac{y_2|y_2|}{2\gamma}, \delta) \end{cases} \quad (2)$$

where $v_0(t)$ is the input signal, y_1 is the tracking signal, y_2 is the approximate differential signal of $v_0(t)$, $\text{sat}(x, \delta)$ is the saturation function, i.e.,

$$\text{sat}(x, \delta) = \begin{cases} -1, & x < -\delta \\ \frac{x}{\delta}, & |x| \leq \delta \\ 1, & x > \delta \end{cases} \quad (3)$$

$\gamma > 0$, and the value of γ determines the tracking speed of NTD. From (2), the following equality is satisfied when $v_0(t)$ is bounded and γ is sufficiently large

$$\lim_{\gamma \rightarrow \infty} \int_0^T |y_1(t) - v_0(t)| dt = 0 \quad (4)$$

with $T > 0$. We can know that NTD does not affect the convergence of the tracking error of the control system^[22]. And y_2 is obtained by integrating the differential signal, which can effectively avoid the influence of noise.

3.2 Controller design

Define the tracking error of the states in the control system

$$\begin{cases} e_1 = x_1 - x_{1c} \\ e_2 = x_2 - x_{2c} \end{cases} \quad (5)$$

where $x_{1c} = y_c, x_{2c}$ is the expected virtual input of the inner loop. The derivative of e_1 is

$$\dot{e}_1 = \dot{x}_1 - \dot{e}_{1c} = f_1 + g_1 x_2 + M_1 - \dot{y}_c. \quad (6)$$

NDO is adopted to estimate uncertainty M_1 , then

$$\begin{cases} \hat{M}_1 = z_1 + p_1 \\ \dot{z}_1 = -L_1 z_1 - p_1 (L_1 + f_1 + g_1 x_2) \end{cases} \quad (7)$$

where $L_1 = \text{diag}\{L_{11} \ L_{12} \ L_{13}\}$ is a positive constant, p_1 is a nonlinear function to be designed, and $L_1 = \partial p_1(x) / \partial x$. The virtual control \bar{x}_{2c} to drive $e_1 \rightarrow 0$ based on NDO can be determined as

$$\bar{x}_{2c} = -g_1^{-1}(k_1 e_1 + f_1 + \hat{M}_1 - \dot{y}_c) \quad (8)$$

where $k_1 = \text{diag}\{k_{11} \ k_{12} \ k_{13}\}$ is a positive constant. In order to obtain the filtering virtual control x_{2c} , we pass \bar{x}_{2c} through an NTD with $\gamma > 0$. The derivative of e_2 is

$$\dot{e}_2 = \dot{x}_2 - \dot{x}_{2c} = f_2 + g_2 u + M_2 - \dot{x}_{2c}. \quad (9)$$

The NDO of the inner loop is given by

$$\begin{cases} \hat{M}_2 = z_2 + p_2 \\ \dot{z}_2 = -L_2 z_2 - L_2 (p_2 + f_2 + g_2 u). \end{cases} \quad (10)$$

Define a non-singular terminal sliding mode surface as follows:

$$S = [S_1, S_2, S_3]^T = e_2 + a\dot{e}_2^{\frac{\rho_1}{\rho_2}} \tag{11}$$

where $a = \text{diag}\{a_1, a_2, a_3\}$, $a_i > 0$, ρ_1 and ρ_2 are positive odd constants to be designed and $1 < \frac{\rho_1}{\rho_2} < 2$, $\dot{e}_2^{\frac{\rho_1}{\rho_2}} = [\dot{e}_{21}^{\frac{\rho_1}{\rho_2}}, \dot{e}_{22}^{\frac{\rho_1}{\rho_2}}, \dot{e}_{23}^{\frac{\rho_1}{\rho_2}}]^T$. Let $S(t) = 0, t \geq t_r$, then

$$\lim_{t \rightarrow t_s} e_2 = 0, \quad \lim_{t \rightarrow t_s} \dot{e}_2 = 0 \tag{12}$$

where

$$t_s = t_r + \frac{\rho_1}{\rho_1 - \rho_2} \max_{1 \leq i \leq 3} \left(a_i^{\frac{\rho_1}{\rho_2}} \|e_{2i}(t_r)\|^{\frac{\rho_1 - \rho_2}{\rho_2}} \right). \tag{13}$$

Therefore, the system will remain in the second-order sliding mode when $t \geq t_s$. The values of ρ_1, ρ_2, a determine the speed of convergence of the control system. In this paper, a high-order terminal sliding mode control law is proposed as

$$\begin{cases} u = u_1 + u_2 \\ u_1 = -g_2^{-1}(f_2 + \hat{M}_2 - \dot{x}_{2c}) \\ u_{2i} = -(g_2^{-1})_i \int_0^t \left[\frac{\rho_2}{a_i \rho_1} \dot{e}_{2i}^{2-\frac{\rho_1}{\rho_2}} + k_{2i} S_i + k_{3i} \text{sgn}(S_i) \right] d\tau \\ u_2 = [u_{21}, u_{22}, u_{23}]^T \end{cases} \tag{14}$$

where

$$k_2 = \text{diag}\{k_{21}, k_{22}, k_{23}\}, \quad k_{2j} > 0, \quad j = 1, 2, 3$$

$$k_3 = \text{diag}\{k_{31}, k_{32}, k_{33}\}, \quad k_{3j} > 0, \quad j = 1, 2, 3.$$

3.3 Stability analysis

It can be assumed that the disturbances are slowly time-varying, so we can consider that $\dot{M} \approx 0$ and $\dot{e}_{\text{NDO}} = -L(x)e_{\text{NDO}}$ [19].

Consider the following Lyapunov function candidate:

$$V_1 = \frac{1}{2} e_1^T e_1 + \frac{1}{2} e_{\text{NDO}1}^T e_{\text{NDO}1}. \tag{15}$$

The derivative of V_1 is

$$\begin{aligned} \dot{V}_1 &= e_1^T \dot{e}_1 + e_{\text{NDO}1}^T \dot{e}_{\text{NDO}1} = \\ &e_1^T (-k_1 e_1 + g_1 e_2 + e_{\text{NDO}1}) - e_{\text{NDO}1}^T L_1 e_{\text{NDO}1}. \end{aligned} \tag{16}$$

From Lemma 2,

$$\begin{aligned} \dot{V}_1 &\leq -\lambda_{\min}(k_1 - 2I) \|e_1\|^2 + e_1^T g_1 e_2 - \\ &\lambda_{\min} \left(L_1 - \frac{1}{4} I \right) \|e_{\text{NDO}1}\|^2. \end{aligned} \tag{17}$$

Let $k_1 > I$ and $L_1 > \frac{1}{4} I$. Then,

$$\dot{V}_1 \leq 0. \tag{18}$$

Therefore, we can know that e_1 and $e_{\text{NDO}1}$ are uniformly ultimately bounded if $\lim_{t \rightarrow \infty} e_2(t) = 0$. Consider the following Lyapunov function candidate

$$V_2 = \frac{1}{2} S^T S + \frac{1}{2} e_{\text{NDO}2}^T e_{\text{NDO}2}. \tag{19}$$

The derivative of V_2 is

$$\dot{V}_2 = S^T \dot{S} + e_{\text{NDO}2}^T \dot{e}_{\text{NDO}2}. \tag{20}$$

From (11),

$$\dot{S}_i = a_i \frac{\rho_1}{\rho_2} \dot{e}_{2i}^{\frac{\rho_1}{\rho_2}-1} \left(\ddot{e}_{2i} + \frac{\rho_2}{a_i \rho_1} \dot{e}_{2i}^{2-\frac{\rho_1}{\rho_2}} \right). \tag{21}$$

So,

$$\dot{V}_2 = \sum_{i=1}^3 \left[S_i a_i \frac{\rho_1}{\rho_2} \dot{e}_{2i}^{\frac{\rho_1}{\rho_2}-1} \left(\ddot{e}_{2i} + \frac{\rho_2}{a_i \rho_1} \dot{e}_{2i}^{2-\frac{\rho_1}{\rho_2}} \right) - L_{2i} e_{\text{NDO}2}^2 \right]. \tag{22}$$

Substituting (14) into (9) yields

$$\dot{e}_2 = g_2 u_2. \tag{23}$$

The derivative of \dot{e}_2 is

$$\ddot{e}_{2i} = -\frac{\rho_2}{a_i \rho_1} \dot{e}_{2i}^{2-\frac{\rho_1}{\rho_2}} - k_{2i} S_i - k_{3i} \text{sgn}(S_i). \tag{24}$$

Substituting (24) into (20) yields

$$\begin{aligned} \dot{V}_2 &= \\ &\sum_{i=1}^3 \left[S_i a_i \frac{\rho_1}{\rho_2} \dot{e}_{2i}^{\frac{\rho_1}{\rho_2}-1} [-k_{2i} S_i - k_{3i} \text{sgn}(S_i)] - L_{2i} e_{\text{NDO}2}^2 \right] = \\ &-\sum_{i=1}^3 \left[a_i k_{2i} \frac{\rho_1}{\rho_2} \dot{e}_{2i}^{\frac{\rho_1}{\rho_2}-1} S_i^2 + a_i k_{3i} \frac{\rho_1}{\rho_2} \dot{e}_{2i}^{\frac{\rho_1}{\rho_2}-1} |S_i| + L_{2i} e_{\text{NDO}2}^2 \right]. \end{aligned} \tag{25}$$

Let $1 < \frac{\rho_1}{\rho_2} < 2, k_2 > 0, k_3 > 0, L_2 > 0$ and $a > 0$. Then,

$$\dot{V}_2 \leq 0. \tag{26}$$

Accordingly, we can know that the tracking errors of the control system designed in this paper are locally uniformly ultimately bounded when $k_1 > I, k_2 > 0, k_3 > 0, L_1 > \frac{1}{4} I, L_2 > 0$ and $1 < \frac{\rho_1}{\rho_2} < 2$.

4 Simulation results

The proposed controller is tested by a numerical simulation on the attitude maneuver flight control system of an F-16 aircraft. The following command values of α_d, β_d , and ϕ_d are applied to the aircraft in a steady-state level flight of $V = 200$ m/s, $h = 4000$ m, $F_T = 60$ kN:

$$\alpha_d = 2.659, \beta_d = 0, \phi_d = 0, 0 \leq t < 1$$

$$\alpha_d = 10, \beta_d = 0, \phi_d = 50, 1 \leq t < 10$$

$$\alpha_d = -2, \beta_d = 0, \phi_d = 0, 10 \leq t < 20.$$

y_c is obtained from y_d by the following command filter to satisfy Assumption 1:

$$\frac{[y_c]_i}{[y_d]_i} = \frac{\omega_n^2}{s^2 + 2s\xi_n\omega_n + \omega_n^2}, \omega_n = 4, \xi_n = 0.8, i = 1, 2, 3$$

where s is Laplace operator. The controller design parameters are chosen as $k_1 = 10I, k_2 = 5I, \gamma = 10I, a = 5I,$

$\tau_2 = 0.05$, $\delta(0) = 10$, where I represents the 3×3 identity matrix. NDO gains are chosen as

$$L_1 = \text{diag}\{2(1 + \alpha^2), 2(1 + \beta^2), 2(1 + \phi^2)\}$$

$$L_2 = \text{diag}\{5(1 + p^2), 5(1 + q^2), 5(1 + r^2)\}.$$

We assume that the uncertainties of the aerodynamic coefficients and external moment disturbance are time-varying. The time-varying uncertainties are given as

$$C_j = [1 + 0.5 \sin(0.5\pi t)]C_j^r, j = x, y, z, l, m, n$$

$$d(t) = [0.5 \quad 1.2 \quad 1.5] \times 10^4 \sin(t)$$

where $C_x^r, C_y^r, C_z^r, C_l^r, C_m^r$ and C_n^r are the standard aerodynamic coefficients.

Figs. 1–3 present the simulation results when uncertainties do not exist. 0 represents the command signal. 1 represents the simulation result of the controller proposed in this paper. From Figs. 1–3, it is clear that the control law proposed in this paper can track the reference command signal effectively and make the tracking error converge.

To demonstrate the tracking performance of the proposed control law, the backstepping controller in [18] is applied contrastively. Figs. 4–9 present the simulation results when the uncertainties exist. 1 represents the simulation result of filtering backstepping terminal sliding mode controller proposed in this paper. 2 represents the simulation result of the backstepping controller proposed in [18]. The tracking error convergence curves of $e_1 = [e_{1\alpha}, e_{1\beta}, e_{1\phi}]$ are used to reflect the tracking control performance of the two controllers. The simulation results reveal that, under the condition of aerodynamic parameter perturbation and external disturbance uncertainties, the proposed control scheme can track the reference command signal more quickly and more accurately. Figs. 7–9 show that the nonsingular high-order terminal sliding mode control method can effectively weaken the chattering.

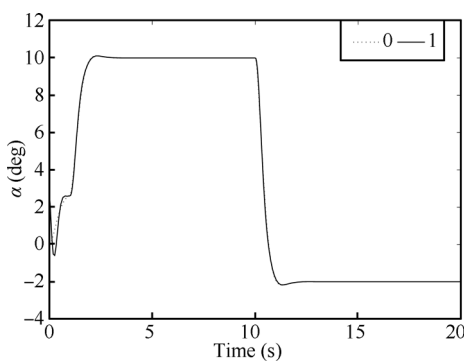


Fig. 1 Time response of α without uncertainties

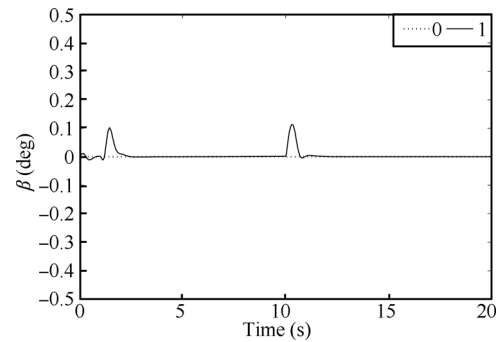


Fig. 2 Time response of β without uncertainties

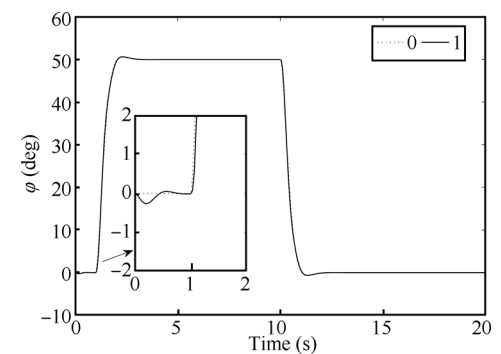


Fig. 3 Time response of ϕ without uncertainties

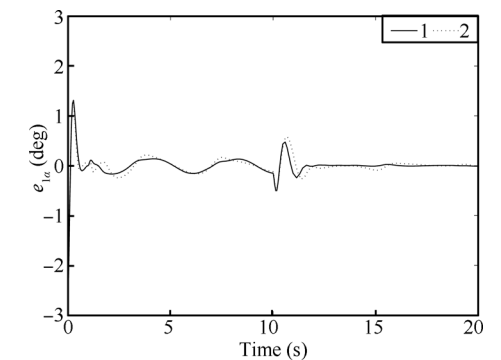


Fig. 4 Time response of $e_{1\alpha}$ with uncertainties

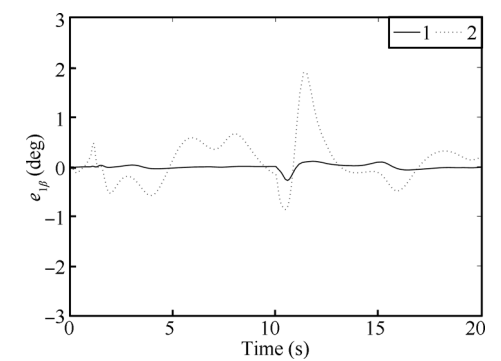
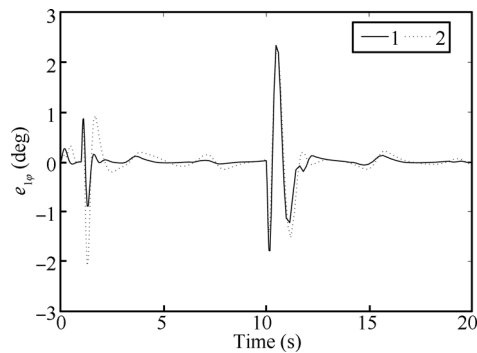
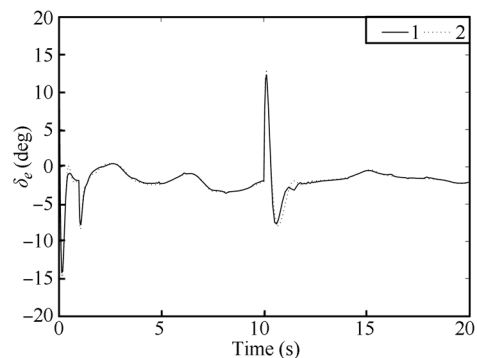
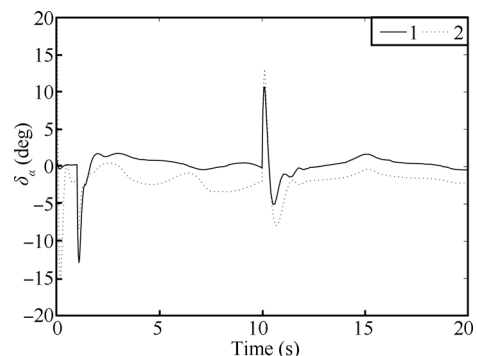
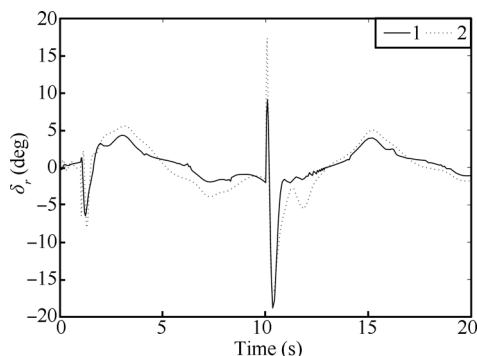


Fig. 5 Time response of $e_{1\beta}$ with uncertainties

Fig. 6 Time response of $e_{1\phi}$ with uncertaintiesFig. 7 Time response of δ_e with uncertaintiesFig. 8 Time response of δ_a with uncertaintiesFig. 9 Time response of δ_r with uncertainties

5 Conclusions

A filtering backstepping terminal sliding mode controller is designed in this paper to compensate for the effect of

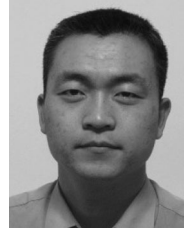
system uncertainties in CPS with time-varying parameter perturbations and external disturbances. NTD is used to obtain the derivation of the virtual control signal, simplifying the design of the controller and reducing the amount of computation. Nonlinear disturbance observers can effectively observe the uncertainties of CPS. Nonsingular terminal sliding mode controller can increase system robustness and tracking accuracy, and can effectively weaken the control signal chattering. Simulation results show that the proposed control system can quickly and accurately track the reference command signal. The method proposed in this paper may be also used in the design in other CPS controllers with aerodynamic coefficients and external disturbance uncertainties.

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