Improved Discrete-Time Sliding Mode Control for Lift Aircraft Based on Disturbance Observer

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Abstract: Lift-type aircraft has the characteristics of wide flight airspace, large range of speed changes, strong maneuverability requirements, which makes it a research focus in recent years. Aiming at difficulties of large uncertainty and strong external disturbance in the control model of lift-type aircraft, an improved discrete-time sliding mode variable structure control method based on disturbance observer is presented. Firstly, the discrete control model of the pitch channel is established. Secondly, an improved discrete-time sliding mode variable structure control system based on disturbance estimation is designed and its stability is proved. Thirdly, the influence of parameter selection on control system is analyzed, and the validity of control law is verified. Finally, the comparison with the traditional discrete sliding mode variable structure control system is carried out. The control system's simulation results demonstrate that, compared with the traditional discrete-time sliding mode control system, the proposed control system has higher control accuracy, stronger robustness, faster convergence to zero and less chattering. The proposed control law can effectively improve the flight quality, and can realize stable control for complex mission of lift-type aircraft.

Key words: lift-type aircraft; disturbance observer; discrete-time sliding mode control; robust control; chattering

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0 Introduction

Lift-type aircraft is a kind of aircraft with a large lift-drag ratio. They utilize aerodynamic force to glide in the atmosphere and realize fast long-distance navigation[1-10]. The flight mission will cause the aircraft to face wide flying airspace, wide speed range, high maneuverability requirement, complex and changeable external environment. Besides, the model of the aircraft has strong nonlinear, strong coupling, fast time-varying[11]. Those factors cause large model uncertainties and strong external disturbances in the control system of the aircraft. The traditional linear system design method will linearize the control object with small disturbances, and design the control system based on the linearized control model. This method can ensure the system is stable, as long as the difference between the linearized control mode and the real model is not significant. Since the lift-type aircraft has the characteristics of large model uncertainties and strong external disturbances in the control system, there is a significant difference between the linearized control model and the real model. Therefore the traditional linear system design method is no longer applicable. How to achieve high-precision robust control under large model uncertainties and strong external disturbances has become the focus of the lift vehicle research in recent years.

The sliding mode variable structure control (SMVSC) has been widely concerned since its inception due to its insensitivity to parameter perturbation and external disturbances[12-18]. In recent years,

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scholars have applied it to control systems' design of lift-type aircraft. Shtessel et al.[19] introduced sliding mode control based on X-33 model to realize decoupling control of inner loop angular velocity and outer loop attitude angle. Cheng et al.[20] proposed a fixed-time method for the tracking control of a quadcopter subject to external disturbances. Li et al.[21] proposed a time delay estimation based adaptive sliding mode control technique with the exponential reaching law to achieve high-precision coordinated control between the spacecraft base and the robotic arm. Guo et al.[22] presented a fixed-time sliding mode control law to track the velocity and altitude references. To sum up, most scholars have studied sliding mode variable structure control for continuous-time systems. But the practical systems are discrete. Due to the limitation of sampling frequency, the control systems can not only produce chattering in the sliding mode, but also make the sliding mode that is originally stable in the continuous-time systems become unstable. The ideal robustness of the continuous-time systems will not exist in the practical systems. The study of sliding mode variable structure control for discrete-time systems is of great significance in engineering practice[23-24].

In this paper, a discrete-time sliding mode variable structure control method is studied. The mathematical model is given in Section 1. The design process is given in Section 2. The stability proof is given in Sections 3 and 4. Simulation analysis is given in Section 5. Conclusions are given in Section 6.

Aiming to investigate the problems encountered in the engineering practice of lift-type aircraft, this paper's research and innovation points are as follows: (1) Propose a discrete-time sliding method which is more suitable for engineering implementation; (2) design a disturbance observer which can effectively estimate the internal and external disturbances for lift-type aircraft; (3) provide a discrete integral sliding mode surface which can improve the control accuracy for complex flight mission; (4) analyze the influence of parameter selection, and provide a basis for parameter tuning.

1 Mathematical Model

Lift-type aircraft realizes the flight speed and altitude change through the attitude adjustment of the pitch channel, so the control system of the pitch channel is significant. Therefore, this paper only analyzes the attitude control problem of the pitch channel.

Ignoring the motion of the center of mass, we can define that the rate of the change of flight path angle is 0. Therefore, the kinematic and dynamic equations of the lift-type aircraft can be described as

$$\begin{cases} \dot{\alpha} = \omega_z \\ \dot{\omega}_z = \dfrac{M_z}{J_z} + f(\omega_z) \end{cases} \tag{1}$$

where α is the angle of attack; ω_z the pitch angular velocity; J_z the the moment of inertia of the pitch channel; M_z the control moment of the pitch channel; and $f(\omega_z)$ the external disturbance.

We define the state variables $\boldsymbol{x} = [\alpha \quad \omega_z]^{\mathrm{T}}$, $\boldsymbol{u} = \boldsymbol{\delta}_z$, then the attitude control model of the lift-type aircraft pitch channel can be written as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{H} \tag{2}$$

where

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 \\ \dfrac{C_{mz}^{\alpha} QSl}{J_z} & \dfrac{C_{mz}^{\omega_z} QSl^2}{2VJ_z} \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} 0 \\ \dfrac{C_{mz}^{\delta_z} QSl}{J_z} \end{bmatrix}$$

$$\boldsymbol{H} = \begin{bmatrix} 0 \\ f(\omega_z) \end{bmatrix}$$

where C_{mz}^{α} is the pitch channel static stability derivative; $C_{mz}^{\omega_z}$ the pitch channel damping moment coefficient; $C_{mz}^{\delta_z}$ the rudder effect of the pitch channel; Q the dynamic pressure; S the reference area; and l the reference length.

Discretize Eq.(2) to Eq.(3), and use the Z-transform theory, we have

$$\boldsymbol{x}(k+1) = \boldsymbol{G}\boldsymbol{x}(k) + \boldsymbol{F}\boldsymbol{u}(k) + \boldsymbol{D}\boldsymbol{f}(k) \tag{3}$$

where $\boldsymbol{G}$ and $\boldsymbol{F}$ are the coefficient matrixes of the discrete-time system. $\boldsymbol{D}\boldsymbol{f}(k)$ is the discretized expression of the disturbances. $G \rightarrow R^2 x^2$, $F \rightarrow R^2 x$, $\rightarrow R^2 x$.

Suppose the conditions are met, $\boldsymbol{D}\boldsymbol{f}(k) = \boldsymbol{F}\tilde{\boldsymbol{D}}\boldsymbol{f}(k)$, Eq.(3) can be written as

$$\begin{cases} \boldsymbol{x}(k+1)=\boldsymbol{G}\boldsymbol{x}(k)+\boldsymbol{F}(\boldsymbol{u}(k)+\boldsymbol{d}(k)) \\ \boldsymbol{d}(k)=\tilde{\boldsymbol{D}}\boldsymbol{f}(k) \end{cases} \tag{4}$$

2 Control Law Design

We set that the command signal as $\boldsymbol{r}(k)$, and its rate of change is $\boldsymbol{r}_d(k)$.

Define $\boldsymbol{R}=[\boldsymbol{r}(k) \quad \boldsymbol{r}_d(k)]^{\mathrm{T}}$, $\boldsymbol{R}_1=[\boldsymbol{r}(k+1) \quad \boldsymbol{r}_d(k+1)]^{\mathrm{T}}$.

The linear exploration is used to forecast $\boldsymbol{r}(k+1)$ and $\boldsymbol{r}_d(k+1)$, and we can define that $\boldsymbol{R}_1=[\boldsymbol{r}(k+1) \quad \boldsymbol{r}_d(k+1)]^{\mathrm{T}}$, $\boldsymbol{r}(k+1)=2\boldsymbol{r}(k)-\boldsymbol{r}_d(k-1)$, $\boldsymbol{r}_d(k+1)=2\boldsymbol{r}_d(k)-\boldsymbol{r}_d(k-1)$.

Define $\boldsymbol{e}(k)=\boldsymbol{r}(k)-\boldsymbol{x}_1(k)$.

Using the sliding mode surface discretization method in Ref.[25], the continuous sliding mode surface with integral term is discretized. The continuous sliding mode surface with integral term is

$$\boldsymbol{s}(t)=\dot{\boldsymbol{e}}(t)+c_1\boldsymbol{e}(t)+c_2\int_0^t \boldsymbol{e}(\tau)\mathrm{d}\tau \tag{5}$$

The discrete sliding mode surface after introducing the integral term is

$$\begin{cases} \boldsymbol{s}(k)=\boldsymbol{C}_e(\boldsymbol{R}-\boldsymbol{x}(k))+\boldsymbol{\theta}(k) \\ \boldsymbol{\theta}(k)=\boldsymbol{\theta}(k-1)+c_2T\boldsymbol{e}(k-1) \end{cases} \tag{6}$$

where $\boldsymbol{C}_e=[c_1 \quad 1]$, and T is the sampling time.

The discrete exponential approach rate is

$$\boldsymbol{s}(k+1)=\boldsymbol{s}(k)-qT\boldsymbol{s}(k)-\varepsilon T\operatorname{sgn}(\boldsymbol{s}(k)) \tag{7}$$

where q is the approach rate parameter; ε the gain parameter of the sign function, and $\varepsilon>0$, $q>0$, $(1-qT)>0$.

Let $t=(k+1)T$, Eq.(6) can be written as

$$\boldsymbol{s}(k+1)=\boldsymbol{C}_e(\boldsymbol{R}_1-\boldsymbol{x}(k+1))+\boldsymbol{\theta}(k)+c_2T\boldsymbol{e}(k) \tag{8}$$

According to Eqs.(4, 7, 8), it can be known that the improved discrete sliding mode variable structure control law is

$$\begin{cases} \boldsymbol{u}(k)=-\boldsymbol{d}(k)+(\boldsymbol{C}_e\boldsymbol{F})^{-1}\{\boldsymbol{C}_e\boldsymbol{R}_1-\boldsymbol{C}_e\boldsymbol{G}\boldsymbol{x}(k)- \\ \qquad (1-qT)\boldsymbol{s}(k)+\varepsilon T\operatorname{sgn}(\boldsymbol{s}(k))+\boldsymbol{\Delta}(k)\} \\ \boldsymbol{\Delta}(k)=\boldsymbol{\theta}(k)+c_2T\boldsymbol{e}(k) \end{cases} \tag{9}$$

A disturbance observer is designed and applied to the improved discrete sliding mode variable structure control law. The design formulas of the sliding mode controller and disturbance observer are obtained as

$$\begin{cases} \boldsymbol{u}(k)=-\hat{\boldsymbol{d}}(k)+(\boldsymbol{C}_e\boldsymbol{F})^{-1}\{\boldsymbol{C}_e\boldsymbol{R}_1-\boldsymbol{C}_e\boldsymbol{G}\boldsymbol{x}(k)- \\ \qquad (1-qT)\boldsymbol{s}(k)+\varepsilon T\operatorname{sgn}(\boldsymbol{s}(k))+\boldsymbol{\Delta}(k)\} \\ \hat{\boldsymbol{d}}(k)=\hat{\boldsymbol{d}}(k-1)+(\boldsymbol{C}_e\boldsymbol{F})^{-1}g\{(1-qT)\boldsymbol{s}(k-1)- \\ \qquad \varepsilon T\operatorname{sgn}(\boldsymbol{s}(k-1))-\boldsymbol{s}(k)\} \\ \boldsymbol{\Delta}(k)=\boldsymbol{\theta}(k)+c_2T\boldsymbol{e}(k) \end{cases} \tag{10}$$

where $\hat{\boldsymbol{d}}(k)$ is the estimated disturbance, and $\tilde{\boldsymbol{d}}(k)$ the estimated disturbance error, $\tilde{\boldsymbol{d}}(k)=\hat{\boldsymbol{d}}(k)-\boldsymbol{d}(k)$, $g>0$.

3 Inference Proof

3.1 Corollary 1

The dynamic characteristics of sliding mode and disturbance estimation errors satisfy the following expression

$$\begin{aligned} &\boldsymbol{s}(k+1)=(1-qT)\boldsymbol{s}(k)-\varepsilon T\operatorname{sgn}(\boldsymbol{s}(k))+\boldsymbol{C}_e\boldsymbol{F}\tilde{\boldsymbol{d}}(k) \\ &\tilde{\boldsymbol{d}}(k+1)=\boldsymbol{d}(k)-\boldsymbol{d}(k+1)+(1-g)\tilde{\boldsymbol{d}}(k) \end{aligned} \tag{11}$$

Proof:

Substituting Eqs.(4, 10) into Eq.(12), we obtain

$$\begin{aligned} \boldsymbol{s}(k+1)&=\boldsymbol{C}_e(\boldsymbol{R}_1-\boldsymbol{x}(k+1))+\boldsymbol{\theta}(k)+c_2T\boldsymbol{e}(k)= \\ &\boldsymbol{C}_e(\boldsymbol{R}_1-\boldsymbol{G}\boldsymbol{x}(k)-\boldsymbol{F}[\boldsymbol{u}(k)+\boldsymbol{d}(k)])+\boldsymbol{\Delta}(k)= \\ &\boldsymbol{s}(k)-qT\boldsymbol{s}(k)-\varepsilon T\operatorname{sgn}(\boldsymbol{s}(k))+\boldsymbol{C}_e\boldsymbol{F}\tilde{\boldsymbol{d}}(k) \end{aligned} \tag{12}$$

Substituting Eqs.(10, 12) into Eq.(13), we get

$$\begin{aligned} \tilde{\boldsymbol{d}}(k+1)&=\hat{\boldsymbol{d}}(k+1)-\boldsymbol{d}(k+1)= \\ &\hat{\boldsymbol{d}}(k)+(\boldsymbol{C}_e\boldsymbol{F})^{-1}g\{(1-qT)\boldsymbol{s}(k)-\varepsilon T\operatorname{sgn}(\boldsymbol{s}(k))- \\ &\boldsymbol{s}(k+1)\}-\boldsymbol{d}(k+1)=\hat{\boldsymbol{d}}(k)-g\tilde{\boldsymbol{d}}(k)-\boldsymbol{d}(k+1)= \\ &\boldsymbol{d}(k)-\boldsymbol{d}(k+1)+(1-g)\tilde{\boldsymbol{d}}(k) \end{aligned} \tag{13}$$

Certificate completed.

3.2 Inference 2

There is a positive constant m, If $|\boldsymbol{d}(k)-\boldsymbol{d}(k+1)|<m$, then there is k_0, when $k>k_0$, $\tilde{\boldsymbol{d}}(k)<m/g$, where $0<g<1$.

Proof:

Firstly, decompose $\tilde{\boldsymbol{d}}(k)$ into $\tilde{\boldsymbol{d}}(k)=\tilde{\boldsymbol{d}}_1(k)+\tilde{\boldsymbol{d}}_2(k)$.

Set $\tilde{\boldsymbol{d}}_1(k)=0$, then $\tilde{\boldsymbol{d}}_2(k)=0$, due to

$$\tilde{\boldsymbol{d}}(k+1)=\tilde{\boldsymbol{d}}_1(k+1)+\tilde{\boldsymbol{d}}_2(k+1), \quad \tilde{\boldsymbol{d}}_1(k+1)=(1-g)\tilde{\boldsymbol{d}}_1(k)+\boldsymbol{d}(k)-\boldsymbol{d}(k+1), \quad \tilde{\boldsymbol{d}}_2(k+1)=(1-g)\tilde{\boldsymbol{d}}_2(k)$$

Prove by induction.

Secondly, prove $\tilde{\boldsymbol{d}}_1(k)<m/g$.

(1) When $k=0$, it is known that, $\tilde{\boldsymbol{d}}_1(0)=0<m/g$.

(2) Assuming $\tilde{\boldsymbol{d}}_1(k)<m/g$, then

$$\tilde{\boldsymbol{d}}_1(k+1)=(1-g)\tilde{\boldsymbol{d}}_1(k)+\boldsymbol{d}(k)-\boldsymbol{d}(k+1)\leqslant (1-g)\left|\tilde{\boldsymbol{d}}_1(k)\right|+|\boldsymbol{d}(k)-\boldsymbol{d}(k+1)|\leqslant (1-g)m/g+m=m/g \tag{14}$$

Therefore, $\tilde{\boldsymbol{d}}_1(k)<m/g$, $k\geqslant 0$, $\tilde{\boldsymbol{d}}_2(k+1)=(1-g)\tilde{\boldsymbol{d}}_2(k)\leqslant\tilde{\boldsymbol{d}}_2(k)$.

Therefore, $\tilde{\boldsymbol{d}}_2(k)$ decreases gradually. There is k_0, when $k>k_0$, $\tilde{\boldsymbol{d}}_2(k)$ can be arbitrarily small.

It can be seen from the above analysis that there is k_0, when $k>k_0$

$$\tilde{\boldsymbol{d}}(k)=\tilde{\boldsymbol{d}}_1(k)+\tilde{\boldsymbol{d}}_2(k)\leqslant\left|\tilde{\boldsymbol{d}}_1(k)\right|+\left|\tilde{\boldsymbol{d}}_2(k)\right|\leqslant m/g \tag{15}$$

4 Stability Analysis

Set $Q=1-qT$, $\eta=\varepsilon T$, $\boldsymbol{v}(k)=\boldsymbol{C}_e\boldsymbol{F}\tilde{\boldsymbol{d}}(k)$, then

$$\boldsymbol{s}(k+1)=Q\boldsymbol{s}(k)-\eta\,\mathrm{sgn}(\boldsymbol{s}(k))+\boldsymbol{v}(k) \tag{16}$$

Assuming that the following conditions are met:

(1) $0<Q<1, 0<g<1$;

(2) There is a positive constant m, $|\boldsymbol{d}(k)-\boldsymbol{d}(k+1)|<m$;

(3) $\boldsymbol{C}_e\boldsymbol{F}(m/g)<\eta$.

According to corollary 2, $\tilde{\boldsymbol{d}}(k)<m/g$, then $|\boldsymbol{v}(k)|<\boldsymbol{C}_e\boldsymbol{F}(m/g)<\eta$.

The stability analysis is divided into the following four cases for discussion.

(1) When $\boldsymbol{s}(k)\geqslant\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta$.

$$\boldsymbol{s}(k+1)-\boldsymbol{s}(k)=(Q-1)\boldsymbol{s}(k)-\eta+\boldsymbol{v}(k)<0 \tag{17}$$

$$\boldsymbol{s}(k+1)+\boldsymbol{s}(k)=(Q+1)\boldsymbol{s}(k)-\eta+\boldsymbol{v}(k)\geqslant (Q+1)(\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta)-\eta+\boldsymbol{v}(k)= Q(\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta)+\boldsymbol{C}_e\boldsymbol{F}(m/g)+\boldsymbol{v}(k)>0 \tag{18}$$

Then

$$\boldsymbol{s}^2(k+1)<\boldsymbol{s}^2(k) \tag{19}$$

(2) When $\boldsymbol{s}(k)\leqslant-\boldsymbol{C}_e\boldsymbol{F}(m/g)-\eta\leqslant 0$

$$\boldsymbol{s}(k+1)-\boldsymbol{s}(k)=(Q-1)\boldsymbol{s}(k)+\eta+\boldsymbol{v}(k)>0 \tag{20}$$

$$\boldsymbol{s}(k+1)+\boldsymbol{s}(k)=(Q+1)\boldsymbol{s}(k)+\eta+\boldsymbol{v}(k)\leqslant -\boldsymbol{C}_e\boldsymbol{F}(m/g)-\eta+\eta+\boldsymbol{v}(k)= -\boldsymbol{C}_e\boldsymbol{F}(m/g)+\boldsymbol{v}(k)<0 \tag{21}$$

Then

$$\boldsymbol{s}^2(k+1)<\boldsymbol{s}^2(k) \tag{22}$$

(3) When $0<\boldsymbol{s}(k)<\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta$

$$\boldsymbol{s}(k+1)=Q\boldsymbol{s}(k)-\eta+\boldsymbol{v}(k)< Q\{\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta\}-\eta+\boldsymbol{v}(k)< Q\{\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta\}< \boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta \tag{23}$$

$$\boldsymbol{s}(k+1)=Q\boldsymbol{s}(k)-\eta+\boldsymbol{v}(k)> -\eta+\boldsymbol{v}(k)>-\boldsymbol{C}_e\boldsymbol{F}(m/g)-\eta \tag{24}$$

Then

$$|\boldsymbol{s}(k+1)|<\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta \tag{25}$$

(4) When $-\boldsymbol{C}_e\boldsymbol{F}(m/g)-\eta<\boldsymbol{s}(k)<0$

$$\boldsymbol{s}(k+1)=Q\boldsymbol{s}(k)+\eta+\boldsymbol{v}(k)> -\boldsymbol{C}_e\boldsymbol{F}(m/g)-\eta+\eta+\boldsymbol{v}(k)> -\boldsymbol{C}_e\boldsymbol{F}(m/g)-\eta \tag{26}$$

$$\boldsymbol{s}(k+1)=Q\boldsymbol{s}(k)+\eta+\boldsymbol{v}(k)< \eta+\boldsymbol{v}(k)<\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta \tag{27}$$

Then

$$|\boldsymbol{s}(k+1)|<\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta \tag{28}$$

Through the above analysis, the following conclusions can be drawn:

When $|\boldsymbol{s}(k)|\geqslant\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta$, the discrete sliding mode arriving conditions are met

$$\boldsymbol{s}^2(k+1)<\boldsymbol{s}^2(k) \tag{29}$$

When $|\boldsymbol{s}(k)|\geqslant\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta$, if $\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta$ is small enough, $\boldsymbol{s}(k)$ will be close to zero, $|\boldsymbol{s}(k+1)|<\boldsymbol{C}_e\boldsymbol{F}(m/g)+\eta$.

The Lyapunov function is set as $V(k)=\frac{1}{2}\boldsymbol{s}^2(k)$. According to the above analysis, the conditions $\Delta V(k)=\boldsymbol{s}^2(k+1)-\boldsymbol{s}^2(k)<0, \boldsymbol{s}(k)\neq 0$ are satisfied, then we can prove that the discrete sliding mode exists and can be reached, and the stability of the system can be guaranteed.

5 Simulation Analysis

The improved discrete sliding mode variable structure controller based on disturbance observer has five adjustable parameters: The sliding mode surface parameters c_1 and c_2, the approach speed parameter q, the sign function gain parameter ε and the disturbance observer parameter g. This section analyzes parameter selection on control system performance and robustness. The effect of stickiness is also given, and the verification of the validity of the control law is given.

Taking a lift-type aircraft as an example, we define that the reference length is 5.0 m, the reference area is 0.4 m^2, the moment of inertia of the pitch channel is 1 200 kg·m^2, the center of mass is 2.6 m, the flight speed is 1 950 m/s, the flight altitude is 35 km and the sampling period is 0.005 s.

5.1 Influence of control system's parameter selection

We define that the initial angle of attack is $-3°$, the pitch rate is 0 °/s, and the command signal is a sinusoidal signal with an amplitude of 0.5° and a step signal with an amplitude of 1°. The influence of parameter selection on the performance of an improved discrete sliding mode variable structure control system based on disturbance observer is analyzed. The conclusion is as follows, which provides a basis for the control system's parameter adjustment.

(1) According to the simulation results in Figs. 1,2, without considering parameter perturbation and external interference, the increase of parameters c_1 and q will improve the response speed of the control system and make it track the command signal faster.

(2) According to the simulation results in Fig.3, the increase of parameter c_2 will reduce the stable error and improve the quality of the control system. Those results also prove the effectiveness of the integral sliding surface proposed in this paper.

(3) According to the simulation results in Fig.4, with the influence of disturbance, when we set $g=0$, then the tracking performance of the control system is poor, and the sliding mode surface cannot converge to zero stably after being affected

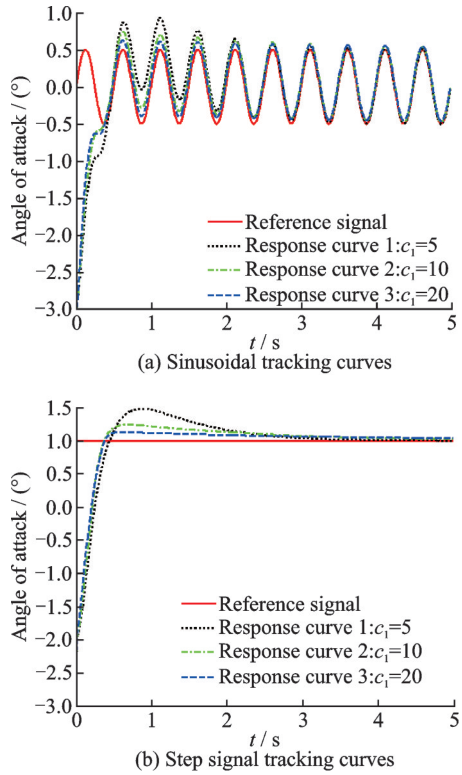


Fig.1 Effect of parameter changes on the rapidity of an improved discrete sliding mode variable structure control system based on disturbance observer ($c_2=5, q=5, \varepsilon=1, g=0$)

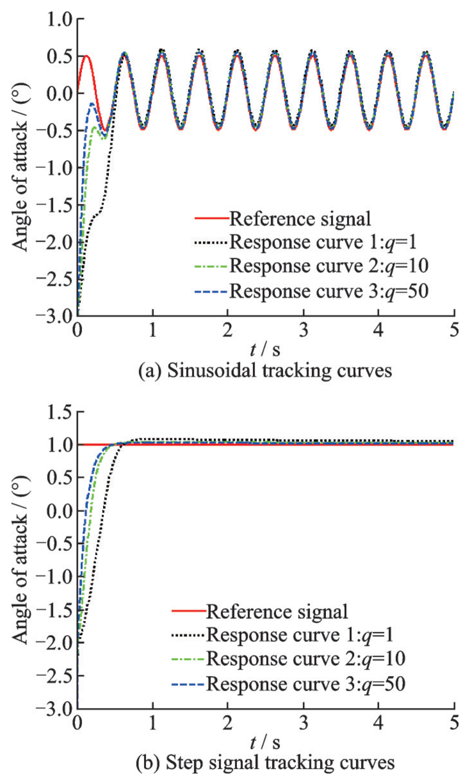


Fig.2 Effect of parameter changes on the rapidity of an improved discrete sliding mode variable structure control system based on disturbance observer ($c_1=10, c_2=1, \varepsilon=1, g=0$)

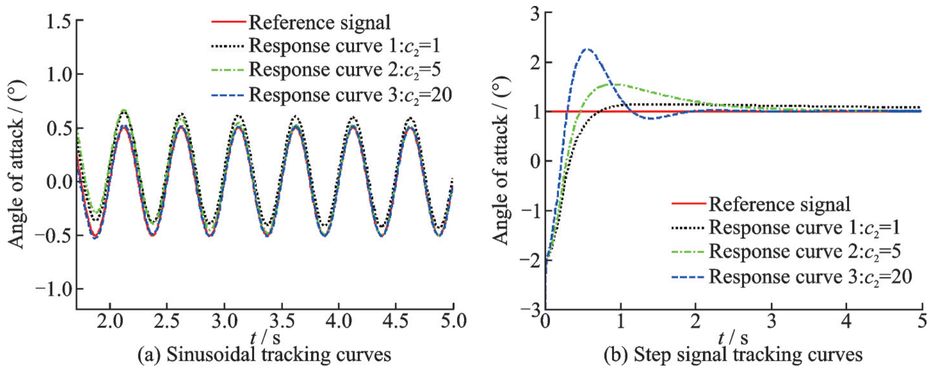
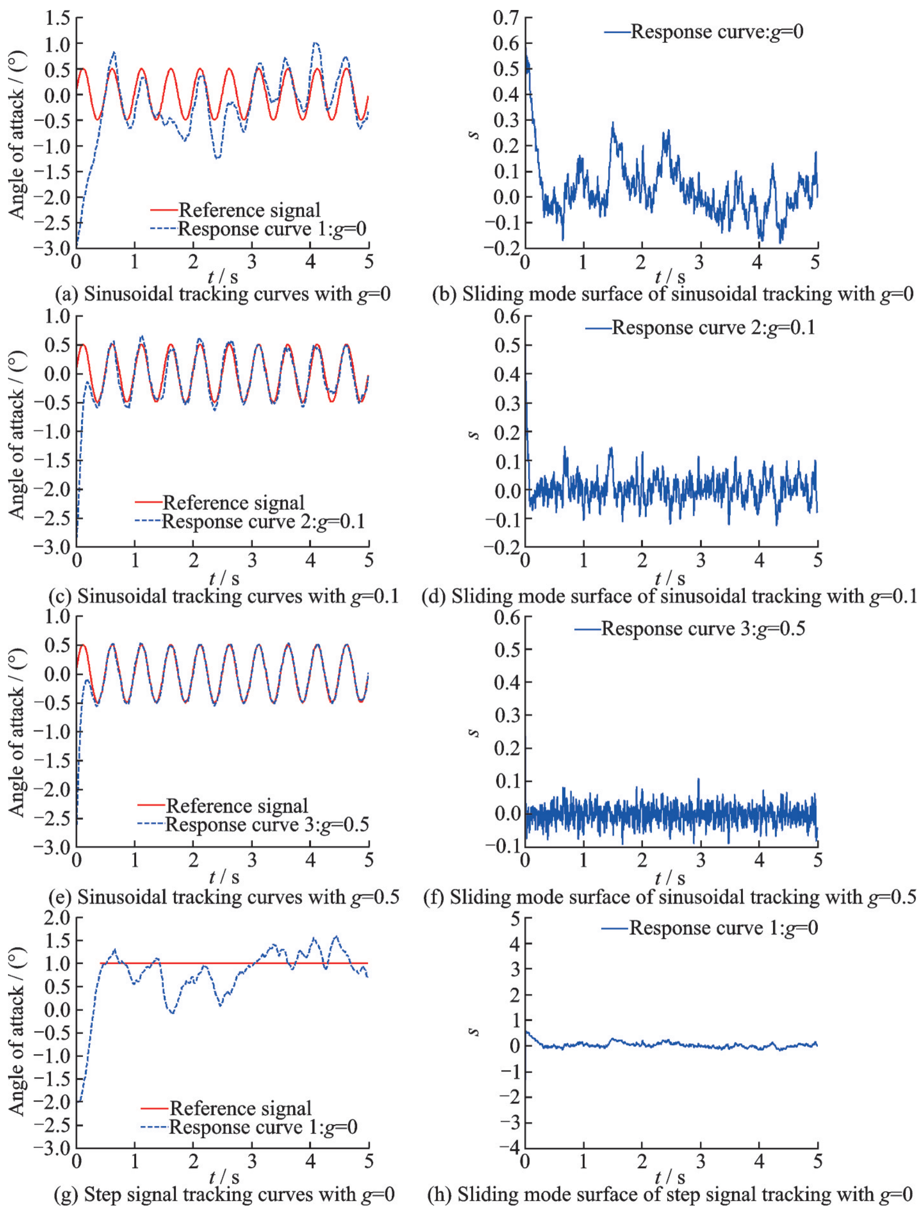
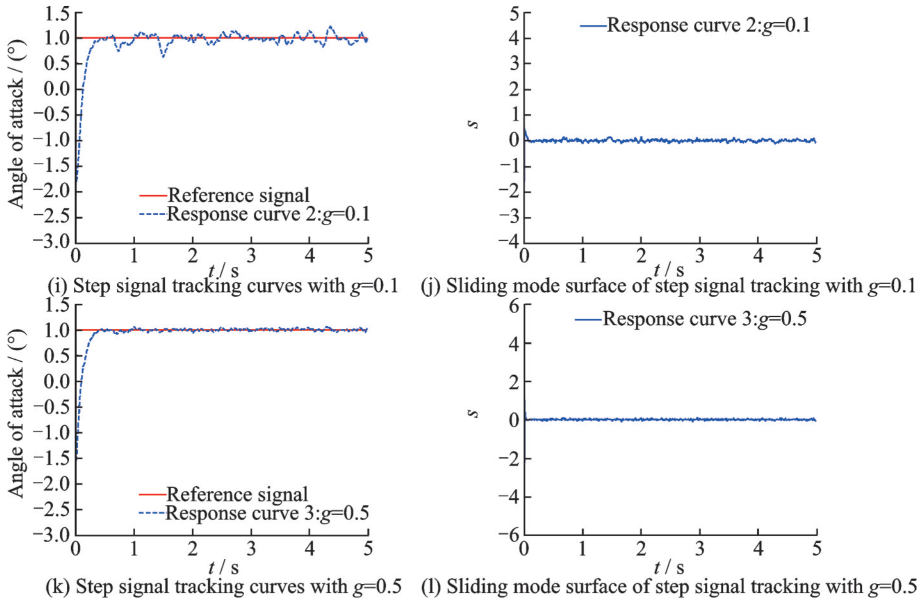


Fig.3 Effect of parameter changes on the stable error of an improved discrete sliding mode variable structure control system based on disturbance observer ($c_1=5, q=1, g=0, \varepsilon=1$)

by the disturbance. The increase of parameter g will improve the tracking accuracy of the control system, and the sliding mode surface can converge to zero stably. The effectiveness of the disturbance observer proposed is verified.

(4) According to the simulation results of Fig.5, with the disturbance influence, the increase of parameter ε will reduce the disturbance effectively and improve the robustness of the control system, as well as increase the chattering accordingly.

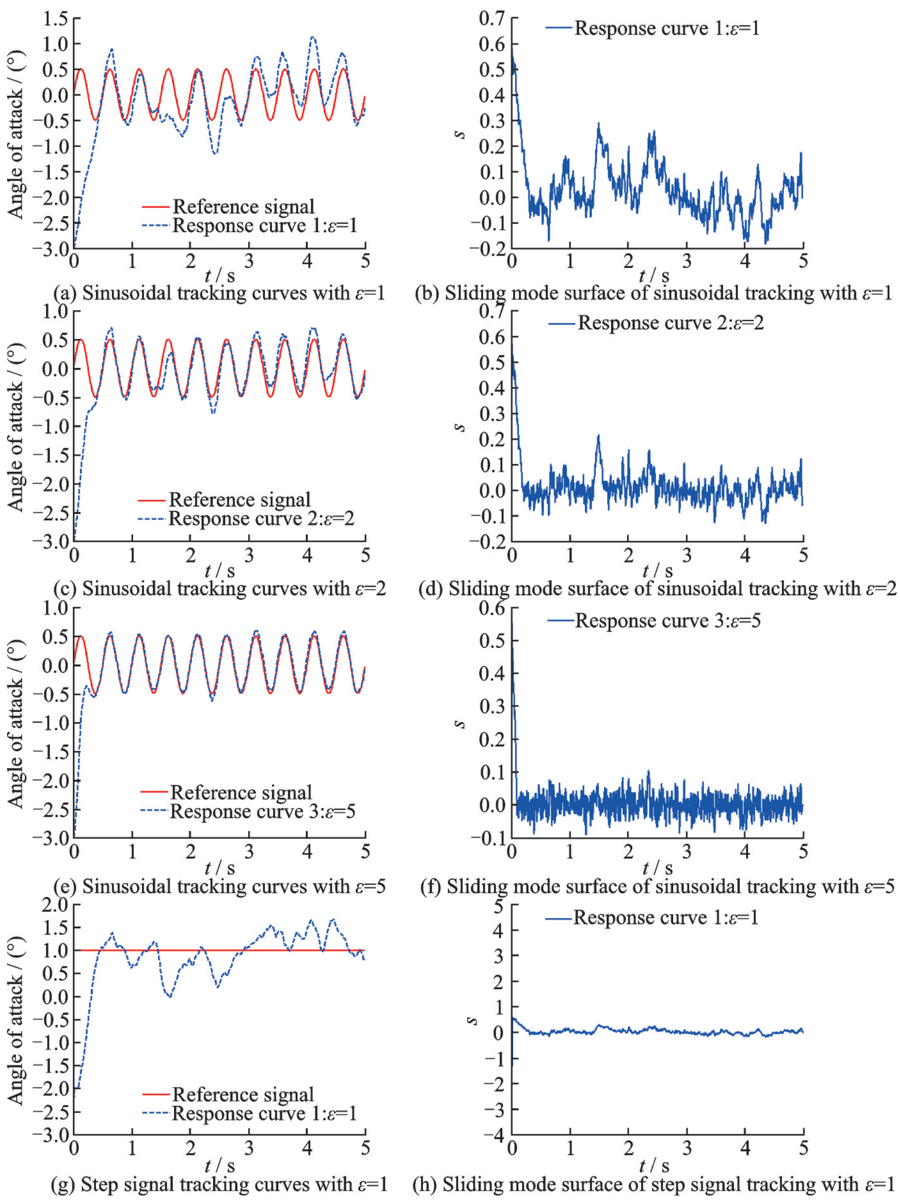




(i) Step signal tracking curves with g=0.1 (j) Sliding mode surface of step signal tracking with g=0.1

(k) Step signal tracking curves with g=0.5 (l) Sliding mode surface of step signal tracking with g=0.5

Fig.4 Effect of parameter changes on the robustness of an improved discrete sliding mode variable structure control system based on disturbance observer ($c_1=10$, $c_2=0$, $\varepsilon=1$, $q=1$)



(a) Sinusoidal tracking curves with ε=1 (b) Sliding mode surface of sinusoidal tracking with ε=1

(c) Sinusoidal tracking curves with ε=2 (d) Sliding mode surface of sinusoidal tracking with ε=2

(e) Sinusoidal tracking curves with ε=5 (f) Sliding mode surface of sinusoidal tracking with ε=5

(g) Step signal tracking curves with ε=1 (h) Sliding mode surface of step signal tracking with ε=1

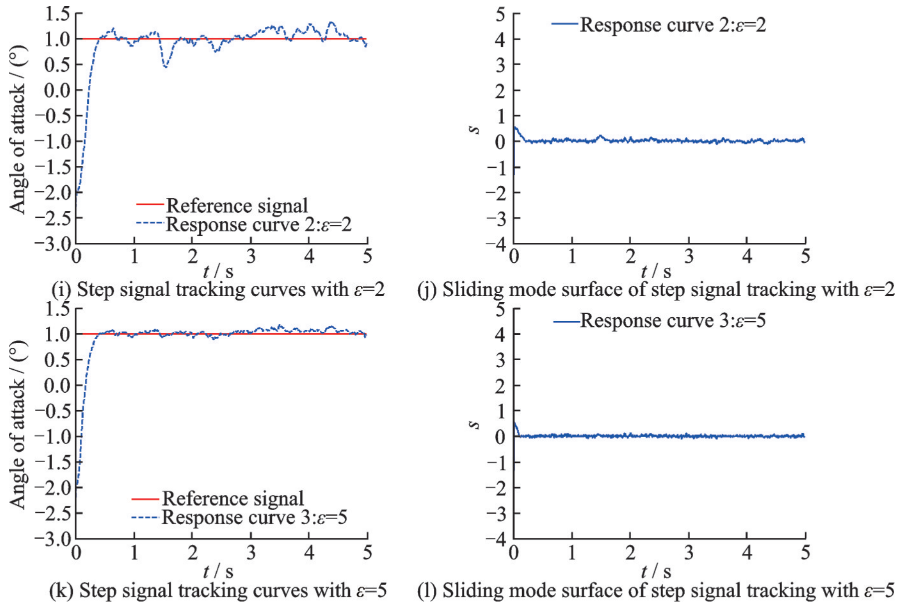


Fig.5 Effect of parameter changes on the robustness of an improved discrete sliding mode variable structure control system based on disturbance observer ($c_1=10, c_2=1, q=1$)

5.2 Simulation results of the control system

Compared with the traditional discrete-time sliding mode variable structure control system, the improved discrete sliding mode variable structure controller based on the disturbance observer proposed in this paper has the following improvements:

(1) This controller uses the disturbance observer, which compensates the disturbance and increases the robustness of the system;

(2) This controller adds the integral link to the sliding surface, which reduces the stable error and improves the quality of the system.

Given that the initial attack angle is $-3°$, the pitching angular velocity is 0 °/s, and a Gaussian white noise interference signal is added to the input part of the system control quantity. If we set $c_2=0$ and $g=0$, the system is the traditional discrete-time sliding mode variable structural control system. That is, Fig.6 shows the simulation results of the traditional discrete-time sliding mode variable structural control system. If we set $c_2=1$ and $g=0.95$, the system takes into account disturbance observa-

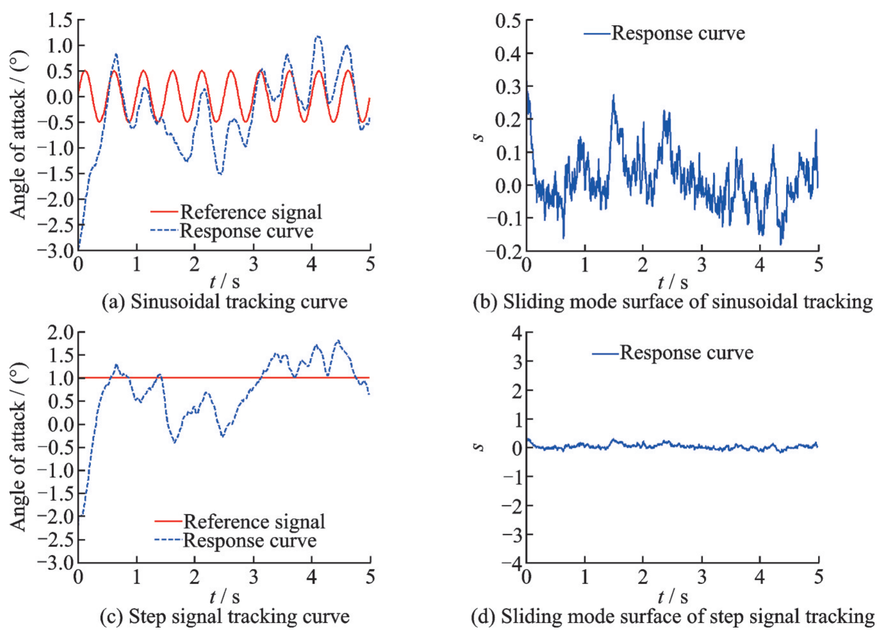


Fig.6 Traditional discrete sliding mode variable structure control system ($c_1=5, c_2=0, g=0, q=2, \varepsilon=1$)

tion compensation and integral sliding mode surface. That is, Fig.7 shows the simulation results of the improved discrete-time sliding mode variable structure control system proposed in this paper.

Comparing the two control systems, we get that, under a Gaussian white noise interference, the response curves in Fig.7 allow for better tracking of reference signal. And the sliding mode surfaces can converge to the vicinity of zero faster and with less chattering in Fig.7. Therefore, the simulation results in Fig.7 verify the effort of the improved control system proposed in this paper.

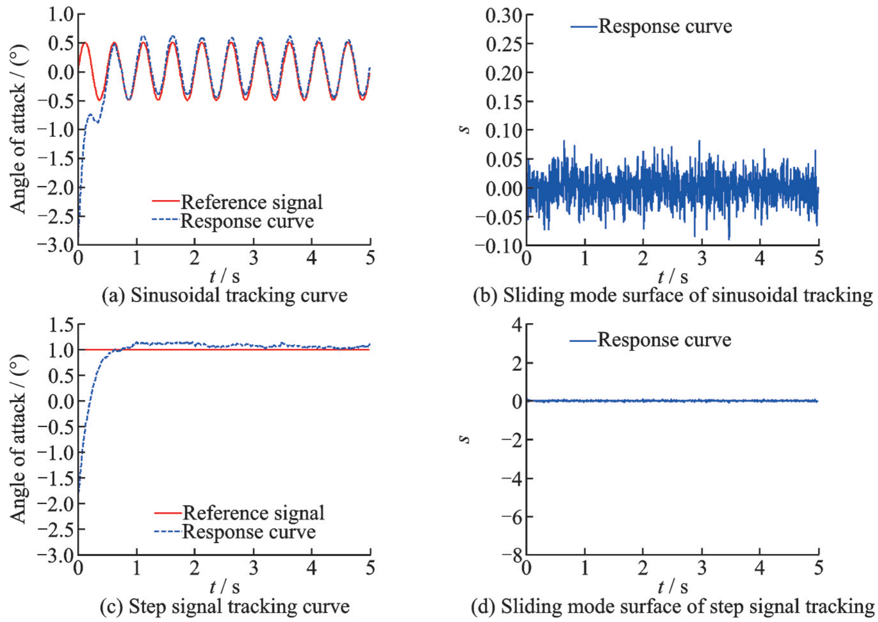


Fig.7 Improved discrete sliding mode variable structure control system based on disturbance observer ($c_1=5$, $c_2=1$, $g=0.95$, $q=2$, $\varepsilon=1$)

6 Conclusions

An improved discrete-time sliding mode variable structure control system based on disturbance observer has been developed for a lift vehicle. The main research contents are summarized as follows:

(1) Based on the analysis of the forces acting on the lift-type vehicle, the discrete control model of the pitch channel has been established. The discrete attitude control model of the pitch channel has been derived. The expressions of external disturbance, model parameter uncertainty and model cross-link coupling terms have been given, which could provide model reference for the control system research of lift-type aircraft in the atmosphere.

(2) An improved discrete-time sliding mode variable structure control system based on disturbance estimation has been designed and its stability has been proved. Based on the traditional discrete sliding mode variable structure controller, the following improvements are made: Firstly, a discrete integral sliding mode surface is proposed to reduce the steady state error of the control system and improve the control quality; secondly, a disturbance observer is proposed to estimate the internal and external disturbances in order to improve the robustness of the control system. At the same time, the Lyapunov function is designed to prove that the discrete sliding mode exists and is reachable, and the stability of the system is guaranteed.

(3) The influence of parameter selection on control system is analyzed, and the validity of control law is verified. The conclusion are as follows: The increase of parameters c_1 and q would improve the response speed of control system; the increase of parameter c_2 would reduce the steady error of control

system; the increase of parameter g would improve the robustness of control system under disturbance; the increase of parameter ε would suppress the disturbance effectively, but increase the chattering.

(4) The comparison with the traditional discrete sliding mode variable structure control system is carried out. Compared with the traditional discrete-time sliding mode control system, the proposed control system in this paper had higher control accuracy, stronger robustness, faster convergence to zero and less chattering.

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基于干扰观测器的升力式飞行器改进离散滑模控制研究

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摘要: 升力式飞行器具有飞行空域宽、速度变化范围大、机动性强等特点,是近年来国内外的研究热点。本文针对升力式飞行器模型大不确定及外界干扰强带来的控制难题,提出了一种基于干扰观测器的改进离散滑模变结构控制方法。首先,建立了俯仰通道的离散控制模型。其次,设计了一种基于干扰估计的改进离散滑模变结构控制律,并证明了其稳定性。再次,分析了参数选择对控制系统的影响,验证了控制律的有效性。最后,与传统的离散滑模变结构控制方法进行了比较。仿真结果表明,与传统的离散滑模控制方法相比,本文提出的控制律控制精度更高、鲁棒性更强、滑模面收敛速度更快及抖振更小,可有效提高升力式飞行器的飞行品质,实现复杂任务的稳定控制。

关键词: 升力式飞行器;干扰观测器;离散滑模控制;鲁棒控制;抖振