Design of dual-loop attitude controller for target missile based on fuzzy variable structure

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Abstract

Aiming at the nonlinearity and model uncertainty of the target missile attitude system, a dual-loop fuzzy variable structure target missile attitude control method is proposed, based on variable structure control and fuzzy systems universal approximation theorem, to improve the response speed and robustness of the attitude control system. The performance of the designed attitude control system is simulated under different perturbation conditions of aerodynamic parameters. The results show that compared with the traditional attitude control system, the designed target attitude control system has faster response and stronger robustness.

Keywords

Target missile; Variable structure control; Fuzzy control; Attitude control system.

1. Introduction

As a common target for the development, shaping, identification and actual combat training of air defense weapon systems, the target missile can be used to simulate the missile's size, motion characteristics, infrared radiation characteristics, and microwave. Reflective characteristics and confrontational characteristics are important equipments that are indispensable for the air defense weapon system test and identification department 1-3]. The performance of the target missile directly affects the credibility of the test and evaluation of the air defense weapon system. With the improvement of the performance of air defense weapon systems and the actual training requirements of the troops, higher requirements are placed on the target elastic energy. In order to meet the requirements of high-performance target bombs for target accuracy, reliability and safety, it is necessary to improve its attitude control system.

The target missile attitude control system is a complex nonlinear time-varying system. The parameters of the attitude control system change continuously with the gravity and the external environmental factors such as air pressure and temperature during the flight of the target missile. This type of target missile has large flight space, severe environmental changes, and a large range of aerodynamic parameters. Traditional control methods are difficult to meet the attitude control accuracy and robustness requirements under aerodynamic parameter perturbation, model uncertainty and external disturbance conditions. Consider adopting more advanced control methods to meet the corresponding requirements.

2. Sliding mode variable structure control

For n order nonlinear systems

$$x^{(n)} = f(\boldsymbol{x},t) + b(\boldsymbol{x},t)u(t) + d(t) \tag{1}$$

Where, $\boldsymbol{x}=\left(x \quad \dot{x} \quad \cdots \quad x^{(\mathrm{n}-1)}\right)^{\mathrm{T}}$ is system state variable; $u(t)$ is Input control amount for the system; $d(t)$ is bounded interference, $|d(t)|\le D$.

System state tracking error vector

$$\boldsymbol{e}=\boldsymbol{x}_{\mathrm{d}}-\boldsymbol{x}=(e,\dot{e},\cdots,e^{(n-1)})^{\mathrm{T}} \tag{2}$$

Defining a sliding modal hyperplane in the system state space

$$s(\boldsymbol{x},t)=c_1e_1+c_2e_2+\cdots+c_{n-1}e_{n-1}+e_n \tag{3}$$

Where $e_i=(x_d-x)^{(i-1)}$ $i=1,\cdots,n$, x_d is system status command; $c_1,c_2,\cdots,c_{n-1}$ is constant and satisfy Hurwitz polynomial $p^{n-1}+c_{n-1}p^{n-2}+\cdots+c_2p+c_1$ [4,5].

The design of the sliding mode control law can be divided into two parts: equivalent control and switching robust control. Corresponding sliding mode control law

$$u=u_{eq}+u_{sw} \tag{4}$$

Equivalent control u_{eq} is the amount of control that keeps the system state moving along the sliding surface. When Regardless of external interference and system uncertainty, let $\dot{s}=0$,then

$$\begin{aligned}\dot{s}(\boldsymbol{x},t)&=c_1\dot{e}+c_2\ddot{e}+\cdots+e^{(n)}\\&=c_1\dot{e}+c_2\ddot{e}+\cdots+c_{n-1}e^{(n-1)}+x_d^{(n)}-x^{(n)}\\&=\sum_{i=1}^{n-1}c_ie^{(i)}+x_d^{(n)}-f(x,t)-bu(t)=0\end{aligned} \tag{5}$$

The equivalent control design is

$$u_{eq}=b^{-1}\left(\sum_{i=1}^{n-1}c_ie^{(i)}+x_d^{(n)}-f(x,t)\right) \tag{6}$$

In order to ensure that the sliding mode arrival condition is established, the system state can reach the switching surface within a limited time, and the system state has good dynamic quality in the approaching segment. Generally, the approaching law method is used to design the switching robust control[6,7].

Taking the constant velocity approach law as an example, design switching robust control

$$u_{sw}=b^{-1}K\operatorname{sgn}(s) \tag{7}$$

Where, K is content and satisfy $K=D+\eta$.

Therefore, the designed sliding mode control law is

$$\begin{aligned}u&=u_{eq}+u_{sw}\\&=b^{-1}\left[\sum_{i=1}^{n-1}c_ie^{(i)}+x_d^{(n)}-f(x,t)\right]+b^{-1}K\operatorname{sgn}(s)\\&=b^{-1}\left[\sum_{i=1}^{n-1}c_ie^{(i)}+x_d^{(n)}-f(x,t)-K\operatorname{sgn}(s)\right]\end{aligned} \tag{8}$$

3. Universal approximation characteristics of fuzzy system

For fuzzy systems with product inference engine, single value fuzzifier, central average defuzzifier and Gaussian membership function, it can be expressed as:

$$f(x)=\frac{\sum_{l=1}^{M}\bar{y}^{l}\left(\prod_{i=1}^{n}\mu_{A_i^{li}}(x_i)\right)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{A_i^{li}}(x_i)\right)} \tag{9}$$

Where, M is the number of fuzzy rule; $\bar{y}^{l}$ is the center of fuzzy set; $\mu_{A_i^{li}}(x_i)$ is the membership function of the fuzzy variable x_i .

According to the lierature[8], the fuzzy system shown by equation(9) has a universal approximation theorem: Assuming that the input domain U is a compact set above R^n , then for any real continuous function $g(x)$ defined above U and arbitrary $\varepsilon > 0$, there must be a fuzzy system, which make equation(10) true:

$$\sup_{x\in U}\left|f(x)-g(x)\right|<\varepsilon \tag{10}$$

Set fuzzy basis function

$$P_l(x)=\frac{\prod_{i=1}^{n}\mu_{A_i^{li}}(x_i)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{A_i^{li}}(x_i)\right)} \tag{11}$$

Fuzzy basis function vector

$$\boldsymbol{P}(x)=\begin{bmatrix}P_1(x) & P_2(x) & \cdots & P_M(x)\end{bmatrix}^{\mathrm{T}} \tag{12}$$

Determine the weighting parameter vector as

$$\boldsymbol{\xi}=\begin{bmatrix}\bar{y}^{1} & \bar{y}^{2} & \cdots & \bar{y}^{M}\end{bmatrix}^{\mathrm{T}} \tag{13}$$

Then the fuzzy system output shown in equation(9) can be expressed as

$$f(x)=\boldsymbol{\xi}^{\mathrm{T}}\boldsymbol{P}(x) \tag{14}$$

And there is a set of optimal weighting parameter vectors $\boldsymbol{\xi}^{*}=\begin{bmatrix}\xi_1^{*} & \xi_2^{*} & \cdots & \xi_M^{*}\end{bmatrix}^{\mathrm{T}}$, such that

$$\boldsymbol{\xi}^{*}=\arg\min_{\xi\in\Omega}\left[\sup_{x\in U}\left|f(x)-\mathrm{g}(x)\right|\right] \tag{15}$$

Where, Ω is collection of ξ .

4. Target missile attitude motion model

The attitude motion equation of the target missile is

$$\begin{cases}\dfrac{\mathrm{d}\varphi}{\mathrm{d}t}=\omega_y\sin\gamma+\omega_z\cos\gamma \\ \dfrac{\mathrm{d}\psi}{\mathrm{d}t}=\dfrac{1}{\cos\varphi}(\omega_y\cos\gamma-\omega_z\sin\gamma) \\ \dfrac{\mathrm{d}\gamma}{\mathrm{d}t}=\omega_x-\tan\varphi(\omega_y\cos\gamma-\omega_z\sin\gamma) \\ M_x=J_x\dfrac{\mathrm{d}\omega_x}{\mathrm{d}t}+(J_z-J_y)\omega_z\omega_y \\ M_y=J_y\dfrac{\mathrm{d}\omega_y}{\mathrm{d}t}+(J_x-J_z)\omega_x\omega_z \\ M_z=J_z\dfrac{\mathrm{d}\omega_z}{\mathrm{d}t}+(J_y-J_x)\omega_y\omega_x\end{cases} \tag{16}$$

To simplify the description of the target missile attitude motion, let

$$\boldsymbol{\theta}=\begin{bmatrix}\varphi & \psi & \gamma\end{bmatrix}^{\mathrm{T}} \tag{17}$$

$$\boldsymbol{\omega}=\begin{bmatrix}\omega_x & \omega_y & \omega_z\end{bmatrix}^{\mathrm{T}} \tag{18}$$

$$\boldsymbol{M}=\begin{bmatrix}M_x & M_y & M_z\end{bmatrix}^{\mathrm{T}} \tag{19}$$

Considering various uncertain factors and external disturbance effects, the equation of motion of the target bullet shown in equation(16) can be written as

$$\begin{cases}\boldsymbol{J}\dot{\boldsymbol{\omega}}+\boldsymbol{\Omega}\boldsymbol{J}\boldsymbol{\omega}=\boldsymbol{M}+\boldsymbol{d}\\ \dot{\boldsymbol{\theta}}=\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}\end{cases} \tag{20}$$

Where, $\boldsymbol{d}$ is the disturbance torque vector, $\boldsymbol{d}=\begin{bmatrix}d_1 & d_2 & d_3\end{bmatrix}^{\mathrm{T}}$ including the uncertainty of the target missile model and various external disturbance moments, $|d_i|\le D\ (i=1,2,3)$ 。

$\boldsymbol{J}$ is the moment of inertia matrix of the target's rotation around the centroid in the projectile coordinate system

$$\boldsymbol{J}=\begin{bmatrix}J_x & 0 & 0\\ 0 & J_y & 0\\ 0 & 0 & J_z\end{bmatrix} \tag{21}$$

$\boldsymbol{\Omega}$ is the matrix of the relationship between the moment of action and the angular velocity of the target missile

$$\boldsymbol{\Omega}=\begin{bmatrix}0 & -\omega_z & -\omega_y\\ \omega_z & 0 & -\omega_x\\ -\omega_y & \omega_x & 0\end{bmatrix} \tag{22}$$

$\boldsymbol{R}(\boldsymbol{\theta})$ is the matrix of the relationship between the angular velocity of the target missile and the rate of change of the attitude angle with time.

$$\boldsymbol{R}(\boldsymbol{\theta})=\begin{bmatrix}1 & \tan\psi\sin\gamma & \tan\psi\cos\gamma\\ 0 & \cos\gamma & -\sin\gamma\\ 0 & \sin\gamma/\cos\psi & \cos\gamma/\cos\psi\end{bmatrix} \tag{23}$$

5. Target missile attitude controller

According to the attitude motion model of the target missile, the target missile attitude system is divided into the attitude velocity control inner loop with fast response speed and the attitude angle control outer loop with slow response speed. The sliding mode variable structure control theory is used to design the attitude angular velocity inner loop respectively. And the attitude angle outer loop control law, using the universal approximation characteristics of the fuzzy system to approximate the variable structure control switching control term to suppress the system chattering phenomenon[9,10].

The structure of the dual-loop sliding mode variable structure control system is shown in Figure 1.The attitude angular velocity inner loop controller takes the attitude angular velocity control command and the attitude angular velocity as input, and the control torque as the output; the attitude angle outer loop controller uses the attitude angle control command. The attitude angle is an input, and the attitude angular velocity control command is an output.

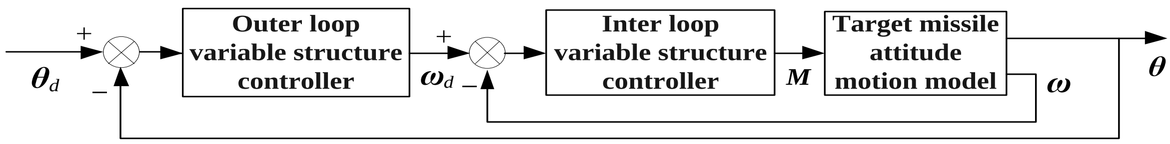


Fig. 1 Block diagram of double loop sliding mode variable structure attitude control system

5.1 Design of inner loop adaptive fuzzy variable structure controller

The target missile attitude inner loop controller realizes that attitude angular velocity $\boldsymbol{\omega}$ track attitude angular velocity command $\boldsymbol{\omega}_d$, and suppresses the disturbance caused by various uncertainties and disturbance moments.

According to equation(20), the state equation of the target missile inner attitude control loop is

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\Omega}\boldsymbol{J}\boldsymbol{\omega} = \boldsymbol{M} + \boldsymbol{d} \tag{24}$$

$$\dot{\boldsymbol{\omega}} = \frac{1}{\boldsymbol{J}}(\boldsymbol{M} + \boldsymbol{d} - \boldsymbol{\Omega}\boldsymbol{J}\boldsymbol{\omega}) \tag{25}$$

The inner loop controller is designed by sliding mode variable structure control method, and the inner loop switching function with integral term is selected as

$$\boldsymbol{s}(\boldsymbol{\omega},t) = \boldsymbol{C}_1\int_0^t \boldsymbol{e}(\boldsymbol{\omega},t)\mathrm{d}t + \boldsymbol{e}(\boldsymbol{\omega},t) \tag{26}$$

Where, $\boldsymbol{s} = [s_1 \ \ s_2 \ \ s_3]^{\mathrm{T}}$ is Switching function vector, s_1 , s_2 , s_3 are pitch, yaw, and roll channel switching functions; $\boldsymbol{e}(\boldsymbol{\omega},t)$ is tracking angular velocity tracking error, $\boldsymbol{e}(\boldsymbol{\omega},t) = \boldsymbol{\omega}_d - \boldsymbol{\omega}$; $\boldsymbol{C}_1 = \mathrm{diag}\left\{c_{11}, c_{12}, c_{13}\right\}$ is Gain matrix.

When various interference factors are not considered, let $\boldsymbol{s}(\boldsymbol{\omega},t) = 0$.

$$\dot{\boldsymbol{s}} = \boldsymbol{C}_1\boldsymbol{e} + \dot{\boldsymbol{e}} = \boldsymbol{C}_1\boldsymbol{e} + \dot{\boldsymbol{\omega}}_d + \frac{1}{\boldsymbol{J}}(\boldsymbol{\Omega}\boldsymbol{J}\boldsymbol{\omega} - \boldsymbol{M}) = 0 \tag{27}$$

Equivalent control

$$\boldsymbol{M}_{eq} = \boldsymbol{\Omega}\boldsymbol{J}\boldsymbol{\omega} + \boldsymbol{J}(\boldsymbol{C}_1\boldsymbol{e} + \dot{\boldsymbol{\omega}}_d) \tag{28}$$

The switching robust control quantity uses the exponential approach law form:

$$\boldsymbol{M}_{sw} = \boldsymbol{k}\boldsymbol{s} + \boldsymbol{\varepsilon}\mathrm{sign}(\boldsymbol{s}) \tag{29}$$

Where, $\boldsymbol{k} = \mathrm{diag}\left\{k_1, k_2, k_3\right\}$, k_1 , k_2 , k_3 is constants greater than zero; $\boldsymbol{\varepsilon} = \mathrm{diag}\left\{\varepsilon_1, \varepsilon_2, \varepsilon_3\right\}$, ε_1 , ε_2 , ε_3 are constants greater than zero and satisfy $\varepsilon_i > D \ (\mathrm{i} = 1,2,3)$.

Then design the inner ring sliding mode variable structure control law:

$$\begin{aligned} \boldsymbol{M} &= \boldsymbol{M}_{eq} + \boldsymbol{M}_{sw} \\ &= \boldsymbol{\Omega}\boldsymbol{J}\boldsymbol{\omega} + \boldsymbol{J}(\boldsymbol{C}_1\boldsymbol{e} + \dot{\boldsymbol{\omega}}_d) + \boldsymbol{k}\boldsymbol{s} + \boldsymbol{\varepsilon}\mathrm{sign}(\boldsymbol{s}) \end{aligned} \tag{30}$$

Roll, yaw and pitch channel control laws are

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} \omega_y\omega_z(J_z - J_y) + J_x(c_{11}e_x + \dot{\omega}_{xd}) + k_1s_1 + \varepsilon_1\mathrm{sign}(s_1) \\ \omega_x\omega_z(J_x - J_z) + J_y(c_{12}e_y + \dot{\omega}_{yd}) + k_2s_2 + \varepsilon_2\mathrm{sign}(s_2) \\ \omega_x\omega_y(J_y - J_x) + J_z(c_{13}e_z + \dot{\omega}_{zd}) + k_3s_3 + \varepsilon_3\mathrm{sign}(s_3) \end{bmatrix} \tag{31}$$

In order to reduce the control amount chattering, based on the universal approximation characteristics of the fuzzy system, the fuzzy system output $\hat{h}(s|\xi)$ is used to approximate the switching control items of each channel. As can be seen from the previous section, the fuzzy system output can be expressed as

$$\hat{h}(s|\xi) = \boldsymbol{\xi}\boldsymbol{P}(s) \tag{32}$$

Since the switching control coefficient ε is unknown, and its general design rule is: when the system state is far away from the switching surface, in order to make the system state quickly approach the switching surface, take ε a larger value; when the system state is closer to the switching surface, Reduce system chattering and take ε a smaller value[11-13]. Therefore, the optimal weighting parameter vector $\boldsymbol{\xi}^* = \left[\xi_1^* \quad \xi_2^* \quad \ldots \quad \xi_M^*\right]^{\mathrm{T}}$ also changes as the state of the system changes.

Design weighted parameter vector adaptive law

$$\dot{\xi} = \lambda s\boldsymbol{P}(s) \tag{33}$$

Where, $\lambda > 0$.

The following is an example of the rolling channel control law to analyze the stability of the designed control law:

$$\begin{aligned}\dot{s}_1 &= c_{11}e_x + \dot{e}_x \\ &= c_{11}e_x + (\dot{\omega}_{xd} - \dot{\omega}_x) \\ &= c_{11}e_x + \dot{\omega}_{xd} - J_x^{-1}(M_x - (J_z - J_y)\omega_y\omega_z + d_1) \\ &= -\hat{h}(s_1|\xi) - J_x^{-1}(d_1 + k_1s_1) \\ &= -\hat{h}(s_1|\xi) - J_x^{-1}(d_1 + k_1s_1) + \hat{h}(s_1|\xi^*) - \hat{h}(s_1|\xi^*) \\ &= \tilde{\boldsymbol{\xi}}^{\mathrm{T}}\boldsymbol{P}(s_1) - J_x^{-1}(d_1 + k_1s_1) - \hat{h}(s_1|\xi^*)\end{aligned} \tag{33}$$

Where, $\tilde{\boldsymbol{\xi}} = \xi^* - \xi$.

Take the Lyapunov function as

$$V = \frac{1}{2}\left(s_1^2 + \frac{1}{\lambda}\tilde{\xi}^{\mathrm{T}}\tilde{\xi}\right) \tag{34}$$

$$\begin{aligned}\dot{V} &= s_1\dot{s}_1 + \frac{1}{\lambda}\tilde{\xi}^{\mathrm{T}}\dot{\tilde{\xi}} \\ &= s_1(\tilde{\boldsymbol{\xi}}^{\mathrm{T}}\boldsymbol{P}(s_1) - J_x^{-1}(d_1 + k_1s_1) - \hat{h}(s_1|\xi^*)) + \frac{1}{\lambda}\tilde{\xi}^{\mathrm{T}}\dot{\tilde{\xi}} \\ &= s_1\tilde{\boldsymbol{\xi}}^{\mathrm{T}}\boldsymbol{P}(s_1) + \frac{1}{\lambda}\tilde{\xi}^{\mathrm{T}}\dot{\tilde{\xi}} - s_1(J_x^{-1}(d_1 + k_1s_1) - \hat{h}(s_1|\xi^*))\end{aligned} \tag{35}$$

Because $\hat{h}(s_1|\xi^*) \approx \varepsilon_1 \operatorname{sgn}(s_1)$,it is substituted into the equation (35):

$$\dot{V} = \frac{1}{\lambda}\tilde{\xi}^{\mathrm{T}}(\lambda s_1\boldsymbol{P}(s_1) + \dot{\tilde{\xi}}) - s_1J_x^{-1}(d_1 + k_1s_1) - |s_1|\varepsilon_1 \tag{36}$$

According to $\tilde{\boldsymbol{\xi}} = \xi^* - \boldsymbol{\xi}$,then

$$\dot{\tilde{\xi}} = -\dot{\xi} = -\lambda s_1R(s_1) \tag{37}$$

Substituting the equation (37) into the equation (36):

$$\dot{V} = -s_1J_x^{-1}(d_1 + k_1s_1) - |s|\varepsilon_1 \le 0 \tag{38}$$

According to the Lyapunov stability that the designed control law satisfies the reachable condition of the system sliding mode.

5.2 Design of outer loop sliding mode variable structure controller

The attitude angle outer loop control loop realizes that the target missile attitude angle track the target missile attitude angle commend. The outer loop attitude angle control loop equation of state is

$$\dot{\boldsymbol{\theta}} = \boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega} \tag{39}$$

Same as the design of the inner loop controller, select the outer loop switching function with integral term

$$\boldsymbol{S}(t) = \boldsymbol{C}_2\int_0^t \boldsymbol{E}(t)\mathrm{d}t + \boldsymbol{E}(t) \tag{40}$$

Where, $\boldsymbol{S} = [\boldsymbol{S}_1\ \ \boldsymbol{S}_2\ \ \boldsymbol{S}_3]^{\mathrm{T}}$ is switching function vector, $\boldsymbol{S}_1$, $\boldsymbol{S}_2$, $\boldsymbol{S}_3$ are pitch, yaw, and roll channel switching functions; $\boldsymbol{E}(t)$ is attitude angle tracking error, $\boldsymbol{E}(t) = \boldsymbol{\theta}_d - \boldsymbol{\theta}$; $\boldsymbol{C}_2 = \operatorname{diag}\{c_{21}, c_{22}, c_{23}\}$ is the gain matrix.

According to

$$\begin{aligned}\dot{\boldsymbol{S}} &= \boldsymbol{C}_2\boldsymbol{E}(t)+\dot{\boldsymbol{E}}(t)\\ &= \boldsymbol{C}_2(\boldsymbol{\theta}_d-\boldsymbol{\theta})+\dot{\boldsymbol{\theta}}_d-\dot{\boldsymbol{\theta}}\\ &= \dot{\boldsymbol{\theta}}_d-\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}_d+\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}_e+\boldsymbol{C}_2(\boldsymbol{\theta}_d-\boldsymbol{\theta})\end{aligned} \tag{41}$$

Since the attitude angular velocity command needs to be derived in the design of the inner loop control loop, it will be designed as a derivable function. Design outer ring sliding mode control law

$$\boldsymbol{\omega}_d=\boldsymbol{R}^{-1}(\boldsymbol{\theta})[\dot{\boldsymbol{\theta}}_d+\boldsymbol{C}_2(\boldsymbol{\theta}_d-\boldsymbol{\theta})]+\boldsymbol{R}^{-1}(\boldsymbol{\theta})\boldsymbol{\rho}\boldsymbol{S} \tag{42}$$

Where, $\boldsymbol{\rho}=\mathrm{diag}\{\rho_1,\rho_2,\rho_3\}$, $\rho_i>0\ (i=1,2,3)$ are constants greater than zero.

Prove the stability of the designed outer loop sliding mode control law: construct Lyapunov function:

$$V=\frac{1}{2}\boldsymbol{S}^{\mathrm{T}}\boldsymbol{S} \tag{43}$$

In order to ensure that the sliding mode arrival condition is established, the derivative of equation(43) must satisfy the following conditions.

$$\begin{aligned}\dot{V} &= \boldsymbol{S}^{\mathrm{T}}\dot{\boldsymbol{S}}=\boldsymbol{S}^{\mathrm{T}}(\dot{\boldsymbol{\theta}}_d-\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}_d+\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}_e+\boldsymbol{C}_2(\boldsymbol{\theta}_d-\boldsymbol{\theta}))\\ &= \boldsymbol{S}^{\mathrm{T}}\left\{\dot{\boldsymbol{\theta}}_d-\boldsymbol{R}(\boldsymbol{\theta})\left[\boldsymbol{R}^{-1}(\boldsymbol{\theta})(\dot{\boldsymbol{\theta}}_d+\boldsymbol{C}_2(\boldsymbol{\theta}_d-\boldsymbol{\theta})+\boldsymbol{\rho}\boldsymbol{S})\right]+\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}_e+\boldsymbol{C}_2(\boldsymbol{\theta}_d-\boldsymbol{\theta})\right\}\\ &= -\boldsymbol{\rho}\left\|\boldsymbol{S}\right\|^2+\boldsymbol{S}^{\mathrm{T}}\boldsymbol{R}(\boldsymbol{\theta})\boldsymbol{\omega}_e\end{aligned} \tag{44}$$

It can be seen from the equation that in order to ensure $\dot{V}\le 0$ that the angular velocity error of the attitude $\boldsymbol{\omega}_e$ is sufficiently small, the convergence speed of the inner ring sliding mode control is required to be faster than that of the outer loop sliding mode control. Therefore, k should be larger in the design of the inner loop controller. And make $C_1\ge C_2$ to eliminate the attitude angular velocity error as soon as possible.

6. Simulation analysis

In order to verify the effectiveness of the proposed target attitude control method, the target model of the target attitude control system is established by Matlab/Simulink simulation platform. The simulation model is shown in Figure 2, where the inner and outer loop controllers are implemented by S-function. The simulation initial conditions are: initial attitude angle of the target, initial attitude angular velocity, input pitch, yaw and roll angle control commands as unit step signals. The fourth-order Runge-Kutta method is used to solve the model. The simulation uses a fixed step size of 0.01. Under the condition of aerodynamic parameter perturbation of 10%, 30% and 50%, the traditional attitude control system and the attitude control system based on dual-loop fuzzy variable structure (hereinafter referred to as method 1 and method 2) are simulated respectively. The simulation results are shown in Figure 3.

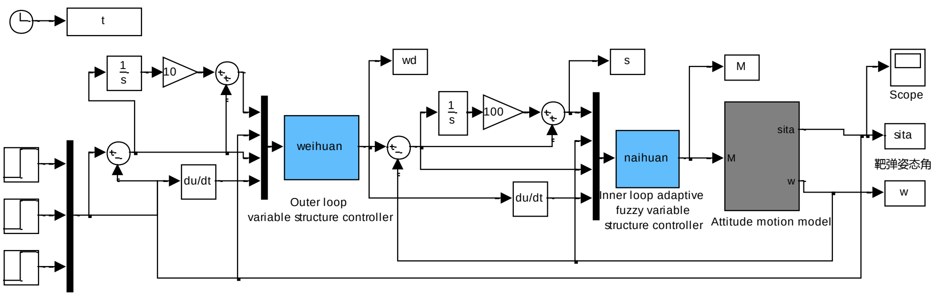
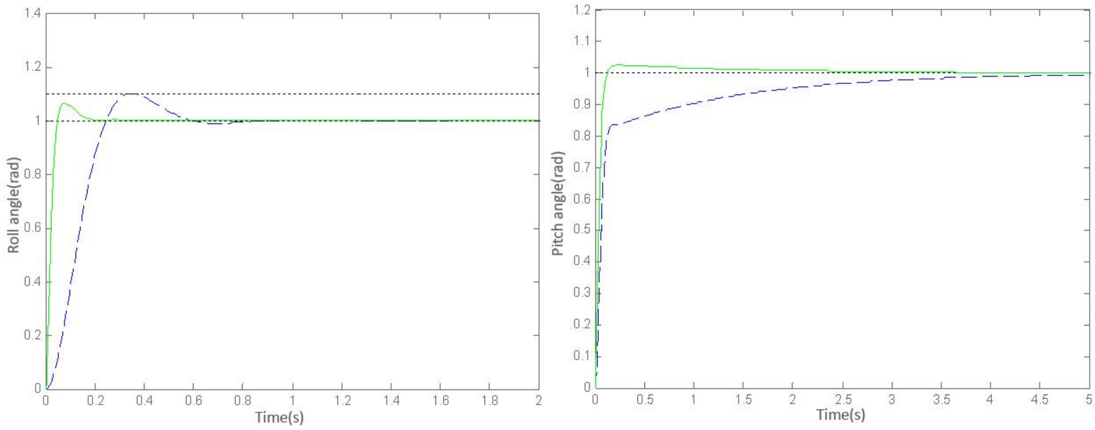
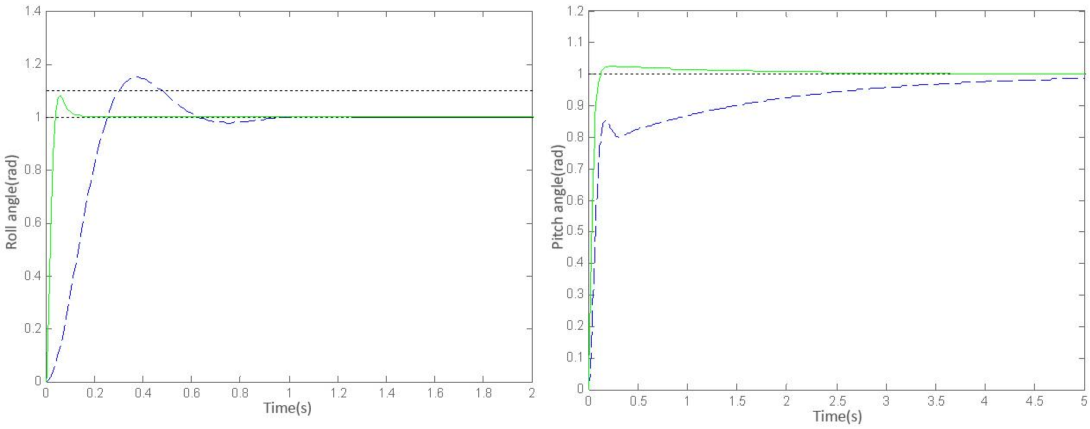


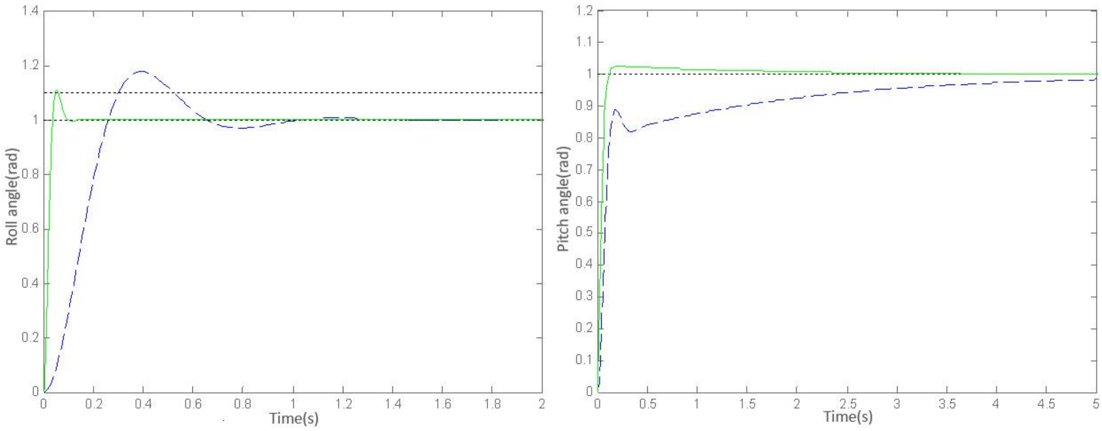
Fig. 2 Simulation model of the target missile attitude control system



Roll and pitch angle response curve under
10% aerodynamic parameter perturbation condition



Roll and pitch angle response curve under
20% aerodynamic parameter perturbation condition



Roll and pitch angle response curve under
30% aerodynamic parameter perturbation condition

——— Dual-loop fuzzy variable structure control

– – – – – Classical control

Fig. 3 Unit step response curves of roll and pitch channels under different aerodynamic parameters perturbation condition

For the convenience of analysis, the simulation results of the two attitude control system design methods under different aerodynamic parameters perturbation conditions are counted, as shown in Table 1

Table 1 Simulation results under different aerodynamic parameters perturbation conditions

	Performance	Control method	Pneumatic parameter perturbation		
			10%	30	50%
Roll angle	Adjustment time t_r (s)	1	0.5	0.5	0.6
		2	0.11	0.08	0.08
	Overshoot σ (%)	1	10	14	18
		2	6	8	11
	Steady-state error e_{ss} (%)	1	0	0	0
		2	0	0	0
Pitch angle	Adjustment time t_r (s)	1	1.9	2.6	2.7
		2	0.2	0.2	0.3
	Overshoot σ (%)	1	0	0	0
		2	2.5	2.6	3
	Steady-state error e_{ss} (%)	1	0	2	2
		2	0	0	0

It can be seen from Figure 3 and Table 1 that when the aerodynamic parameters are perturbed by 10%, the dynamic performance and steady state performance of the methods 1 and 2 are not greatly affected, and the performance requirements of the target attitude control system are still met. Both methods have certain robustness to system parameter perturbation; when the aerodynamic parameters are perturbed by 30%, the rollover angle overshoot of method 1 reaches 14%, and the pitch angle adjustment time reaches 2.6 s. The control system corresponding index demand, method 2 is affected by the aerodynamic parameter perturbation, the pitch angle and the roll angle overshoot have increased to some extent, but still not more than 10%. The simulation results show that compared with method 1, method 2 is aerodynamic parameters. The robustness of the deviation is stronger; when the aerodynamic parameters are perturbed by 50%, the rollover overshoot of the method 2 reaches 11%, which exceeds the design requirements, but still has better performance as a whole. It can be seen from the above analysis that the attitude control system designed based on double loop fuzzy variable structure control is more robust than the traditional control system.

7. Conclusion

This paper studies the control problem of the target attitude system. Aiming at the nonlinearity and model uncertainty of the target attitude system, a dual-loop fuzzy variable structure target attitude control method is proposed. imulation results show that compared with the traditional attitude control system, the designed target attitude control system has faster response and stronger robustness.

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