The Attitude Stability Control Method of Unmanned Aerial Vehicles Based on Sliding Mode Theory

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Abstract. Unmanned aerial vehicles have been increasingly widely applied in various fields in the last decade. However, during the execution of tasks, unmanned aerial vehicles (UAVs) are prone to be disturbed by gusts of wind, which affects the mission execution efficiency of UAVs and threatens flight safety. Aiming at the problem of unstable flight of unmanned aerial vehicles (UAVs) under gust disturbances during flight, this paper first establishes the flight dynamics model and gust model of UAVs and designs an attitude controller for UAVs under gust disturbances by using the sliding mode algorithm. It's proved that the controller is stable through Lyapunov stability theory. Finally, numerical simulation tests were carried out to verify the control effect of the designed controller under wind interference. The simulation test shows that the sliding mode controller designed in this paper has better robustness under gust interference than the traditional method-PID control, improving the stability and anti-interference ability of the unmanned aerial vehicle under gust disturbance.

Keywords: Unmanned Aerial Vehicle, Gust disturbance, sliding mode control.

1. Introduction

Unmanned aerial vehicles (UAVs) have been increasingly applied in various fields with the technique development and breakthrough. They are commonly used in military [1], civilian [2], aerial photography [3], agriculture [4], among others. Their application prospects are very broad. However, during the operation of unmanned aerial vehicles (UAVs), various environmental disturbances are inevitable. Among them, gust disturbances are one of the most common situations. Gust disturbances can cause changes in the flight attitude of UAVs and threaten their flight safety. Therefore, research on the stable flight control of UAVs under gust disturbances is needed.

At present, many studies have proposed various control methods to reduce external disturbances or self-jitter to ensure the stable flight of unmanned aerial vehicles. For instance, regarding the quadcopter unmanned aerial vehicle (UAV), Huang Yi et al. [5] first established a flight dynamics model of the quadcopter aircraft and designed a quadcopter flight control system based on the PID control algorithm. Finally, through simulation experiments, it was verified that the UAV could achieve stable flight under the designed PID controller. Aiming at the flight control problem of aircraft under atmospheric disturbances, Ke Jie et al. [6] designed a flight controller for unmanned aerial vehicles based on the $H\infty$ control theory and applying the control linear matrix inequality. Simulation results show that this method has a good anti-interference ability, thereby improving the robustness of unmanned aerial vehicles against atmospheric disturbances. Furthermore, in response to the issue of civilian unmanned aerial vehicles (UAVs) being disturbed by external factors, researchers have also proposed reasonable solutions through studies to reduce the interference of external factors on UAVs. For instance, Feng Junhong et al. [7], based on the variable payload of civilian UAVs and the problem of external disturbances, adopted the principle of minimizing dynamic tracking errors and proposed a hierarchical control strategy combining inner and outer loops. It can achieve better robustness of the closed-loop control system, thereby enhancing the flight performance of civilian unmanned aerial vehicles.

Besides the control methods aforementioned, sliding mode control, an effective robust control method, has garnered significant attention from researchers due to its anti-interference feature [8] [9]. Sliding mode control is a variable structure control method. By introducing a sliding mode surface, the state of the control system slides on the sliding mode surface during the dynamic process and remains in a sliding state, thereby achieving precise control of the system. Since the sliding mode control will change its own structure according to the system changes during the sliding process, it has strong robustness against uncertain parameters and external disturbances. Liu Huibo et al. [10] conducted flight control research by combining model prediction and high-order sliding mode algorithm. The numerical simulation results show that this method can effectively improve the stability of unmanned aerial vehicles under wind interference. Gao Junshan et al. [11] proposed a double closed-loop control strategy based on the backstepping method and the adaptive sliding mode algorithm to eliminate self-jitter, making the unmanned aerial vehicle more stable during flight. All the above studies show that sliding mode control can effectively improve the stability and anti-interference ability of unmanned aerial vehicles.

Based on the above discussion, this paper intends to conduct research on the unmanned aerial vehicles (UAVs) stable flight controlling under gust disturbances. Firstly, the flight dynamics model of the UAV and the gust model are established to simulate the dynamic response of the aircraft under gusts. The sliding mode method is adopted to design the controller, and the Lyapunov stability theory is used to prove the stability of the designed controller. Then, numerical simulation is carried out using MATLAB/SIMULINK software to achieve stable attitude control under gusts disturbance.

2. Modeling of unmanned aerial vehicle flight dynamics and gust disturbance

2.1. Unmanned Aerial Vehicle Flight Dynamics Model

The object studied in this research is a fixed-wing unmanned aerial vehicle, including three sets of control surfaces: ailerons, elevators and rudders. Its flight dynamics model is shown as follows:

$$\begin{cases} \dot{\phi} = p + \tan\theta\,(q\sin\phi + r\cos\phi) \\ \dot{\theta} = q\cos\phi - r\sin\phi \\ \dot{\psi} = \frac{q\sin\phi + r\cos\phi}{\cos\theta} \end{cases} \tag{1}$$

$$\begin{cases} \dot{p} = I_1 pq + I_2 qr + I_3 L + I_4 N \\ \dot{q} = I_5 pr - I_6(p^2 - r^2) + I_7 M \\ \dot{r} = I_8 pq - I_1 qr + I_4 L + I_9 N \end{cases} \tag{2}$$

Among them, they respectively represent the roll Angle, pitch Angle and yaw Angle; They respectively represent the roll Angle velocity, pitch Angle velocity and yaw Angle velocity; They respectively represent the rolling moment, pitch moment and yaw moment, and their expressions are as follows:

$$\begin{cases} L = \left[C_l + C_{l\delta_a}\delta_a + C_{l\delta_r}\delta_r + \frac{bp}{2V}C_{lp} + \frac{br}{2V}C_{lr}\right]\bar{q}Sb \\ M = \left[C_m + C_{m\hat{\delta}_e}\delta_e + \frac{\bar{c}q}{2V}C_{mq}\right]\bar{q}Sc \\ N = \left[C_n + C_{n\delta_a}\delta_a + C_{n\delta_r}\delta_r + \frac{bp}{2V}C_{np} + \frac{br}{2V}C_{nr}\right]\bar{q}Sb \end{cases} \tag{3}$$

Among them, they respectively represent the aileron deflection Angle, elevator deflection Angle and rudder deflection Angle; Represent dynamic pressure; Represent the wing area; Represent the wingspan; Represents the flight speed of the unmanned aerial vehicle.

In the attitude flight control process of this paper, the attitude Angle changes are all small quantities. Therefore, according to formulas (1) and (2), they can be transformed into the following form of the state space equation:

$$\begin{cases} x_1 = x_2 \\ x_2 = f + gu \end{cases} \tag{4}$$

Among them $\mathbf{x}_1 = [\phi \quad \theta \quad \psi]^T, \mathbf{x}_2 = [p \quad g \quad r]^{\mathrm{T}}, \mathbf{u} = [\delta_a \quad \delta_{\mathrm{e}} \quad \delta_r]^{\mathrm{T}}$, F and g are the system structure matrices

2.2. Gust Disturbance Model

In this paper, the Von Karman model is adopted to simulate the interference of gusts on unmanned aerial vehicles. According to reference [12], the energy spectral function of gusts in the Von Karman model is as follows:

$$E(\Omega) = \sigma^2 \frac{55L}{9\pi} \frac{(aL\Omega)^4}{[1+(aL\Omega^2)^{17/6}]} \tag{5}$$

Among them, $\mathcal{L}$ is the turbulence scale, Ω is the spatial frequency, and σ is the turbulence intensity

Further, based on Equation (5), the simulation results of gust disturbance established in MATLAB/SIMULINK are shown in Figure 1 as follows:

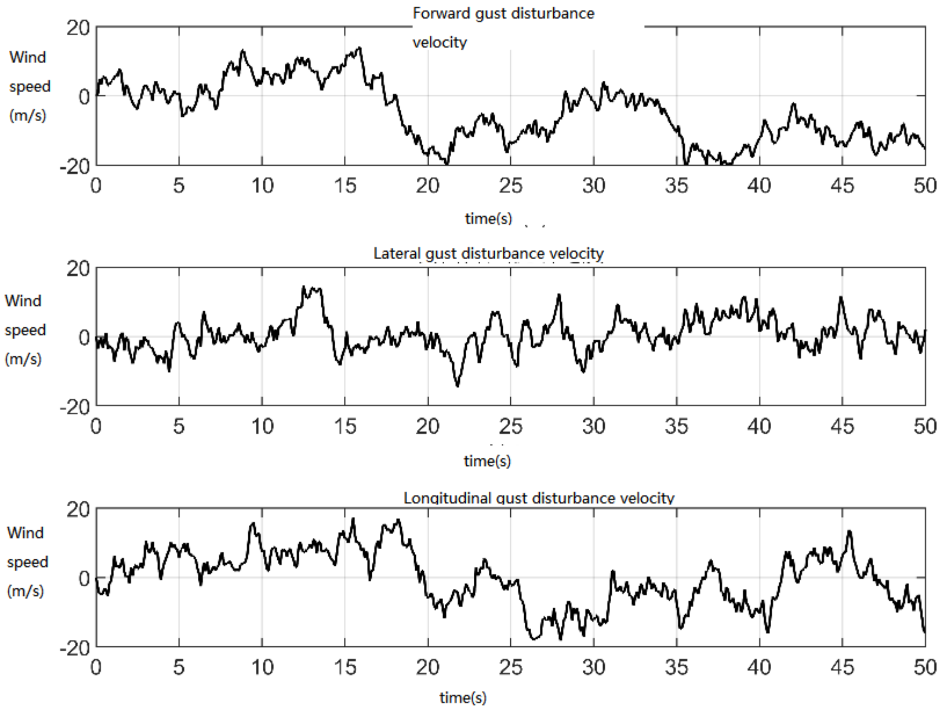


Figure 1. Simulation result diagram of gusty wind interference

3. Design of Attitude Stability Controller

Sliding mode control, as a special variable structure control, can change its own structure according to the system changes, thereby having a better anti-interference ability against external disturbances. This section will take the longitudinal channel of unmanned aerial vehicle (UAV) attitude control as an example to describe in detail the design steps and stability proof of the UAV attitude sliding mode controller.

3.1. Design of Attitude Sliding Mode Controller

According to formulas (1) - (4), the state space equation for the longitudinal attitude control of unmanned aerial vehicles can be written in the following form:

$$\begin{cases} \dot{\theta} = q \\ \dot{q} = f + gu \end{cases} \tag{6}$$

Among them $f = I_5 pr - I_6(p^2 - r^2) + I_7(C_m + \frac{\bar{c}q}{2V}C_{mq})\bar{q}\bar{s}\bar{c}$, $g = I_7 C_{\omega\delta_e}\bar{g}\bar{s}\bar{c}$.

Suppose the expected pitch Angle is θ_d , then the pitch Angle tracking error is defined as $e = \theta - \theta_d$. The sliding mode surface is designed as follows:

$$S = \dot{e} + K\int_0^t e d\tau \tag{7}$$

Among them K are the control parameters of the sliding mode surface.

Taking the derivative of Equation (7) and substituting it into Equation (6), we obtain:

$$\begin{aligned} \dot{S} &= \ddot{e} + Ke \\ &= \ddot{\theta} - \ddot{\theta}_d + Ke \\ &= f + gu - \ddot{\theta}_d + Ke \end{aligned} \tag{8}$$

According to the sliding mode surface in Formula (8), the longitudinal attitude sliding mode controller is designed as:

$$u = g^{-1}(-f + \ddot{\theta}_d - Ke - c_1 S - c_2\mathbf{sgn}(S)) \tag{9}$$

Among them, c_1 and c_2 represent the controller parameters.

3.2. Proof of Stability

The stability of the sliding mode controller designed by Equation (9) is proved below. First, the Lyapunov function is defined as:

$$W = \frac{1}{2}S^2 \tag{10}$$

Taking the derivative of Equation (10) and substituting it into Equation (8), we can obtain:

$$\begin{aligned} \dot{W} &= S\dot{S} \\ &= S(f + gu - \ddot{\theta}_d + Ke) \end{aligned} \tag{11}$$

Further substituting Equation (9) into Equation (11) yields:

$$\begin{aligned} \dot{W} &= S(-c_1 S - c_2\mathrm{sgn}(S)) \\ &= -c_1 S^2 - c_2|S| \le 0 \end{aligned} \tag{12}$$

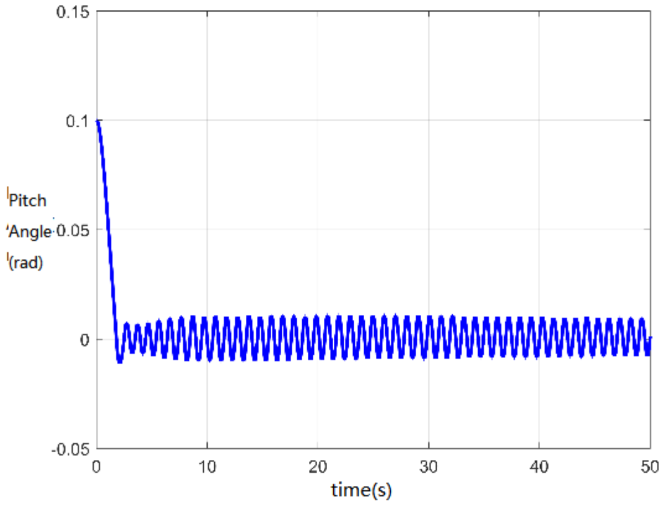
Thus, according to Lyapunov's direct stability criterion, it can be obtained that the longitudinal attitude sliding mode controller designed in Equation (9) is stable.

4. Numerical Simulation and Result Discussion

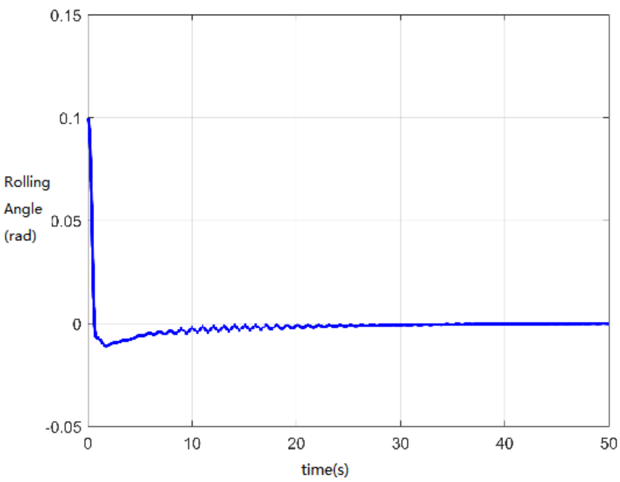
In this section, a simulation experiment of unmanned aerial vehicle (UAV) attitude control under gust disturbance is conducted by using MATLAB/SIMULINK software to simulate the changes of the aircraft flight attitude Angle caused by PID control and sliding mode control of the UAV with and without gust disturbance.

The simulation test conditions set in this paper are as follows: The initial position coordinates of the unmanned aerial vehicle in the geodetic coordinate system are [0, 0 -2000]. The initial velocities of the unmanned aerial vehicle under the body-axis system: the forward velocity is 68m/s, the lateral velocity is 0m/s, and the longitudinal velocity is 5.9m/s. Initial attitude angles: Pitch Angle is 0.1rad, pitch Angle is 0.2rad, yaw Angle is 0.1rad. Initial angular velocity: Rotational angular velocity is 0rad/s, pitch angular velocity is 0rad/s, yaw angular velocity is 0rad/s. The longitudinal direction adopts a sliding mode controller, and each control parameter is:$K = 1$,$c_1 = 10$,$c_2 = 0.1$; The PID controller is adopted horizontally, among which the parameters of the rolling PID controller are rolled $P_{\mathrm{roll}} = 500$, $I_{roll} = 2$, $D_{roll} = 80$;Parameters of yaw PID controller: $P_{\mathrm{yaw}} = 300$, $I_{\mathrm{yaw}} = 2$,$D_{ya\omega} = 250$.

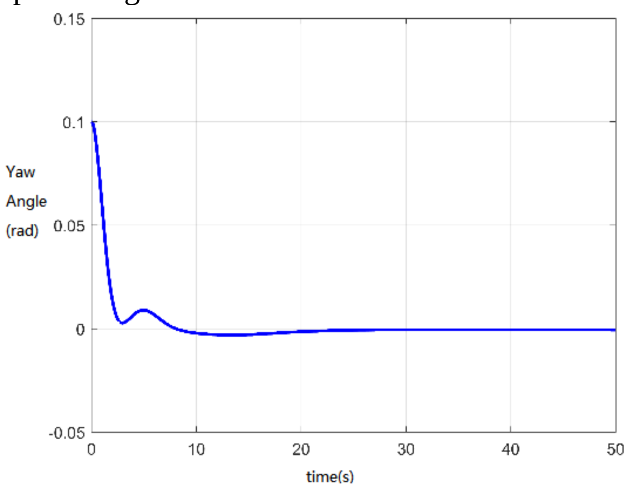
In the absence of gust interference, the simulation results are shown in Figure 2. As shown in the figure, the longitudinal, transverse and heading control effects are all relatively ideal. Among them, the pitch Angle converges to 0 in about two seconds and the fluctuation amplitude is within ± 0.01rad. The convergence effect of the rolling Angle is the most obvious and has converged to 0 within about 1 second. Although the deflection Angle converges to 0 in about 10 seconds, it remains stable after convergence. The above results indicate that under the designed controller, the attitude angles of the three axes can all converge to the expected value at a relatively fast speed.



(a) Change in pitch Angle



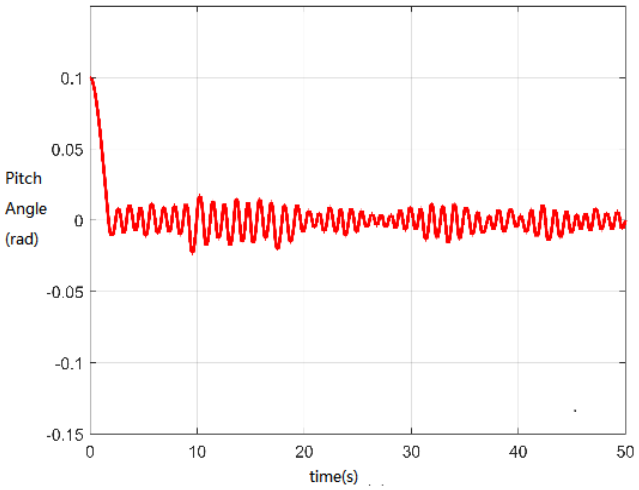
(b) Change in roll Angle



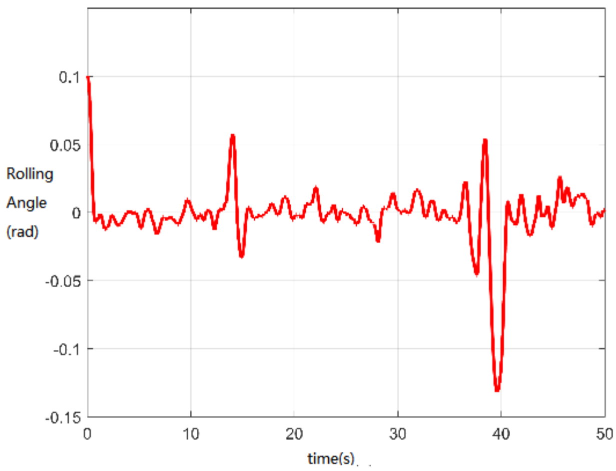
(c) Deflection Angle

Figure 2. shows the result of attitude Angle variation without gusts of wind interference

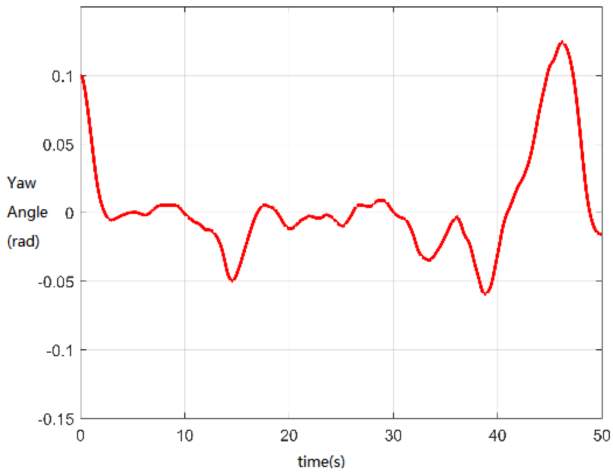
The simulation experiment results under the condition of gust interference are shown in Figure 3. As shown in the figure, the longitudinal control effect using the sliding mode controller is still relatively ideal. The results in Figure 4 (a) indicate that the pitch Angle converges to around 0 in approximately 2 seconds and fluctuates stably within the range of ± 0.01rad. However, the transverse direction with the PID controller has a poor convergence effect. As shown in Figure 4 (b), although the roll Angle converges to 0 quickly, it does not gradually level off or stabilize after converging to 0. Instead, there will be a sudden large fluctuation. For example, at 40 seconds, the fluctuation amplitude of the roll Angle reaches -0.125rad. The same problem is also reflected in Figure 4 (c), among which the yaw Angle error fluctuates most significantly at 45 seconds, reaching 0.12rad.



(a) Change in pitch Angle



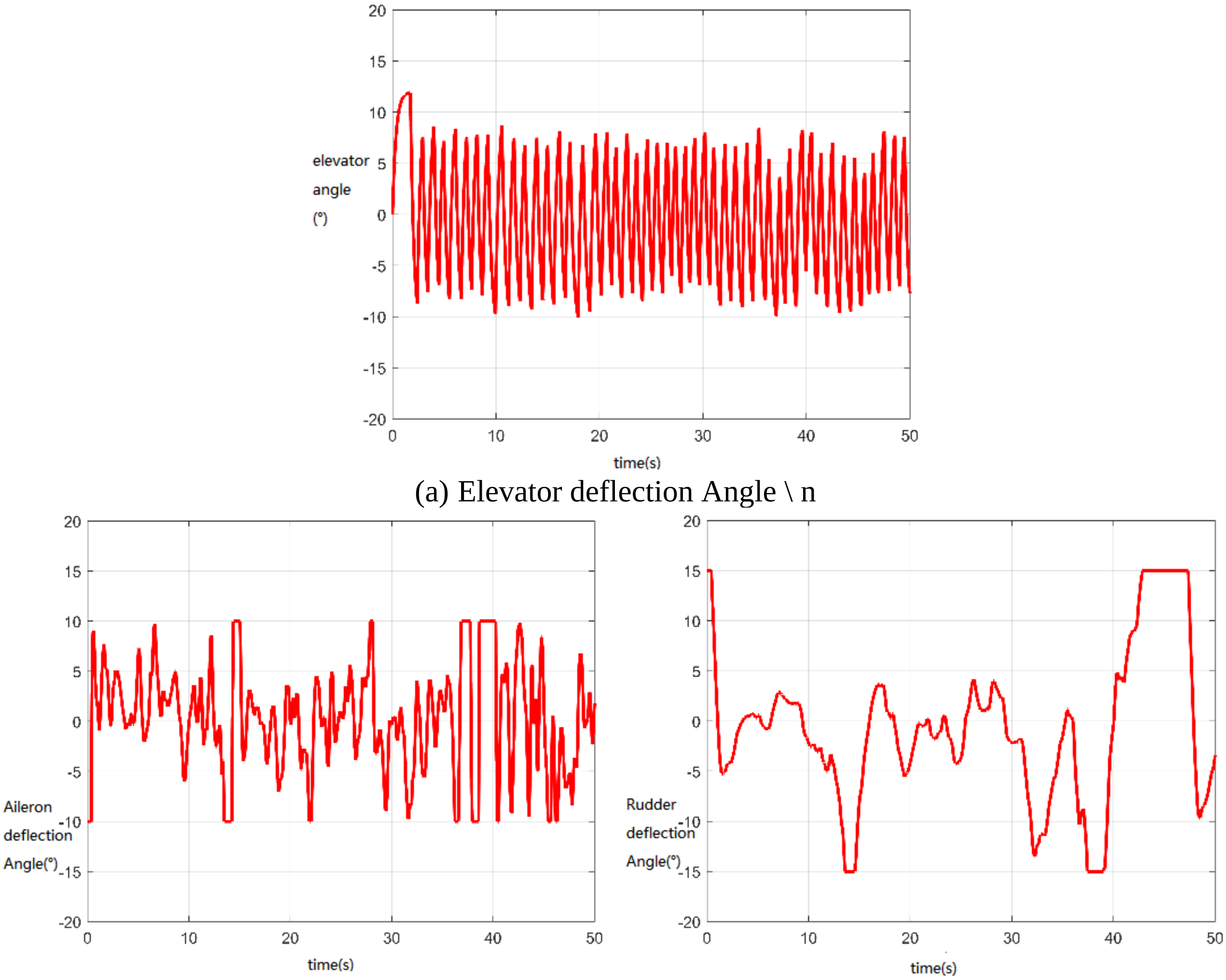
(b) Change in roll Angle



(c) Changes in yaw Angle

Figure 3. shows the result of attitude Angle changes under gusty wind interference

The deflection of the rudder surface under gust interference is shown in Figure 4. It can be seen that although the sliding mode controller can achieve a better convergence effect, the deflection frequency of the elevator rudder surface is very high, and there is a buffeting phenomenon. It can be seen from Figure 4 (a) that the buffeting frequency of the elevator rudder surface is very high. Buffeting is a problem that cannot be ignored, and it may have a serious impact on the aircraft during flight. This is also a problem that needs to be further addressed in the subsequent work.



(a) Elevator deflection Angle \ n

(b) Aileron deflection Angle (c) Rudder deflection Angle

Figure 4. shows the deflection of the rudder surface under the interference of gusts

5. Conclusion and Prospect

The gusts of wind disturbance that unmanned aerial vehicles (UAVs) experience during flight can have a serious impact on them, reducing their flight stability, interfering with their normal flight, and even causing accidents. This paper aims to explore the influence of gust disturbances during the flight of unmanned aerial vehicles (UAVs) and propose corresponding attitude stability control methods. This paper first establishes the flight dynamics model of unmanned aerial vehicles and the gust disturbance model, and then conducts research on the attitude stability control method. Based on the excellent anti-interference characteristics of sliding mode control, a drone attitude stability controller is designed based on the sliding mode algorithm, and the stability of the controller is proved by using the Lyapunov function method. Furthermore, by establishing a numerical model in MATLAB/SIMULINK, digital-analog simulation experiments were carried out. The simulation test results show that in the environment without gust interference, both the sliding mode control and the traditional PID controller designed in this paper can achieve better attitude stability control effects. When the influence and interference of gusts are introduced, the control effect of PID method deteriorates significantly as a tradinational method. However, the sliding mode can still achieve better attitude stability control, indicating that the method apllied in this paper has better robustness against gusts disturbance. However, it was also found in the simulation experiment that the sliding mode control would cause the rudder surface of the unmanned aerial vehicle to shake very frequently. This is a problem needs to be further explored and solved in the subsequent research.

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