Attitude Control of Flying Wing UAV Based On Advanced ADRC

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Abstract. The main points of the problem are that the flying wing UAV has strong coupling, obvious nonlinear characteristics and significant changes in steering efficiency during the flight, a combination of ADRC (active disturbance rejection control) and PID (proportional-integral-derivative) was proposed. The adaptive control method is designed with the angle and angular velocity as the controlled variables. The UAV flight attitude control system was designed, where the ADRC control law is used as the outer ring to control the angle, and the inner ring uses the PID to control the angular velocity. In order to solve the problem of high frequency jitter in traditional ADRC, a new nonlinear function is used to optimize the design. Simulink simulation shows that the attitude control overshoot is less than 1% and the adjustment time is less than 2s, which satisfies the control of the flying wing UAV. The flight test was finally carried out to verify the feasibility of the algorithm at the request.

1. Introduction

The flying wing is more and more used during the design of unmanned fighter aircraft because of its excellent stealth performance, such as X-45, X-47B in the United States, Rainbow 7 in China and so on[1]-[2]. But the flying wing also has congenital shortcomings: short control arm of elevator, low control efficiency, no horizontal tail, longitudinal stability decline, or even static instability; no vertical tail, its lateral natural stability also decreases, as strong coupling effects between channels were appeared [3]-[4]. Therefore, how to design the control law to make the UAV with flying wing has good stability and maneuverability, becomes the main research focus in this field [5]-[6].

Active Disturbance Rejection Control (ADRC) has been widely used in the conventional UAV and achieved good results, because it does not need to study the internal mechanism and external disturbance law of the controlled system [7]. However, there are few reports on the flight control of UAV with flying wing configuration and fewer actual flight validations [8]. Firstly, in this article, a new type of smooth continuous extended state observer is constructed to solve the common high frequency chattering problem of the conventional ADRC and designs an improved ADRC-PID attitude adaptive controller for the flying wing drone. Finally, through simulation and actuality. Finally, the effectiveness of the controller were verified by simulation and during the real flight.
2. Principle analysis of ADRC

2.1. Principle and structure of ADRC

Active Disturbance Rejection Control (ADRC) technology was formally and systematically proposed by Han Jingqing in 1999. It originates from the combination of classical PID and modern control theory. The ADRC is mainly composed of four parts: tracking differentiator (TD), extended state observer (ESO), nonlinear state error feedback (NLSEF) \[9\]-\[10\], and disturbance compensation. Second-order ADRC is often used in practical applications \[11\].

The main idea of the control law is to take the simple integral series type as the standard type. Regarding the parts of system dynamics, including internal and external disturbances, those are different from the standard form, including system uncertainties and disturbances, as total disturbances. By means of extended state observer, the total disturbance can be estimated and eliminated in real time. Thus, the controlled object full of perturbation, uncertainty and nonlinearity can be reduced to the standard integral series type. It makes the design of control system from complexity to simplicity \[12\]-\[13\].

![ADRC topology](image)

Fig 1. ADRC topology.

2.2. ADRC Algorithm

ADRC algorithm does not depend on the model of the controlled object, it only focus on the input \(u(k)\) and output \(y(k)\) for the anti-interference control. Taking second-order ADRC as an example, the complete algorithm of ADRC with disturbance tracking compensation ability is as follows.

1) TD (Tracking differentiator) and the arrangement of the Transient Process

With the set value \(v\) as input, the TD process can quickly follow the input signal \(x_1\) without overshoot, while as the approximate differential of \(v\), \(x_2\) can track the differential signal of the system \[14\].

\[
\begin{align*}
fh &= f_{han}(x_1(k), x_2(k), r_0, h_0) \\
x_1(k + 1) &= x_1(k) + h x_2(k) \\
x_2(k + 1) &= x_2(k) + fh
\end{align*}
\]

(1)

Among them, \(f_{han}(x_1,x_2,r_0,h_0)\) is the fastest synthesis function, \(x_1,x_2\) is the state of the system, \(r_0,h_0\) is the control parameter of the function, \(r_0\) is determined by the needs of the transition process and the endurance of the system, it is the speed tracking factor, and \(h_0\) is the filtering factor, \(h\) is the integral step, the specific equation of the function is as follows:
\[
\begin{align*}
\text{d} &= r_0 h_0^2 \\
\alpha_0 &= h_0 x_2 \\
y &= x_1 + \alpha_0 \\
a_1 &= \sqrt{d(d + 8)} y \\
a_2 &= \alpha_0 + \text{sign}(y)(a_1 - d)/2 \\
s_y &= \left[ \text{sign}(y + d) - \text{sign}(y - d) \right]/2 \\
a &= (\alpha_0 + y - a_2)s_y + a_2 \\
s_x &= \left[ \text{sign}(a + d) - \text{sign}(a - d) \right]/2 \\
\text{fhan} &= -r \left[ a/d - \text{sign}(a) \right] s_x - r_0 \text{sign}(a)
\end{align*}
\] (2)

Sign (x) is a sign function, and its specific formula is as follows.

\[
\text{sign}(x) = \begin{cases} 
1, & x > 0 \\
0, & x = 0 \\
-1, & x < 0 
\end{cases}
\] (3)

2) ESO (Extended state observer)

The basic idea of the extended state observer is to expand the total disturbance into a new state variable \( z_3 \) of the system, and then use the input \( u \) and output \( y \) of the system to reconstruct (observe) all states \( (x_1, x_2, x_3) \), which include the original state variables and disturbances of the system. \( z_1, z_2, z_3 \) in the formula are the estimated values of all state variables.

\[
\begin{align*}
\text{c}(k) &= z_1(k) - y(k) \\
z_1(k + 1) &= z_1(k) + h \left[ z_2(k) - \beta_{01} \text{e}(k) \right] \\
z_2(k + 1) &= z_2(k) + h \left[ z_3(k) - \beta_{02} \text{fal}(e, 0.5, \delta) + ba \right] \\
z_3(k + 1) &= z_3(k) - h \beta_{03} \text{fal}(e, 0.25, \delta)
\end{align*}
\] (4)

\( \text{fal}(x,a,\delta) \) is a non-linear function:

\[
\text{fal}(x,a,\delta) = \begin{cases} 
\frac{x}{\delta} & |x| \leq \delta \\
\text{sign}(x)|x|^{\mu} & |x| > \delta 
\end{cases}
\] (5)

Among them: \( \beta_{01}, \beta_{02}, \beta_{03}, b, \delta \) are the parameters of the controller, \( \beta_{01}, \beta_{02}, \beta_{03} \) are the non-linear factors, \( b \) is the estimated value of compensation factor, \( \delta \) is the filter factor. By adjusting the parameters of the observer appropriately, the state variables \( z_i(k) \) of the system can track the state variables \( x_i(k) \) of the system in real time \( (i = 1, 2, 3) \).

3) NLSEF (Non-linear state error feedback control law)

Based on TD and the arrangement of the transient process, the error signal of transient process can be tracked. By using the error signal \( e_1 \) and the differential of the error signal \( e_2 \), the integration of the error signal \( e_0 \) can be generated, and then the PID control could be realized, also the non-linear combination can achieve better efficiency. Moreover, since the disturbance can be estimated and compensated, the integration of the error signal may not be needed. Non-linear ADRC usually adopts the following formula:
\[
e_{1} = v_{1} - z_{1}
\]
\[
e_{2} = v_{2} - z_{2}
\]
\[
u_{0} = \beta_{1} \text{fal}(e_{1}, a, \delta) + \beta_{2} \text{fal}(e_{2}, a, \delta)
\]

Among them: \(\beta_{1}, \beta_{2}, \delta\) are the parameters of the controller, \(\beta_{1}, \beta_{2}\) are the non-linear factors, \(\delta\) is the filter factor. \(v_{1}\) is \(x_{1}\) of the TD output, \(v_{2}\) is \(x_{2}\) of the TD output, \(z_{1}\) is an estimated value of the system state quantity \(x_{1}\) of the NLSEF output, and \(z_{2}\) is an estimated value of the system state quantity \(x_{2}\) of the NLSEF output.

4) Generation of the Control Quantity

\[
u = \frac{u_{0} - z_{3}}{b_{0}}
\]

In this structure, the control quantity is actually divided into two parts, in which \(-z_{3}/b_{0}\) is the component that compensates for the disturbance, and \(u_{0}/b_{0}\) is the component that controls the integrator type of the integrator with nonlinear feedback.

3. Improved Design Of Active Disturbance Rejection Controller

3.1. Problem analysis

The extended state observer is an important part of the ADRC controller, but the traditional ESO has its shortcomings. The nonlinear function commonly used in the traditional ESO is the fal() function, but the fal() function is not the optimal nonlinearity. The traditional nonlinear function is not conductive at the origin and the segmentation point. After a lot of simulations, the high-frequency jitter phenomenon occurs at the origin, which reduces the control performance of ADRC [15]-[16]. Therefore, constructing a continuous and derivable function is the key to solving the problem. Both documents [17] and [18] use a smooth and continuous new nonlinear function to solve the high frequency flutter problem at the origin.

3.2. Improved Design

In this paper, an extended state observer is designed based on the inverse hyperbolic sine function. The expression of the inverse hyperbolic sine function is:

\[
arsh x = \ln(x + \sqrt{x^2 + 1})
\]

The inverse hyperbolic sine function is used instead of the original nonlinear function fal(), so the improved extended state observer of the constructed second-order system is:

\[
\begin{align*}
e(k) &= z_{i}(k) - y(k) \\
z_{i}(k + 1) &= z_{i}(k) + h \left[ z_{i}(k) - \beta_{01} e(k) \right] \\
z_{j}(k + 1) &= z_{i}(k) + h \left[ z_{i}(k) - \beta_{02} \text{arsh}(gama_{2} e(k)) + bu \right] \\
z_{j}(k + 1) &= z_{i}(k) - h \beta_{03} \text{arsh}(gama_{3} e(k))
\end{align*}
\]

Among them: \(gama_{2}, gama_{3}\) are new parameters of the controller, which can adjust the rate of change of the inverse hyperbolic sine function in the controller. \(\beta_{01}, \beta_{02}, \beta_{03}, b, z_{1}, z_{2}, z_{3}, y, u\) have the same meaning as traditional ESO.
Since the inverse hyperbolic sine function is smooth and continuous, it is used for state feedback of the second-order system, which can avoid the high-frequency chatter phenomenon of sliding mode variable structure control, and proves the stability of the new ESO error system, also can effectively suppress the differential peak phenomenon. As a conclusion the response of the system is fast and stable, and the steady-state error is small [19]-[20].

4. Improved Analysis And Design Of Attitude Controller
Since the flying wing UAV has no conventional rudder, so this paper uses the ADRC algorithm to control the pitch angle and the roll angle. The yaw angle only uses the resistance rudder for damping stabilization.

Both the pitch angle and the roll angle loop use the same controller structure and parameters. In this paper, the expected input of the two attitude angles is treated as two independent variables, and the attitude loop is divided into two independent channels.

Taking the pitch angle loop as an example, a second-order improved ADRC controller is designed to control the pitch angle. A P-proportional controller is designed to control the pitch rate. For a given initial value, the controller structure is designed as shown below:

![Fig 2. Pitch Angle controller.](image)

The input of the improved ADRC in the illustrated controller is the actual pitch angle and the desired pitch angle of the flying wing UAV, and the output is compared with the actual pitch angular velocity, according to all statements, the difference is generated as the input of the P controller. The output of P controller is the desired amount of elevator rudder.

The control algorithm of the new ADRC controller is Equations 1, 6, 7, and 9, so the input v in Equation 1 (TD) is the target pitch angle (°) of the UAV, and the output x⃗1 is the tracking value of the target pitch angle. The output x⃗2 (°/s) is the approximate differential value of the desired pitch angle. In Equation 9, the input y is the actual pitch angle of the flying wing UAV, and u is the control output through the NLSEF. The input of NLSEF in Equation 6 is the estimated value z⃗1 of pitch Angle of TD’s output x⃗1, x⃗2 and ESO’s output z⃗1 and the estimated value of pitch Angle velocity z⃗2, and the output u⃗0 is compared with the real angular velocity of the UAV, and is used as the input of the angular velocity loop PID.

5. Simulation Analysis
In order to verify the performance of the controller, which were designed and constructed in this paper on the flying wing UAV, such UAV model is used as an example to simulate the system. According to the applied systems, the attitude control simulation is performed in the MATLAB software. The results of the improved ADRC-P algorithm and the results of the ADRC-P algorithm are compared and analyzed.

Taking the pitch angle as an example to design the improved ADRC-P and the ADRC-P controllers, the initial pitch angle of the flying wing UAV is 0°, and the target angle of the pitch angle is set to a square wave excitation with an amplitude of 5°. The period is 20s. The parameters of the improved ADRC-P are shown in Table 1, and the parameters of the ADRC-P are shown in Table 2.
Table 1. Improved Adrc-P Parameters

| Symbol | Quantity |
|--------|----------|
| \( h_0 \) | 35 |
| \( r_0 \) | 0.2 |
| \( \beta_{01} \) | 8 |
| \( \beta_{02} \) | 6 |
| \( \beta_{03} \) | 65 |
| \( b \) | 15 |
| \( \gamma_2 \) | 5 |
| \( \gamma_3 \) | 5 |
| \( \beta_{01} \) | 3 |
| \( \beta_{02} \) | 7 |
| \( b \) | 15 |
| \( \delta \) | 0.1 |

\( p \) 1

Table 2. Adrc-P parameters

| Symbol | Quantity |
|--------|----------|
| \( h_0 \) | 11 |
| \( r_0 \) | 0.2 |
| \( \beta_{01} \) | 8 |
| \( \beta_{02} \) | 6 |
| \( \beta_{03} \) | 65 |
| \( b \) | 15 |
| \( \delta \) | 0.1 |
| \( \beta_{01} \) | 5 |
| \( \beta_{02} \) | 5 |
| \( b \) | 15 |
| \( \delta \) | 0.01 |

\( p \) 1

In case of disturbance absence, the simulation results of the pitch angle are shown in the following figure:
As can be seen from the figure, the overshoot of both controllers is less than 1% from the input, but the adjustment time of the improved ADRC-P controller is 1s less than the adjustment time of the ADRC-P controller.

Considering the real flight mode, wind disturbance is added to the simulation. In case of that, the pitch channel is greatly affected by the vertical airflow, only the vertical wind field is added in the simulation, as shown in the figure:

In the case of the above wind disturbance, the improved ADRC-P and ADRC-P control simulation results of the flying wing UAV's attitude control channel are shown in the figure:
From the simulation results shown in the figure, in the case of vertical wind field interference, since ADRC can estimate and compensate the disturbance, ADRC still has good control effect. In the process of the whole simulation time, most of the time the simulation error are maintained within 0.5°, and the maximum angular error is less than 1°, which meets the requirements of practical applications. In addition, the above simulation results also show that the improved ADRC-P errors had been reduced by 1s in comparison to the conventional ADRC-P controller. Under the same interference conditions, the overshoot of the improved ADRC-P controller is smaller than the same parameters of the conventional ADRC-P controller. It can be seen that the controller performance of the improved ADRC-P is superior to the state of the conventional ADRC-P controller.

6. Flight-Test
In order to further verifying the effectiveness of the improved ADRC-P attitude control algorithm, this paper conducted a prototype flight test (taking the pitch channel as an example). The ambient wind of this flight test is about 1 to 3 (2m/s < wind speed < 6m/s).

Flying wing UAV prototype’s System parameters: Wing area is 80dm², the flight weight is 3500g, wingspan is 2120mm, the fuselage is 790mm.
As could be seen from the figure that the pitch angle in the steady mode can basically satisfy the control error below 1° (maximum 1.2 degree). When the wind speed is small, the angular error of the stable phase can be even less than 0.2°, and accordingly to the whole square wave response, The adjustment time is maintained within 2s, which is consistent with the simulation results and can meet the attitude control requirements of the flying wing UAV. There are occasional reasons for the stability phase error of more than 1 degree. There are two main reasons for the analysis: one, the interference of the ambient wind; the second, the coupling problem of the pitch channel and the airspeed control, In the process of pitch Angle square wave excitation, the airspeed fluctuates by +2m/s.

7. Conclusion
In this paper, an improved ADRC controller was designed and made on a new extended state observer based on inverse hyperbolic sine function, which solves the common high frequency jitter problem of traditional ADRC. On this basis, an ADRC-P integrated adaptive controller combining ADRC and PID is proposed, and SIMULINK simulation is carried out for a flying wing UAV model. The simulation results show that in the case of no wind and wind. The high-precision attitude tracking of the pitch channel under square wave excitation can be realized under the square wave excitation, and the performance of the improved ADRC-P controller is superior to the conventional ADRC-P in overshoot and adjustment time.

The improved ADRC-P controller is used to simulate the pitch attitude of the real flying wing UAV prototype. The flight test results showed that the tracking error of the improved ADRC-P controller in the steady phase is basically within 1°, which can meet the established requirements.

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