Design and Nonlinear Simulation about Flight Control Law of Small UAV

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***Abstract*—This paper takes a small unmanned aerial vehicle (UAV) as the research object, designs the control loop of the UAV flight control system and carries out a detailed analysis of each control mode. According to the actual application characteristics, the design of the UAV flight control system adopts proportion-integration-differentiation (PID) control method which has been verified by practice. Its control law has been verified by nonlinear simulation.**

***Index Terms*—UAV; Control mode; Control law design; PID control**

I. DESIGN ABOUT FLIGHT CONTROL LOOP OF UAV

The flight control system control law design attempts to complete the selection of control algorithm points, the determination of control parameters, the setting of initial values and given values, and the logical relationship of the on-line determination control links of the UAV flight control system. For unmanned aerial vehicle (UAV), its control system has two main functions. One is ensuring the safe flight of the aircraft, the designed flight control system must ensure that the aircraft meets the requirements of flight quality within the entire flight course. The other is designing the corresponding flight control system for completing the relevant flight missions. The design methods of longitudinal and lateral control laws are discussed below.

A. Design of longitudinal control law

According to the mission type of UAV, the established longitudinal flight control system should have the function of keeping the pitch attitude and keeping the flight altitude to ensure UAV to complete the required mission successfully. As the outer loop of the system, keeping pitch attitude and altitude requires its inner loop system to have good modal characteristics.

The longitudinal free disturbance motion of an aircraft is generally composed of short and long period modes. After analyzing the dynamic characteristics of UAV, the characteristic root of the longitudinal free disturbance motion are as follows:

Short period modal characteristic root: -1.2906 (plus-minus 6.0053i)

Damping ratio: 0.2234

Free oscillation frequency: 6.2085 (radians per second)

Long period modal characteristic root: -0.0387 (plus-minus 0.2345i)

Damping ratio: 0.1354

Free oscillation frequency: 0.2644 (radians per second)

In the design of the outer loop of the longitudinal flight control system, the pitch angle mode is maintained with the pitch angle rate feedback as the inner loop, because simple pitch angle feedback can improve the long-period modal characteristics and make them stable from instability, but the short-period modal characteristics obviously deteriorate, that is the short-period damping ratio decreases too fast, so pitch angle rate feedback is introduced as an inner loop to improve the short-period modal characteristics. Keeping altitude mode can maintain pitch angle mode as inner loop. Because the stabilization and control of the flight altitude cannot be accomplished by the stabilization and control of the pitch angle, the pitch angle stabilization system cannot maintain the altitude when the aircraft is subjected to the longitudinal constant disturbance torque. The keeping altitude system controls the attitude of the airplane by setting the signal of altitude difference between the altitude and the actual altitude. Change the inclination angle of the airplane, and the airplane returns to the predetermined altitude. As an inner loop, the pitch angle feedback system, dampens the altitude maintaining system and reduces the oscillation of the system. In order to increase the damping of height keeping system further, it is necessary to introduce feedback of height differential signal. When UAV is making longitudinal angle flight, the altitude system must be disconnected, otherwise it will affect the UAV's longitudinal maneuver capability.

B. Design of lateral control law

The lateral disturbance motion of an airplane is generally composed of rolling convergence mode, spiral mode and Dutch rolling mode. The requirements of lateral flight include damping ratio of Dutch rolling mode is not less than 0.19; frequency is not less than one radian per second; time constant of rolling convergence mode should not be more than one second; the minimum amplitude time of spiral mode is 12 seconds, and rolling spiral coupling is not allowed to appear.

Through calculation, the characteristic roots of the lateral free disturbance motion are as follows:

Characteristic root of Dutch rolling mode: -1.075 (plus-minus 3.2282i)

Damping: 0.3226

Frequency: 3.3197 (radians per second)

Characteristic root of rolling convergence mode: -228.9091

Time constant: 0.0043 (second)

Spiral modal characteristic root: -0.0650

The calculation result shows that the root of the rolling convergence mode of the UAV is too large, and it leads to the lateral stability of the aircraft and makes the lateral control more difficult. The modal characteristics under Dutch roll mode and spiral mode are good, but the lateral modal characteristics of flight control system will deteriorate when designing outer loop, so it is also necessary to add feedback signals. Generally, rudder deflection mainly causes movement of the Dutch rolling modal, and the influence on the rolling mode is not very obvious. Aileron deflection mainly causes movement of rolling modal, which has a certain influence on Dutch rolling modal.

In the design of outer loop of lateral flight control system, the roll angle attitude mode is maintained with the rolling rate feedback as the inner loop, which changes the damping of the roll convergence mode while improving the damping ratio of the Dutch roll mode. Maintain heading mode takes keeping roll angle attitude mode as inner loop. The flight control structure of rudder channel is shown as “Fig. 1”.

The flight control structure of elevon channel is shown as “Fig. 2”

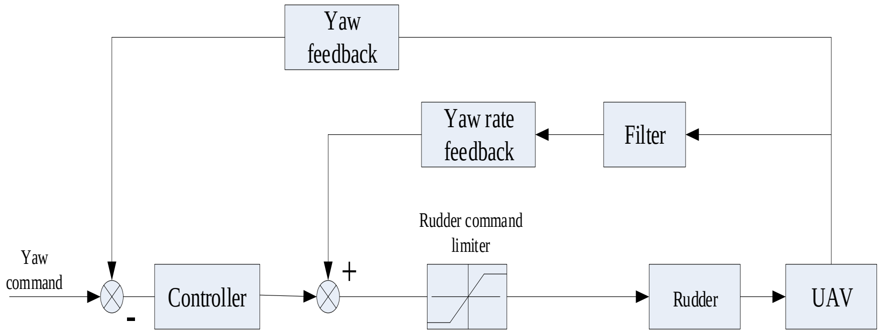

Figure 1. Flight control structure of rudder channel

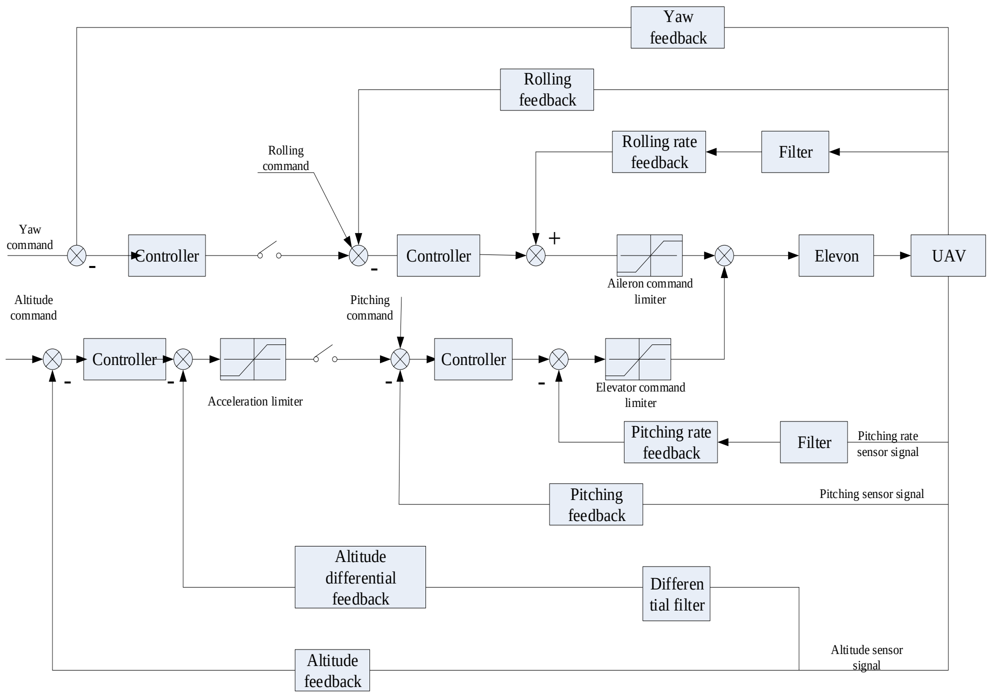

Figure 2. Flight control structure of elevon channel

II. DESIGN ABOUT CONTROL LAW OF FLIGHT STATES

For small UAVs, there are three flight States: take-off/climbing, cruising reconnaissance and dive attack. Because UAVs use television guidance and need human in the loop, there are also three control States, remote control flight, programed control flight and autonomous flight. The control modes of UAV include pitching attitude maintenance/control mode, altitude maintenance/control mode, rolling attitude maintenance/control mode and heading maintenance/control mode. The corresponding control laws are designed as follows.

A. Design about control law of pitching attitude maintenance/control mode

The pitch attitude control mode is usually used in the plane's lateral flight state, climbing state and dive attack state. The input of the control system is the pitch attitude angle and the sensor is an attitude gyro. The pitch attitude maintenance mode can keep the airplane in a given pitch attitude, after the control system is connected, it will try to keep this attitude constant. The pitch attitude maintenance mode consists of a pitching feedback loop and a pitching rate feedback loop. The control law can be expressed as follows:

$$u = K_z^{\vartheta}(\vartheta_c - \vartheta) - K_z^{\omega_z}\omega_z$$

With proportion-integration-differentiation (PID) control:

$$K_z^{\vartheta} = K_{p\vartheta} + K_{i\vartheta}(1/s) + K_{d\vartheta}s$$

where $K_z^{\omega_z}$ is the gain of damping loop.

B. Design about control law of altitude maintenance/control mode

The maintenance and control of aircraft altitude cannot be accomplished only by the stabilization and control of its pitching. The altitude maintenance system needs an altitude difference sensor, and the altitude deviation signal is input into the pitching control system to control the attitude of aircraft. Change the flight path angle of aircraft, and control the elevation and descent of aircraft until the altitude difference is zero and the aircraft returns to the predetermined altitude.

The flight altitude control system is formed by adding altitude control sensitive elements to longitudinal attitude control system. During designing the altitude control system, the designed attitude control system usually does not change. The control law of attitude control system is expressed as follows:

$$u = K_z^{\vartheta}(\vartheta_c - \vartheta) - K_z^{\omega_z}\omega_z + K_z^{H}(H_c - H) - K_z^{\dot H}\dot H$$

With PID control:

$$K_z^{\vartheta} = K_{p\vartheta} + K_{i\vartheta}(1/s) + K_{d\vartheta}s$$

$$K_z^{H} = K_{pH} + K_{iH}(1/s) + K_{dH}s$$

where $K_z^{\omega_z}$ and $K_z^{\dot H}$ are the feedback gain of damping loop.

When UAV is making longitudinal maneuver flight, the altitude maintenance system must be disconnected, otherwise it will affect longitudinal maneuver capability.

C. Design about control law of rolling attitude maintenance/control mode

In this mode the rolling angle should be stabilized and controlled. When the plane is flying in a straight line or during dive attack, it is necessary to stabilize the rolling and try to keep the rolling zero under the influence of external forces. When the airplane needs to make a large turning, it needs to use the rolling control system by inputting a given control signal to cause the airplane tilting and changing course. The control law is:

$$u = K_x^{\gamma}(\gamma_c - \gamma) + K_x^{\omega_x}\omega_x$$

With PID control:

$$K_x^{\gamma} = K_{p\gamma} + K_{i\gamma}(1/s) + K_{d\gamma}s$$

where $K_x^{\omega_z}$ is the feedback gain of damping loop.

D. Design about control law of heading maintenance/control mode

The heading maintenance/control mode is mainly used in the predetermined flight and dive attack. The heading maintenance/control loop takes the rolling maintenance/control loop as its inner loop. Its control law is:

$$u = K_x^{\gamma}(\gamma_c - \gamma) + K_x^{\omega_x}\omega_x + K_x^{\psi}(\psi_c - \psi)$$

With PID control:

$$K_x^{\psi} = K_{p\psi} + K_{i\psi}(1/s) + K_{d\psi}s$$

Where $K_y^{\omega_y}$ and $K_x^{\omega_x}$ are the feedback gain of damping loop.

When the aircraft heading is aiming at the target for dive attack, maintain the rolling of aircraft and adjust the rudder to change/stabilize the heading. When UAV is flying horizontally or making a large turning, the aileron channel of aircraft is used to control the flight course.

III. EXAMPLE ANALYSIS AND NONLINEAR SIMULATION

The initial conditions of the simulation are that UAV has a flying speed of 120 kilometers per hour and a flying height of 3,000 meters, and other state variables are all zero. The step response curve of pitching to elevator is shown in “Fig. 3” and the step response curve of rolling to aileron is shown in “Fig. 4”.

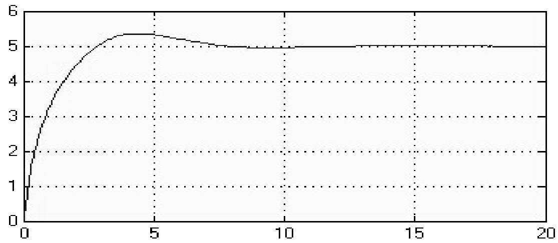

Figure 3. Step response curve of pitching to elevator

“Fig. 3” shows that the pitching response has a small overshoot and can converge rapidly.

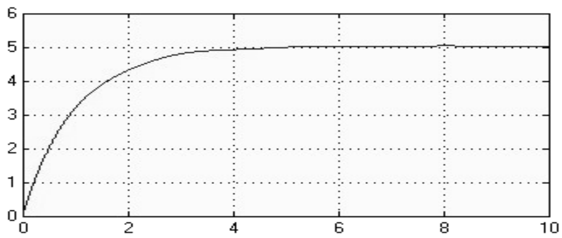

Figure 4. Step response curve of rolling to aileron

“Fig. 4” show that the control system can quickly stabilize the rolling to the commanded rolling.

In order to verify the design of UAV flight control law, because the nonlinear model is used in the simulation, some errors may occur in the control law designed before. Appropriate corrections must be made. If giving a step command of 5 degrees to the pitching and the rolling, the response results of simulation are shown in “Fig. 5”.

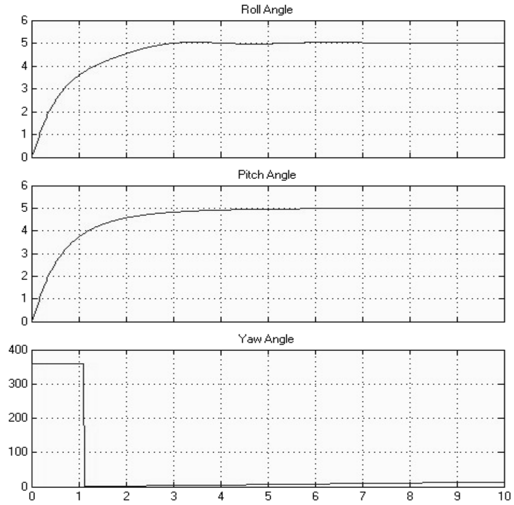

Figure 5. Step response curves of pitching and rolling

“Fig. 5” shows that both the pitching and the rolling can rapidly converge to a given command angle. Since the setting range of the yaw angle is 0 to 360 degrees, there will be a certain step in the response curve of the yaw angle, which is generated when the angle changes from 360 degrees to 0 degree. After the plane has a certain rolling angle, the heading angle steadily increases and begins to turn continuously.

IV. CONCLUSION

This paper designs a flight control system of a certain type of UAV by using PID controller design method, and finishes control of the nonlinear model. The simulation results show that the control system is simple and clear in structure, fast in dynamic response, free of steady-state error and strong in robustness, which meets the control requirements of UAV.

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