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A POLE CONFIGURATION CONTROLLER FOR FIXED HEIGHT CONTROL OF TILT ROTOR AIRCRAFT

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Abstract

In this paper, a height control method of tilt rotor UAV in longitudinal plane motion is studied. Firstly, a tiltrotor UAV is introduced, and the available control methods in each working mode are analyzed. The control strategies in rotor mode, fixed wing mode and transition mode are summarized respectively. The Dynamic model of the tilt rotor UAV in general plane is established and simplified according to the controller design process. The basic principle of pole assignment adaptive control is described. According to the principle, the design method of pole assignment adaptive controller and the realization of control law are obtained. Finally, a simulation experiment using the dynamic model of a tilt rotor UAV is conducted, the results show that this control method has a certain tracking performance for altitude and airspeed, while the control performance of pitch angle needs to be improved.

Keywords: tilt rotor aircraft; flight control; pole configuration controller.

1. Introduction

Tilt rotor UAV is a kind of aircraft with unique configuration and characteristics of both helicopter and fixed wing aircraft. The tilt rotor UAV has three flight states: rotor mode, fixed wing mode and transition mode. In the rotor mode, it has the capability to take off and land vertically, hover at a fixed position, and the good low-speed, low-altitude flight ability as rotor aircrafts; at the same time, it also has the characteristics of fixed wing aircraft, such as the ability of high-speed cruise and large angle flight. Also the flight speed and range can reach 2-3 times of the ordinary rotor aircraft [1].

The transition mode of tilt rotor UAV is realized by a set of tilting rotor system, which is generally installed on the wing and changes the tilt angle with the increase of flight speed. At this stage, the lift required by the UAV is shared by the rotor and wing. When the forward flight speed increases, the lift provided by the UAV's wing also increases gradually. When the rotor turns from the vertical position to the horizontal position, the UAV enters the fixed wing mode. At this time, the gravity of the aircraft is completely balanced by the wing lift, and the forward flight pull is provided by the rotor [2]. Therefore, compared with rotor UAV, tilt rotor UAV has wider flight envelope coverage, which can be widely used in various fields [3, 4].

Although the advantages of tilt rotor UAV are outstanding, the new structure of tilt rotor system brings many problems. In the transition mode of the tilt rotor UAV switching between different modes, the tilt angle of the rotor nacelle and the rotor speed will change greatly. This time-varying, nonlinear and strong coupling change will make the dynamic model of the tilt rotor aircraft very complex [5–8]. Therefore, it is necessary to introduce a control method which can overcome the above disadvantages to control the UAV. Many researchers have studied this problem.

Methods as PID control, fuzzy PID control and fuzzy self-tuning PID control control, which are not dependent on the model or require low accuracy of the model, have been successfully applied in the flight control law design of tilt rotor UAV [5, 6].

In addition, the linear quadratic regulator (LQR), which has good time-frequency performance and robustness, and can minimize the control output, can also be used in the control of tilt rotor UAV. The design idea is as follows: firstly, the roll, pitch and yaw attitude loops are decoupled; secondly, the attitude angle model is obtained by system identification; finally, the control rule is applied to the model [9].

In the process of mode conversion, the aerodynamic model of tilting twin rotor changes with the change of nacelle inclination, so the single system model can not accurately describe the whole transition process. At the same time, the time of mode conversion is limited. Therefore, the longitudinal transition process of tilt rotor aircraft can be modeled as a multi-mode switching system. Based on the average dwell time method, the optimal control strategy and the optimal switching time of the mode conversion can be obtained through the optimal control parameterization method of the switching system [10].

As the pole placement self-tuning control method is based on the target performance of the system, it is suitable for time-varying system to solve the control problem [11]. Based on this method, a controller design method is proposed in this paper. The direct pole placement self-tuning controller is used to control the transition height of tilt rotor UAV.

2. Description of Controlled Object

2.1 Configuration of the Tilt Rotor UAV

The UAV as the research object in this paper is shown in Fig 1.

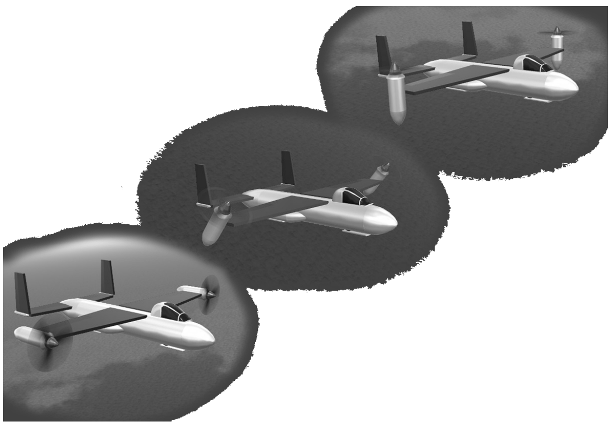

Figure 1 – Flight rendering of tilt rotor UAV

This UAV adopts a horizontal aerodynamic configuration, and the controllable control variables include total pitch angle of left and right rotors, longitudinal periodic pitch, elevator, flap, aileron, flap, rudder, nacelle angle and throttle opening [12].

2.2 Control Strategy in Each Working Mode

As mentioned in section 1, tilt rotor UAV has three working modes: rotor mode, fixed wing mode and transition mode. In the take-off phase, the tilt rotor UAV first works in the rotor mode, and then enters the transition mode after rising from the ground to a certain height. The direction of the rotor rotation axis gradually turns from the vertical direction to the horizontal direction, and accelerates forward at the same time. When the rotor rotaion axis is flush with the wing surface, it enters the fixed wing mode, and the landing process is the reverse process of the above process [13]. The specific control strategies of each working mode are as follows:

- Rotor mode
  UAV completes fixed-point take-off and landing in this mode, and the altitude gradually increases from zero to the specified altitude (take-off process) or decreases from the specified altitude to zero (landing process). Adjust the throttle median value in rotor mode, change the total pull force of rotor, and achieve height control. The pitch angle is controlled by adjusting the pitch angle median value and changing the pitch moment; Adjust the throttle difference, change the rolling torque to achieve roll angle control, adjust the tilt angle difference, change the heading torque to achieve yaw control. By changing the pitch angle and roll angle, the front and back offset and side offset can be controlled. In rotor mode, if the airspeed is zero, the elevator, aileron and rudder have no control efficiency and control effect.

- Fixed wing mode
  The UAV will use fixed wing mode in level flight. The same as the traditional fixed wing aircraft, in this mode, the throttle is used to control the airspeed, the elevator is used to control the pitch motion, the aileron is used to control the roll motion, the rudder is used to control the yaw motion, and the altitude and side offset are controlled by the pitch motion and roll motion respectively.

- Transition Mode
  This is the working mode of UAV during the transition between rotor mode and fixed wing mode. In this mode, the UAV needs to be controlled in a stable flight state, and the control altitude at the specified safe altitude is particularly important. In the transition mode, the control strategy is to use the pitch angle median value and the elevator to control the pitch motion, the throttle difference value and the aileron to control the roll motion, and the pitch angle difference value and the rudder to control the yaw motion. It should be noted that in the conversion process from rotor mode to fixed wing mode, the height control method is gradually changed from changing the throttle value to changing the pitch angle, and the sideslip is controlled by changing the roll angle.

3. Longitudinal Dynamic Model

The longitudinal dynamic model of UAV is based on the following assumptions:

- Ignoring the influence of earth rotation and revolution;
- The UAV is symmetrical in left and right, with uniform mass distribution;
- Ignoring the deformation of UAV in flight, it is regarded as a rigid body.

Let all lateral and lateral parameters be zero, and the motion equation of tilt rotor UAV flying symmetrically in plumb plane is show below:

$$\begin{cases} m\frac{du}{dt} = F_{xh} - mg\cdot\sin\theta \\ m\frac{dv}{dt} = F_{zh} - mg\cdot\cos\theta \\ I_y\frac{d\omega_y}{dt} = M_y \\ \frac{d\theta}{dt} = \omega_y \\ \alpha = \theta - \gamma \end{cases} \tag{1}$$

In which, u,v is the velocity component along x axis and y axis, F_{xh}, F_{zh} is respectively the resultant force on the airframe. m is the mass of the aircraft, ω_y is the pitching angular velocity, γ is the track inclination angle, θ is the pitching angle, α is the angle of attack. In the track coordinate system, I_y is the component of the axis is the moment of inertia of the airframe when it rotates around the track axis, and M_y is the pitching moment.

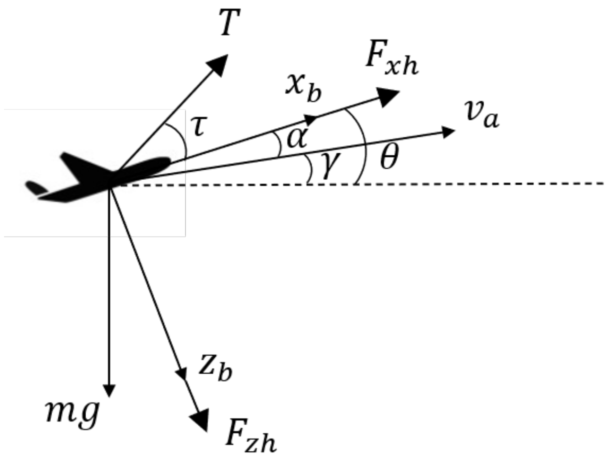

Figure 2 – Schematic diagram of force

$$\begin{cases} F_{xh} = F_{xhB} + F_{xhR} \\ F_{zh} = F_{zhB} + F_{zhR} \\ M_y = M_{yB} + M_{yR} \end{cases} \tag{2}$$

Where F_{xhB}, F_{zhB} is the component of aerodynamic force on the axis of x, y, F_{xhR}, $F_{zhR}$is the component of engine pull vector on x and y axis of track system, M_{yB}, $M_{yR}$is the pitching moment of the engine block and engine pull vector in the block coordinate system.

$$\begin{cases} F_{xhB} = (\frac{1}{2}\rho v_k^2)SC_D \\ F_{zhB} = (\frac{1}{2}\rho v_k^2)SC_L \end{cases} \tag{3}$$

Where, S is the wing area; ρ is the atmospheric density; C_D and C_L are the drag coefficient and lift coefficient of the body respectively. In addition

$$\begin{bmatrix} F_{xhR} \\ F_{zhR} \end{bmatrix} = \begin{bmatrix} \cos(\alpha+\tau) & \sin(\alpha+\tau) \\ -\sin(\alpha+\tau) & \cos(\alpha+\tau) \end{bmatrix} \begin{bmatrix} 2T \\ 0 \end{bmatrix} \tag{4}$$

In which, $\tau \in [0°, 90°]$ is the tilt angle, T is the propulsion force produced by a single rotor.
The pitching moment generated by the aerodynamic force of the body is

$$M_{yB} = (\frac{1}{2}\rho v_k^2)Sb_A M_{y1} \tag{5}$$

b_A is the average aerodynamic chord length of the wing, m_{z1} is the pitching moment coefficient.
The pitching moment generated by rotor tension is

$$M_{yR} = \ 2Tx_s \tag{6}$$

Where x_s is the distance from UAV gravity center to rotor extension line.

4. Pole Configuration Controller

The controller can be designed according to the desired closed-loop pole polynomial, and the performance of the controller can be changed to make the whole system have more desirable dynamic characteristics with the closed-loop pole configuration method.

The structure of the linear time invariant discrete time model of the plant(used for controller design) is

$$y_k = \frac{z^{-d}B(z^{-1})}{A(z^{-1})}u_k + \frac{C(z^{-1})}{A(z^{-1})}\xi_k \tag{7}$$

In which y_k represents output value, u_k represents input value, ξ_k is an independent random sequence which has a mean value of zero and variance of σ^2, and d represents the lag time between output and input value.

$$\begin{aligned} A(z^{-1}) &= 1 + a_1 z^{-1} + \cdots + a_{n_a} z^{-n_a} \\ B(z^{-1}) &= b_1 z^{-1} + \cdots + b_{n_b} z^{-n_b} \\ C(z^{-1}) &= 1 + c_1 z^{-1} + \cdots + b_{n_c} z^{-n_c} \end{aligned}$$

where $A(z^{-1})$, $B(z^{-1})$, $C(z^{-1})$ are polynomials in the complex variable z^{-1} and n_a, n_b, and n_c represent their orders. The transfer function of the plant is obtained by system identification. $C(z^{-1})$ is a Hurwitz polynomial, which means all zeros of $C(z^{-1})$ is located in the unit circle of the z-plane. The pole placement control law is shown as follows:

$$F(z^{-1})u_k = z^{-d}R(z^{-1})y_{rk} - G(z^{-1})y_k \tag{8}$$

in which $F(z^{-1})$,$R(z^{-1})$,$G(z^{-1})$ are undetermined polynomials. y_k is the reference input value.

The block diagram of the system is shown in Fig. 3.

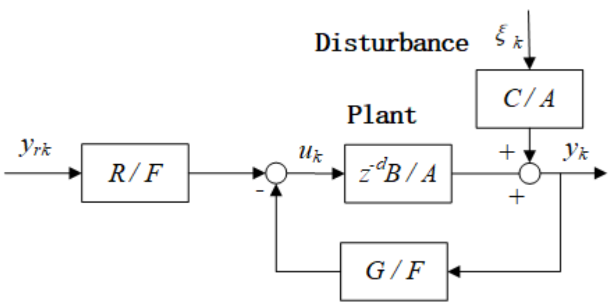

Figure 3 – Block diagram of pole configuration control

The closed-loop output is

$$\begin{aligned} y_k = &\frac{z^{-d}B(z^{-1})R(z^{-1})}{A(z^{-1})F(z^{-1}) + z^{-d}B(z^{-1})G(z^{-1})}y_{rk} \\ &+ \frac{C(z^{-1})F(z^{-1})}{A(z^{-1})F(z^{-1}) + z^{-d}B(z^{-1})G(z^{-1})}\xi_k \end{aligned} \tag{9}$$

The characteristic equation of the closed-loop system at this time is

$$A(z^{-1})F(z^{-1}) + B(z^{-1})G(z^{-1}) = T(z^{-1}) \tag{10}$$

The target polynomial $T(z^{-1})$ is determined by the target performance. Suppose the input and output relationship of the expected system is

$$A_t(z^{-1})y_k = z^{-d}B_t(z^{-1})y_{rk+d} \tag{11}$$

in which A_t and B_t are denominator and numerator of the target system, and they relatively prime. To get desired input and output, the following equation should be satisfied

$$\frac{z^{-d}BR}{AF + z^{-d}BG} = \frac{z^{-d}B_t}{A_t} \tag{12}$$

If the unstable pole of the controlled object is canceled by the controller, it will have an adverse effect on the system. Therefore, decompose the polynomial B into two parts

$$B = B_s B_u \tag{13}$$

in which B_s is composed by stable poles, while B_u is composed by unstable poles, it shuold not be canceled by the controller. Then, Eq. (12) can be written as

$$\frac{B_s B_u R}{AF + z^{-d}B_s B_u G} = \frac{B_t}{A_t} \tag{14}$$

As A and B relatively prime, if B_s can be canceled, then F can be divided by B_s

$$F = F_1 B_s \tag{15}$$

Eq. (14) can be written as

$$\frac{B_u R}{AF_1 + z^{-d}B_u G} = \frac{B_t}{A_t} \tag{16}$$

Due to the unstable poles of the object shoult not be canceled, B_u is not a factor of polynomial $AF_1 + z^{-d}B_u G$. Then B_u should be represented in B_t

$$B_t = B_t' B_u \tag{17}$$

From the Eq. (9), (16) and (13), the closed-loop output of the system can be obtained as

$$y_k = \frac{B_t' B_u}{A_t}y_{rk} + \frac{CF}{AF + z^{-d}BG}\xi_k \tag{18}$$

In order to make the steady state error zero, let B_t' equal to the following value

$$B_t' = \frac{A_t(1)}{B_u(1)} \tag{19}$$

Then, Eq. (16) can be written as

$$\frac{R}{AF_1 + z^{-d}B_uG} = \frac{B_t'}{A_t} \tag{20}$$

From Eq. (20), A_t is a factor of polynomial $(AF_1 + z^{-d}B_uG)$, so that

$$\begin{cases} AF_1 + z^{-d}B_uG = A_{ob}A_t \\ R = A_{ob}B_t' \end{cases} \tag{21}$$

in which A_{ob} is the polynomial of a stable obsever, its respond speed should be faster than A_t; when the Disturbance characteristics are known, it is desirable to let A_{ob} equal to C.
In summary, the calculation steps of the pole configuration self-tuning controller are as follows [7, 14, 15]:

- Obtain the new observation data y_{rk}, y_k;
- Compose the observation data vector φ_k;
- Use the recursive least square method to estimate the polynomial $\widehat{A}(z^{-1})$, $\widehat{B}(z^{-1})$ and $\widehat{C}(z^{-1})$;
- Solve Eq. (21) to get polynomial $\widehat{F}(z^{-1})$, $\widehat{G}(z^{-1})$ and $\widehat{R}(z^{-1})$;
- Substitute the estimated value into Eq. (8) to get the control law;
- Let $k+1 \Rightarrow k$ and go back to the first step and continue the cycle.

5. Experiment and Result Analysis

The longitudinal linearization model and pole assignment adaptive controller of tilt rotor UAV are built based on Matlab and Simulink.
Pitch angle control loops of the control system are on PI controller, while the height controll loops are based on the pole configuration controller.
Given value of airspeed is composed of two step signals in order to simulate the change of given value in the transition mode. The curve of airspeed, height and pitch angle changing with time obtained in the simulation experiment of the model under fixed wing mode are shown in Fig. 4 to Fig. 6.

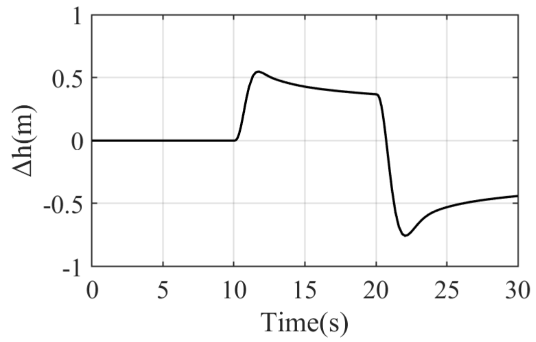

Figure 4 – Height curve of fixed wing mode

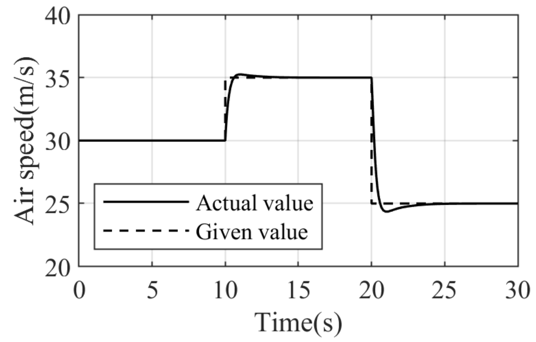

Figure 5 – Airspeed curve of fixed wing mode

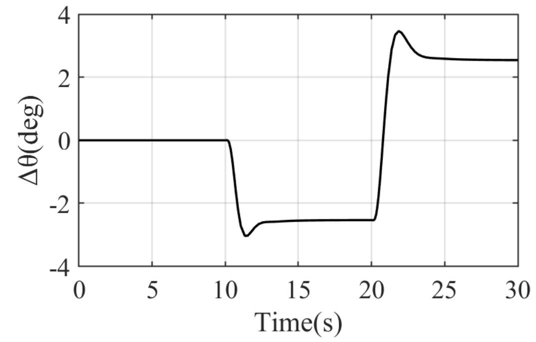

Figure 6 – Pitch angle curve of fixed wing mode

The curves above shows that the pole assignment adaptive controller can realize the fix height contral. Meanwhile, the change of airspeed and pitch angle are within the acceptable range.

The simulation experiment results under a transition mode workpoint are shown in Fig. 7 to Fig. 9.

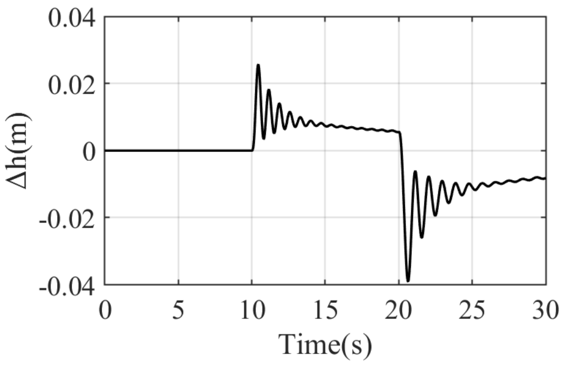

Figure 7 – Height curve of transition mode

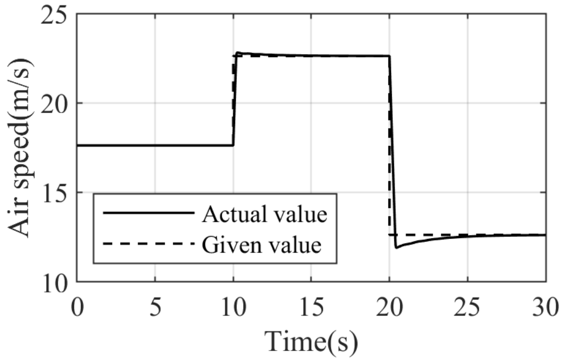

Figure 8 – Airspeed curve of transition mode

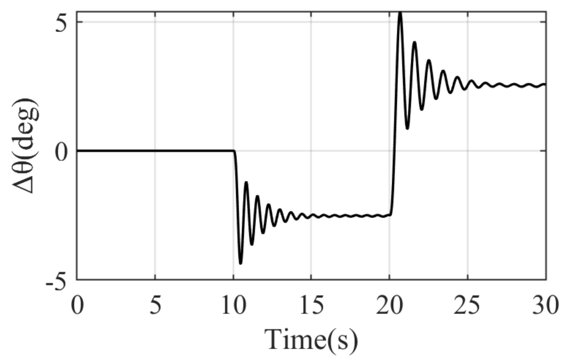

Figure 9 – Pitch angle curve of transition mode

It can be seen from the curve that when the pole assignment adaptive controller is used to control the altitude of the aircraft, the fix height control can be basically realized. Due to the oscillation of pitch angle, there is also oscillation in the height curve, which can Cause adverse effects to the UAV.

6. Conclusion

The pole assignment adaptive controller is designed based on the target performance of the system, and it can track the system with unknown and time-varying parameters in theory. In this paper, the problem of altitude control of tilt rotor UAV in the transition mode is partly solved through experiments, and the basic altitude tracking control is realized, but it is urgent to remove the oscillation of pitch angle by using other strategies. For the shortcomings found so far, it is necessary to continue to work on the following aspects: First, design the tilt trajectory according to the constaints of angle of attack, pitch angle, control surface, etc. These constraints will determine the law of the tilt angle changing over time; Second, apply other control strategies as throttle-elevator compound control to improve the stability of the system and reduce the possibility of oscillations. Then, use more accurate dynamic model to reduce the adverse effects of simplification on the model. The CFD method [16] can be used to reestablish the mathematical model.

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