CONTROL STRATEGY FOR COMPOUND COAXIAL HELICOPTER TRIMMING IN STEADY-STATE FLIGHT

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Abstract

According to the characteristics of the compound coaxial helicopter, general aerodynamic forces and moments of rotors, wing, fuselage, horizontal stabilizer（contains the elevator）, vertical stabilizers (contains the rudder) and auxiliary propeller are modeled. A control strategy and its corresponding trimming algorithm are studied for the compound coaxial helicopter under various steady-state flight conditions. The conditions include the hover and low speed flight in helicopter mode, high speed flight in airplane mode，especially the conversion mode from helicopter to airplane with the linear transition method . Together with the control strategy, the trimming method is investigated to obtain the trimming values. A small-scale compound coaxial helicopter is taken as an example to demonstrate the effectiveness of the method. The result shows that the trimming values, the lift distribution of rotors and the wing under the whole steady-state flight conditions are reasonable.

1. Introduction

The compound coaxial helicopter ，which is to supplement a coaxial helicopter as a lift and propulsion source using an additional wing and/or propulsion device (see Fig.1), has much to offer as a means of expanding the flight envelope of rotorcraft.
The compound coaxial helicopter has two control systems (the helicopter control system and the fixed-wing aircraft control system), which bring controlling redundancy problem.

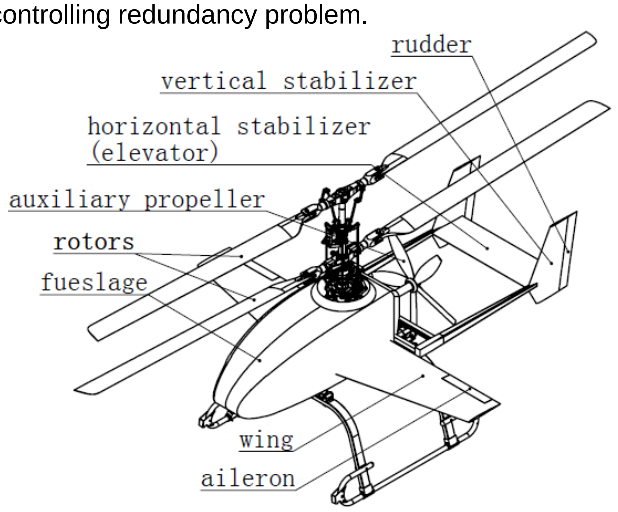


Fig.1 A small-scaled compound coaxial helicopter

Recently, there have been some investigations on the compound helicopter, Hyeonsoo Yeo and Wayne Johnson have made a design and aeromechanics investigation on a compound helicopter[1], Bühler, M. S.J.Newman have made an investigation on the aeromechanic interactions of the rotors[2], the fuselage and the wing . Most of the precious work focused on the aeromechanics analysis of a compound helicopter, but few on the control strategy of a compound coaxial helicopter.
In this study, a control strategy and its corresponding trimming algorithm are studied for the compound coaxial helicopter under various symmetrical steady-state flight conditions. The conditions cover three kinds of flight mode, the helicopter mode (hover and low speed flight), the conversion mode(from the helicopter to a airplane mode) as well as the airplane mode (high speed flight), just like a tilt-rotor aircraft.
The controlling redundancy problem is complicated, especially in the conversion mode. In this mode the two control systems work at the same, the speed range must be reasonable, the movement of the control and the attitude of the helicopter must be smooth and continuous.

2. Computational Model

According to the characteristics of the compound coaxial helicopter, general aerodynamic forces and moments of rotors, wing(contains the aileron), fuselage, horizontal stabilizer, vertical stabilizers(contains the rudder) and propulsor are modeled.

2.1 Aerodynamic forces and moments of the rotors

The flow field, the aerodynamic forces and the moments of the coaxial rotors can be given by free-vortex wake method (FVM)[3][4]. In discretized form, the governing equation is

(1) $$\frac{\mathrm{d}r(\psi,\zeta)}{\mathrm{dt}} = \Omega\left(\frac{\partial r(\psi,\zeta)}{\partial\psi} + \frac{\partial r(\psi,\zeta)}{\partial\zeta}\right) = V_\infty + v_{\mathrm{ind}} r(\psi,\zeta)$$

Where r is the position vector of a collocation point on vertical wake, V_∞ is the velocity of the free-stream, ψ is the blade azimuthal location and ζ is the cortex age.

For the coaxial configurations, a differential thrust requirement on the two rotors is specified so as to result in a specified net thrust, while maintaining equal shaft torque on both rotors, i.e.

(2) $$C_{T1} + C_{T2} = C_{Ttotal}$$
$$C_{Q1} = C_{Q2}$$

2.2 Aerodynamic forces and moments of the wing

The aerodynamic environment of the wing is very complicated because of the rotor-wing interaction, especially in hover and low speed forward flight. Aerodynamic forces and moments of the wing consist of two parts, the part inside the rotor slipstream (can be written as wss) and the part in the free-stream(can be written as wfs) (see Fig.2). Then the area of the two can be written as S_{wss} and S_{wfs} .

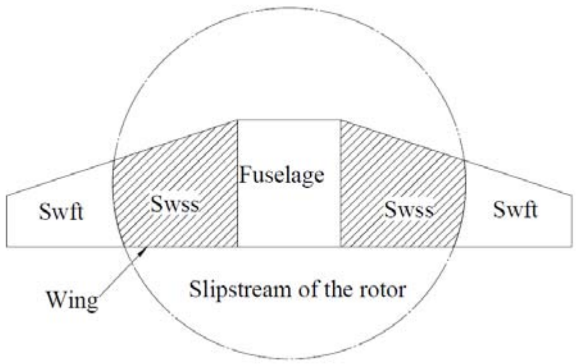


Fig.2 The area in slipstream S_{wss}
and the area in free-stream S_{wfs}

The area of the wing in the slipstream is a maximum at hover and decreases with forward speed. The following equation, which is used to calculate the wing area in the slipstream, is conducted from the equation of the tilt-rotor [5]

(3) $$S_{wss} = S_{ss\max}[\sin(1.386 * In) + \cos(3.114 * In)]\frac{\mu_{\max} - \mu}{\mu_{\max}}$$

Where $S_{ss\max}$ is the maximal area of wing in the slipstream, which is equal to the slipstream area on the wing in hover. In is the nacelle forward tilt angle of the tilt-rotor. When the equation is conducted for a coaxial helicopter, In should be $\pi/2$. μ is the advanced ratio and $\mu_{\max}$ is the maximal advanced ratio when the wing is in the slipstream.

The velocity of the area in slipstream can be conducted by adding the velocity of the free-stream and the induced velocity of the rotors together as the follow

(4) $$v_{wss} = V_\infty + v_{\mathrm{ind}} = \begin{vmatrix} V_{\infty,x} \\ V_{\infty,y} \\ V_{\infty,z} \end{vmatrix} + \begin{vmatrix} v_{ind,x} \\ v_{ind,y} \\ v_{ind,z} \end{vmatrix}$$

The total aerodynamic forces and moments of the wing can, therefore, be written as

(5) $$F_w = F_{wss} + F_{wfs}$$
$$M_w = M_{wss} + M_{wfs}$$

The area of the wing then can be disparted to left and right part to simplify the computation.

The aerodynamic forces and moments of the left wing (D_{wss1} is the resistance force, L_{wss1} is the lift and $M_{x,wss1}$ is the pitching moment) in slipstream can, therefore, be written as

(6) $$D_{wss1} = q_{wss}.S_{wss} / 2.C_{D,w}$$
$$L_{wss1} = q_{wss}.S_{wss} / 2.(C_{D,w} + \Delta C_{L,w})$$
$$M_{x,wss1} = q_{wss}.S_{wss} / 2.b.C_{mx,w}$$

Where q_{wss} is the dynamic pressure, $C_{D,w}, C_{L,w}, C_{mz,w}$ are resistance coefficient, lift coefficient and pitching moment coefficient of the wing respectively(the affect of the aileron is included). b is the distance of the pressure center to the longitudinal symmetry plane of the helicopter.

The aerodynamic forces and moments of the left wing in the free-stream are almost the same as in the slipstream, the difference is that the flow velocity is $(V_{\infty,x}, V_{\infty,y}, V_{\infty,z})$ (the velocity of the free-stream).

The aerodynamic forces and moments of the right wing is almost the same as the left one. Then the force on the wing is given by adding all of the force on the wing together, as well as the moment on the wing.

2.3 Aerodynamic forces and moments of the fuselage

The aerodynamic environment of the fuselage is complicated because of the interaction with the rotors and wing, especially in hover and low speed forward flight. An effective way to get the aerodynamic forces and moments of the fuselage is wind tunnel testing(see Fig.3).

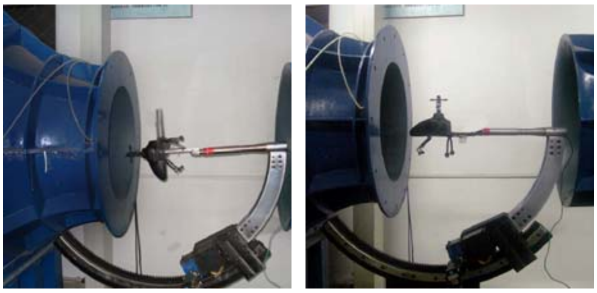


Figure 3 Wind tunnel testing of fuselage

The resistance coefficient C_{xf}, the lift coefficient lateral force C_{yf} and rolling moment coefficient m_{xf} ,yawing moment coefficient m_{yf} and pitching moment coefficient m_{zf}, can be given by the testing. All of them are the functions of the attack angle α_f, the sideslip angle β_f and the forward flight velocity V.

The aerodynamic forces and moments of the fuselage can, therefore, be given by

(7) $$\begin{bmatrix} F_{xf} \\ F_{yf} \\ F_{zf} \end{bmatrix} = \begin{bmatrix} -C_{xf}C \\ C_{yf}C-(K_{\perp}-1)G \\ C_{zf}C \end{bmatrix}$$

(8) $$\begin{bmatrix} M_{xf} \\ M_{yf} \\ M_{zf} \end{bmatrix} = \begin{bmatrix} m_{xf}CL \\ m_{yf}CL \\ m_{zf}CL \end{bmatrix}$$

Where $C=1/2\,\rho V^2 S_f$, ρ is the density of the air, V is the forward flight speed of the helicopter, $V=\sqrt{V_x^2+V_y^2+V_z^2}$, S_f is the cross section area of the fuselage, L is the characteristic length of the fuselage, $K_{\perp}$ is the impact factor of the rotors download to the fuselage.

2.4 Aerodynamic forces and moments of the horizontal stabilizer

The horizontal stabilizer, which is always in the slipstream of the rotors, is an all-movable tailplane. The velocity of the horizontal stabilizer area in slipstream $(V_{h,x},V_{h,y},V_{h,z})$ can be conducted by using the free-vortex wake method (FVM)[9][10].

Where the dynamic pressure of the horizontal stabilizer q_h can be written as

(9) $$q_h=\frac{1}{2}\rho({V_{h,x}}^2+{V_{h,y}}^2+{V_{h,z}}^2)$$

The aerodynamic forces and moments of the horizontal stabilizer can, therefore, be given by

(10) $$L_h=q_hS_hC_{L,h}$$ $$D_h=q_hS_hC_{D,h}$$

Where S_h is the area of the horizontal stabilizer, lift coefficient $C_{L,h}$ and the resistance coefficient $C_{D,h}$ can be given by wind tunnel testing. Both of them are the functions of the attack angle of the horizontal stabilizer α_h.

2.5 Aerodynamic forces and moments of the vertical stabilizer

The modeling of the aerodynamic force and moment of the vertical stabilizer is almost the same as the horizontal stabilizer. The lift force L_v and the resistance force D_v can be written as[6]

(11) $$L_v=q_vS_v(C_{L,v}+\Delta C_{L,v})$$ $$D_v=q_vS_vC_{D,v}$$

Where q_v is the area of the vertical stabilizer, lift coefficient $C_{L,v}$, $\Delta C_{D,v}$ and the resistance coefficient $C_{D,v}$ can be given by wind tunnel testing. They are the functions of the attack angle of the vertical stabilizer α_v.

2.6 Aerodynamic forces and moments of the propulsor

The aerodynamic environment of the propulsor is almost the same as the horizontal stabilizer and the vertical stabilizer. The modeling of the aerodynamic force and moment of the propulsor is almost the same as the rotor, except that there is only the collective pitch control θ_{cp} for the propulsor.

3. Trimming algorithm and control strategy

The trimming algorithm is written as an equation set, which includes an Euler equation set and some other added equations.

The Euler equation set is written as[7]

(12) $$\begin{aligned} &\sum F_x - G\sin\vartheta = 0 \\ &\sum F_y - G\cos\vartheta\cos\gamma = 0 \\ &\sum F_z - G\cos\vartheta\sin\gamma = 0 \\ &\sum M_x = 0 \\ &\sum M_y = 0 \\ &\sum M_z = 0 \end{aligned}$$

Where $\sum F_x,\sum F_y,\sum F_z,\sum M_x,\sum M_y,\sum M_z$ are the resultant aerodynamic force and moment of the rotors, the wing, the fuselage, the horizontal stabilizer, the vertical stabilizer and the propulsor at the center of gravity respectively.

The control of the compound coaxial helicopter is complicated. That's because it has two control systems, the helicopter control system (the value of which is written as U_h ,where $U_h=(\theta_0,A_{1c},B_{1c},\theta_c)$, including the collective pitch control θ_0, the longitudinal cyclic pitch control A_{1c}, the lateral cyclic pitch control B_{1c}, and the heading control θ_c) and the fixed-wing aircraft control system (the value of which is written as U_f , where $U_f = (\delta_a, \delta_e, \delta_r, \theta_{cp})$, including the aileron control δ_a , the elevator control δ_e , the rudder control δ_r and the propeller control θ_{cp}).

So the variables in all of the equations is as the follow,

$$(\theta_0, A_{1c}, B_{1c}, \theta_c, \delta_a, \delta_e, \delta_r, \theta_{cp}, \vartheta, \gamma)$$

Where ϑ, γ are the pitch angle and the roll angle of the helicopter respectively.

A control strategy is studied to solve the redundancy of the control under various steady-state flight conditions in helicopter mode, conversion mode and airplane mode as follows, which will add four another equations respectively.

Helicopter mode

In helicopter mode (hover and low speed), the control is the same as the traditional helicopter. Only the helicopter control system works, the fixed-wing aircraft control system is fixed, as follows

$$\begin{aligned} \delta_a &= 0^\circ \\ \delta_e &= 0^\circ \\ \delta_r &= 0^\circ \\ \theta_{cp} &= 14^\circ \end{aligned} \tag{13}$$

Where the twist angle of the propulsor is -20° . When the collect pitch of the propulsor $\theta_{cp} = 14^\circ$, the thrust of it will be about 0 N in hover.

(12) and (13) make up the equation set in helicopter mode.

Conversion mode

In conversion mode, the value of the helicopter control system starts to transit to a certain value, while the fixed-wing control system starts to work. In this process, the two systems work at the same time. So it required that the flight speed should be proper and the change of the control value as well as the attitude of the aircraft should be continuous. One way to achieve this is conversion from helicopter to airplane with the linear transition method as the follow

$$U_h = \frac{U_{h1} - U_{h0}}{\mu_1 - \mu_0}(\mu - \mu_0) + U_{h0} \tag{14}$$

When the forward flight advance ratio exceeds μ_0 , the conversion mode starts while the helicopter mode ends (the control value of the helicopter control system is U_{h0} at μ_0). When the forward flight advance ratio reaches μ_1 , the conversion mode ends while the airplane mode starts (the control value of the helicopter control system is fixed to U_{h1} at μ_1). And from U_{h0} to U_{h1} , it is proportional changed with the advance ratio. In this paper , $U_{h1} = (5°, 0°, 0°, 0°)$, when the lift shared by the wing is in nearly 30% of the total.

Then (12) and (14) make up the equation set in conversion mode.

Airplane mode

In airplane mode (high speed), the control is the same as the traditional fixed-wing aircraft. Only the fixed-wing aircraft control system works, the helicopter control system is fixed to U_{h1} as follows

$$\begin{aligned} \theta_0 &= 5^\circ \\ A_{1c} &= 0^\circ \\ B_{1c} &= 0^\circ \\ \theta_c &= 0^\circ \end{aligned} \tag{15}$$

Then (12) and (15) make up the equation set in airplane mode.

4. Results

A small-scaled compound coaxial helicopter (see Fig.1, Table 1 and Table 2) is taken as an example to demonstrate the effectiveness of the methodology.

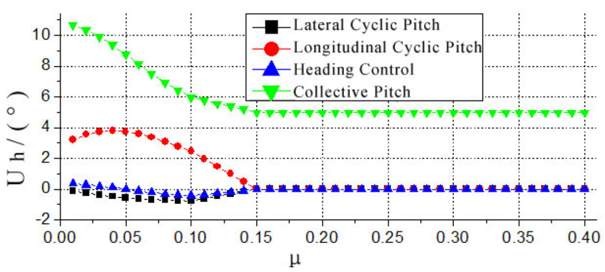
Table 1 Main rotor and propulsor geometries

	Main Rotor	Propulsor
Rotor Radius	R_c (1.5m)	R_t (0.25 R_c)
Solidity	0.04	0.2
Aerofoil Sections	NACA 23012	NACA 0012
Twist	-10°	-20°

Table 2 Wing and empennage geometries

	Wing	Vertical Stabilizer	Elevator
Aerofoil Sections	NACA23012	NACA0012	NACA0012
Span	0.6 R_c	-	0.26 R_c
Chord	0.27 R_c	0.2 R_c	0.2 R_c

The result of trimming is shown as Fig.4.



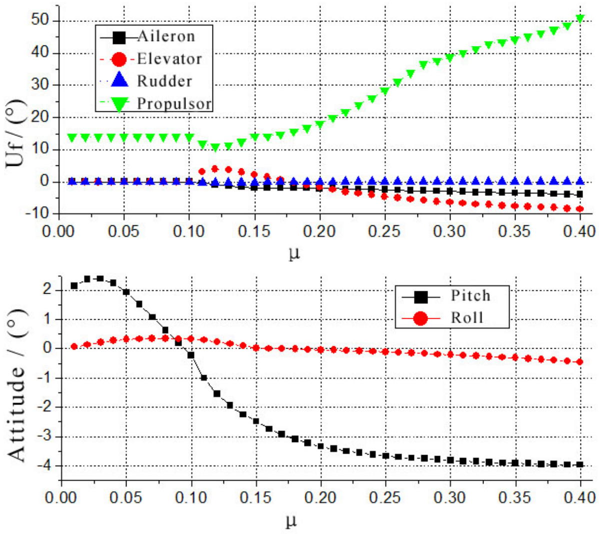


Fig.4 Result of trimming

From Fig.4, we can see that

(1)The control value of the two systems and the attitude are smooth and continuous in all the three flight modes.

(2)The pitch is nose up in low speed, that's because the downwash of the rotors act on the horizontal stabilizer. As the speed goes up, the pitch becomes a little nose down, just like a conventional helicopter.

(3)When the speed is higher, the propulsor shares more and more thrust, while the focus of the wing goes in front of the center of gravity and makes a nose up moment. So the longitudinal attitude keeps in a low level(only 4° nose down), which makes the drag much lower than a conventional helicopter.

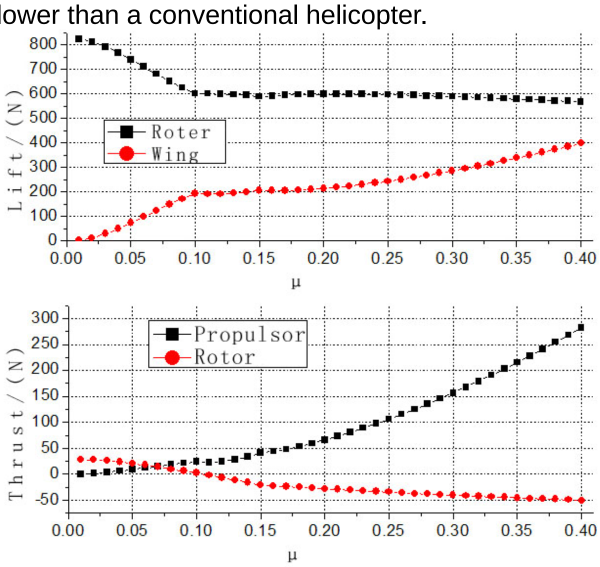


Fig.5 Lift and thrust distribution

From Fig.5, we can see that

(1)The lift is mainly produced by the rotors in hover and low flight speed. With the increasing of the advance ratio, the lift shared by the wing is more and more while the rotors is unloaded gradually and share about 60% of the total lift when $\mu = 0.4$.

(2) In hover and low flight speed, the thrust is low and is mainly produced by the rotors. With the increasing of the advance ratio, the thrust shared by the propulsor is more and more and reached more than 90% of the total after $\mu = 0.1$.

5. Conclusions

From the upper study, we can get the conclusion as follows:

(1)To satisfy both the low speed and high speed flight conditions, the compound coaxial helicopter must have two control systems, the helicopter control system and the fixed-wing aircraft control system, so come the control redundancy problem. A control strategy and its corresponding trimming algorithm are studied and solve the problem very well.

(2) The linear transition method is used to solve the control redundancy problem in the conversion mode. The results of the trimming show that the attitude and the control value are smooth, continuous and in a reasonable area.

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