AERODYNAMIC MODELING AND FLIGHT PERFORMANCE RESEARCH OF THE COAXIAL RIGID HELICOPTER IN POP-UP PROCESS

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Abstract

In this paper, a rigid body motion model is used to superimpose the aerodynamic forces and moments of various parts of the helicopter (rotor, fuselage, tail, etc.) on the centroid of the helicopter. An aerodynamic model for the pop-up process of a coaxial rigid helicopter is established. Taking the XH-59A helicopter flying over obstacles in vertical plane in the specified time as an example, the control parameters (rotor collective pitch, cyclic pitch and engine power) varying with time are analyzed through simplified methods such as preset trajectory and overload. The helicopter attitude angle, speed and power are analyzed with flight performance predicted. The CFD model of XH-59A helicopter rotor is also established and verified to facilitate the development of subsequent research.

Keywords: helicopter XH-59A pop-up control parameters

1. Introduction

The coaxial rigid helicopter is composed of a pair of counter-rotating rotors for aerodynamic symmetry and a propulsion propeller for high speed performance. It has the characteristics of high speed, high maneuverability, high hovering and forward flight efficiency. Thus it becomes an important development direction for armed helicopters.

Generally, the research on the maneuvering process of a helicopter is based on flight mechanics and kinematics. It is used to grasp the law of changes in control amount over time, obtain changes in helicopter trajectory and attitude, evaluate flight performance and make flight decisions. The pop-up process is a typical representative of the longitudinal maneuver. Due to the redundant control parameters of the coaxial rigid helicopter and the interference of the dual rotor flow, it is of great significance to study the aerodynamic model and flight performance of the pop-up process.

Compared with the steady-state forward flight research, the research literature on maneuvering process is less. But it is roughly divided into two methods: flight test and dynamic modeling. The example of the former can be found in a flight test of the XH-59A helicopter in Alabama[1] to verify the performance, control quality, and maneuverability of the forward blade solution rotor. The latter can be found in Zhou's[2] flight dynamics mathematical model for a coaxial helicopter. The helicopter dynamic response numerical simulation was completed with the flight dynamics linearization model obtained. Moreover, Dong[3] constructed a coaxial dual-rotor unmanned helicopter flight dynamics model, and compiled flight dynamics calculation software including stable flight trim characteristics analysis, motion stability analysis, and manipulation response analysis functions.

2. Aerodynamic Model of Helicopter Parts

Take the XH-59A helicopter for an example, the aerodynamic model includes three parts: rotor, fuselage and propeller[4][5]. For vertical plane maneuverability, the vertical tail and horizontal tail ares ignored[6]. Figure 1 shows the simplified model of the helicopter, the relative positions of the center of gravity, rotor, and horizontal tail have been marked.

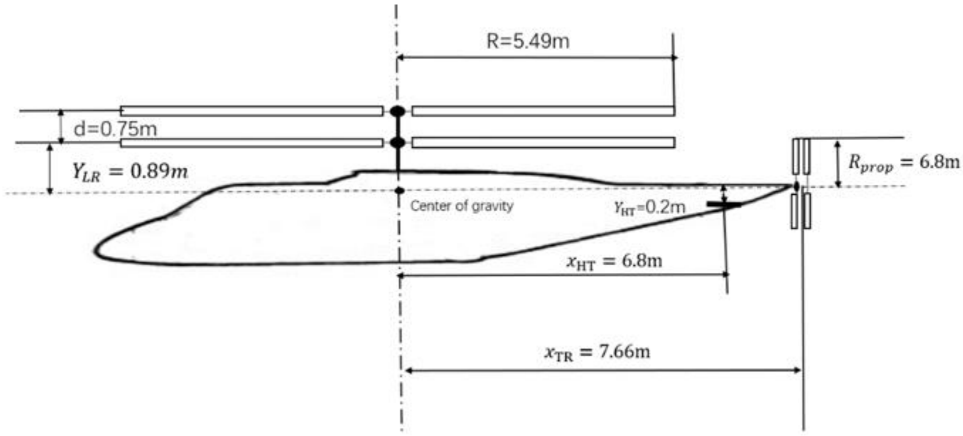

Figure 1 – Approximate drawing of real size of XH-59A helicopter.

Forces applied on the helicopter are simplified into rotor thrust T, lift L and drag D on fuselage, propeller thrust T_p and gravity mg, referring to figure 2. Two methods have been applied for rotor thrust prediction. One method is the engineering formula of thrust with rotor collective and periodic pitches, which is used for preliminary analysis. The other is based on the momentum blade element theory and the Pitt/Peters inflow model,,taking into account the collective and cyclic pitches as well as mutual interferencebetween the upper and lower rotors. The result of the latter one is validated with flight test and CFD simulation result of the rotors in steady forward flight. The fuselage aerodynamic performance is calculated according to the aerodynamic characteristic matrix of the XH-59A airframe obtained from the Felker wind tunnel test[7]. Results are related to flight speed and angle of attack. The performance of the propeller is only considered in compound mode, where propeller thrust and required power are discussed.

3. Analysis of the Trajectory and Force of the Pop-up Process

Using the quasi-static hypothesis, the instantaneous state of the helicopter during the pop-up process is decomposed into several stable flight states. Take the longitudinal maneuver as an example, set the coordinate system along the horizontal and vertical directions, and give the trajectory of the helicopter, as shown in Fig.2. Assuming that the helicopter flies over a mountain with a height of h of 200m within the specified time t_0=60s, its horizontal displacement L is limited to 800m.Taking the ground coordinate system as an example, the corresponding trajectory of the helicopter can be decomposed into three sections: in stage 1, the helicopter moves forward at a constant speed of 60m/s, and then in stage 2, it moves forward at a variable speed. After jumping a certain height, it changes to the constant forward motion of stage 3.

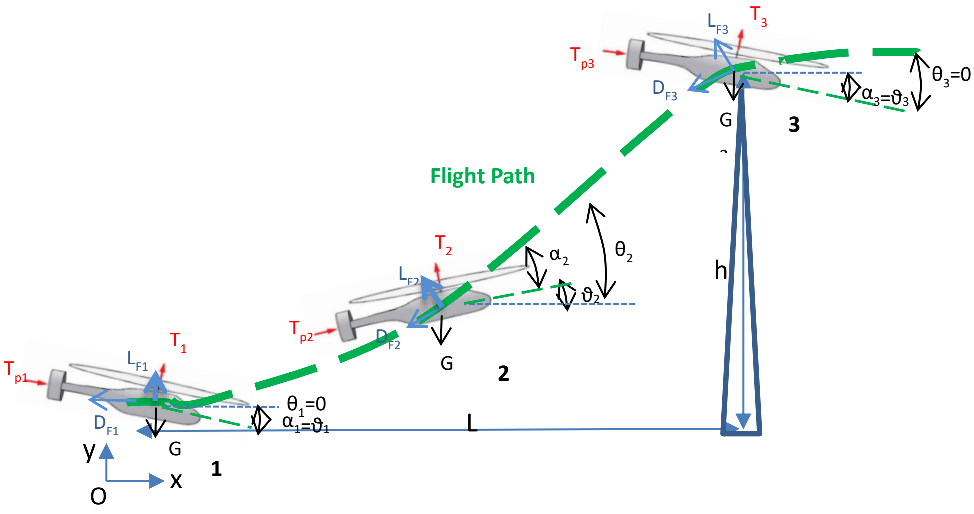

Figure 2 – Schematic diagram of the helicopter pop-up process.

The constraints are summarized as follows.(1)The required power should be less than engine power. (2)The lateral displacement, velocity and yaw angle of the aircraft are all 0. （3）The normal overload range of the helicopter is in range -0.5g to 3g. (4)The climb rate of the pure helicopter mode is no more than 10m/s, and the climb rate of the compound mode is unlimited. (5)There is no height drops during the whole process. (6) The helicopter is flying forward at a constant speed of 60m/s in stages 1, where pitch Angle are derived from the flight test .

According to the dynamic equations, when considering the vertical maneuver of the helicopter, the lifting resistance of the vertical tail is approximately 0 for processing. In addition to the above parameters, on the premise of no lateral motion of the helicopter, we can also get $V_z=\omega x=\omega y=F_z=0$. The forces acting on the helicopter are mainly gravity, rotor pull, rotor backward force, fuselage lift, fuselage resistance, fuselage pitching moment, and rotor pitching moment to the hub of the propeller, and many of the forces are related to the pitch Angle and track Angle of the aircraft. In the dynamic equation, the number of independent variables exceeds the number of constraints. Therefore, it is very difficult to solve the general solution of the whole system, especially through numerical discretization, iteratively solving the derivative term of the formula. In order to solve the dynamic equation of maneuver process conveniently, the helicopter model is simplified as follows:

1) On the helicopter, except for rotor pull, fuselage resistance and thrust propeller thrust, other aerodynamic forces are ignored to be 0, and other aerodynamic moments are 0;

2) The airframe resistance is approximately proportional to the square of the speed, and has nothing to do with the pitch Angle of the aircraft;

3) The helicopter is approximately a particle, without considering the rotation of the fuselage.

4) Given the helicopter accelerations a_x and a_y, the trajectory and transient velocity of the helicopter can be obtained.The acceleration is converted into non-inertial force, and the magnitude and direction of the rotor pull are obtained according to the force balance of the helicopter.

According to the above simplification, the jumping state of the helicopter is divided into helicopter mode and compound mode for analysis.

3.1 Helicopter mode

3.1.1 ForceForce analysis

The motion trajectory in helicopter mode is curved upward, and the forces on the helicopter are shown in Figure 3, with only gravity G, fuselage drag D_F and rotor thrust T. Due to the negative lift of the fuselage is small compared to the rotor thrust, the lift of the fuselage is ignored.

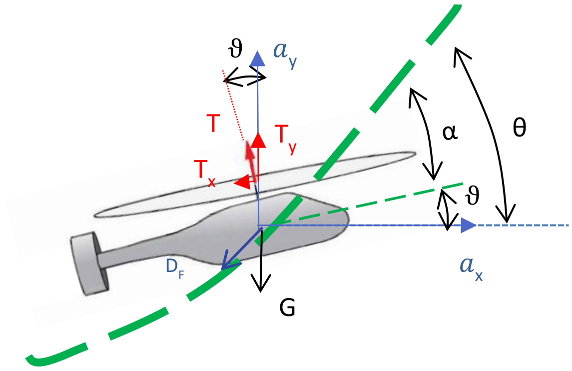

Figure 3 – Force analysis in helicopter mode.

Non-inertial forces (contrary to the direction of acceleration) are generated due to the acceleration $a_x$and a_y in the horizontal and vertical directions.The above four forces remain in balance, as shown in formulas (1) and (2).Where into, the rotor tension is decomposed into two components, namely T_x and T_y, which are positive in the same direction with the coordinate axis, and negative in the other direction. Since the other three forces are known, the rotor pull component can be determined, and the size and direction of the rotor pull can be determined according to formulas (3) and (4) (the pitch Angle of the helicopter can be determined according to the direction of the rotor pull ϑ).According to formulas (5), the relationship between attitude angles of the helicopter can be established.

$$T_y - D_F \sin\theta - mg = ma_y \tag{1}$$

$$T_x - D_F \cos\theta = ma_x \tag{2}$$

$$T = \sqrt{T_x^2 + T_y^2} \tag{3}$$

$$\vartheta = -\arctan\left(T_x/T_y\right) \tag{4}$$

$$\alpha = \vartheta - \theta \tag{5}$$

3.1.2 Trajectory design

Through testing, the trajectory is segmenting into one calculation point per second to find a maneuver trajectory satisfying all constraints.Fig. 4 shows the change rule of acceleration, and the change of flight path is shown in Fig. 5.In 35 seconds, the altitude of the plane reached 200m and the horizontal flight distance was 798m.The black dotted lines in the following figures indicate the parameters corresponding to the time of jumping over obstacles.

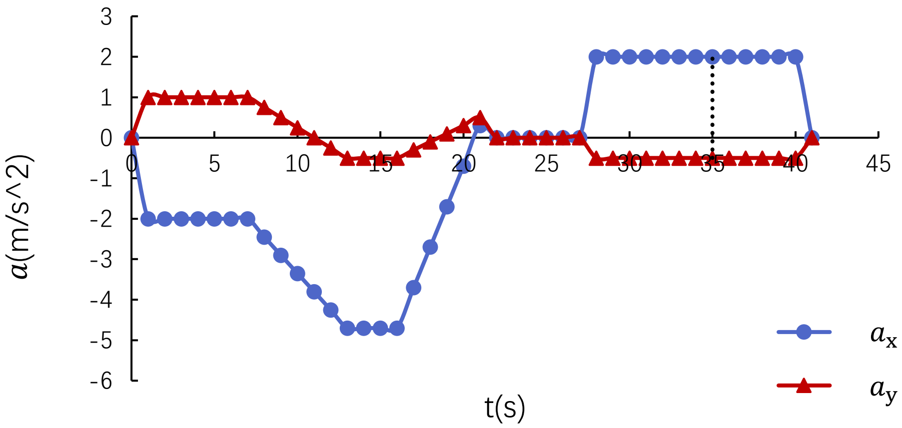

Figure 4 – Variation of helicopter mode acceleration.

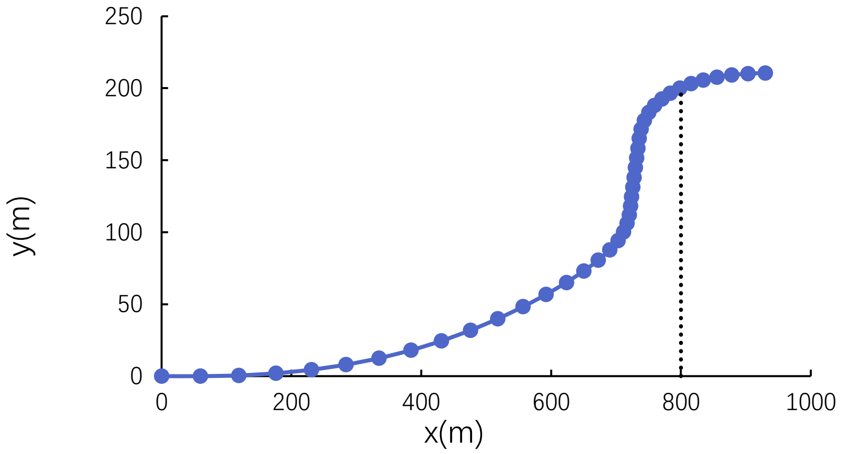

Figure 5 – Helicopter mode track.

Figure 5 shows the motion trajectory. It can be seen that the helicopter slows down at first and moves mainly in a horizontal direction with a trajectory similar to a parabola. At 17s, with a horizontal displacement of about 700m, the helicopter gained sufficient vertical velocity. After 17s, the helicopter moved in the vertical direction, with the trajectory tilting to the vertical direction to complete the pop-up.

3.1.3 Dynamic performance

According to the formula (3) of the helicopter's rotor force, the variation of the rotor force during the jumping process can be obtained, as shown in Fig. 6. Reference[8], the pull coefficient of the rotor, the power coefficient of the rotor and the power required by the rotor can be obtained. The results are shown in Figure 7.

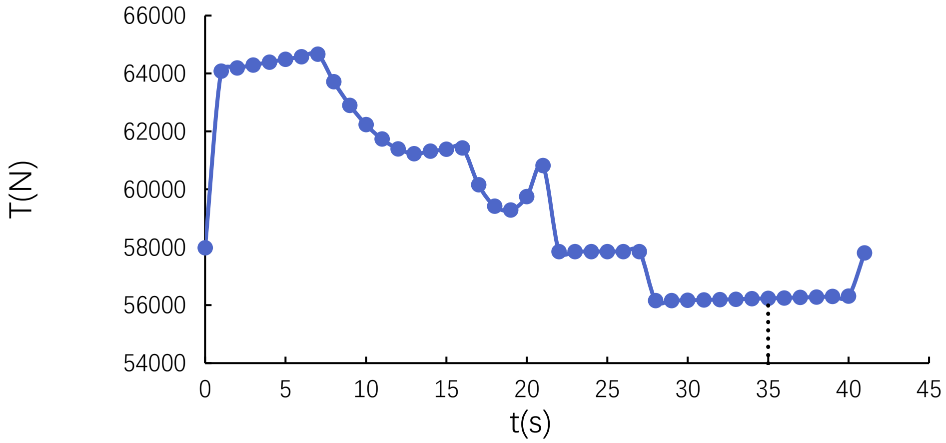

Figure 6 – Variation of rotor thrust in helicopter mode.

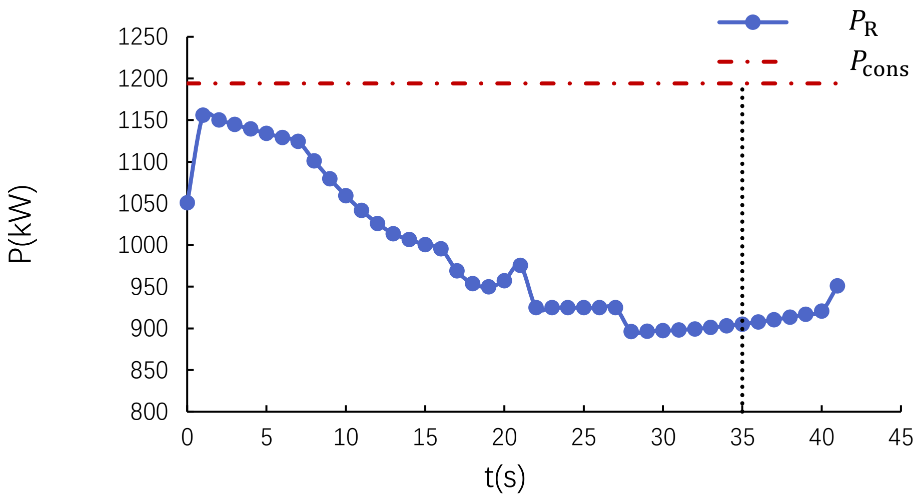

Figure 7 – Variation of rotor power required in helicopter mode.

It can be seen from Figure 6 that in the pop-up stage, the rotor tension increases sharply and gradually reaches the maximum value (64579N), and then decreases step by step, with the minimum value (56161N) at 35s, and slightly increases (58000N) when it is changed to flat flight.Figure 7 shows the variation of rotor power demand. P_R represents the calculated rotor power demand, and P_{cons} represents the maximum continuous power of the rotor.It can be seen that the power required by the rotor increases sharply at 1s, and then decreases gradually and tends to be stable.The power required is always lower than the maximum continuous rotor power of 1194KW, of which the maximum rotor power required is 1156KW.

3.1.4 Attitude and maneuverability prediction

From formula (4), the pitch Angle of the helicopter ϑ can be obtained.Track inclination (climbing Angle)θ can be obtained according to the tangential direction of the trajectory, as shown in Formula (6).

$$\theta = arctan(V_y/V_x) \tag{6}$$

The helicopter Angle of attack α can be obtained from formula (5) above.

The control quantity is the total rotor pitch and the period pitch. According to literature [9] The total rotor pitch θ_0 and the rotor pull coefficient, the rotor pitch can be obtained.According to literature [9] the engineering formula of the rotor longitudinal periodic pitch $A_1$and transverse periodic pitch B_1 can determine the periodic pitch.The changes of attitude Angle and maneuvering quantity in the jumping stage are shown in Fig. 8-12.

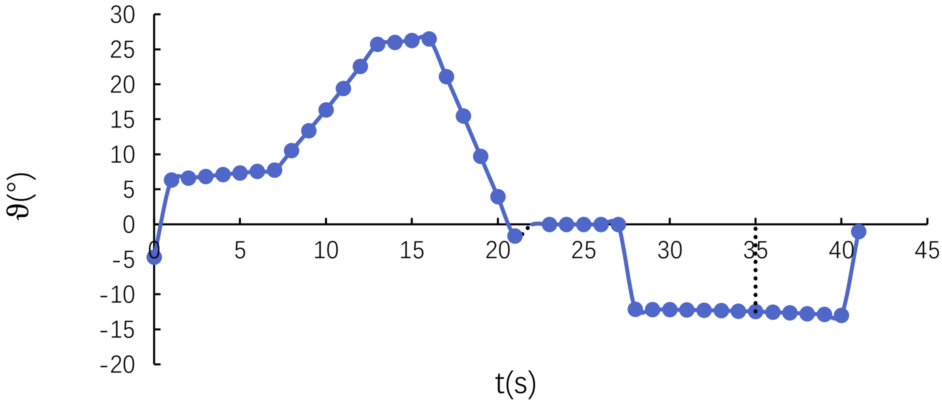

Figure 8 – Variation of pitch Angle in helicopter mode

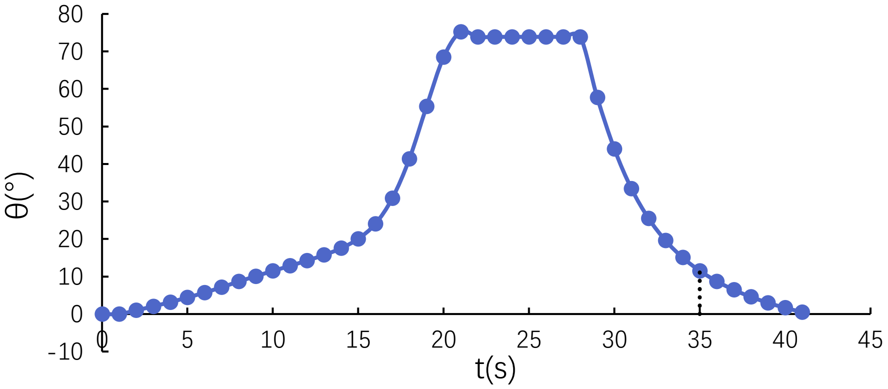

Figure 9 – Changes of helicopter mode track inclination Angle (i.e. climb Angle).

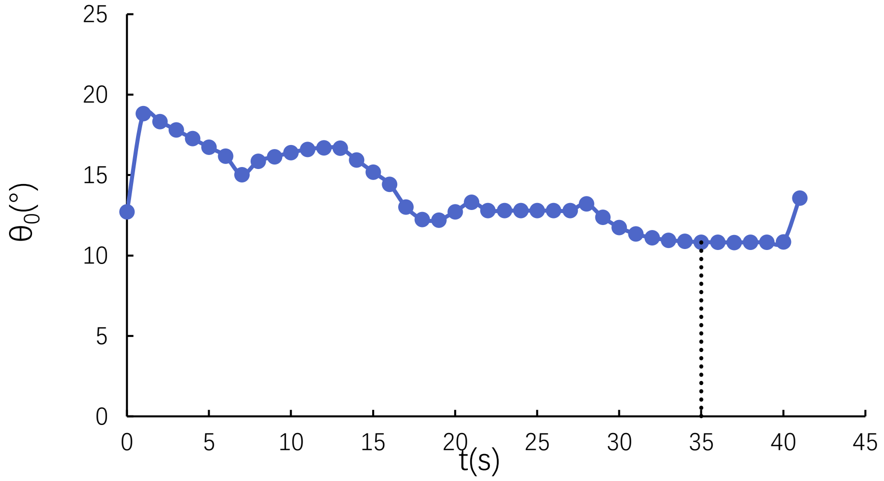

Figure 10 – Variation of total rotor pitch in helicopter mode.

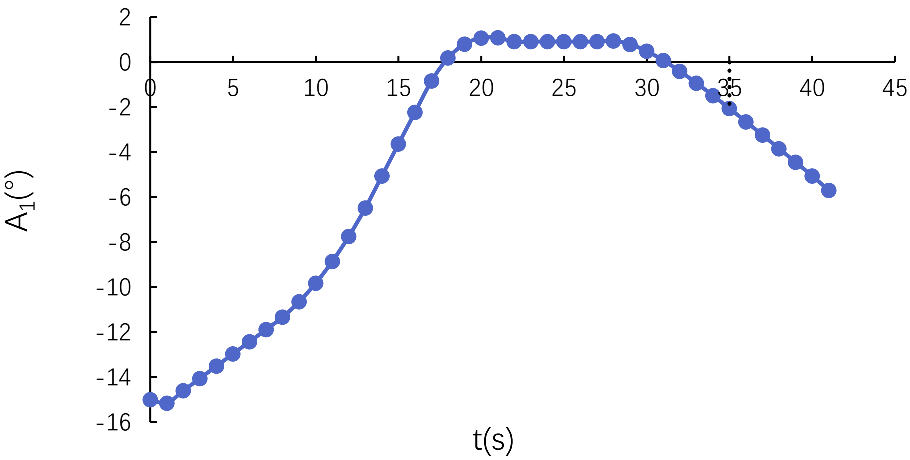

Figure 11 – Variation of longitudinal periodic pitch of rotor in helicopter mode.

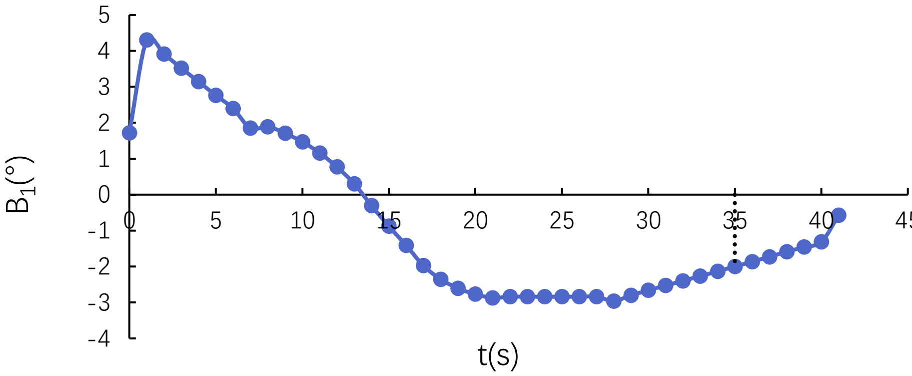

Figure 12 – Lateral periodic pitch variation of helicopter mode rotor.

As can be seen from the above attitude Angle and control quantity, the relevant angle changes of the helicopter are staged, and the parameter changes within each segment are smooth, while the junction between segments is not smooth enough. But it is basically reasonable, and there is no repeated fluctuation of parameters and numerical mutation different from flight control.

3.2 Compound mode

3.2.1 Forceanalysis

In compound mode, the rotor does not have to lean forward because of the thrust parallel to the fuselage.Therefore, consider the addition of the tail thrust unknown, but the number of constraints remains two.At the same time, the climbing rate in compound mode is no longer limited to 10m/s.The force analysis of the compound state helicopter is shown in Fig. 13.The helicopter enters the initial state of pop-up as in section 5.2.1 of the helicopter mode.After 1s, the auxiliary thrust turns on and the helicopter pitch Angle and other parameters change. This paper temporarily ignores the change process within the middle 1s.

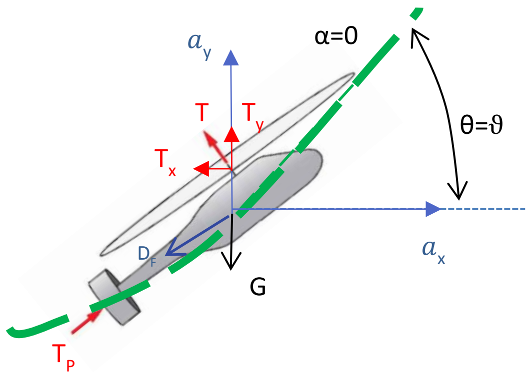

Figure 13 – Force analysis in compound mode.

Assuming that the Angle of attack of the aircraft is 0, equation (9) is supplemented as the constraint, that is, the aircraft flies along the direction of the trajectory to obtain the minimum drag.The direction of rotor force and auxiliary thrust is determined, and the path Angle can be obtained according to the trajectory. Three formulas (7)~(9) are used as constraints, and three independent variables T_x, T_y and T_p can be used to uniquely determine the magnitude of the rotor tension component and the auxiliary thrust.Where, the pitch Angle of the helicopter ϑ is equal to the track Angle. Other parameters are consistent with the pure helicopter mode. The rotor force is still calculated by Formula (3) and ϑ is still calculated by Formula (4).

$$T_p \sin\theta + T_y - D_F \sin\theta - mg = ma_y \tag{7}$$

$$T_p \cos\theta - T_x - D_F \cos\theta = ma_x \tag{8}$$

$$\vartheta = \theta, \quad \alpha = 0 \tag{9}$$

3.2.2 Trajectory design

According to online information, the XH-59A helicopter uses a turbojet engine as an auxiliary propulsion system. Therefore, the auxiliary thrust T_p should be greater than 0. After calculation, the acceleration a_x in the x direction should be within the interval of (-0.9,0).Therefore, in view of the special situation of compound mode, the trajectory of maneuver process satisfying the constraint is redesigned.Fig. 14 shows the change rule of acceleration in compound mode, and the change of track is shown in Fig. 15. At 14.5s, the aircraft reached an altitude of 208m and a horizontal flight distance of 797m. The black dotted lines in the following figures indicate the parameters corresponding to the time of jumping over obstacles.

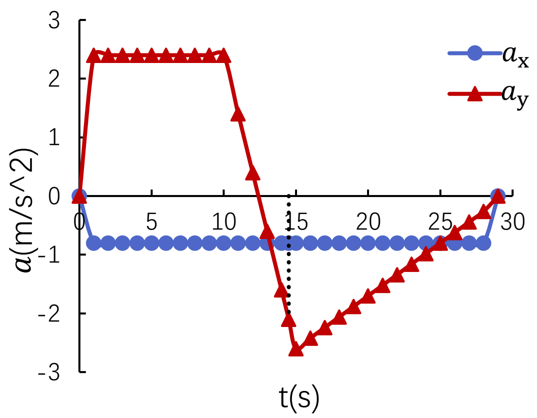

Figure 14 – Variation of acceleration in compound mode.

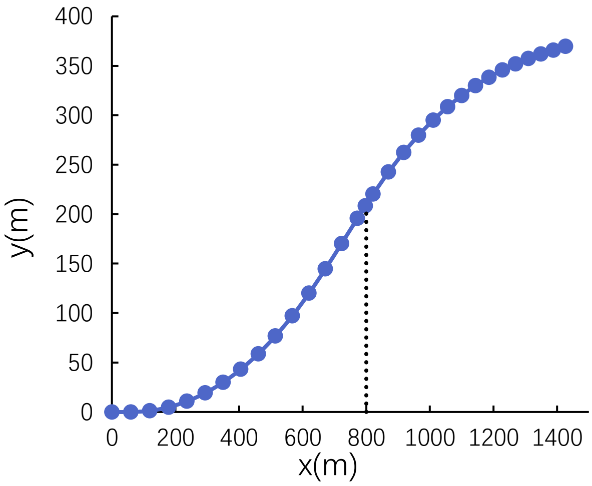

Figure 15 – Compound mode track.

As can be seen from Figure 14, the helicopter basically carries out constant acceleration movement in the horizontal direction and variable acceleration movement in the vertical direction.After receiving the pop-up command, the helicopter flying at a uniform speed will decelerate in the horizontal direction and accelerate in the vertical direction in 1s, and keep the acceleration constant.After 10s, the horizontal acceleration keeps a constant value of -0.8m/s^2, and the vertical acceleration begins to decrease.The helicopter flew over the obstacle at 14.5s, and then continued to maintain an acceleration of -0.8m/s^2 in the X direction after 15s, while the Y acceleration gradually changed from a minimum of -2.6m/s^2 to 0. Finally at 29s near level flight.

Fig. 15 shows that the motion trajectory is approximately an S-shaped curve. Before 14.5s, the helicopter accelerated and jumped in the vertical direction, and the jumping time was short. The vertical displacement had reached 208m when the horizontal displacement was 797m. After flying over the obstacle, the helicopter began to slow down in the vertical direction to get ready to change out. Due to the high horizontal speed, the horizontal displacement in the whole process from the beginning of maneuver to the change out reached 1426m.

3.2.3 Dynamic performance

In the compound mode, the variation of the rotor tension in the jumping process is also obtained according to the formula (3) of the helicopter rotor tension.The results are shown in Figure 16, where T_R represents the rotor pulling force and T_P represents the auxiliary thrust force.

The power of the rotor can be calculated according to the formula in the literature[8], and the power required by the thrust propeller can be estimated by Equation (10).The power variation of the rotor engine is shown in Figure 17. P_R represents the power required by the rotor, and P_P represents the power required by the auxiliary thrust, and the sum of the two results in P_T the total power required by the helicopter, P_{cons} represents the maximum continuous power of the rotor, and P_{max} represents the maximum power of the engine.

$$P_P = T_P \cdot V \tag{10}$$

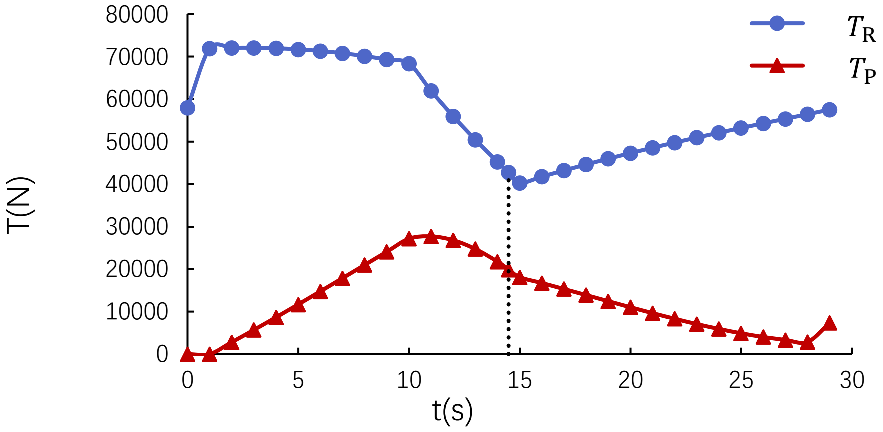

Figure 16 – Variation of tension and thrust in compound mode.

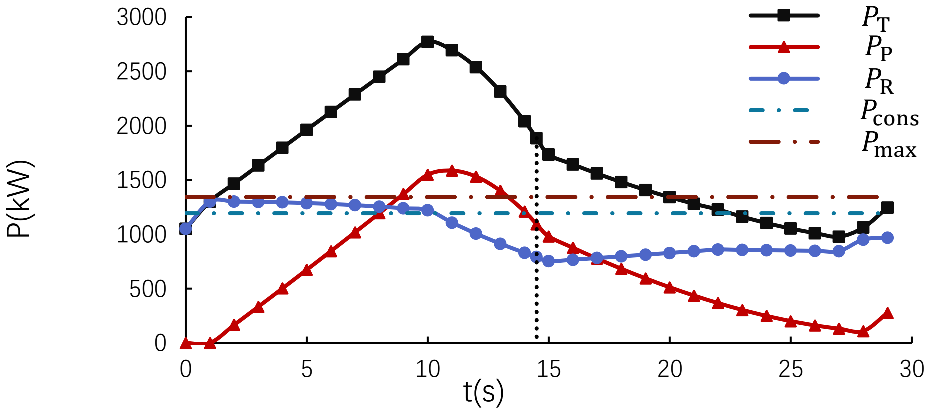

Figure 17 – Variation of power in compound mode.

As can be seen from Fig. 16, the rotor tension increases sharply to the maximum value (72088N) at 1s, and then decreases gradually, and reaches the lowest value (40277N) at 15s after leaping over the obstacle, and then gradually increases to 57530N at the time of removal, while the auxiliary thrust increases from 0 to 11N at 1s, and then increases gradually to the maximum value (27705N) at 11s.After that, the auxiliary thrust was 19911N at 14.5s over the obstacle, and then gradually reduced to 7352N and changed out.

Fig. 17 shows the variation curve of rotor power demand, auxiliary thrust power demand (propeller power) and total power demand with time. The power required for the rotor shows a sudden increase (to 1302KW), followed by a decline and then a rise. In the first 10s, the rotor power exceeds the maximum continuous power of 1194KW, but it is still less than the maximum power of the engine of 1343KW.Then it dropped to a minimum of 753kW, then slowly picked up until 969kW at the time of exiting.The power required by the propeller increases first and then decreases with time, and the maximum power is 1587kW at 11s.Before 9s, the power required by the rotor is obviously greater than that of the propeller; from 9s to 17s, the power required by the propeller is greater than that of the rotor; after 17s, the power of the rotor is higher than that of the propeller again.According to the analysis, in order to realize the pop-up process, the propeller power increases gradually, and then the auxiliary thrust decreases and the power required decreases until the end of the maneuver process.

3.2.4 Attitude and maneuverability prediction

The formula for calculating the track Angle in the compound mode is the same as (6), and the corresponding pitch Angle is determined.According to the engineering formula of the rotor longitudinal periodic pitch A_1 and transverse periodic pitch B_1 in literature, the periodic pitch can be determined.

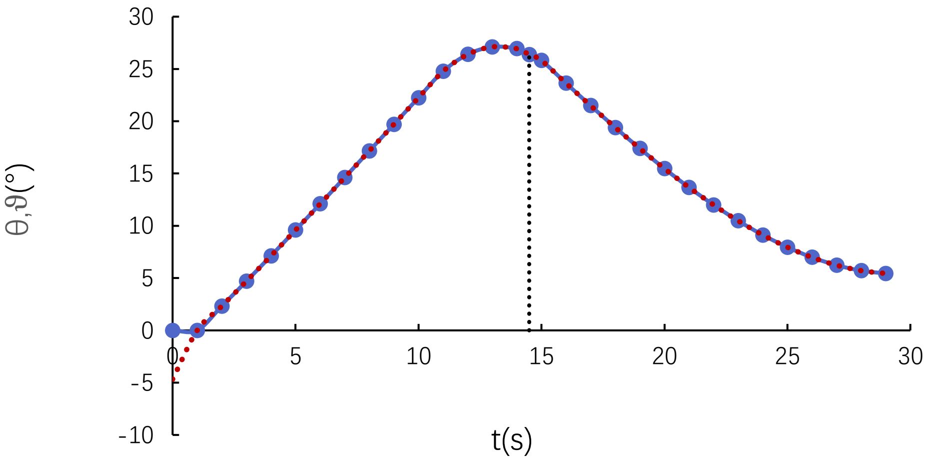

Figure 18 – Changes of track inclination Angle and pitch Angle in compound mode.

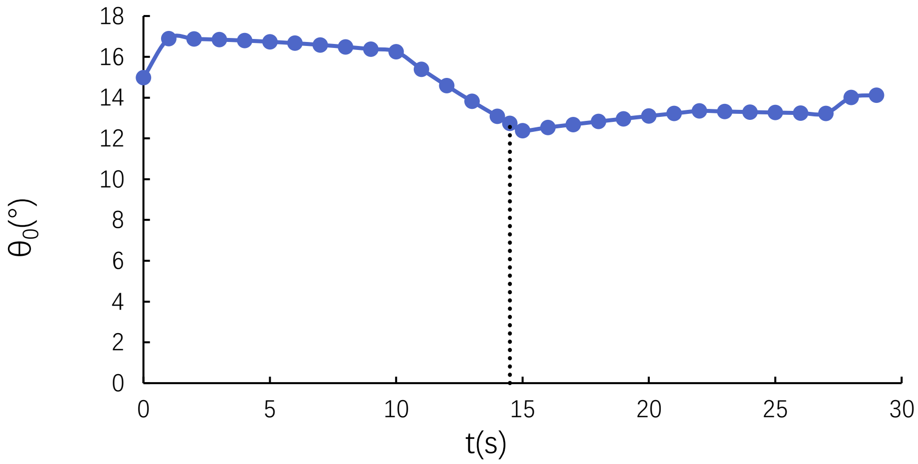

Figure 19 – Changes of total rotor pitch in compound mode.

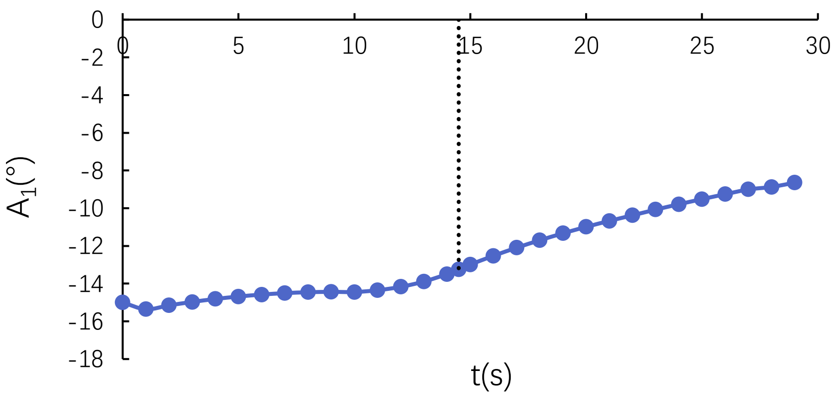

Figure 20 – Variation of longitudinal periodic pitch of rotor in compound mode.

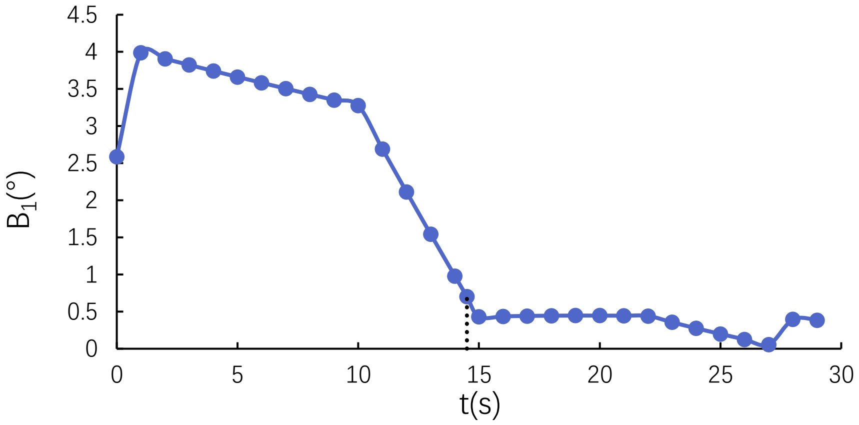

Figure 21 – Variation of transverse periodic pitch of rotor in compound mode.

The above attitude Angle and control quantity are basically reasonable, and the law is basically consistent, and there is no repeated fluctuation.

3.3 Comparison between helicopter mode and compound mode

To sum up, the advantages of helicopter mode are low power consumption, high power consumption efficiency, easy to change out after the pop-up, but long time consuming and large range of operation.The advantages of the compound mode are short pop-up time, stable attitude, small operating range, but the disadvantages are slow change out, high power, low power consumption efficiency.Therefore, for the compound helicopter, the pure helicopter mode or the compound mode can be chosen to pop-up and complete the task of flying over obstacles according to the actual situation and comprehensive factors such as time, power consumption and maneuverability.

4. Comparison of Theoretical Prediction and CFD Simulation of Aerodynamic Performance of Rotor in Steady Forward Flight

The rotor aerodynamic performance prediction based on the momentum blade element theory has been analyzed in literature[10] . The CFD simulation is discussed in this paper.

The k-ε turbulence model is used to simulate the rotor motion, including rotation, periodic pitch and flap-wise motion, by using the nested mesh technique.The local mesh of the lower rotor is shown in Figure 22.

Working condition is set as forward flight speed of the helicopter 60m/s (advance ratio 0.3) corresponding to and the rotor rotation speed 35rad/s. The control variables for the rotors are collective pitch, differential collective pitch, longitudinal cyclic pitch, differential longitudinal cyclic pitch, lateral cyclic pitch, differential lateral pitch, disc inclination angle. They are [0.2019,0.0087,-0.1145,0,-0.0087,0,-0.1326] in radians. The time step for the CFD model of the lower rotor is 0.001s (rotor rotation is 0.035rad within 0.001s, about 2˚).

Figure 22 – Local model of lower rotor for forward flight simulation.

The calculation results are compared in Tab 1. Based on the estimated value of the flight test, the predicted value is the percentage of the test value. Because only the lower rotor model is currently simulated, regarding the aerodynamic performance of the upper rotor is approximately the same as the lower rotor (the torque is opposite).

Tab 1 – Comparison of rotor aerodynamic performance in forward flight

	Rotor Thrust T (N)	The rotor power（kW）
Estimation of flight test	49561	882
Theoretical prediction	54081.1 （109.1%×49561）	672.7 （76.3%×882）
CFD prediction	45112 （91.0%×49561）	799 （88.3%×882）

It can be seen from Table 1 that the CFD method verifies the flight test data better than theoretical method. It is reliable with less relative error and can be used to calculate the aerodynamic performance of the pop-up process of the helicopter.In addition, the periodic fluctuation results of rotor thrust and yaw torque on hub using CFD simulation are shown in Figure 5, which lays a foundation for the study of rotor dynamic load.

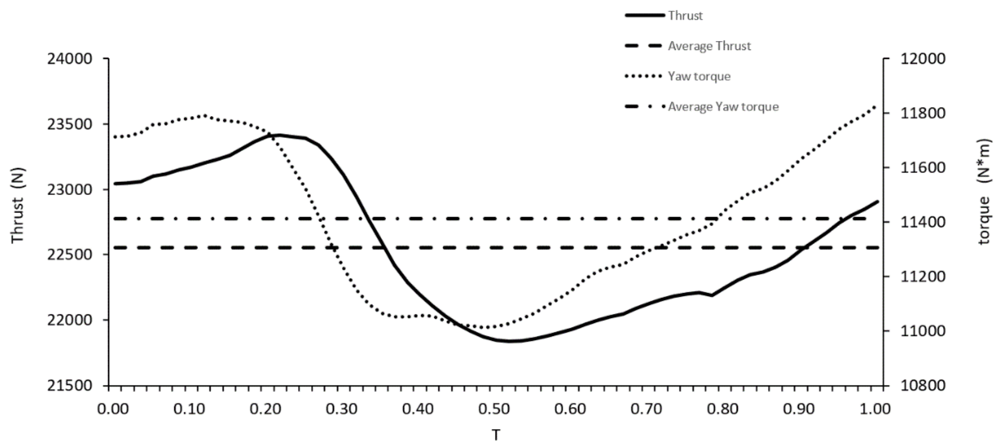

Figure 23 – The thrust and torque of the lower rotor with time.

5. Conclusion

In this paper, an aerodynamic model of the pop-up process of a coaxial rigid helicopter is established based on the rigid body motion model. Taking XH-59A helicopter flying over obstacles in horizontal and longitudinal positions at specified time as an example, the simplified method such as preset trajectory and overload is adopted. The jumping state of the helicopter was divided into helicopter mode and compound mode for analysis, and the variation law of control variables, attitude angle and velocity dynamic travel energy of the XH-59A helicopter with time during the jumping process under the two modes was compared, as well as other flight performance of the helicopter during the jumping process.Moreover, the CFD model of the rotor of XH-59A helicopter is established, and the aerodynamic force of XH-59A helicopter under the condition of constant forward flight at 0.3 advancing ratioadvancing ratio is calculated by theoretical prediction and CFD, which verifies the accuracy of both, and lays a foundation for further research.

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7. Copyright Statement

8. Acknowledgments

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