CFD Simulation of Unsteady Interaction Between Rotor and Fuselage for Canard Rotor Wing in Hovering Using Overset Grids

Pang Chao*, Gao Zhenghong
1 Northwestern Polytechnical University, School of Aeronautics, 710072 Xi’an, China
pangs_c@163.com

Abstract. Different from the traditional helicopter, there would be a severe interaction between rotor and fuselage with canard and horizontal tail during hovering for canard rotor wing (CRW) aircraft. The un-steady RANS (URANS) equations discretized on overset grid are solved in this paper to simulate this kind of aerodynamic interaction. A UH60-A rotor hovering case is used to validate the numerical method. Subsequently, the numerical method is employed on two configurations, i.e., Isolated rotor configuration and Full CRW configuration under numerous collective pitch angle. The force and moment coefficients for different parts with respect to different collective pitch angles are obtained. The result shows that downwash of rotor has a stronger impact on fuselage than canard wing and horizontal tail. Compared with isolated rotor, fuselage with canard wing and horizontal tail has a slight impact on the trust and torque of the rotor in full CRW aircraft configuration.

1. Introduction
The concept of canard rotor wing (CRW) aircraft is firstly proposed by Rutherford etc. al [1], which can be regarded as a combination conception of the fixed wing and the helicopter. The advantages in vertical landing and taking off of helicopter as well as the high-speed cruise of fixed wing are gathered in CRW. The most famous demonstrator vehicle is Dragon fly X-50A [2], which was assisted by NASA Ames and so on.

Helicopter mode, conversion mode and fixed wing mode are three typical modes during the whole fight. Helicopter mode is used to vertically take off or land. Fixed wing mode is used to cruise with high speed. Aerodynamic lifting forces are transferred from rotor to canard wing and horizontal tail with the increasing free stream velocity during conversion mode. Lifting force for CRW aircraft in cruise state mainly comes from canard wing and horizontal tail, which means that area of those lifting surface must be big enough to provide sufficient lifting force. Meanwhile, interaction between those fixed wings and rotor will be quite severe due to the big area of canard wing and horizontal tail, which causes the aircraft hard to control.

Researchers have done many experiments [3-6] including wind tunnel experiment and flying test to explore the aerodynamic interaction between different parts of CRW. As for numerical simulation, Saeid [7] etc. al. has used momentum disk source method to simulate the hovering configuration of CRW aircraft near the ground, where the ground may have a “ground effect” on the rotor. Due to plenty of assumptions, the accuracy of momentum source method is less than that of URANS method. Li etc. al. [8] has solved URANS equations to simulate downwash effect on canard wing and horizontal tail during hovering. But they didn’t consider the fuselage of CRW aircraft as well as their
effects on the rotor. Sun et al. [9] has solved the URANS equations to study the interactions during the forward flight. But they consider only one case, which was not sufficient for designers to use.

In this paper, URANS equations combined with SA turbulence model are solved on the overset grid to simulate a full CRW aircraft configuration as well as an isolated rotor configuration. CRW aircraft model (Fig. 1) in this paper is self-designed by NPU (Northwestern Polytechnical University) Smart Loong work team. The rotor is trapezoid without twist. Due to special aerodynamic characters, airfoil of rotor must be symmetric in flow direction (x direction), which is now an elliptic airfoil. The canard wing and horizontal tail were assigned far away from the rotor. A T type tail is designed for this CRW aircraft. All of these shape characters were designed to avoid the severe unsteady aerodynamic interaction of CRW aircraft.

The rest of this paper is outlined as follows. Section 2 gives a brief introduction to numerical schemes including governing equations of CFD simulation and grid assemble method for overset grids. A hovering case for UH60-A rotor will be simulated using CFD simulation based on overset grids to validate the method in section 3. The result shows good agreement between CFD simulation and experiment. In section 4, the aerodynamic interactions between rotor and fuselage are analyzed respectively, which shows a severe effect on total thrust as well as torque for rotor. Some conclusions are summarized in section 5.

Figure 1. The geometry of a CRW aircraft.

2. Numerical Methods

2.1. Governing Equations
Unsteady RANS equations are used in this paper, which can be derived from the Navier-Stokes (NS) equations. Unsteady compressible NS equations in Cartesian coordinate can be written as:

$$\frac{\partial}{\partial t} \int_V \int_{S} Q dV + \int_{S} F_i \cdot n dS = \int_{S} F_v \cdot n dS$$

(1)

where S is the surface of control volume; n denotes surface normal vector; V represents volume of control volume; Q is solution vector, $Q = [\rho, \rho u, \rho v, \rho w, \rho E]$; $\rho$ is density, u, v and w are three components of velocity, E is total energy; $F_i$ denotes inviscid flux; $F_v$ represents viscous flux. The 1-eq SA turbulence model is employed in this paper. A finite volume method is used to discretize these equations. Roe upwind scheme is employed to get inviscid flux. Central difference scheme is used to obtain viscous flux. The implicit dual time step time marching scheme is adopted to get time accurate solutions. Multigrid algorithm is applied in pseudo time marching to accelerate convergent rate in one physical time step. Characteristic boundary conditions based on Riemann invariant is set for far filed boundary condition and the adiabatic no-slip boundary condition is set for all viscous walls

2.2. Geometry and Grids
The geometry of CRW aircraft in this paper is shown in Fig. 1. The radius of the rotor is 1.397 m, whose angular speed is 870 rpm. Collective pitch angle of rotor varies from 0° to 13°. The area of canard wing and horizontal tail is 1.2 m² and 1.5 m² respectively.

The overset grids for the full CRW configuration can be divided into two parts, i.e., near-body grids and off-body grids (Fig. 2). 3-D hyperbolic equations are solved to get near-body grids, and off-body grid is a series of Cartesian grids. The outer grid boundary is far enough away from the aircraft in all directions (nearly 20 times of rotor radii).

2.3. Grid Assemble
Grid assemble is an important step in overset grid method, which includes hole cutting and interpolation. Chiu and Meakin [10] proposed hole-map method for hole cutting. This method contains 4 major steps.

1. Make a Cartesian box around all of the closed surfaces.
2. Set the x-y plane of the Cartesian box as a “map”. A serial of rays in z direction can be obtained from the “map”, then get the intersection point between these rays and all closed surfaces (water tight surfaces).
3. Use Eq. (2) to verify the position in the “map” for an arbitrary point P.

\[
i_p = \text{int}\left(\left(\frac{x_p - x_{min}}{x_{max} - x_{min}}\right) + 1\right)
\]

\[
j_p = \text{int}\left(\left(\frac{y_p - y_{min}}{y_{max} - y_{min}}\right) + 1\right)
\]

Compare the z value of point P with it of those intersection points to verify the P position roughly.
4. Use bilinear interpolation equation defined in Eq. (3) to determine whether point P is a hole point or not.

\[
B_p = C_1B_{zp,jp} + C_2B_{zp+1,jp} + C_3B_{zp,jp+1} + C_4B_{zp+1,jp+1}
\]

\[
C_1 = \frac{(x_{p+1} - x_p)(y_{p+1} - y_p)}{\Delta x \Delta y}
\]

\[
C_2 = \frac{(x_{p+1} - x_p)(y_{p+1} - y_p)}{\Delta x \Delta y}
\]

\[
C_3 = \frac{(x_{p+1} - x_p)(y_{p+1} - y_p)}{\Delta x \Delta y}
\]

\[
C_4 = \frac{(x_{p+1} - x_p)(y_{p+1} - y_p)}{\Delta x \Delta y}
\]
$B_{p,p}, B_{p+p+1,jp}, B_{p,p+1}, B_{p+p+1,jp+1}$ are obtained from step 3. When $B_p$ is less than 0.5, point P is considered as hole point.

The interpolation procedure in grid assembly aims at finding donor cells for those boundary cells without boundary condition (like hole boundary). Inverse map method [11] can find the nearest donor cells for boundary cells, as well as locate them in the donor cells. If one boundary cell cannot find a donor cell, this boundary cell will become an orphan cell. The solution variables would be obtained by trilinear interpolation using Eq. (4).

$$Q_{bp} = Q_1 + Q_2\xi + Q_3\eta + Q_4\zeta + Q_5\xi\eta + Q_6\eta\zeta + Q_7\xi\zeta + Q_8\xi\eta\zeta$$

where $Q_{bp}$ represents the solution vector for one of the eight vertices in boundary cells; $Q_{1-8}$ denotes the solution vector for eight vertices in donor cells respectively; $\xi, \eta, \zeta$ represent relative position in donor cells for boundary cells vertices, which are between 0 and 1.

3. UH-60A Validation Case

3.1. UH60-A Rotor and Flow Conditions

The blade of UH60-A rotor has a nonlinear twist, and the tip is swept. Fig. 3 shows the platform of blade. The rotor contains 4 blades whose radius is 8.17m. Section geometry of rotor contains two airfoil i.e., SC1094-R8 and SC1095. Rotor solidity is 0.0826.

![Figure 3. UH60-A blade platform geometry.](image)

The validation case used in this section is hovering status. Tip Mach number of rotor is 0.628, and the collective pitch angle is 9°. Reynold number is $2.75\times10^6$.

3.2. Validation Result

Total number of vertices in grid is 9 million with 12 near-body grids as well as 27 off-body grids. Fig. 4 shows the near-body grids and the off-body grids. Boundary of off-body grids is located 3 blade radii [12] far from the rotation center of rotor.

![Figure 4. Overset grids for UH60-A blade. (red lines mean cut-off plane of near-body grids; black lines mean cut-off of off-body grids)](image)
The experiment section pressure coefficient can be found in Ref [13], where 6 sectional stations are chosen to compare. Note that reference velocity used to calculate the pressure coefficient is local speed instead of blade tip velocity. The calculation results compared with experiment data are shown in Fig. 5.

![Figure 5](image)

**Figure 5.** Comparisons of the CFD result (red line) about sectional pressure distribution with experimental data. (black delta symbol ▲)

Results show good agreement between CFD and experiment in blade root and tip region. In the area which is very close to blade tip, CFD simulation cannot correctly predict the pressure distribution due to a strong 3-D effect.

Table 1 gives the thrust and torque coefficient comparison. Note that reference velocity used to calculate those coefficients is blade tip speed, and reference area is rotor disk area. Reference length is the radius of rotor.

|          | CFD  | EXP  | EROOR |
|----------|------|------|-------|
| C_{T/\sigma} | 0.083 | 0.085 | 2.3%  |
| C_{Q/\sigma} | 0.0067 | 0.0069 | 2.8%  |
| FM       | 0.72  | 0.73  | 1.3%  |

Errors for all coefficients are within 5%. Thus, CFD solver used in this paper has great accuracy to predict rotor aircraft in hovering status.

4. Results and Discussions

To better understand the interaction between rotor and other parts of CRW aircraft, two different configurations are simulated using CFD method in this section. One of these two configurations is an isolated rotor without any other parts, another is the full CRW configuration which includes all parts of this aircraft.

There are five revolutions in each calculation case. The physical time step is set as 1 degree per step based on the 30 sub-iterations.
4.1. Aerodynamic Effect on Rotor Performance

Fig. 6 shows the difference in thrust and torque coefficient of rotors in those two configurations. Reference velocity is blade tip velocity which is nearly 0.374 Ma. Reference area and length are the area and radius of rotor respectively. Note that force and moment coefficient shown in Fig. 6 is an average of instant value in the final revolution. Torque coefficient is not zero when thrust coefficient is nearly zero due to skin friction and a separation region near the trailing edge of this elliptic airfoil [14]. Trailing edge separation region will always exist, which will cause an additional pressure drag. Meanwhile, this additional pressure drag will make the FM value lower than normal rotors with sharp trailing edge.

![Graphs showing thrust and torque coefficients](image)

**Figure 6.** Performance comparison for the rotor between two configuration: rotor of full CRW (red line) configuration and isolated rotor(green line)

According to Fig. 6 (a), it can be observed that other parts of CRW aircraft have little effects on thrust coefficient of rotor unless collective pitch angle is big enough. Torque coefficient of rotor in full CRW configuration is obviously less than that of isolated rotor. It means that less energy will be needed to produce the same magnitude of thrust (Fig. 6 d).

![Graphs showing instant coefficients](image)

**Figure 7.** Instant coefficients of rotor in last revolution. (red line full configuration rotor; blue line isolated rotor)

Fig. 7 separately gives instant thrust and torque coefficient with respect to azimuth angle in the last revolution of rotor with 13° collective pitch angle. In this case, the azimuth angle equals 0 when rotor blade lie in y direction. The fluctuation of these coefficient is very small due to hovering status. There is an evident difference between these two configurations. In full CRW configuration, the coefficients have an obvious variation compared to isolated configuration when the blade of rotor is approaching the fuselage. The reason is that fuselage will resist the downwash flow induced by rotor while they are
closed to each other. This kind of resistance can produce an additional local pitch angle for the blades. Therefore, coefficient for both thrust and torque is raised up rapidly.

4.2. Aerodynamic Effect on Fuselage

Fig 8 shows the downwash flow of rotor. The canard wing and horizontal tail of this CRW aircraft is designed as far as possible from the rotor disk. Velocity above the rotor disk is much smaller than it below the rotor disk from momentum theory. T type tail and the long distance mentioned above will help those fixed wings to avoid effect of rotor downwash flow. In this full CRW configuration, main aero-dynamic interaction will appear between fuselage and rotor.

Figure 8. The downwash flow velocity of rotor.

Fuselage under the rotor disk can be considered as a cylinder, which would produce a loss of thrust for full CRW configuration due to the large separation area. With collective pitch angle increasing, this kind of thrust loss becomes more obviously. Thrust loss is getting smaller because of the additional thrust of the rotor mentioned in previous section when the collective pitch angle is 13 degree.

Figure 9. Thrust loss due to existence of fuselage.
Figure 10. Total thrust coefficient for full CRW (blue line) compared with isolated rotor (red line). Thrust loss of full CRW configuration has an effect on the flight performance during helicopter mode, like hover ceiling, rate of climb and so on.

Conclusion and Discussion
1. The CFD method based on overset grids has well accuracy in predicating the rotor aircraft in hovering status.
2. Other parts of CRW aircraft have little effect on the thrust of rotor unless collective pitch angle is big enough. But these parts will drop the torque coefficient, which will improve the figure of merit.
3. The downwash of rotor only has obvious effect on a finite region under rotor disk for hovering status. Make fixed wings far away from or above the rotor disk is a sufficient method to avoid the downwash flow from the rotor disk.
4. Fuselage under the rotor disk will suffer from the downwash and it will cause an obvious thrust loss for the total aircraft. This point should be considered while designing.

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