A coupled CFD and wake model simulation of helicopter rotor in hover

Qinghe Zhao  Xiaodong Li
School of Energy and Power Engineering, Beihang University, Beijing 100083, China
E-mail: zhaqinghe2001@163.com

Abstract. The helicopter rotor wake plays a dominant role since it affects the flow field structure. It is very difficult to predict accurately of the flow-field. The numerical dissipation is so excessive that it eliminates the vortex structure. A hybrid method of CFD and prescribed wake model was constructed by applying the prescribed wake model as much as possible. The wake vortices were described as a single blade tip vortex in this study. The coupling model is used to simulate the flow field. Both non-lifting and lifting cases have been calculated with subcritical and supercritical tip Mach numbers. Surface pressure distributions are presented and compared with experimental data. The calculated results agree well with the experimental data.

1. Introduction
The precise wake description is an important aspect in rotor aerodynamic predictions, because a flow-field induced by the wake changes The characteristic of the whole rotor. If the rotor wake can be accurately simulated, then aerodynamic characteristics of the rotor can be accurately obtained. Due to numerical dissipation the wake structure is difficult to distinguish. And it cannot create induced velocity and the flow field. For this reason, some methods are developed to describe the wake flow field.

There are two commonly used methods to simulate the wake. One is wake capturing and another is wake coupling. The wake capturing methodology models the entire flowfield and attempt to Capture the structure of the solution as part of the solution. The wake capturing methodology has the advantage without any empiricism. However, it does suffer from Higher computational costs and numerical diffusion. In the wake coupling methodology, the geometry of the wake and circulation strength are Prescribed. Then the wake position obtained are embedded into the CFD analysis. The advantages of the wake coupling methodology are computational efficient and experimental support. meanwhile, It takes some experience to simulate the wake structure.

That is to say, The CFD solver provides the sectional aerodynamic loading to the wake solver, These are inputs to generate the wake model. the wake solver in turn gives the wake positions, their circulation strengths and vortex diffusion parameters to the CFD solver. Coupling analysis has been used to simulate the rotor aerodynamic and wake flowfield.

2. Governing Equations and Numerical Schemes
For hover cases, because of the periodicity of the flow in rotational coordinate system, the computational domain can be replaced by a domain around one blade. The periodicity boundary condition is used to consider the influence of other blades. Furthermore, the periodicity boundary condition can be used to reduce cost of computing. The government equation is given below
\[
\frac{d}{dt} \int_{V(t)} \tilde{w} dV + \int_{\partial V(t)} (\tilde{F}(\tilde{w}) - \tilde{F}_v(\tilde{w})) dS = \tilde{S}
\]  

(1)

Where \( \tilde{w} \) is the conserved variables. \( \tilde{F} \) and \( \tilde{F}_v \) are the inviscid and viscous fluxes, respectively.

There is a source term in the non-inertial frame of reference. It means the influence of the centripetal and the Coriolis force. For an hovering rotor rotating around the y-axis with the angular velocity \( \omega = [0, \Omega, 0] \), the source term \( \tilde{S} \) can be expressed by equation 2.

\[
\tilde{w} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{bmatrix}, \quad \tilde{F} = \begin{bmatrix} \rho(q - q_u) \\ \rho u(q - q_u) + pi_i \\ \rho v(q - q_u) + pi_i \\ \rho w(q - q_u) + pi_i \\ \rho h(q - q_u) + pq_i \end{bmatrix}, \quad \tilde{S} = \begin{bmatrix} 0 \\ -\rho \Omega w \\ 0 \\ 0 \end{bmatrix}
\]  

(2)

Where \( q_u \) is the grid velocity, it produce a grid flux. The finite volume discretization with central differencing for the flux approximation leads to 2 order scheme. The implicit Lower-Upper Symmetric Gauss Seidel operator(LUSGS) is used to obtain the update solution. Besides, the grid around the rotor is fixed.

3. Prescribed Wake Model

3.1 Landgreb wake model

The prescribed wake model employs experimental data to determine the wake location and structure. Because experimental data is applied, it's very fast to predict. This method can also be extended to the forward flight state. Some wake models have been developed such as the model introduced by Landgreb. For Landgreb wake model, the axial and radial coordinates of the tip vortex are given below

\[
z_{tip} = z_{tip} + k_1 \phi_w
\]  

(3)

\[
r_{tip} = A + (1 - A) \exp(-Y \phi_w)
\]  

(4)

\[
k_1 = -0.25(C_T / \sigma + 0.001 \theta_w)
\]  

(5)

\[
k_2 = -(1.41 + 0.0141 \theta_w) \sqrt{C_T / 2}
\]  

(6)

Where \( \phi_w \) is the age angle, \( N_b \) is the number of blades, \( R \) is the rotor radius, \( \theta_w \) is the value of blade twist, \( \sigma \) is the rotor solidity and \( C_T \) is the thrust coefficient. \( A \) is the contraction ratio of the wake, its experimental value is 0.78 and \( Y \) can be obtained by \( Y = 0.145 + 27 C_T \). The vortex strength is the maximum of tip vortex.

\[
\rho v^2 b = dl = \frac{1}{2} \rho v^2 c b C_i
\]  

(7)

\[
\Gamma = \frac{1}{2} c v C_i
\]  

(8)

The vortex radial is about 0.1 chord. The induced velocity associated with each vortex filament can be computed by the Biot-Savart law.
\[ V_0 = \frac{\Gamma}{4\pi} \frac{h^2}{\sqrt{h^2 + r_1^2}} \left( \frac{\mathbf{r}_1 \times \mathbf{r}_2}{|\mathbf{r}_1 \times \mathbf{r}_2|} \right) \left[ r_0 \left( \frac{\mathbf{r}_1 - \mathbf{r}_2}{|\mathbf{r}_1 - \mathbf{r}_2|} \right) \right] \]

(9)

Where \( dl \) is the differential element of prescribed wake geometry, \( \Gamma \) is the circulation and \( r \) is the vector connecting between the wake filament and grid. and \( h \) is the perpendicular distance of the evaluation point from the influencing vortex element. A Rankine vortex core model with a radius of one-tenth of the blade radius is used. The tip vortex strength is set to the maximum of bound circulation.

3.2 Hybrid method
The CFD gives the span load of the rotor in hover. This is used to give a vortex intensity. The trailing edge of the rotor according to starting position of the wake mode. The wake is generated according to the wake model. and the induction flow field is generated. The induced velocity changes the effective angle of the rotor.

The vortex age is shown in Fig 1. The left figure denotes the axial location. The right figure denotes the radial location. It's quite well comparing with the experiment data. So it is suitable to couple the wake model with CFD simulation.

Figure 1 : Vortex age position

Figure 2 shows a courtor of the induced velocity. In the left figure the vortex denotes the theory wake model, and the right figure represents a vortex equivalent surface

4. Results and Discussion
An experimental study of a model helicopter in hover had been carried out by Caradonna and Tung. The blade was NACA0012 profile and was untwisted and untapered, which had a diameter of 2.286
meter, and a chord length of 0.191m, according to the aspect ratio was 6. Fig 3 shows the grid topology.

![Grid topology](image)

**Figure 3**: Grid topology

A summary of the simulation cases is given in Table 1.

| Case    | Ma    | $\theta$ |
|---------|-------|----------|
| Case-1  | 0.439 | 8°       |
| Case-2  | 0.877 | 8°       |

In the Caradonna-Tung experiment, the surface pressure distribution was measured at five rotor blade sections (0.50, 0.68, 0.80, 0.89, 0.96). The CFD coupled with prescribed wake model is simulated to get the aerodynamic of the rotor in hover. Five different sections of the blade were compared to the experimental data.

### 4.1 Case-1 Subcritical Tip Mach Number Flow

The tip Mach number is 0.44. Fig 4 shows the computed results of the pressure distribution. There is much bigger difference without the wake model. And the simulation with wake model shows very good agreement for the radial stations between 0.5 to 0.95 stations. Also it also gives the contour of pressure on the wall in the lower right corner of the figure.
Figure 4: Pressure distribution comparison between with wake model at subcritical condition.

4.2 Case-2 Supercritical Tip Mach Number Flow
The tip Mach number is 0.877. Fig 5 shows the results. In this condition there is a shockwave in the tip position. If without the wake model the difference can be seen clearly. The comparison between experiment data is quite very well with the wake model. The flowfield on the rotor is also given in the lower right corner of the figure.
5. Conclusions
Accurate simulation of rotor wake is very important. Comparing with wake capturing methodology, wake coupling methodology is efficient and it is also tested and verified. The accurate wake structure is given by the flow calculation parameter. The wake model induced the flowfield and changes the effective angle. Two pitch angles are calculated, one according to subcritical condition, and another according to supercritical condition. The CFD coupled with wake model agree well the experimental data.

References
[1] Hariharan N, Egolf A, Sankar L, Simulation of Rotor in Hover: Current state and challenges. 2014 AIAA paper 2014-0041
[2] Srinivasan G.R, Baeder J.D, Flowfield of lifting rotor in hover: A Navier-Stokes simulation, AIAA Journal, 1992, Vol.30, No.10
[3] Jacques S, Klansdieter P, Michel C, Numerical simulation of flows around helicopters at DLR and ONERA. Aerosp.Sci.Technol. 2001 5:35-53
[4] Pomin H, Wagner S, Navier-Stokes analysis of isolated rotor flow in helicopter hover flight. Journal of Aircraft. 2002 39(5):813-821
[5] Steijl R, Barakos G, Badcock K, A framework for CFD analysis of helicopter rotors in hover and forward flight. International Journal for numerical methods in fluids. 2006 51:819-847
[6] Renzoli P, D’Alascio A, Kroll N, Peshkin D and H.L.Hounjet M, *EROS-a common European Euler code for the analysis of the helicopter rotor flowfield*, Progress in Aerospace Sciences. 2000 36:437-485

[7] Caradonna F.X, Tung C, *Experimental and analytical studies of a model helicopter rotor in hover*, 1981

[8] Caradonna F.X, Laub G.H, Tung C, *An experimental investigation of the parallel blade-vortex interaction*. 1984 NASA/TM 86005