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High-resolution simulation for rotorcraft aerodynamics in hovering and vertical descending flight using a hybrid method

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Abstract A high-resolution simulation tool for rotorcraft aerodynamics is developed by coupling CFD with a Vorticity Transport Model (VTM). An Eulerian-based CFD module is used to model the blade near body flowfield, and a Lagrangian-based VTM module is employed for vortex tracking in the far wake. The coupling procedure is implemented by transmitting vortex sources to the VTM module and feeding boundary conditions back to the CFD module. The presented CFD/VTM hybrid solver is firstly validated by hover cases of three different rotor configurations. Simulation results, including the blade surface pressure distribution, rotor downwash, and hover figure of merit, exhibit favorable correlations with available experimental data. Then, a rotor operated in vertical descending flight with a fixed collective pitch is investigated. It is shown that the CFD/VTM coupling method is suitable for rotor wake simulation. Wake instabilities (far wake breakdown in hover and toroidal wake pattern in the vortex ring state) are successfully demonstrated with a moderate computational cost.

1. Introduction

Rotorcraft plays an important role in aviation for its unique ability in hovering and vertical descending flight. However, an accurate prediction of the rotor flowfield remains a challenging problem. The three-dimensional rotor wake is unsteady and complex. In a hovering condition, highly energetic tip vortices shed from the blade tip region, swirl downward, and then undergo vortex breakdown in the far wake. In descending flight, tip vortices constantly persist near the rotor disk and interact with the blades, which may cause a high level of fuselage vibration and remarkable induced power consumption. Moreover, when a rotorcraft is operated over certain ranges of descent rate, convection of the wake would be inhibited. It results in a doughnut-shaped ring around the rotor disk, which is known as the Vortex Ring State[1] (VRS,

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see Fig. 1). The VRS is regarded as the roughest flight regime of a rotorcraft. According to statistical data,[2] at least 32 helicopter accidents were attributed to this dangerous regime between 1982 and 1997.

Over the past few decades, studies about the unsteady characteristics of rotor wake in hovering and descending flight have been focused on experiments[3–11] and qualitative analysis.[12–15] Meanwhile, relatively sparse numerical simulations have been paralleled. The aerodynamics near the blade surface, like compressible and viscous effects, are predicted well by conventional Eulerian-based CFD methods, but they are computationally expensive, and inherent numerical dissipation makes the rotor wake diffuse too early.[16] To date, conventional CFD methods are insufficient in far wake capturing of the rotor.

Lagrangian-based models can address the problem of non-physical wake diffusion, and they are more computationally efficient than CFD. In recent years, coupled Eulerian/Lagrangian simulation methods have shown promise in rotor wake simulations and received much attention.[17–20] However, simple Lagrangian models (e.g., prescribed wake models[21] and free wake models[22]) rely heavily on empirical parameters such as vortex core size and decay factor. Furthermore, they cannot provide detailed information of the wake structure. Due to the progress in wake modeling techniques, more advanced Lagrangian models have been developed. Those models are referred to as Vorticity Transport Models (VTMs).[23–25] They can explicitly conserve wake vorticity without any artificial dissipation and cancel the restriction of empirical parameters.

The main work of the present study is to couple a novel Lagrangian-based VTM model with an Eulerian-based CFD solver. The hybrid solver proposed in this paper combines the merits of CFD and the VTM. A CFD module is used to resolve the compressible blade near body aerodynamics and a VTM module is used to predict the complex wake convection. Details of the CFD/VTM hybrid solver are described in Section 2. Numerical simulations of rotorcraft in hovering and vertical descending flight are performed in Section 3. Results show good predictions of both the blade near body aerodynamics and the wake structure in hover. Induced inflow and time history of rotor thrust in descending flight are also investigated. Main conclusions are summarized in Section 4.

2. CFD/VTM model description

The computational zone is decomposed into two domains (Fig. 2): the blade body-fitted Eulerian domain, which covers a relatively small region near the blade and follows a C-O topology grid (Fig. 3), and the background Lagrangian domain, which employs a set of particles to model the wake vorticity. These two domains are solved by CFD and a VTM, respectively. Since the VTM only solves incompressible flow, the C-O grid of the Eulerian domain extends far enough (over two chord lengths) to ensure that outside the grid, air compressibility could be neglected.

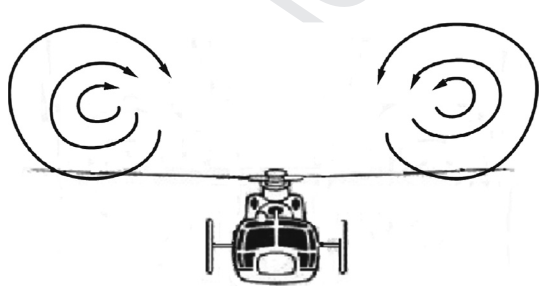

Fig. 1 Schematic of the air flow for a rotorcraft in the vortex ring state.

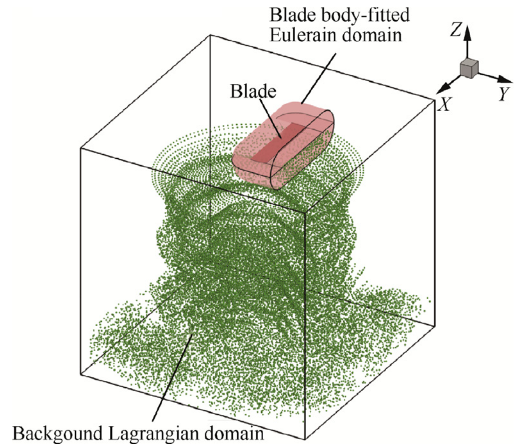

Fig. 2 Schematic of the computational zone.

2.1. CFD solution of blade body-fitted Eulerian domain

The simulation of the rotor blade near flowfield follows the Eulerian description, which relates to the grid-based solutions of compressible Reynold Averaged Navier-Stokes (RANS) equations. RANS equations are solved in terms of the conservation forms of mass, momentum, and energy, and can be written in tensor form as[26]

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial (\rho E + p) u_j}{\partial x_j} = \frac{\partial u_i \tau_{ij}}{\partial x_j} - \frac{\partial q_j}{\partial x_j} \tag{3}$$

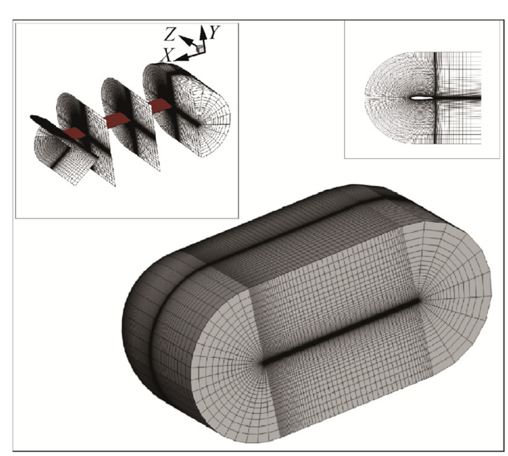

Fig. 3 Rotor blade near body C-O topology grid.

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