Rotor wake capture improvement based on high-order spatially accurate schemes and chimera grids

Li XU (徐 丽)¹, Pei-fen WENG (翁培奋)²

(1. School of Mathematics and Physics, Shanghai University of Electric Power, Shanghai 200090, P. R. China; 2. Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, P. R. China)

Abstract A high-order upwind scheme has been developed to capture the vortex wake of a helicopter rotor in the hover based on chimera grids. In this paper, an improved fifth-order weighted essentially non-oscillatory (WENO) scheme is adopted to interpolate the higher-order left and right states across a cell interface with the Roe Riemann solver updating inviscid flux, and is compared with the monotone upwind scheme for scalar conservation laws (MUSCL). For profitably capturing the wake and enforcing the period boundary condition, the computation regions of flows are discretized by using the structured chimera grids composed of a fine rotor grid and a cylindrical background grid. In the background grid, the mesh cells located in the wake regions are refined after the solution reaches the approximate convergence. Considering the interpolation characteristic of the WENO scheme, three layers of the hole boundary and the interpolation boundary are searched. The performance of the schemes is investigated in a transonic flow and a subsonic flow around the hovering rotor. The results reveal that the present approach has great capabilities in capturing the vortex wake with high resolution, and the WENO scheme has much lower numerical dissipation in comparison with the MUSCL scheme.

Key words hovering rotor, vortex wake, Navier-Stokes equation, chimera grid, weighted essentially non-oscillatory (WENO) scheme

1 Introduction

Since the flow field around the helicopter rotor is dominated by compressibility effects and complex vortex wake structures, the accurate numerical prediction of rotary-wing aerodynamics remains to be a challenging problem. Especially, in the hover, the strong tip vortex coils beneath the rotor and significantly alters the effective angle of attack of the rotor. The generated vortex wake through the induced velocity field by itself causes modifications of the aerodynamic loads on the blade, which has a significant influence on the helicopter performance, the structure vibration, the aeroelastic stability, and the aeroacoustic properties. Therefore, accurately capturing the vortex wake is very important in rotor calculations.
However, traditional low-order spatially accurate computational methodologies tend to dis- sipate the vortex wake due to the excessive numerical dissipation inbuilt in such numerical schemes, which leads to the tip vortex to be captured with much less intensity than the physical reality\[1–4\]. Thus, one of the central issues facing the future of the first principles by using the Navier-Stokes simulation for rotor wakes is their ability to capture the vorticity with the minimal numerical dissipation\[4–6\].

During the past decade, a relatively successful attempt to build a low numerical dissipation and high-order scheme was presented by Hariharan and Sankar\[7\] and Hariharan\[8\], who used the essentially non-oscillatory (ENO) scheme to capture three-dimensional (3D) rotary-wing vortex wakes. Besides the ENO schemes, various other high-order schemes, such as the symmetric total variation diminishing (STVD) scheme\[9\], and the monotone upwind scheme for scalar conservation laws (MUSCL)\[10\], have been tried for researching rotorcraft wakes with varying degrees of success.

The easiest way to reduce the dissipation errors is to increase the formal accuracy of the upwind scheme. Therefore, this paper focuses on the use of an improved fifth-order spatially accurate weighted ENO (WENO) scheme\[11\] for capturing the vortices while minimizing the numerical dissipation. The WENO scheme proposed by Liu et al.\[12\] and extended by Jiang and Shu (WENO-JS)\[13\] can obtain good convergence properties while keeping the robustness and uniformly high-order accuracy of the ENO schemes. Borges et al.\[11\] developed the WENO-JS scheme by the novel use of a linear combination of the low-order smoothness indicators already presented in the framework of the WENO-JS scheme, and provided a new WENO (WENO-Z) scheme with less dissipation and higher resolution than the classical WENO scheme. In an attempt to better capture the tip vortex and its trajectory, in the present work, the fifth-order WENO-Z scheme is reconstructed to interpolate the higher-order left and right states across a cell interface. The obtained results from the WENO scheme are compared with those of the commonly used third-order MUSCL for a two-bladed rotor in the hover.

Even with the use of high-order methods, millions of grid points are still entailed, especially in the wake regions. To enhance the grid resolution in the wake regions, the cylindrical background grid of the chimera grids is refined in the course of the computation. Besides, the complex property of the flow field around the hovering rotor makes the numerical simulation of the flow be still a very expensive problem for computational fluid dynamics (CFD) methods. Virtually, for the vortex capture, not only rotary-wing flow computations normally require finer meshes than fixed-wing flow computations, but also a large numerical integration time is required for the wake to develop several turns. To improve the efficiency, a lower-upper symmetric Gauss-Seidel (LU-SGS) implicit algorithm with a local time step is valuable in reducing the run times\[14–15\].

2 Numerical methods for wake prediction

2.1 Governing equations

The flow computation on a hovering rotor requires a rigid but rotating grid. In a blade-fixed rotating reference frame, the flows around the hovering rotor can be transformed to the steady state when the absolute velocities are considered. Then, the Navier-Stokes equations in an integral form can be expressed as

$$\frac{\partial}{\partial t} \iiint_V W \, dV + \iint_{\partial V} H \cdot ndS - \iint_{\partial V} H \cdot ndS + \iiint_V G \, dV = 0,$$

(1)

where

$$W = (\rho \quad \rho u \quad \rho v \quad \rho w \quad \rho E)^T,$$

$$G = (0 \quad \rho(\omega \times q)_x \quad \rho(\omega \times q)_y \quad \rho(\omega \times q)_z \quad 0)^T,$$