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Simulation of Vortex Convection in a Compressible Viscous Flow with Dynamic Mesh Adaptation

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Abstract. In this work, vortex convection is simulated using a dynamic mesh adaptation procedure. In each adaptation period, the mesh is refined in the regions where the phenomena evolve and is coarsened in the regions where the phenomena deviate since the last adaptation. A simple indicator of mesh adaptation that accounts for the solution progression is defined. The generation of dynamic adaptive meshes is based on multilevel refinement/coarsening. The efficiency and accuracy of the present procedure are validated by simulating vortex convection in a uniform flow. Two unsteady compressible turbulent flows involving blade-vortex interactions are investigated to demonstrate further the applicability of the procedure. Computed results agree well with the published experimental data or numerical results.

AMS subject classifications: 65M50, 76M99

Key words: Mesh adaptation, vortex-convection, blade-vortex interaction, unsteady flow, time-dependent problem, shock-vortex interaction.

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1 Introduction

Theoretically, a Navier-Stokes solver can capture vortex convection correctly. However, in the practical simulation of a flowfield including vortex convection, the predicted vortex structure may be dissipated quickly because of the inherent numerical dissipation and the insufficient mesh resolution in the region of vortex. Vortex convection appears inevitably in a rotor flowfield. This problem limited the full utilization of Navier-Stokes analysis in the rotary wing aerodynamics.

There are several approaches to address this issue in the simulation of vortex convection. Many researches focused on coupling Navier-Stokes solutions with a separate

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wake model [1–3]. Among them, the prescribed vortex method [1] (also called perturbation method) is frequently used in the aerodynamic design of a helicopter, the essence of which is to split each dependent variable into a prescribed part (vortex disturbance) and a remaining part. The nonlinearity can not be simulated correctly in this approach, so the perturbation method is not suitable to simulate strong blade-vortex or shock-vortex interactions. Using high-order schemes that have less numerical dissipation is also an attempt to simulate blade-vortex interactions [4,5]. But, compared to low-order schemes, the convergence of high-order schemes is poor for a transonic flow with shock waves present [5].

Mesh adaptation can be an effective approach to reduce the numerical dissipation and preserve the intensity of a convected vortex. Till now, a large number of papers about mesh adaptation for the time-independent problems have been published, while the number of papers addressing unsteady flows is relatively small. For unsteady flows, most of the existing methods for dynamic mesh adaptation adjust the mesh per n time-steps (one adaptation period) using the adaptation indicators based on the initial solution in the current period, and the adapted mesh always lags behind the computed unsteady solution. In order to reduce the phase shift in time between the adapted mesh and the computed solution, the mesh was adapted very frequently [6,7]. However, an important source of error due to solution transferring (by interpolation) from the old mesh to the new one is introduced in this case.

Zhou and Ai developed an approach of mesh adaptation for unsteady flows in [8]. In that approach, there exists no lag between mesh and solution and the adaptation frequency can be controlled to reduce the errors due to solution transferring. In this work, we modify the adaptation indicator and the method of adaptive-mesh generation and apply the approach to the simulation of vortex convection in a compressible turbulent flow around an airfoil.

The outline of this article is as follows. In Section 2, the governing equations and the basic numerical schemes are described in brief. In Section 3, the approach for dynamic mesh adaptation is given. In Section 4, results and discussions for numerical experiments are presented. Finally, in Section 5, this work is summarized and concluded.

2 Governing equations and numerical methods

In this work, a compressible turbulent flow is governed by the following two-dimensional Favre-averaged Navier-Stokes equations

$$\frac{\partial \mathbf{w}}{\partial t}+\frac{\partial \mathbf{f}_i}{\partial x_i}+\frac{\sqrt{\kappa}M_\infty}{Re_\infty}\frac{\partial \mathbf{g}_i}{\partial x_i}=0, \tag{2.1}$$

where Re_∞ and M_∞ are the Reynolds number and Mach number of free stream respectively, κ is the ratio of specific heats of a gas, and $\mathbf{w}$, $\mathbf{f}_i$ and $\mathbf{g}_i$ are the vectors of conserva-