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On the improved finite volume procedure for simulation of turbulent flows over real complex terrains

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ABSTRACT

This article presents a new and substantially improved finite volume procedure for simulation of incompressible flows on non-orthogonal grids. Cell-centered least-squares gradients are obtained in a robust and highly accurate way. A new discretization of the diffusive terms is employed, which is based on extension of the original cell-face gradient interpolation and is more suitable for complex grid distortions. A flexible flux-limited interpolation of dependent variables on distorted computational grids is introduced. An efficient preconditioner for Krylov method solution of linear systems is proposed, which substantially improves the solution of Poisson equation for pressure correction. The pressure-correction algorithm is adapted for efficient convergence on highly complex grids using a sequence of non-orthogonal corrector solutions and its effect on iteration convergence is analyzed. The non-orthogonalities treated by current procedure are more accustomed to numerical grids generated from a real complex terrain elevation data. The main focus is on the simulation of atmospheric micro-scale flows pertinent to wind energy application.

1. Introduction

Accurate simulation of wind flows over real terrains is a challenging task. To represent terrains with complex orography, highly non-orthogonal body-fitted meshes are produced. They in turn require substantially improved numerical procedures to provide accurate solutions.

Some authors have recently made attempts to circumvent that problem either by smoothing the mesh using dense grid-point distribution near surface irregularities and at the same time using elliptic grid generators to enforce orthogonality of grid lines near surface [1,2], or by diverting to the Immersed Boundary Method approach [3]. The overset grid method (see [4] for aerodynamic flows over smooth bodies), to the best of our knowledge, has not yet been applied to rough terrains. Dense patches can be used to increase resolution near irregular parts of topography while avoiding expensive global grid refinements. Locally adapted methods as in [5] that have been used with success for industrial internal flows may be a viable alternative as well, except that regular patches of Chimera grids enable the use of simple finite-difference formulations of higher order, while latter approach works only with unstructured finite-volume methodology.

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A significant amount of work in the field of the weather research and forecast and the mountain meteorology research is motivated by complex terrains [6–8]. Important question in simulating flows over complex terrain is the accurate approximation of the pressure gradients. Discretization error in pressure gradient term leads to spurious circulations over topography and leads to numerical instabilities when steep slopes are encountered. Based on this observation Zängl [9] proposed a pressure gradient approximation in terrain following coordinates, improving the earlier work by Mahrer [10], that increases the numerical stability of the simulation over steep terrain. With similar motivation we develop in our work an accurate pressure gradient approximation scheme for complex terrain simulation. We show that the conventional body-fitted finite-volume approaches are not immune to producing spurious pressure fields near grid distortions, in particular near sudden changes in topography, and how these are fixed by using the proposed approach.

Modern solvers for flows over complex terrains have recognized the flexibility of the finite volume method. Various general purpose CFD codes have been used with success for simulation of such flows, but were mostly focused on validation studies of turbulence models, e.g. [1,11,12]. Inherent difficulties of these general purpose CFD codes related to complex topographies, such as accurate interpolation of dependent variables, in the presence of grid distortions present at complex terrains, however, are not studied in detail. Some extensively used research codes were specifically targeted for flow over hilly terrain and have addressed these issues by, e.g. using blend of higher order (fourth-order centered and third order upwind) interpolation schemes for convective terms [13]. There authors discretized Navier–Stokes equations in general curvilinear coordinates using a block-structured approach which results in a specific data structure that enabled larger interpolation molecules. In [14,15] the authors recognize how limitations in codes for flow over complex terrains may be imposed within discretizations of differential operators in implementations relying on restrictive local mesh regularities, orthogonality, or shape uniformity of cells. They employed highly flexible edge-based data structure which benefits the accuracy of calculations on skewed meshes. They used median-dual finite volume meshes to alleviate the problems encountered with complex terrains and enabling alleviated spatial resolution.

The complexity of the micro-scale flows in the atmospheric environment is not limited to complex topography. There is often a need to introduce flow obstacles such as buildings for the studies of wind forces on structures and urban-physics questions like the pollutant dispersion, e.g. [16,17]. Smolarkiewicz et al. [16] is an important example with two-fold contribution: the exhibited numerical efficiency of the Immersed Boundary Method for atmospheric flows with complex obstacles not limited to cubic building-like objects, and the demonstration that the continuous transformations often used with terrain-following coordinates can be used with very steep, even vertical slopes.

This work presents a part of the development of an integral in-house computational code, which is able to simulate the laboratory scale and real-scale environmental flows with advanced numerical methods and turbulence models. In our previous work, we addressed modeling and simulations of some important aspects of the environmental flows, including the turbulent dispersion (passive scalars) in street canyons and some real-scale applications dealing with the time-dependent (diurnal cycles) simulations of flow, turbulence and dispersion over a complex terrain orography, e.g. [18–20,17,21]. In the present work we remain in the context of a second-order, cell-centered, body-fitted, finite-volume discretization paradigm. The coupled solution approach, e.g. [22,23], despite demonstrating better convergence has large memory requirements, therefore the segregated solution approach is used.

The paper focuses on: (i) improvements of cell-centered gradient calculation procedure, (ii) bounded high-order discretization of convective terms on irregular three-dimensional grids, (iii) analysis of the diffusion term discretization procedures anticipating highly distorted grids, (iv) improvements of pressure-correction algorithm, and finally (v) efficient preconditioning of linear systems. All these components are necessary for the accurate simulation of flows over complex terrain.

The original contribution is the new least-squares based cell-centered gradient reconstruction algorithm based on QR decomposition that minimizes required operations during variable gradient update. Next we give new generalized formulation of some well known diffusion term approximation approaches for skewed cell arrangements, used widely in CFD codes. This generalization, dependent on a smooth parameter enables formulation of new approximations, which will be demonstrated. A different family of diffusion term approximations which improve approximations in case of the *intersection point offset* (a notion defined in Section 3) is improved and two new diffusion term approximation approaches are formulated, owing to the previous insights from the methods for skewed meshes. New diffusion schemes give improved accuracy and convergence characteristics relative to schemes that only treat cell skewness. Finally, a widely used solver for linear systems originating from the discretization of conservation equations on structured grids – the SIP solver [24], is used as a preconditioner for the members of Krylov subspace family of solvers (CG and Bi-CGSTAB), with tests demonstrating superior results compared to common incomplete factorization preconditioners.

Discretization makes no assumptions of grid topology admitting unstructured meshes with arbitrarily shaped cells, making it applicable in general purpose CFD codes. We assumed that grid is structured only when applying mentioned preconditioner. The fact that the improvement present in this study may be implemented trough minor changes into general purpose CFD codes suggests that the advancements proposed here may significantly influence the way flows over real terrain are simulated in the future.

For the purpose of testing the proposed algorithm we have introduced the artificial grid distortions in well known benchmark cases. The grid distortion is introduced systematically, and is controlled by a parameter. These distorted meshes are designed to have a series of unfavorable features, all usually present in real-life flow-over-complex-terrain applications, such as cell skewness, grid-line discontinuity, and misalignment with flow direction. After presenting cases where artificial