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Extending Seventh-Order Dissipative Compact Scheme Satisfying Geometric Conservation Law to Large Eddy Simulation on Curvilinear Grids

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Abstract. Seventh-order hybrid cell-edge and cell-node dissipative compact scheme (HDCS-E8T7) is extended to a new implicit large eddy simulation named HILES on stretched and curvilinear meshes. Although the conception of HILES is similar to that of monotone integrated LES (MILES), i.e., truncation error of the discretization scheme itself is employed to model the effects of unresolved scales, HDCS-E8T7 is a new high-order finite difference scheme, which can eliminate the surface conservation law (SCL) errors and has inherent dissipation. The capability of HILES is tested by solving several benchmark cases. In the case of flow past a circular cylinder, the solutions of HILES fulfilling the SCL have good agreement with the corresponding experiment data, however, the flowfield is gradually contaminated when the SCL error is enlarged. With the help of fulling the SCL, ability of HILES for handling complex geometry has been enhanced. The numerical solutions of flow over delta wing demonstrate the potential of HILES in simulating turbulent flow on complex configuration.

AMS subject classifications: 76Fxx, 76Gxx

Key words: Implicit large eddy simulation, high-order hybrid cell-edge and cell-node dissipative compact scheme (HDCS), geometric conservation law (GCL), complex geometry.

1 Introduction

Large Eddy Simulation (LES) is a promising approach for engineering problems with lower cost than direct numerical simulation (DNS) and higher accuracy than Reynolds

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averaged NavierStokes (RANS) models. In large eddy simulation of turbulent flows, the small-scale structures are left unresolved and should be accounted by a subgrid-scale (S-GS) turbulence model. As well known, there is complex interaction between SGS model and truncation errors of numerical methods [1–4]. This complex interaction leads to that it is difficult to quantify and control discretization errors in LES methods. However, this interference can also be beneficial. Kawamura et al. [5] indicated that the truncation error of a linear upwind scheme in some cases may function as implicit SGS model, and this is the conception of monotone integrated LES (MILES), which is proposed by Boris et al. [6]. Instead of an explicit computation of the SGS stress, the truncation error of the discretization scheme itself is employed to model the effects of unresolved scales. For MILES, the resolved scales are connected with the unresolved scales properly [7, 8]. In 2007, a theoretical connection between explicit LES models and the implicit modeling of MILES was derived by Margolin et al. [8] using modified equation analysis (MEA). In particular, they have developed a structural explanation of why some numerical methods work well as implicit subgrid models whereas others are inadequate. Following the idea of MILES, ILES is developed by Visbal et al. [9]. Nowadays, MILES and ILES are widely accepted and applied [10–12]. Although the conception of ILES and MILES is similar, there are two main differences between MILES and ILES. Firstly, the descretization schemes of ILES are the fourth-order and sixth-order central compact scheme proposed by Lele [13]. Secondly, numerical dissipation of ILES is introduced by high-order filtering, not by the schemes themselves.

Applications of LES to increasingly complex configurations of engineering interest is motivated by the need to provide more realistic characterizations of complex flows. On the other hand, the necessity of high-order scheme for LES of turbulent flows has been recognized by many researchers [1–3]. Then high-order schemes with ability handling complex geometry are attractive methods for the LES. Finite difference schemes are widely used for their relative simpleness and flexibility. However, applications of high-order finite difference schemes are still challenged by complex meshes. When the numerical simulation is performed by these schemes on complex mesh, there may be some challenges, such as robustness and grid-quality sensitivity [14, 15]. Fortunately, this deficiency can be largely removed by the researches of the Geometric Conservation Law (GCL) [16–20]. The GCL contains surface conservation law (SCL) and volume conservation law (VCL). The VCL has been widely studied for time-dependent grids, while the SCL is merely discussed for finite difference schemes. If the SCL has not been satisfied, numerical instabilities and even computing collapse may appear on complex curvilinear grids during numerical simulation. In order to fulfill the SCL for high-order finite difference schemes, a conservative metric method (CMM) is derived by Deng et al. [16]. The CMM is achieved by computing grid metric derivatives through a conservative form with the same scheme applied to fluxes. According to the principle of satisfying the CMM, a seventh-order hybrid cell-edge and cell-node dissipative compact scheme (HDCS-E8T7) has been proposed for complex geometry [21]. The HDCS-E8T7 has inherent dissipation to dissipate unresolvable wavenumbers, therefore the filtering is not needed. The