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A Higher Order Interpolation Scheme of Finite Volume Method for Compressible Flow on Curvilinear Grids

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Abstract. A higher order interpolation scheme based on a multi-stage BVD (Boundary Variation Diminishing) algorithm is developed for the FV (Finite Volume) method on non-uniform, curvilinear structured grids to simulate the compressible turbulent flows. The designed scheme utilizes two types of candidate interpolants including a higher order linear-weight polynomial as high as eleven and a THINC (Tangent of Hyperbola for INterface Capturing) function with the adaptive steepness. We investigate not only the accuracy but also the efficiency of the methodology through the cost efficiency analysis in comparison with well-designed mapped WENO (Weighted Essentially Non-Oscillatory) scheme. Numerical experimentation including benchmark broadband turbulence problem as well as real-life wall-bounded turbulent flows has been carried out to demonstrate the potential implementation of the present higher order interpolation scheme especially in the ILES (Implicit Large Eddy Simulation) of compressible turbulence.

AMS subject classifications: 35L65, 68U01, 76N06

Key words: Higher order interpolation, BVD scheme, finite volume method, ILES, Compressible turbulence simulation.

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1 Introduction

Numerical simulation of compressible turbulence flow requires that numerical methods can resolve the turbulence at various length scales while simultaneously capturing sharp discontinuity without introducing spurious oscillations. The design of such numerical scheme has been an active research area and drawing more and more attention due to its importance to the research of shock-turbulence simulation. Nevertheless, the two properties in terms of capturing discontinuities with monotone profiles and achieving low dissipation to resolve small-scale structure are often conflicting. There has been an abundance of work to deal with this conflict and among the broad range of algorithms in the literature, shock-capturing methods may be the most popular techniques [1,2].

However, most traditional shock-capturing schemes that are mature and widely applied in computational fluid dynamics community are found to be too dissipative to adequately resolve small flow structures. Such popular numerical methods include high-resolution TVD (Total Variation Diminishing) [3], ENO (Essentially Non-oscillatory) [4,5] and WENO (Weighted Essentially Non-oscillatory) [6, 7] et al. In order to reduce the numerical dissipation within traditional shock-capturing schemes, the so-called hybrid schemes [8–13] are developed. The basic idea is to combine the advantages of different schemes and therefore to avoid the disadvantages inherent in each method. In most of early researches, schemes with either spectral-like resolution [8–10] or with a high order of accuracy and high efficiency in smooth regions [11–13] were employed coupling with the ENO/WENO schemes to handle discontinuities. The performance of such hybrid schemes usually relies on shock sensors for properly switching between different types of schemes. Different from most priori shock sensors, the idea of posteriori detection approach known as MOOD (Multi-dimensional Optimal Order Detection) has been introduced in [14]. And based on the concept of MOOD, hybrid schemes along with implicit time discretization are designed and extended to compressible turbulence simulation [15,16]. Apart from various kinds of hybrid schemes, there has also been continuous effort in improving classic shock- capturing schemes like WENO [17–19] and artificial viscosity/diffusivity method [20,21] in order to make them to be more suitable for compressible turbulence simulation. The authors of [22] have systematically investigated a comprehensive range of high order shock-capturing methods, which demonstrate the hybrid schemes to be suitable methods for high-fidelity compressible turbulence simulations.

While shock-capturing schemes of various degrees of sophistication exist in the publication, for DNS (Direct Numerical Simulation) or LES (Large Eddy Simulation) of the turbulence with strong shocks, the most popular choices may still be the FD (Finite Difference) method equipped with high order shock capturing schemes, particularly in many academic flow solvers. Since the FV (Finite Volume) discretizations are more popular choices among most commercial flow solvers, it is desirable to develop efficient and accurate FV schemes for compressible turbulence simulation. Specifically in this work, we are interested in developing FV schemes that are suitable for ILES (Implicit Large Eddy