

Detonation Simulations with a Fifth-Order TENO Scheme

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Received 10 January 2018; Accepted (in revised version) 27 June 2018

Abstract. In [Fu et al., JCP 305(2016): 333-359], a family of high-order targeted ENO (TENO) schemes is proposed. The weighting strategy of TENO either applies a candidate stencil with its optimal weight, or removes its contribution completely when it is crossed by discontinuities. This ENO-like stencil selection procedure significantly diminishes the numerical dissipation induced by the nonlinear adaptations of classical WENO schemes. In this paper, the fifth-order TENO scheme is extended to simulate reactive flows in combination with an uncoupled method [1,2], which splits the reaction source term of detailed chemistry from the flow equations. A set of benchmark cases including the two-dimensional self-sustained detonation is simulated to validate and compare the performance of the fifth-order WENO and TENO schemes. Numerical experiments demonstrate that TENO scheme is robust for simulating chemical reacting flows with using the uncoupled method. In particular, TENO scheme shows better performance in capturing both the shockwaves and the small-scale flow structures, e.g. shear layers and vortices.

AMS subject classifications: 35L65, 65M06, 76J20, 76V05

Key words: WENO, TENO, chemical reacting flow, uncoupled method, shockwave; denotation.

1 Introduction

Detonations are supersonic combustion, where the combustion fronts interact with strong leading shockwaves. During a detonation, the combustible or reactive material, e.g. gas

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fuel, is ignited by the high temperature and pressure. Moreover, the exothermic process of the chemical reactions releases massive energy which further increases the post-shock temperature and pressure, and eventually drives the shockwaves moving to unreacted regions. While the complicated mechanism of self-sustained detonation is interesting with regard to the point of view of fluid dynamics, detonation is extensively investigated for improving the performance of air-breathing combustion engine [3]. Consequently, the development of numerical methods for detonation simulations is an attractive topic in the past decades.

For multi-dimensional denotations, it is proved that numerical simulations play a significant role to elucidate the flow instabilities and the complex flow structures [4, 5]. The solution qualities may be affected by several important numerical issues, e.g. the chemical reaction model [6], the temporal/spatial discretization [7, 8] and the solution of chemical source term [9, 10]. Moreover, several strategies [11, 12] have been proposed to solve the coupling systems of reactive flow equations. An uncoupled method [1, 2] following the idea of Strang splitting [13] can be applied to split the solution of detailed chemistry from the solution of the spatial terms of flow governing equations, and more improvements and/or applications of this method were introduced in several articles [8, 14–16]. In this way, the spatial discretization methods and the chemical reaction solvers can be investigated and developed separately.

Nevertheless, for detonation simulations, developing a high-resolution method to solve the governing equations accurately is still a challenge. The popular second-order finite-volume (FV) method with multi-resolution meshes [17, 18] has shown great potentials. However, since the flow structures in detonations are rather complicated, high-order (third-order or higher) schemes can be useful for resolving delicate flow structures. For example, sufficient resolution is necessary to capture detonation structures [5], e.g. triple point(s), and hydrodynamic instabilities [19–21] may play important roles during the onset and evolution of detonations [22–24] or combustion [25, 26], leading to high demand for numerical accuracy [27]. A more specific situation is that in the simulation of high activation energy gas, high resolution is required to correctly resolve the mixing rate in the flow field, which affects the strength of detonation wave or combustion [28].

Weighted essentially non-oscillatory (WENO) schemes [29], the weights of which are designed to recover the ENO property [30] for capturing discontinuities and to restore the background linear schemes in smooth regions, is extended to solve reactive flows because of its high-resolution property.

The fifth-order WENO-JS scheme [31] has been employed to study the cellular detonation in a straight tube [32], and the self-sustained cellular detonation is well captured. However, the classical WENO-JS scheme fails to recover the formal fifth-order accuracy near critical points, where low-order derivatives vanish. Henrick et al. [33] proposed the WENO-M scheme which maps the WENO-JS weights such that the sufficient criteria for restoring the fifth-order accuracy is suggested to be satisfied. The WENO-M scheme has been applied to simulate detonation phenomena in combination with the uncoupled method [2] within the finite-difference (FD) framework [34]. Borges et al. [35]