Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2018-0145

Vol. **26**, No. 2, pp. 311-345
August 2019

A Targeted ENO Scheme as Implicit Model for Turbulent and Genuine Subgrid Scales

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Received 28 May 2018; Accepted (in revised version) 5 July 2018

Abstract. Even for state-of-the-art implicit LES (ILES) methods, where the truncation error acts as physically-motivated subgrid-scale model, simultaneously resolving turbulent and genuine non-turbulent subgrid scales is an open challenge. For the purpose of dealing with non-turbulent subgrid scales, such as shocks, extra sensors, which often are case-dependent, are generally employed. The problem originates in the lack of scale-separation between low-wavenumber resolved-scale regions, high-wavenumber resolved or non-resolved fluctuations, and discontinuities. The targeted ENO (TENO) approach allows for separately designing the dispersive and dissipative truncation error components. Thus it provides a suitable environment to develop an implicit LES model. In this paper, we extend previous work and propose a variant of TENO family scheme [Fu et al., JCP 305 (2016): 333-359], which can separate resolved and nonresolved scales effectively. The novel idea is to propose a nonlinear dissipation-control strategy by adapting the cut-off parameter C_T dynamically while measuring the nonsmoothness based on the first-order undivided difference. Low-wavenumber smooth scales are handled by an optimized linear scheme while high-wavenumber components, that involve nonresolved fluctuations and discontinuities, are subjected to adaptive nonlinear dissipation. A set of benchmark simulations with a wide range of length-scales and with discontinuities has been conducted without specific parameter adaptation. Numerical experiments demonstrate that the proposed TENO8-A scheme exhibits robust shock-capturing and high wave-resolution properties, and that it is suitable for simulating flow fields that contain isotropic turbulence and shocks. It is a promising alternative to other viable approaches.

AMS subject classifications: 35L65, 65M06, 76J20, 76N15, 76F05

Key words: TENO scheme, high-order scheme, gas dynamics, turbulence, large-eddy simulation.

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1 Introduction

For most practically relevant high-Reynolds-number and supersonic flows, the resolution of all spatial and temporal scales is beyond reach of Direct Numerical Simulation (DNS). Large-eddy Simulation (LES) is an attractive alternative as it reproduces the large-scale flow structures while the effect of non-resolved scales is modeled. A subgrid-scale (SGS) model which represents the nonlinear interaction between the resolved and the non-resolved scales is essential. Explicit LES methods employ physically-motivated SGS models by modifying the underlying conservation laws [1,2]. However, the performance of explicit models strongly depends on the employment of low-dissipation high-order scheme as the numerical truncation error and the SGS model may interact [2]. With the implicit LES method, the discretization truncation error of the convective terms functions as a subgrid-scale model. Early approaches for ILES involved the flux-corrected transport (FCT) method [3], the piecewise parabolic (PPM) method [4] and the weighted essentially non-oscillatory (WENO) method [5], with promising results [6,7].

An issue relevant to such approaches is that the truncation-error structure essentially is given and may not always be consistent with turbulence physics. A different approach has been proposed by Adams et al. [8], where an implicit SGS model is constructed by reinterpreting the cell averaging and reconstruction steps of a finite-volume discretization. The truncation error can be designed to be consistent with established scale-energy-transfer models. This is the basis of the adaptive local deconvolution method (ALDM) [9]. In non-turbulent flow regions, ALDM recovers a 2nd-order central scheme. This method has been applied to a large range of low-speed turbulent flows. The ALDM model has been extended for compressible flows involving also a sensor to distinguish turbulent subgrid scales from discontinuities [10]. Shock-sensors, however, do not capture material discontinuities or contact waves [11]. Other ILES schemes are e.g. the localized artificial diffusivity (LAD) scheme, which has been first proposed by Cook [12] and extended by Kawai and Lele [13] with a high-order compact difference scheme. As assessed by Kawai et al. [14], the performance of LAD schemes strongly depends on the switch functions (shock sensor). Best results are found for the LAD-D2-0 scheme, which employs the Ducros sensor [11]. Yee and Sjogreen [15] propose a flexible framework for dissipation control with a variety of flow sensors. The scheme employs wavelet-based flow sensor and shock-sensor [15], and can be used with or without explicit subgrid scale model [16, 17]. Generally speaking, low-dissipation schemes for turbulence simulation exhibit spurious fluctuations near strong discontinuities, and results are not comparable to that from shock-capturing schemes [14, 18]. The problem of a unified treatment of genuine (shocks, interfaces) and apparent (fluctuations, turbulence) subgrid scales is yet unsolved.

Since their invention, WENO schemes [5] have experienced various developments and applications [19–21]. Numerical experiments show that classical WENO schemes are too dissipative for direct and large-eddy simulations of turbulent flows [18,22]. Hu and Adams [23] have proposed an ILES scheme (WENO-CU6-M) by re-visiting the weight-