

## A Novel High-Resolution TENO Scheme with Adaptive Artificial Anti-Diffusion

Velmani Murugesan<sup>1</sup> and Manoj T. Nair<sup>1,\*</sup>

<sup>1</sup> *Department of Aerospace Engineering, Indian Institute of Space Science and Technology, Thiruvananthapuram, 695 547, Kerala, India.*

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**Abstract.** Low-dissipation higher-order approaches are crucial for flows characterized by shocks and turbulence. The broad applicability of conventional WENO/TENO systems for accurately capturing shocks makes them a preferred option for simulating complex flow phenomena. Nonetheless, the inherent numerical diffusion in these techniques poses a significant challenge in simulating multiscale turbulent flow. This study mitigates the inherent numerical damping by using locally adaptive higher-order artificial anti-diffusion. A switching function quantifies the extent of anti-dissipation in the smooth zone and assesses the local variation of flow field variables. To assure stability, the anti-diffusion coefficient is meticulously assessed using two fixed free parameters. Next strategy utilizes a fourth-order central difference scheme in the highly smooth region, incorporating an additional coefficient modified in a binary fashion. The adaptive regulating parameter  $C_T$  in the fifth-order TENO scheme is integrated with the anti-diffusive function. It is recognized that the new scheme exhibits less numerical diffusion than the original TENO scheme. This is also reflected in the numerical experiments, encompassing a series of benchmark test scenarios featuring shock and fine-scale structures. It is shown that the proposed scheme could resolve the turbulent scales with much higher resolution and capture the shock sharply. It is worth noting that these strategies can easily be implemented in the other variations of the TENO scheme.

**AMS subject classifications:** 35L65, 65M08, 76F05, 76L05, 76J20, 76N15

**Key words:** ENO-like stencil selection, adaptive artificial anti-diffusion, WENO, TENO, low-dissipation schemes, fourth-order central difference.

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\*Corresponding author. *Email addresses:* velmanim.21@res.iist.ac.in (V. Murugesan), manojtnair@iist.ac.in (M. T. Nair)

## 1 Introduction

The numerical simulation of discontinuities (e.g., shock waves), multiscale structures (e.g., turbulence) and their interactions poses a significant challenge in Computational Fluid Dynamics (CFD). Numerical models must have adequate dissipation to effectively capture the shock and contact waves to prevent Gibbs oscillations induced by dispersion. Conversely, resolving fine scales in a turbulent field necessitates minimal numerical dissipation. This demand disparity makes it difficult to design numerical schemes until shock-capturing schemes were developed. Initial shock capturing approaches, such as Godunov's scheme [1] and Total Variation Diminishing (TVD) schemes [2–5] can capture discontinuities in complex flow problems. Although these methods have been used in compressible flow simulation, they would smear the shock waves due to the high inherent numerical diffusion. Higher-order techniques, such as Essentially Non-Oscillatory (ENO) [6,7] and Weighted Essentially Non-Oscillatory (WENO) [8,9] address this issue. The ENO scheme reconstructs the flux at the cell interface using the smoothest stencil.

In contrast, the WENO method estimates the interface flux using a linear combination of all substencils based on their weighted contributions. The WENO approach ensures the highest accuracy in smooth areas, whereas at discontinuities, the ENO characteristics are obtained. Balsara and Shu [10] extend this scheme to a higher order. Nonetheless, the smooth zone has a strong intrinsic numerical diffusion, which damps the vortical scales. The WENO scheme suffers from accuracy deterioration at the critical point where the first derivative approaches zero, but the third derivative remains non-zero [11, 12]. The WENO-M [13], WENO-Z [14], and WENO-CU6 [15] schemes were developed to improve the WENO schemes. These approaches have the potential to significantly reduce numerical dissipation while recovering formal order accuracy at local extrema. Ha et al. [16] introduced the WENO-NS technique, which evaluates the smoothness indicator using the generalized undivided difference operator, resulting in improved order of accuracy. The WENO-P scheme addresses an issue with the WENO-NS system's unbalanced stencil contribution [17]. Xu and Shu [18] attempted to reduce the numerical dissipation of WENO schemes using the anti-diffusive correction previously applied to first-order systems.

Despite the numerical damping, the aforementioned WENO schemes have superior shock-capturing capabilities. The reason for this severe damping is that the schemes fail to converge to optimal weights in smooth regions. Fu et al. [19–21] presented the family of Targeted Essentially Non-Oscillatory (TENOs) schemes of different orders to address this issue. The primary characteristics of the TENO strategy are the scale separation [22] and the ENO-like stencil selection, which aligns the nonlinear weights with the linear ones in highly smooth regions. This method is also equipped with a regulating parameter, which manipulates the spectral properties of the scheme and can either be kept constant or modified based on local criteria. The latter approach is successfully executed in the TENO-A scheme, wherein the parameter is adjusted according to the local smoothness [23]. Wibisono et al. [24] used a Hermite polynomial approximation in the TENO