Assessment of Local Artificial Diffusivity and Gradient-Based Reconstruction Methods for High-Speed Flows

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ABSTRACT High-speed flow simulations require numerical methods capable of accurately capturing sharp discontinuities due to shocks while resolving turbulence scales. However, shock-capturing schemes often introduce artificial numerical dissipation to capture shock waves and maintain scheme stability. In the context of Large Eddy Simulation (LES), several schemes have been proposed in the literature to meet such conflicting requirements. These include WENO, hybrid WENO-central difference, artificial diffusivity, adaptive characteristic-based filter, and shock fitting [1]. Recently, Chamarthi [2] proposed a high-accuracy gradient-based reconstruction approach for simulating high-speed flows. The proposed algorithm efficiently uses the computed gradient between the inviscid and viscous schemes. The inviscid scheme is fourth-order and second-order accurate for non-linear problems. The viscous schemes are fourth-order accurate and are designed with a high-frequency damping property. The methodology utilises a monotonicity-preserving (MP) scheme for capturing shock and material discontinuities. Further, the fluxes are estimated using the HLLC approximate Riemann solver. Chandravamsi et al. [3] extended the gradient-based reconstruction approach of Chamarthi [2] for generalized curvilinear domains.

In the current study, the numerical approach of Chandravamsi et al. [3] has been incorporated into the in-house solver COMPSQUARE [4]. The unsteady three-dimensional compressible Navier Stokes equations are solved in generalized coordinates. The present solver utilizes spectral-like resolution, high-order central difference schemes (explicit/compact) with a low-pass implicit filter to suppress the dispersion associated with high frequencies. The efficacy of the schemes with the enhanced in-house solver is validated across a variety of test cases, including the 2D Riemann problem, 2D shock entropy and a shock-vortex interaction. The computational domain, boundary and initial conditions for the validated test cases are available in the literature [2, 5]. Figure 1 (a) shows the density contours of the 2D Riemann problem at $t_f = 0.8$. The simulation is carried out on a uniform grid of size 400×400. The formation of small structures along the slip line due to Kelvin-Helmholtz instability is evident. Figure 1 (b) shows the density plot for the 2D shock-entropy wave test along $y = 0$ compared with the reference and TENO5 data [2]. The simulation is carried out on a uniform mesh size of 400×80. In comparison with the TENO5 schemes, the current MIG4 schemes can capture density amplitudes with less numerical dissipation. Figure 1 (c) shows the contours of the density gradient for shock-vortex interaction at $t_f = 0.75$. The simulation is performed on a uniform mesh size of 1024×512. Figure 1 (d) shows the associated acoustic noise with the shock-vortex interaction. The circumferential distribution of the pressure field for (M_v, Ms)=(1.7, 1.1) at the three radii is plotted and compared with the reference data [5]. The vortex and the shock Mach number is denoted as M_v and M_s, while the distance to the vortex core is r. The associated acoustic waves precursor ($r = 0.85$), the second sound ($r = 0.48$), and the third sound ($r = 0.22$) are captured well with the present schemes. A digital filter approach [6] will be further incorporated into the in-house solver to yield a realistic, unsteady, turbulent boundary layer. This enhanced solver will be subsequently used to simulate the shock wave boundary layer interactions (SWBLI) across a compression corner and will be presented in the full-length manuscript.

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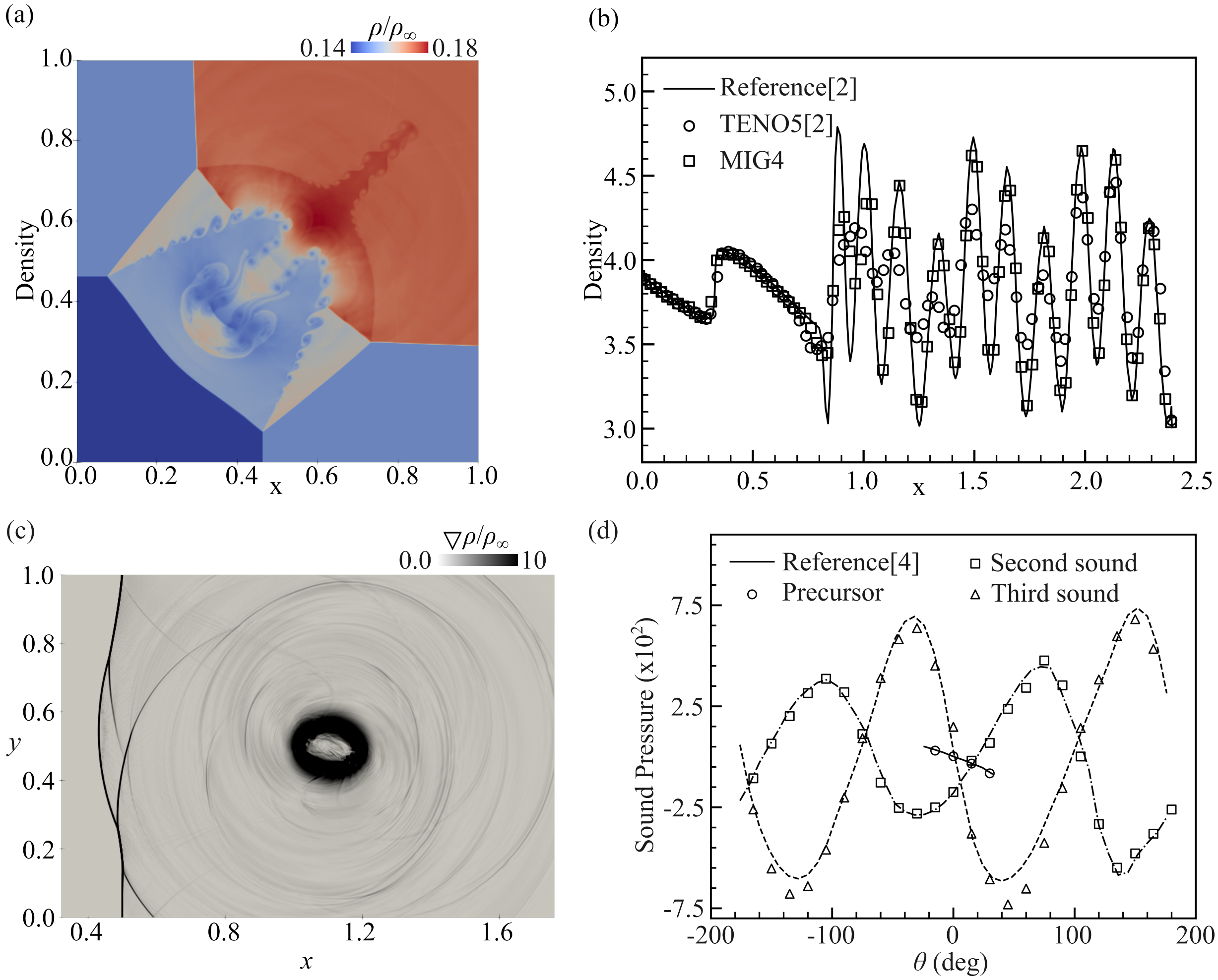

Figure 1: (a) Density contours of the Riemann problem at $t_f = 0.8$, (b) Density plot for 2D shock-entropy wave test compared with the reference and TENO5 data, (c) Contours of density gradient for shock-vortex interaction case at $t_f = 0.75$ and (d) Overpressure for three acoustic waves compared with the reference data for the shock-vortex case (solid, dashed, and dot-dashed lines are the reference data).

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