CHARLES: high-fidelity compressible flow solver

Leveraging advancements in high-performance computing, Large eddy simulation (LES) is emerging as an accurate yet cost-effective computational tool for the prediction of high-speed turbulent flows and their acoustic fields. **CHARLES** is Cascade’s high-fidelity unstructured compressible flow solver for LES, ideally suited for aeroacoustic applications involving high-speed flows and complex geometries. **CHARLES** solves the spatially-filtered compressible Navier-Stokes equations on unstructured grids using a novel finite-volume method where the flux is computed at each control volume face using a blend of a non-dissipative central flux and a dissipative upwind flux. To minimize numerical dissipation and dispersion, the value of the blending parameter is computed locally based on an analysis of the discrete operators such that it is essentially zero in regions where the grid quality is good and the scheme based on the central flux is discretely stable and non-dissipative. In regions of less-than-perfect grid quality, the blending parameter is automatically increased to prevent the pure central scheme from introducing numerical instabilities that would contaminate or destabilize the simulation. Because the local blending is based strictly on an analysis of the discrete operators (and not the solution), the operators can be pre-computed and stored as a pre-processing step at the start of the solution.

Because the underlying numerical method has minimal numerical dissipation, it is critical to employ a sub-grid model to account for the physical effects of the unresolved turbulence on the resolved flow. Several sub-grid scale models are available, including the Dynamic Smagorinsky and Vreman models.

Shocks, like sub-grid scale turbulence, are also sub-grid phenomena and thus require modeling to account for their effect on the resolved flow. However, unlike sub-grid scale turbulence, they are localized in the flow and a surgical introduction of modeling is potentially more appropriate. **CHARLES** uses a hybrid central-ENO scheme to capture shocks, along with the HLLC approximate Riemann solver. The hybrid switch based on the relative smoothness in reconstructed pressure and density is used to activate the 2nd-order ENO shock capturing scheme. This switch ensures that shock-capturing dissipation is only applied local to discontinuous regions, and the bulk of the simulation is based on the low-dissipation and dispersion scheme to produce accurate turbulent transport and mixing.

**CHARLES** has been used to investigate a wide range of high-speed unsteady flows on complicated adapted grids in both simple and complex geometrical configurations. The space-time databases computed by **CHARLES** form the inputs for other post-processing tools in Cascade’s infrastructure, include the far-field noise solver FWH.

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*Top left:* Instantaneous temperature field for a hot supersonic jet issued from a rectangular nozzle with chevrons. In collaboration with J. W. Nichols and S. K. Lele, Stanford University. Nozzle geometry courtesy of James Bridges, NASA Glenn research center. The mesh contains approximately 90 M cells and the simulation was performed on 60000 processors (Computational resources provided by Argonne National Labs).

*Top right (upper):* Instantaneous temperature and pressure field for a supersonic jet impinging on a flat plate. Top right (lower): Instantaneous temperature and pressure field for a heated over-expanded supersonic round jet. (Computational resources provided by ERDC and AFRL supercomputing centers).