C1.5 Radial expansion wave

2nd International Workshop on High-Order CFD Methods

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May 27, 2013

Diablo Flow solver

- Solves the compressible three-dimensional **Euler/Navier-Stokes/RANS** equations on structured multiblock grids with C^0 continuity at block interfaces
  - Spalart-Allmaras 1-equation turbulence model (Currently second-order)
- Spatial discretization is obtained with high-order **Summation-by-Parts (SBP)** finite-difference operators
  - Second derivatives in the viscous fluxes can be computed with either the application of the first derivative twice or a compact-width-stencil operator
- Block interface coupling and boundary conditions are weakly imposed with **Simultaneous-Approximation-Terms (SATs)**
- The nonlinear system is solved using an **Inexact Newton-Krylov** algorithm with a **Pseudo-Transient Continuation** startup phase
- The linear system is solved with **FGMRES** and a **Parallel Approximate-Schur Preconditioner**

Hicken, J. and Zingg, D.W., "A Parallel Newton-Krylov Solver for the Euler Equations Discretized Using Simultaneous Approximation Terms", *AIAA J.*, Vol. 46, No. 11, 2008, pp. 1695-1704

Osusky, M., Hicken, J. and Zingg, D.W., "A parallel Newton-Krylov-Schur flow solver for the Navier-Stokes equations using the SBP-SAT approach", *48th AIAA Aerospace Sciences Meeting*, 2010-116, Jan, 2010, Orlando, FL.

Del Rey Fernández, D.C. and Zingg, D.W., "High-Order Compact-Stencil Summation-By-Parts Operators for the Second Derivative with Variable Coefficients", *ICCFD7*, ICCFD7-2803, 2012

Diablo Flow solver

- General implementation for implicit and explicit **Multistep Runge-Kutta (MRK)** methods which specifically includes:
  - Linear multistep methods (Euler, BDF, Trapezoidal, . . .)
  - Runge-Kutta methods (Explicit RK, SDIRK, ESDIRK, . . .)
- Newton's method is accelerated for implicit time-integration methods using:
  - **Lagrange polynomial extrapolation** from step/stage solution values
  - **Delayed preconditioner updates** for individual stages or steps
  - **Relative tolerance termination of the nonlinear subiterations**
- The quadrature used to obtain integrated quantities is the high-order SBP norm consistent with the discretization
  - Superconergence of functionals if the discretization is dual-consistent and the solution is sufficiently smooth

Osusky, M., Boom, P.D., Del Rey Fernández, D.C. and Zingg, D.W., "An Efficient Newton-Krylov-Schur Parallel Solution Algorithm for the Steady and Unsteady Navier-Stokes Equations", *ICCFD7*, ICCFD7-1801, 2012

Hicken, J. and Zingg, D.W., "Summation-by-Parts Operators and High-Order Quadrature", *J. Comp. and App. Math.*, 237(2013), pp.111-125

Hicken, J. and Zingg, D.W., "Superconvergent Functional Estimates from Summation-by-Parts Finite-Difference Discretizations", *SIAM J. on Sci. Comp.*, Vol. 33, No. 2, 2011, pp. 893-922

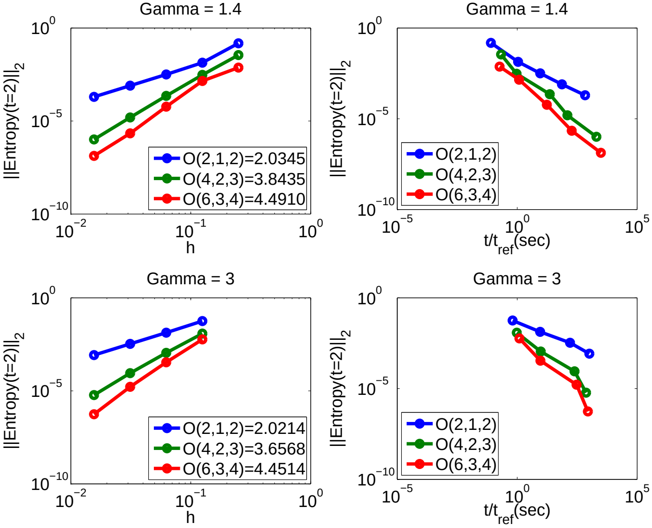
Simulation parameters

- Ratio of specific heats: $\gamma = 1.4$ and $\gamma = 3$
- Time Integration: explicit RK4 with a constant CFL of ~ 0.15
- Grids: Cartesian
- Multiblock simulations have constant block sizes of $33^{2(3)}$
- 2D results, both single and multiblock, were generated on a single processor
- 3D results were generated with a one-to-one block to processor ratio
- TauBench reference time is 9.5968 sec

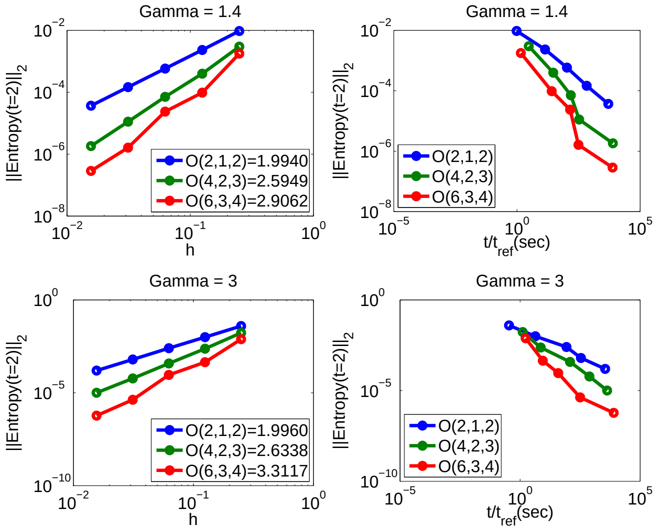
Computations were performed on the Guillimin supercomputer at McGill University, under the auspices of Calcul Qubec and Compute Canada. The operations of Guillimin and Colosse are funded by the Canada Foundation for Innovation (CFI), the National Science and Engineering Research Council (NSERC), NanoQubec, and the Fonds Qubcois de Recherche sur la Nature et les Technologies (FQRNT).

Results

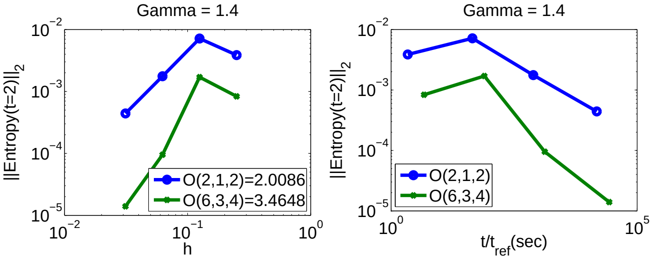
2D Single-Block



2D Multiblock



3D Multiblock



Summary

- 2D single-block cases achieve design order and, for some cases, superconvergence
  - Small variation in the solution at the farfield
  - Supersonic outflow at boundaries
- 2D and 3D multiblock cases achieve more characteristic convergence rates
  - The number of blocks is increased by a factor of 4 on each grid level in 2D, and a factor of 8 in 3D
- At the grid levels studied, higher-order methods are always more efficient, independent of the actual rate of convergence

Questions?

Other cases submitted by our group:

C1.1 Internal inviscid flow over a smooth bump
Del Rey Fernández, Boom, Zingg, Hicken

C1.2 Transonic Ringleb flow
Del Rey Fernández, Boom, Zingg, Hicken

C3.3 Transitional flow over a SD7003 wing
Boom, Del Rey Fernández, Zingg, Hicken

C3.5 Direct Numerical Simulation of the Taylor-Green Vortex at Re = 1600
Boom, Del Rey Fernández, Zingg, Hicken

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