

C1.4 Laminar Boundary Layer on a Flat Plate

1. Code description

XFlow is a high-order discontinuous Galerkin (DG) finite element solver written in ANSI C, intended to be run on Linux-type platforms. Relevant supported equation sets include compressible Euler, Navier-Stokes, and RANS with the Spalart-Allmaras model. High-order is achieved compactly within elements using various high-order bases on triangles, tetrahedra, quadrilaterals, and hexahedra. Parallel runs are supported using domain partitioning and MPI communication. Visual post-processing is performed with an in-house plotter. Output-based adaptivity is available using discrete adjoints.

2. Case summary

The default implicit Newton solver was used for all runs in this case. The residual was converged to an absolute L_1 norm below 10^{-10} using a conservative state vector of $\mathcal{O}(1)$ freestream density, velocity, and pressure, and gas constant $R = 0.4$. Runs were performed on the *nyx* supercomputing cluster at the University of Michigan. The number of cores ranged from 4 on the coarsest meshes to 96 on the finest meshes. On one core of the *nyx* machine, one TauBench unit is equivalent to 16.5 seconds of compute time.

3. Meshes

A series of uniformly refined triangular meshes were used for the calculations. For the truth value, a hanging-node adaptive refinement was run with a mesh consisting of 300 quadrilateral elements each with 49 degrees of freedom ($p = 6$). At each adaptation step 2% of the elements were refined. The refinement was run until the estimated error in the drag calculation was below 10^{-10} . The final mesh had 523 elements corresponding to 25627 degrees of freedom ($p = 6$).

4. Results

The figures and tables below present the results requested for the flat plate case at the specified Mach and Reynolds numbers.

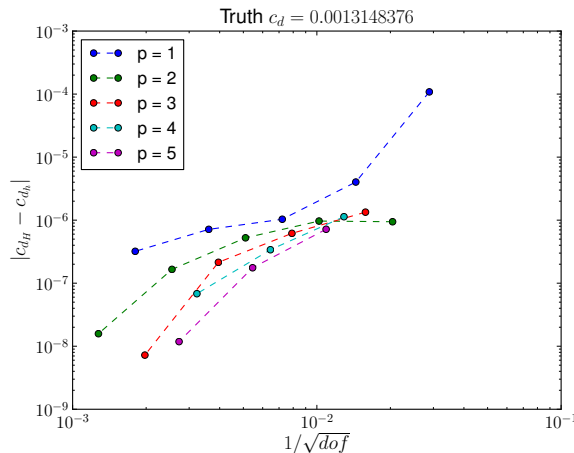


Figure 1: $M = 0.5, \alpha = 0^\circ, Re = 10^6$: drag error convergence with mesh h refinement.

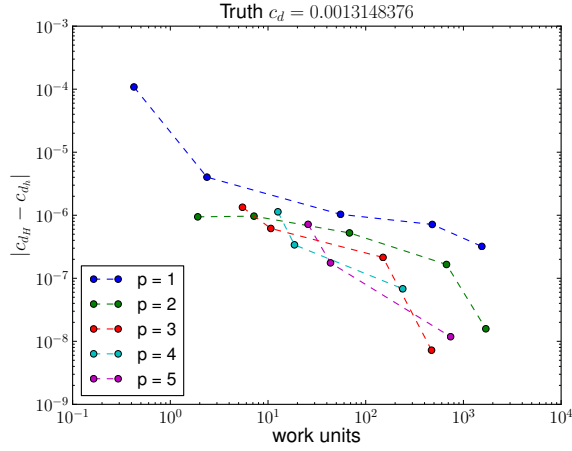


Figure 2: $M = 0.5, \alpha = 0^\circ, Re = 10^6$: drag error convergence with work units.

Table 1: $M = 0.5, \alpha = 0^\circ, Re = 10^6$: drag coefficient errors and rates.

| p | dof/eqn | h | c_d | $c_d - c_{d_{\text{exact}}}$ | work units |
|----------|----------------|-----------------------|-------------------------|--|-----------------------|
| 1 | 1200 | 2.89×10^{-2} | 1.21×10^{-3} | 1.08×10^{-4} | 4.24×10^{-1} |
| | 4800 | 1.44×10^{-2} | 1.31×10^{-3} | 4.02×10^{-6} | 2.37×10^0 |
| | 19200 | 7.22×10^{-3} | 1.32×10^{-3} | 1.03×10^{-6} | 5.52×10^1 |
| | 76800 | 3.61×10^{-3} | 1.32×10^{-3} | 7.14×10^{-7} | 4.80×10^2 |
| | 307200 | 1.80×10^{-3} | 1.32×10^{-3} | 3.20×10^{-7} | 1.54×10^3 |
| 2 | 2400 | 2.04×10^{-2} | 1.31×10^{-3} | 9.44×10^{-7} | 1.91×10^0 |
| | 9600 | 1.02×10^{-2} | 1.32×10^{-3} | 9.68×10^{-7} | 7.18×10^0 |
| | 38400 | 5.10×10^{-3} | 1.32×10^{-3} | 5.25×10^{-7} | 6.82×10^1 |
| | 153600 | 2.55×10^{-3} | 1.32×10^{-3} | 1.66×10^{-7} | 6.71×10^2 |
| | 614400 | 1.28×10^{-3} | 1.31×10^{-3} | 1.58×10^{-8} | 1.70×10^3 |
| 3 | 4000 | 1.58×10^{-2} | 1.32×10^{-3} | 1.34×10^{-6} | 5.48×10^0 |
| | 16000 | 7.91×10^{-3} | 1.32×10^{-3} | 6.17×10^{-7} | 1.07×10^1 |
| | 64000 | 3.95×10^{-3} | 1.32×10^{-3} | 2.14×10^{-7} | 1.50×10^2 |
| | 256000 | 1.98×10^{-3} | 1.31×10^{-3} | 7.23×10^{-9} | 4.72×10^2 |
| 4 | 6000 | 1.29×10^{-2} | 1.32×10^{-3} | 1.13×10^{-6} | 1.26×10^1 |
| | 24000 | 6.45×10^{-3} | 1.32×10^{-3} | 3.39×10^{-7} | 1.86×10^1 |
| | 96000 | 3.23×10^{-3} | 1.31×10^{-3} | 6.81×10^{-8} | 2.39×10^2 |
| 5 | 8400 | 1.09×10^{-2} | 1.32×10^{-3} | 7.17×10^{-7} | 2.57×10^1 |
| | 33600 | 5.46×10^{-3} | 1.32×10^{-3} | 1.76×10^{-7} | 4.36×10^1 |
| | 134400 | 2.73×10^{-3} | 1.31×10^{-3} | 1.18×10^{-8} | 7.39×10^2 |