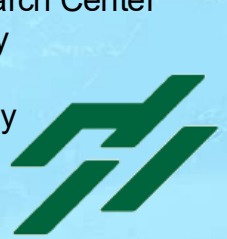
RANS: EVIDENCE FOR MULTIPLE SOLUTIONS

Malte Wegener*, Prahladh Iyer†, Boris Diskin†, Josh Wagner†, Dmitry Kamenetsky‡, Mike Park‖, Mohamed Sereez#

* German Aerospace Center, Institute of Aerodynamics and Flow Technology
† NASA Langley Research Center
‡ The Boeing Company
‖ FlexCompute
De Montfort University



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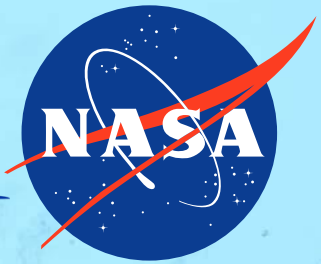
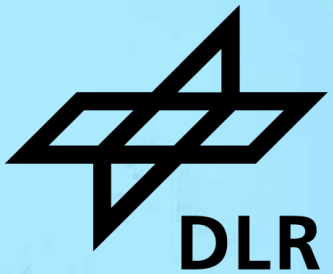
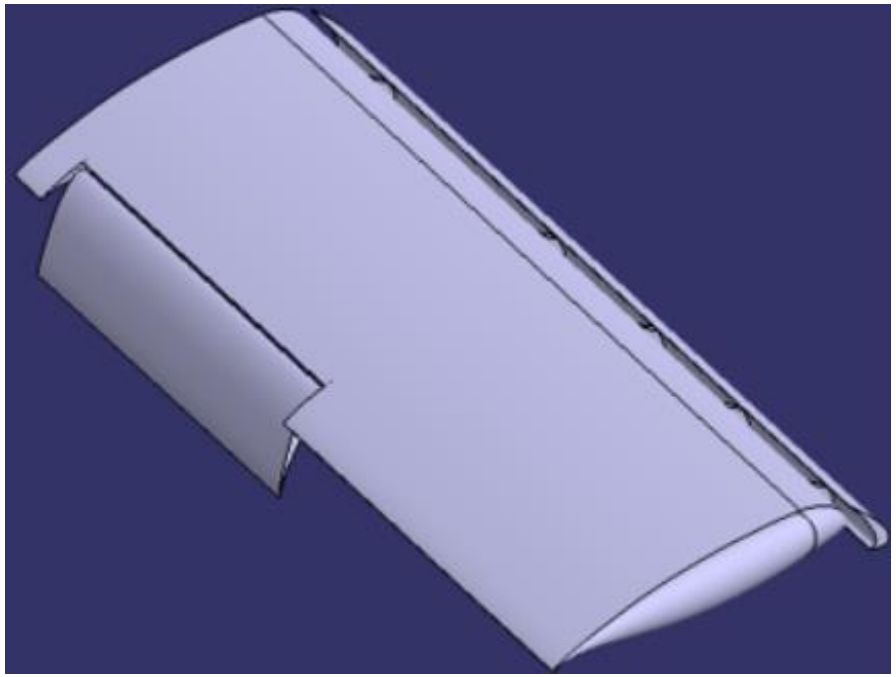
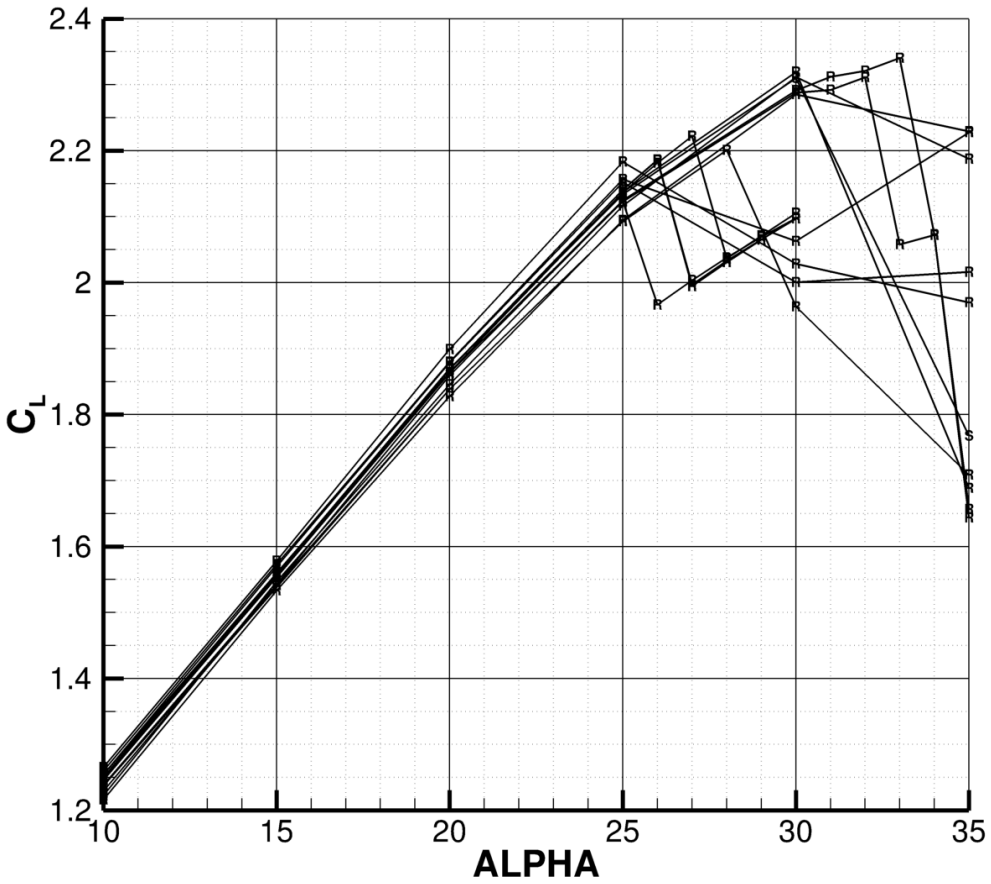




TC1: Differences between RANS solutions for high angles of attack

- At the high angles of attack there is a large spread between different solvers

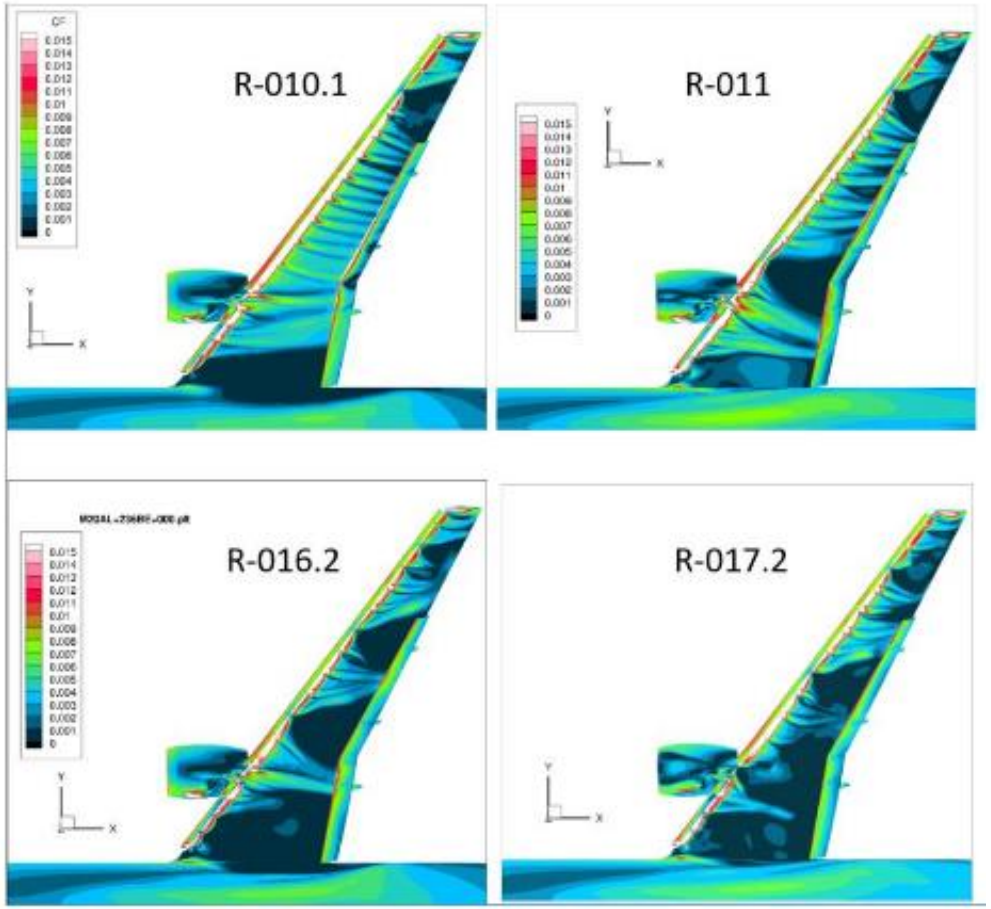




HLPW5: Differences between RANS solutions for high angles of attack

- This was also observed for previous Workshops
- Multiple solutions for the same test case
  - Limited consistency observed between separated flow solutions
  - Solutions are not spatially and iteratively converged

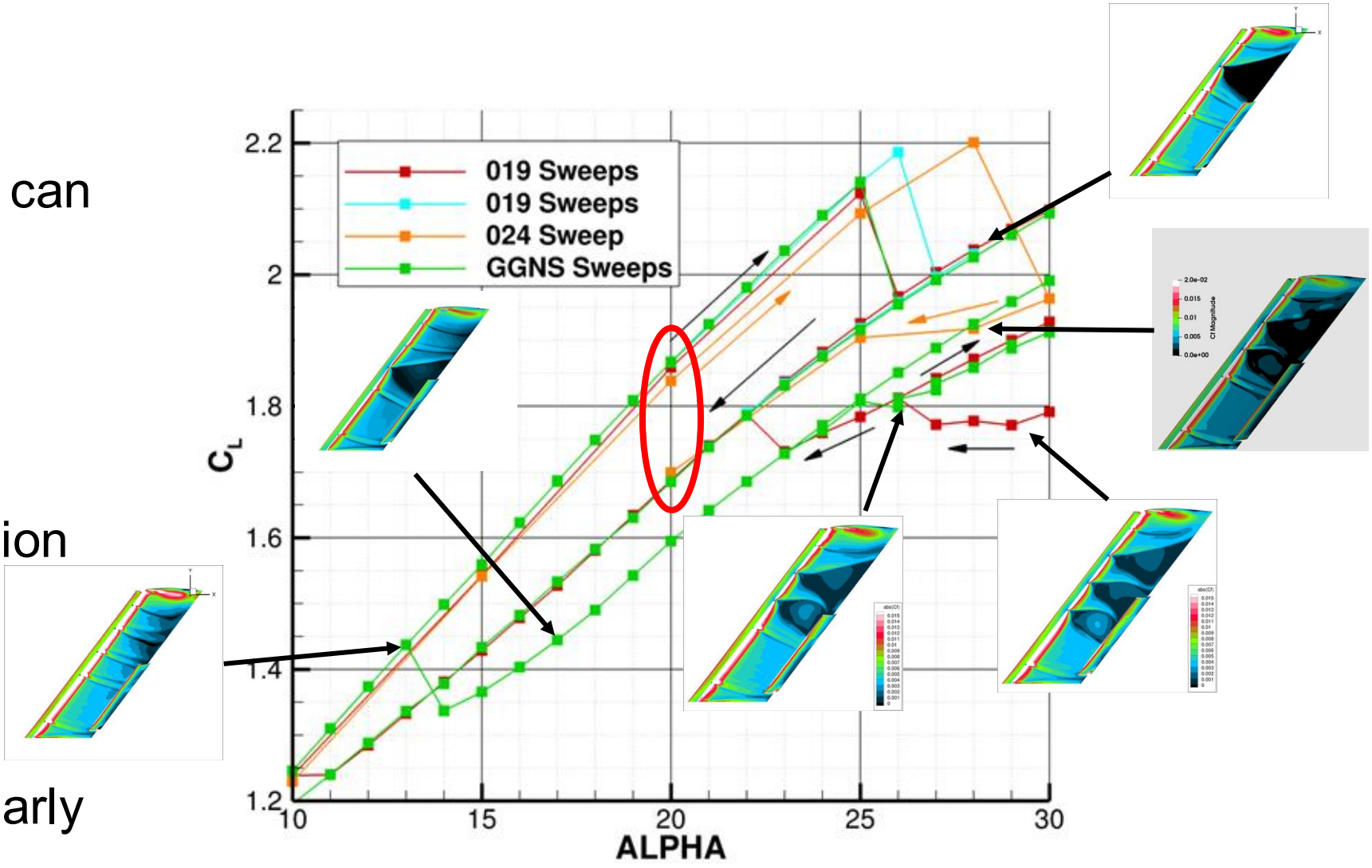
- Is the spread between solvers a sign of the non-uniqueness of the RANS equations for iterative and spatially converged solutions?



HLPW5 Summary slides

Alpha-continuation from perturbed solutions

- Multiple iteratively-converged solutions can be found
- These solutions are obtained by alpha-continuation
- They exist in the region of linear lift
- Switching between branches occurs suddenly and irregularly

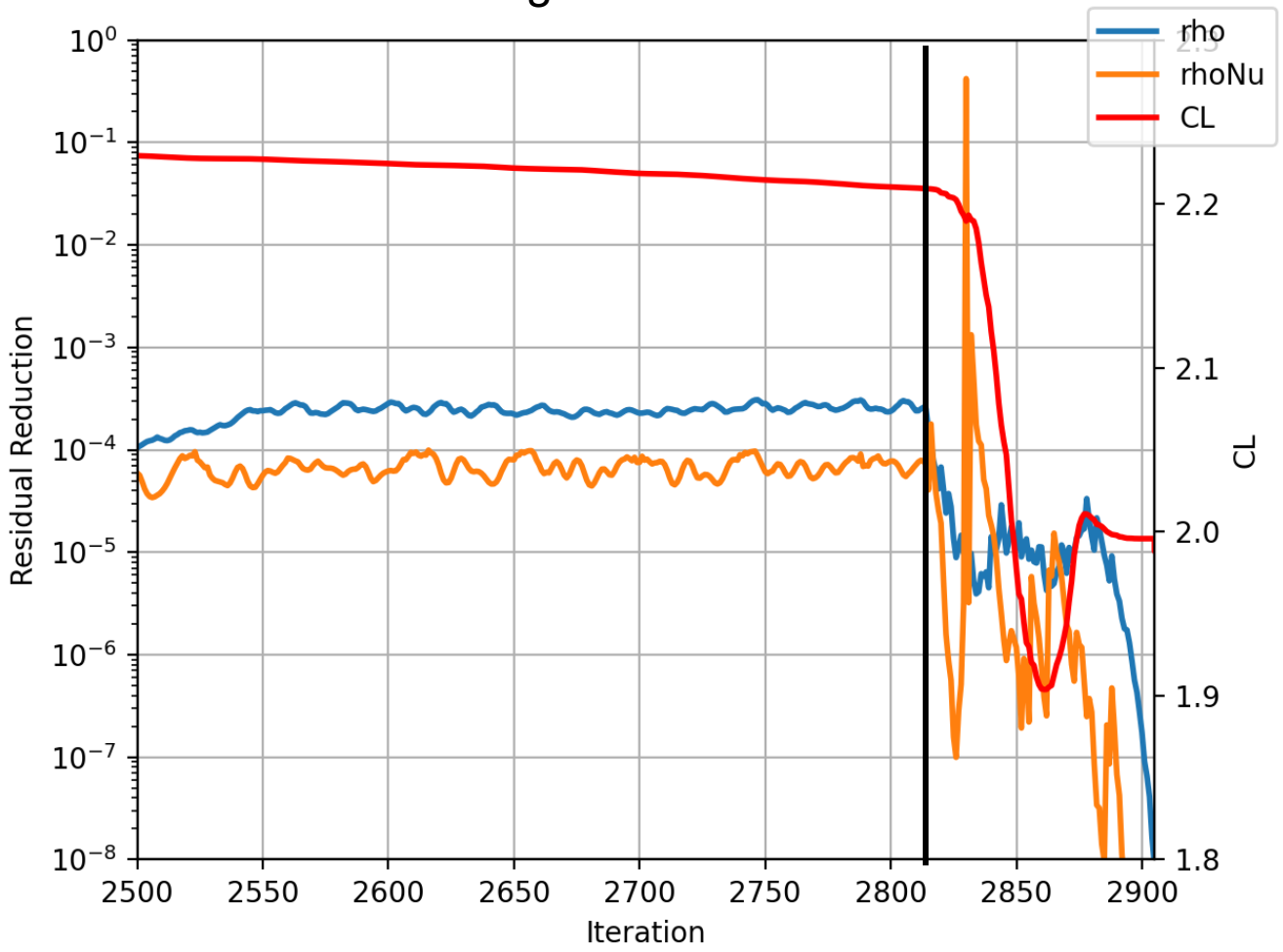


Example convergence history on a fine mesh at 27 degrees

- Residuals approach machine-zero
- Lift switches to low branch after 2800 iterations

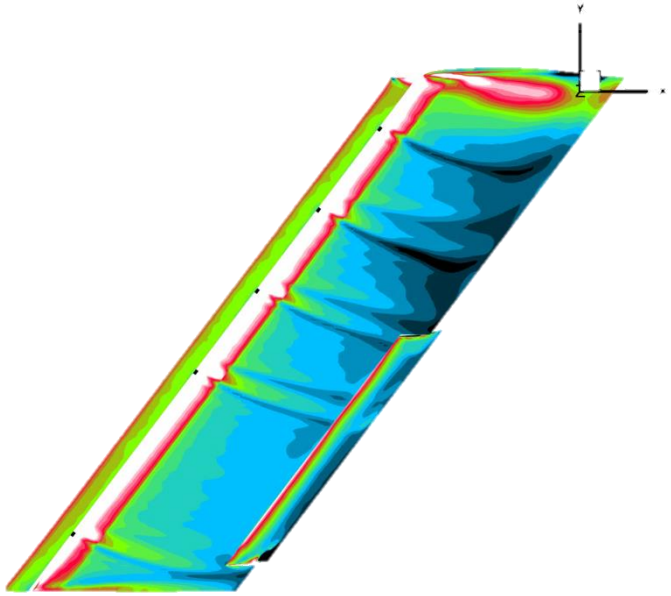
Weak implicit multistage scheme

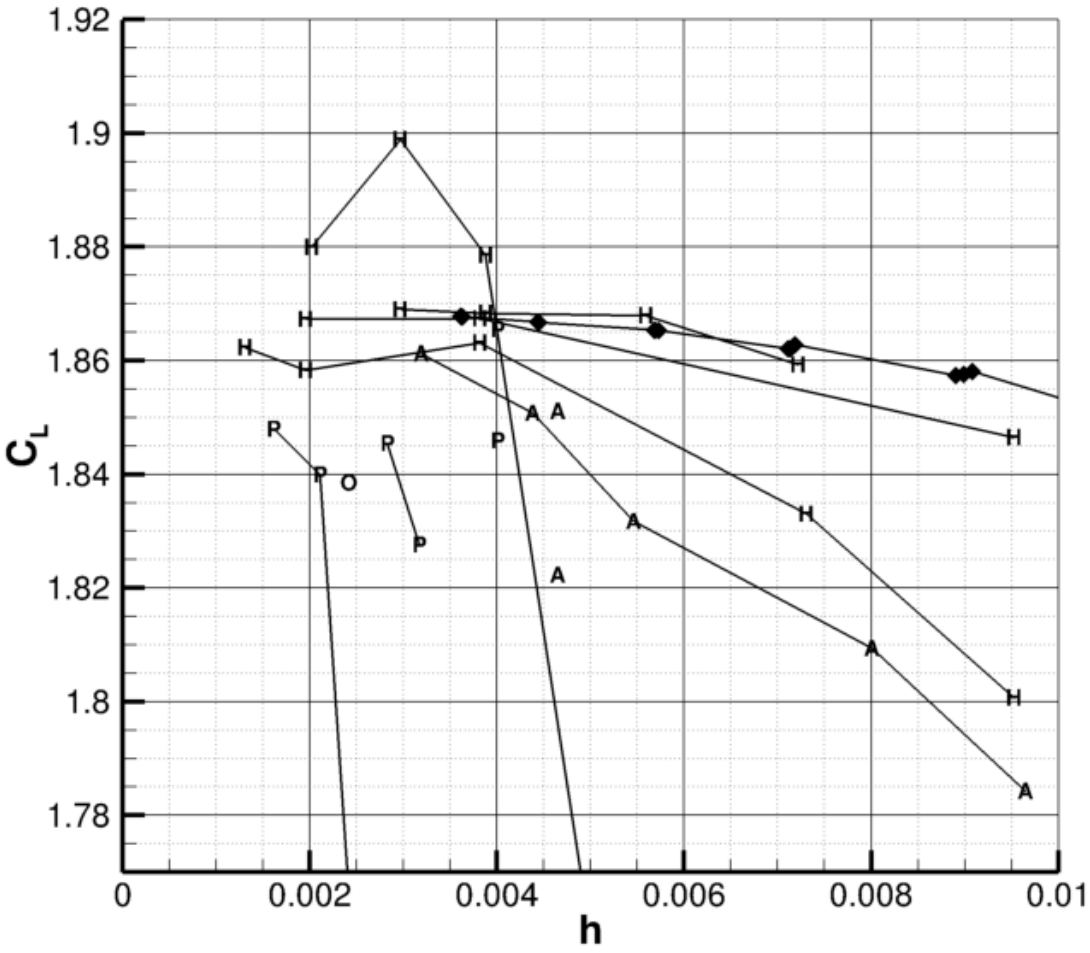
Strong implicit scheme



Spatial convergence at 20 degrees

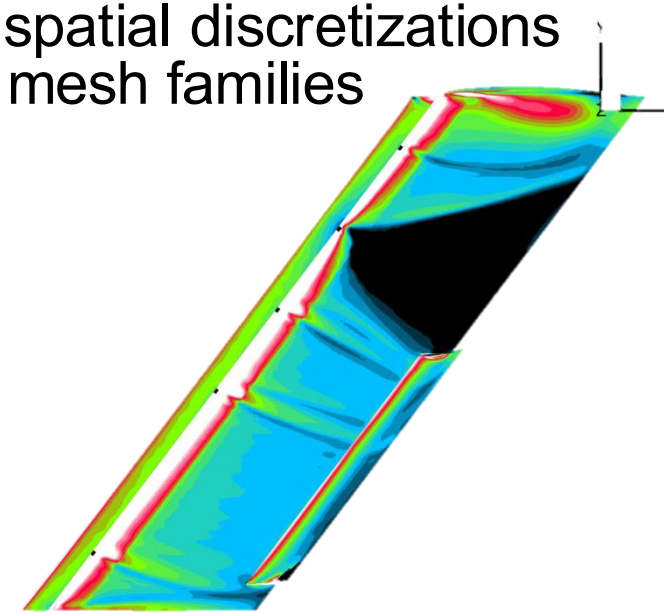
- Agreement between different codes and different mesh families is within 2%

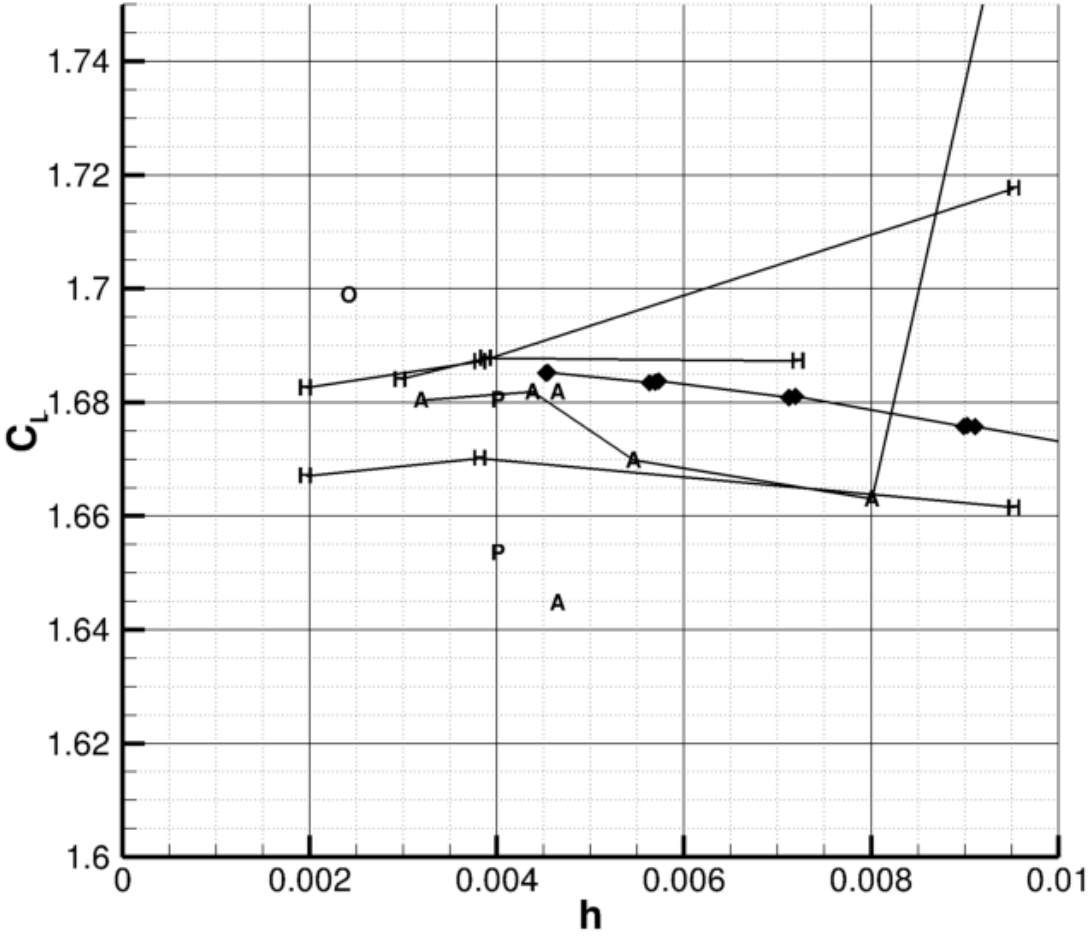




Spatial convergence at 20 degrees

- Spatial convergence looks indistinguishable from the high-branch solution
  - Agreement within 2%
  - All solutions are iteratively converged
- The low-branch solution is found by 6 different spatial discretizations on 5 different mesh families





Main Take-aways

- **The multiple solutions obtained for the TC-1 configuration are consistent between different solvers over different grid families and from examining their grid convergence behavior and iterative convergence behavior none of the solutions can be identified as the "correct" solution.**
- Switching between solution branches happens randomly and participants report different sensitivities
  - Numerical dissipation
  - Turbulence model
  - Geometric variation
  - Mesh variation
- Multiple solutions can be found through a combination of these perturbations of the solver and alpha-continuation

A Vision for dealing with multiple solutions

Physical

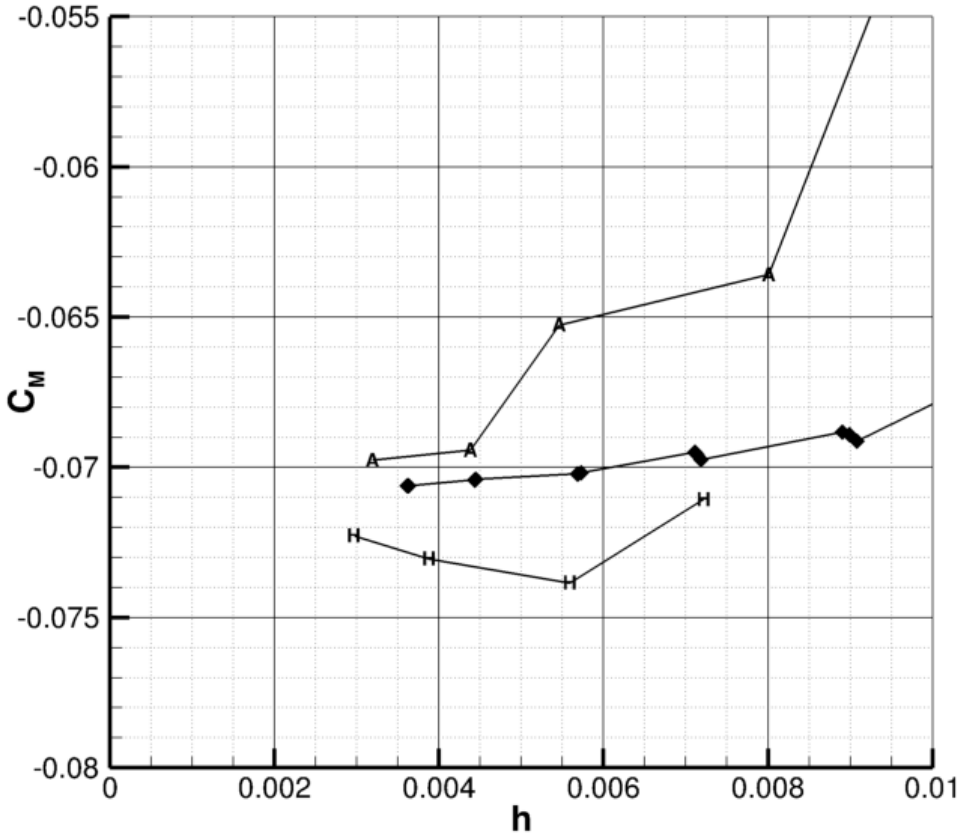
- Turbulence models should allow for multiple solutions to capture hysteresis effects
- Is there a physical condition these pizza slice solutions violate?
  - Can this condition be incorporated into the solution process as a constraint
  - Similar to how the entropy-fix in the Roe scheme prevents unphysical expansion shocks

Numerical

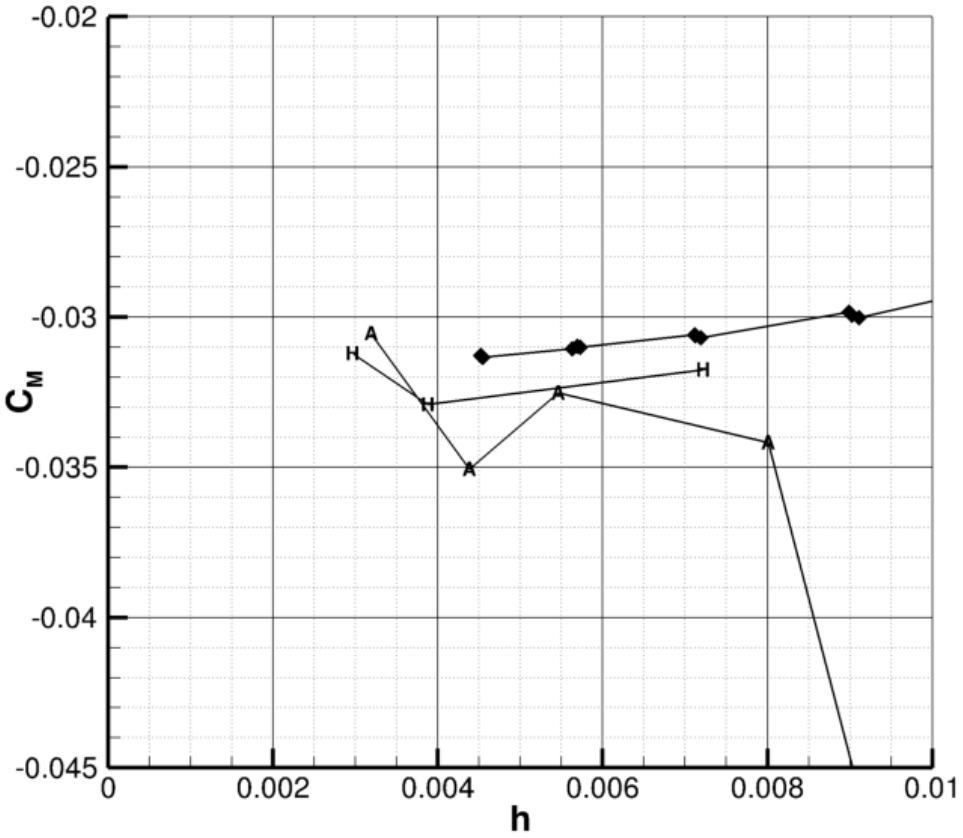
- Can multiple solutions be found systematically?
- Can a regularization of the path that is taken through state-space be made such that the initial condition remains the strongest attractor?
- Can regions be identified which need to be sufficiently fine such that the initial condition remains the strongest attractor?

This is a highly cross-topic problem that can only be solved through collaboration
There is no way to label any of the solutions as the best solution and we want to find all solutions

Spatial convergence at 20 degrees: CM



high-lift solution



low-lift solution