Computational Challenges (MC1)
High-Lift Common Research Model

5th International Workshop on High-Order CFD Methods (HiOCFD5)
January 6th-7th 2018, Kissimmee, FL

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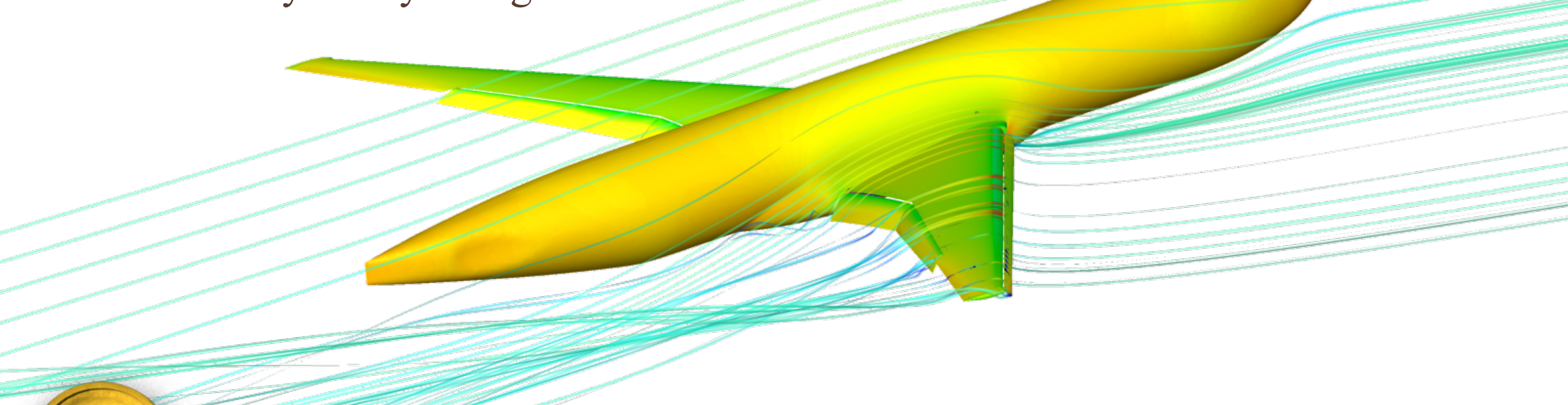
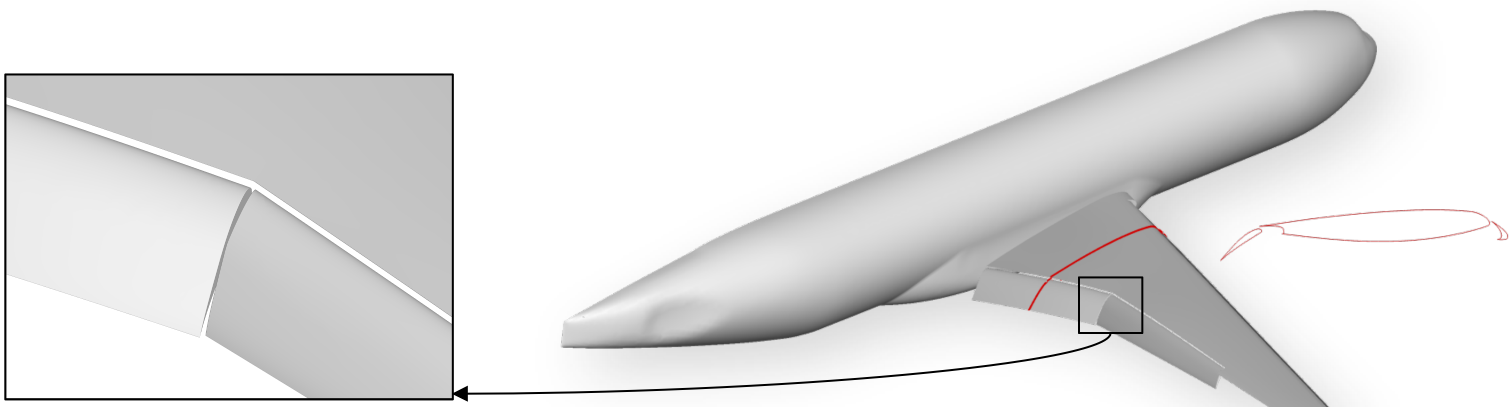


High-Lift Common Research Model

- Configuration
  - A wide-body commercial aircraft with a classical three element high-lift system at the wing leading and trailing edge in a landing setting.
  - Deigned jointly by NASA and Boeing to serve as a test case for high-lift simulations.
- Previous works on this particular configuration
  - 3rd High Lift Prediction Workshop (HLPW3, case 1a)
  - 1st Geometry and Mesh Generation Workshop



Full chord flap gap

High-Lift Common Research Model

- Flow Conditions (HiLPW3, case 1a)
  - Mach = 0.2
  - Reynolds = 3.26 million
  - Alpha = 8^o and 16^o
- Available data from HLPW3:
  - Comparison of grid convergence trends for various discretizations, grid, and turbulence models
  - Comparison of grid convergence trends between pre-defined grid families (global refinement) and adapted grids
  - No exp. data for HL-CRM configuration (Case 1)
- Focus of this workshop
  - Overlay of the new force results on HLPW3 data
  - Discussion of high performance computing (HPC) aspects
  - Discussion of nonlinear and linear convergence

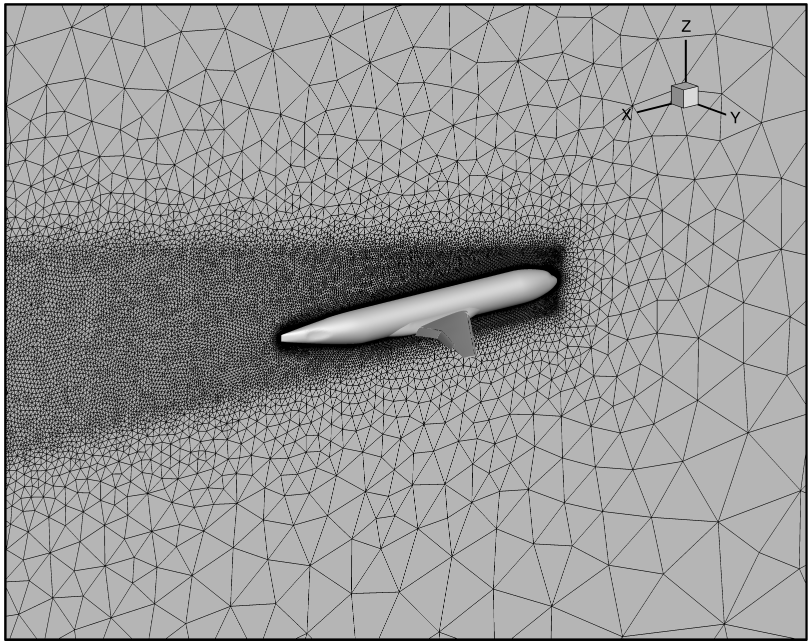
History

Previous high-order workshops:

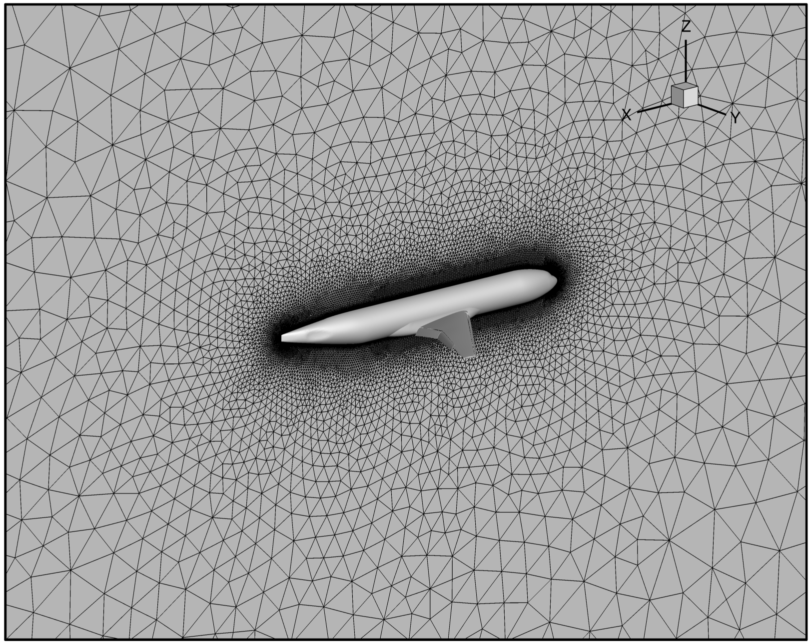
- HiOCFD3 (3rd International Workshop on High-Order CFD Methods)
  - No high-lift case
  - CRM wing/body configuration was put in the "difficult" category.
  - In HiOCFD5, P2 machine converged solutions (in ~100 nonlinear steps) was presented for CRM wing/body. (due to availability of better girds, more refined nonlinear convergence controllers, etc.)
- HiOCFD4
  - First appearance of a high-lift case (DLR F11, Taken from HiLPW2)
  - Considered as a "computationally challenging" case
  - Curved meshes were generated
  - DG (3rd order) and FD (5th order) solutions were presented
  - DLR showed machine convergence residuals and P-Continuation
  - Conclusions:
    - Feasibility of high-order CFD for DLR-F11 configuration was demonstrated.
    - High-lift case still remains as a challenging task.

High-Lift Common Research Model
Grids

- Steve Karman, Pointwise
  - With wake resolution (new to HiOCFD5)
  - Without wake resolution (previous used in HLPW3)



wake (tet), coarse



wake-less (tet), coarse

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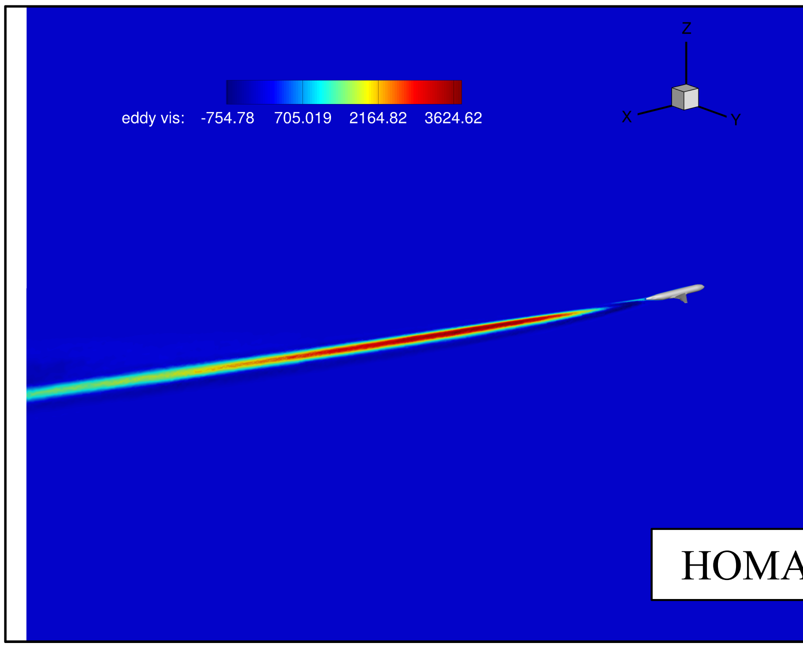
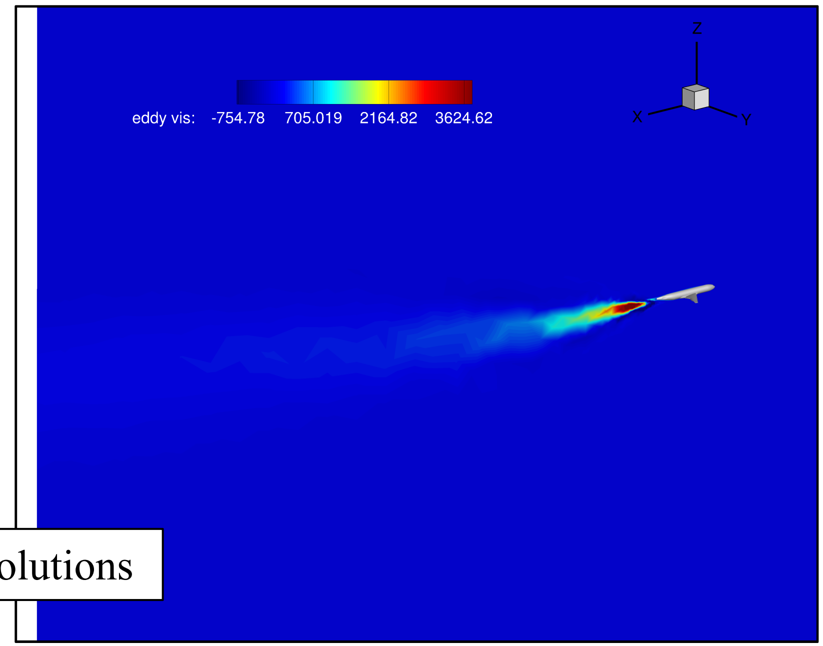


wake (tet), coarse



wake-less (tet), coarse

HOMA solutions

- White strips show the end of the domain (larger domains are required).

High-Lift Common Research Model
Grids

studied

	Wake grids (all tets)					
	Q1 Nodes	Q2 Nodes	Q3 Nodes	Cells	DG P1 Nodes	DG P2 Nodes
Extra Tiny	**1**,430,550	**11**,322,112	**38**,069,514	**8**,394,824	**33**,579,296	**83**,948,240
Tiny	**2**,983,442	**23**,646,157	**79**,548,786	**17**,560,637	**70**,242,548	**175**,606,370
Coarse	**5**,735,514	**45**,507,095	**153**,137,797	**33**,823,050	**135**,292,200	**338**,230,500
Medium	**14**,454,170	**114**,952,652	-	**85**,656,549	**342**,626,196	**856**,565,490
Fine	**38**,906,529	-	-	**231**,515,775	**926**,063,100	**2,315**,157,750

	Wake grids (prism/tet)					
	Q1 Nodes	Q2 Nodes	Q3 Nodes	Cells	DG P1 Nodes	DG P2 Nodes
Extra Tiny	**1**,430,550	**11**,322,112	**38**,069,514	**3**,607,141	**19**,216,247	**55**,222,142
Tiny	**2**,983,442	**23**,646,157	**79**,548,786	**7**,476,453	**39**,989,996	**115**,101,266
Coarse	**5**,735,514	**45**,507,095	**153**,137,797	**15**,535,490	**80**,429,520	**228**,505,140
Medium	**14**,454,170	**114**,952,652	-	**38**,058,876	**199**,833,177	**570**,979,452
Fine	**38**,906,529	-	-	**102**,584,118	**539**,268,129	**1,541**,567,808

	Wake-less grids (all tets)				
	Q1 Nodes	Q2 Nodes	Cells	DG P1 Nodes	DG P2 Nodes
Extra Tiny	933,440	**7**,344,288	**5**,540,545	**22**,162,180	**55**,405,450
Tiny	**2**,016,118	**15**,934,343	**12**,009,584	**48**,038,336	**120**,095,840
Coarse	**5**,591,371	**44**,346,372	**33**,361,746	**133**,446,984	**333**,617,460
Medium	**16**,654,483		**98**,659,138	**394**,636,552	**986**,591,380

High-Lift Common Research Model

Solutions

- Ryan S. Glasby, Taylor Erwin, University of Tennessee
  - Code: COFFE
  - Utilized discretization: SUPG
  - Color in mesh convergence plots: Red
- Behzad R. Ahrabi, University of Wyoming
  - Code: HOMA
  - Utilized discretization: SUPG
  - Color in mesh convergence plots: Blue
- Michael J. Brazell, University of Wyoming
  - Code: DG3D
  - Utilized discretization: DG (SIP)
  - Color in mesh convergence plots: Green
- Marshall Galbraith, Massachusetts Institute of Technology
  - Code: SANS
  - Utilized discretization: DG
  - Color in mesh convergence plots: Pink

Participant Presentations …

HOMA Results + Summary

Description of Code

HOMA Solver (High-Order Multilevel Adaptive Solver)

- SUPG, RANS, neg-SA, strong and weak implementation of BCs.
- Fully implicit with exact linearization through automatic diff.
- Non-Linear Strategies:
  - Pseudo Transient Continuation (PTC)
  - P-multigrid (PMG) solver based on Full Approximation Scheme (FAS)
- Principal Linear Solver: Flexible GMRes (FGMRes)
  - Built-ins:
    - Local ILU(k)
    - Implicit Line Relaxation (with Double-CFL Strategy)
    - Additive Schwarz (Restrictive)
  - External Packages: PETSc (Used only for comparing with home-developed solvers.)

Description of Code

- References:

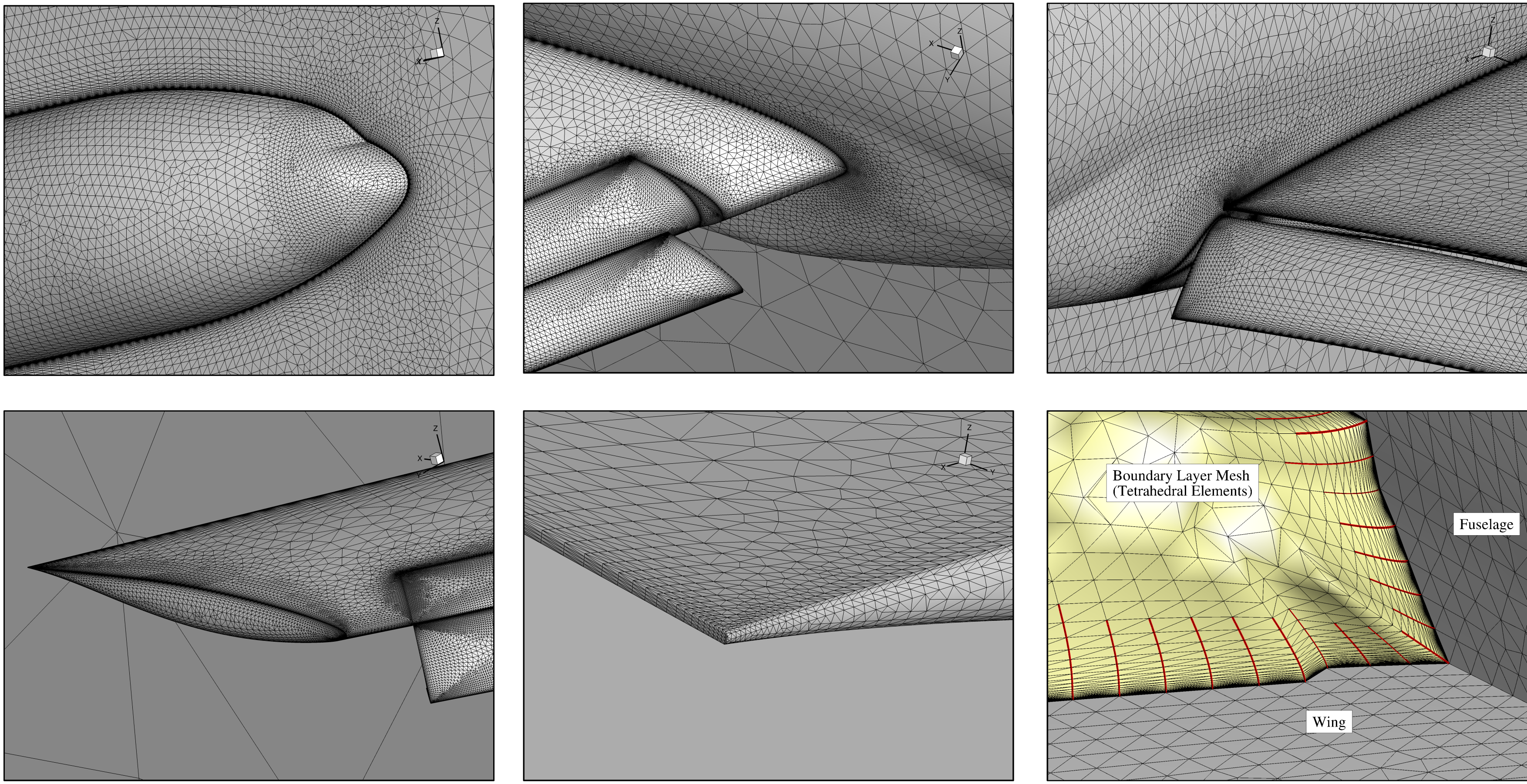
  - Ahrabi, B. R. and Mavriplis D. J., "Scalable Solution Strategies for Stabilized Finite-Element Flow Solvers on Unstructured Meshes", 55th AIAA Aerospace Sciences Meeting, AIAA Paper 2017-0517, Dallas, TX, January 2017.

  - Ahrabi, B. R. and Mavriplis D. J., "Scalable Solution Strategies for Stabilized Finite-Element Flow Solvers on Unstructured Meshes, Part II", 23rd AIAA Computational Fluid Dynamics Conference, AIAA AVIATION Forum, AIAA Paper 2017-4275, Denver, CO, June 2017.

  - Ahrabi, B. R., Brazell, M. J., and Mavriplis D. J., "An Investigation of Continuous and Discontinuous Finite-Element Discretizations on Benchmark 3D Turbulent Flows (Invited)", 2018 AIAA Aerospace Sciences Meeting, Kissimmee, FL, January 2018.

Wake (tet), Coarse

5,735,514 Q1 Nodes

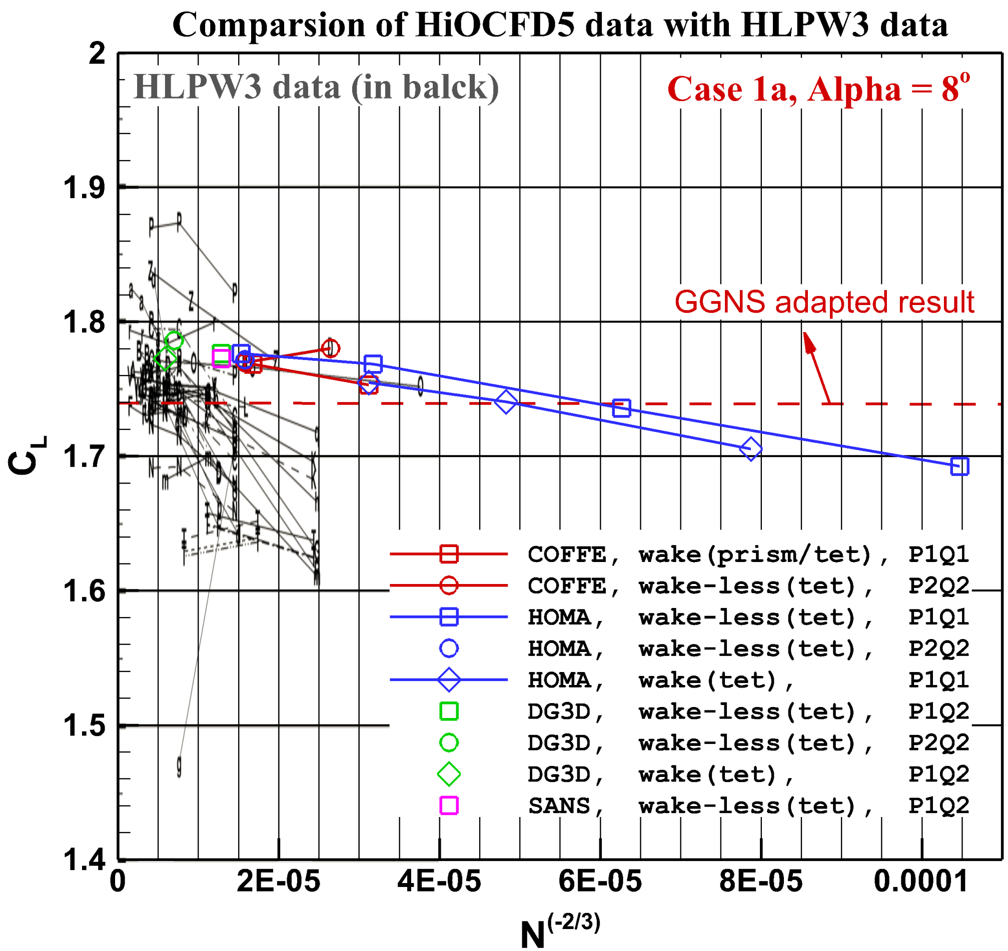


Matrix-based lines shown in red

High-Lift Common Research Model, Case 1a

Aerodynamics Forces, Alpha = 8°

- DG results show a close agreement.
- SUPG results match on coarse grids (mixed and tets)
  - Low sensitivity to grid
- SUPG P1 and P2 solutions are close.
- Difference with HLPW3 results is due to the utilization of different grids.



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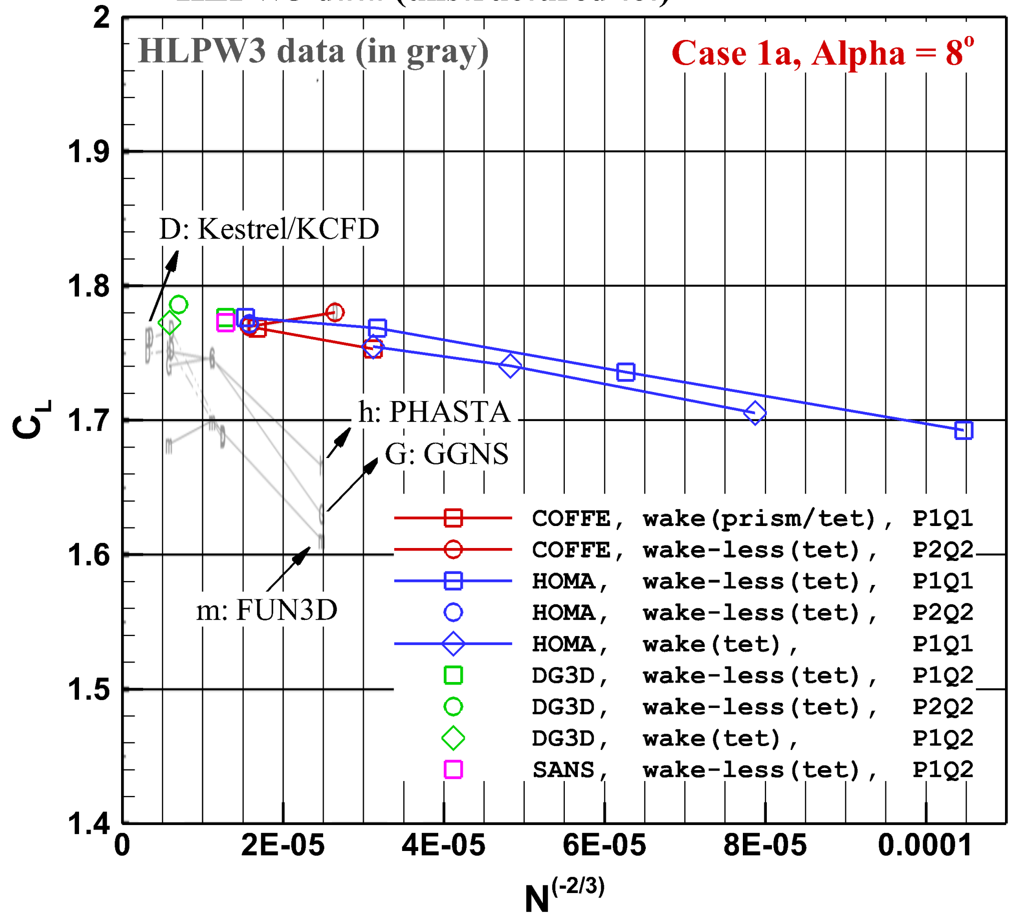
Comparsion of HiOCFD5 data with HLPW3 data (unstructured tet)



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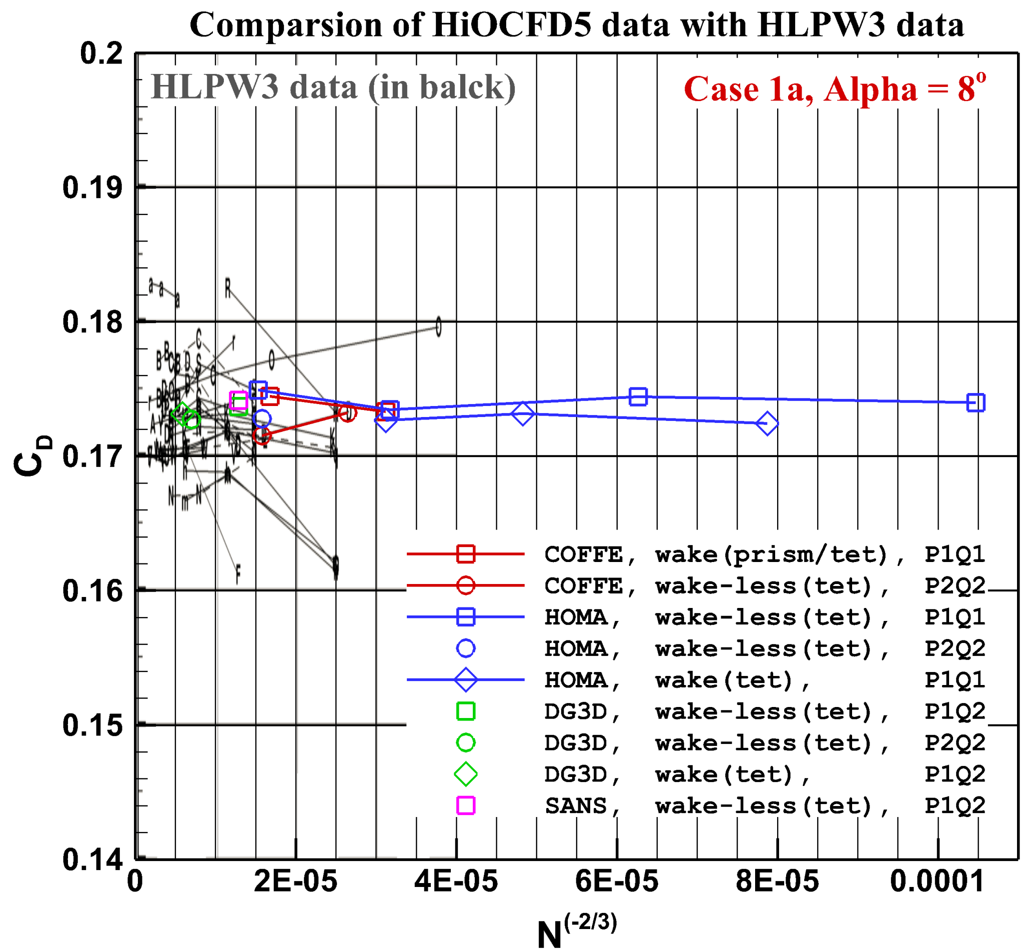
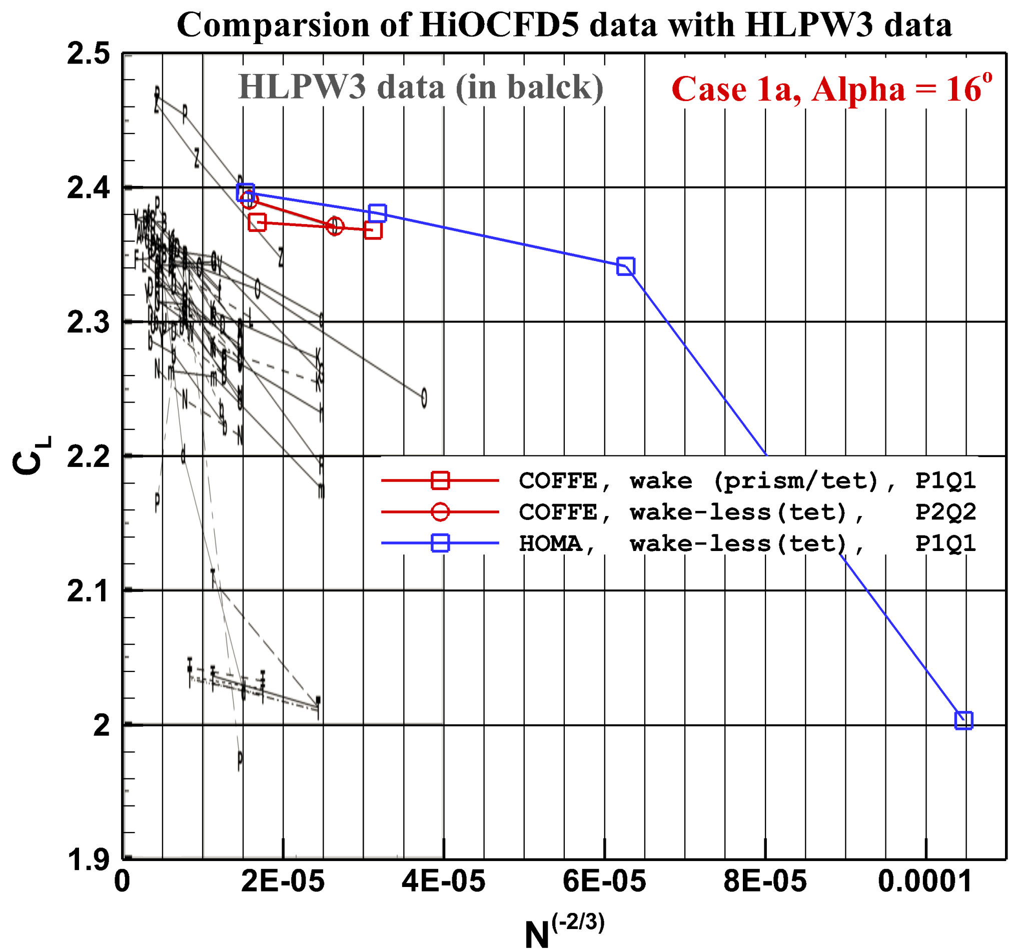


High-Lift Common Research Model, Case 1a
Aerodynamics Forces, Alpha = 16°

- SUPG P1 and P2 solutions are close.
- Difference with HLPW3 results is due to the utilization of different grids.



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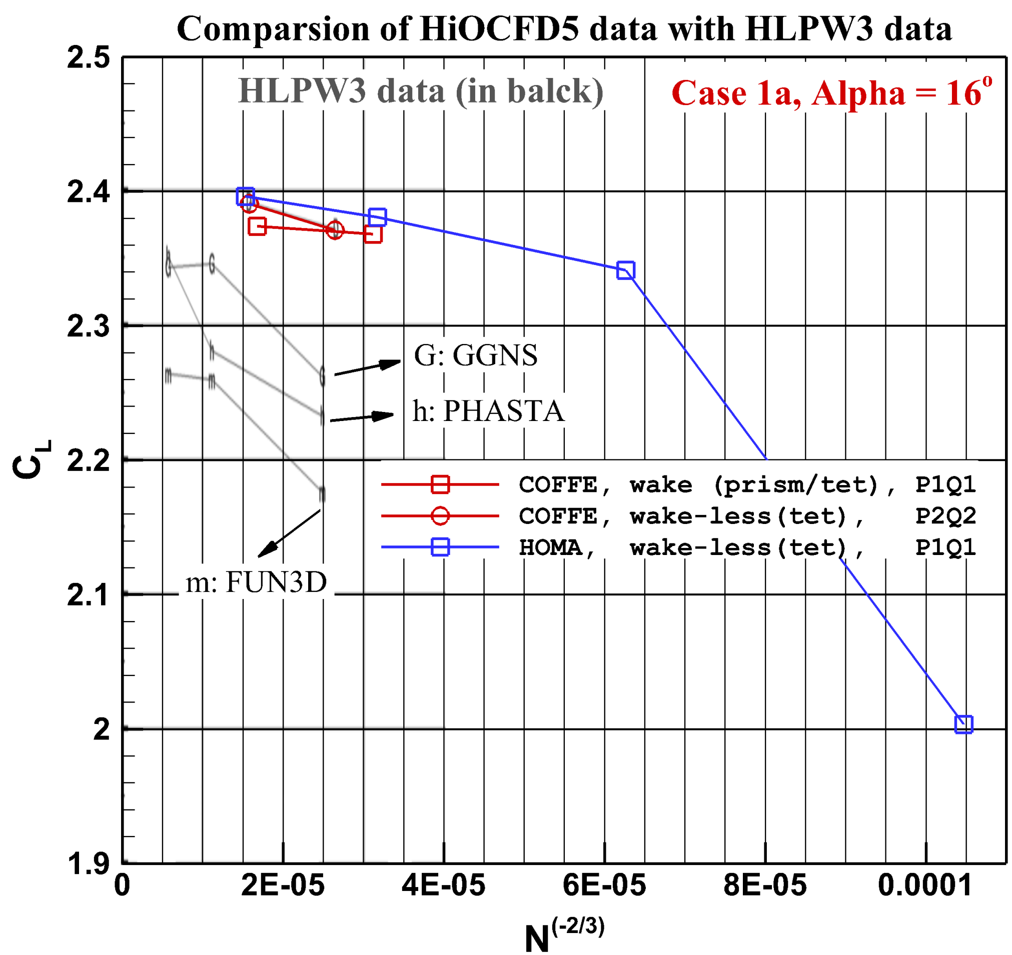

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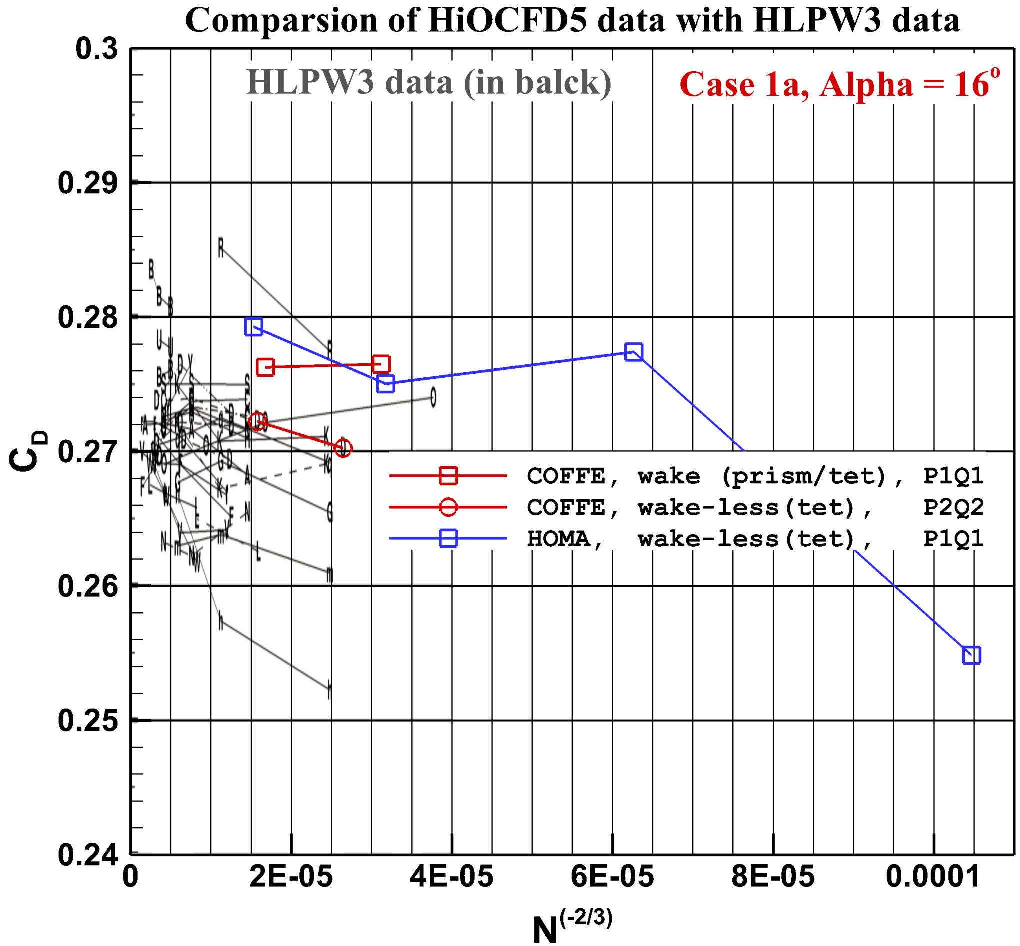
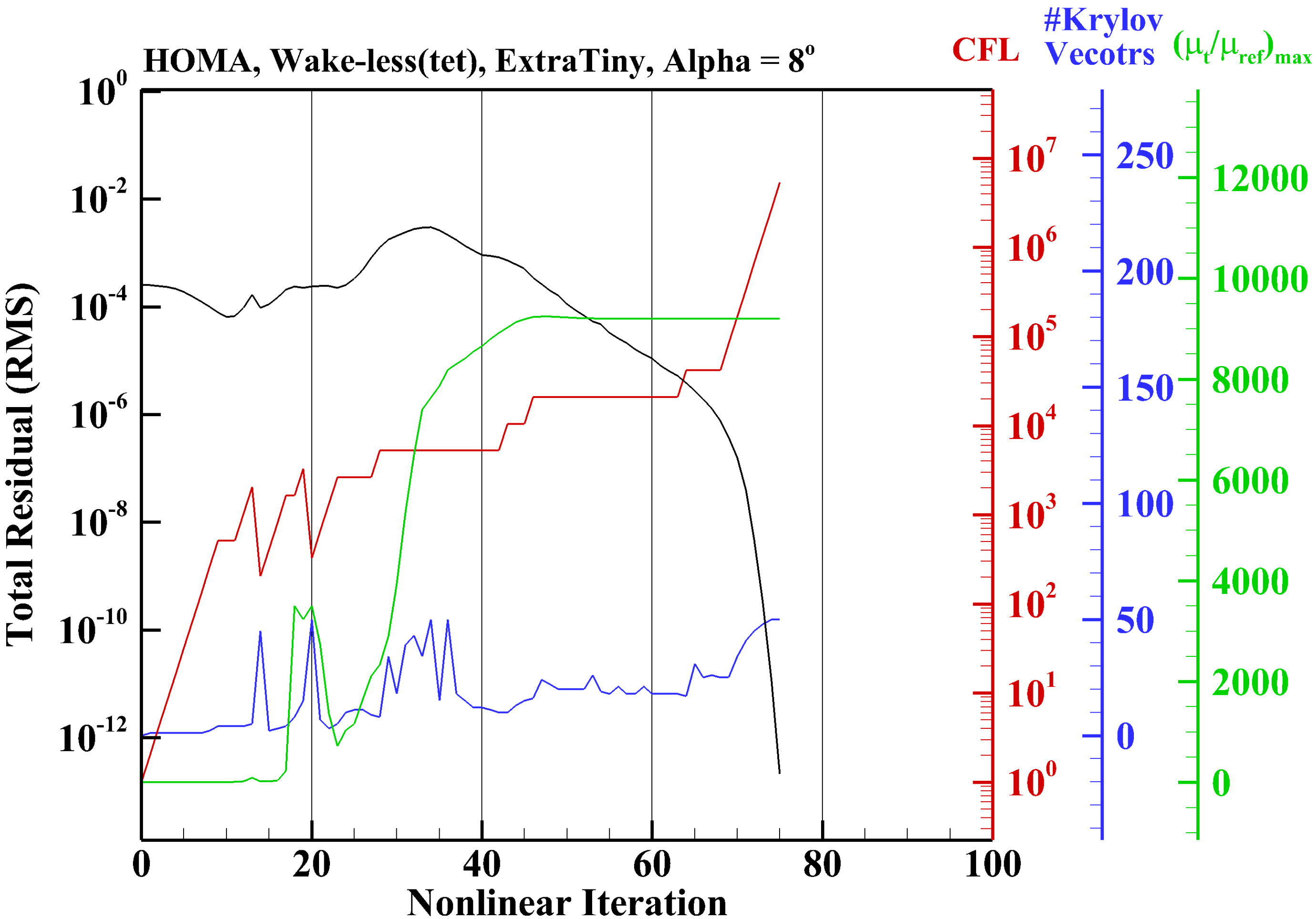


High-Lift Common Research Model, Case 1a
Convergence Histories (HOMA)



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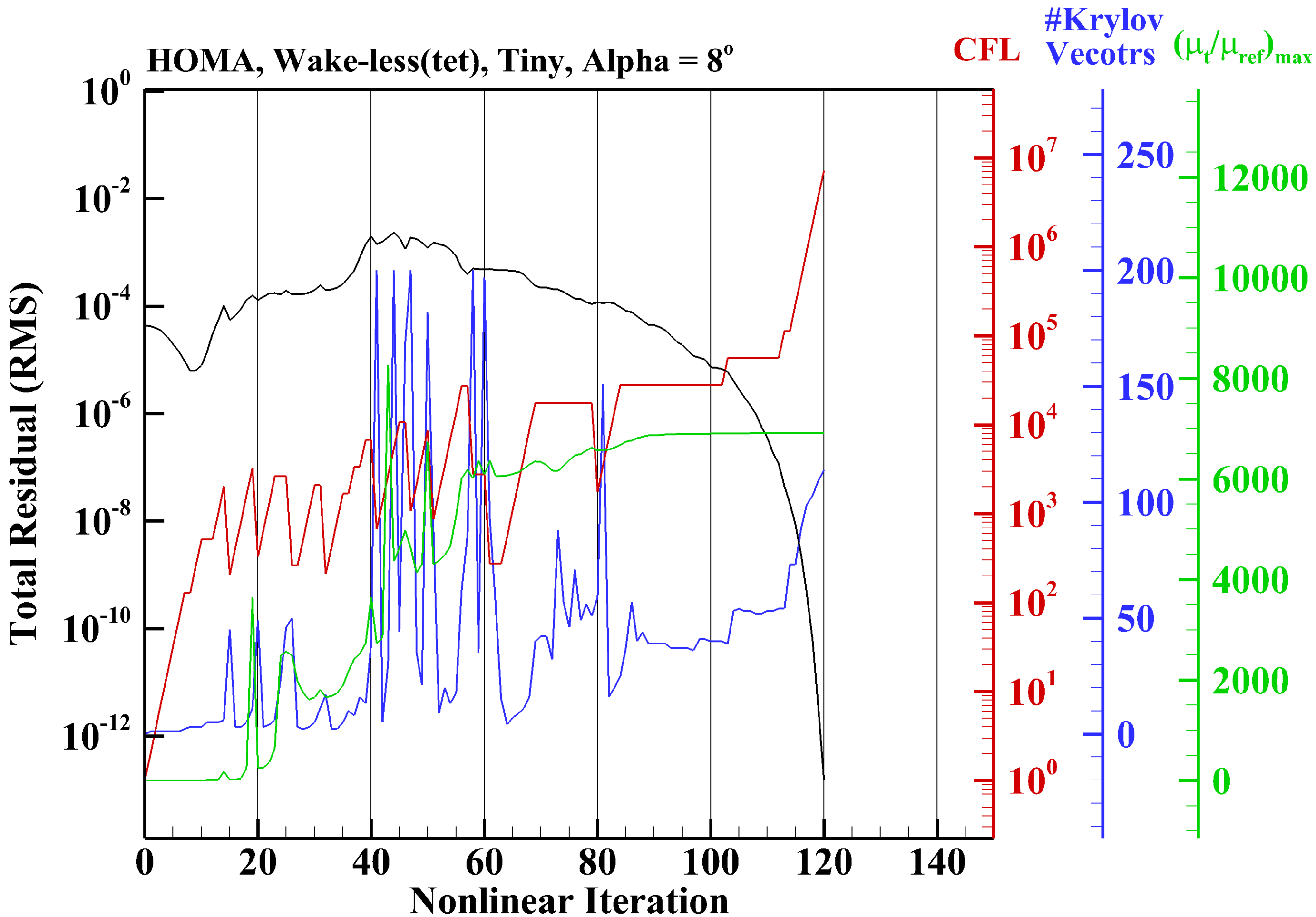

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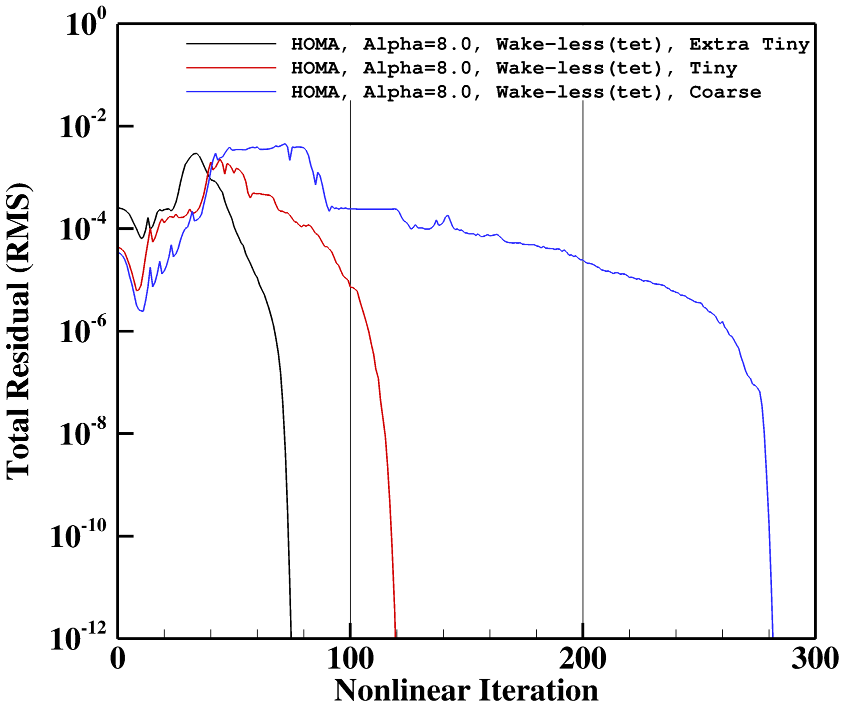
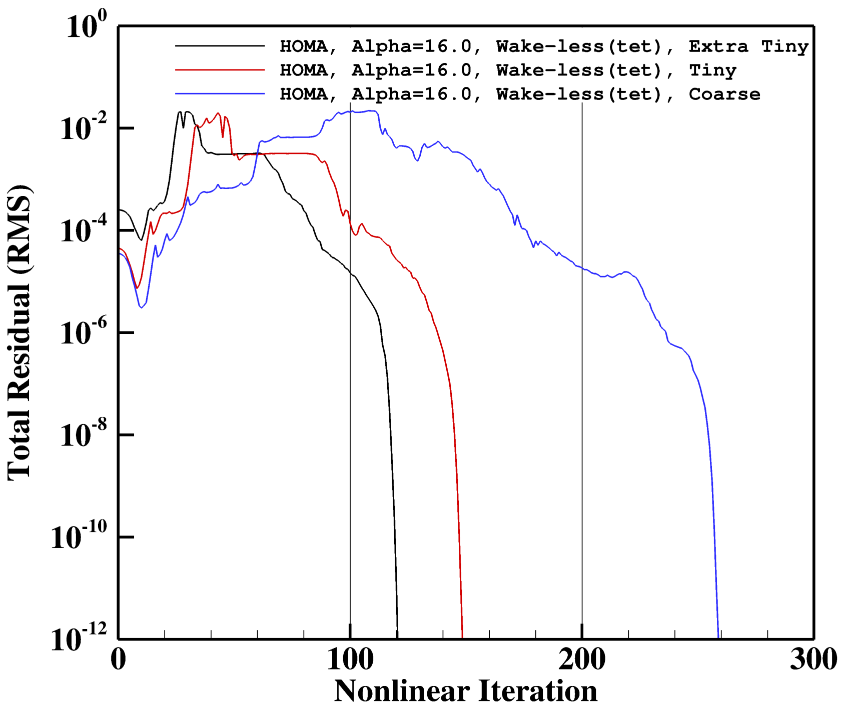
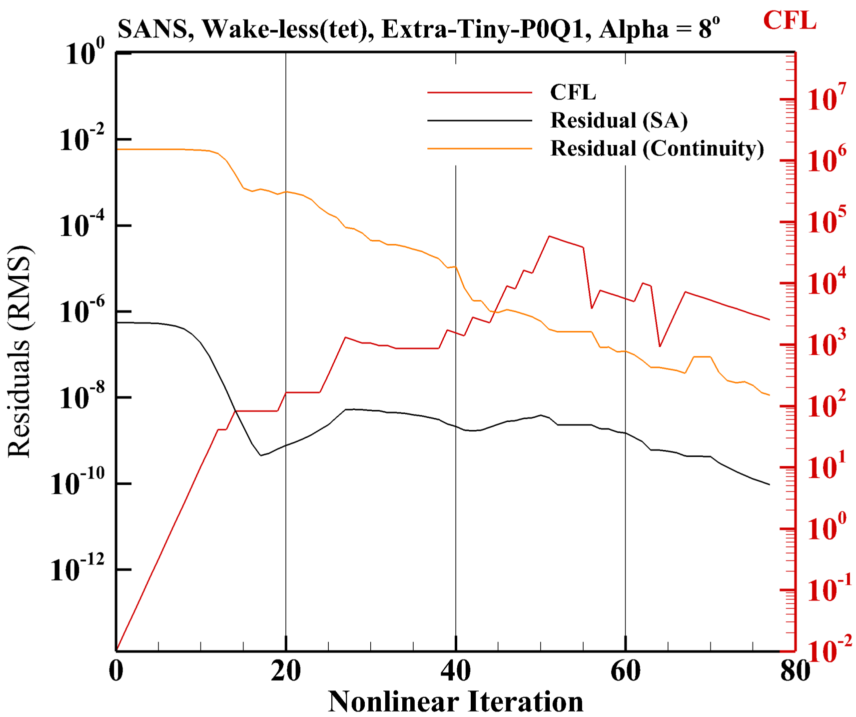
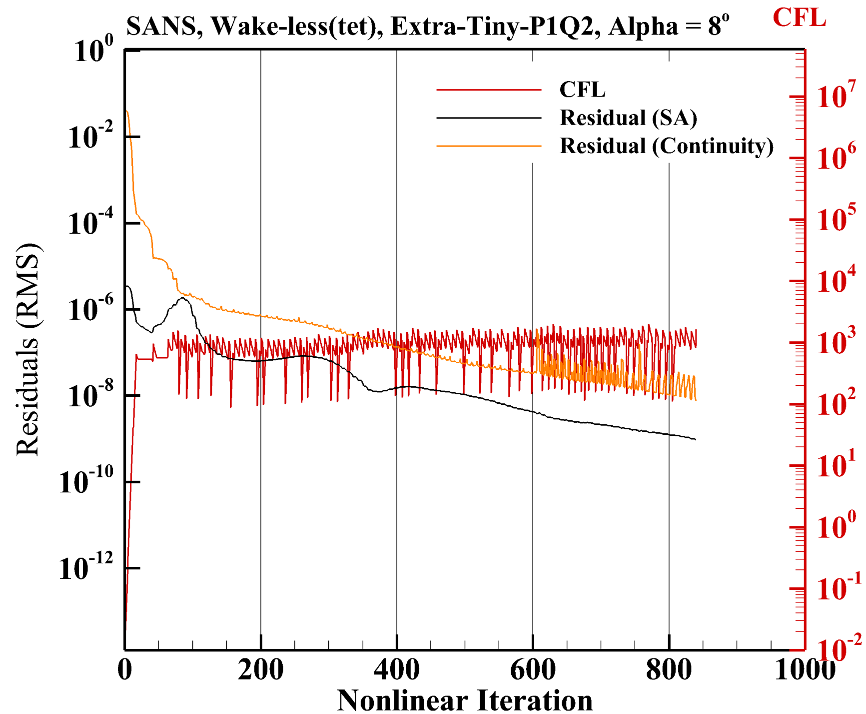




- Nonlinear convergence is notably affected by the mesh resolution.
  - Due to “nonlinear imbalance” (dominant local nonlinearities)

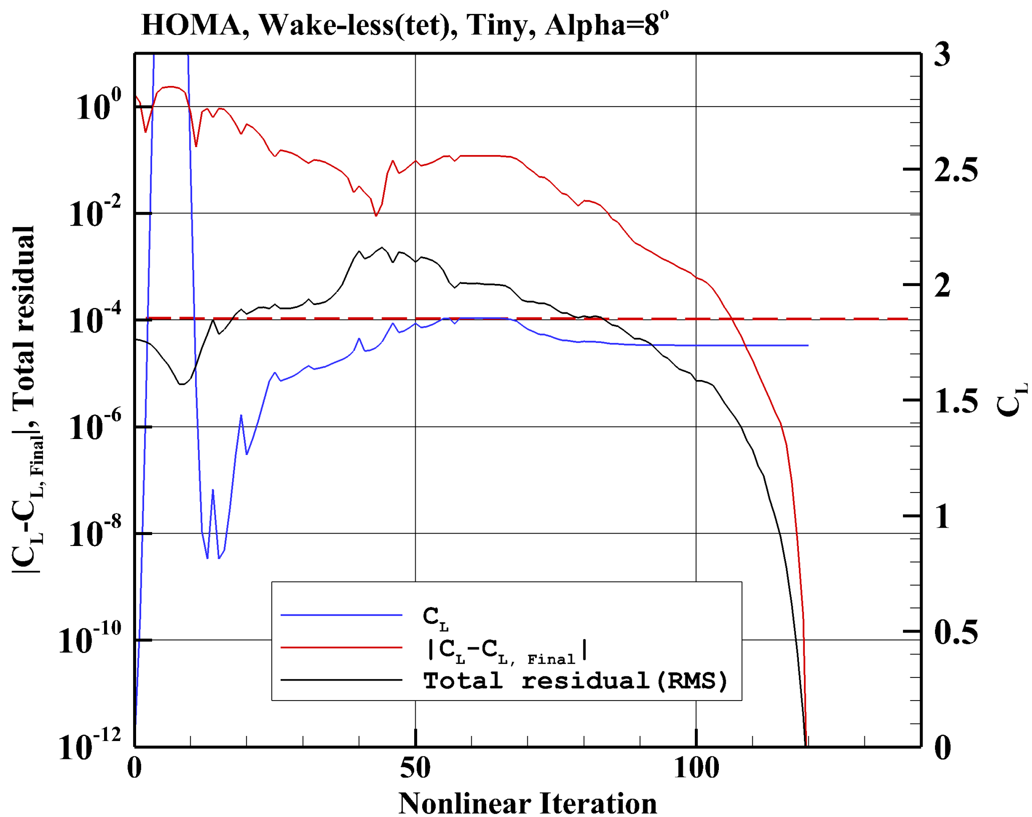
High-Lift Common Research Model, Case 1a
Convergence Histories (SANS)





- SANS needs better connection to PETSc.

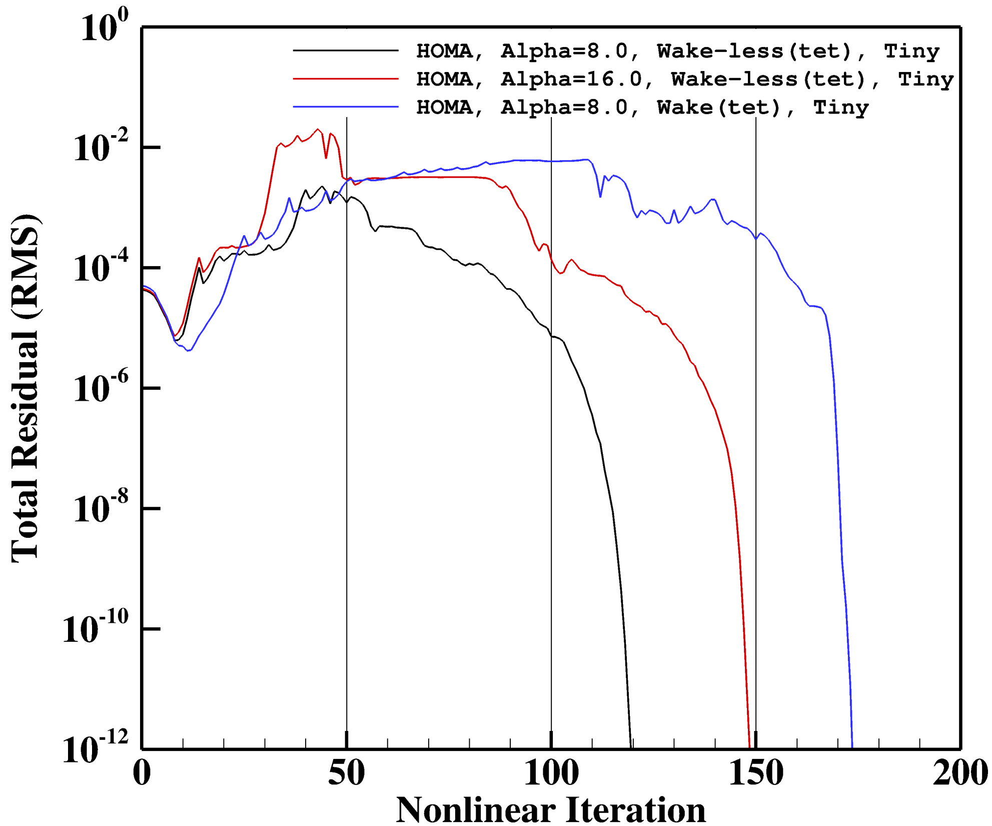
High-Lift Common Research Model, Case 1a
Convergence Histories (HOMA)



- Plateau sections of residual results in plateau sections of lift
  - Indication of isolated local changes in the solution

High-Lift Common Research Model, Case 1a

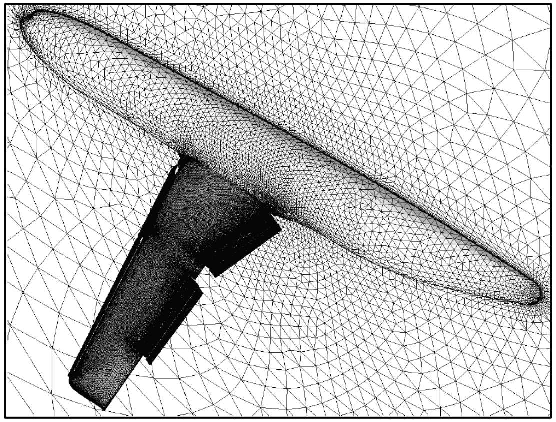
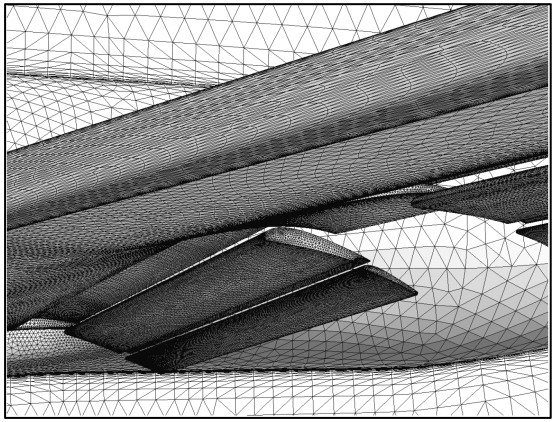
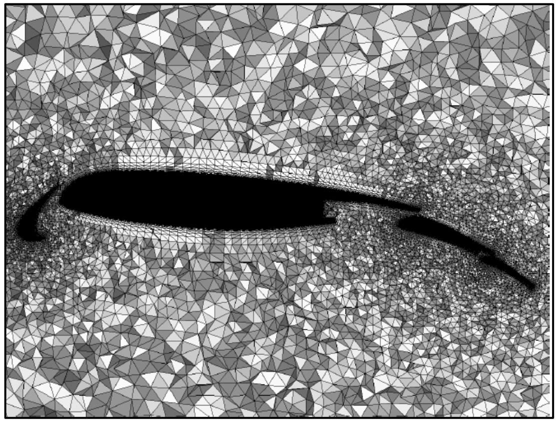
Convergence Histories (HOMA)



- Refinement of grid in the wake region results in more additional iterations compared to increasing the angle of attack.

How did we do?

A Flash Back …

D. Mavriplis and S. Pirzadeh, "Large-Scale Parallel Unstructured Mesh Computations for 3D High-Lift Analysis" Presented at the 37th AIAA Aerospace Sciences Meeting, AIAA Paper 99-0537, Reno NV, January 1999.

"Current estimates place the requirements for accurate Reynolds-averaged Navier-Stokes high-lift analysis of a complete transport aircraft configuration in the range of 10^7 to 10^8 grid points"

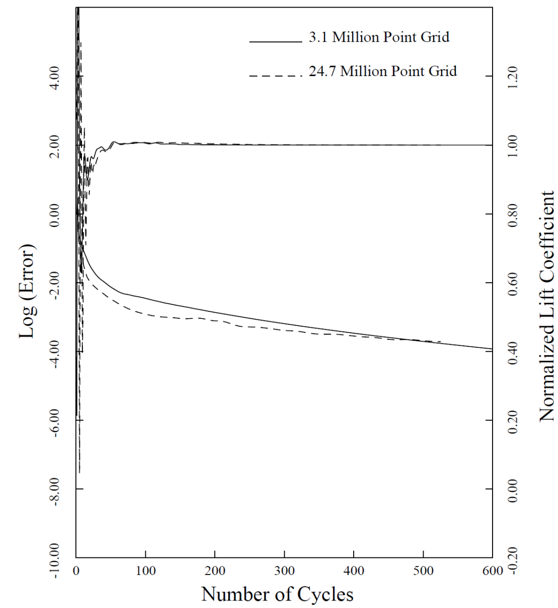
Today: This estimate is still valid and finite-element discretizations are expected to reach mesh resolved solutions at the lower bound of that range. But can they do that efficiently?

A Flash Back …

Required computational expenses reported in AIAA Paper 99-0537:

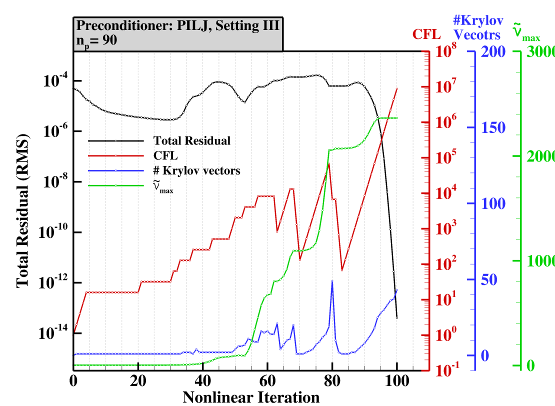
Coarse (fine) grid:

- 3.1 (24.7) million DoFs
- 7 (52) GB of memory
- 62 minutes (4.5 hours) on 256 processors of the Cray T3E-600 (300 MHz) for a 500 multigrid cycles run (residual reduction of 4 order of magnitude)



Today: Finite-element solvers can be robust and they can reach machine convergence. But are they scalable? Is machine convergence important?

- Strong scalability: positive steps toward strong linear solvers
- Weak scalability: lack of research in optimal methods (e.g. multigrid/multilevel methods)



Conclusions

Grids:

- ❑ Grids with and without wake resolutions were utilized.
  - Wake-resolved grids require more nonlinear steps.
- ❑ Larger domains are desired for future works.

Solutions:

- ❑ Different preconditioning techniques were employed by different contributors:
  - ILU(k)
  - Implicit line smoother (more desirable)
- ❑ Nonlinear convergence showed notable dependency on the grid resolution.
  - More research on the nonlinear solver is encouraged

Like HiOCFD4:

- Feasibility of high-order CFD for high-lift configuration was demonstrated.
- High-lift case still remains as a challenging task.

Acknowledgments for HOMA results

"This research was sponsored by NASA's Transformational Tools and Technologies (TTT) Project of the Transformative Aeronautics Concepts Program under the Aeronautics Research Mission Directorate."

Thank you!
Any questions?