BOEING

Boeing Contributions to the Scatter Reduction Working Group of the 8th Drag Prediction Workshop

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Boeing Commercial Airplanes

Flight Sciences - Aerodynamics

AIAA

Outline

- **Flow Solvers**
  - OVERFLOW
  - GGNS-T1
  - FELight
- **Test Cases**
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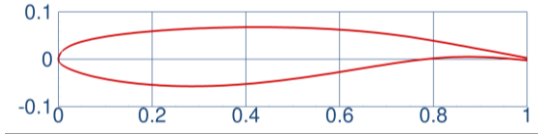
  - Test Case 1b: Joukowski Airfoil
  - Test Case 1c: ONERA OAT15A Airfoil – Part Duex
  - Test Case 1d/1e: DPW-III Case 2 Wing Only (W1/W2)
  - Test Case 2a/2b: NASA CRM Wing/Body
- **Results**
  - Force/Moments
- **Conclusions**

Flow Solvers Utilized

- **OVERFLOW (v2.4d)**
  - NASA developed overset grid solver
  - SA turbulence model (SA-neg) with many corrections (RC, CC, QCR2000, etc.)
  - HLLE++ upwind scheme (IRHS=6) with Improved SSOR algorithm (Implicit BCs + Global Linear Solve) (ILHS=26)
- **GGNS-T1**
  - Boeing developed finite element solver
  - SUPG, piecewise-linear, globally continuous finite elements with residual-based stabilization
  - Shock capturing/artificial dissipation, Newton's method, fully coupled turbulence equations
  - SA, SA-QCR2000, SARC-QCR2000
  - Grid adaptation (EPIC) (tetrahedral cells)
- **FELight**
  - Boeing developed finite element solver
  - SUPG, 2nd-order accurate in space for all equations (fully coupled turbulence equation), BFD2 and SDIRK for temporal disc.
  - Shock capturing, Newton's method with preconditioned GMRes
  - SA, SA-QCR2000, SARC-QCR2000

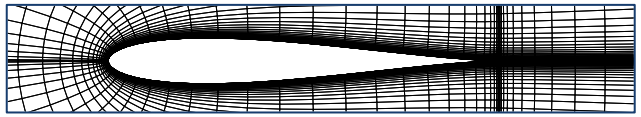
Test Cases

- 1a: ONERA OAT15A Transonic Airfoil



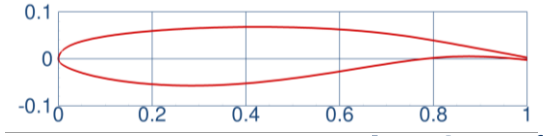
Grids:	OVERFLOW	FELight	GGNS
Cadence_Grids.REV01/Structured	X		
Custom* User Structured Grid	X		
Custom Grid Adaptation			X

- 1b: Joukouwski Airfoil (Subsonic)



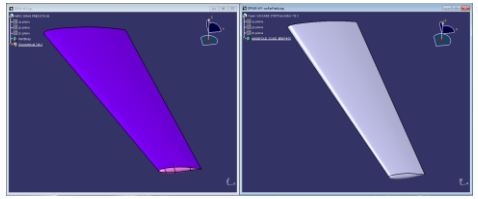
Grids:	OVERFLOW	FELight	GGNS
Python CLASSIC Grid	X	X	

- 1c: ONERA OAT15A (Transonic)



Grids:	OVERFLOW	FELight	GGNS
Helden_Grids.REV02		X	
Cadence_Grids.REV02/Unstructured		X	
Cadence_Grids.REV02/Structured	X	X	

- 1d/1e: DPW-III W1/W2 Wings



Grids	OVERFLOW	FELight	GGNS
Cadence_HexTrex_TetFF.REV00		X	X
Cadence_HexTrex_VoxelFF.REV00		X	X
HeldenMesh_Grids.REV00		X	X
Custom Grid Adaptation			X
Cadence_HexTrex_TetFF.REV01		X	
Cadence_HexTrex_VoxelFF.REV01		X	

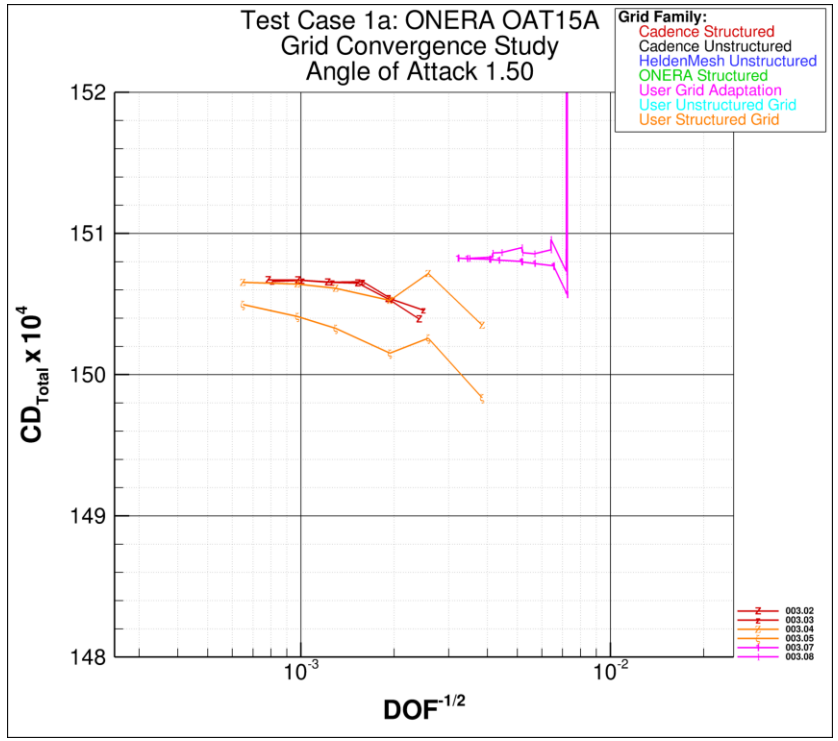
- 2a/2b: NASA CRM Wing/Body

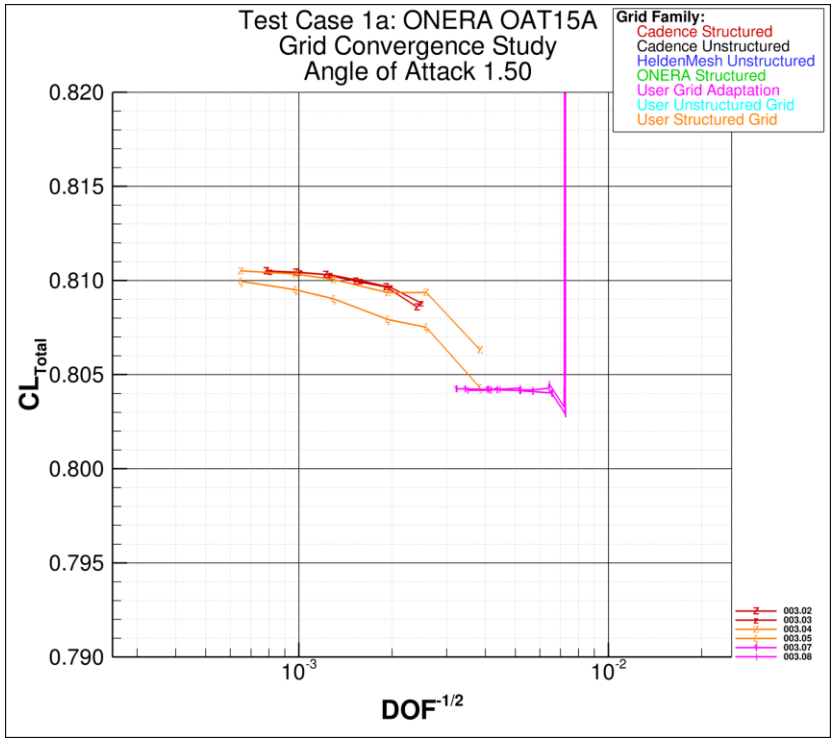
Grids	OVERFLOW	FELight	GGNS
Cadence_Grids.REV00		X	
HeldenMesh_Grids.REV00		X	
Ames_Grids.REV00	X		

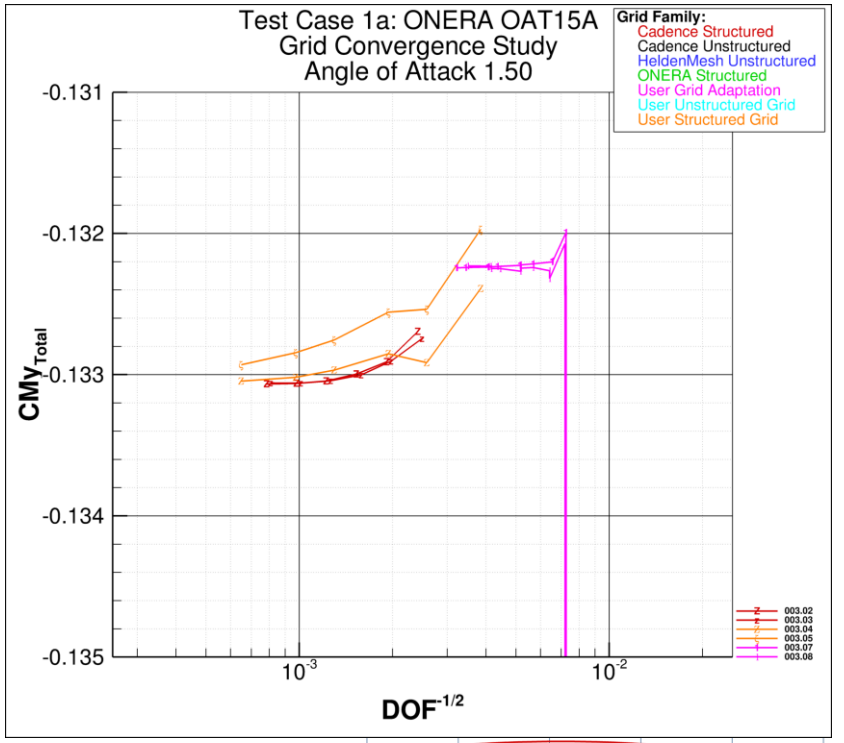
Results: Test Case 1a

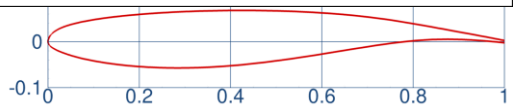
- **ONERA OAT15A Airfoil**
  - Good force/moment grid convergence
  - Some small variation between solvers

Grids:	OVERFLOW	FELight	GGNS
Cadence_Grids.REV01/Structured	X		
Custom* User Structured Grid	X		
Custom Grid Adaptation			X





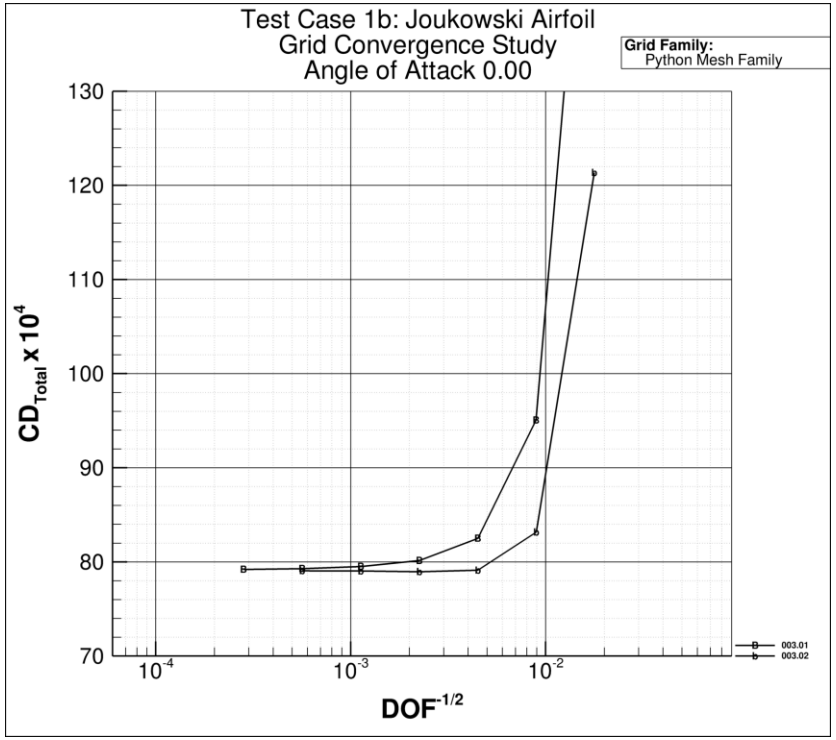


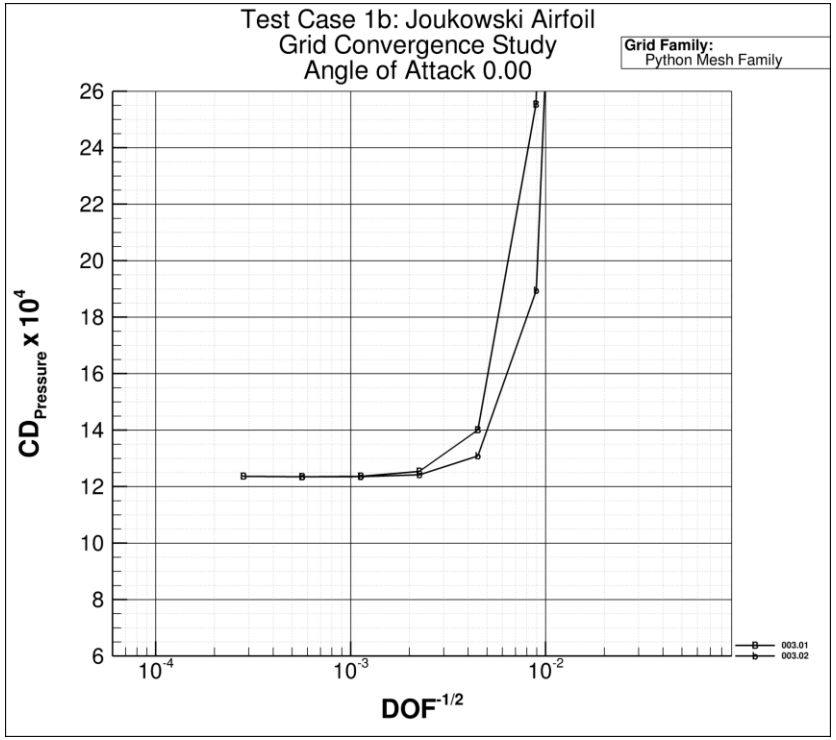


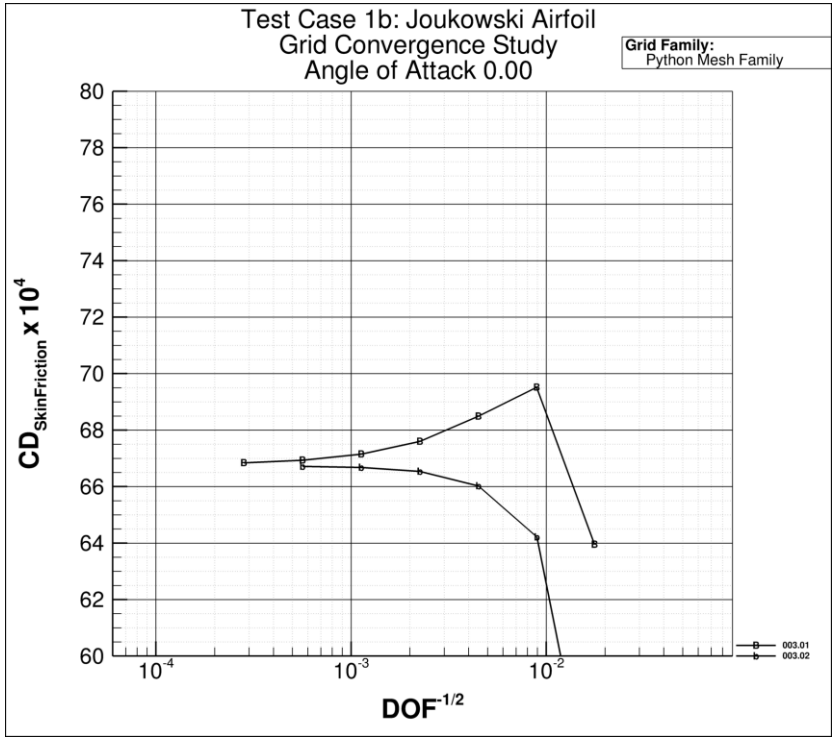
Results: Test Case 1b

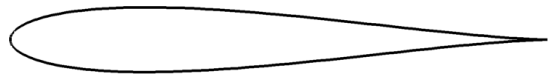
Grids:	OVERFLOW	FELight	GGNS
Python CLASSIC Grid	X	X	

- **Joukowski Airfoil**
  - Good force/moment grid convergence
  - Very small variation between solvers
  - Common grid, farfield, and problem description helped!





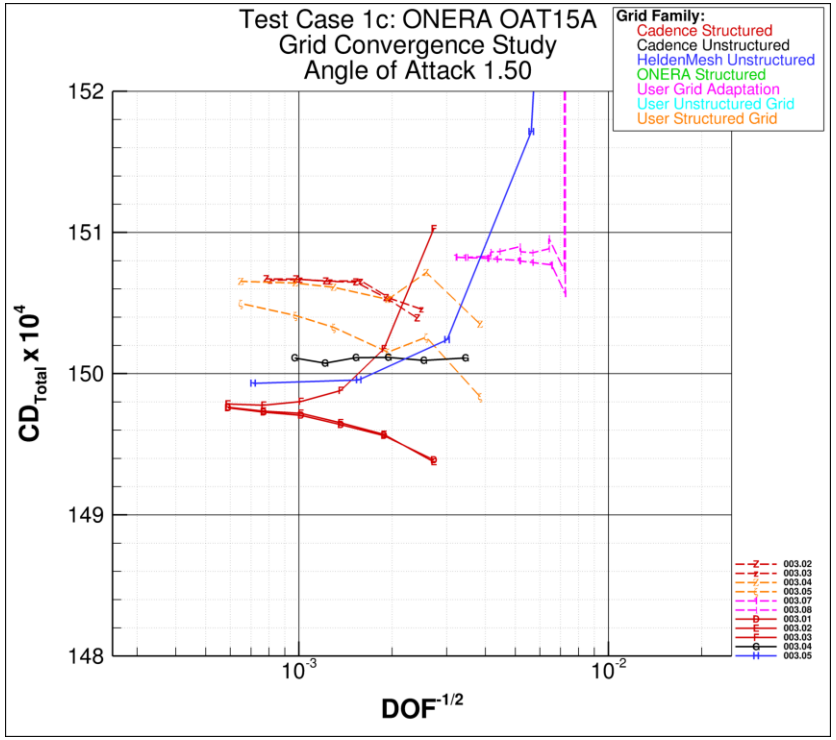


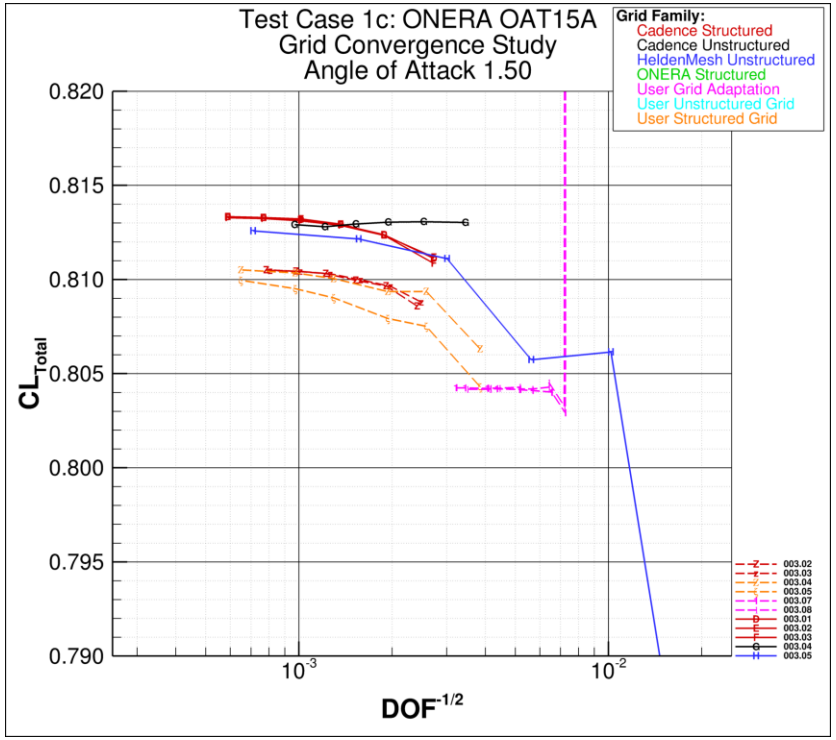


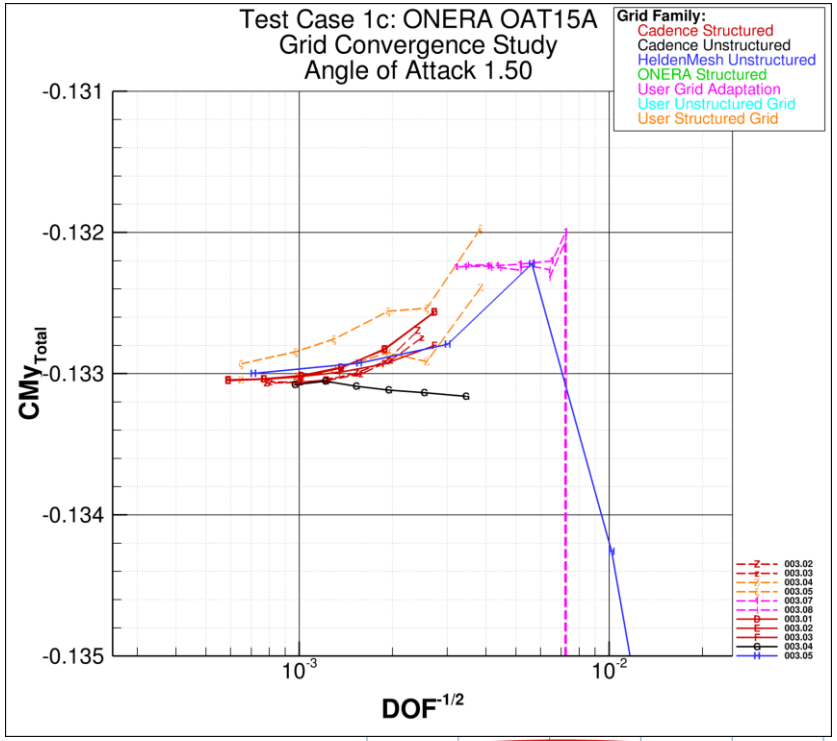
Results: Test Case 1c

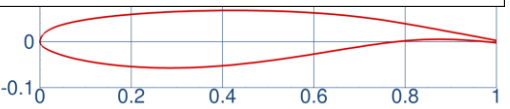
- **ONERA OAT15A Airfoil**
  - Improved agreement – Reduced scatter!
    - Common inputs to the problem between solvers
    - Common farfield distance between grids

Grids:	OVERFLOW	FELight	GGNS
Helden_Grids.REV02		X	
Cadence_Grids.REV02/Unstructured		X	
Cadence_Grids.REV02/Structured	X	X	





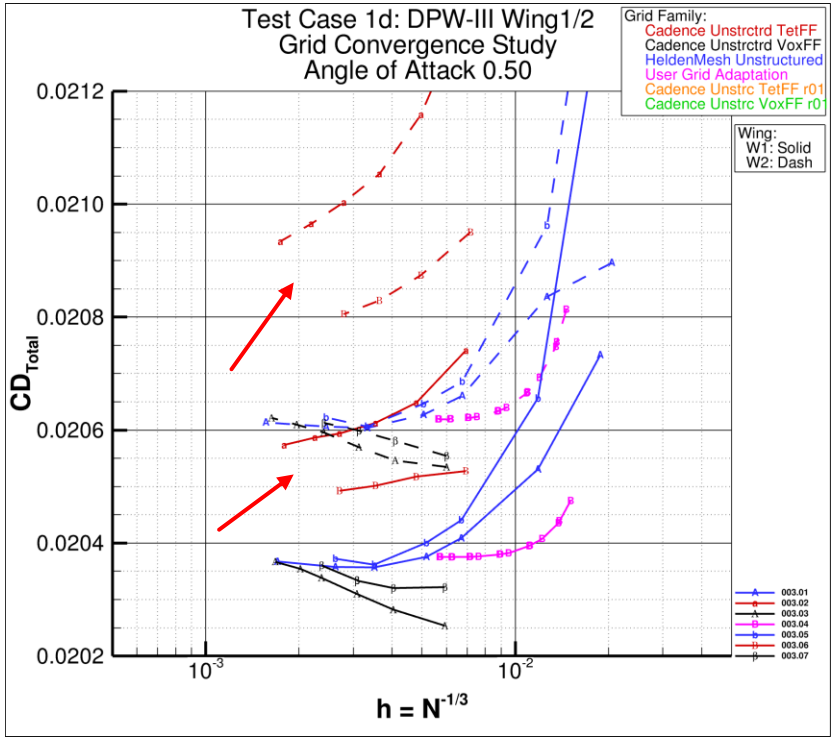


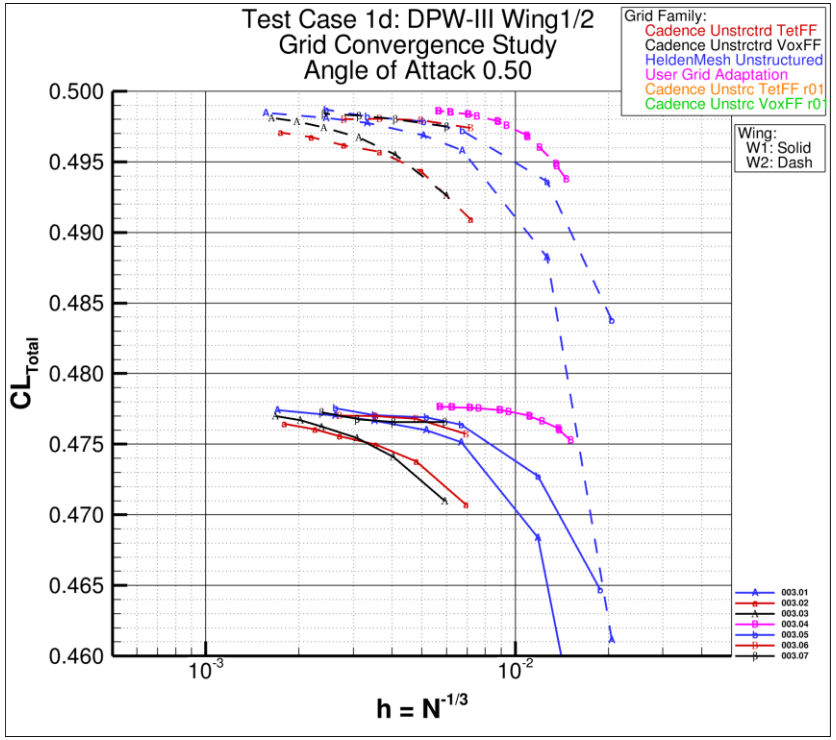


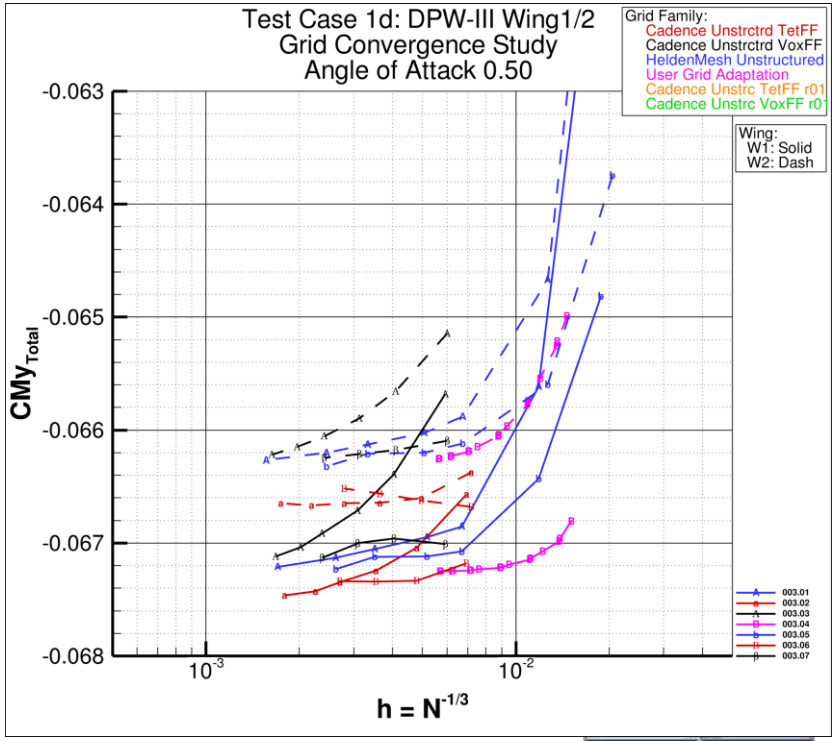
Results: Test Case 1d

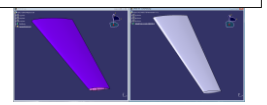
Grids	OVERFLOW	FELight	GGNS
Cadence_HexTrex_TetFF.REV00		X	X
Cadence_HexTrex_VoxelFF.REV00		X	X
HeldenMesh_Grids.REV00		X	X
Custom Grid Adaptation			X

- **DPW-III: Wing-Only Increment Test Case**
  - Grid convergence not yet demonstrated
  - Voxel FF(black), Helden(blue), and Adapted(pink) match
  - Tet Farfield (red) deviates from other results for multiple solvers







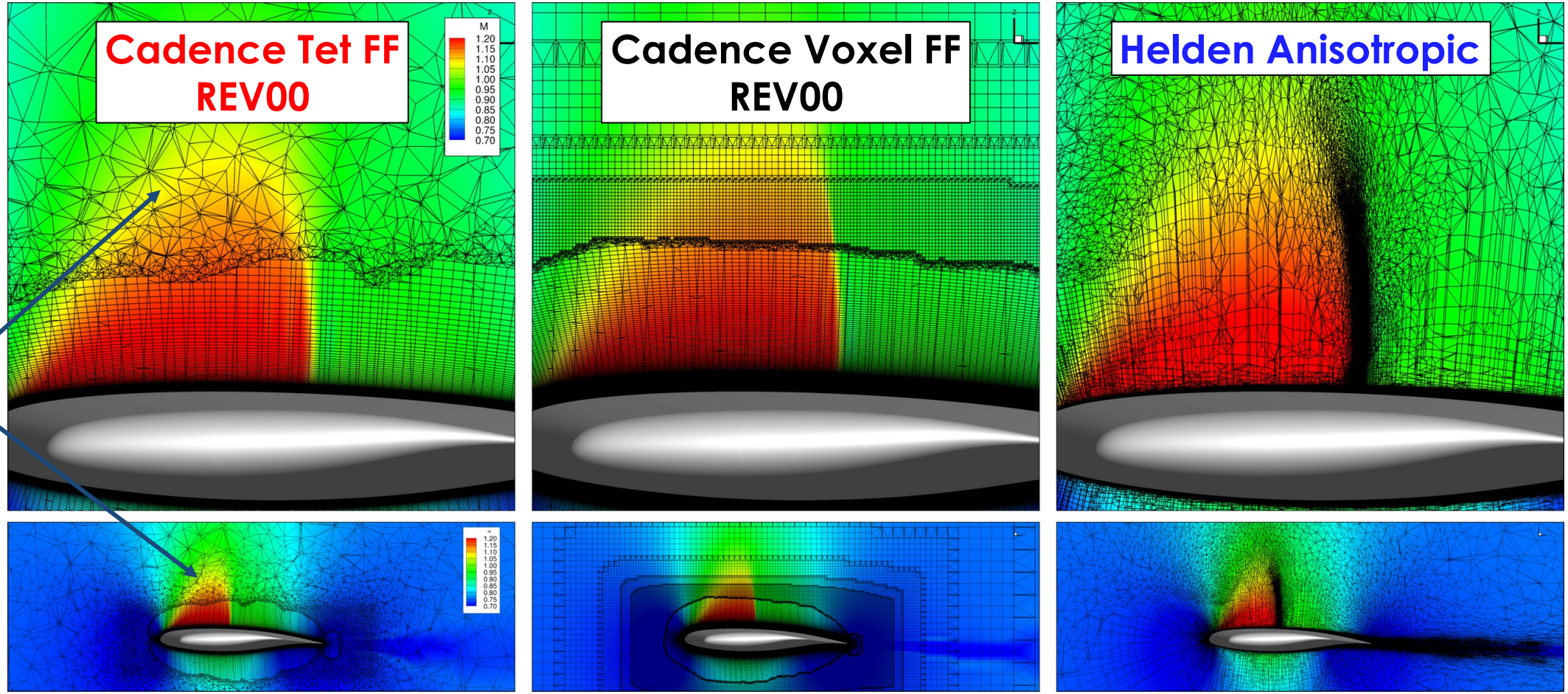


Results: Test Case 1d

- **Supersonic region and shock are not fully within near body mesh refinement**
  - As mesh is refined, the refinement only improves this area very slowly

Mach Contours
W1 | $\alpha = 0.5°$

Refinement limited

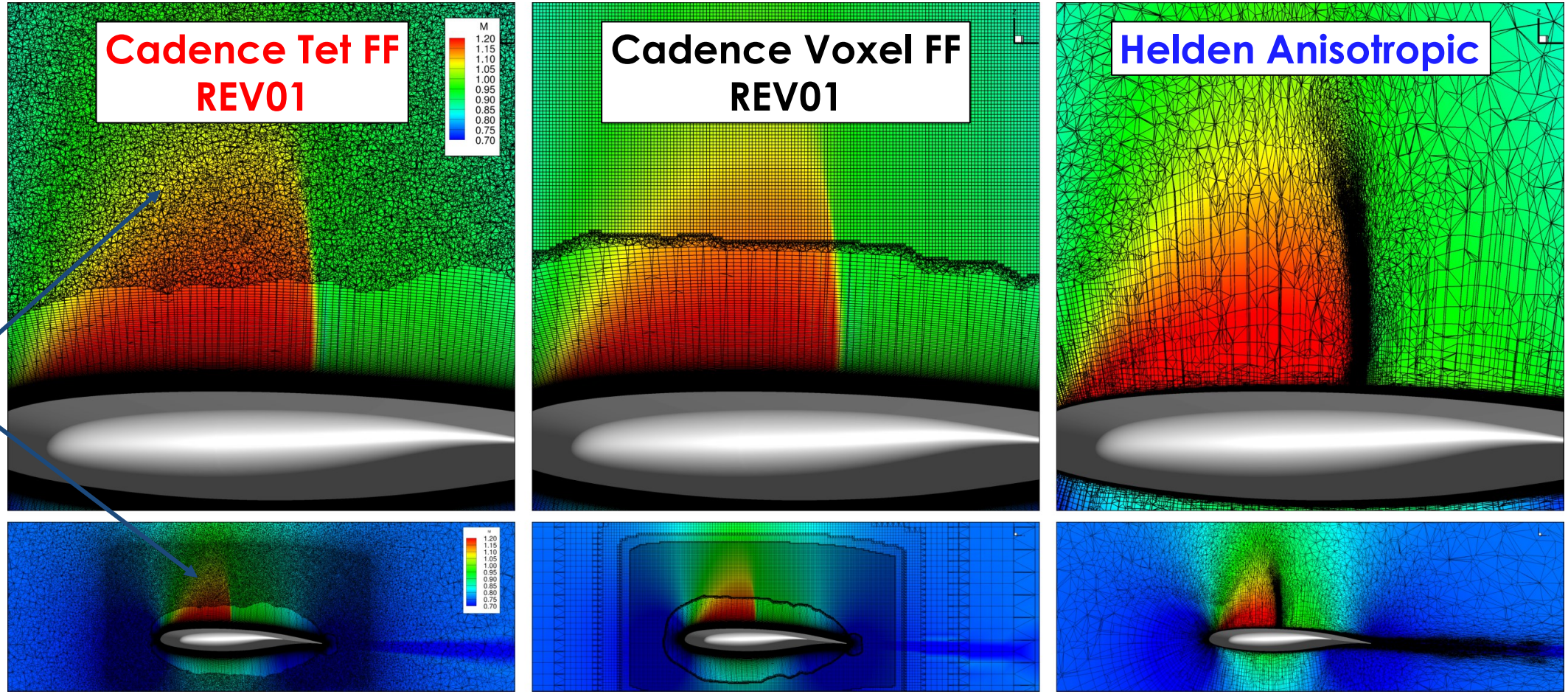


Results: Test Case 1d

- **Revised Tet and Voxel farfield meshes have larger near-body refinement region**
  - Captures the upper surface velocity gradients much more accurately

Mach Contours
W1 | $\alpha = 0.5°$

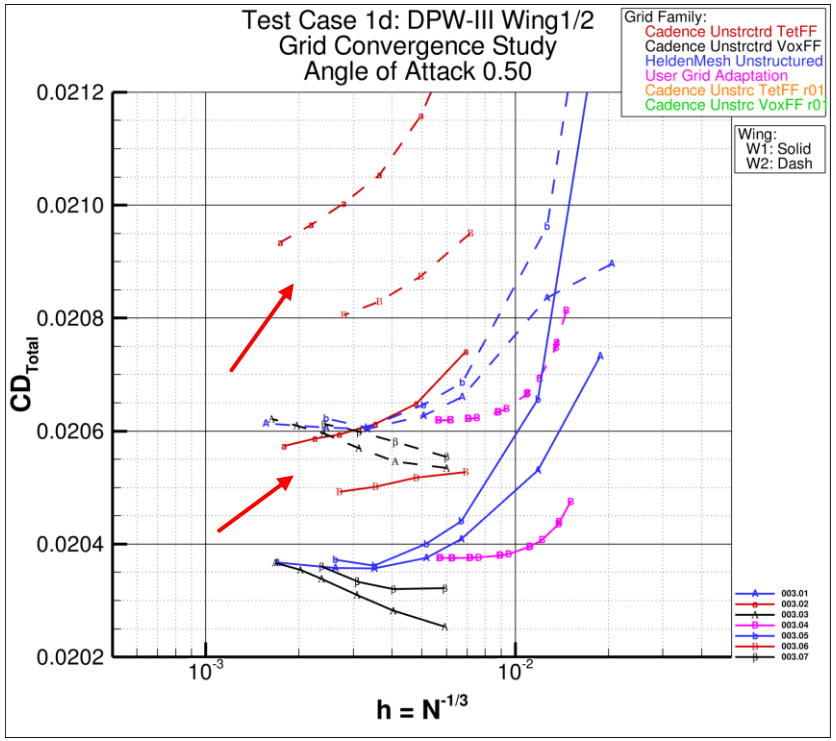
Refinement expanded

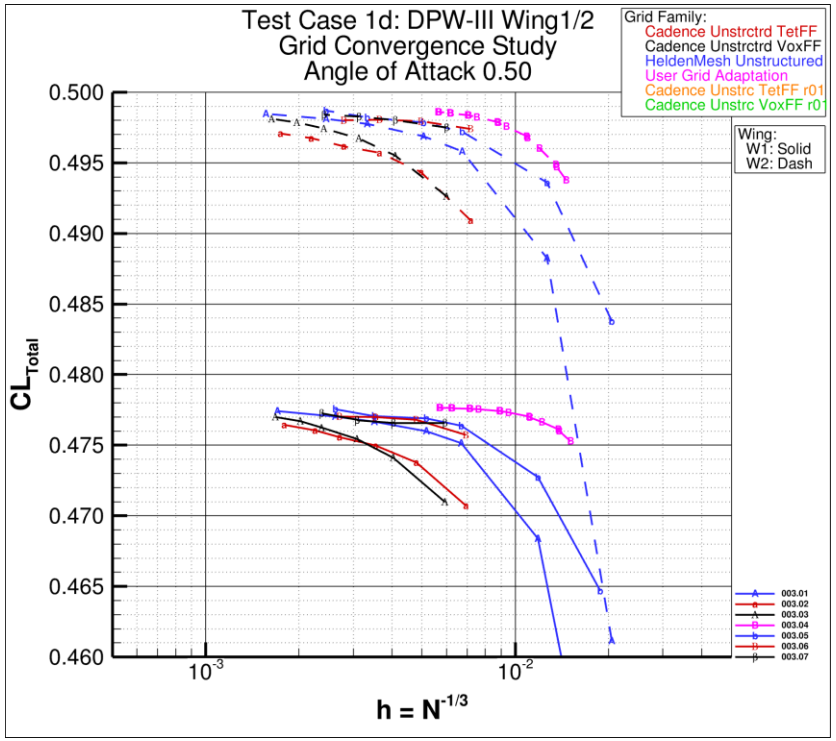


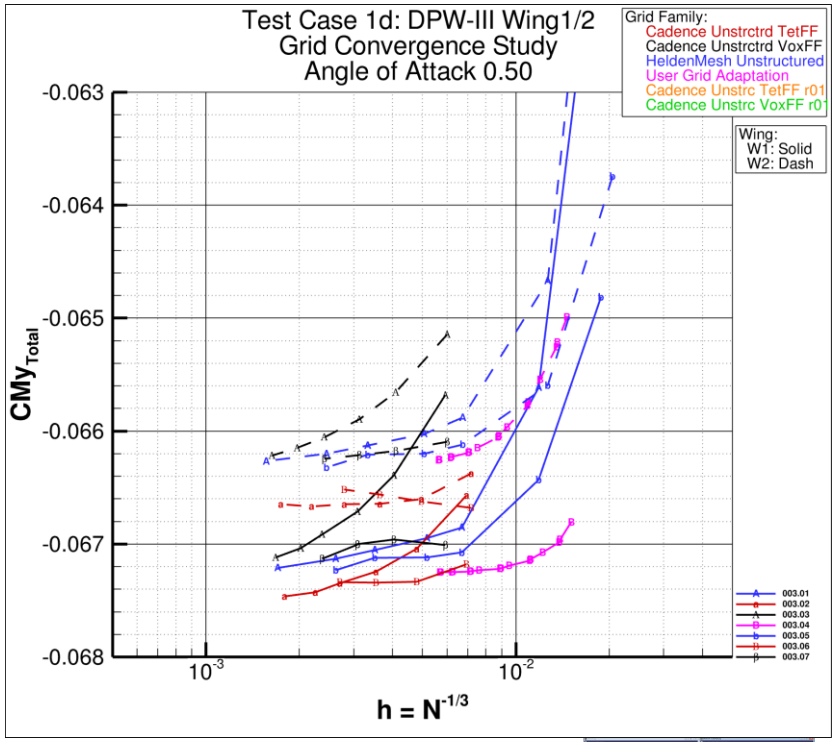
Results: Test Case 1d

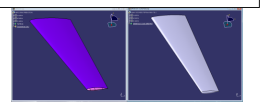
Grids	OVERFLOW	FELight	GGNS
Cadence_HexTrex_TetFF.REV00		X	X
Cadence_HexTrex_VoxelFF.REV00		X	X
HeldenMesh_Grids.REV00		X	X
Custom Grid Adaptation			X
Cadence_HexTrex_TetFF.REV01		X	
Cadence_HexTrex_VoxelFF.REV01		X	

- **DPW-III: Wing-Only Increment Test Case**
  - Grid convergence not yet demonstrated
  - Voxel FF(black), Helden(blue), and Adapted(pink) match
  - Tet Farfield (red) deviates from other results





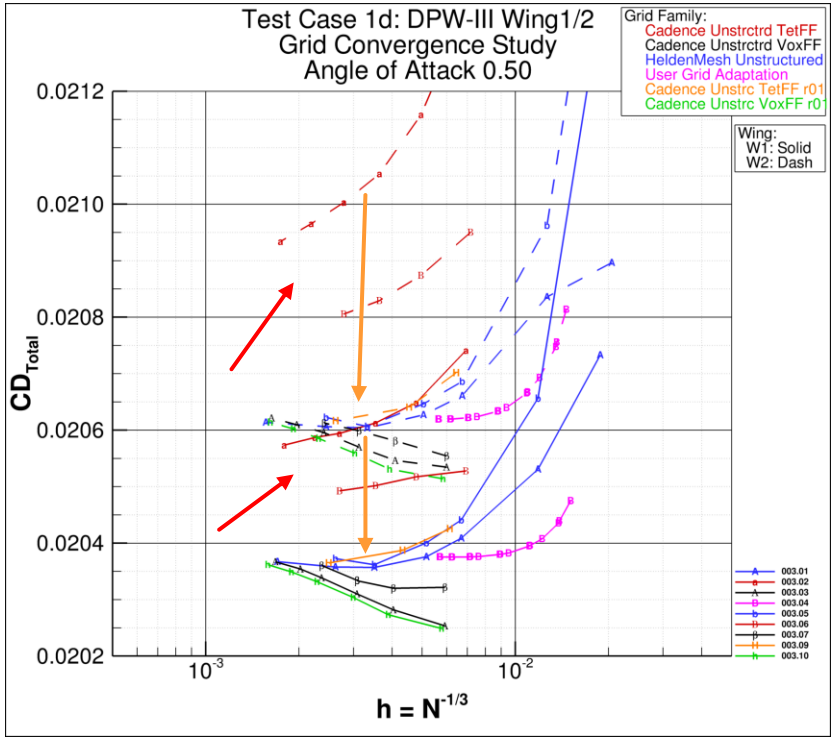


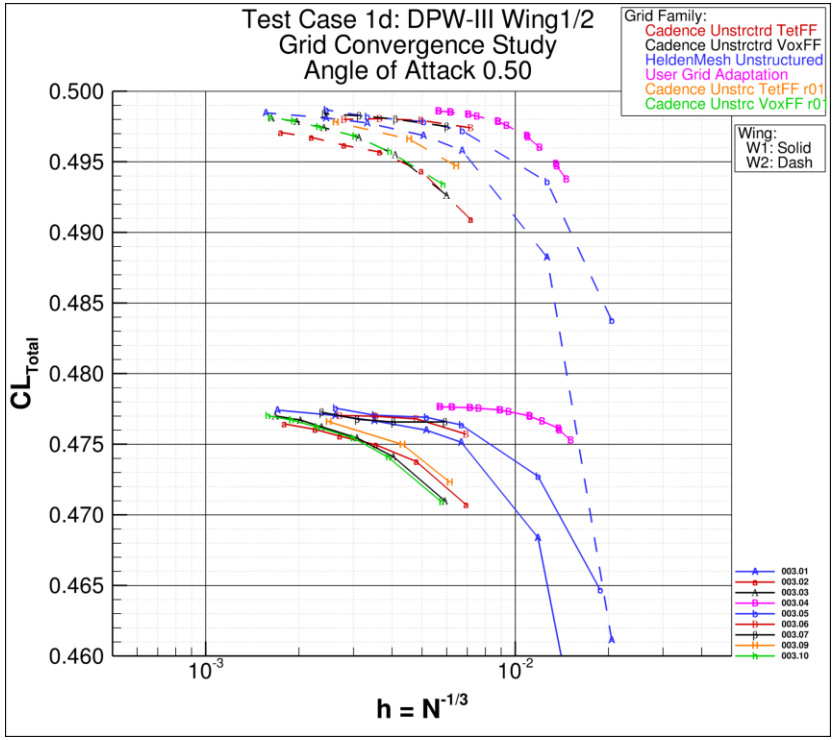


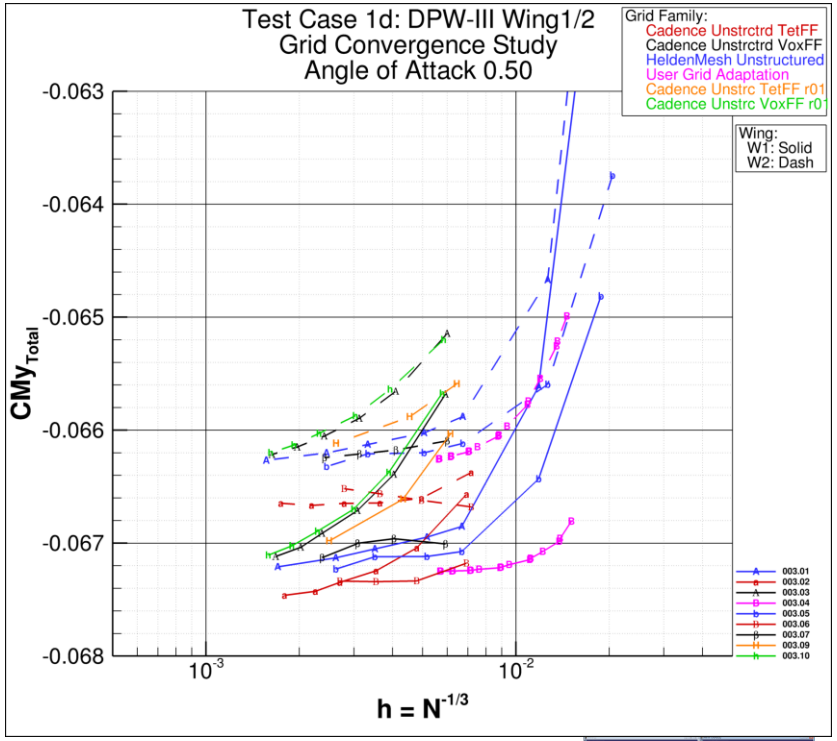
Results: Test Case 1d

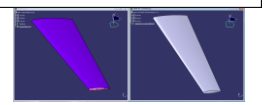
Grids	OVERFLOW	FELight	GGNS
Cadence_HexTrex_TetFF.REV00		X	X
Cadence_HexTrex_VoxelFF.REV00		X	X
HeldenMesh_Grids.REV00		X	X
Custom Grid Adaptation			X
Cadence_HexTrex_TetFF.REV01		X	
Cadence_HexTrex_VoxelFF.REV01		X	

- **DPW-III: Wing-Only Increment Test Case**
  - Grid convergence not yet demonstrated
  - Voxel FF(black), Helden(blue), and Adapted(pink) match
  - REV01 Tet Farfield (orange) shows good agreement





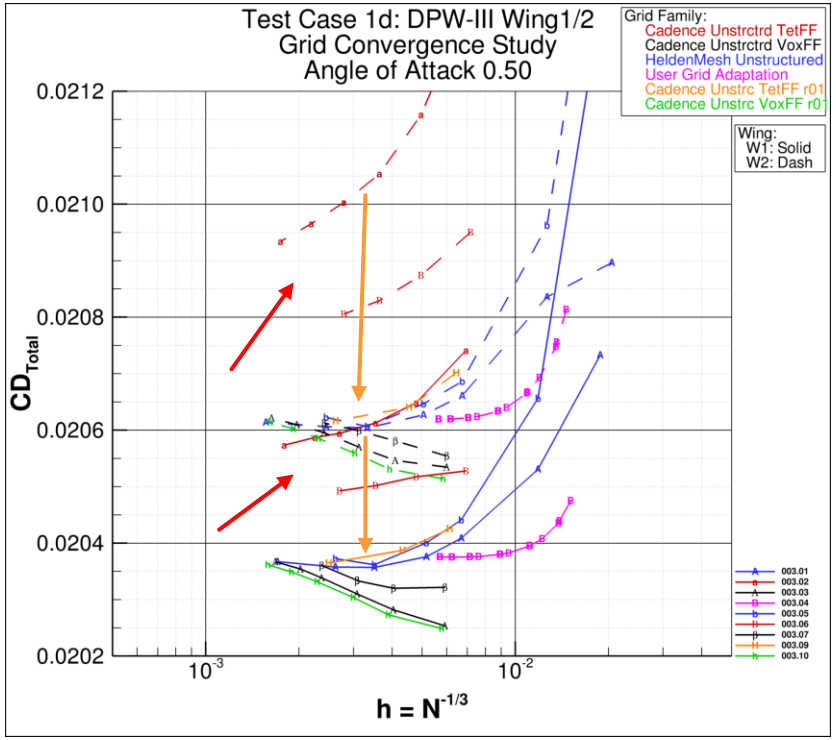


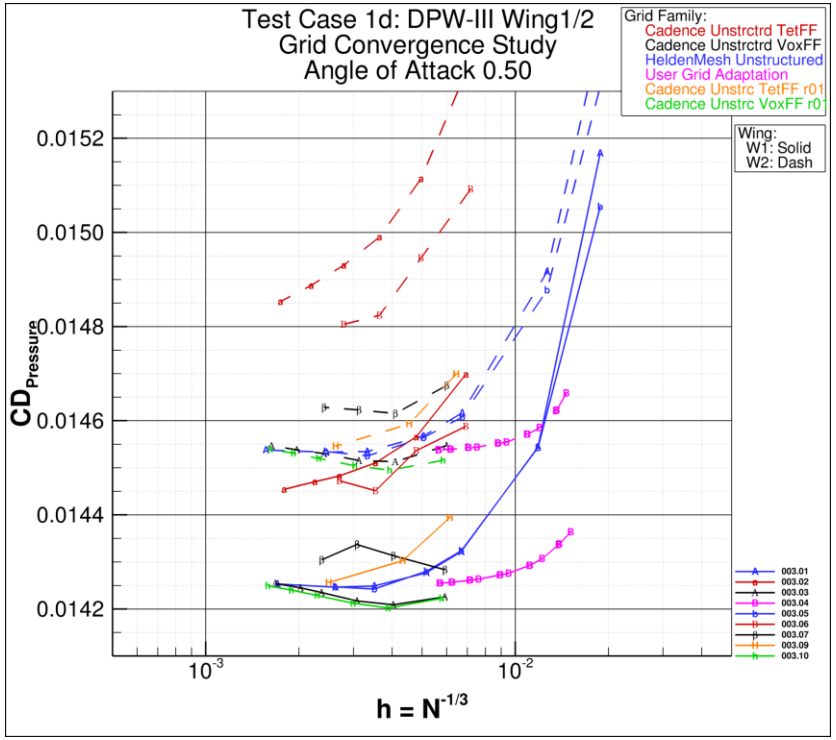


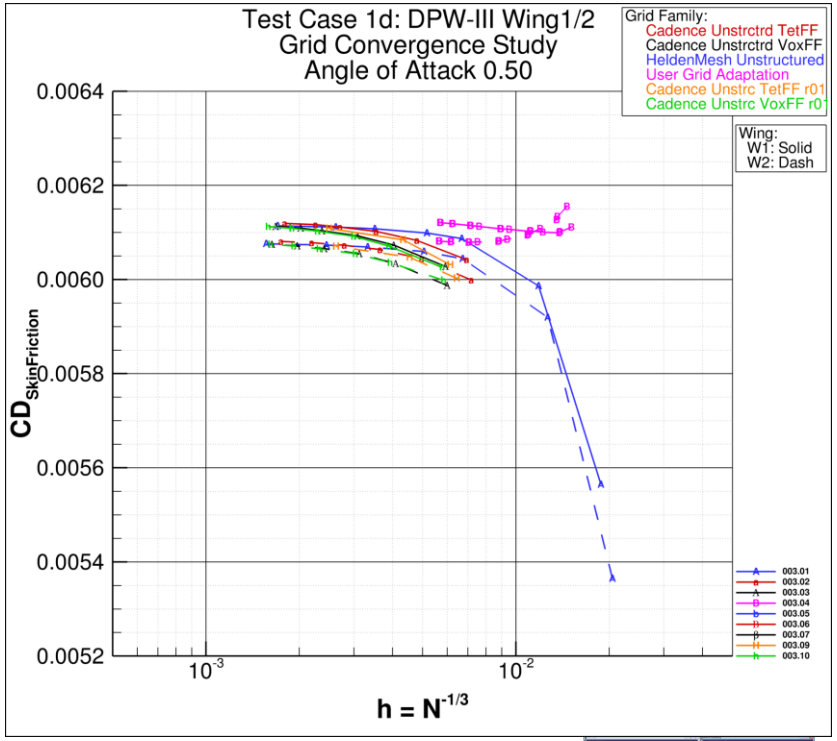
Results: Test Case 1d

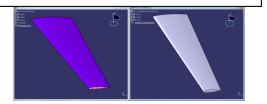
Grids	OVERFLOW	FELight	GGNS
Cadence_HexTrex_TetFF.REV00		X	X
Cadence_HexTrex_VoxelFF.REV00		X	X
HeldenMesh_Grids.REV00		X	X
Custom Grid Adaptation			X
Cadence_HexTrex_TetFF.REV01		X	
Cadence_HexTrex_VoxelFF.REV01		X	

- **DPW-III: Wing-Only Increment Test Case**
  - Grid convergence not yet demonstrated
  - Voxel FF(black), Helden(blue), and Adapted(pink) match
  - REV01 Tet Farfield (orange) shows good agreement





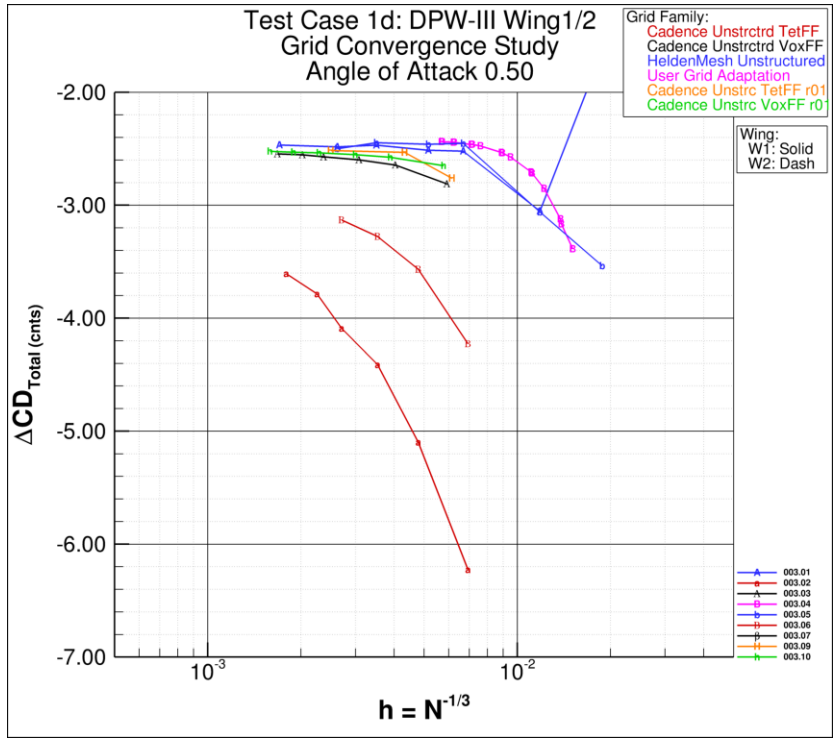


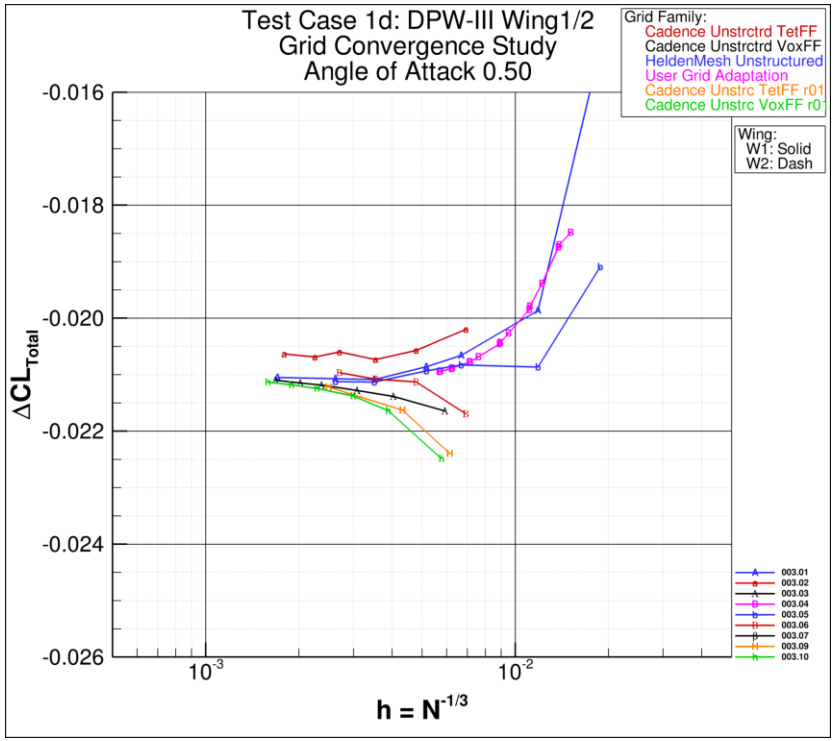


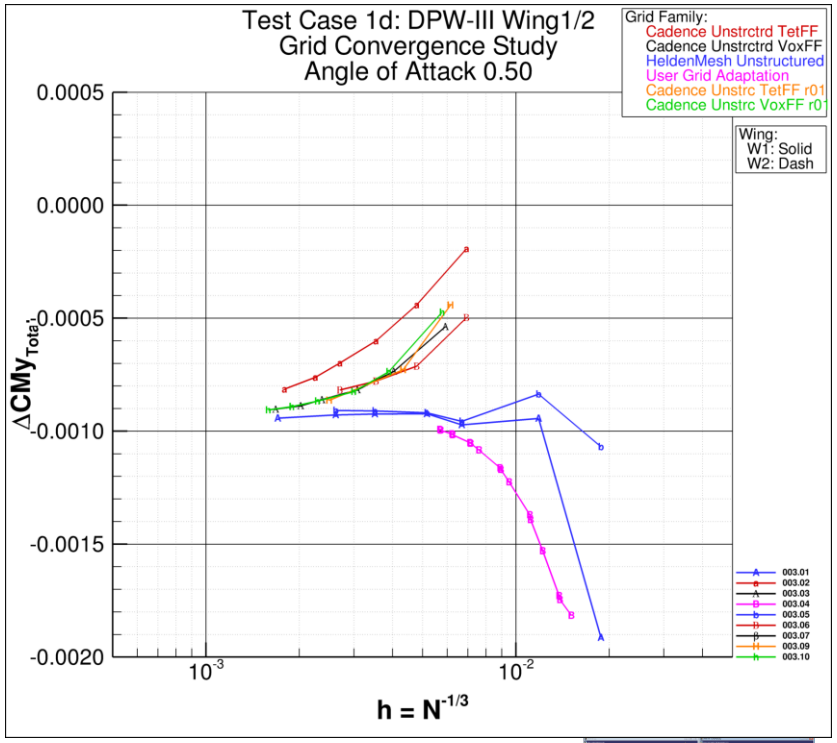
Results: Test Case 1d

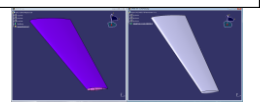
Grids	OVERFLOW	FELight	GGNS
Cadence_HexTrex_TetFF.REV00		X	X
Cadence_HexTrex_VoxelFF.REV00		X	X
HeldenMesh_Grids.REV00		X	X
Custom Grid Adaptation			X
Cadence_HexTrex_TetFF.REV01		X	
Cadence_HexTrex_VoxelFF.REV01		X	

- **DPW-III: Wing-Only Increment Test Case**
  - Tet farfield REV00 (red) increments deviate!
  - Can not assume increments are always good





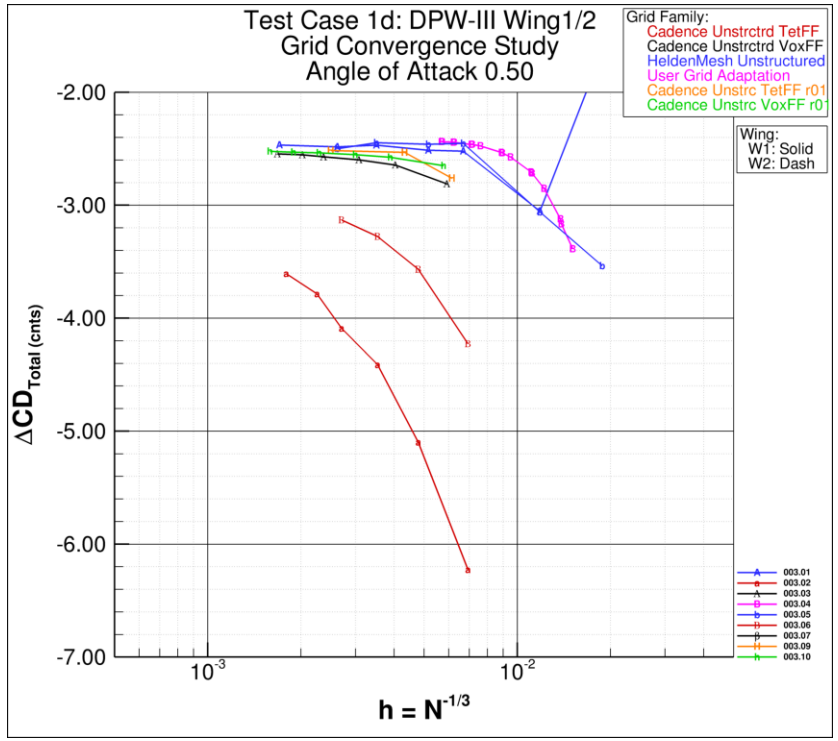


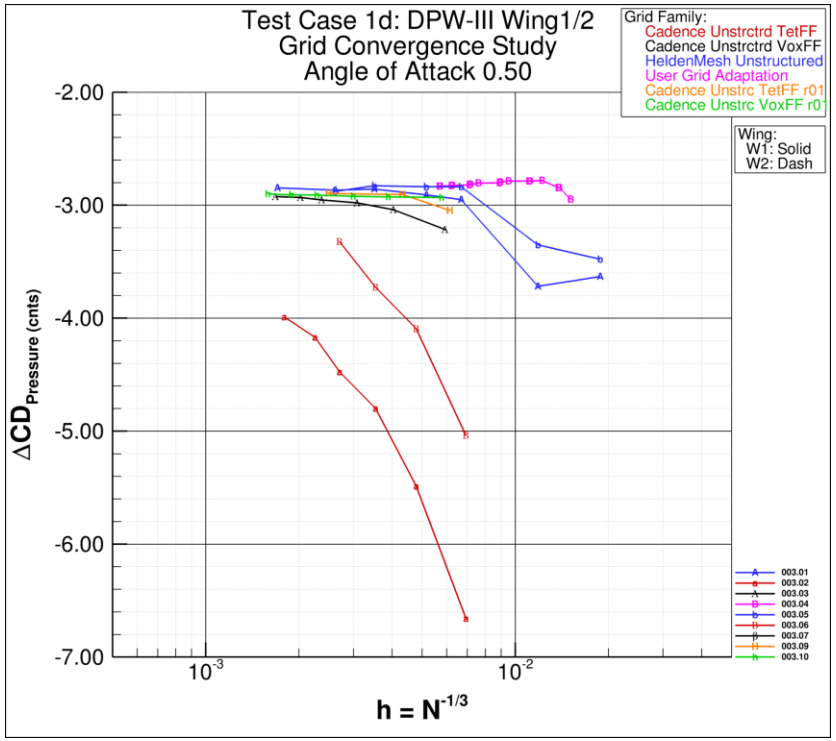


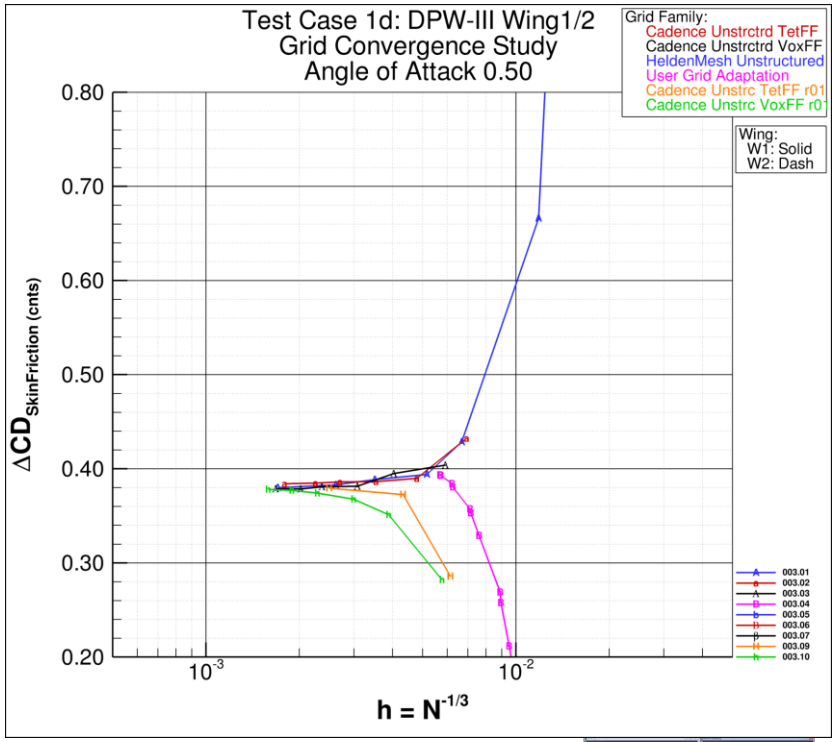
Results: Test Case 1d

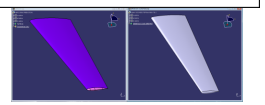
Grids	OVERFLOW	FELight	GGNS
Cadence_HexTrex_TetFF.REV00		X	X
Cadence_HexTrex_VoxelFF.REV00		X	X
HeldenMesh_Grids.REV00		X	X
Custom Grid Adaptation			X
Cadence_HexTrex_TetFF.REV01		X	
Cadence_HexTrex_VoxelFF.REV01		X	

- **DPW-III: Wing-Only Increment Test Case**
  - Tet farfield REV00 (red) increments deviate
  - Pressure drag is the source of the difference
  - Skin friction matches well





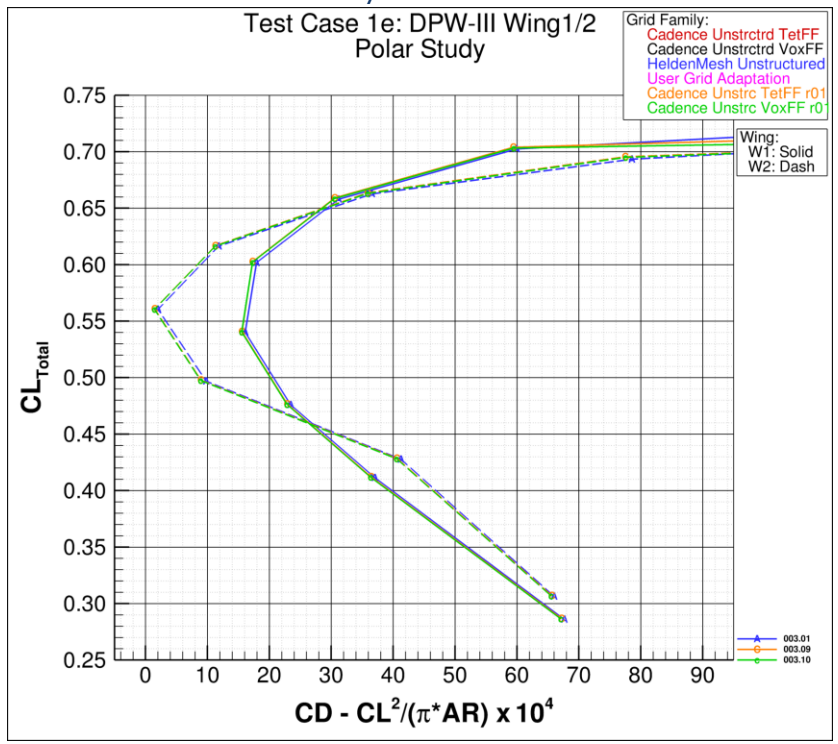


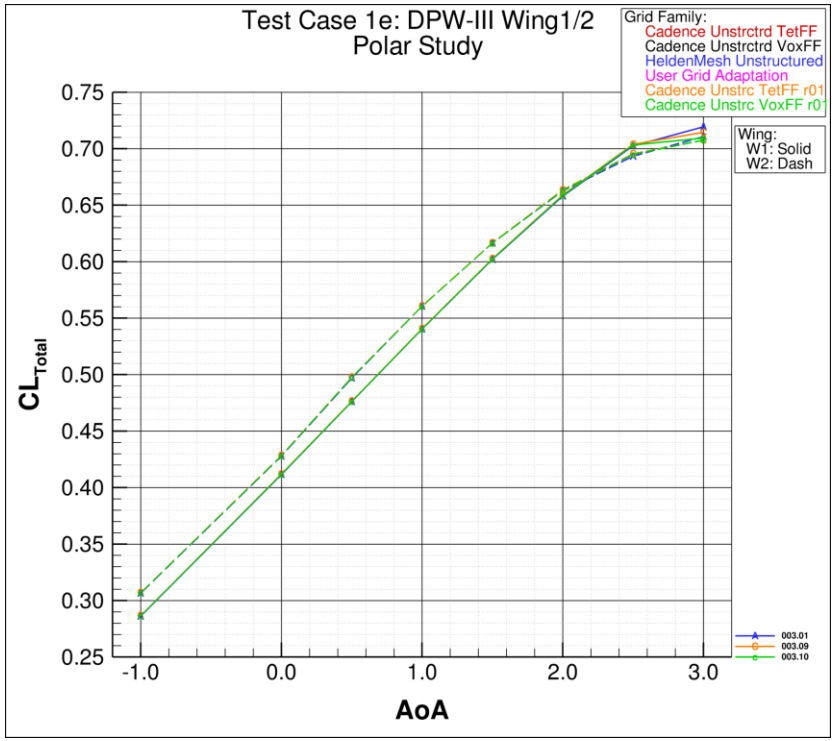


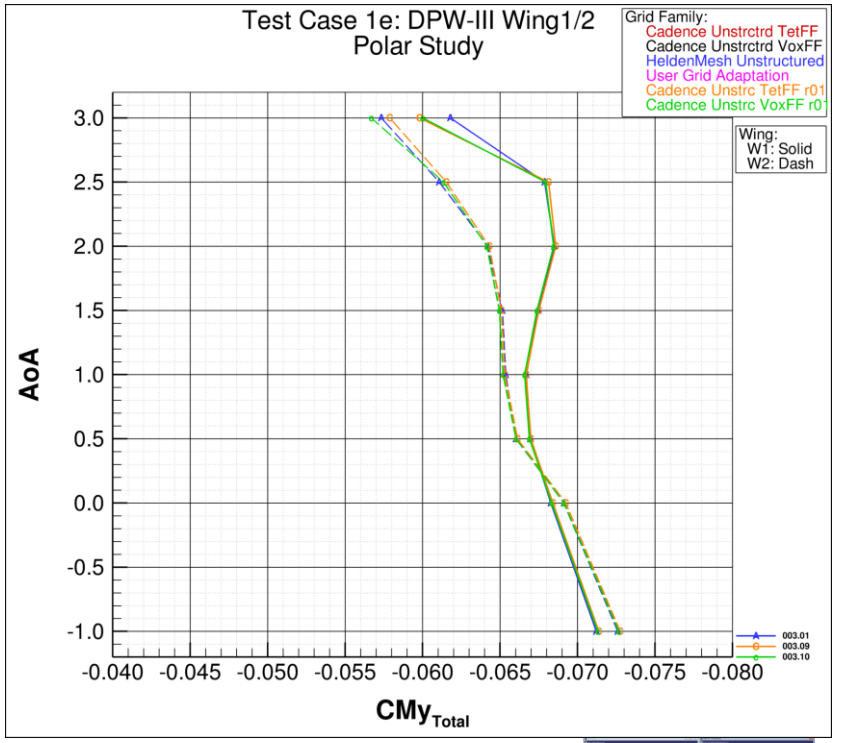
Results: Test Case 1e

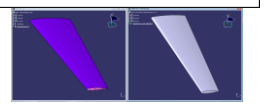
- **DPW-III: Wing-Only Test Case**
  - Good agreement between three meshes for α =[-1.0,2.5]
    - Drag scatter less than +/- 0.5 counts
  - Residual convergence very difficult for α =3.0
    - Likely source of scatter

Grids	OVERFLOW	FELight	GGNS
HeldenMesh_Grids.REV00		X	
Cadence_HexTrex_TetFF.REV01		X	
Cadence_HexTrex_VoxelFF.REV01		X	





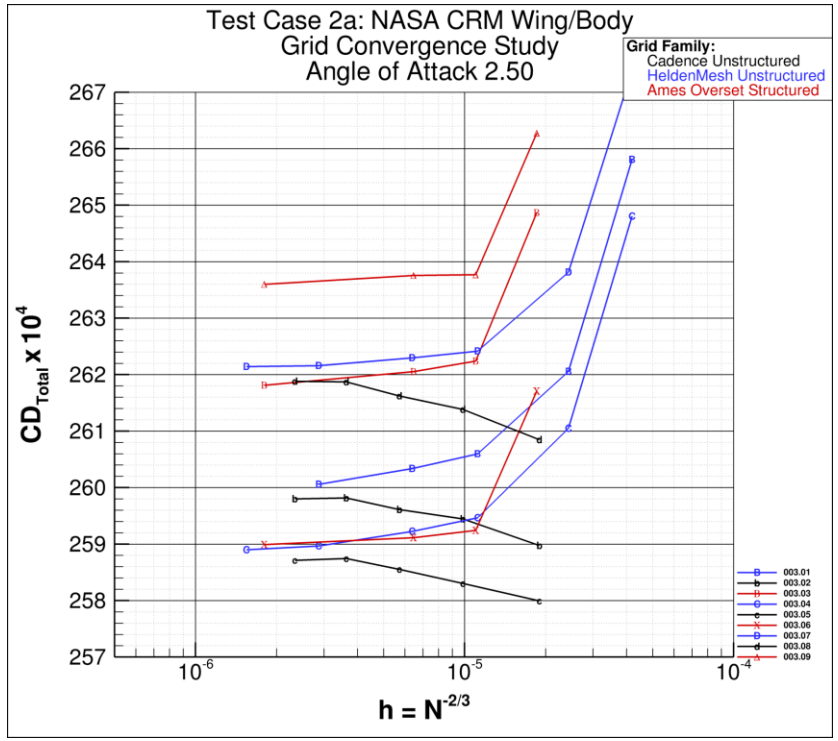


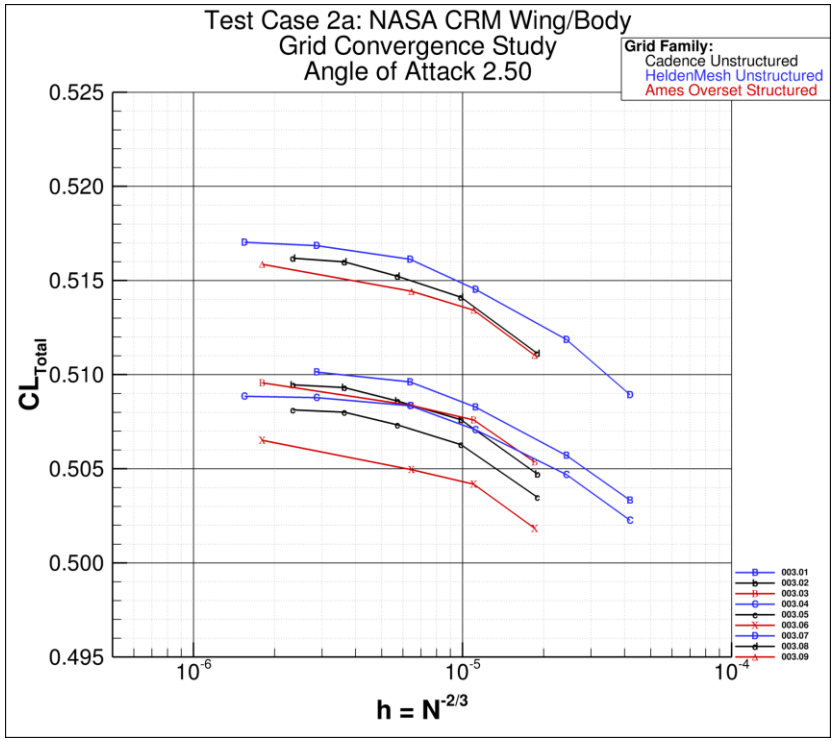


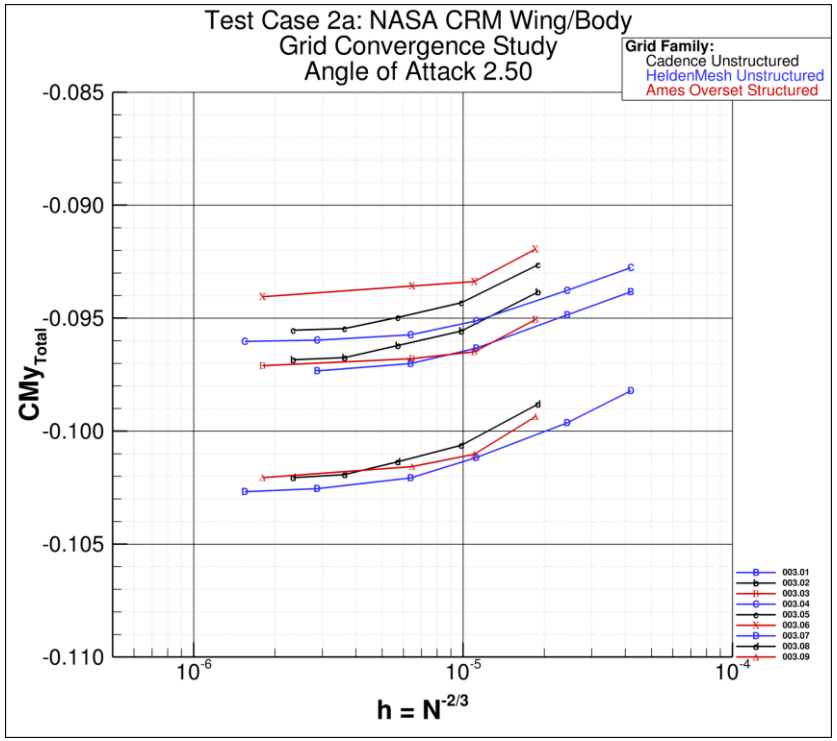
Results: Test Case 2a

- **NASA CRM Wing/Body**
  - Lines colored by grid family
  - Grid convergence not yet demonstrated
  - Drag scatter ~ +/- 2.5 counts

Grids	OVERFLOW	FELight	GGNS
Cadence_Grids.REV00		X	
HeldenMesh_Grids.REV00		X	
Ames_Grids.REV00	X		



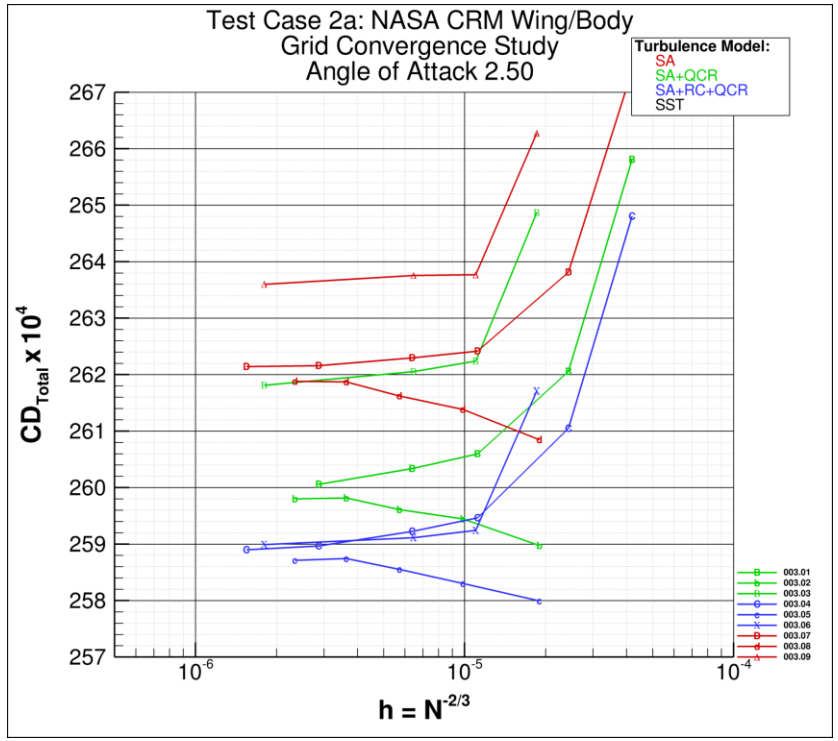


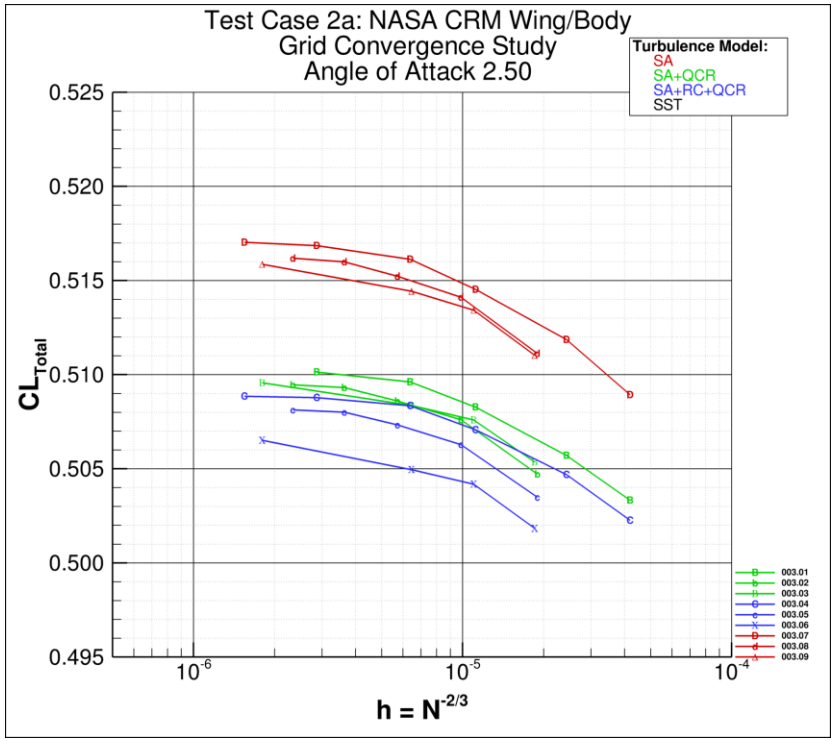


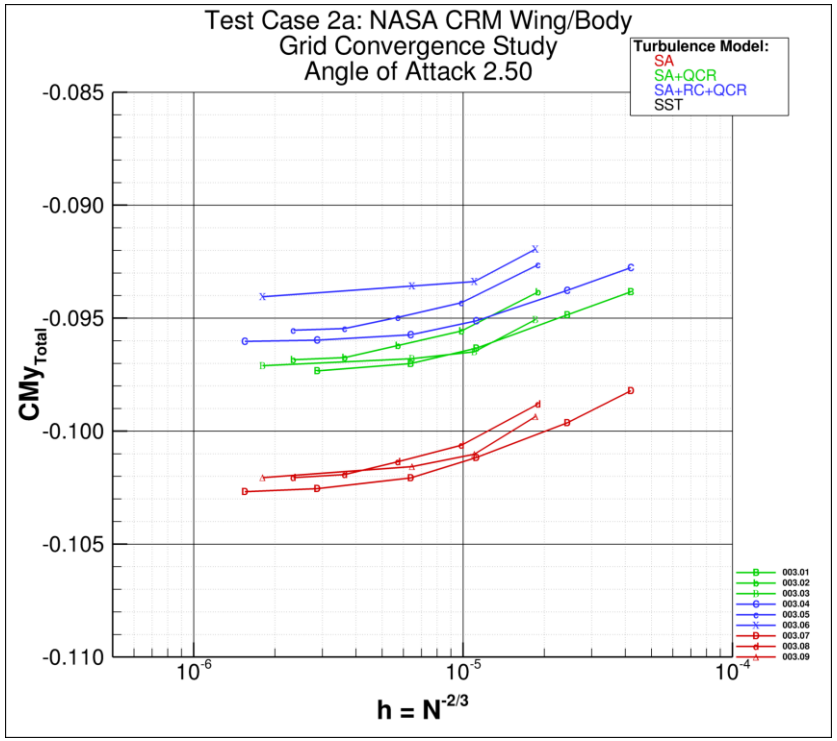
Results: Test Case 2a

- **NASA CRM Wing/Body**
  - Lines colored by turbulence model
  - RC correction to SA model shows clear impact
    - Drag scatter ~ +/- 1 count within the same turbulence model

Grids	OVERFLOW	FELight	GGNS
Cadence_Grids.REV00		X	
HeldenMesh_Grids.REV00		X	
Ames_Grids.REV00	X		



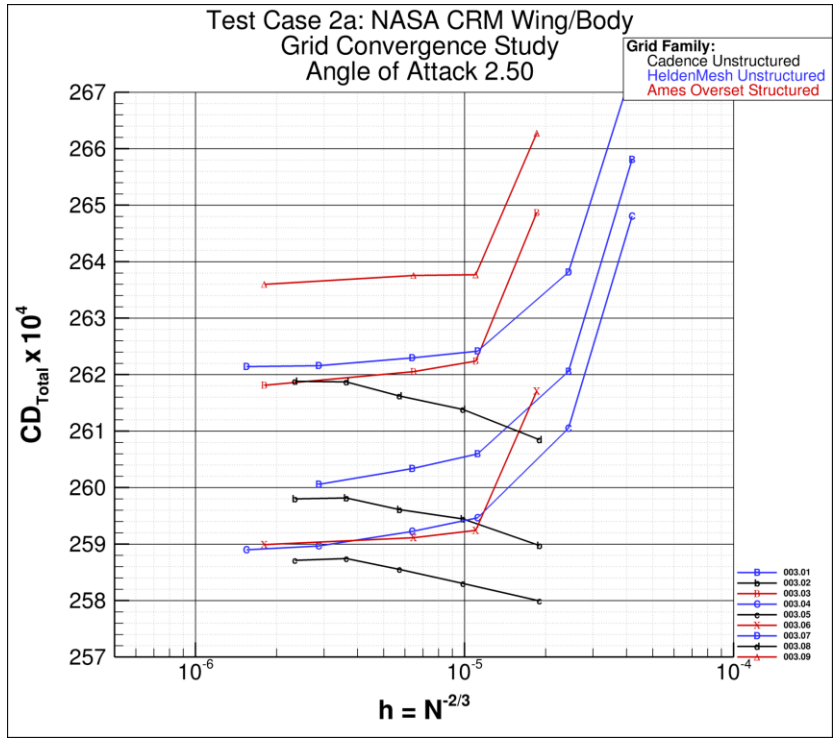


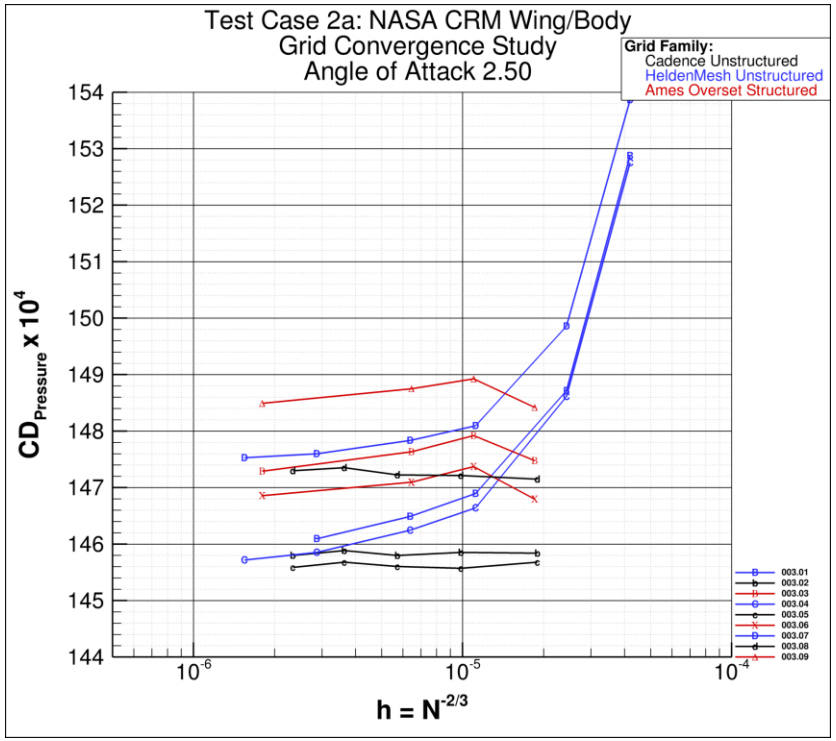


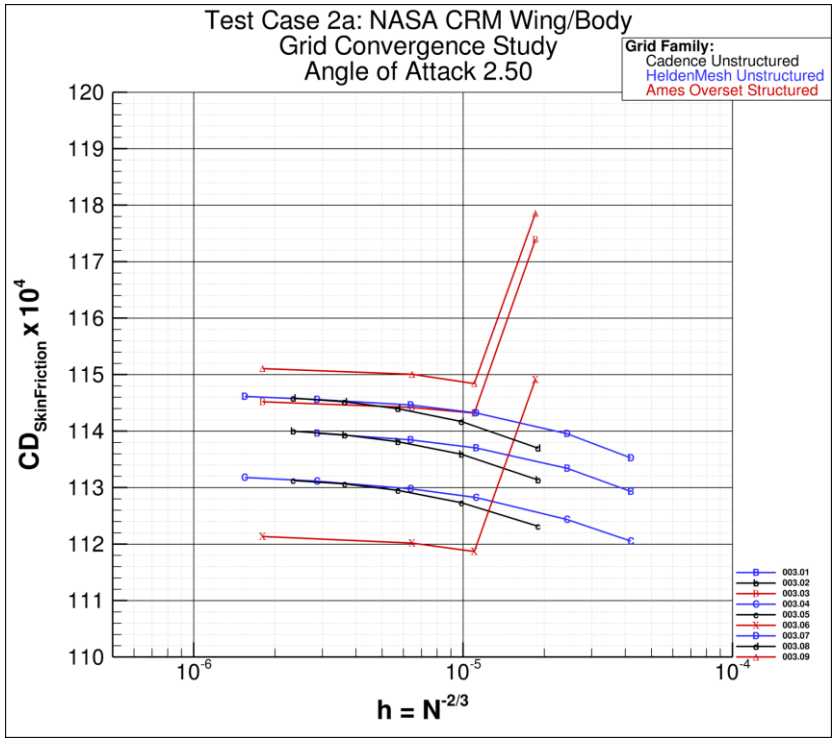
Results: Test Case 2a

- **NASA CRM Wing/Body**
  - Lines colored by grid family
  - Grid convergence not yet demonstrated
  - Drag scatter ~ +/-2.5 count

Grids	OVERFLOW	FELight	GGNS
Cadence_Grids.REV00		X	
HeldenMesh_Grids.REV00		X	
Ames_Grids.REV00	X		



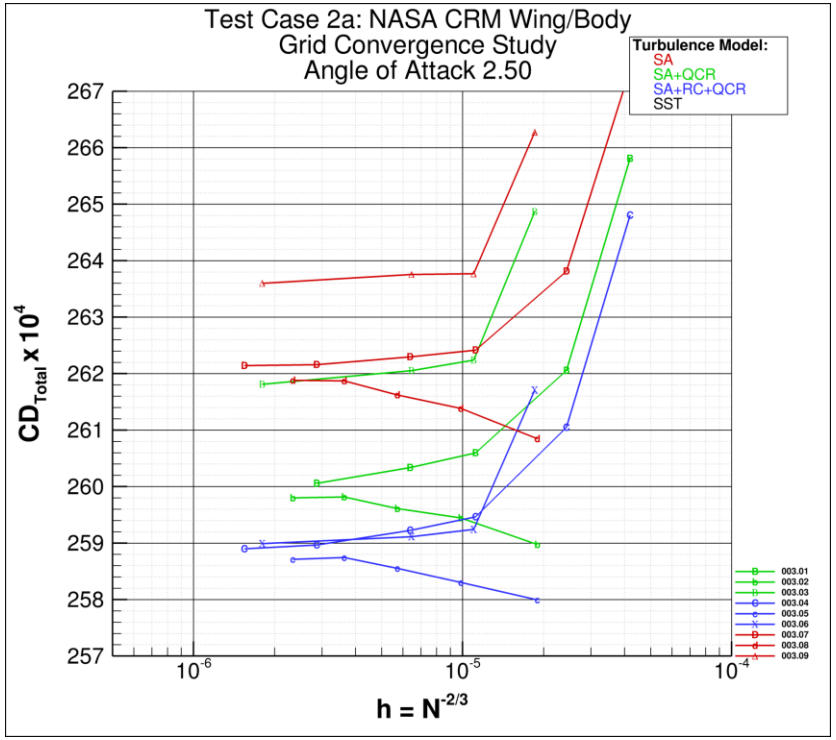


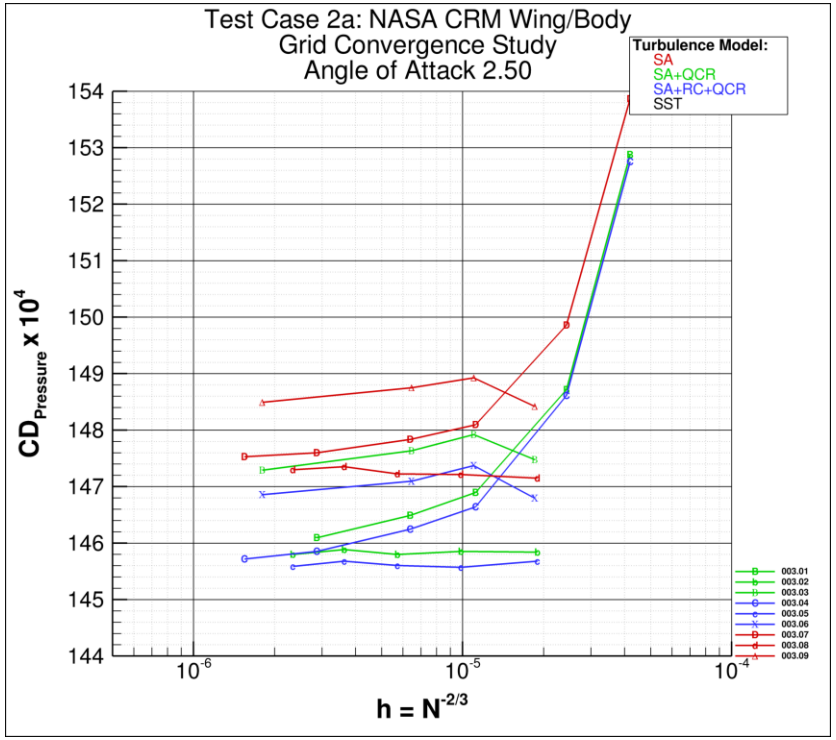


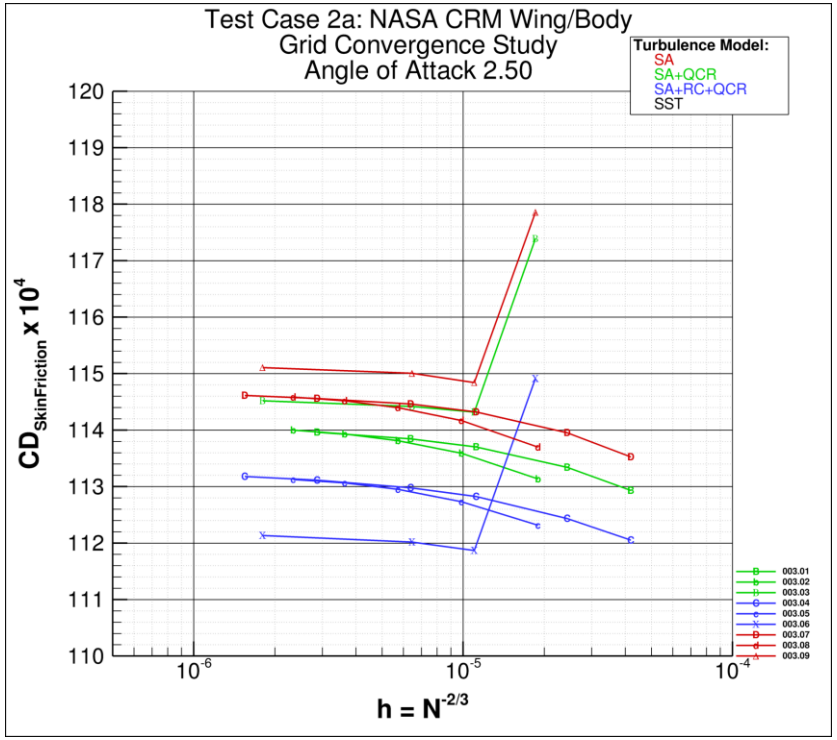
Results: Test Case 2a

- **NASA CRM Wing/Body**
  - Lines colored by turbulence model
  - RC correction to SA model shows clear impact
    - Drag scatter ~ +/- 1 count within the same turbulence model

Grids	OVERFLOW	FELight	GGNS
Cadence_Grids.REV00		X	
HeldenMesh_Grids.REV00		X	
Ames_Grids.REV00	X		



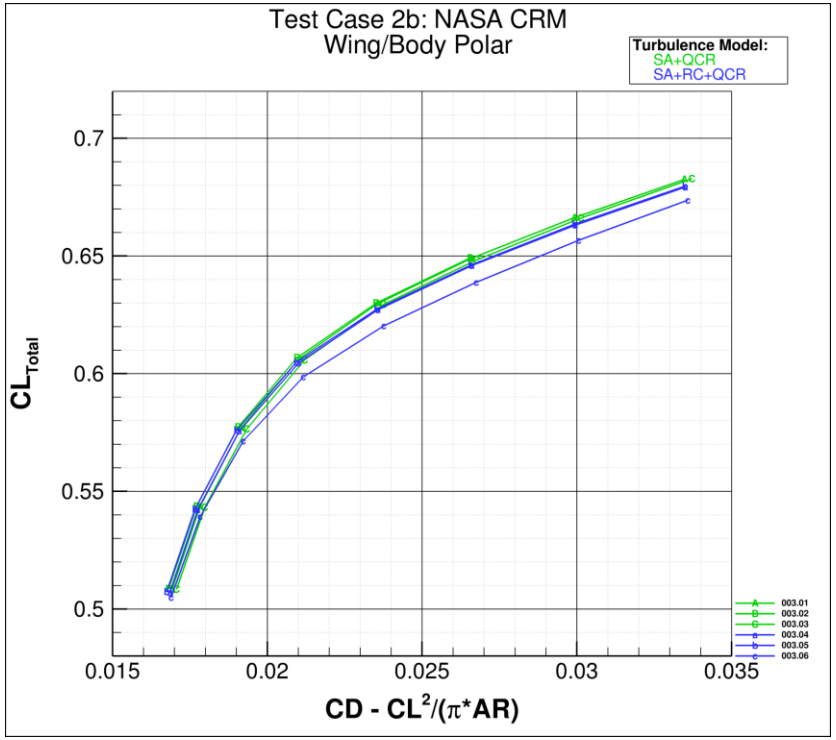


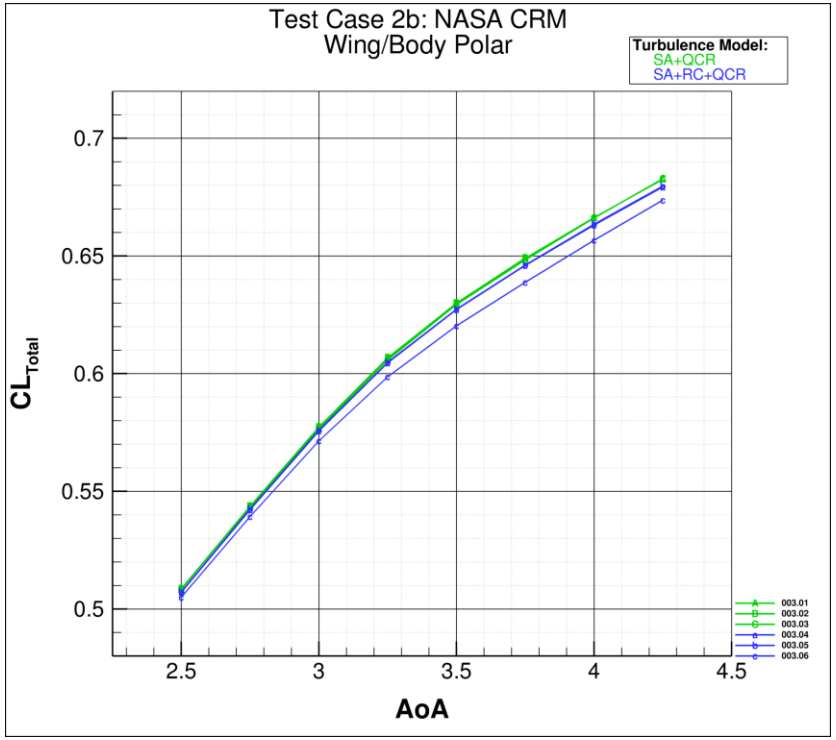


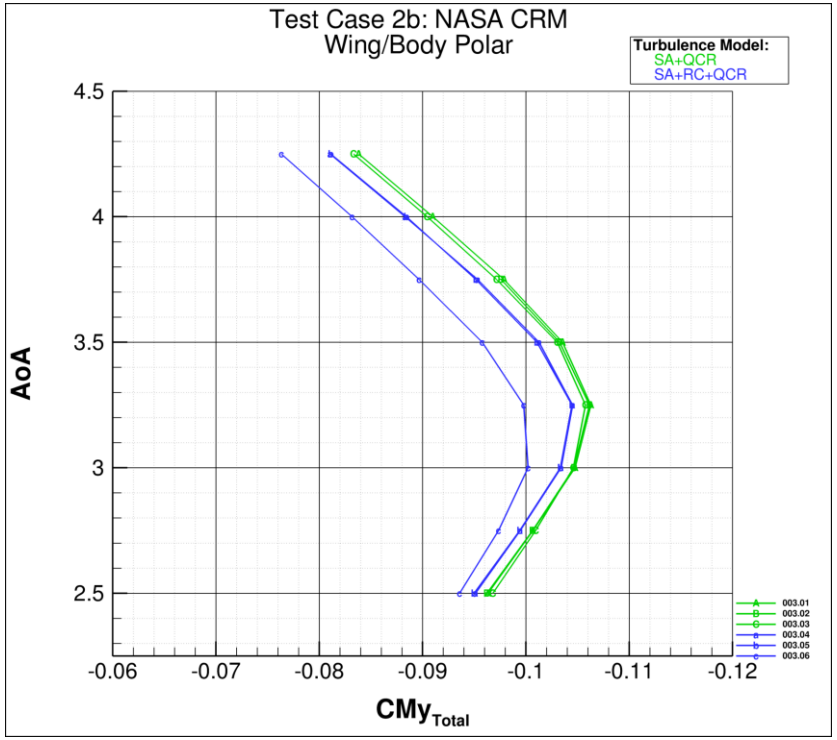
Results: Test Case 2b

- **NASA CRM Wing/Body Polar**
  - Lines colored by turbulence model
  - RC correction to SA model shows clear impact
    - Size of impact varies with solver

Grids	OVERFLOW	FELight	GGNS
Cadence_Grids.REV00		X	
HeldenMesh_Grids.REV00		X	
Ames_Grids.REV00	X		







Conclusions

- **Solver Comparison**
  - The agreement between very different grid and solver strategies is encouraging
- **Turbulence Model**
  - RC terms have an impact on forces/moments
    - Reduced lift and more positive pitching moment at constant alpha
- **Scatter Reduction**
  - Scatter reduction is possible
  - Requires diligent attention to details
    - Problem setup (all inputs, including "defaults")
    - Grid (refinement and farfield extent)
    - Residual convergence is important

Acknowledgements

- Thank you to my colleagues who contributed data, provided support in running these cases, or provided very helpful discussion and feedback.

- Many Thanks to my organization for prioritizing our involvement in DPW efforts!