CRUNCH CFD Calculations for HiLiftPW-2 with Discretization Error Predictions

Peter A. Cavallo
Combustion Research and Flow Technology, Inc. (CRAFT Tech)

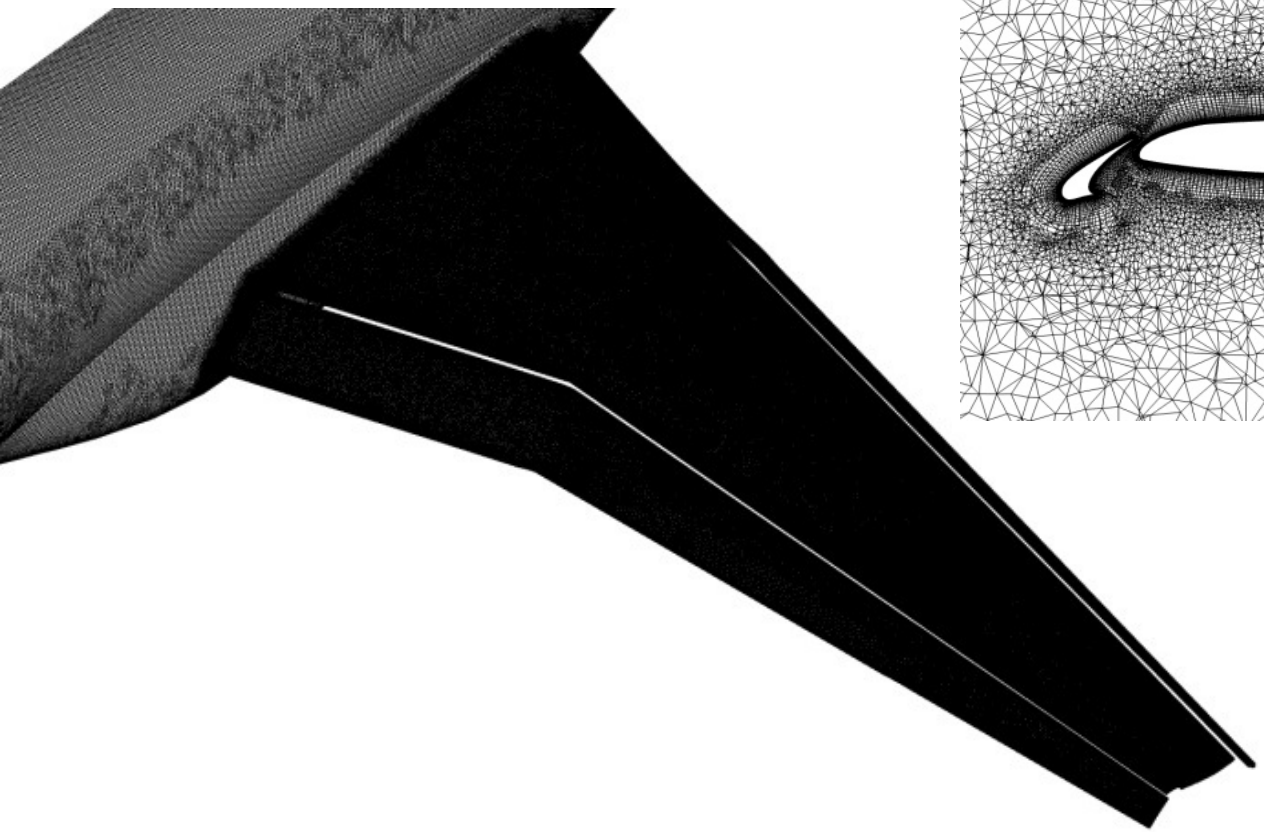
52nd AIAA Aerospace Sciences Meeting
National Harbor, MD
January 15, 2014

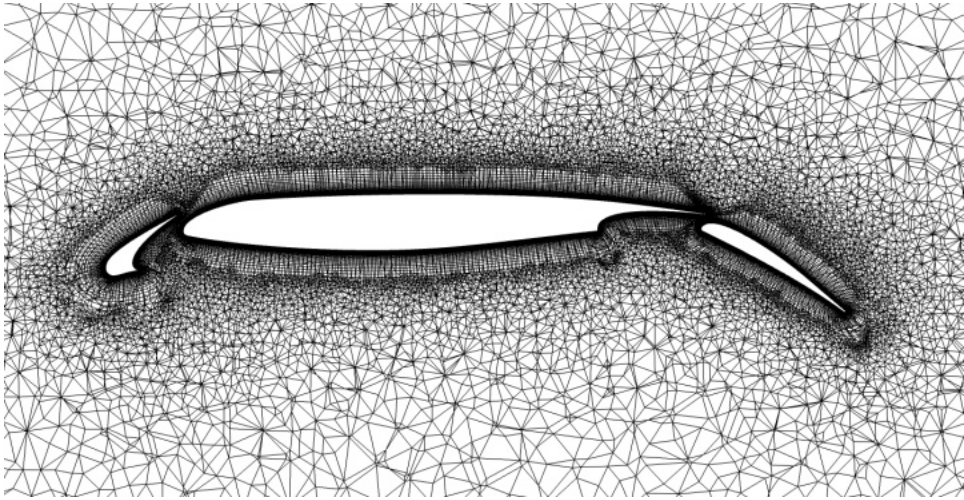
Outline of Discussion

- Overview of grids and flow solver
- Error analysis/prediction method – Error Transport
- Grid convergence studies – Case 1 results
  - Solution increments due to grid resolution
  - Assessment of error quantification/analysis
- Presentation of results for Case 2b and Case 2a (α sweeps)
  - Lift curve and drag polar (2b and 2a)
  - Pressure coefficient comparisons (2b and 2a)
  - PIV comparisons (2a only)
  - Predicted errors from solution of Error Transport Equations
- Concluding remarks and questions

Grid Overview – Case 1

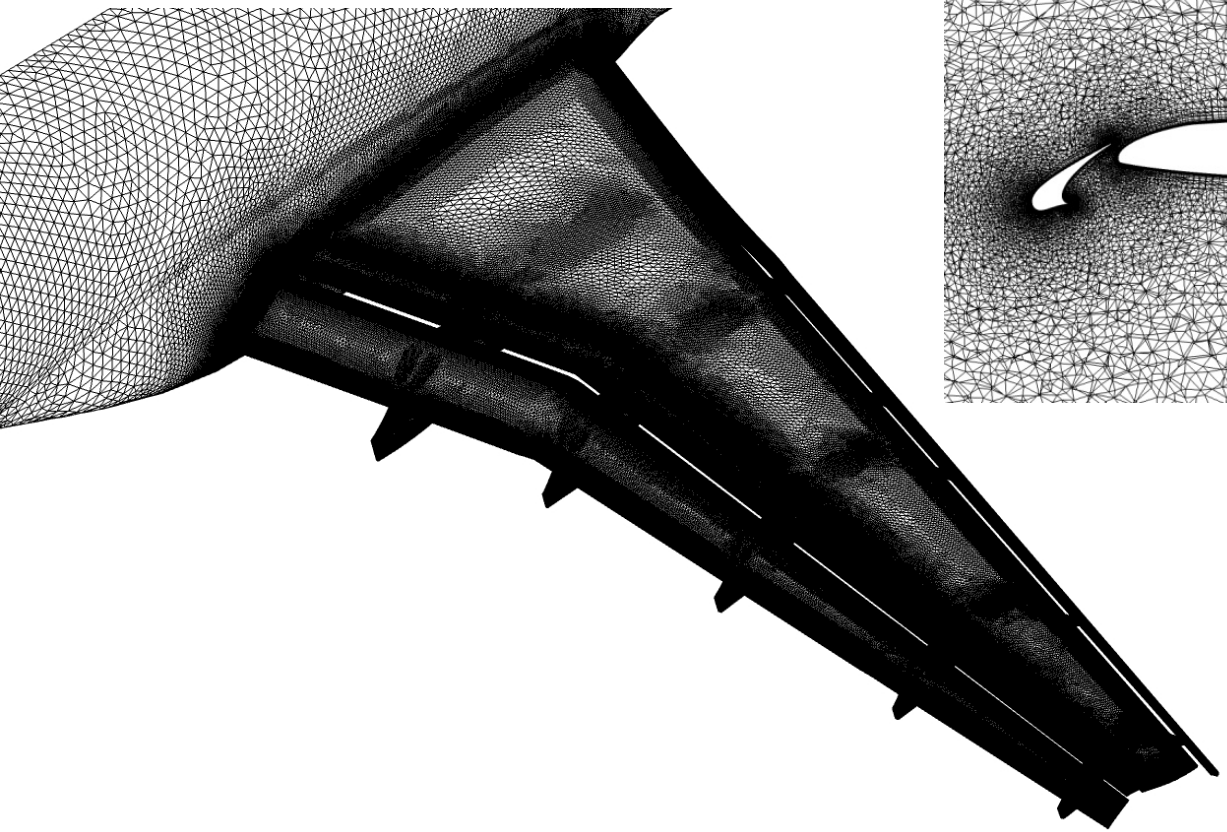
- D_UNS_MIX grid sequence employed for Case 1 studies in original workshop, however these proved difficult to converge with solver
- Revisited Case 1 using C_UNS_MIX grid sequence (4 grids)
- Mixed-element meshes with tetrahedra, pyramids, and prisms

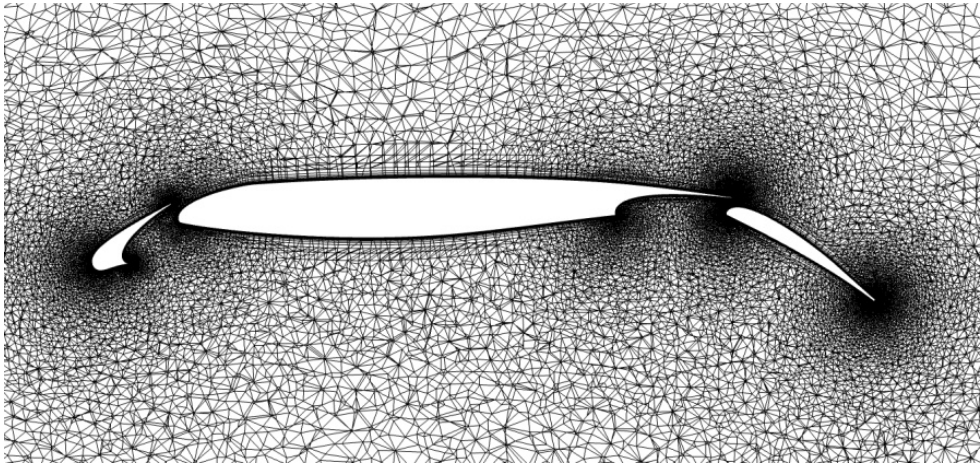




Grid Overview – Case 2

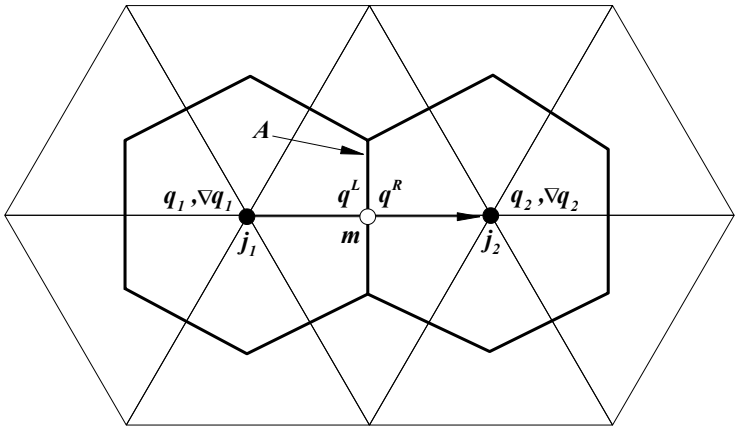
- D_UNS_MIX medium grid employed for Case 2 studies (presented at time of workshop)
- Mixed-element mesh with tetrahedra, pyramids, and prisms
- Version 1 of meshes used, translated into proper position





Flow Solver

- *CRUNCH CFD* node-centered unstructured Navier-Stokes solver
  - Upwind 3-D finite volume formulation, formally 2nd order in space
  - Roe's approximate Riemann solver for inviscid flux
  - Isotropic or edgewise TVD limiting
- Control volume constructed from cells incident to each vertex
  - Solution stored at mesh vertices, polyhedral control volume
  - Edge-based flux computation



- Low Mach number preconditioning
- Physical modeling features:
  - Spalart, k-ω SST turbulence models
  - k-ε model with compressibility extensions
  - LES and hybrid RANS/LES model
  - Finite rate chemical kinetics
  - Multi-phase gas/particle modeling
  - Formally incompressible version for liquids, low speed gases, and two-phase flows with cavitation
- k-ω SST model used for all HiLiftPW-2 cases

Our Objectives

- In any CFD simulation, numerous potential error sources
  - User and setup errors (incorrect inputs)
  - Iterative convergence (lack of)
  - Spatial discretization (grid resolution)
  - Inadequate physical modeling
- Best practices and proper training address usage issues
- Solution verification quantifies spatial resolution issue
- ➢ ***Only when other error sources are quantified can physical modeling deficiencies be properly addressed***
- Objective of Case 1 clean wing study is to quantify increments in the solution due to grid resolution: ***solution verification***
- Objective of Case 2 studies is to assess errors for notional Medium resolution grid, given Case 1 lessons
- Resolution errors bounded using solution of Error Transport Equations (ETE)

Error Prediction Methodology

- 3D Error Transport Equation (ETE) Solver for unstructured grids*

$$\frac{\partial}{\partial t}\iiint\left(\overset{\mathrm{v}}{Q}-\overset{\mathrm{v}}{Q}^{h}\right)dV+\iint\left(\left(\overset{\mathrm{v}}{F}\left(\overset{\mathrm{v}}{Q}\right)-\overset{\mathrm{v}}{F}\left(\overset{\mathrm{v}}{Q}^{h}\right)\right)\cdot\hat{n}\right)dA=\iint\left(\left(\overset{\mathrm{v}}{G}\left(\overset{\mathrm{v}}{Q}\right)-\overset{\mathrm{v}}{G}\left(\overset{\mathrm{v}}{Q}^{h}\right)\right)\cdot\hat{n}\right)dA-\overset{\mathrm{v}}{R}$$

$$\boxed{\frac{\partial}{\partial t}\iiint\overset{\mathrm{v}}{\varepsilon}dV+\iint\left(\left(A\left(\overset{\mathrm{v}}{Q}^{h}\right)\overset{\mathrm{v}}{\varepsilon}\right)\cdot\hat{n}\right)dA=\iint\left(\overset{\mathrm{v}}{G}\left(\overset{\mathrm{v}}{\varepsilon}\right)\cdot\hat{n}\right)dA-\overset{\mathrm{v}}{R}}$$

  - Residual from leading terms of truncation error (upwind terms of Roe flux)
  - Spalart-Allmaras, k–ω, k–ε models supported
  - Recently expanded to support cell-centered solvers to solve ETE using either cell-centered or node-centered discretization*
- Error Function Library
  - Propagates predicted errors into derived variables of interest
  - PLOT3D functions, integrated functions, *etc*.
- Richardson Extrapolation utility

➢ ***Give CFD analyst reliable assessment of error due to resolution***

➢ ***Make error assessment an integral part of postprocessing***

---

* Cavallo, P.A., O'Gara, M.R., Feldman, G.M., and Liu, Z., "Unified Error Transport Equation Solver for Solution Verification on Unstructured Grids," AIAA Paper 2012-3345, 42nd Fluid Dynamics Conference, New Orleans, LA, June 25-28, 2012.

What Are We Looking For?

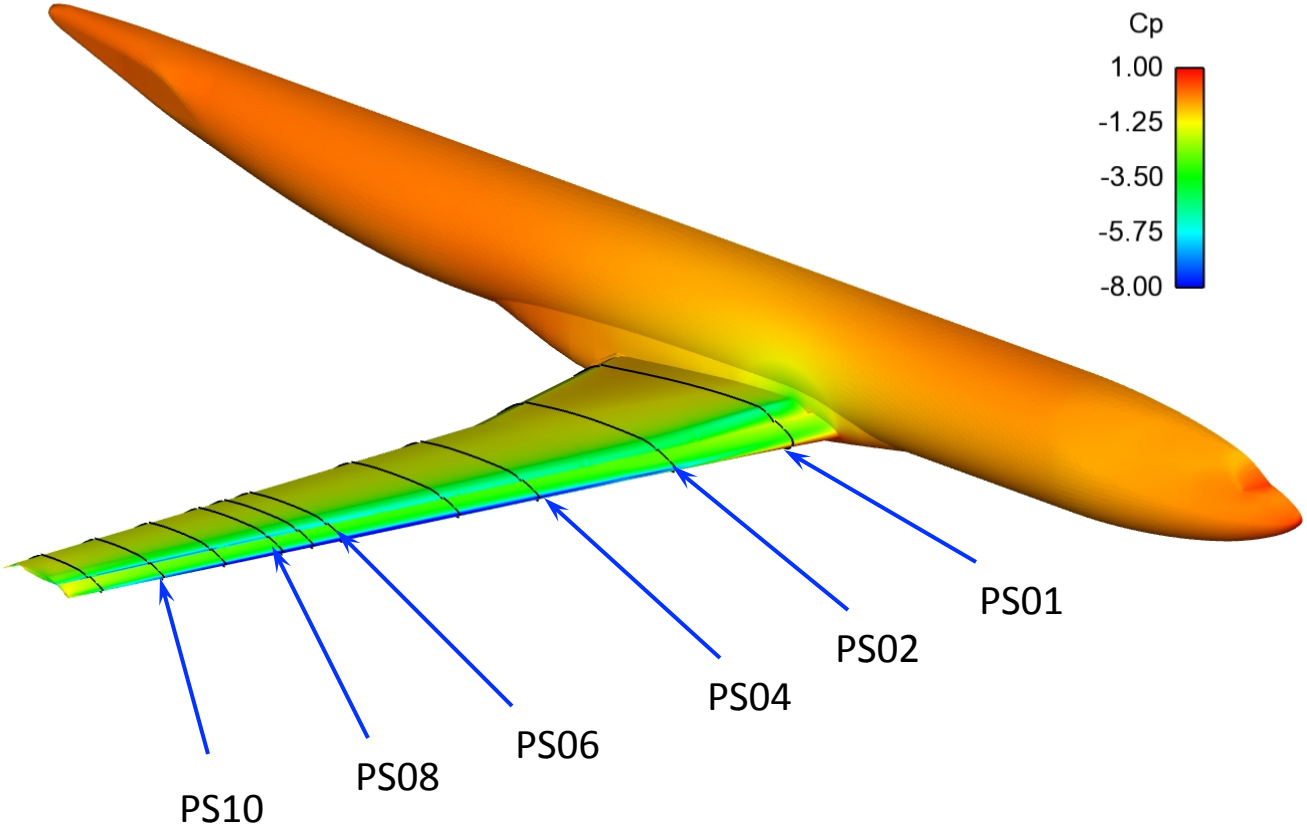
- Solution verification, not validation
  - Prediction of coarse-to-fine grid increments
  - Isolate grid resolution errors from other possible error sources
  - What portion of discrepancy with data is due to grid?
- Error bars predicted by ETE solution and Error Functions should:
  1) Contain fine grid results
  2) Contain results of Richardson extrapolation
  3) Decrease in magnitude with grid refinement
  4) Not be overly conservative as to be unusable
- Provide a level of confidence in fidelity of results

➢ ***If fine grid results fall outside predicted error bars, it potentially indicates new flow features result from grid refinement***

➢ ***If test data falls outside predicted solution and error bars, it potentially indicates a deficiency in physical modeling***

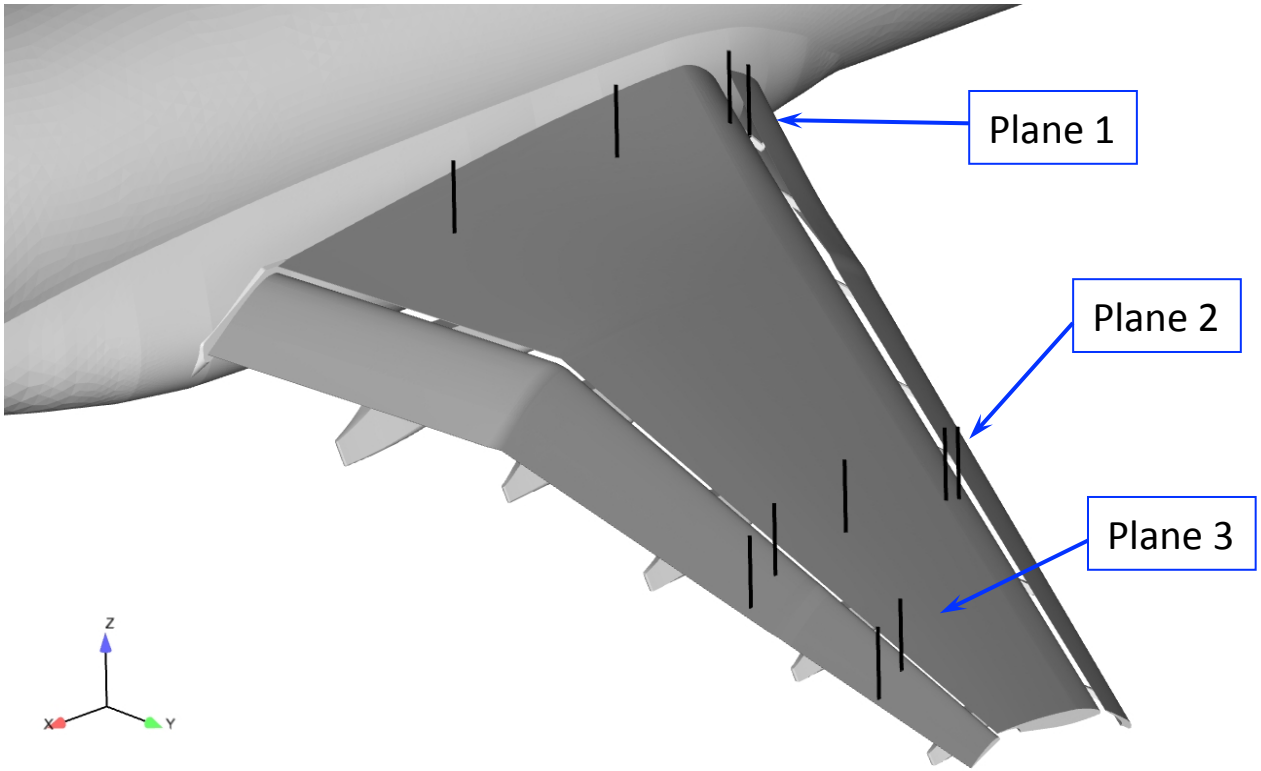
Data Comparisons (1)

- 10 spanwise stations with pressure coefficient data
- Selected stations will be shown to highlight key points



Data Comparisons (2)

- PIV data available at low Reynolds number only
- 11 cuts extracted at the 3 planes shown – selected cuts presented to highlight key points
- Profiles provide detail on both boundary layers and slat and main element wakes

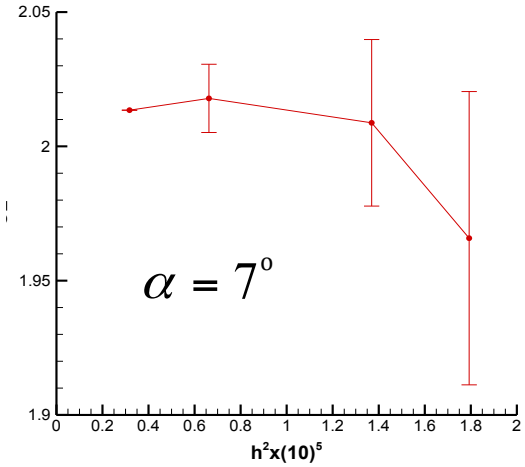


Case 1 – Grid Convergence Study

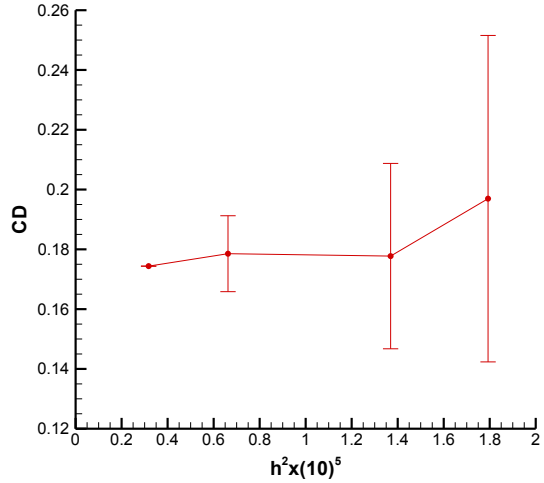
- To serve as validation of capturing increments in solution using error transport (ETE) methodology
  - How well can error prediction capture actual increments?
  - What levels of error can we expect for Medium grid in Case 2?
- Considering α=7 and α=16 only
- Examining:
  - Integrated coefficients
  - Surface pressure coefficients
  - Velocity profiles
- Overall observations:
  - Errors in integrated coefficients tend to be conservative, as integration of errors over surface
  - Errors in surface C_p often well captured
  - Errors in velocity profiles generally overpredicted

➢ ***Note: method cannot account for dissimilar solutions***

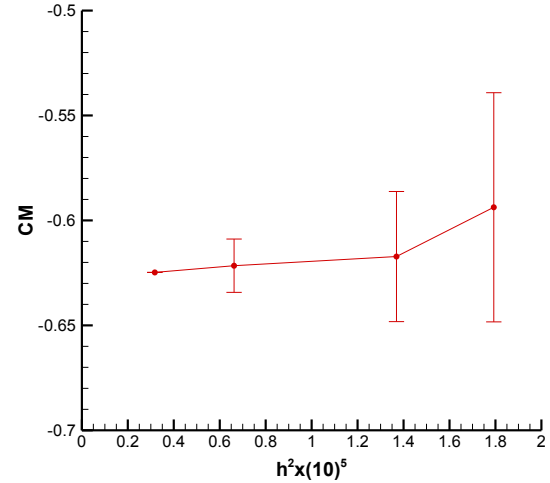
Case 1 – Forces/Moments



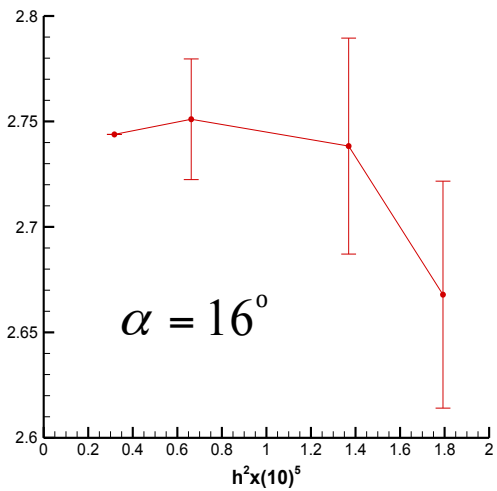
a) Lift



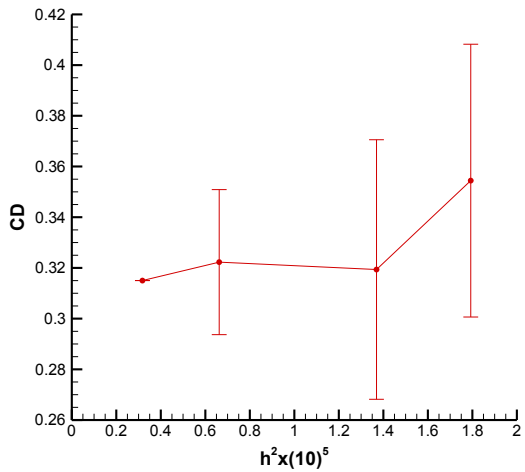
b) Drag



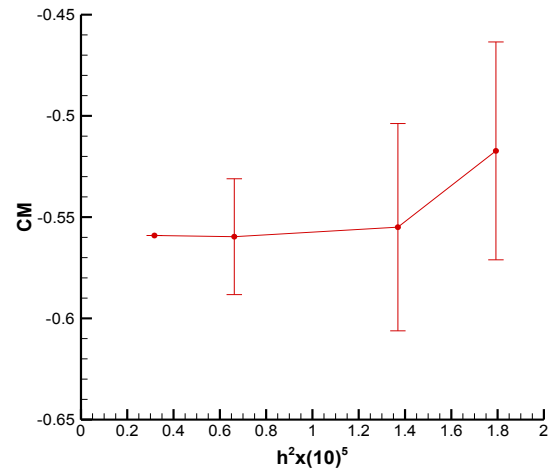
c) Pitching moment



a) Lift

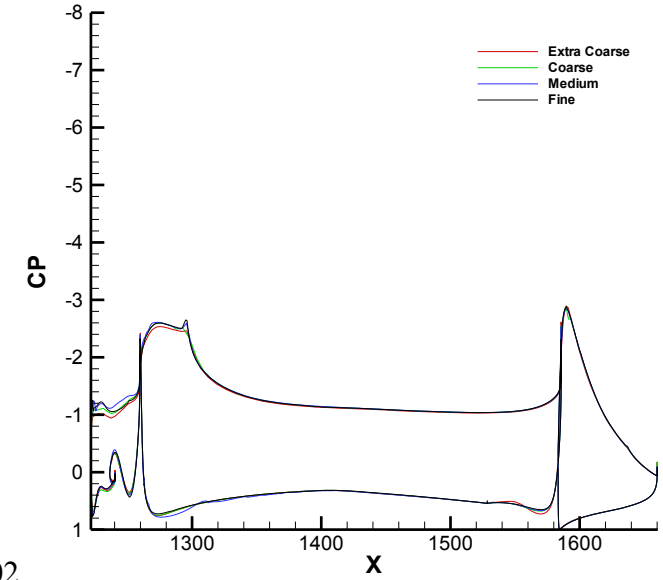


b) Drag

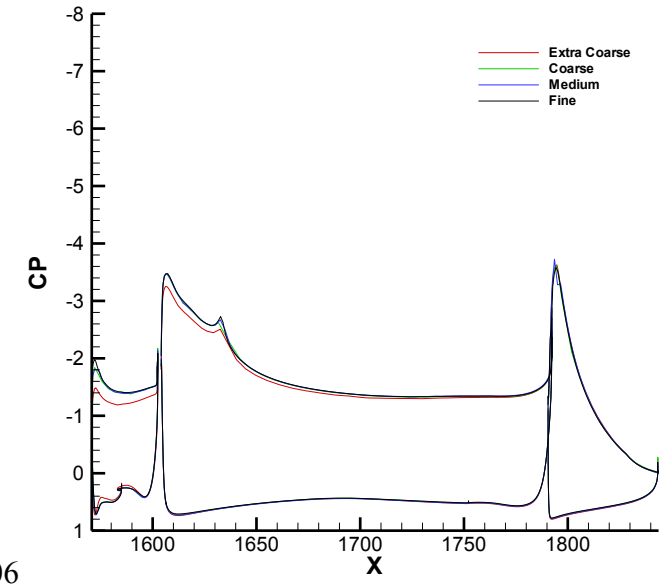


c) Pitching moment

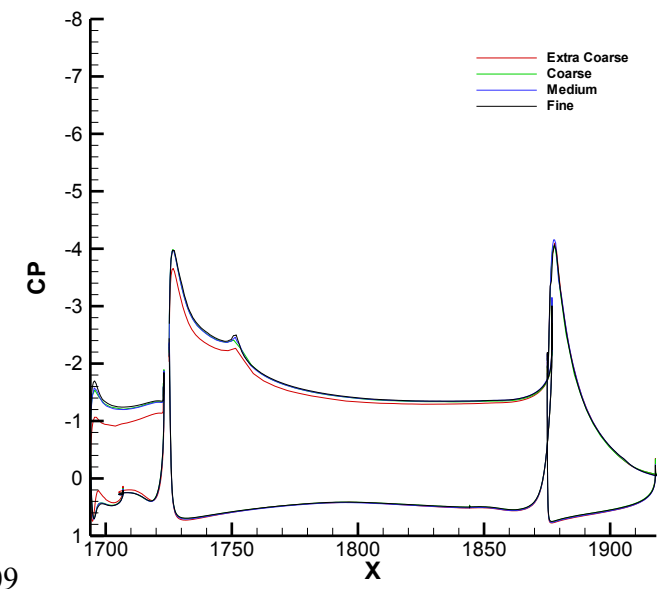
Case 1 C_p Comparisons, α=7



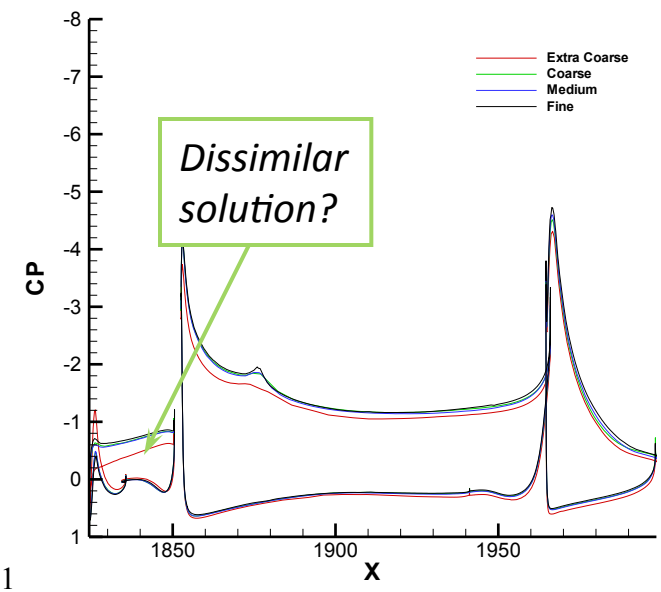
PS02



PS06

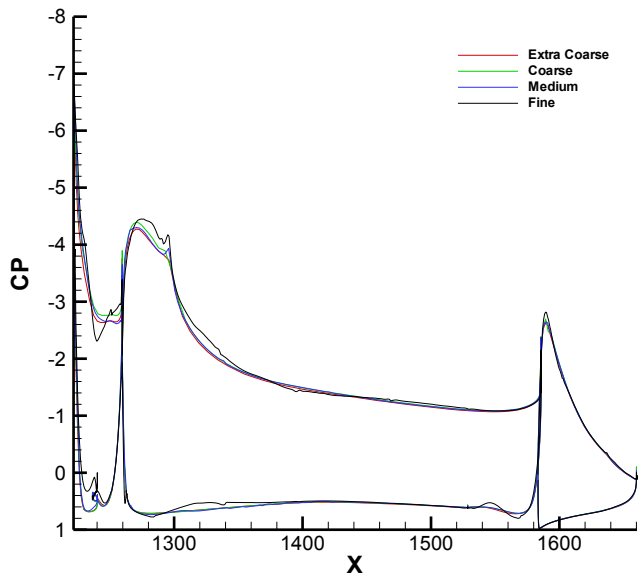


PS09

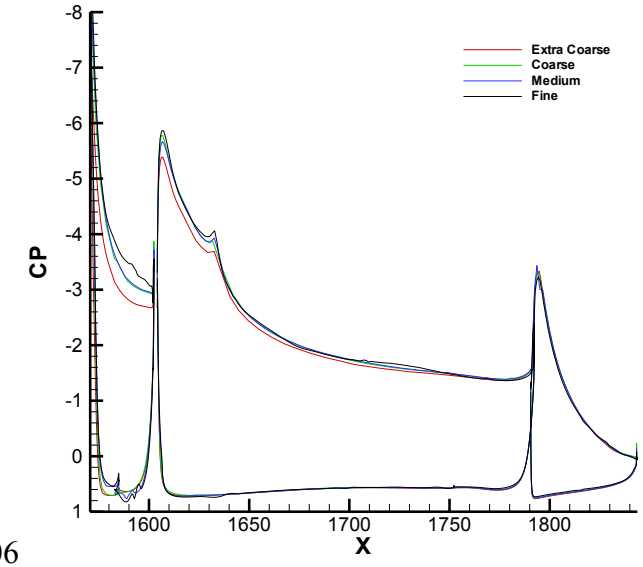


PS11

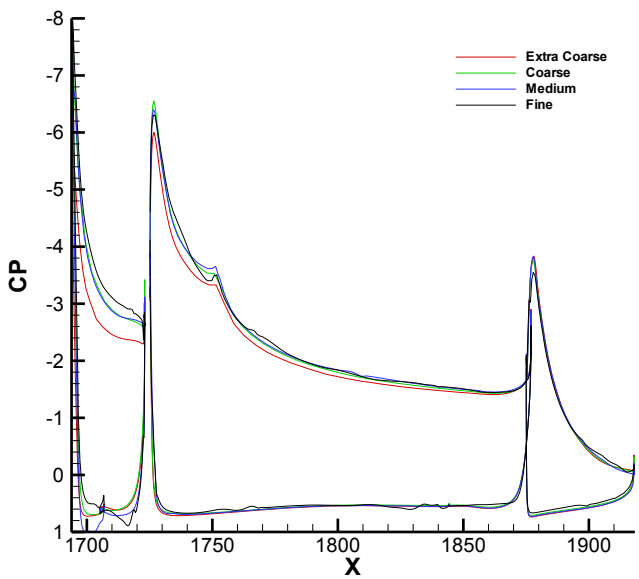
Case 1 C_p Comparisons, α=16



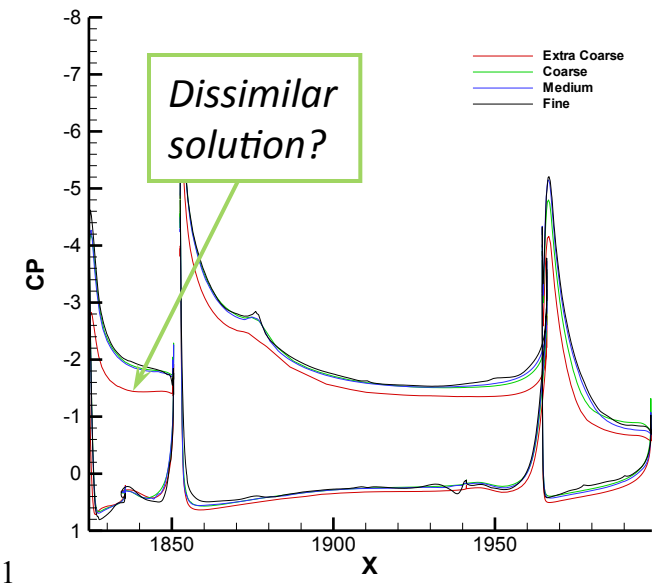
PS02



PS06

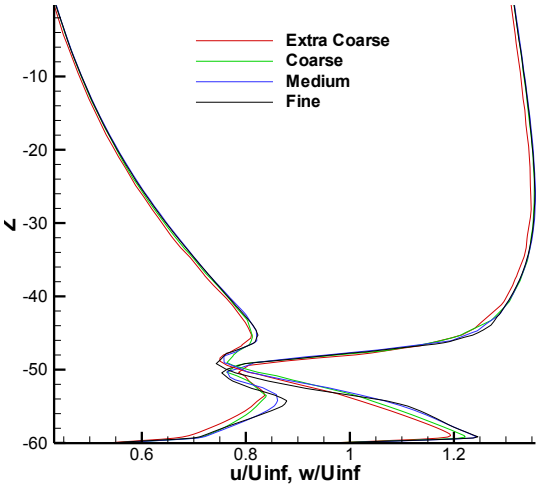


PS09

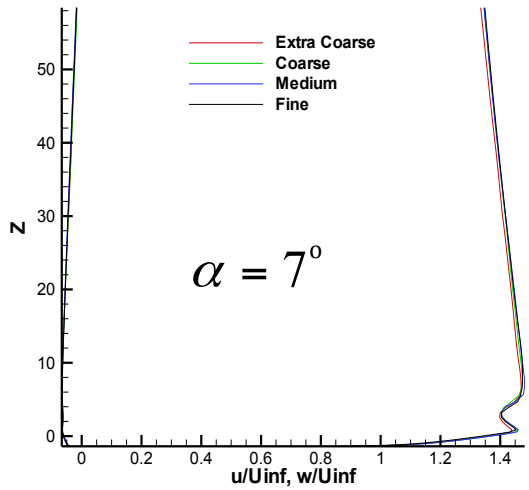


PS11

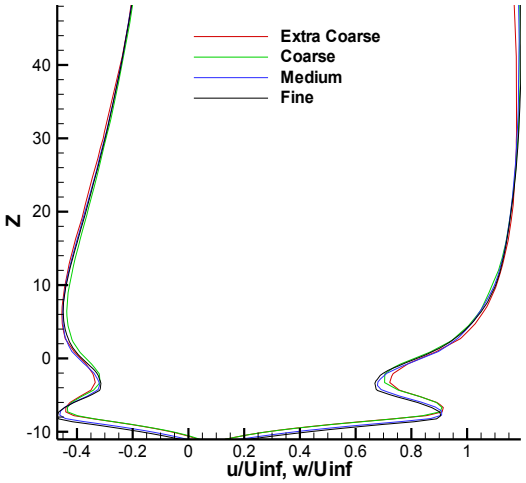
Case 1 Velocity Profiles



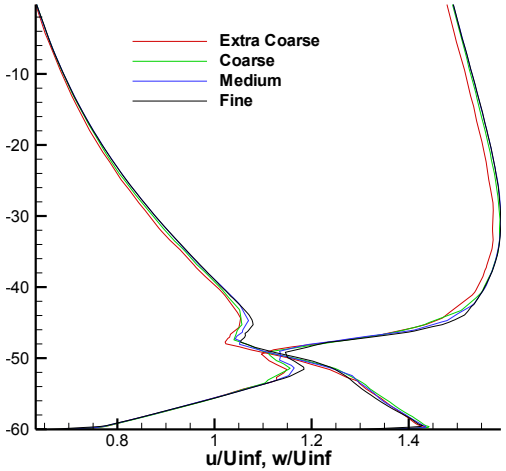
a) Plane 1, Window B, Line 1



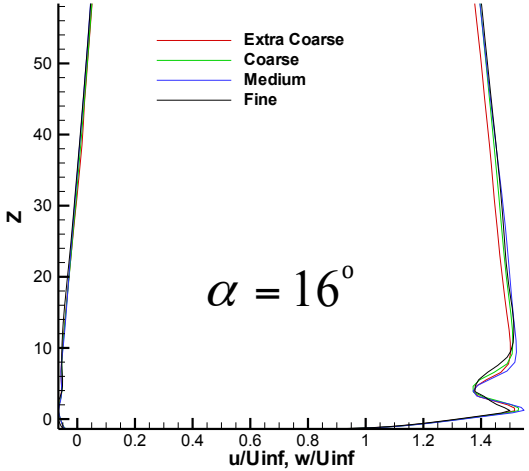
b) Plane 2, Window D, Line 1



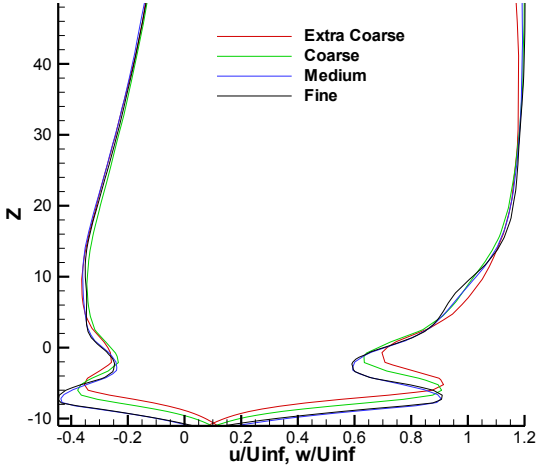
c) Plane 3, Window E, Line 2



a) Plane 1, Window B, Line 1

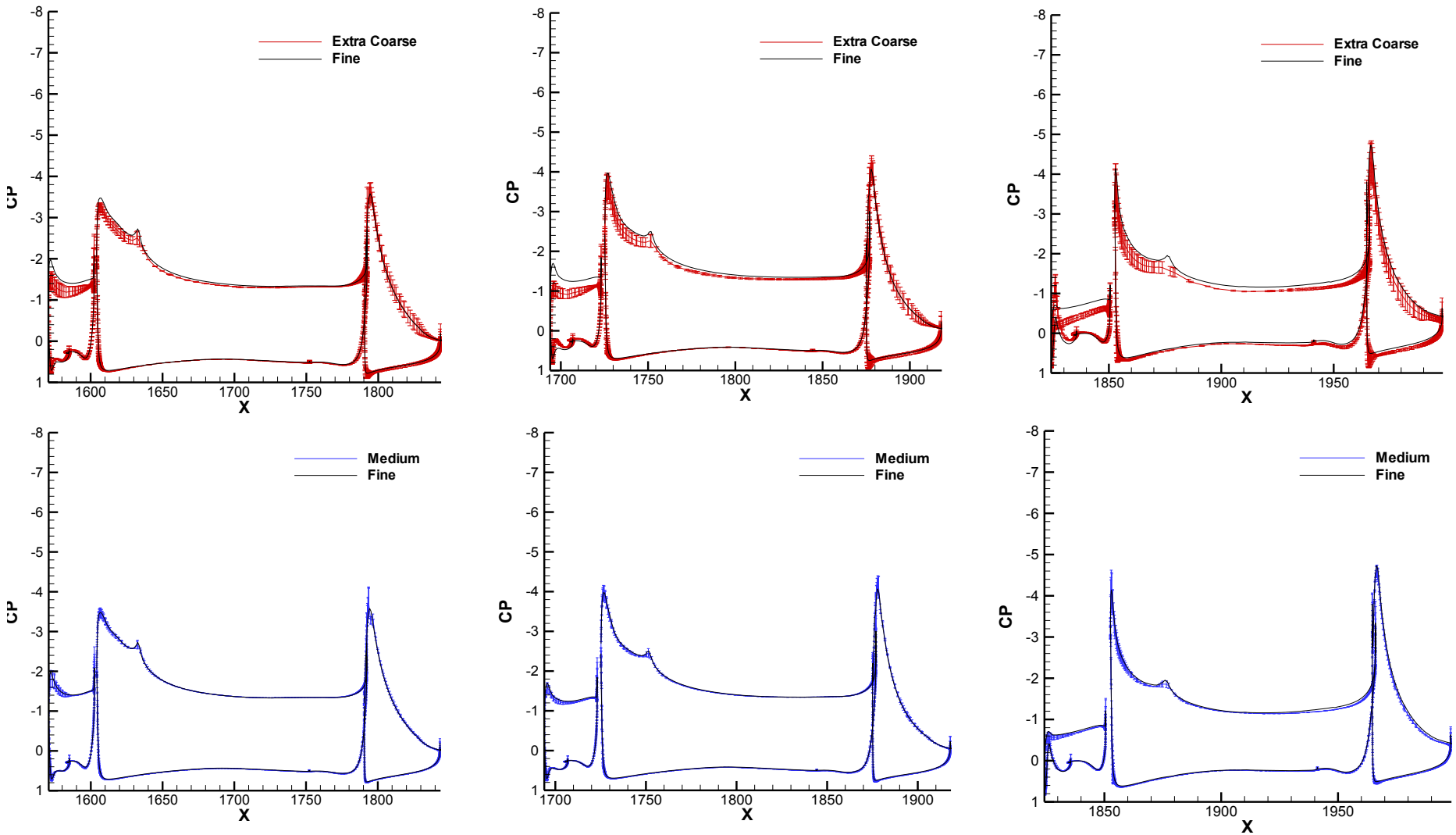


b) Plane 2, Window D, Line 1



c) Plane 3, Window E, Line 2

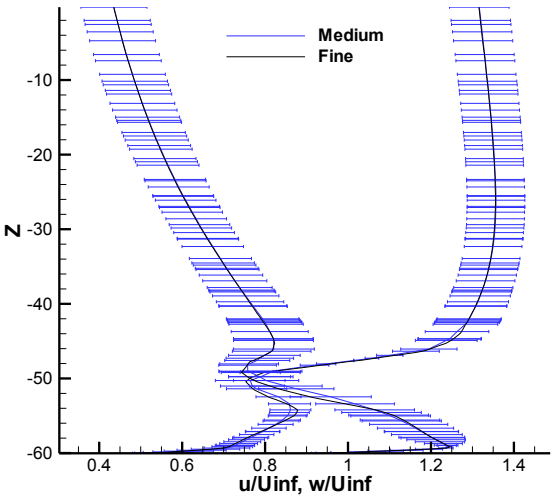
Predicted Errors in C_p, α=7



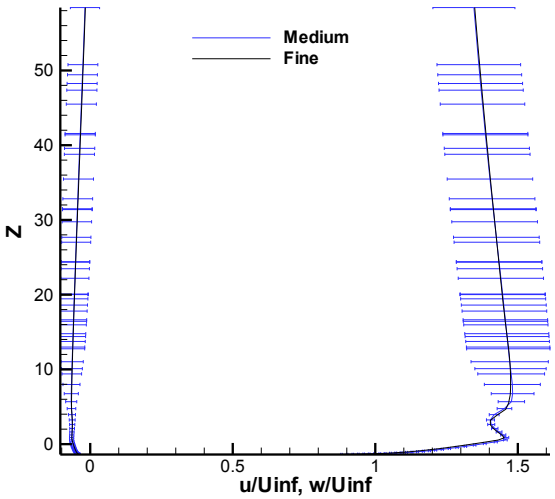
a) PS06 b) PS09 c) PS11

Errors in Velocity Profiles, α=7

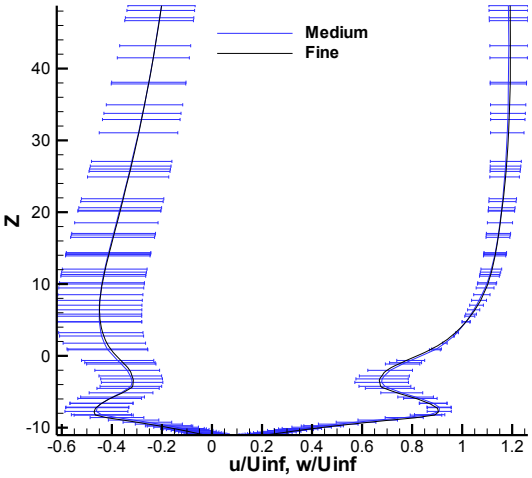
- Considerable overprediction of actual solution increment
- Issue remains an unresolved outstanding item
- Errors in velocity profiles for Case 2 need to be considered in light of these results



a) Plane 1, Window B, Line 1



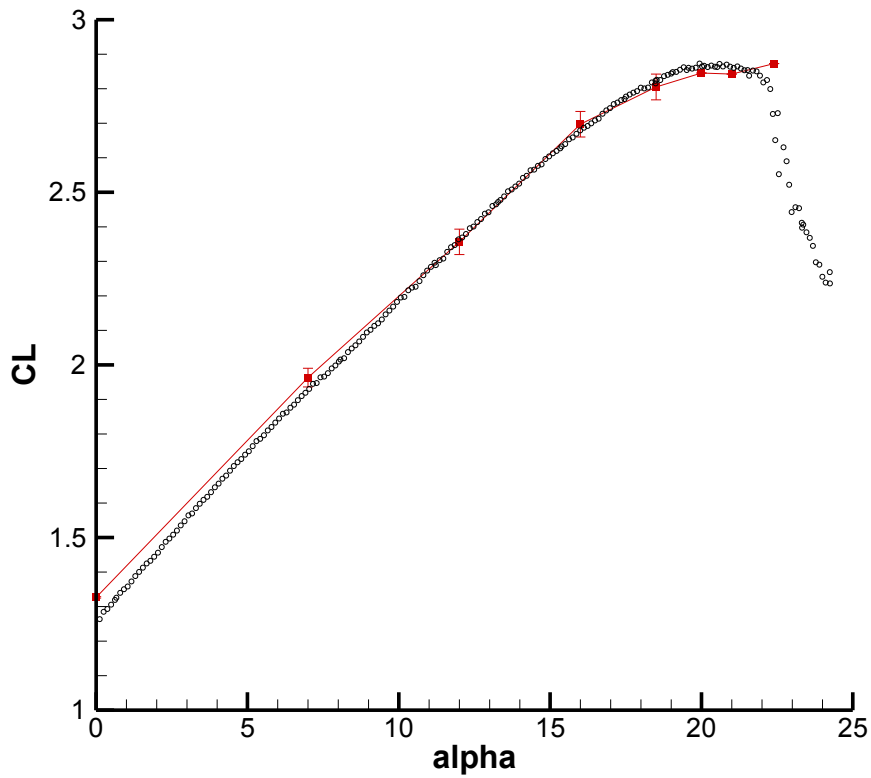
b) Plane 2, Window D, Line 1

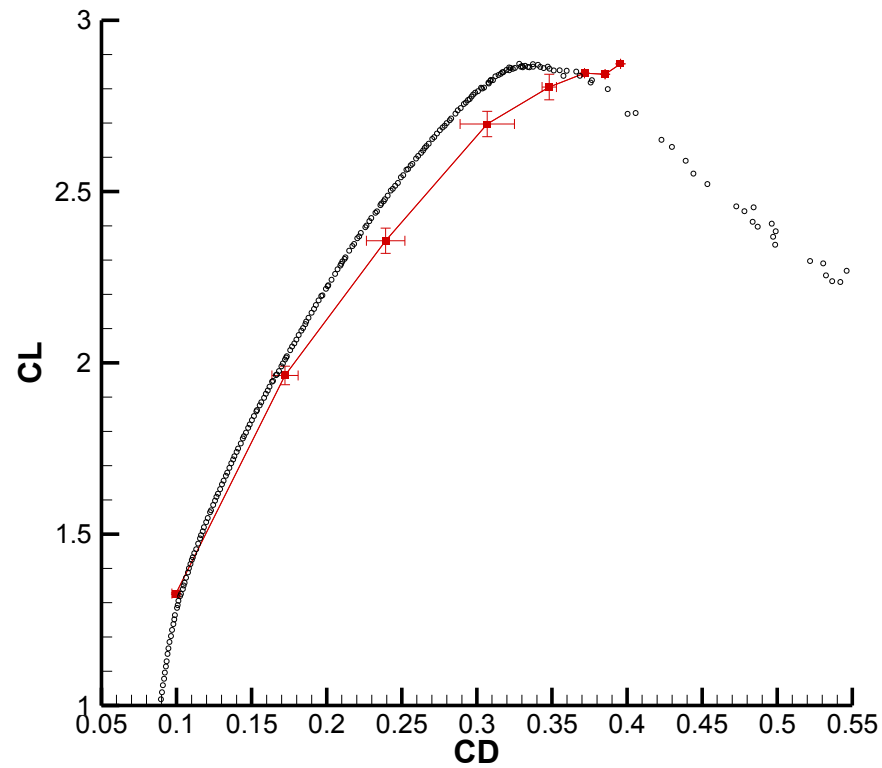


c) Plane 3, Window E, Line 2

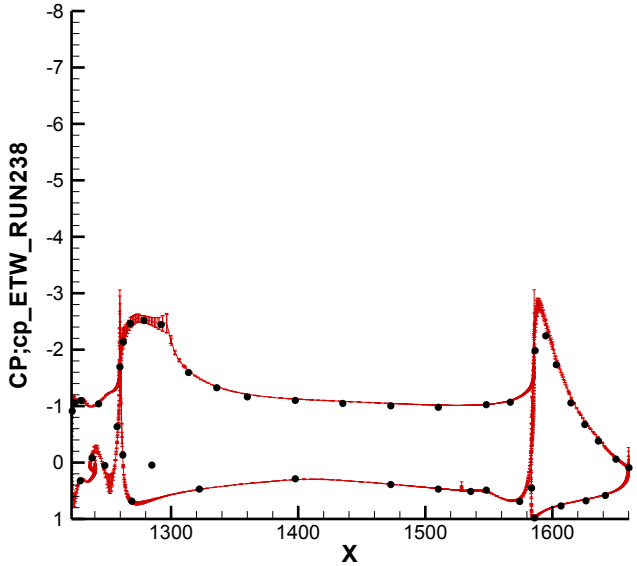
Error Analysis for Case 2b

- Error analyses restricted to attached flow (steady) cases
- Numerical error bars due to discretization nearly span difference between CFD results and test data – suggests modeling may be suitable for cases considered
- Magnitude of error tends to increase with α

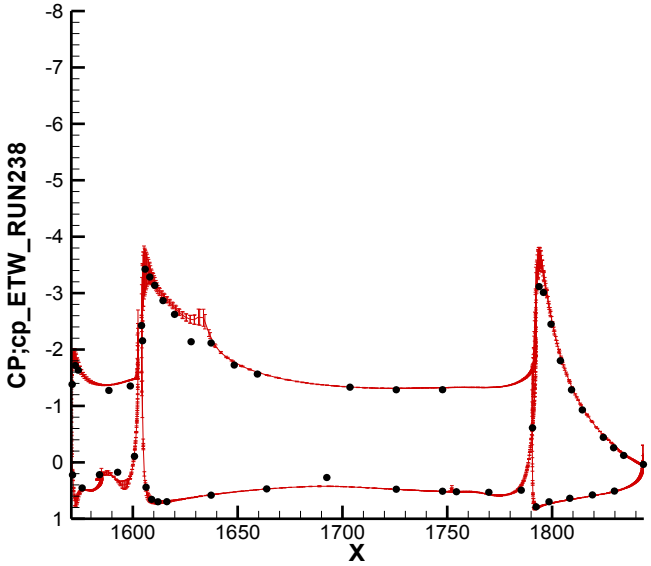




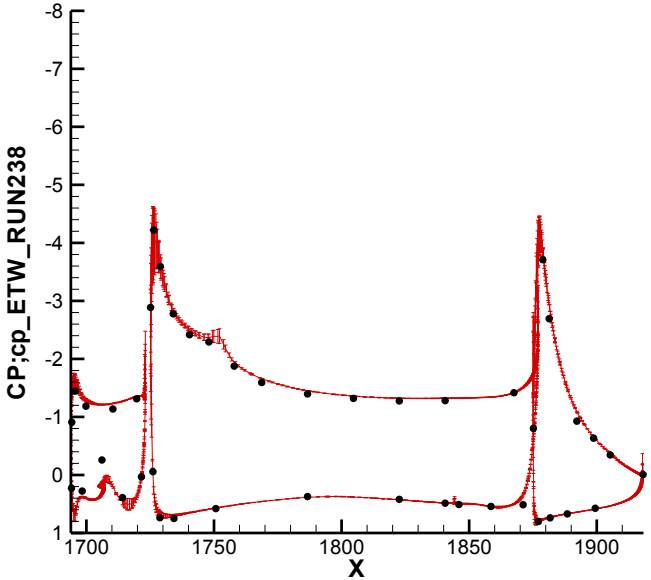
C_p Errors, α=7, Re=15.1(10)^6



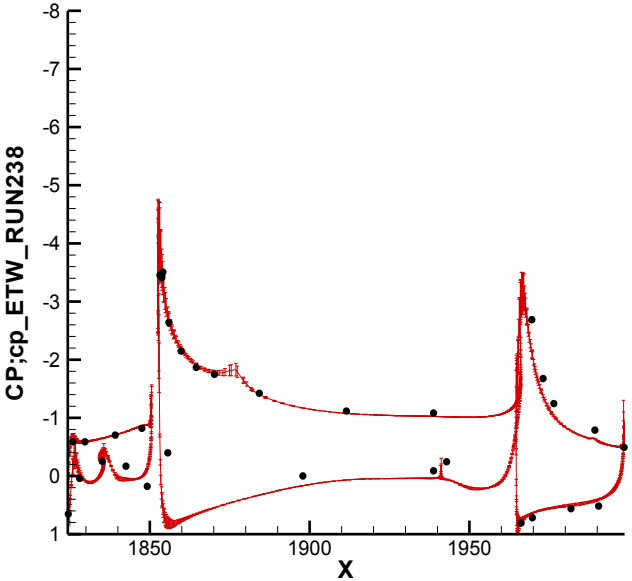
PS02



PS06

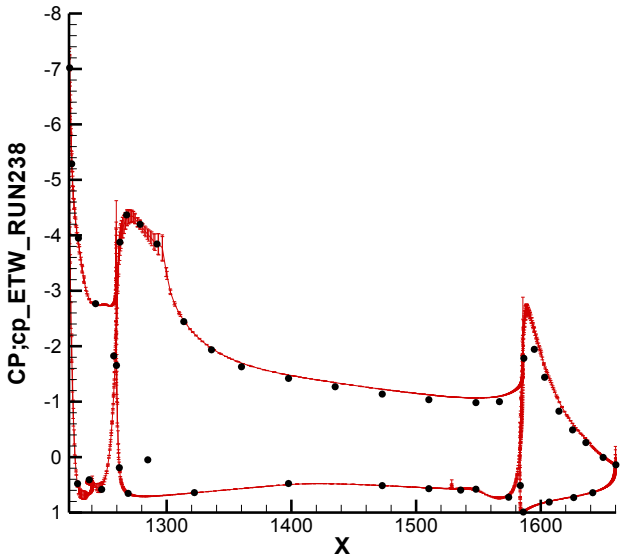


PS09

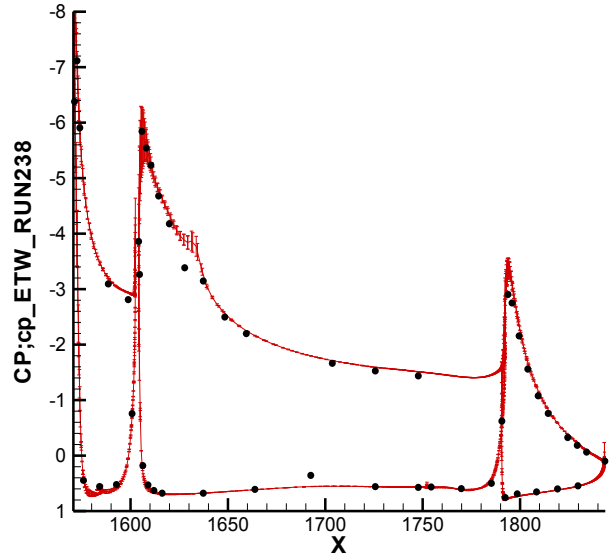


PS11

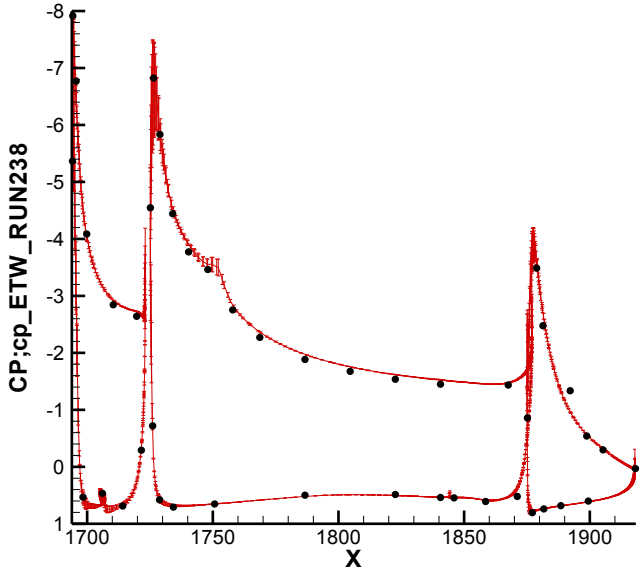
C_p Errors, α=16, Re=15.1(10)^6



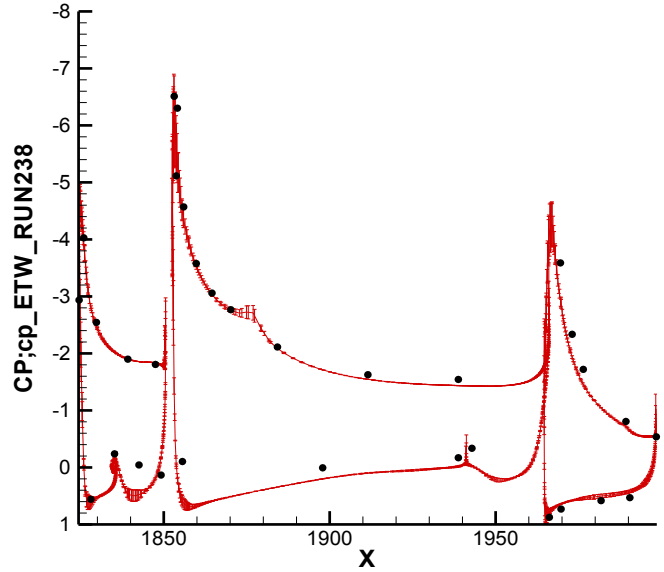
PS02



PS06



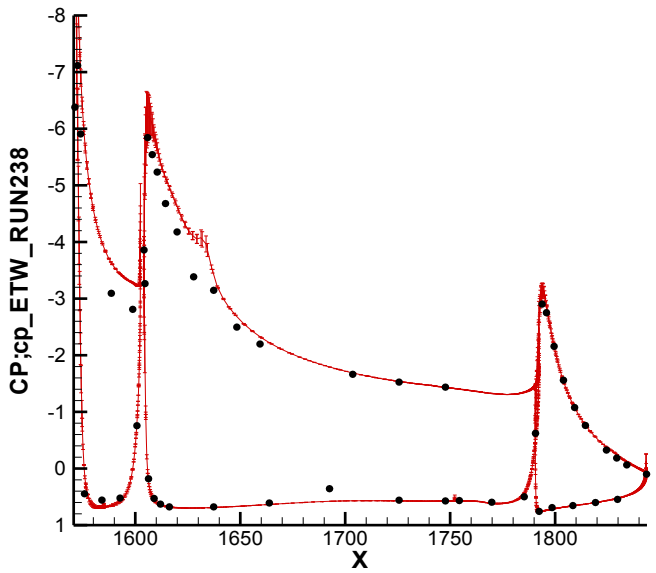
PS09



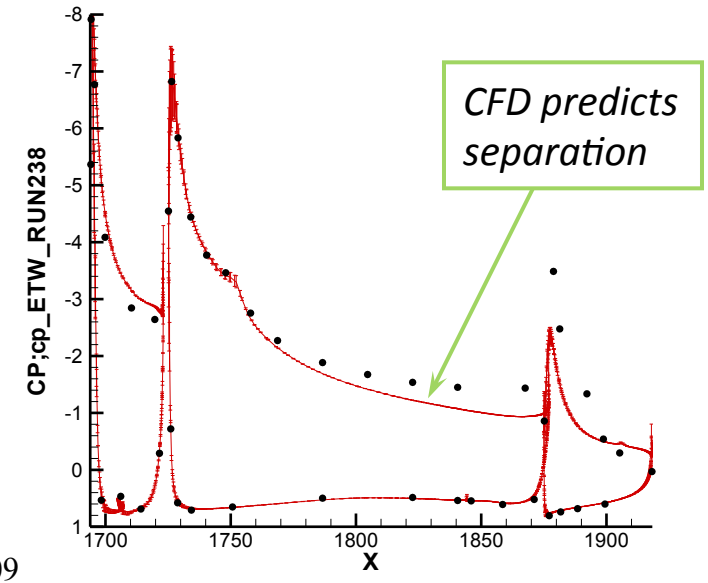
PS11

C_p Errors, α=18.5, Re=15.1(10)^6

- Example of value gained from error analysis – understanding discrepancies with data
- Test data falling outside predicted errors means something other than resolution playing a role – geometry, physical modeling, etc.
- Verification answered, but validation, not yet



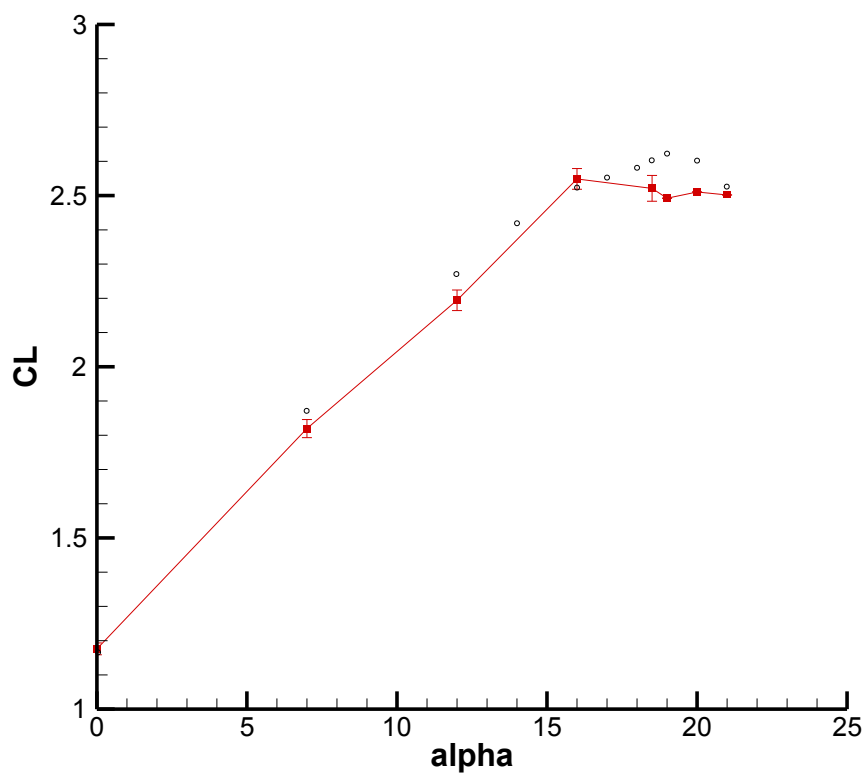
PS06

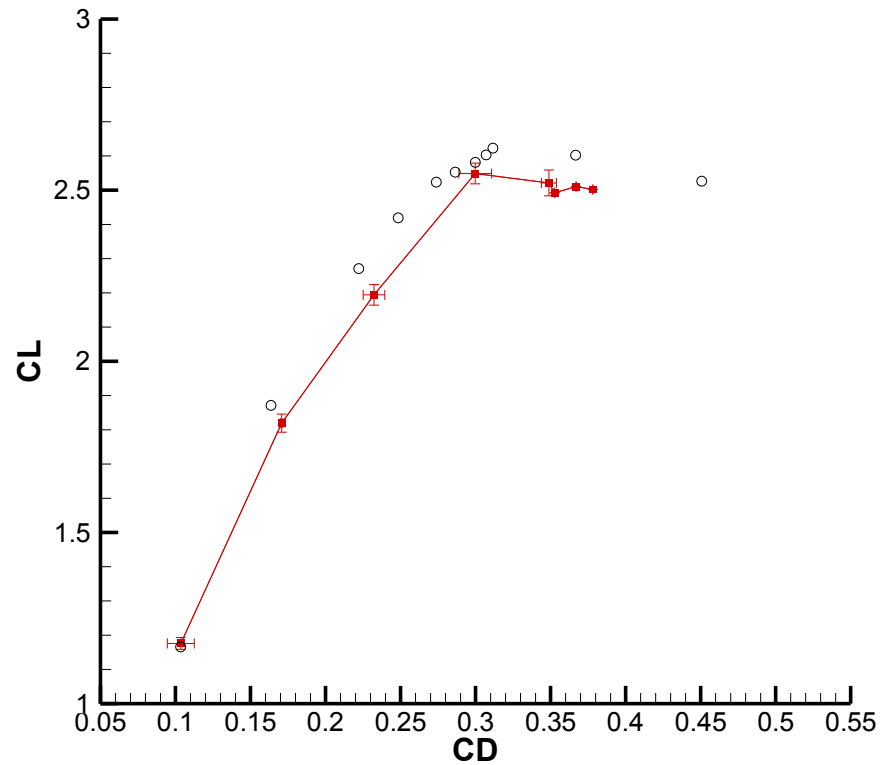


PS09

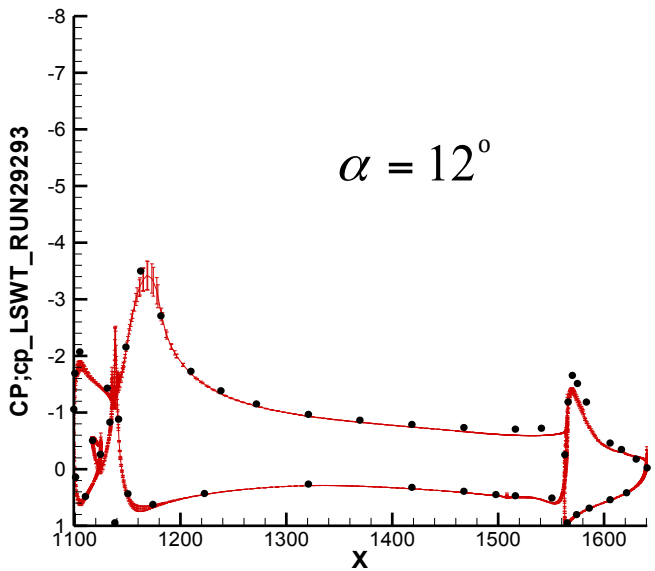
Error Analysis for Case 2a

- Numerical error bars do not quite span difference between CFD results and test data
- Suggests that modeling, not discretization error, may account for observed discrepancies
- Comparison with experiment seems to confirm this conclusion

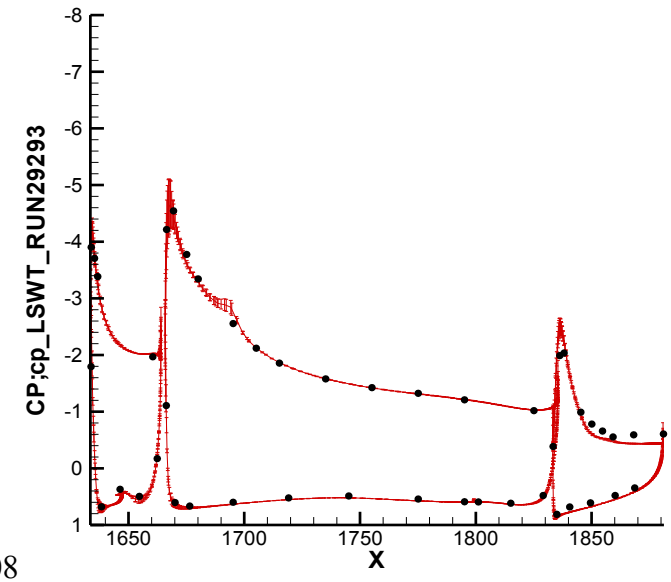




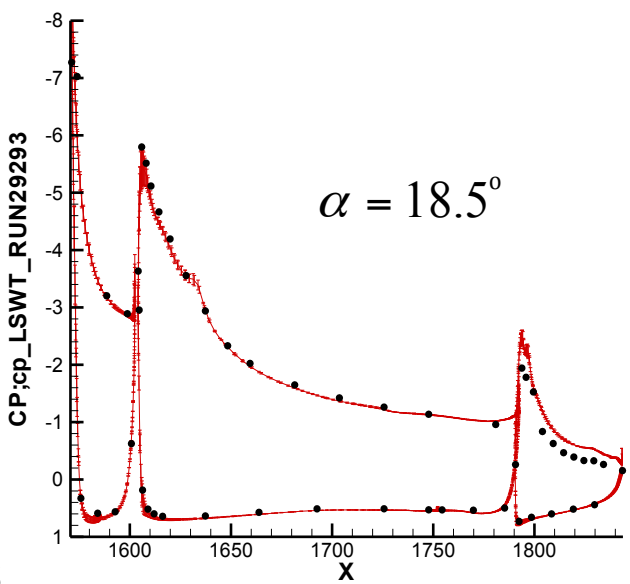
C_p Errors, Re=1.35(10)^6



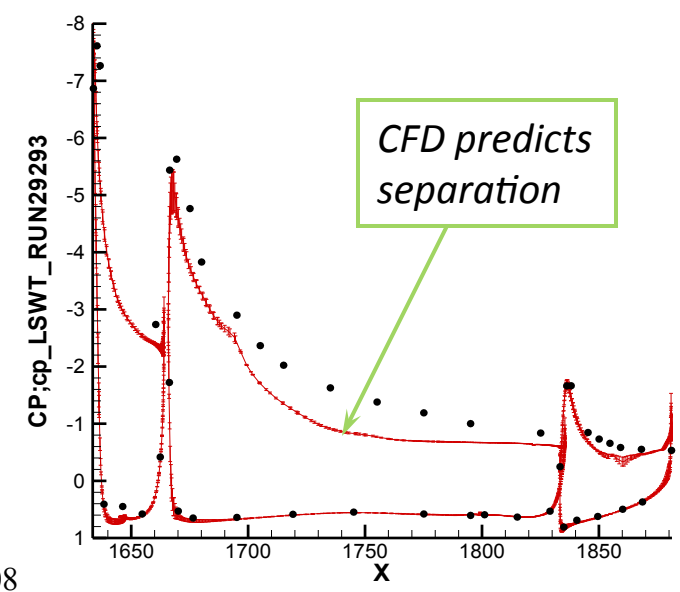
PS01



PS08

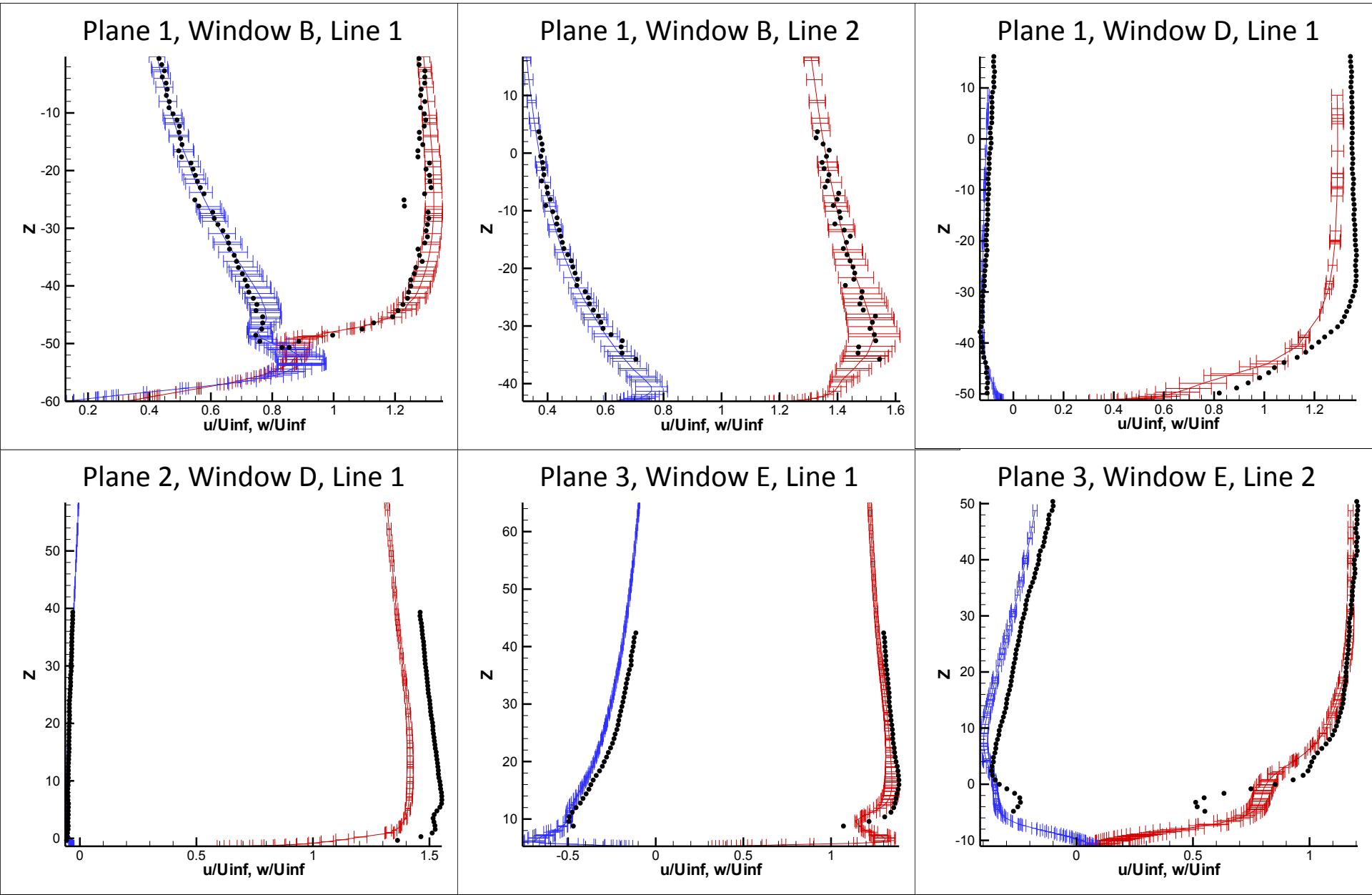


PS06

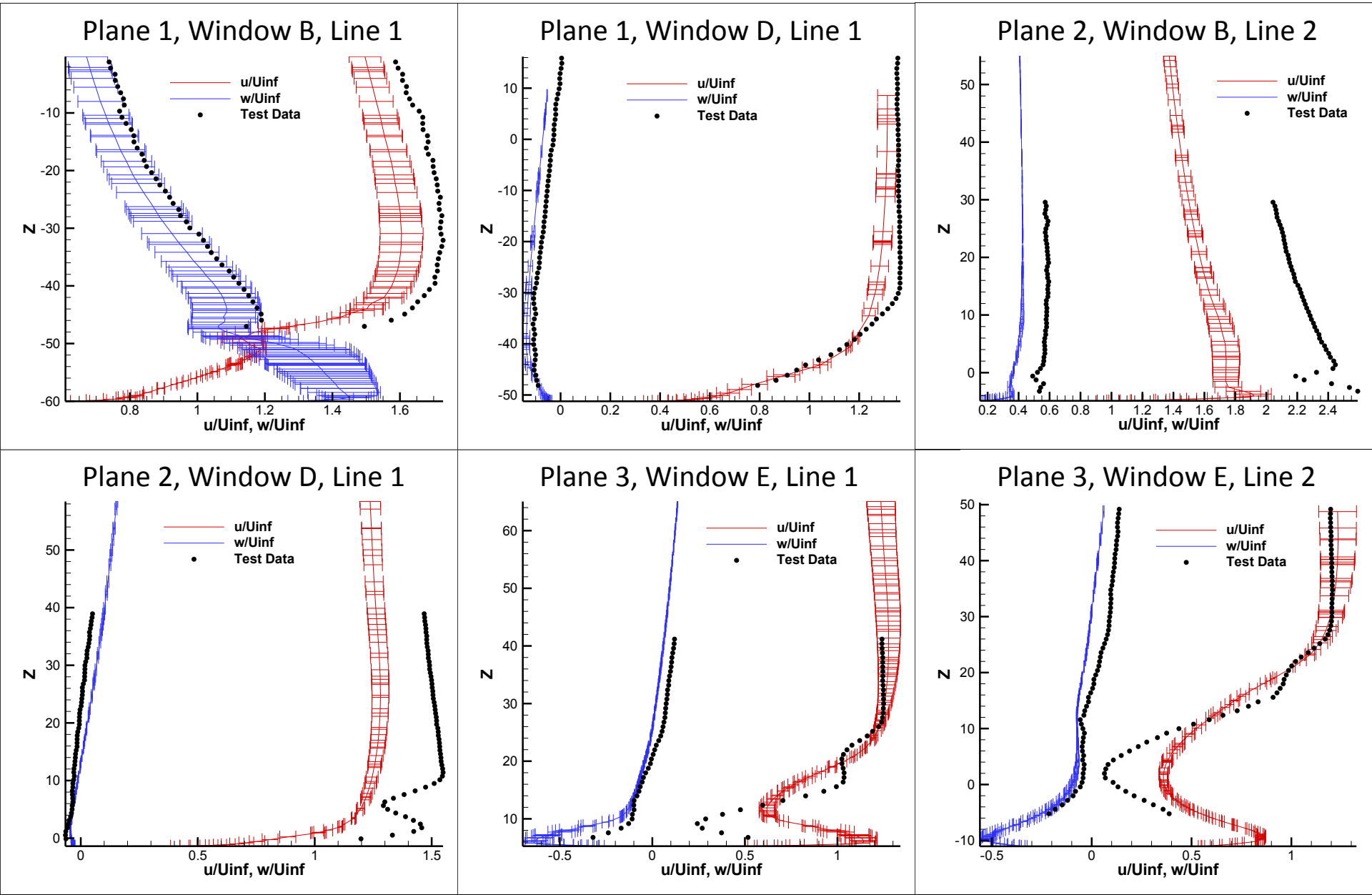


PS08

Velocity Errors, α=7, Re=1.35(10)^6

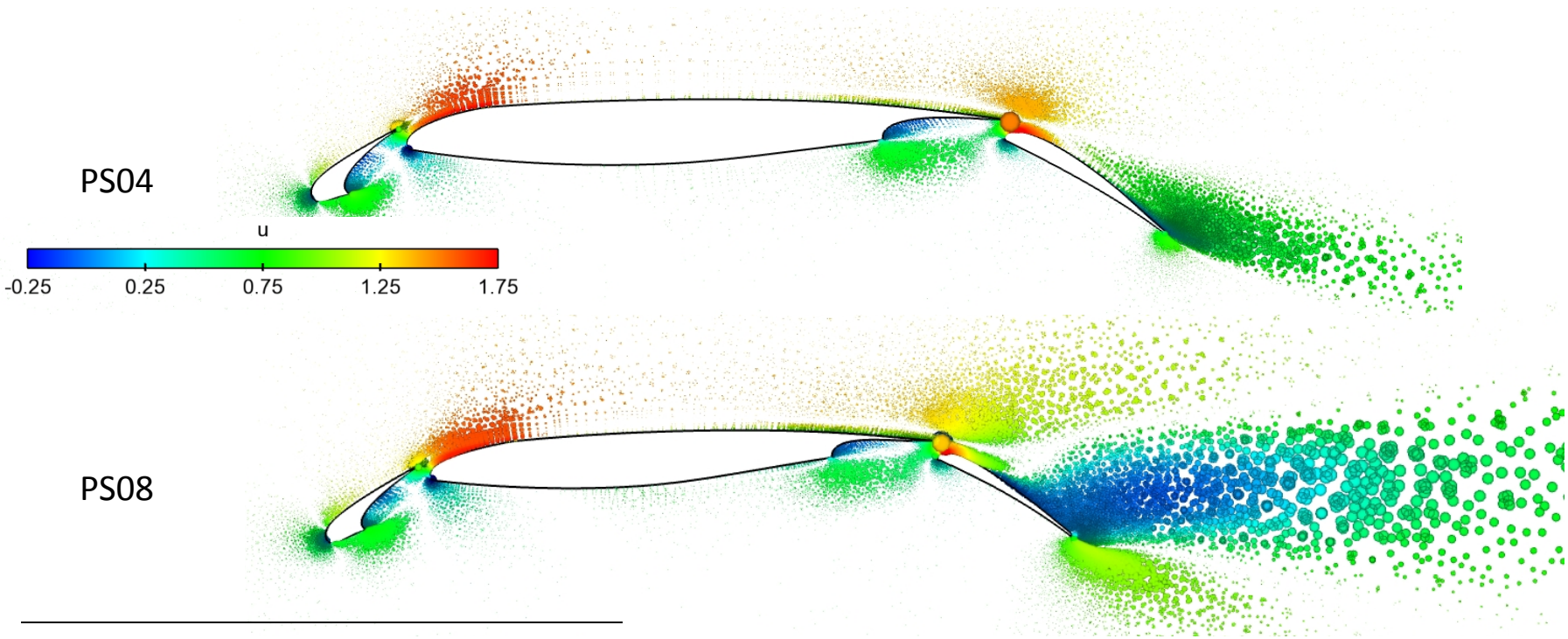


Velocity Errors, α=18.5, Re=1.35(10)^6



2D/3D Error Visualization

- Error bars are just one means of visualizing and interpreting predicted errors
- "Error Bubble" plot* provides for simultaneous rendering of a variable and its associated error
  - Spherical glyphs sized by magnitude of error
  - Glyphs vanish in regions of negligible error



* Cavallo, P.A., O'Gara, M.R., and Schikore, D.R., "Software System for Prediction, Visualization, Analysis, and Reduction of Errors In CFD Simulations," AIAA Paper 2009-3649, 19th AIAA Computational Fluid Dynamics Conference, San Antonio, TX, June 22-25, 2009.

Concluding Remarks

- CRUNCH CFD results compared favorably with test data and were consistent with results of other workshop participants
- Discretization error predictions using ETE method were mixed
  - C_p errors capture mesh increments well
  - Errors in lift/drag/moment generally conservative, but reasonable across angle of attack sweeps, in right direction vs. data
  - Increments in velocity profiles not well captured, overpredicted
- Effective in solution verification, in that discrepancies with data confirmed as due to factors other than grid resolution
- Ultimately, accurate prediction dependent on point placement
  - "C" grids show evidence of slat wake, "D" grid does not
  - Absence/presence of flow feature cannot be predicted by ETE
  - Error equations solved on same discretization as Navier-Stokes equations, subject to similar numerics issues

➢ ***Not yet a solved problem!***

Acknowledgments

- Work conducted under Phase II SBIR program sponsored by NASA Langley Research Center, Hampton, VA

- Computations performed at NAS facility (Pleiades), NASA Ames Research Center

- ***Questions?***

- Contact info:

Dr. Peter Cavallo, Senior Research Scientist
CRAFT Tech
6210 Keller's Church Road
Pipersville, PA 18947
(215)-766-1520
cavallo@craft-tech.com