CRUNCH CFD Calculations for HiLiftPW-2 with Discretization Error Predictions

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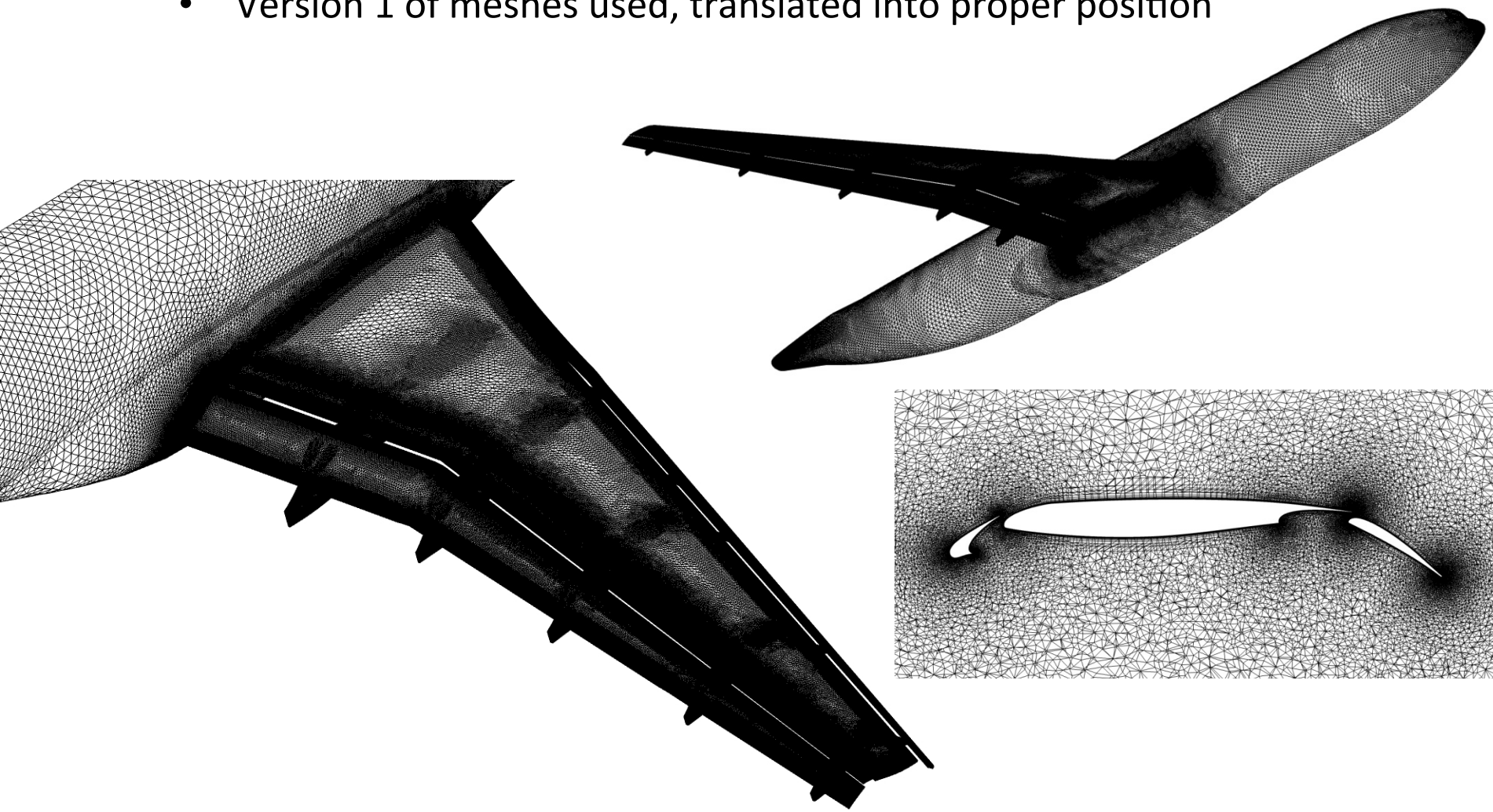
Outline of Discussion

- Overview of grids and flow solver
- Presentation of results for Case 2b and Case 2a (α sweeps)
  - Pressure coefficient comparisons (2b and 2a)
  - Oil flow and PIV comparisons (2a only)
- Grid convergence studies – Case 1 results
  - Solution increments due to grid resolution
  - Introduction to error quantification/analysis
- Overview of error analysis/prediction methods
- Presentation of Case 1 and Case 2 results with predicted errors from solution of Error Transport Equations (ETE)
- Concluding remarks and questions

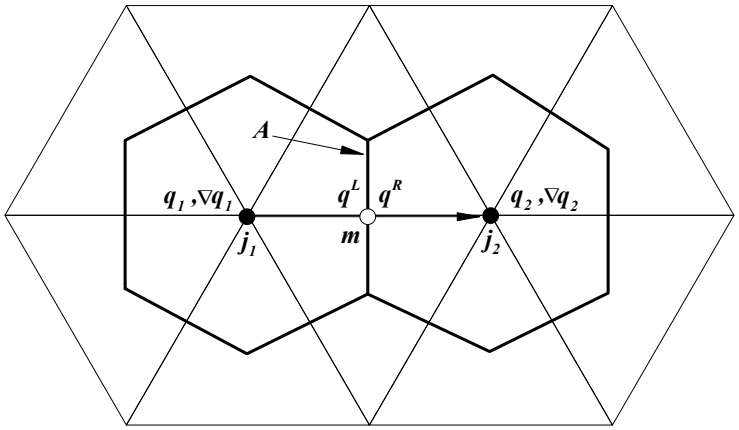
Grid Overview

- D_UNS_MIX grid sequence employed
- Mixed-element meshes 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

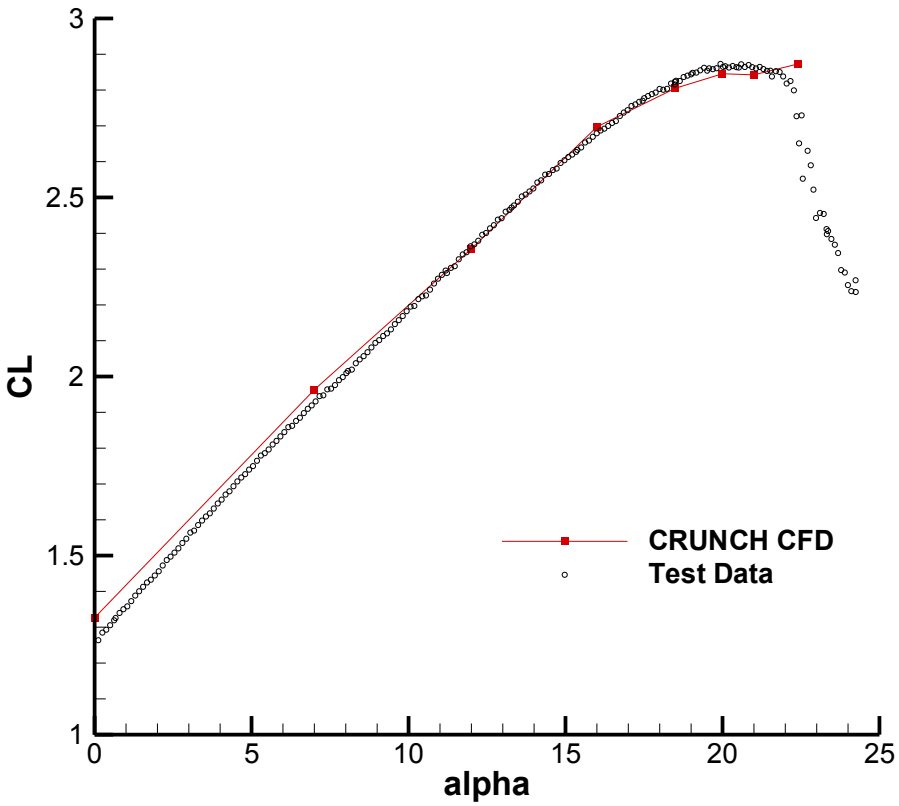


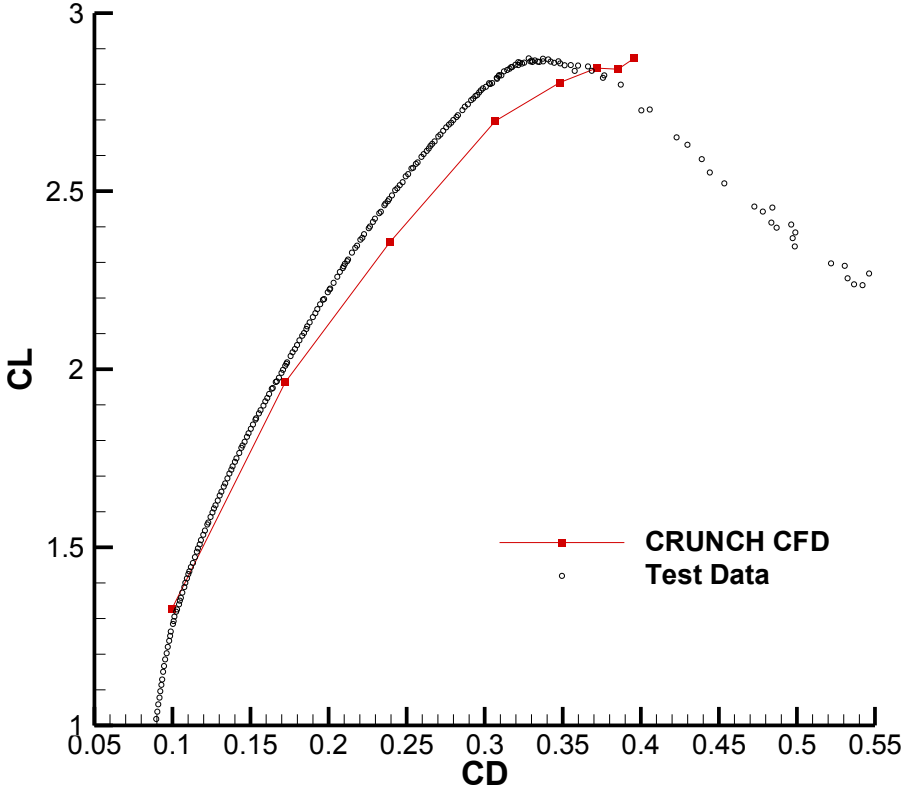
Case 2b: Major Findings

- Excellent agreement with experimental C_p profiles for attached flow cases from α=0 to α=18.5 degrees
- Beyond 18.5 degrees cases are unsteady and difficult to converge – unsteadiness seen in both C_p plots and surface C_f
- Perhaps need to run higher α cases time accurate and examine the time-averaged solution
- Separation observed to occur at outboard wing station (~70 to 75% span) with k-ω model
- Drag typically overpredicted with discrepancy increasing with C_L

Case 2b Results

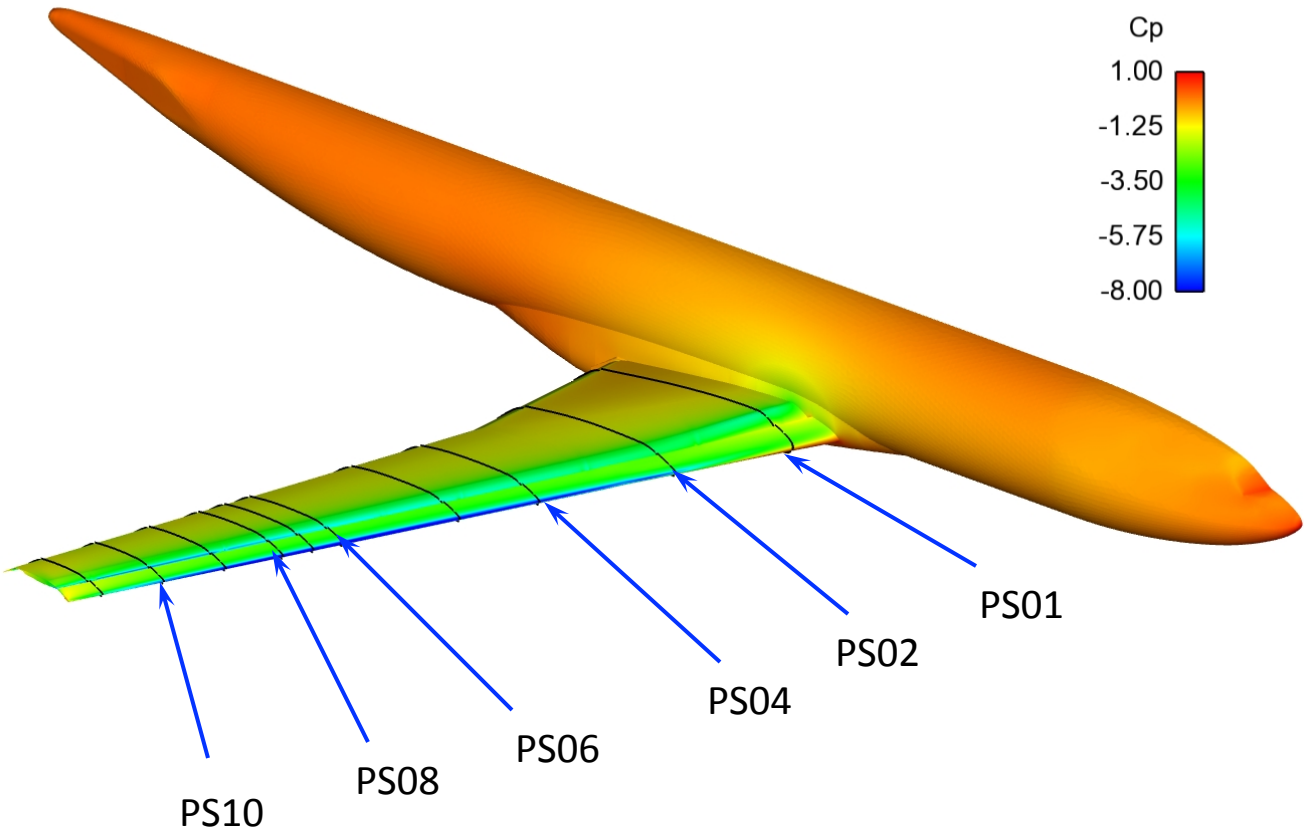
- High Re sweep shown – Re=15.1(10)^6
- Very good agreement for attached flow up to maximum C_L
- Agreement tapers off with onset of separation
- Cases become unsteady beyond 18.5 degrees



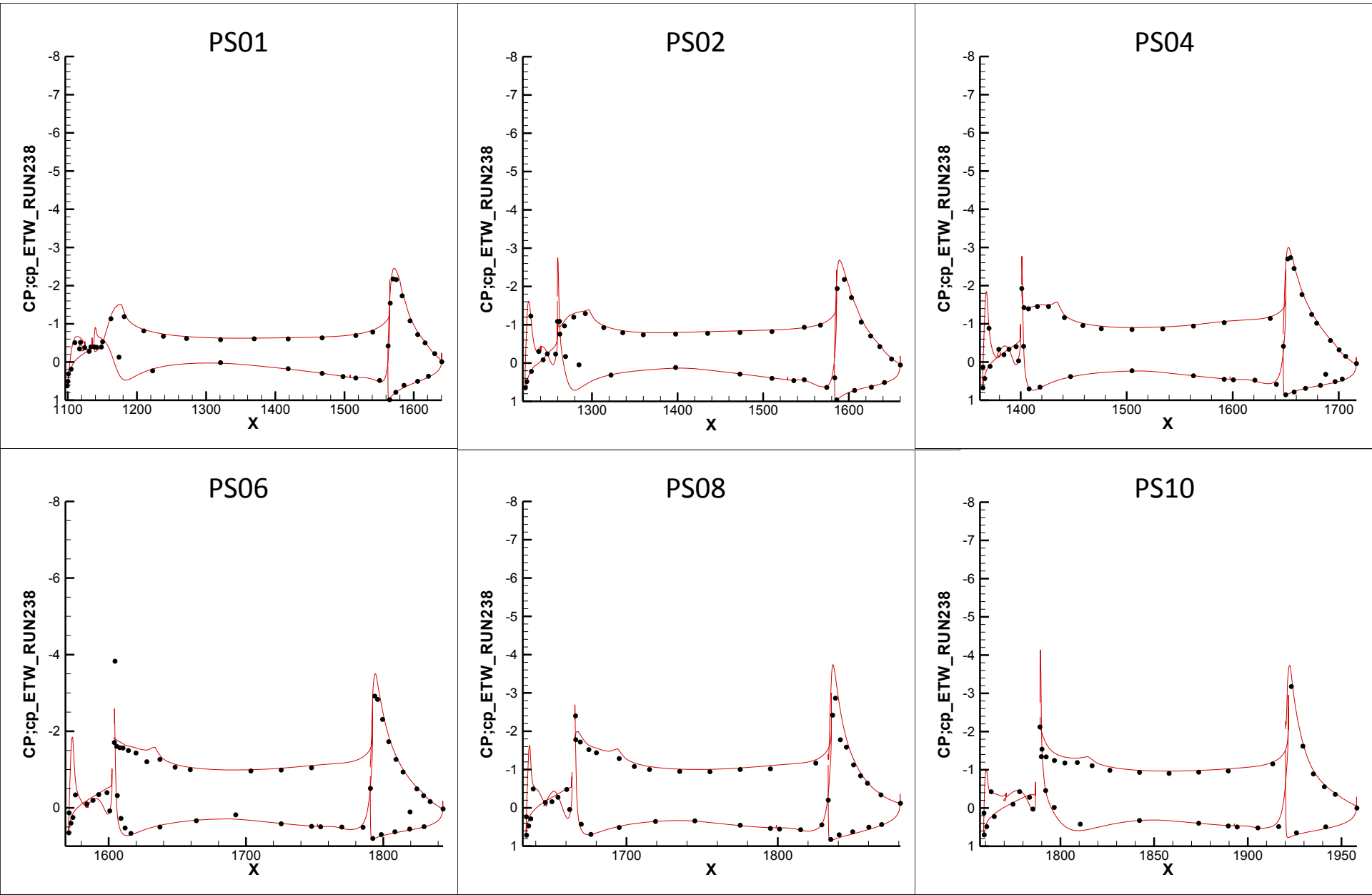


C_p Comparisons

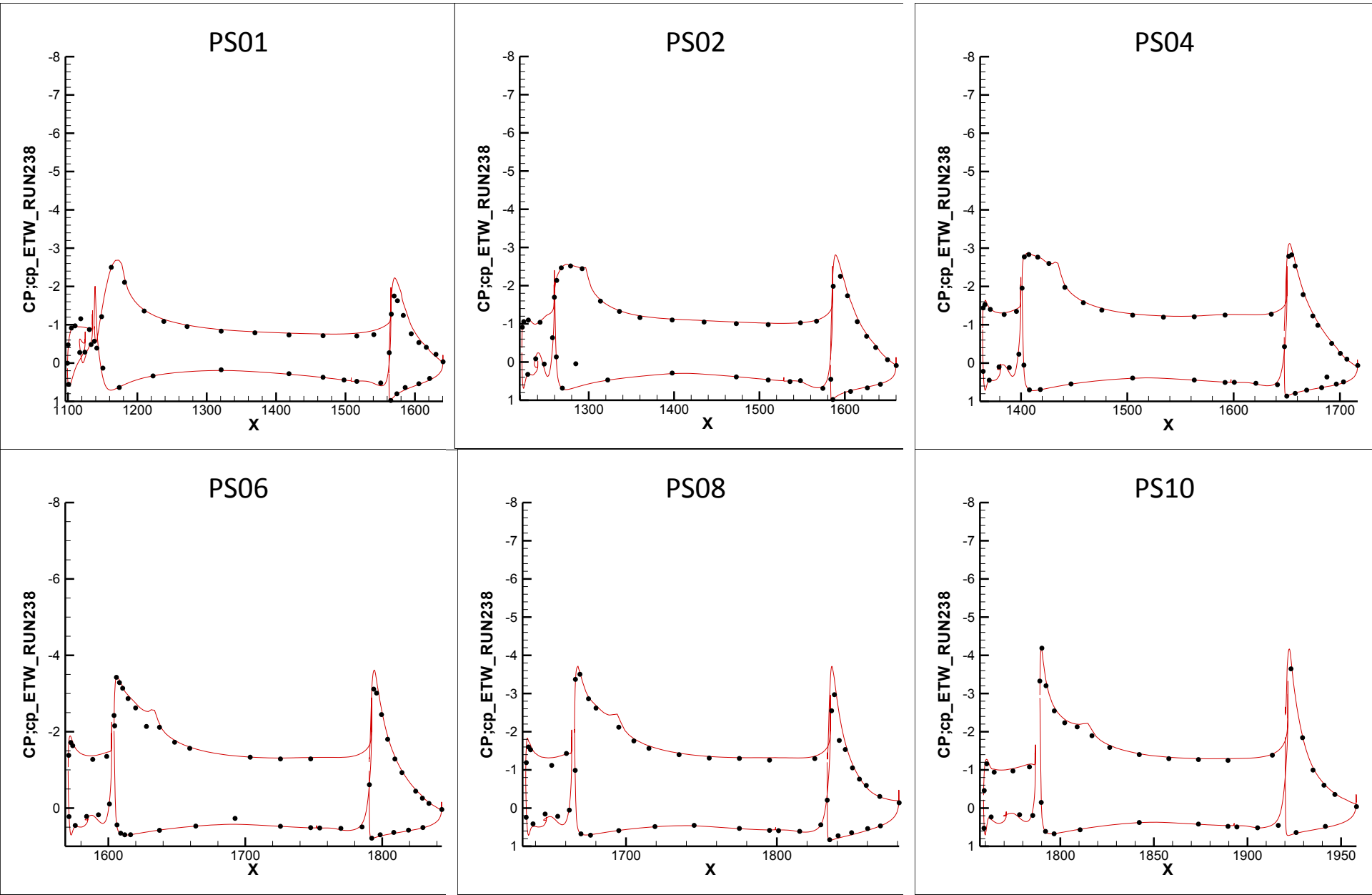
- 10 spanwise stations with data for comparison
- 6 highlighted stations are shown for each angle-of-attack



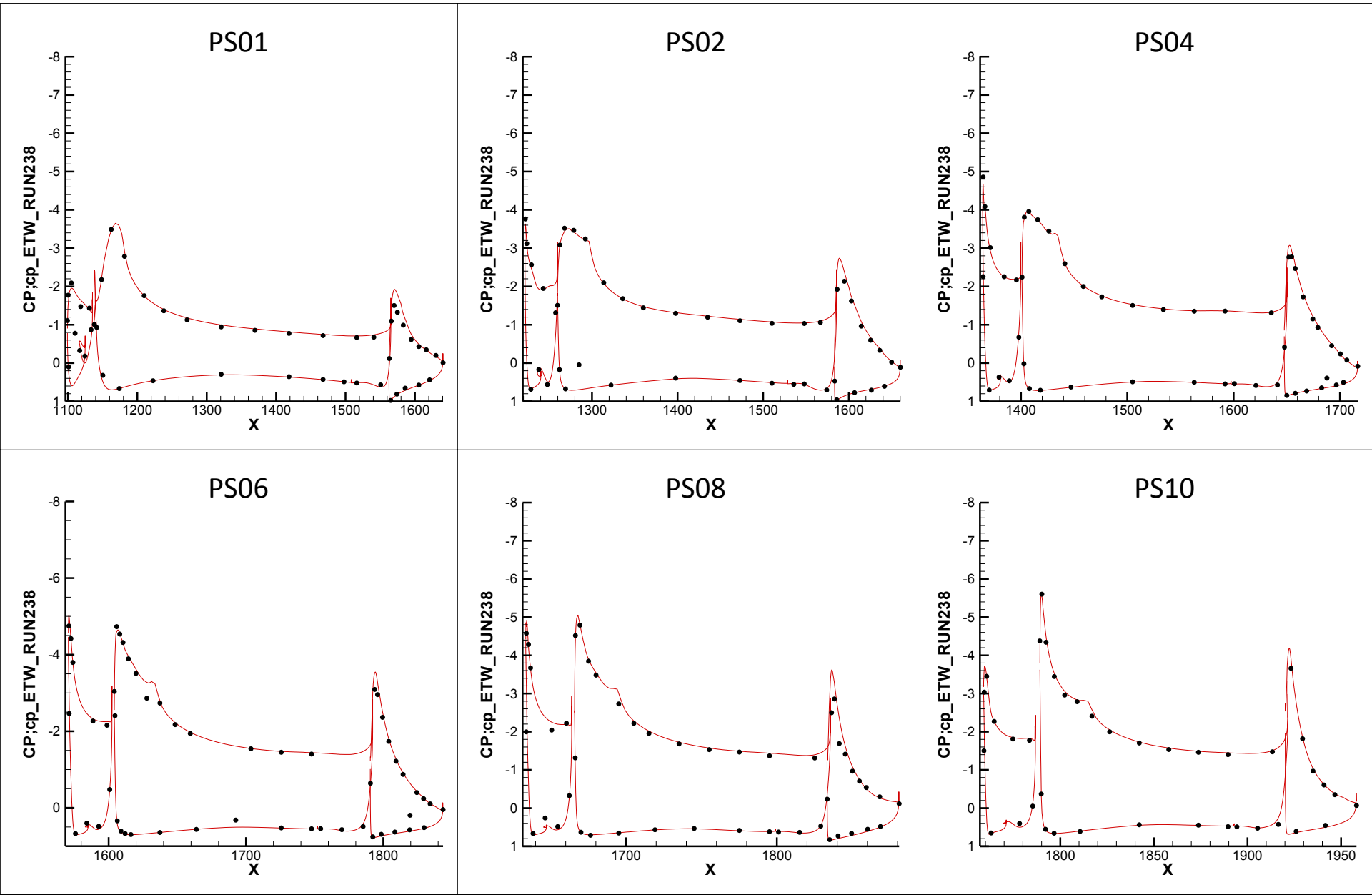
C_p Comparisons, α=0, Re=15.1(10)^6



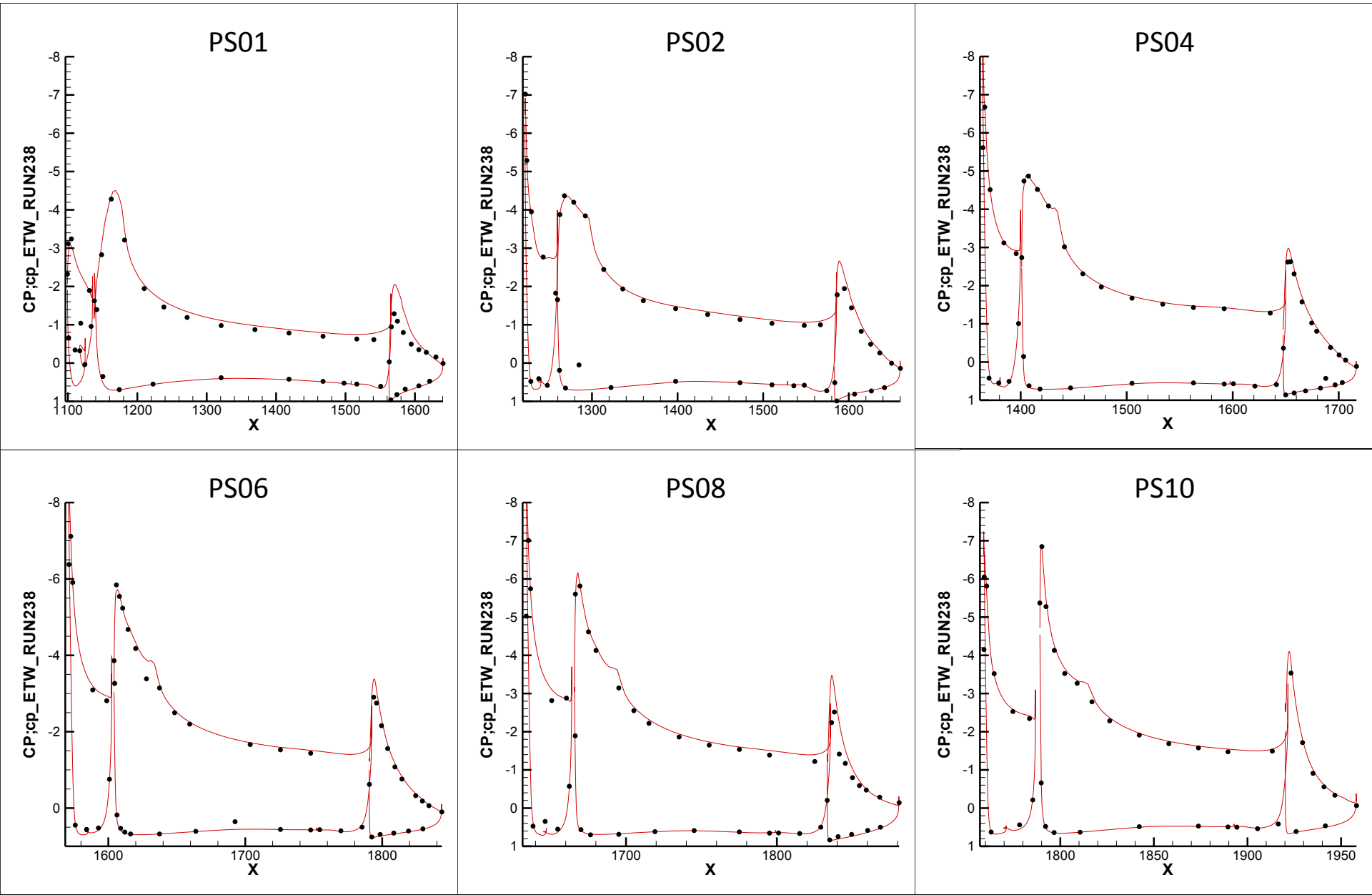
C_p Comparisons, α=7, Re=15.1(10)^6



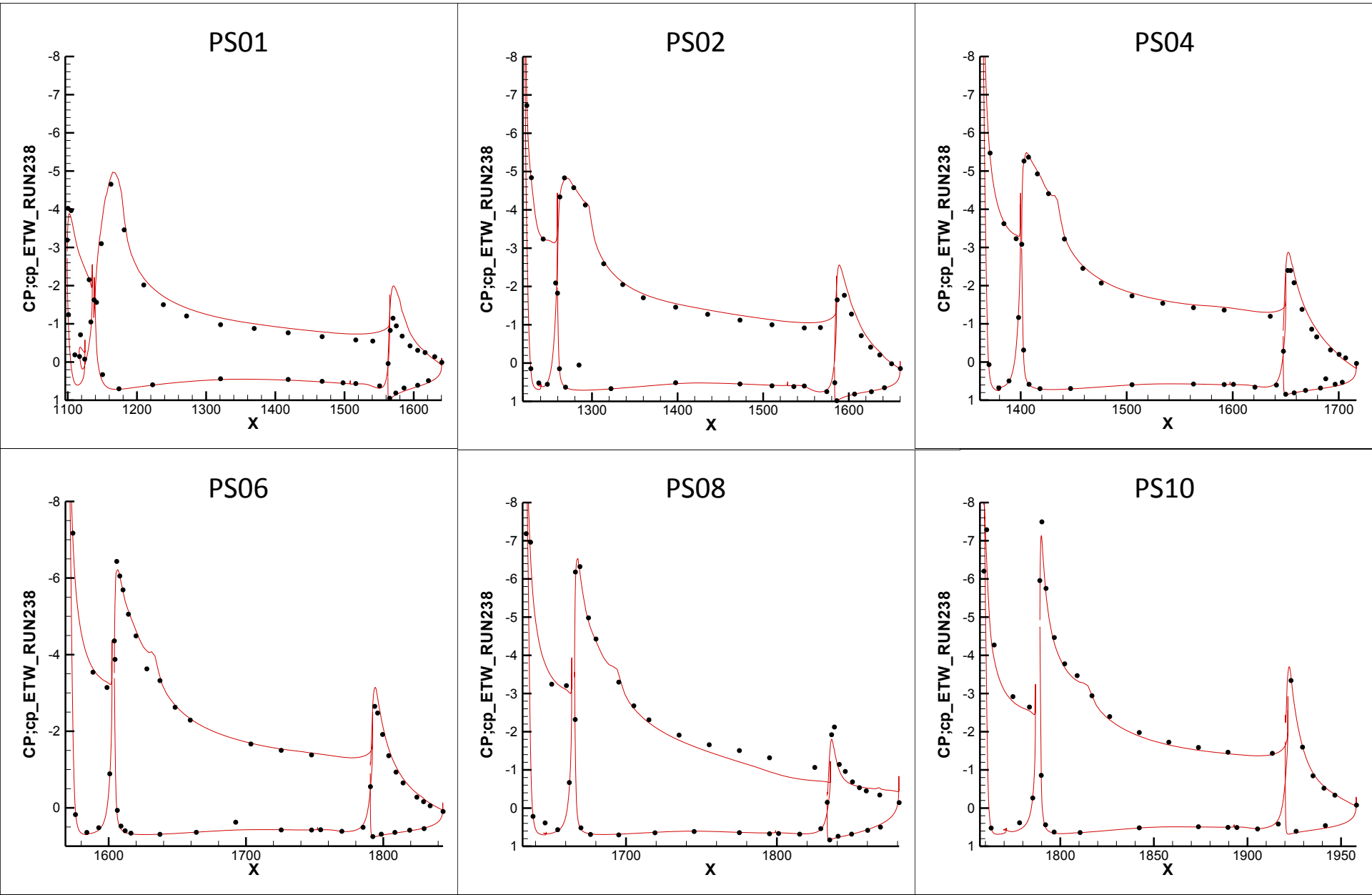
C_p Comparisons, α=12, Re=15.1(10)^6



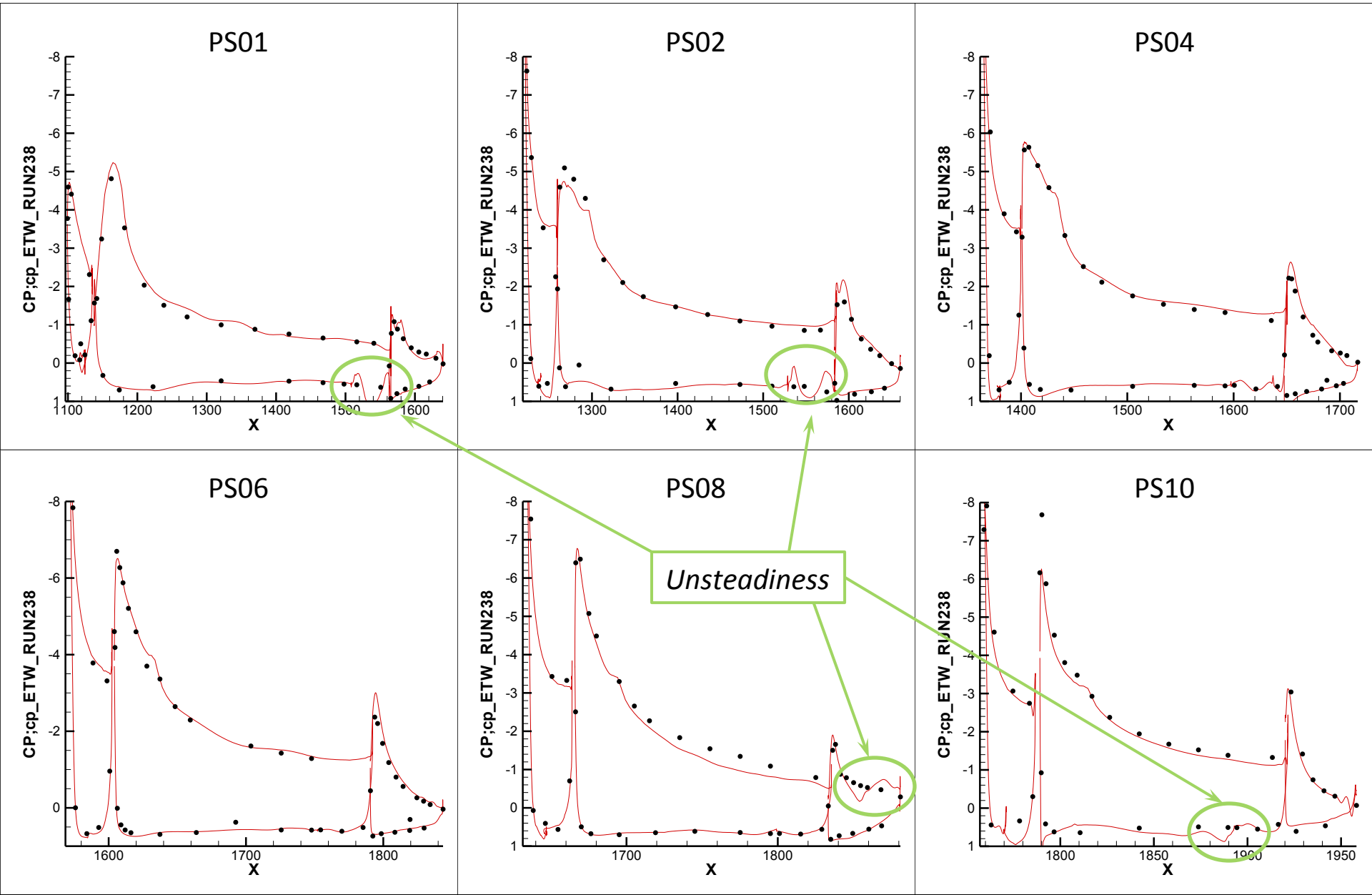
C_p Comparisons, α=16, Re=15.1(10)^6



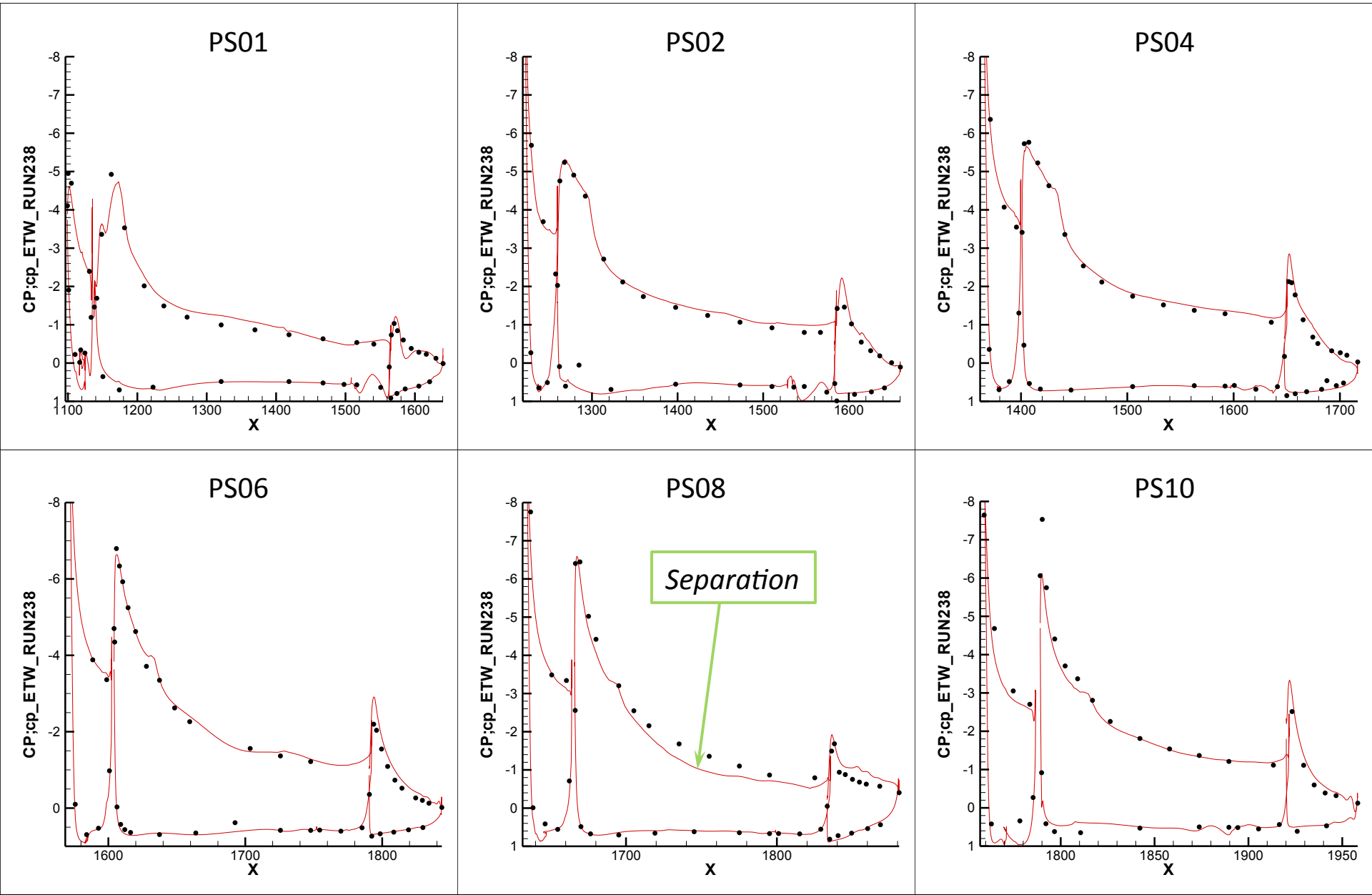
C_p Comparisons, α=18.5, Re=15.1(10)^6



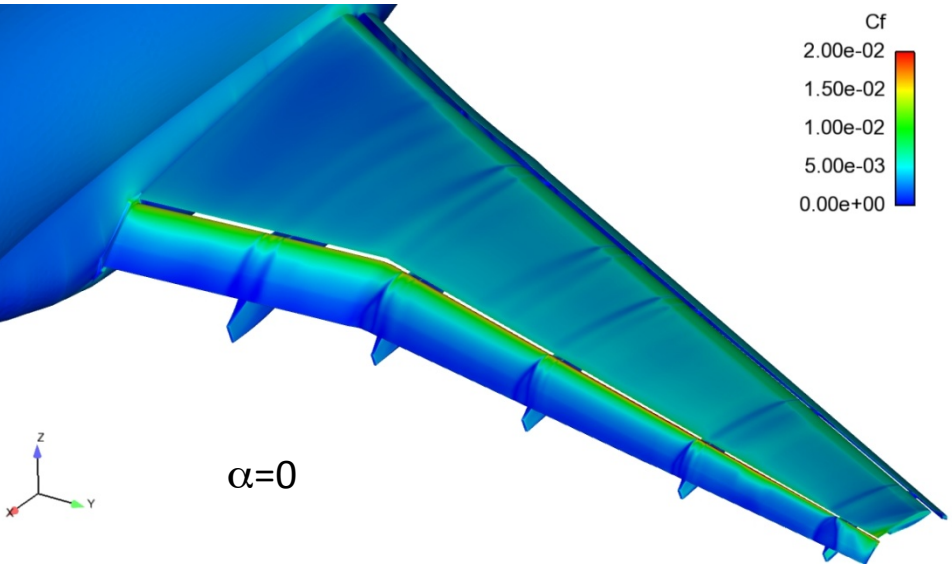
C_p Comparisons, α=20, Re=15.1(10)^6

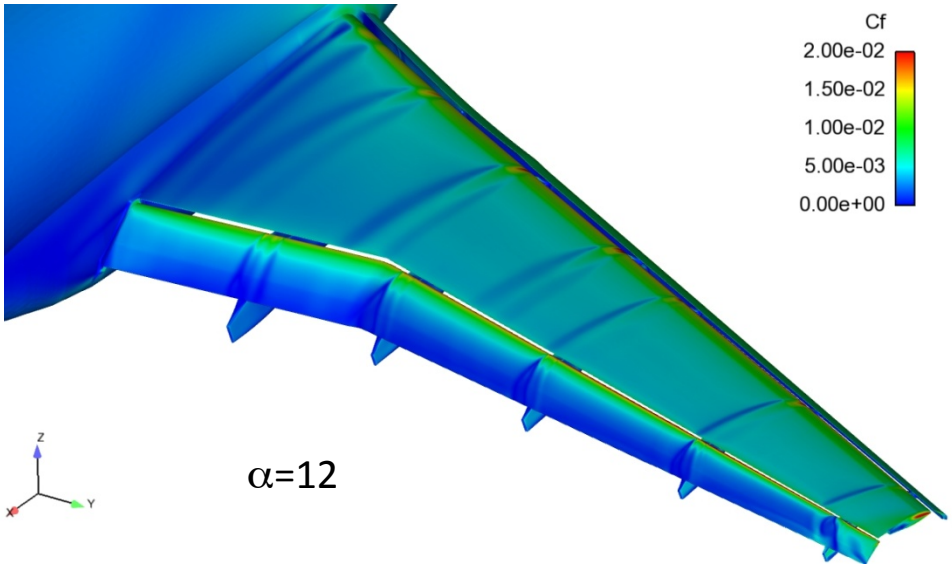


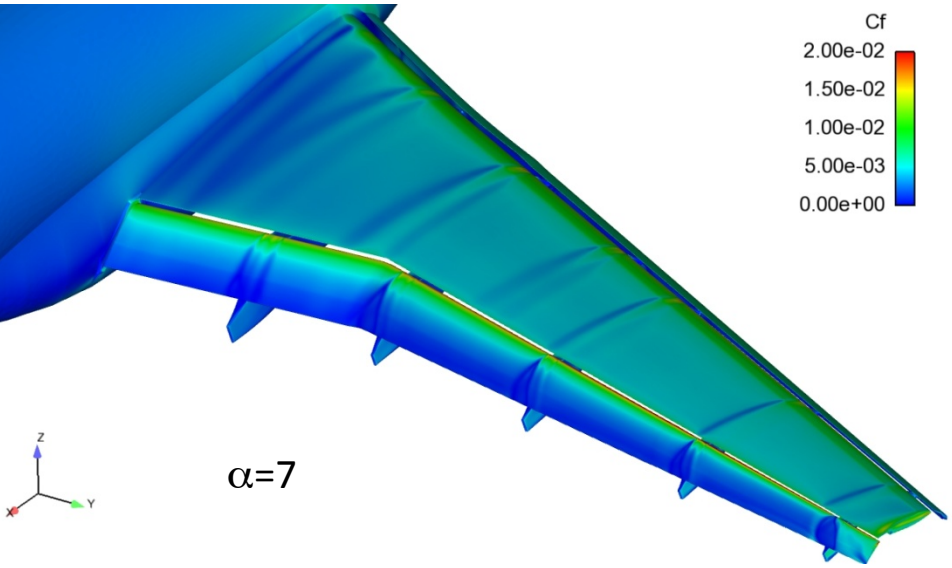
C_p Comparisons, α=21, Re=15.1(10)^6

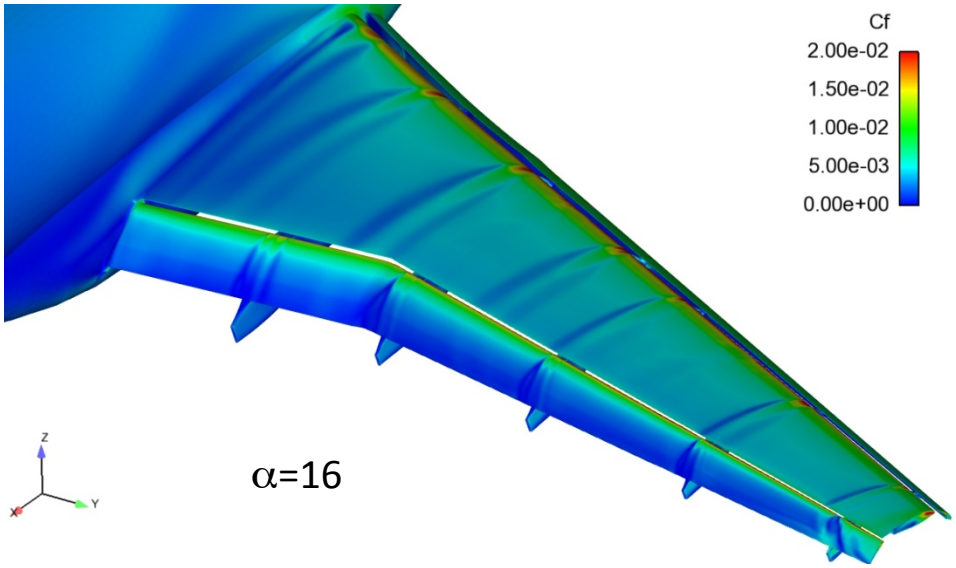


Skin Friction, Re=15.1(10)^6









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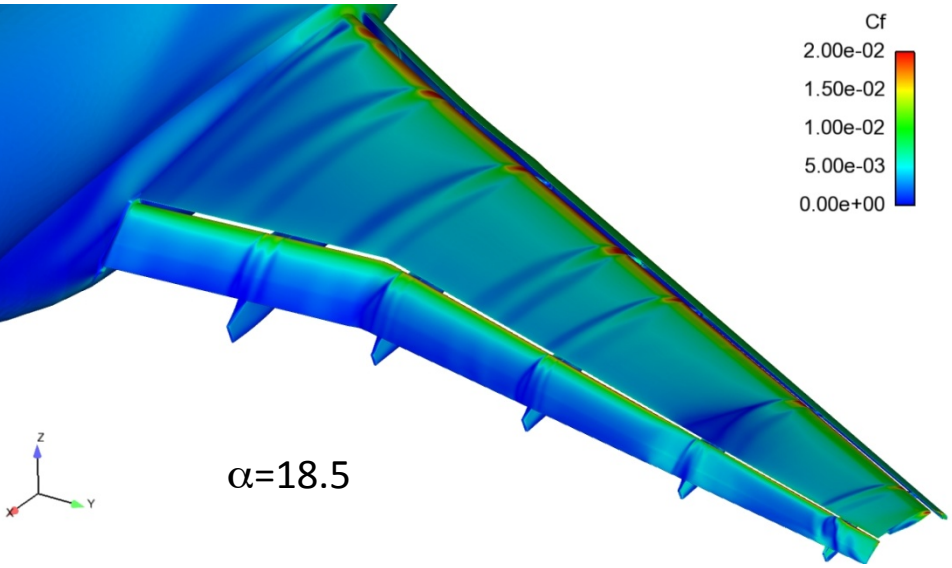
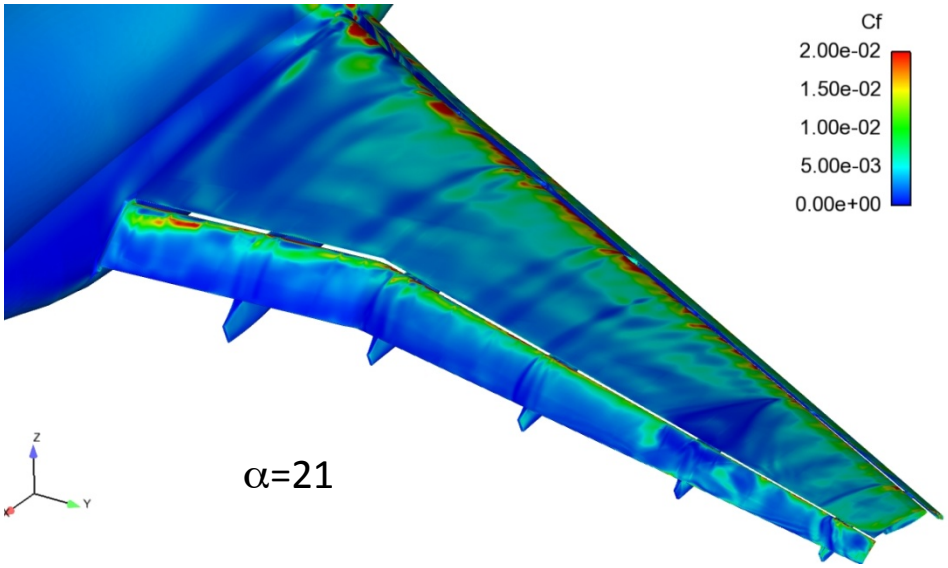
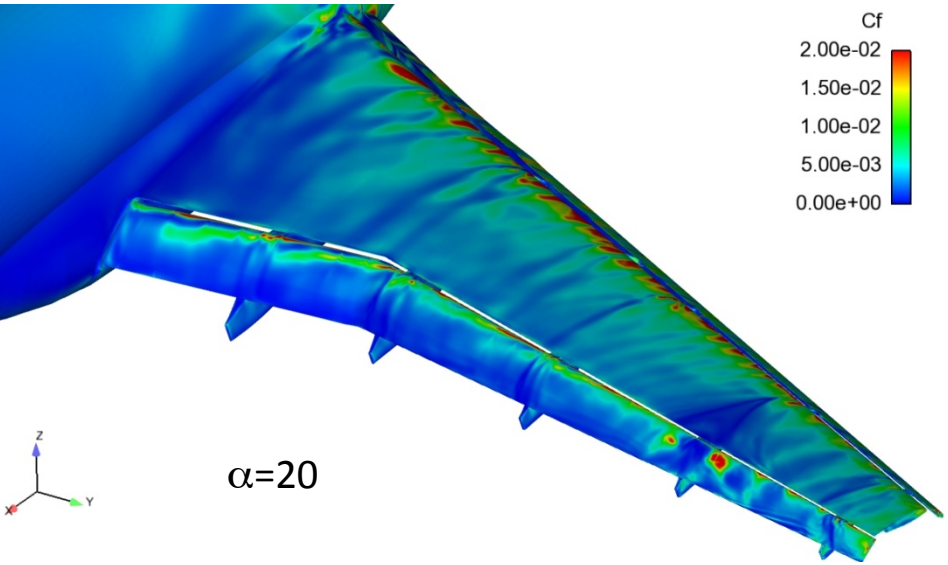






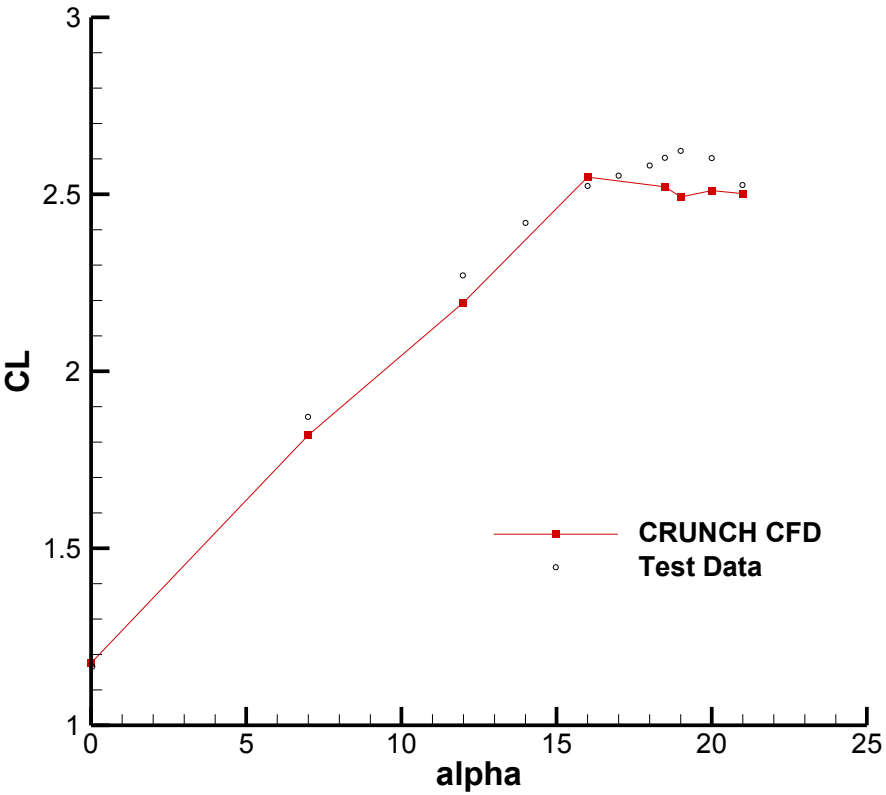
- Beyond 18.5 degrees cases are unsteady, difficult to converge
- Need to time-average solution?
- Separation occurs at outboard station near η=0.7 to 0.75

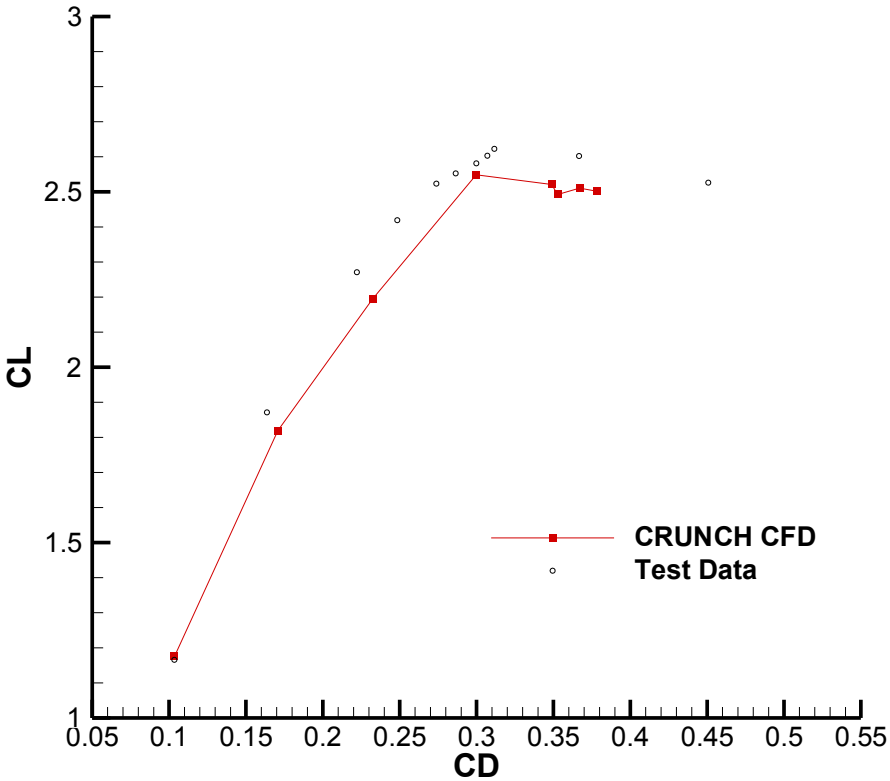
Case 2a: Major Findings

- Very good agreement for attached flow cases from α=0 to α=16 degrees, with slight underprediction of C_L
- Solutions are unsteady beyond 16 degrees, as seen in both C_p plots and surface C_f contours
- Time accurate solution and time-averaging likely needed for higher α conditions
- Separation occurs again occurs at outboard span location, not reflected in experimental oil flow visualization
- Some features in velocity profiles captured well, some not

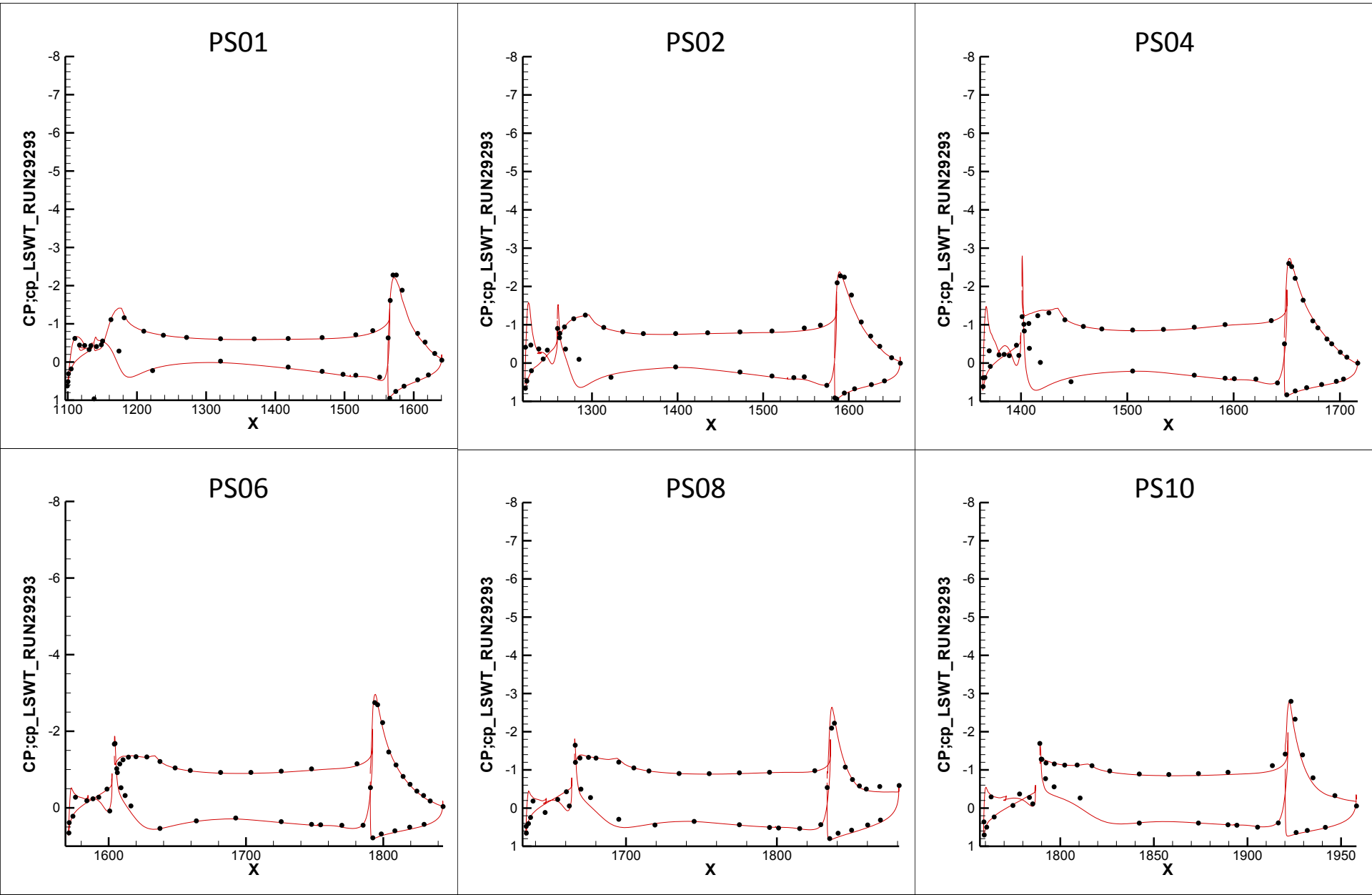
Case 2a Results

- Again very good agreement for attached flow
- Peak C_L not quite predicted, falls below test data
- Agreement tapers off with onset of separation
- Cases become unsteady beyond 16 degrees

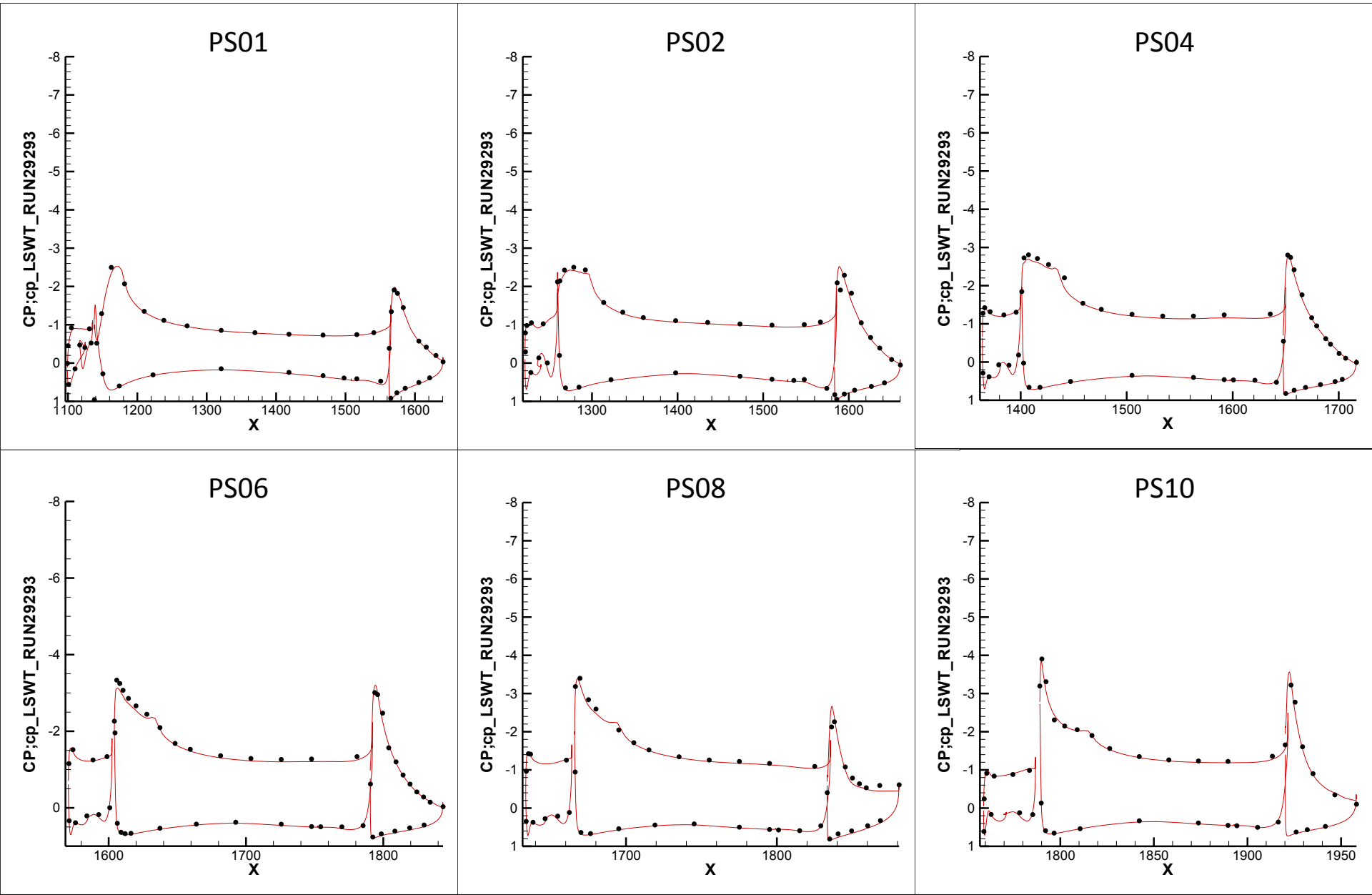




C_p Comparisons, α=0, Re=1.35(10)^6



C_p Comparisons, α=7, Re=1.35(10)^6



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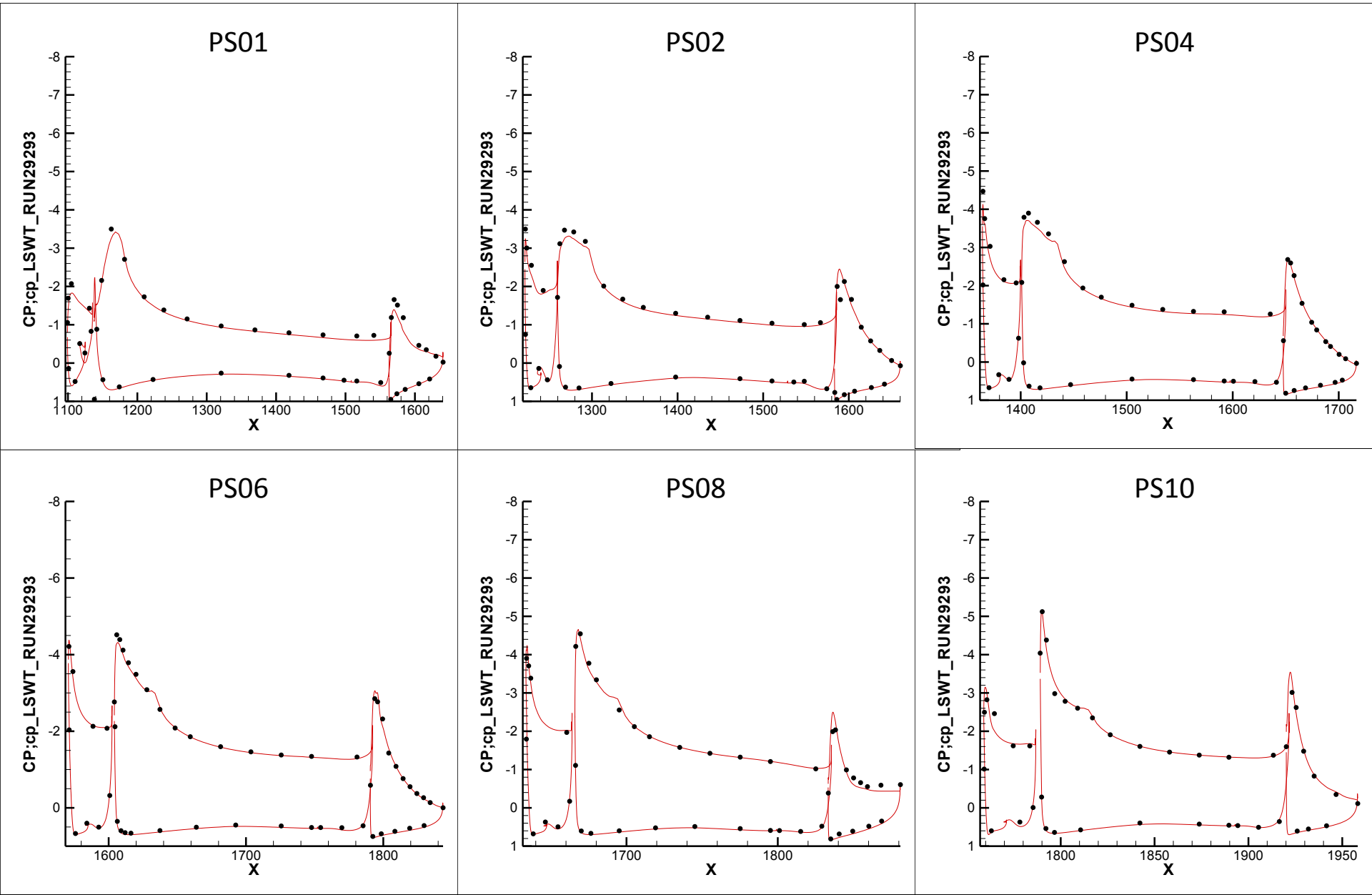
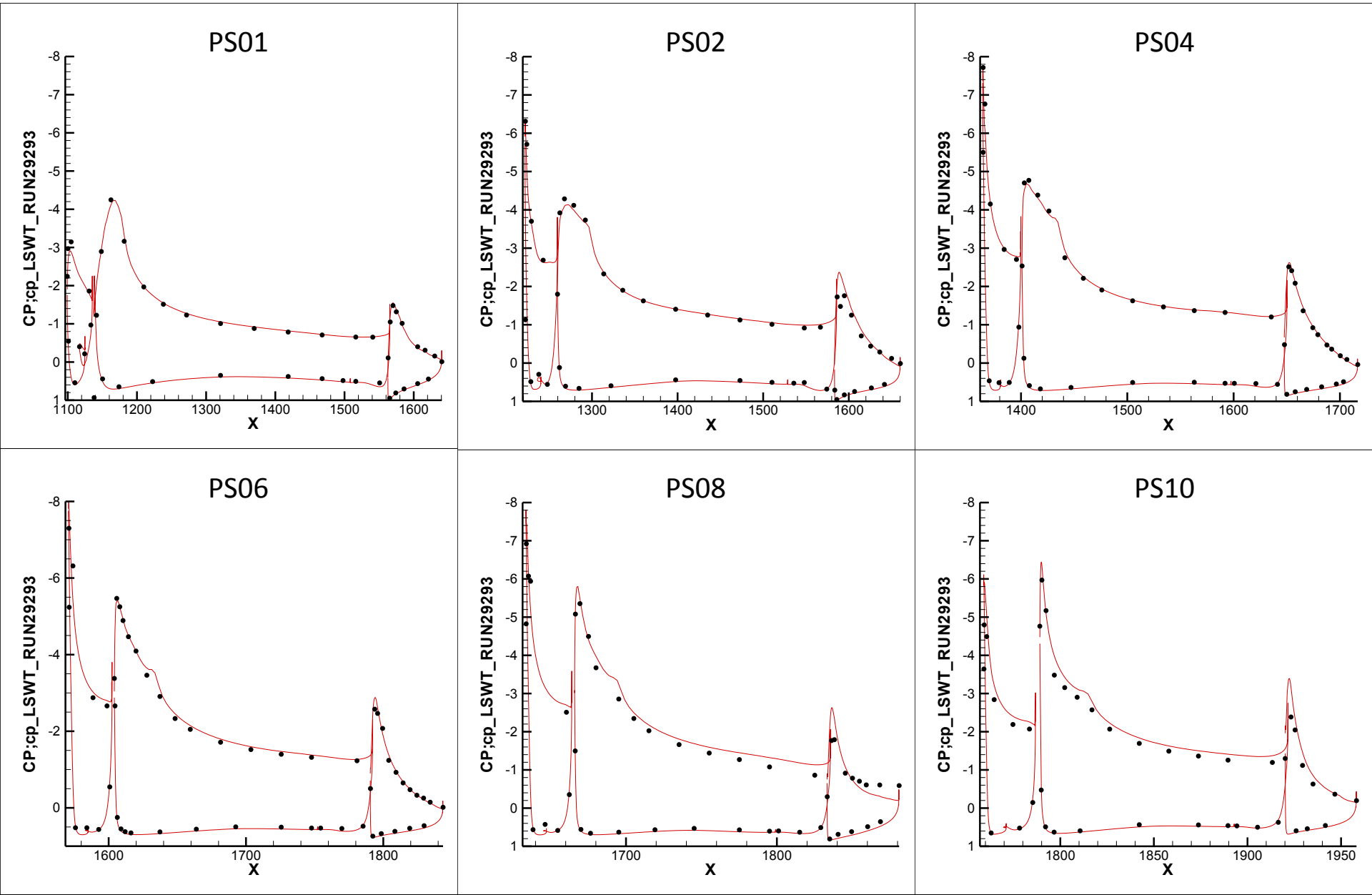
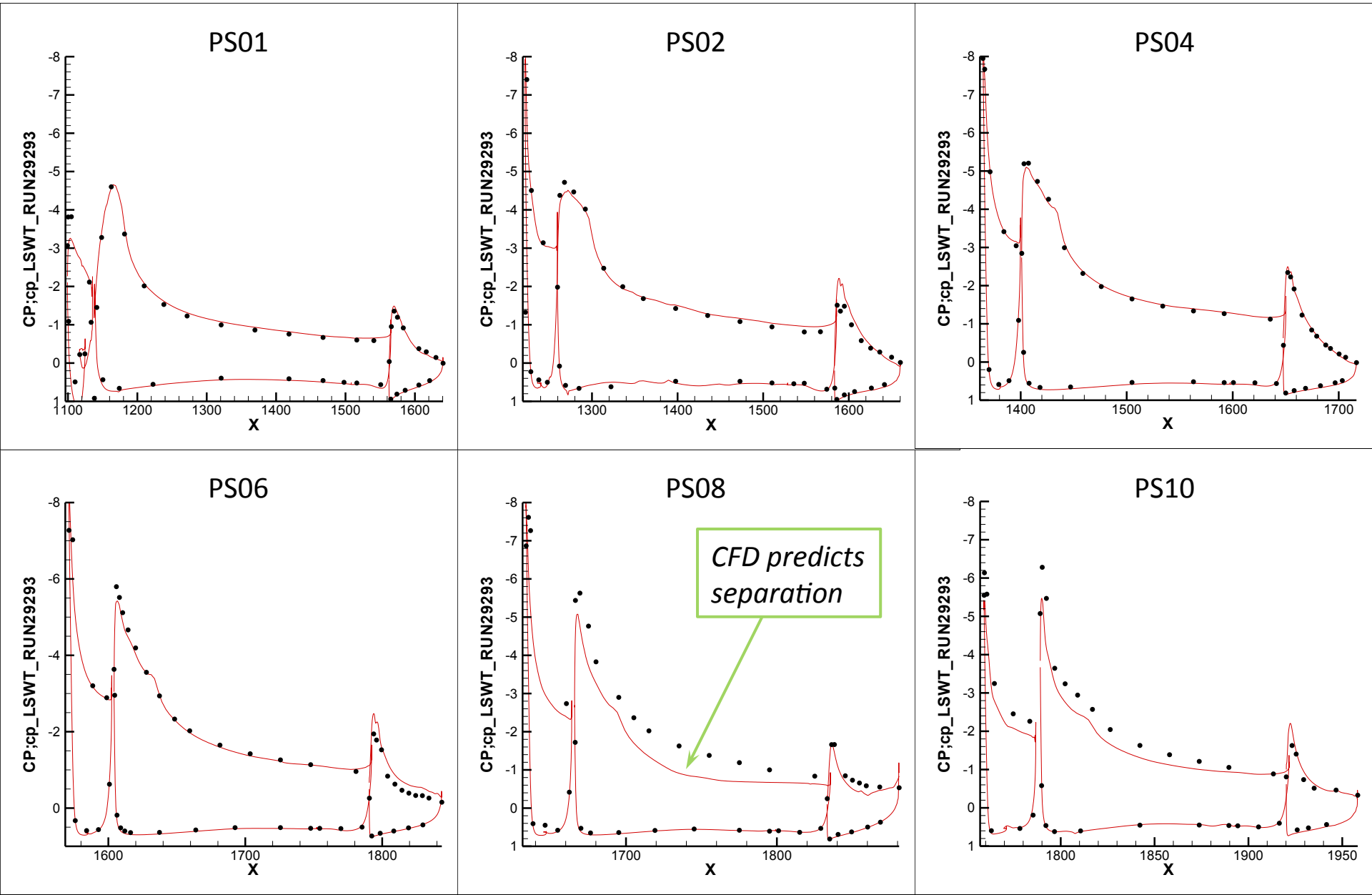


C_p Comparisons, α=16, Re=1.35(10)^6



C_p Comparisons, α=18.5, Re=1.35(10)^6



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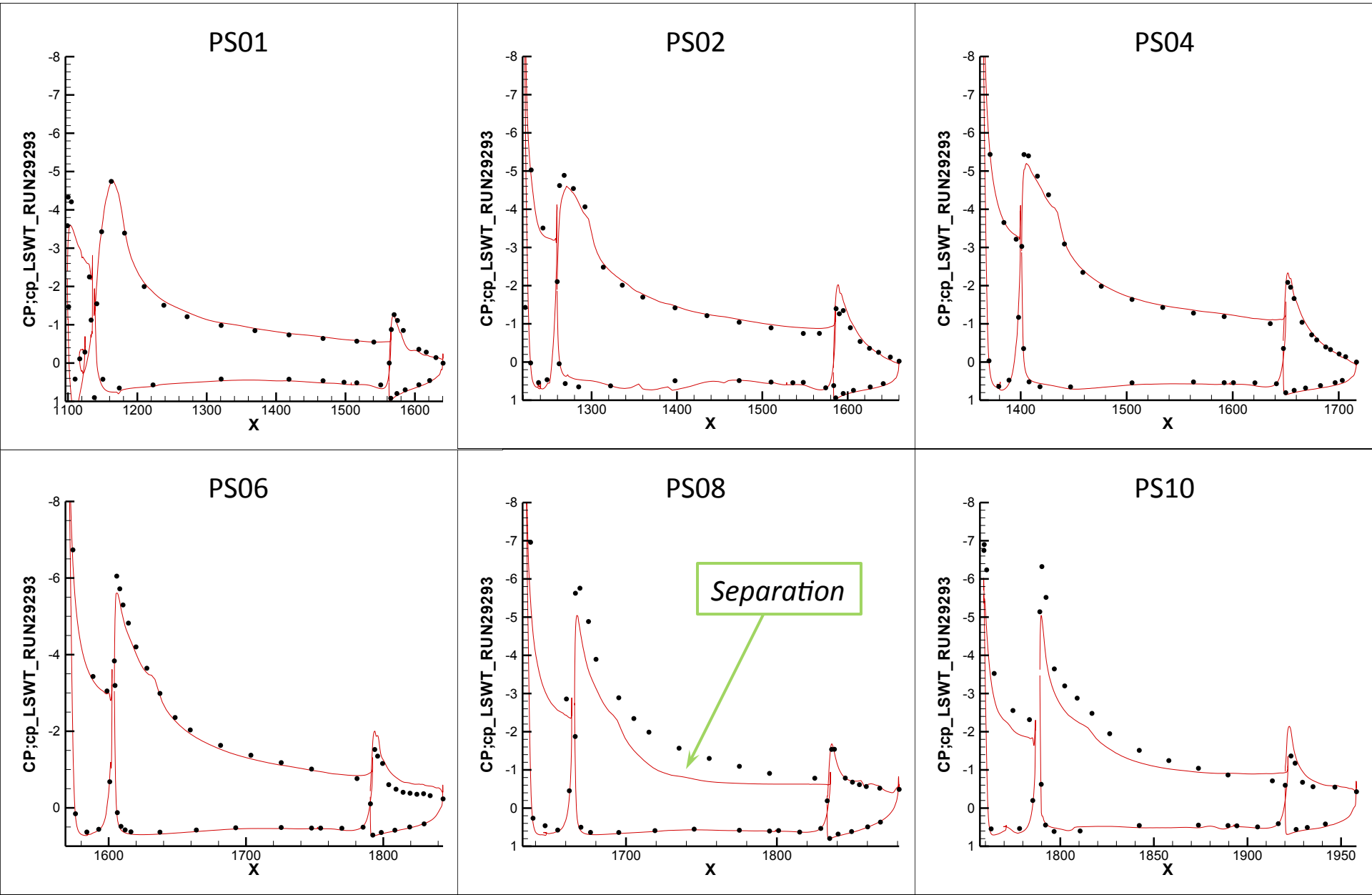
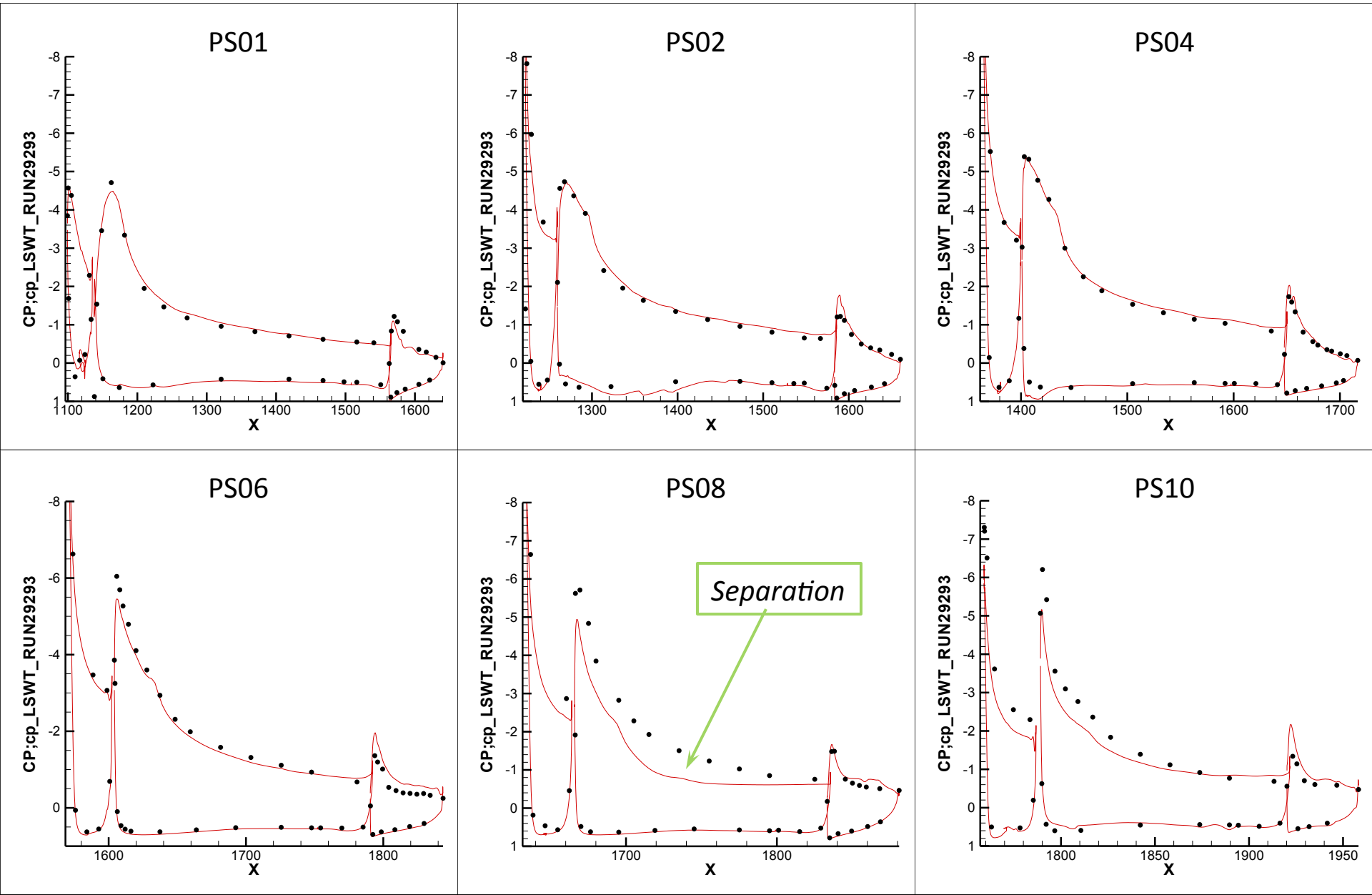
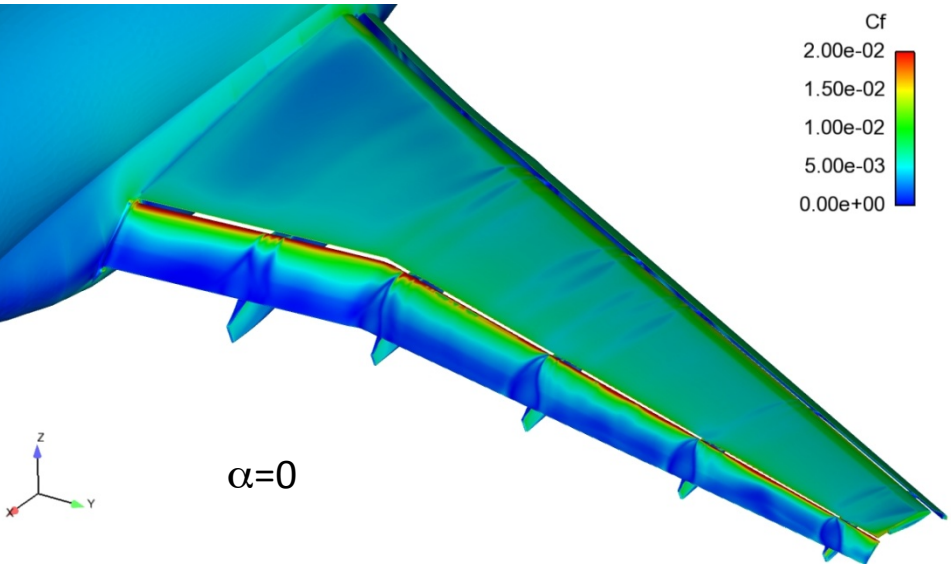
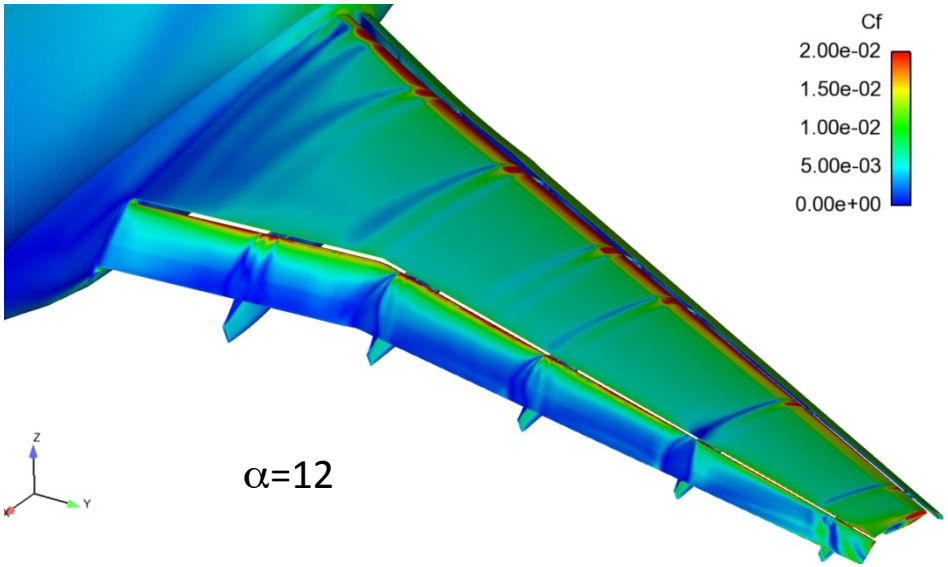


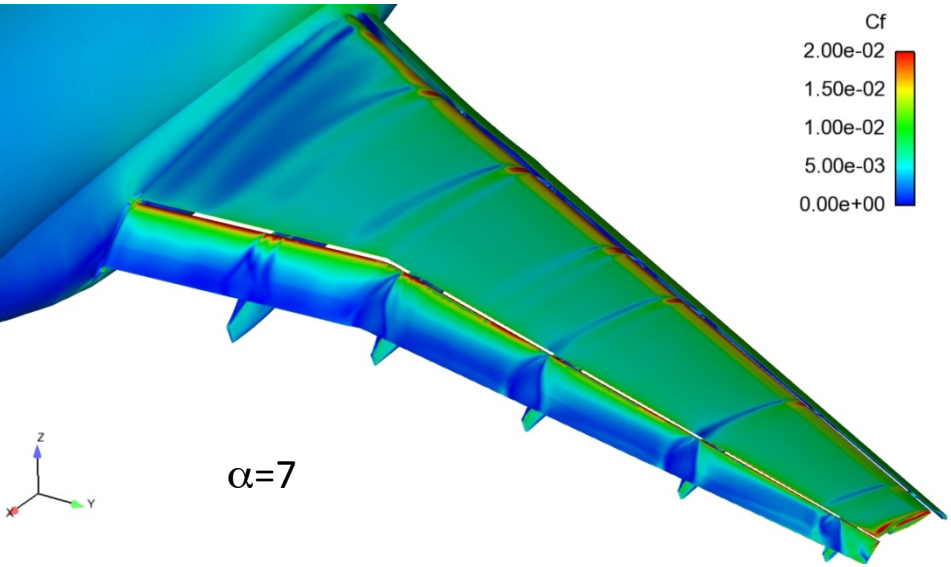
C_p Comparisons, α=21, Re=1.35(10)^6

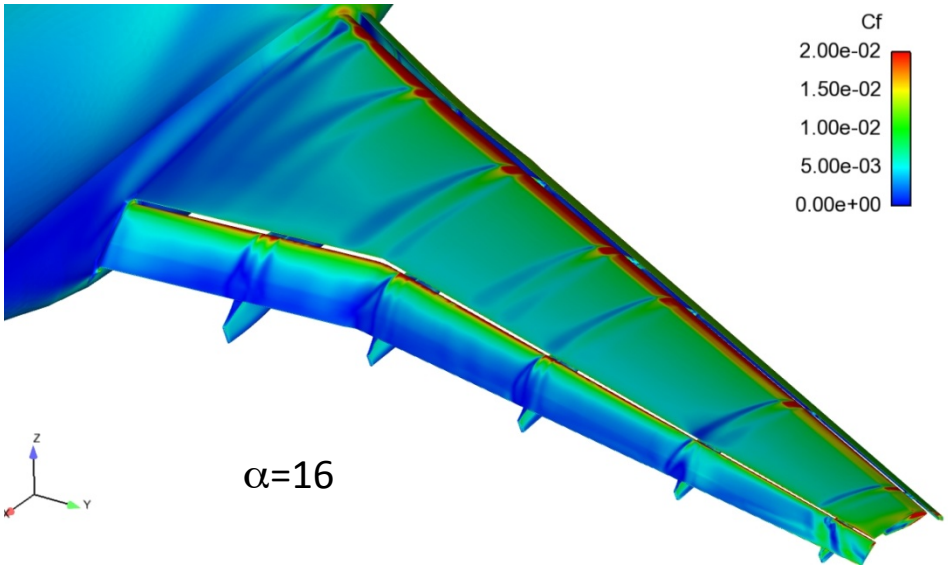


Skin Friction, Re=1.35(10)^6









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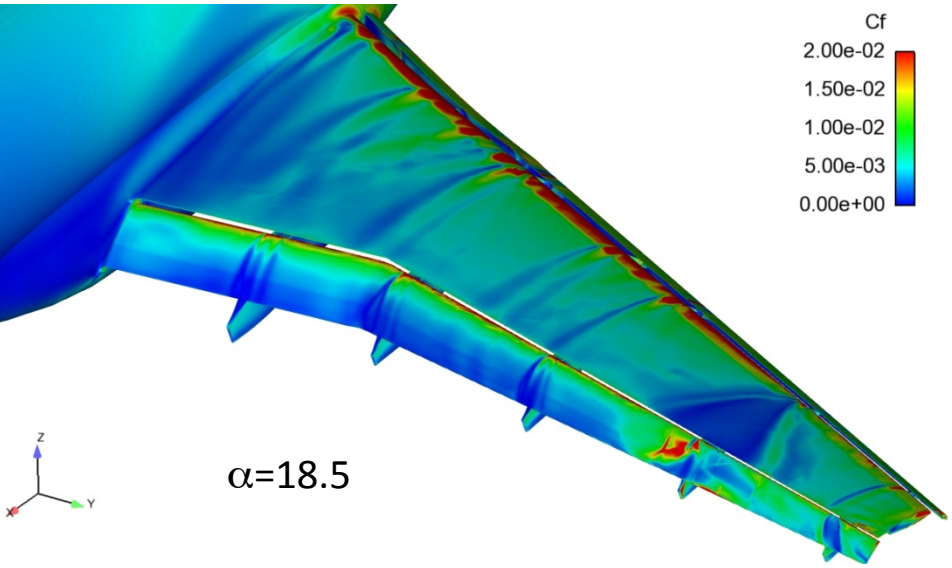
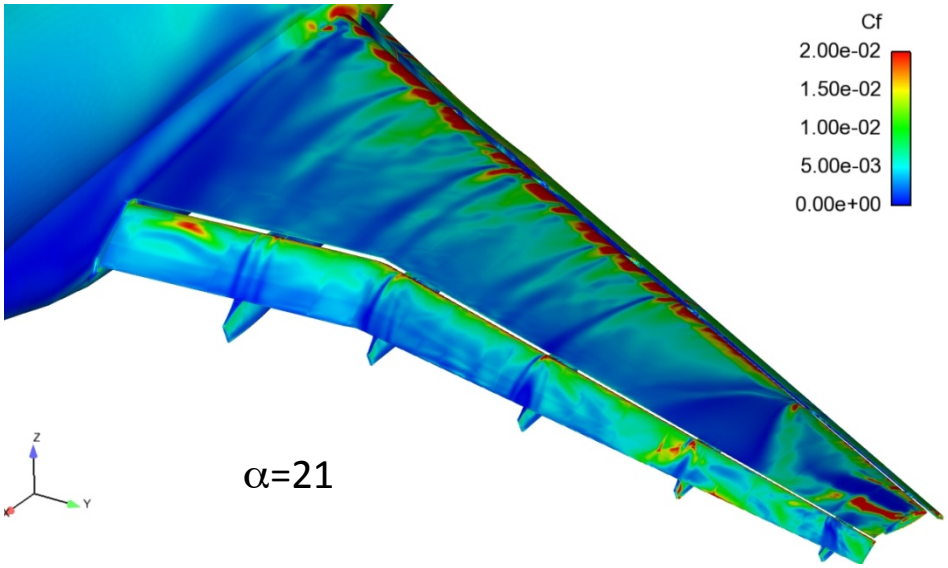
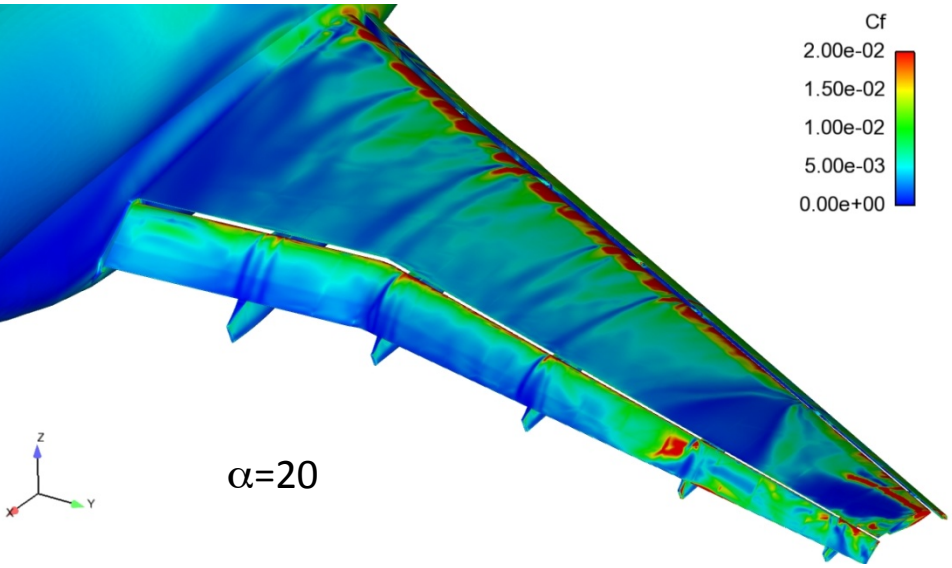
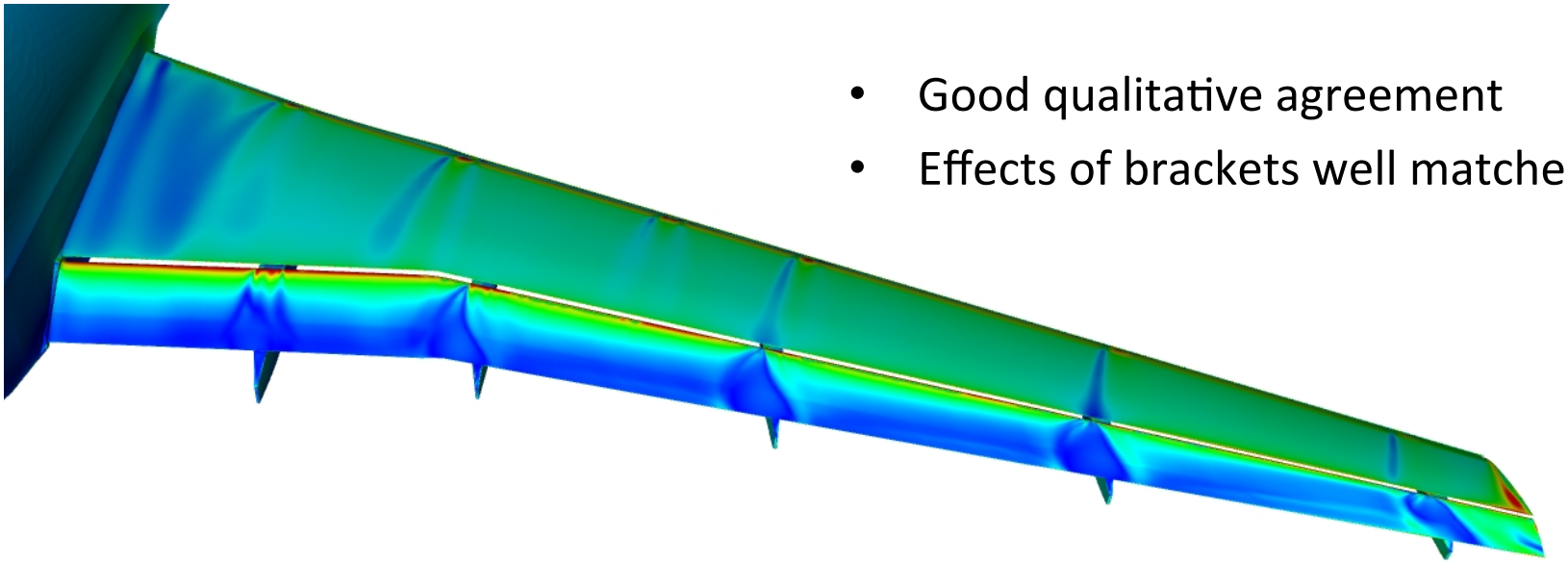




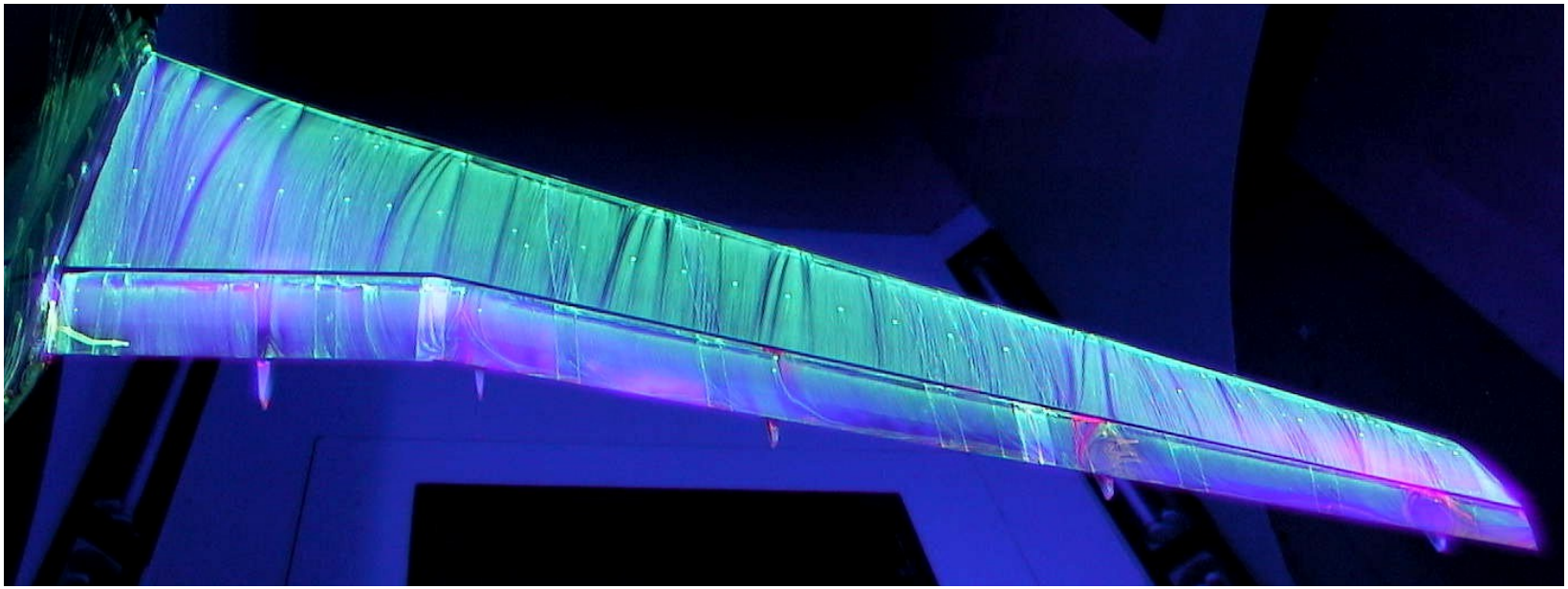


- Beyond 16 degrees cases are unsteady, difficult to converge
- Separation occurs at outboard station near η=0.7 to 0.75, and at wing tip
- In experiment separation is observed at mid-span – turbulence modeling issue?

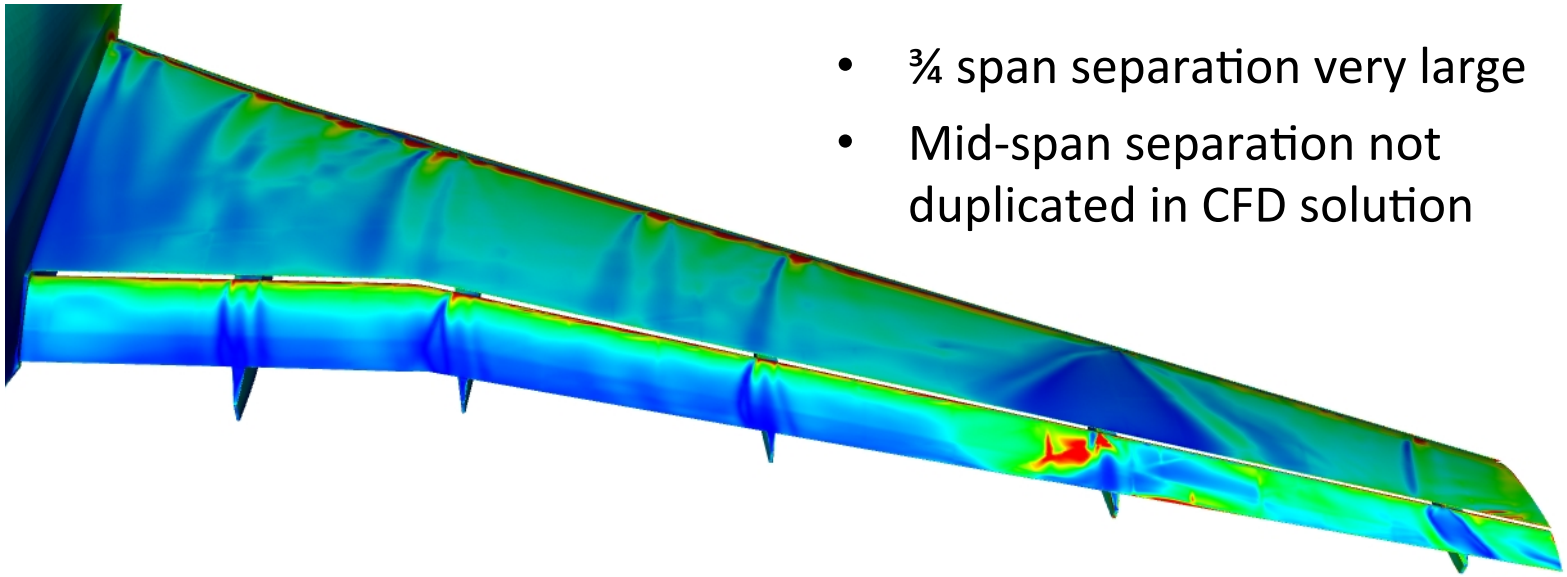
Oil Flow Comparisons, α=7



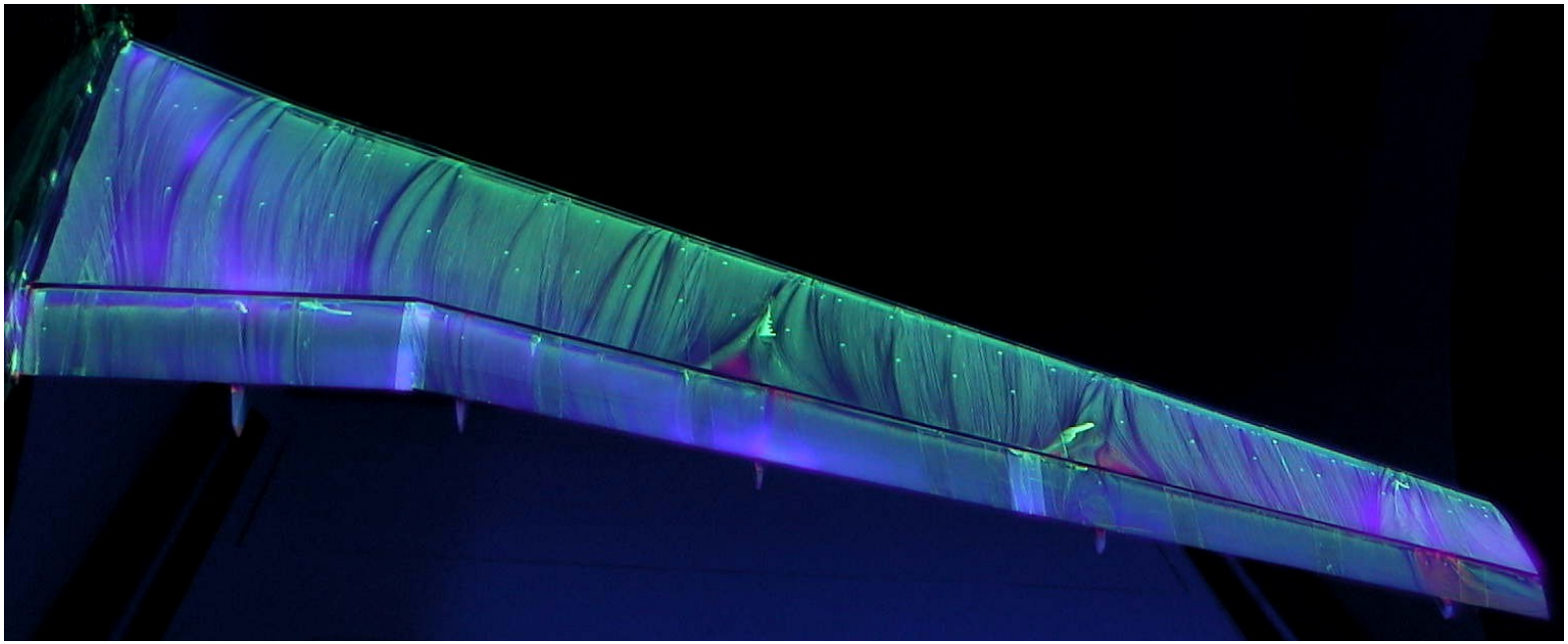
- Good qualitative agreement
- Effects of brackets well matched



Oil Flow Comparisons, α=18.5

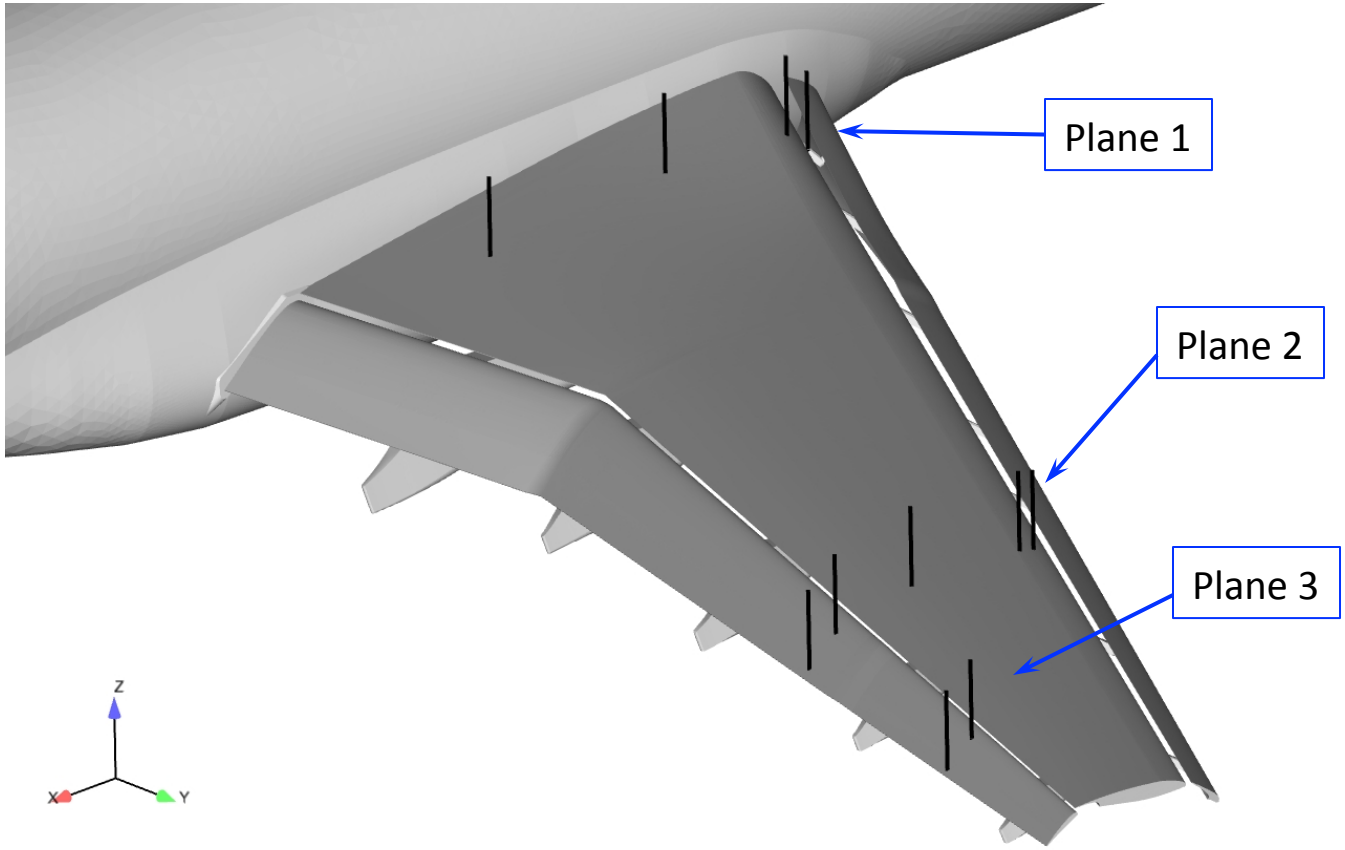


- ¾ span separation very large
- Mid-span separation not duplicated in CFD solution

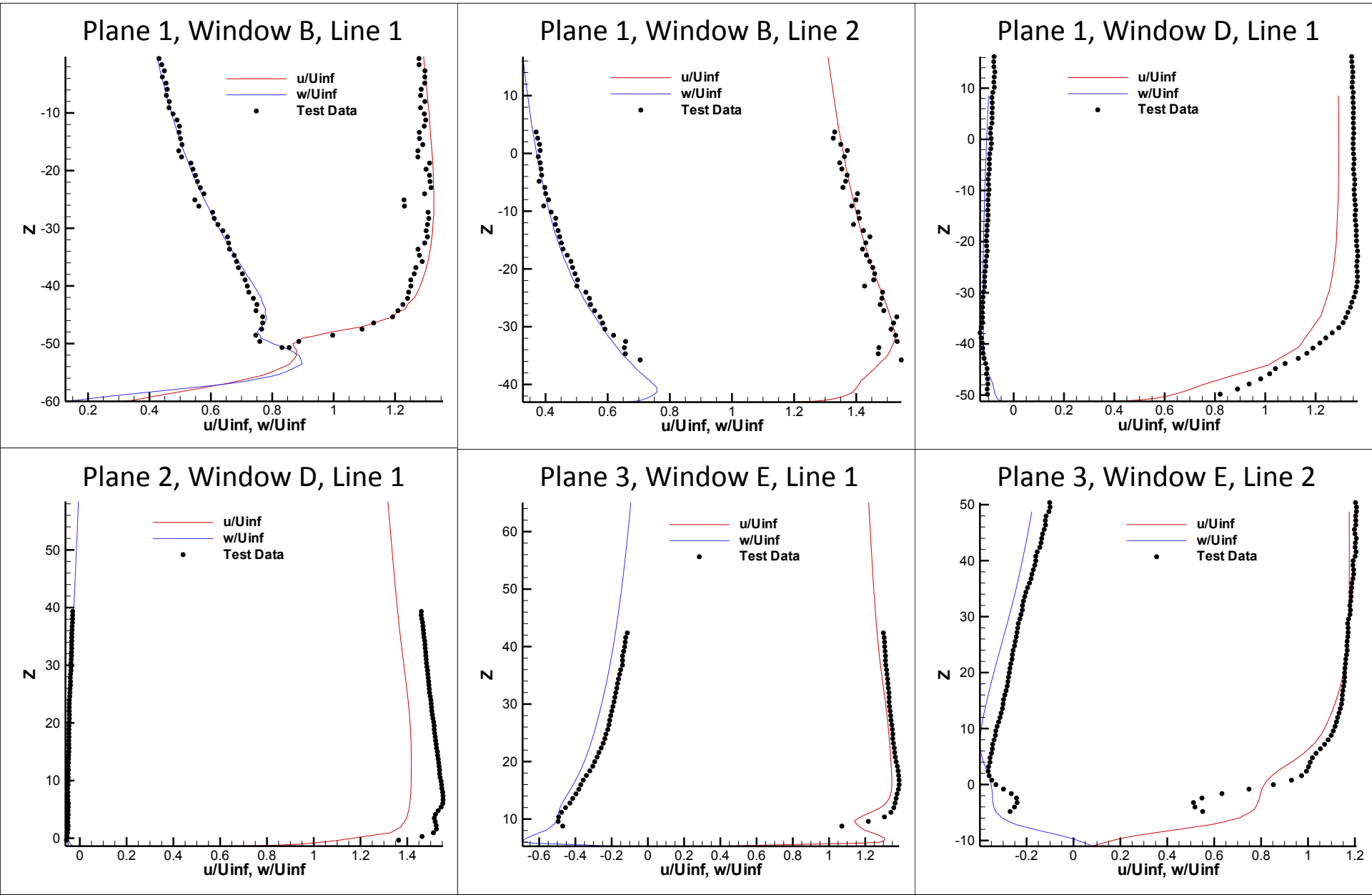


Velocity Profile Comparisons with PIV

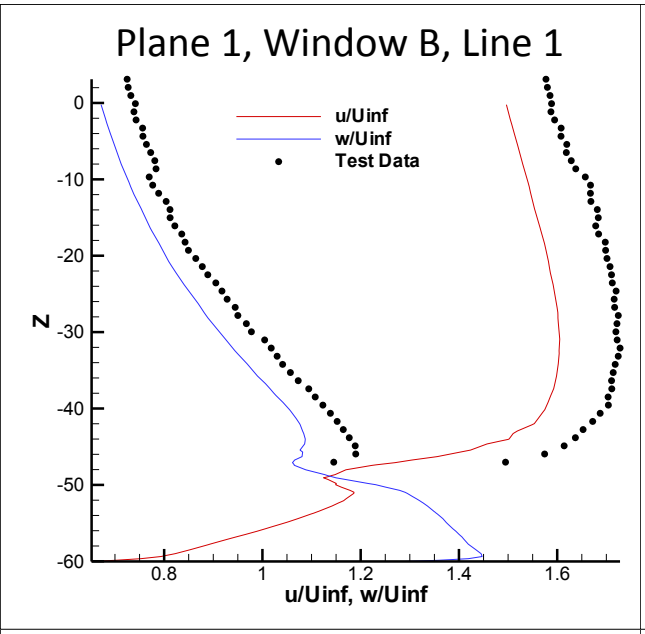
- PIV data available at low Reynolds number only
- 11 cuts extracted at the 3 planes shown
- Profiles provide detail on both boundary layers and slat and main element wakes

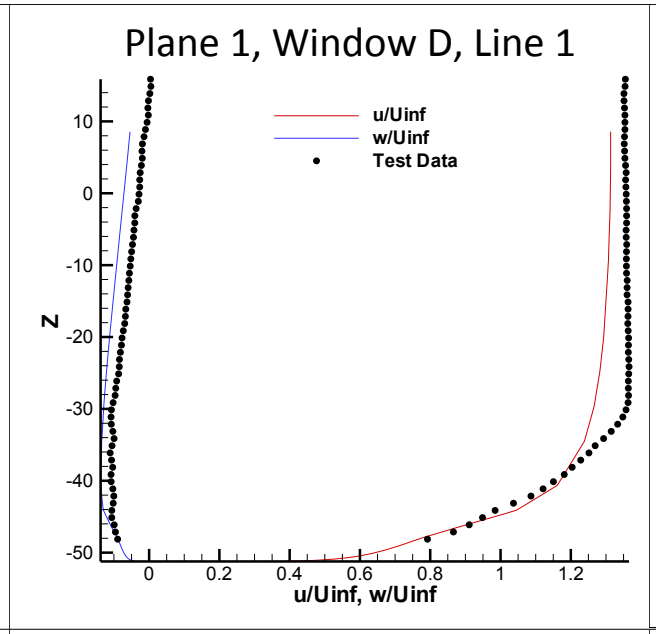


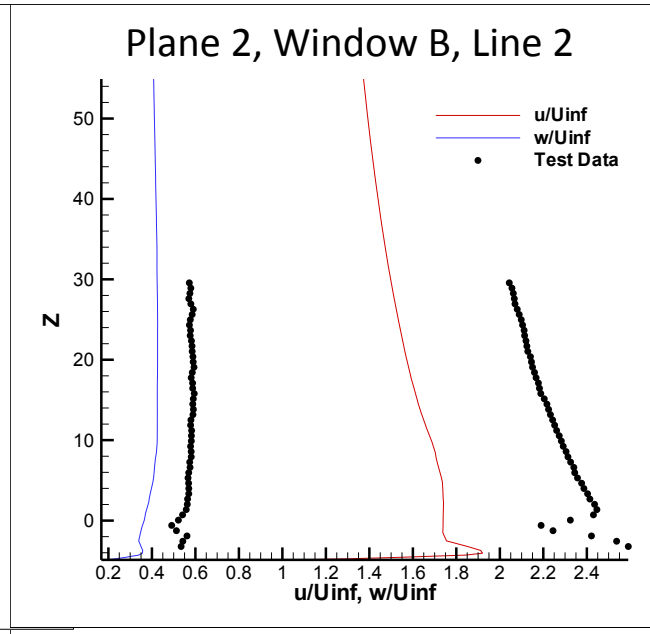
Velocity Profiles, α=7, Re=1.35(10)^6

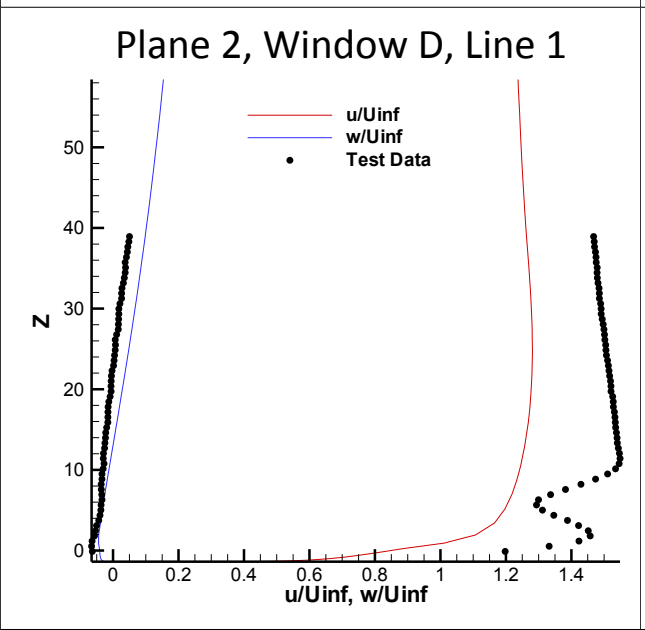


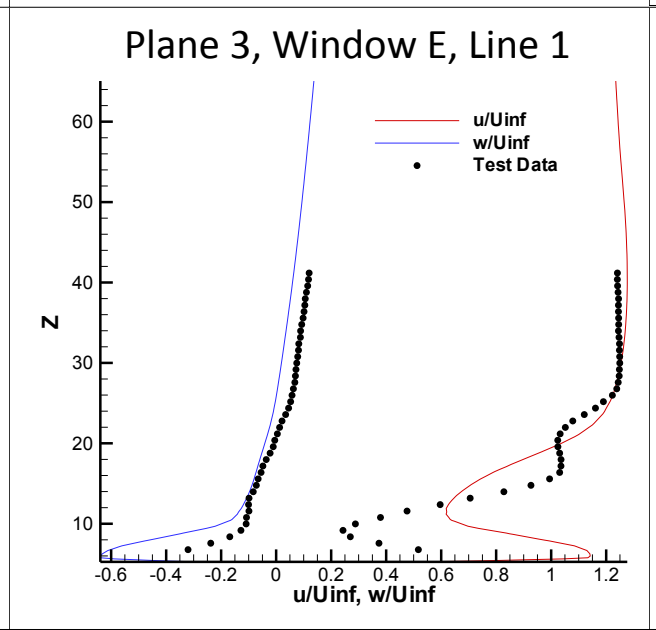
Velocity Profiles, α=18.5, Re=1.35(10)^6

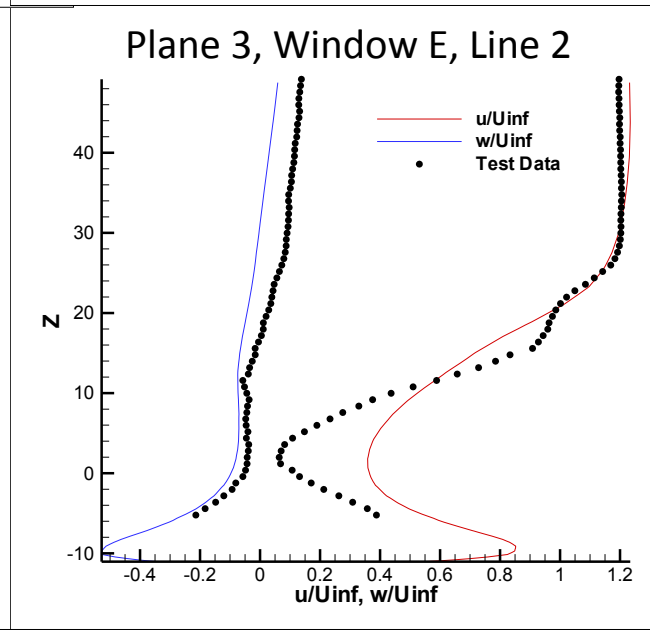












Why Would We Be Off?

- 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

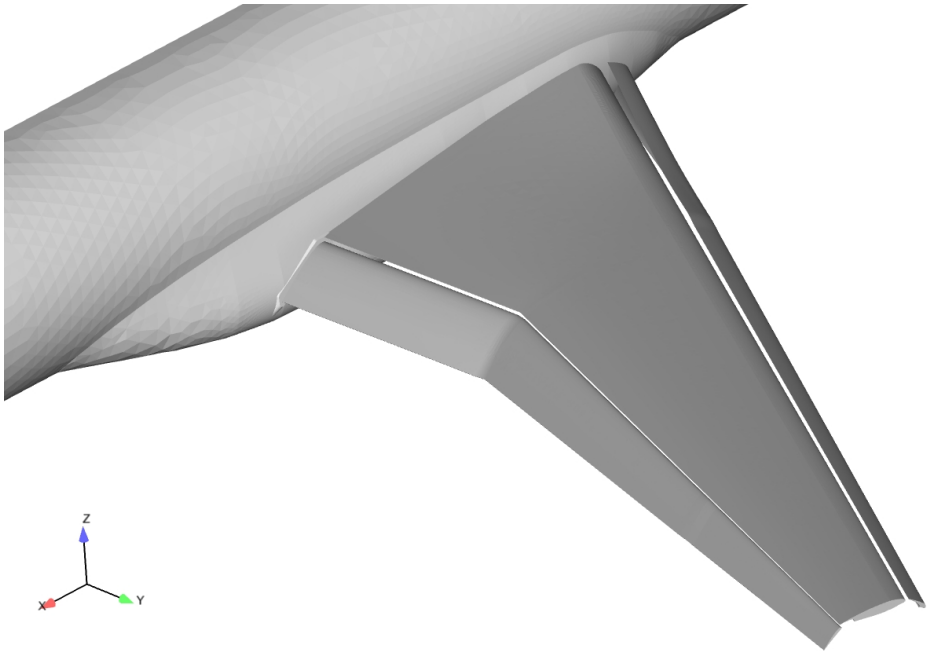
➢ ***Only when other error sources are quantified can physical modeling deficiencies be properly addressed***

- Objective of Case 1 clean wing study is to quantify increments in the solution due to grid resolution: ***solution verification***
- Resolution errors can be bounded using:
  - Conventional Richardson extrapolation
  - Solution of Error Transport Equations (ETE): featured in current studies

Case 1 – Grid Convergence Study

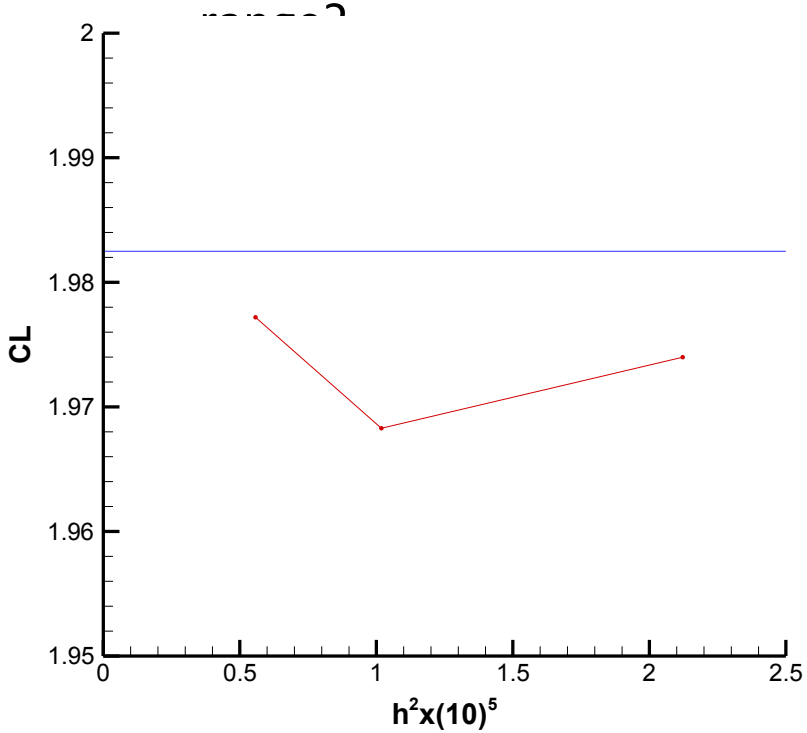
- Validation of capturing increments in solution using error transport (ETE) methodology
- Medium and Fine grids proved quite difficult to run, for reasons unclear – grid quality related?
- Medium and Fine grid solutions at α=16 very troublesome
- Coarse/Medium/Fine grid sequence at α=7 shown here
- Would like to revisit using Pointwise grid sequence (C_UNS_MIX) for 2nd opinion

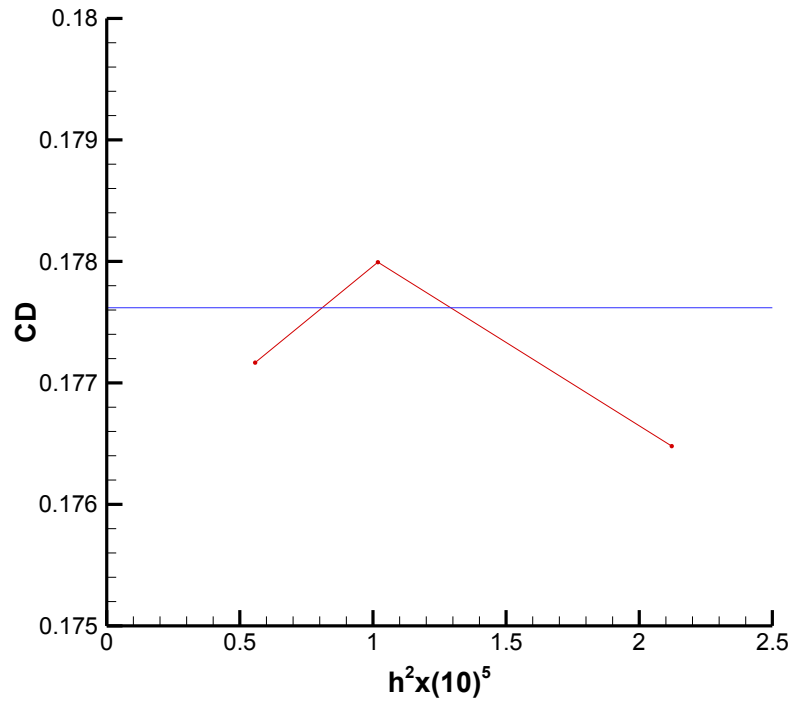
Grid	Cells	Vertices
Coarse	29,369,293	10,229,072
Medium	99,439,948	30,767,679
Fine	274,089,207	75,978,568



Case 1 Lift/Drag, α=7

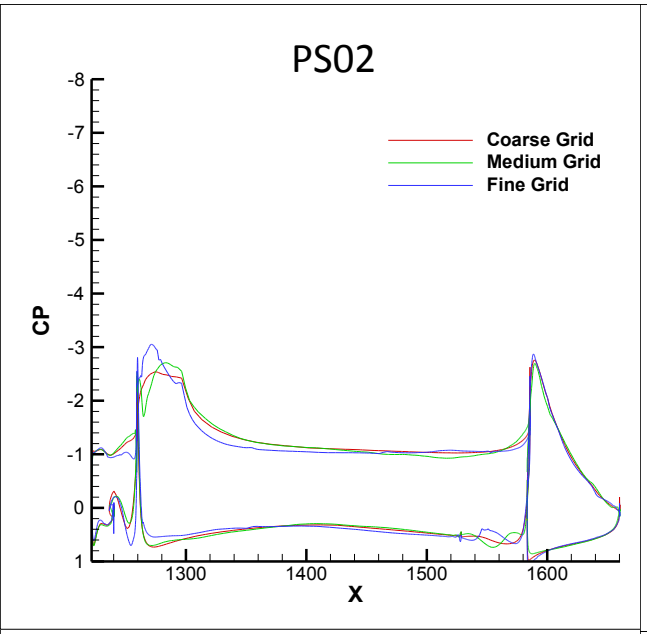
- Convergence plotted vs. mesh width squared ($h=1/N^{1/3}$)
- Extrapolated solution (blue) obtained via mixed-order Richardson extrapolation method*
- Convergence oscillatory for both C_L and C_D – medium grid solution seems anomalous or coarse grid not in asymptotic range?

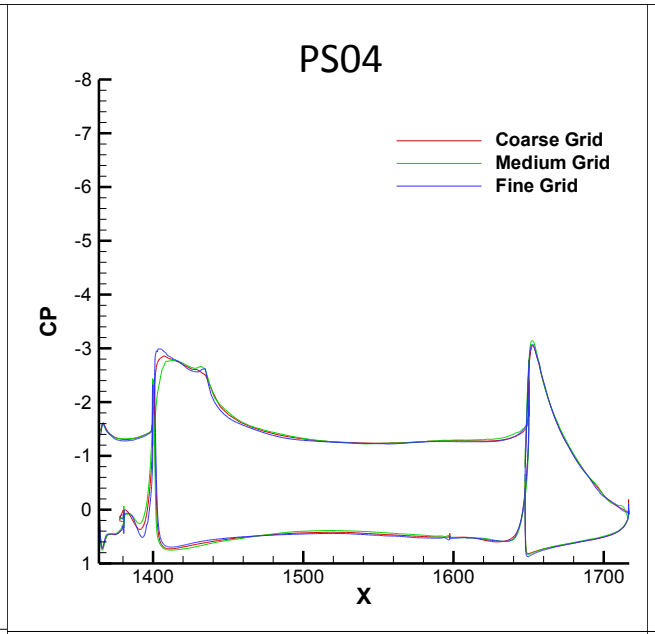


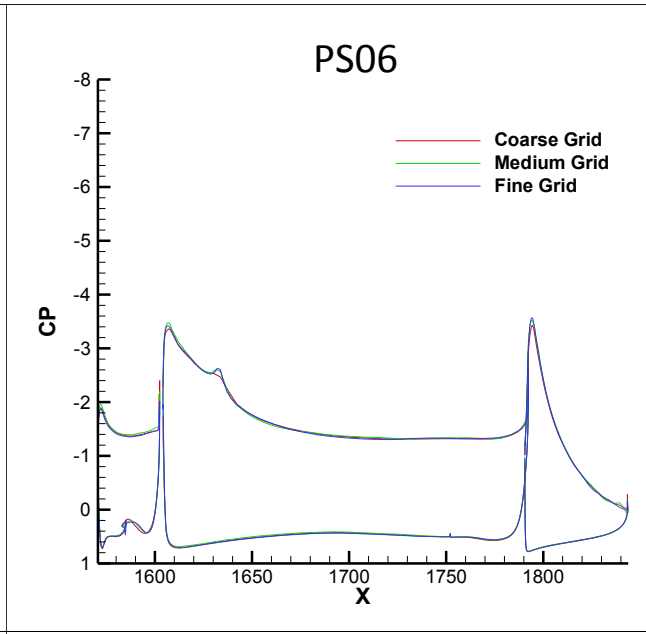


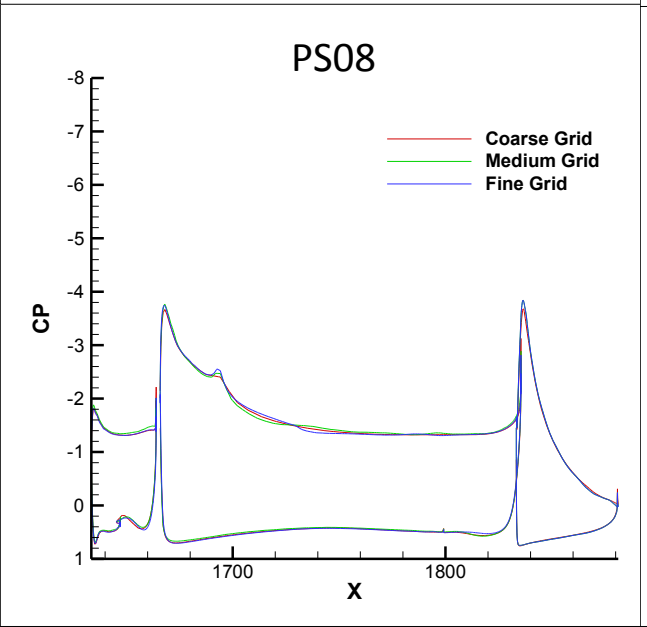
* Roy, C.J., "Grid Convergence Error Analysis for Mixed-Order Numerical Schemes," *AIAA Journal*, Vol. 41, No. 4, April 2003, pp. 595-604.

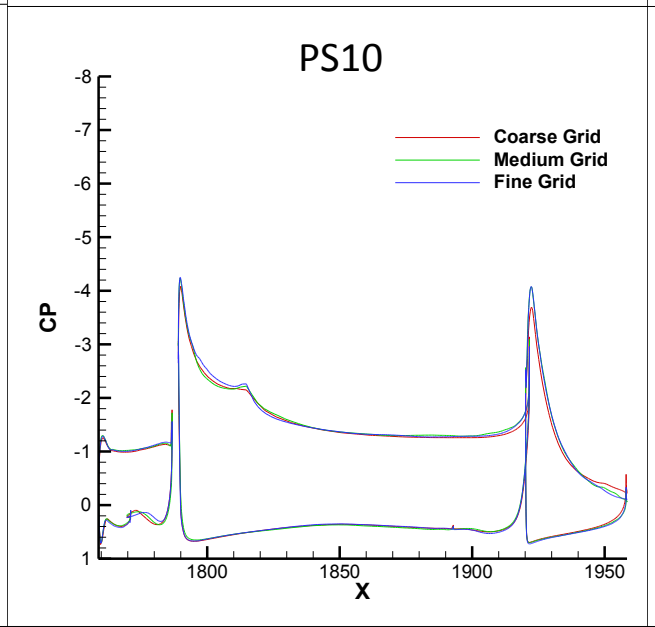
Case 1 C_p Comparisons, α=7

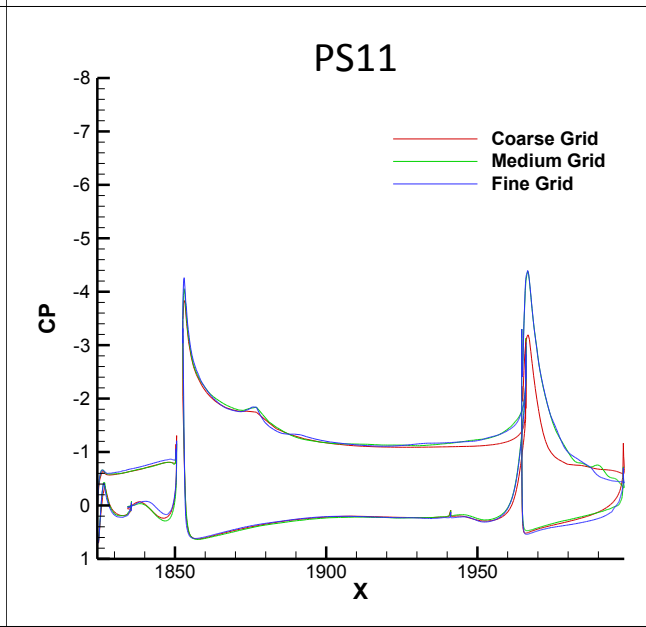




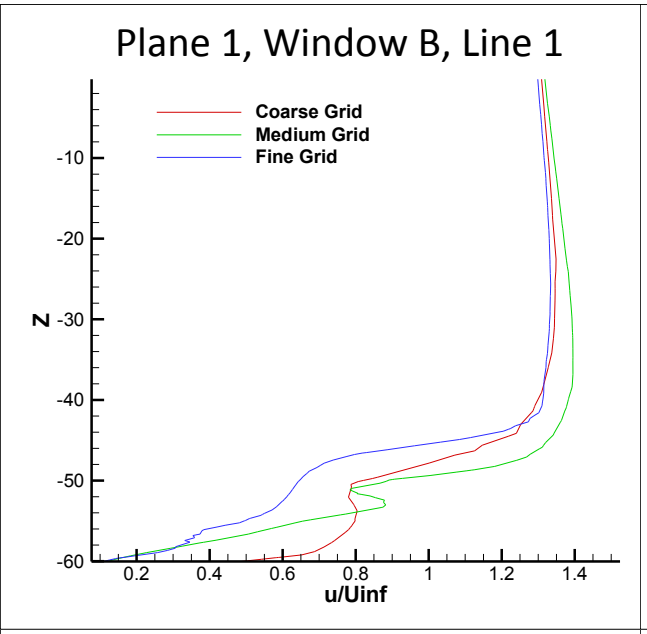


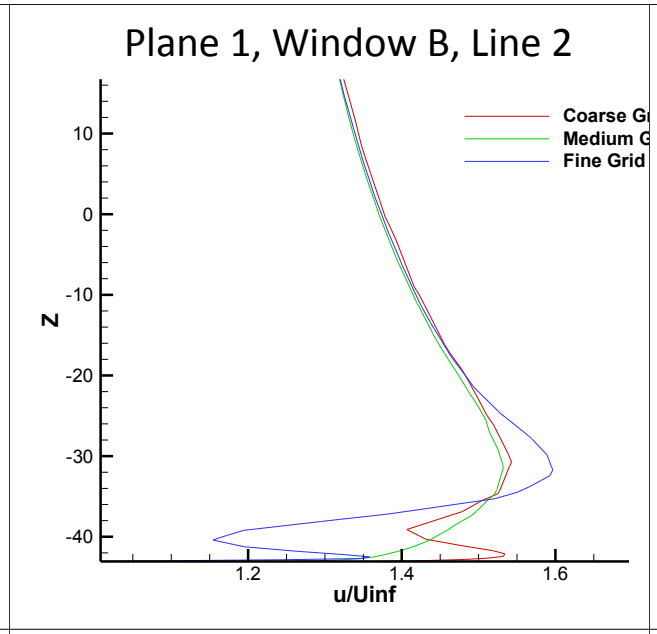


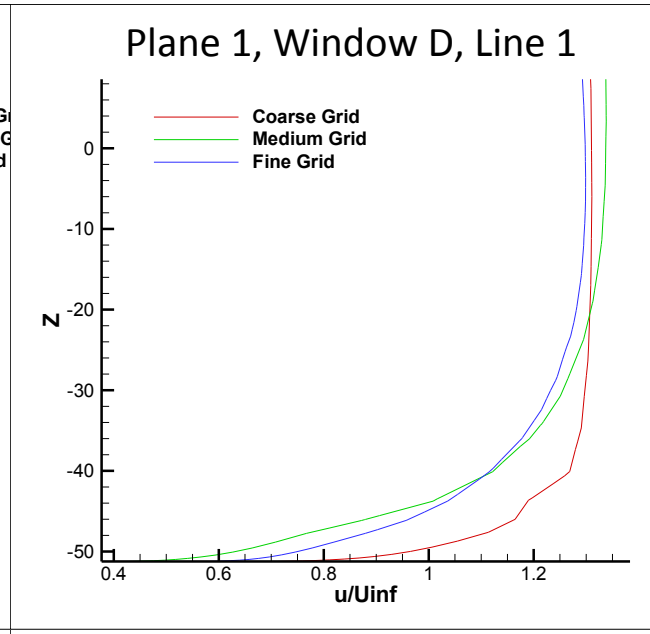


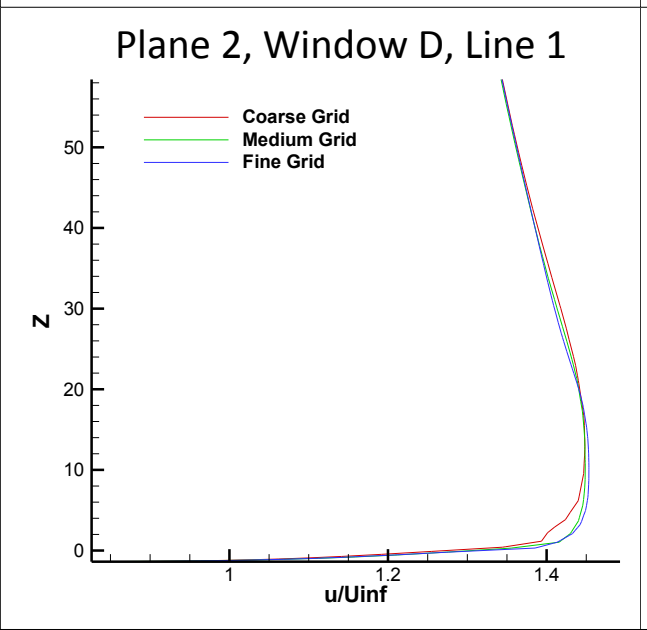


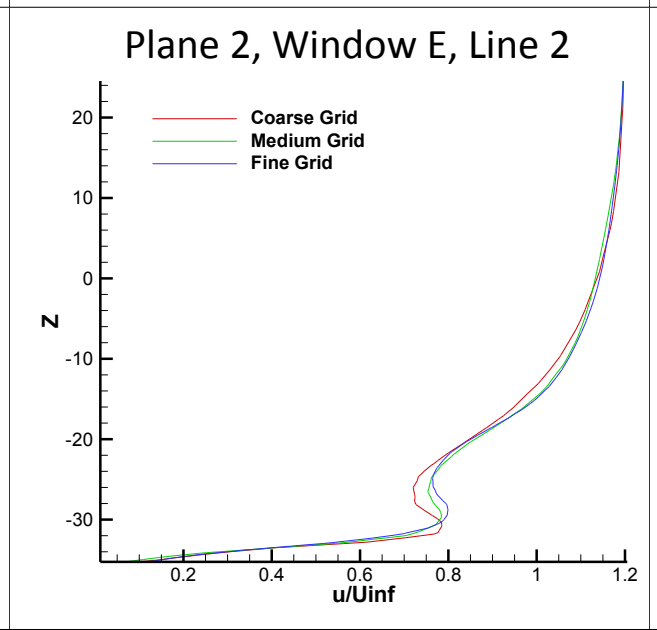
Case 1 Velocity Profiles, α=7

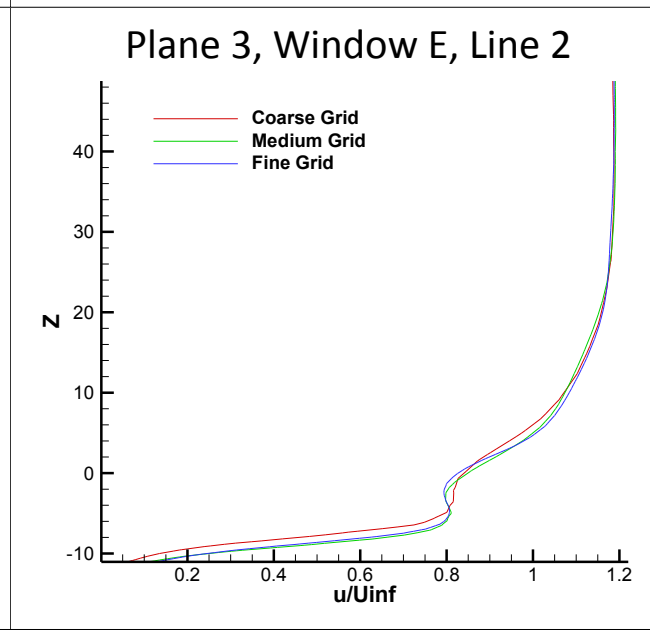












Error Prediction Methodology

- 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

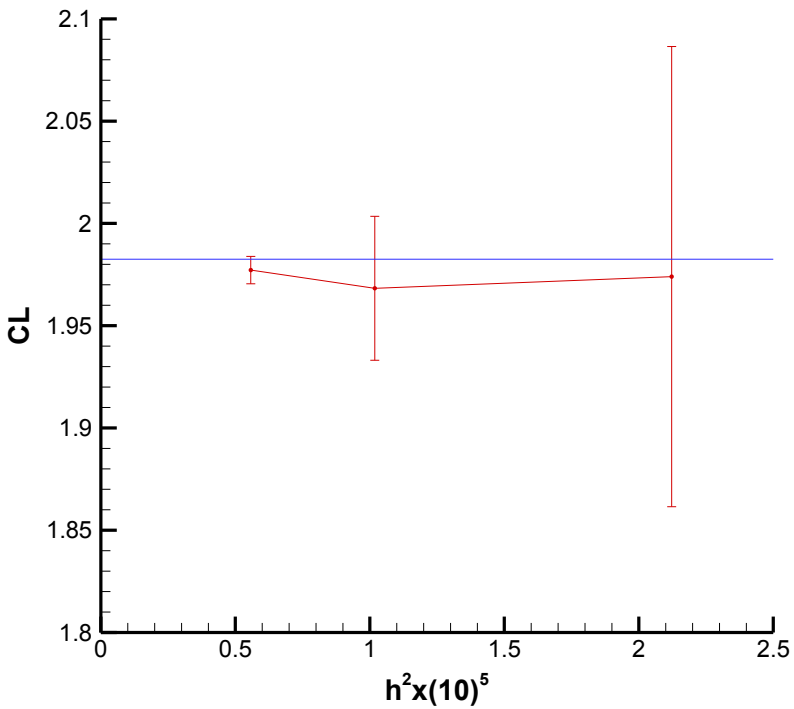
➢ ***If fine grid results fall outside predicted error bars, it potentially indicates new flow features result from grid refinement***

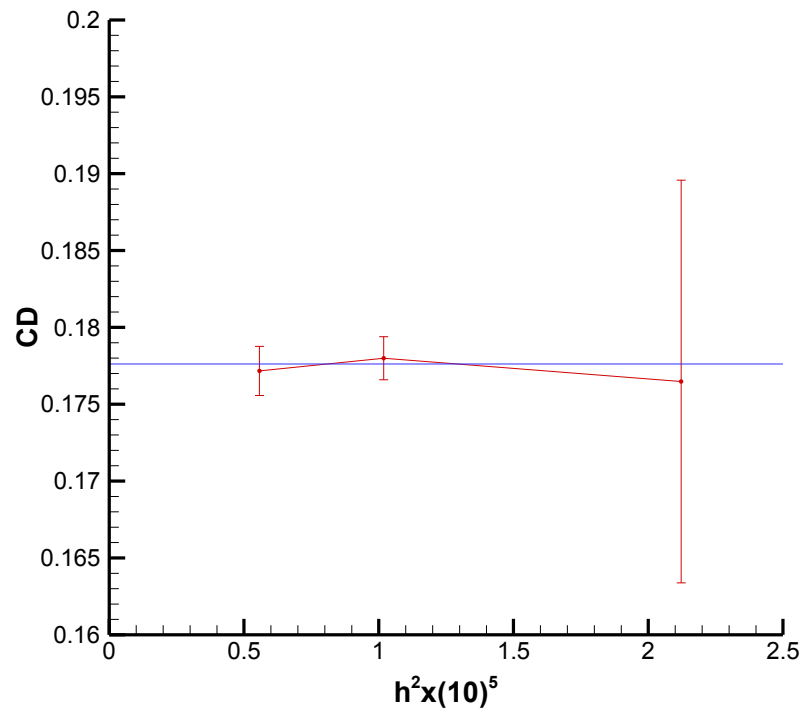
➢ ***If test data falls outside predicted solution and error bars, it potentially indicates a deficiency in physical modeling***

Predicted Errors in Lift/Drag, α=7

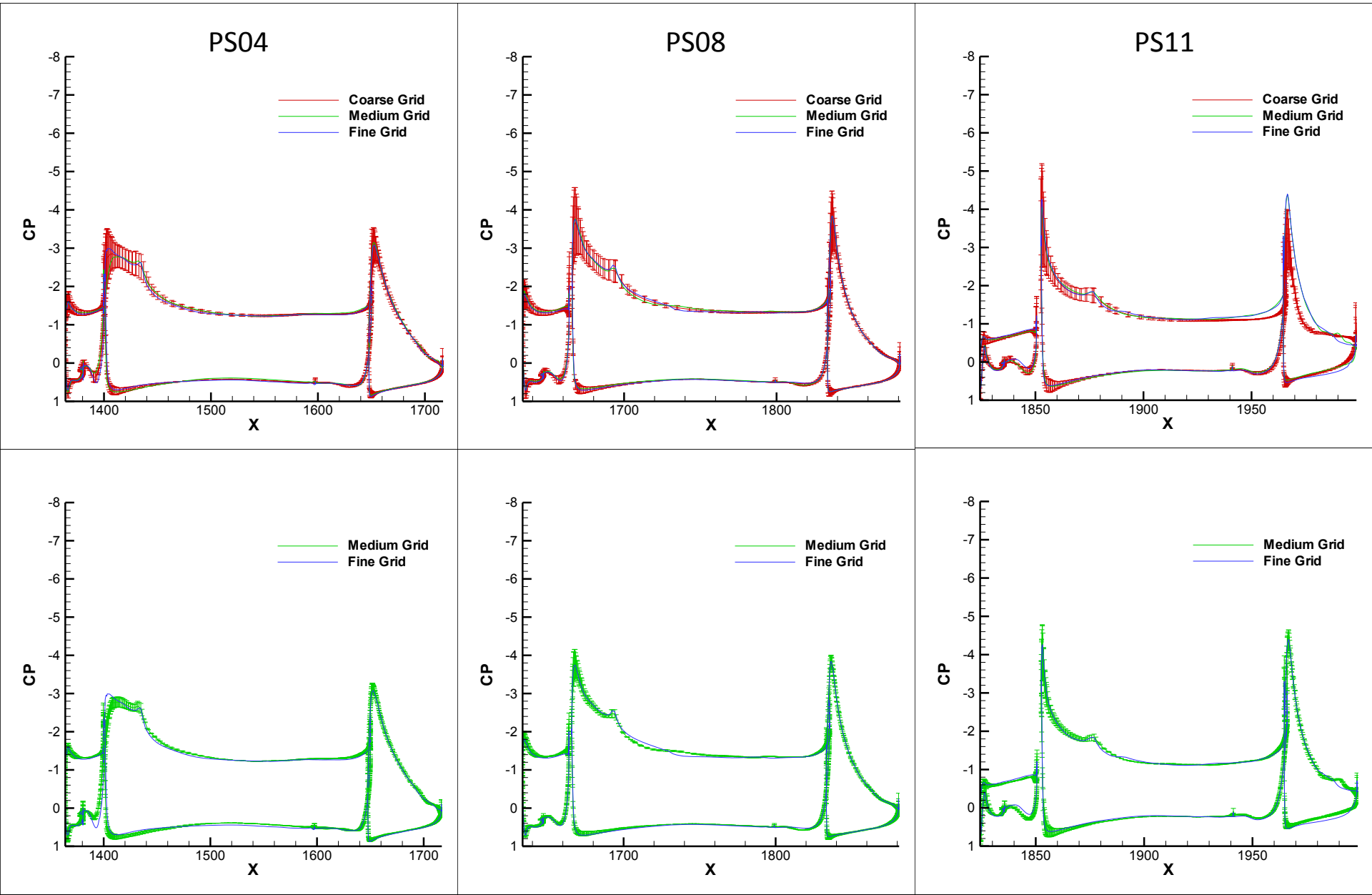
- Reference solution from Richardson extrapolation included
- Numerical error bars from error transport solution contain results of extrapolation and reduce with refinement
- Coarse grid errors quite large – not quite in asymptotic range?

	Coarse	Medium	Fine
C_L	1.9740	1.9684	1.9772
Error	0.1125 **5.7%**	0.0352 **1.8%**	0.0061 **0.3%**
C_D	0.1765	0.1780	0.1772
Error	-0.0131 **-7.4%**	-0.0014 **-0.8%**	-0.0016 **-0.9%**

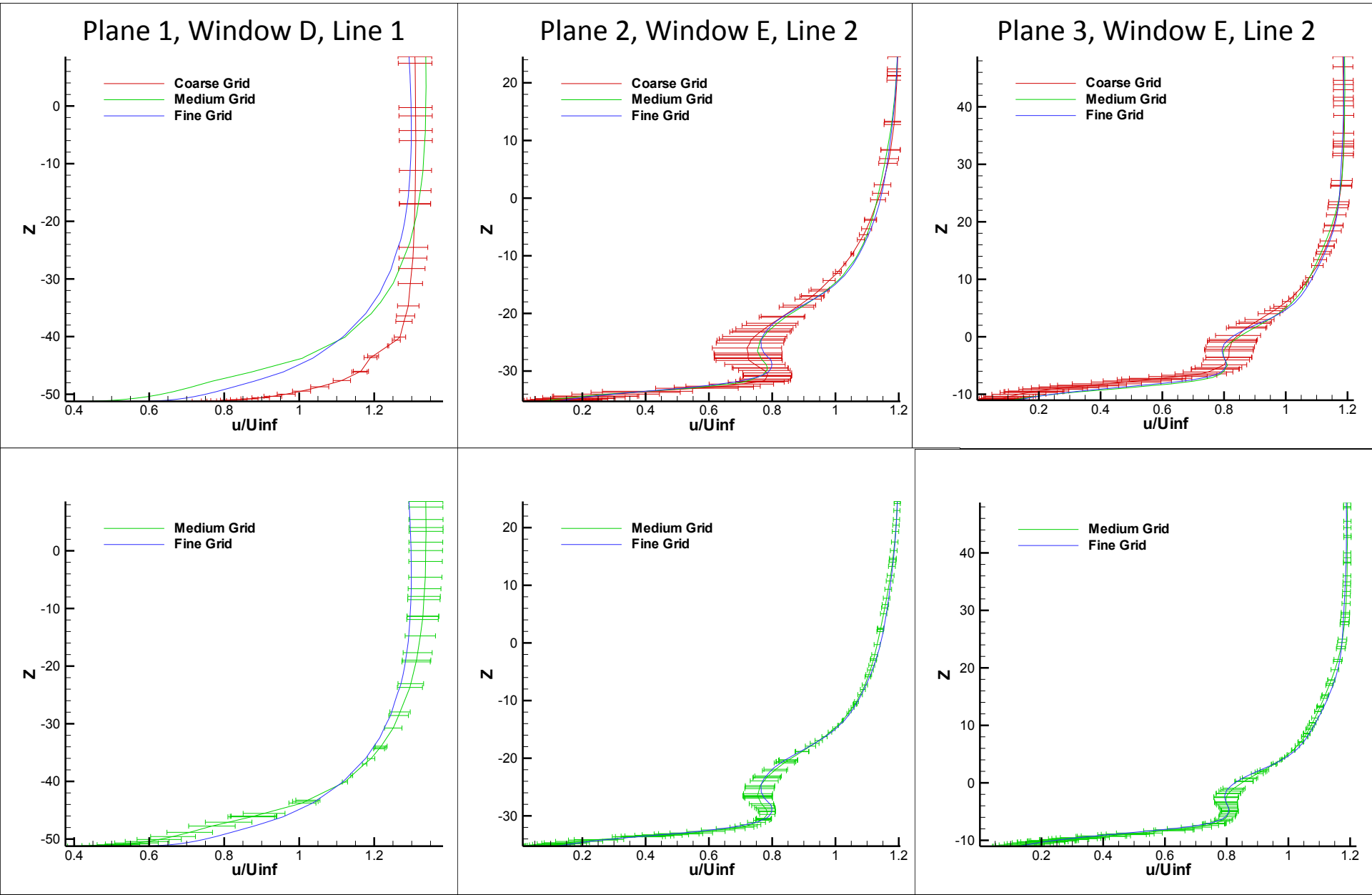




Predicted Errors in C_p, α=7

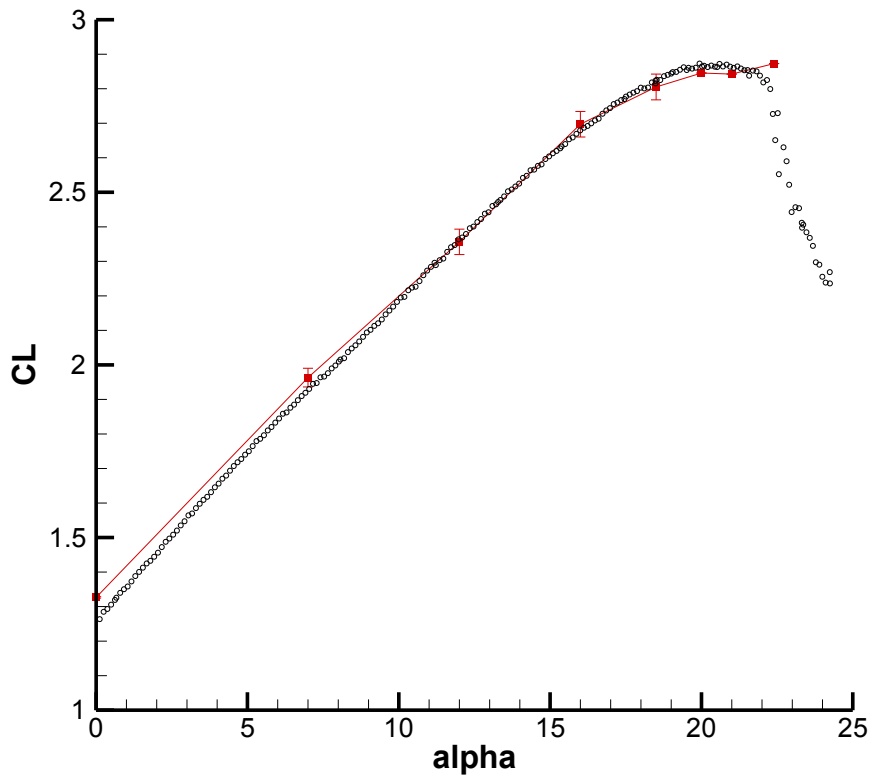


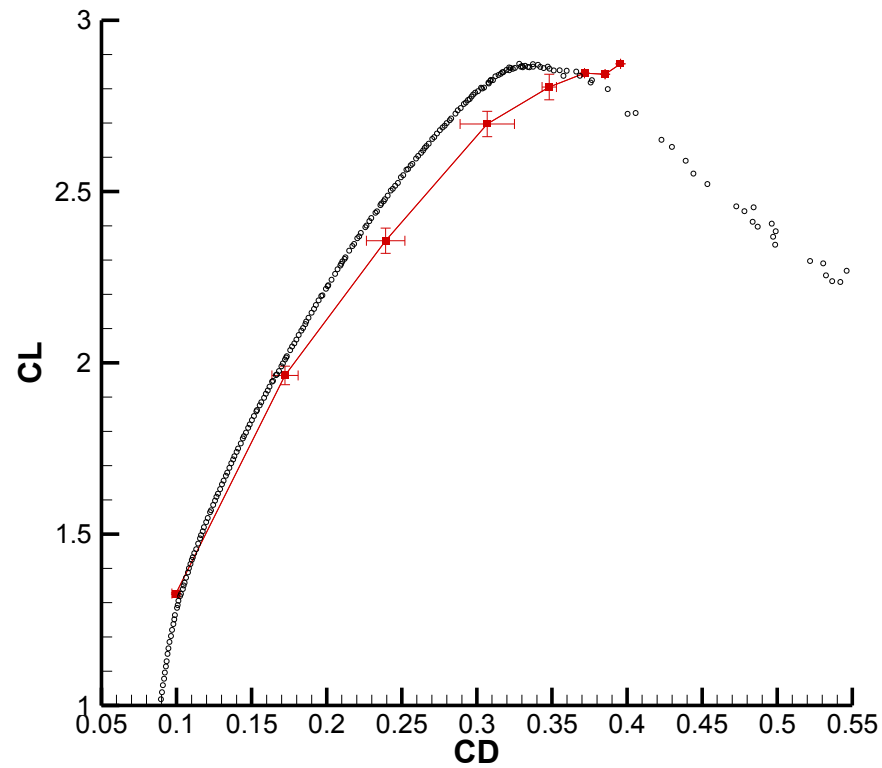
Errors in Velocity Profiles, α=7



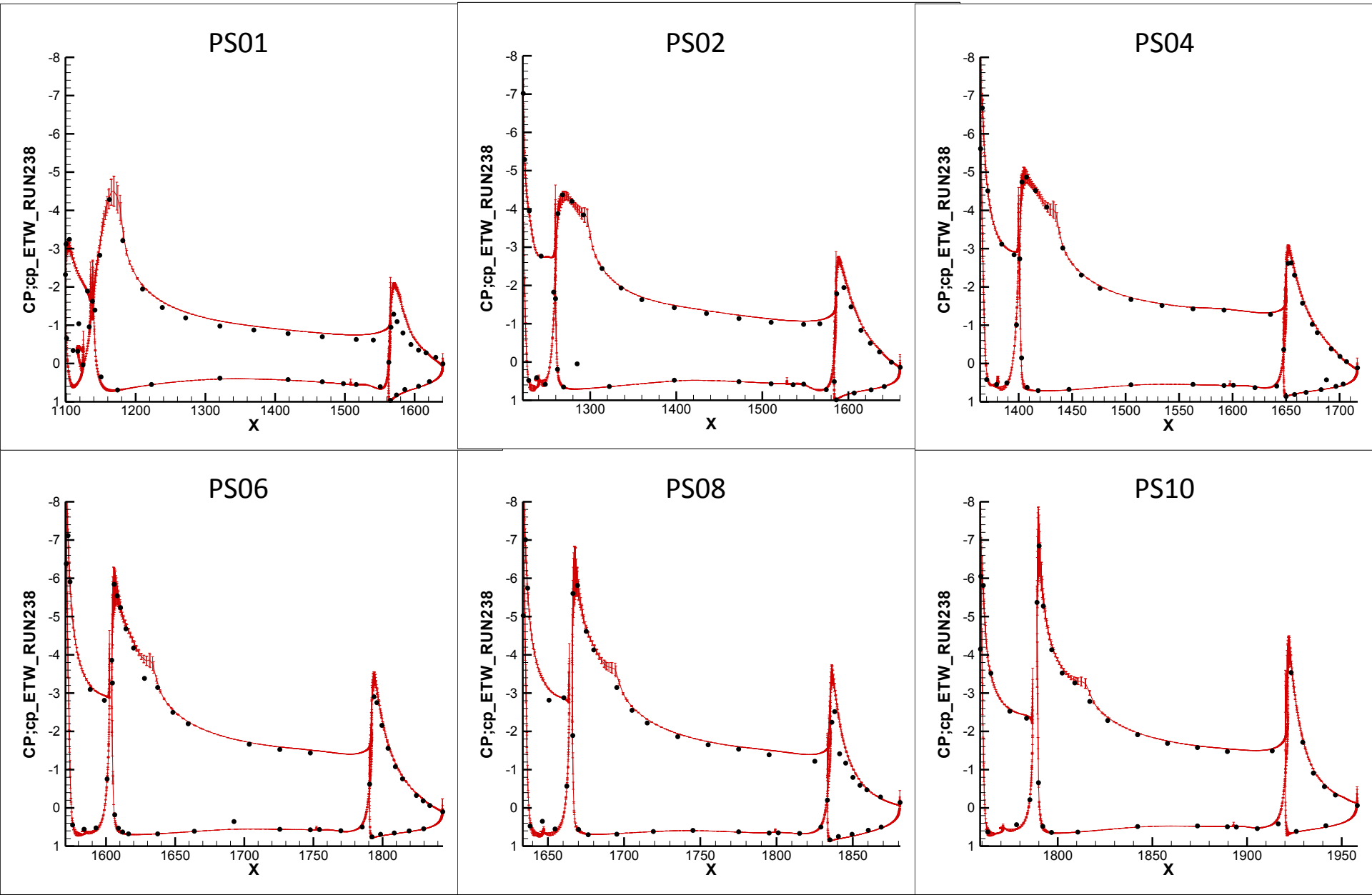
Error Analysis for Case 2b

- 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



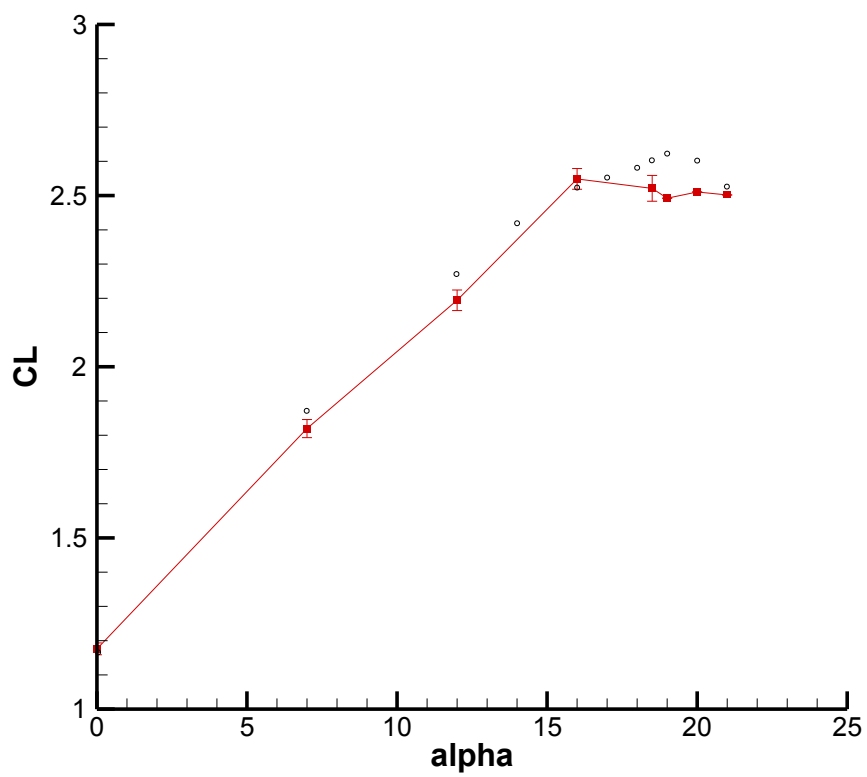


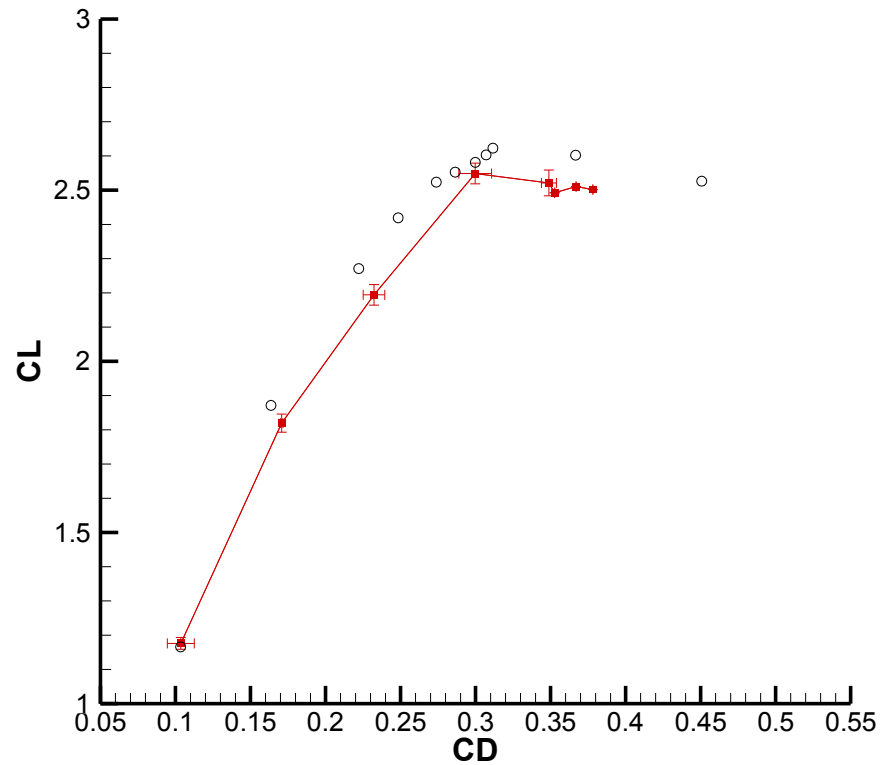
C_p Errors, α=16, Re=15.1(10)^6



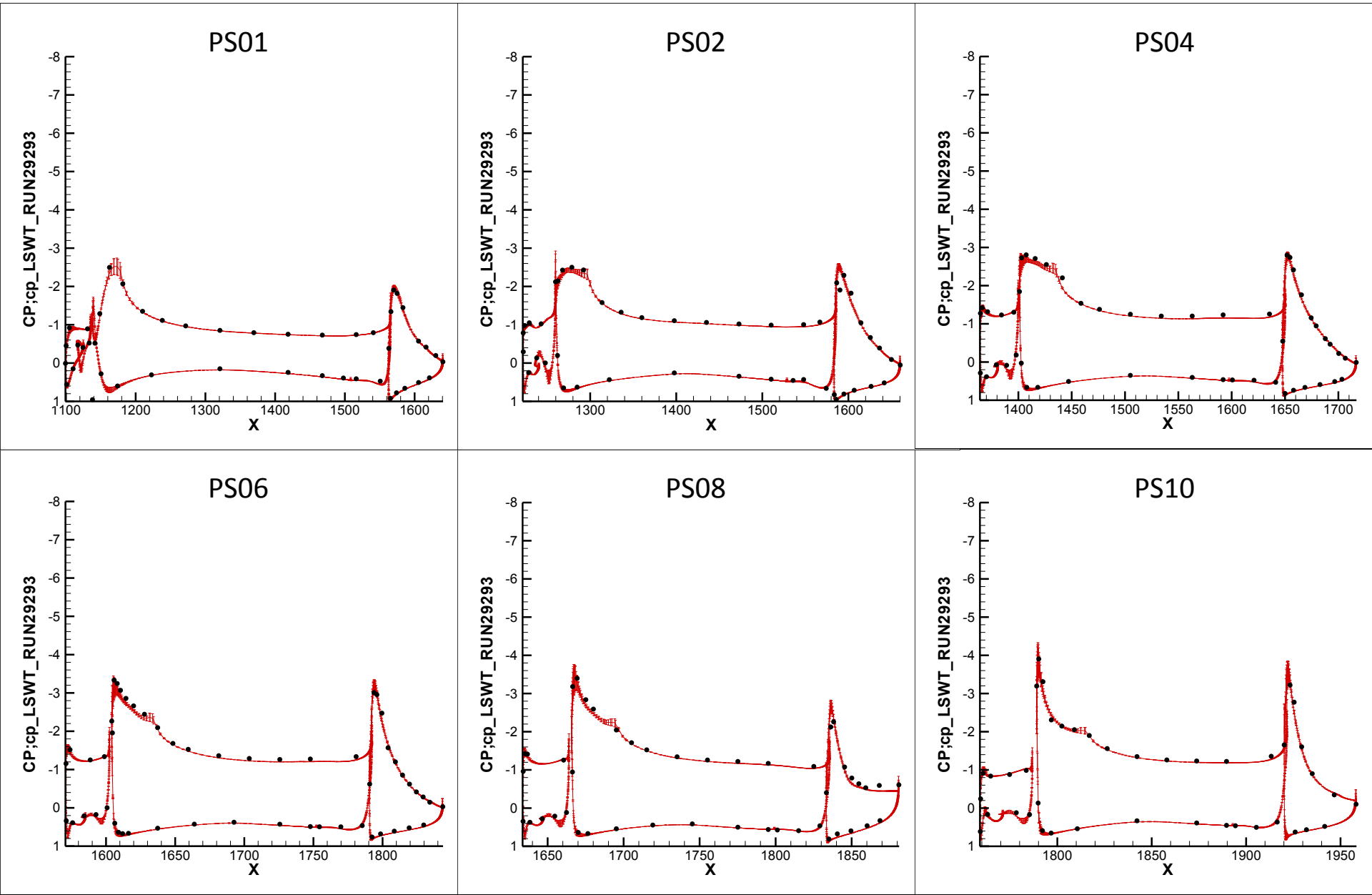
Error Analysis for Case 2a

- 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

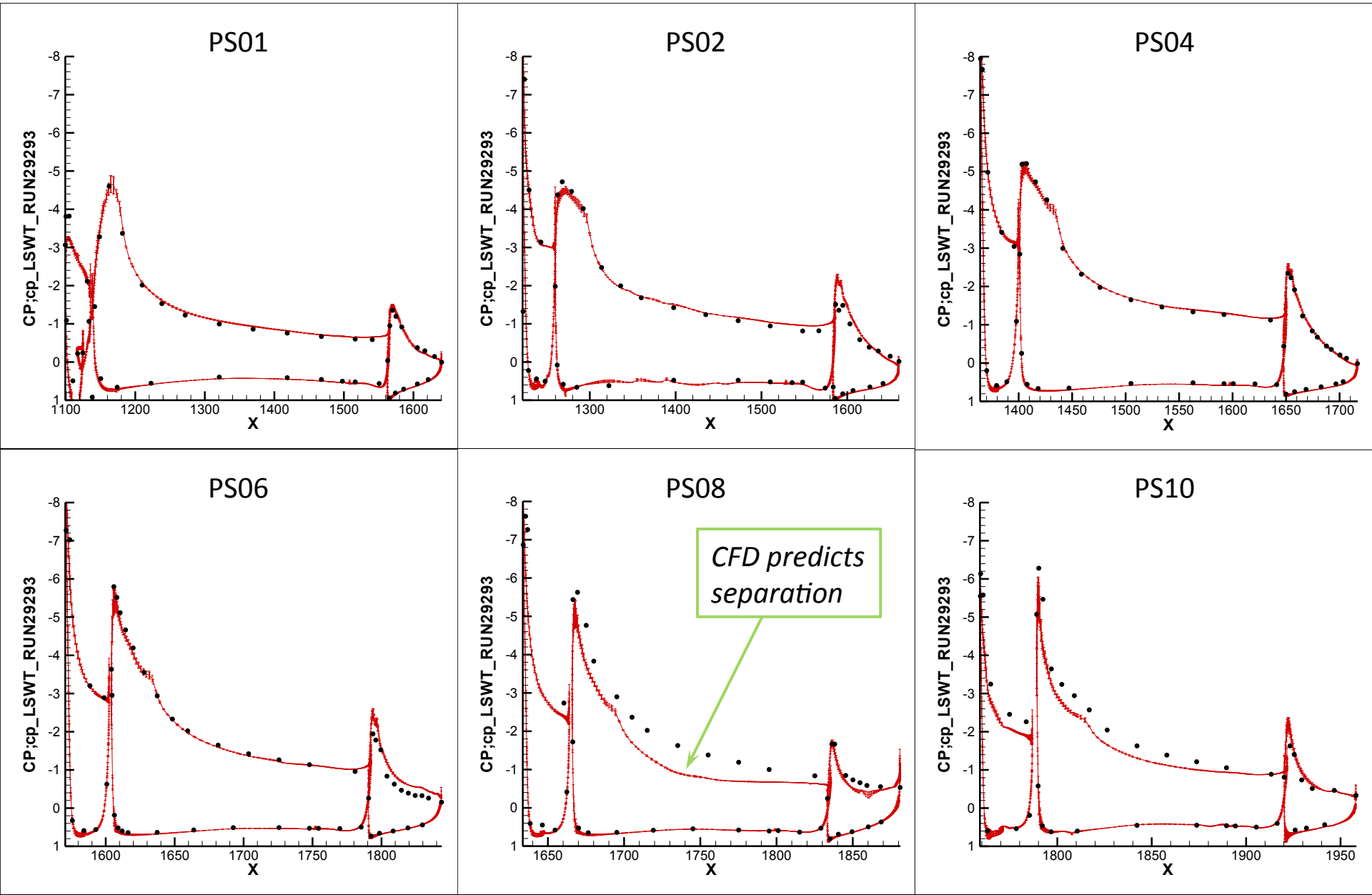




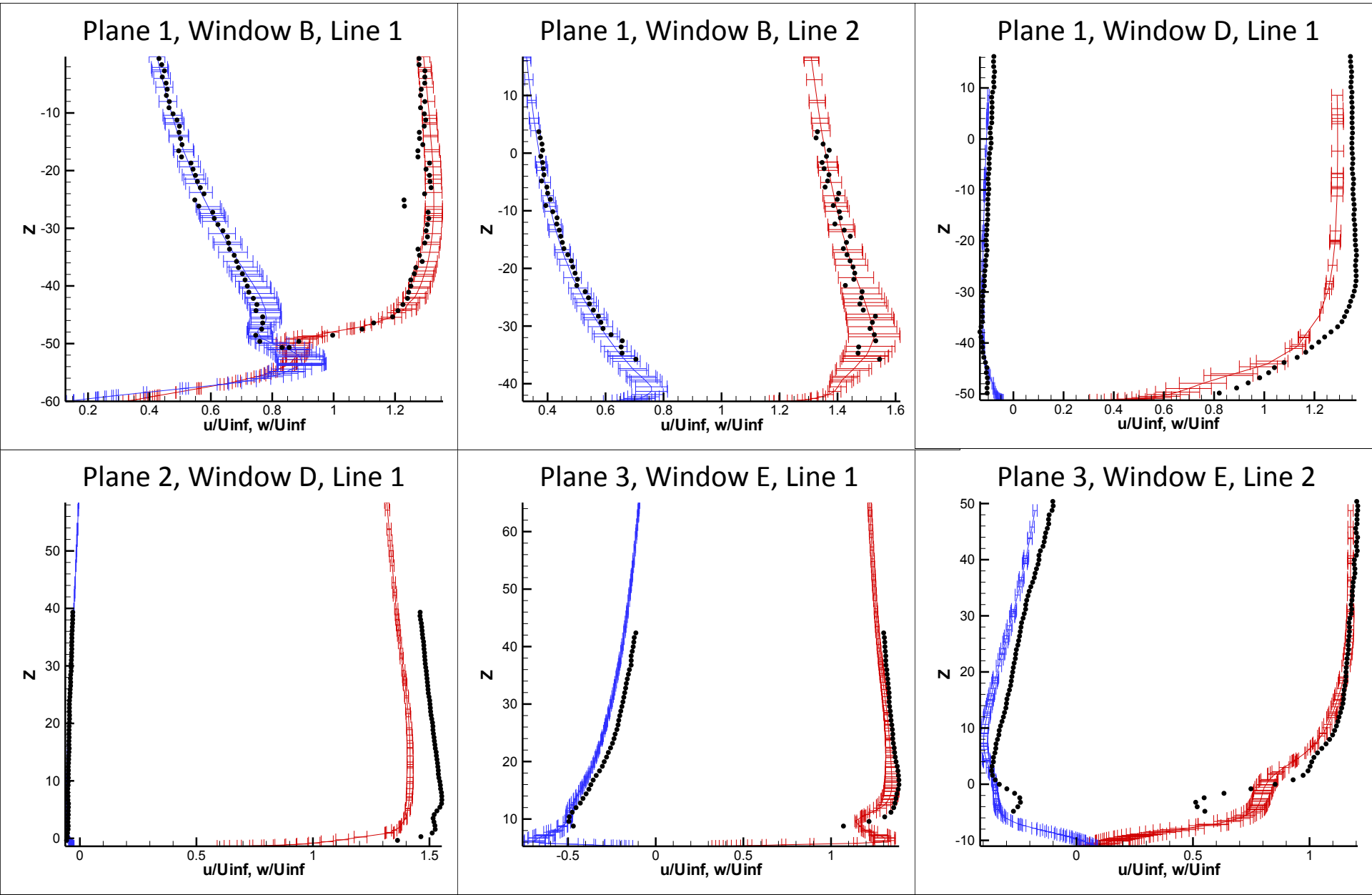
C_p Errors, α=7, Re=1.35(10)^6



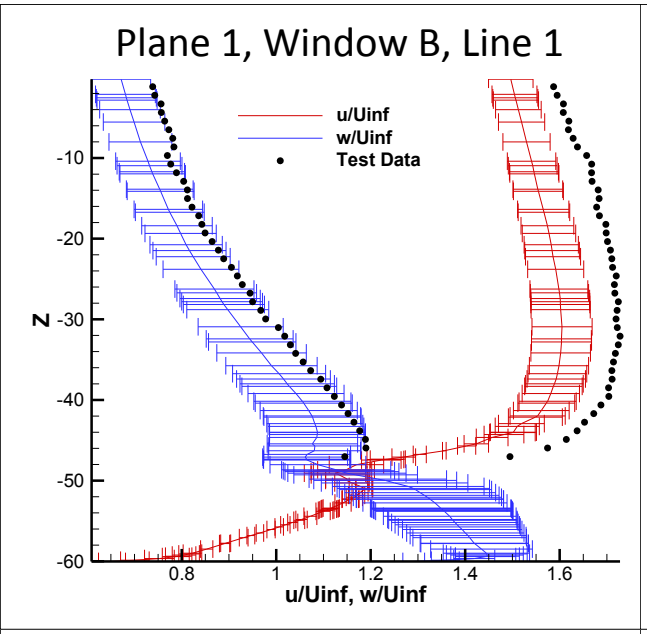
C_p Errors, α=18.5, Re=1.35(10)^6

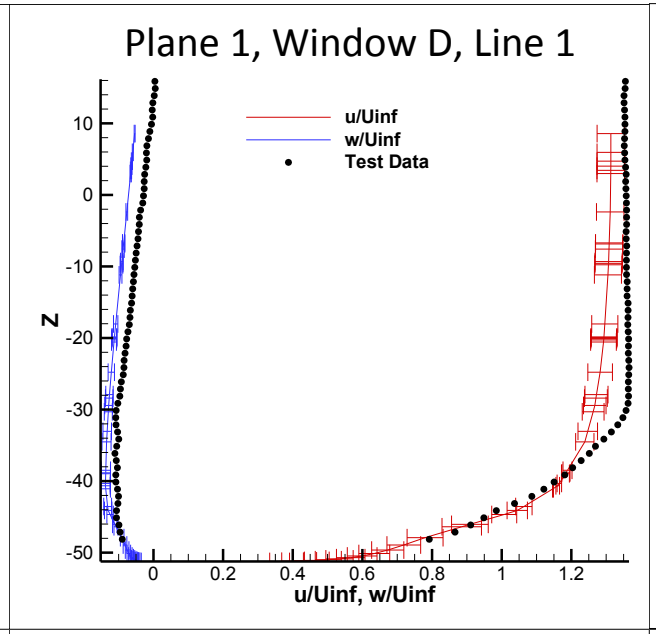


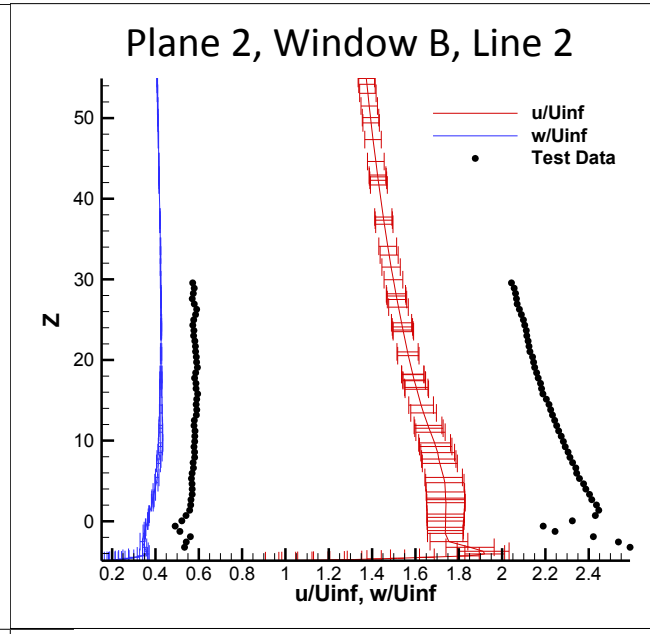
Velocity Errors, α=7, Re=1.35(10)^6

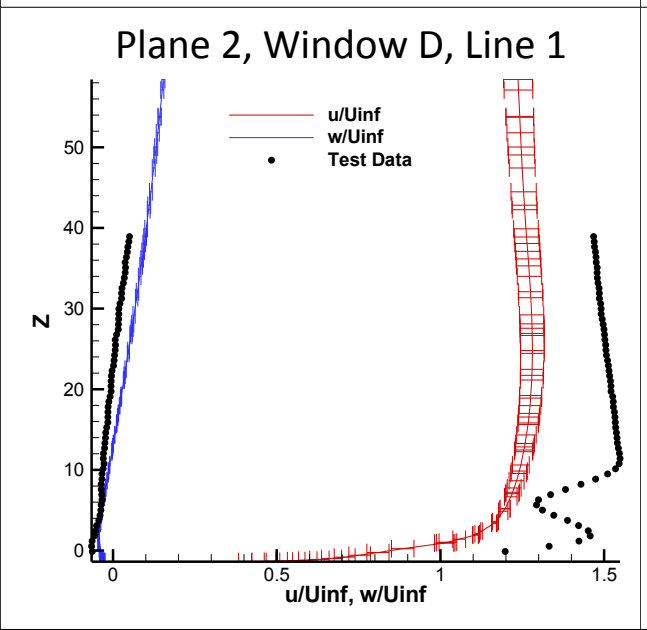


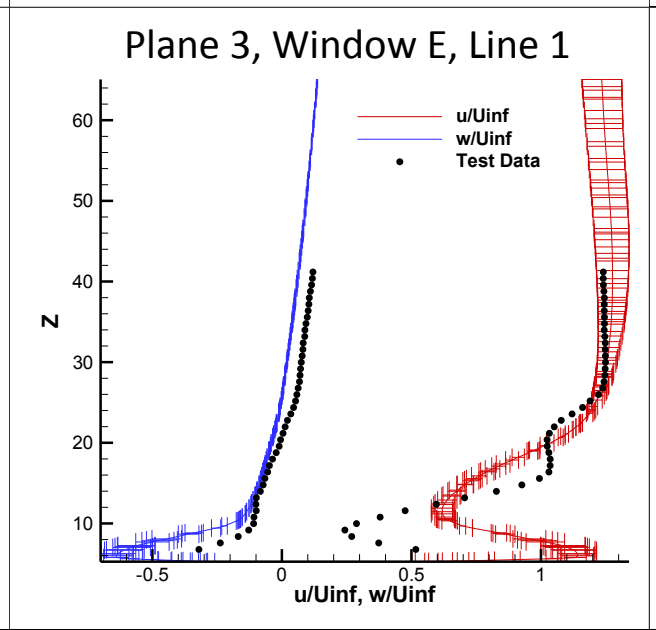
Velocity Errors, α=18.5, Re=1.35(10)^6

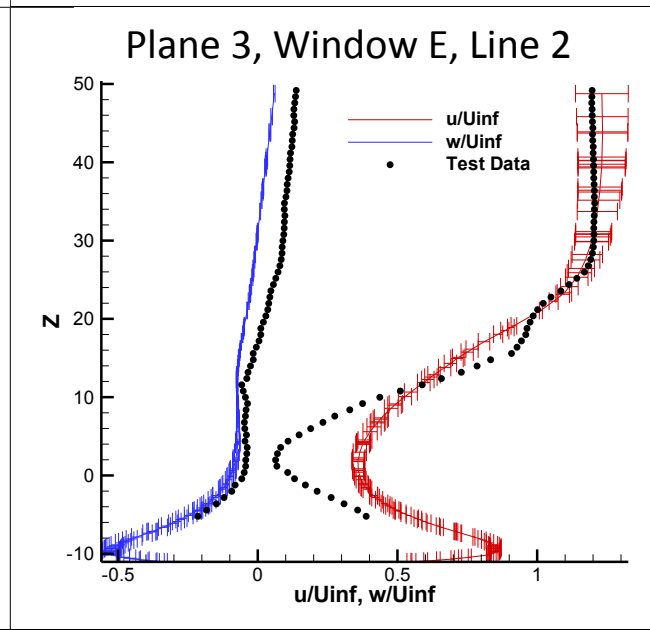






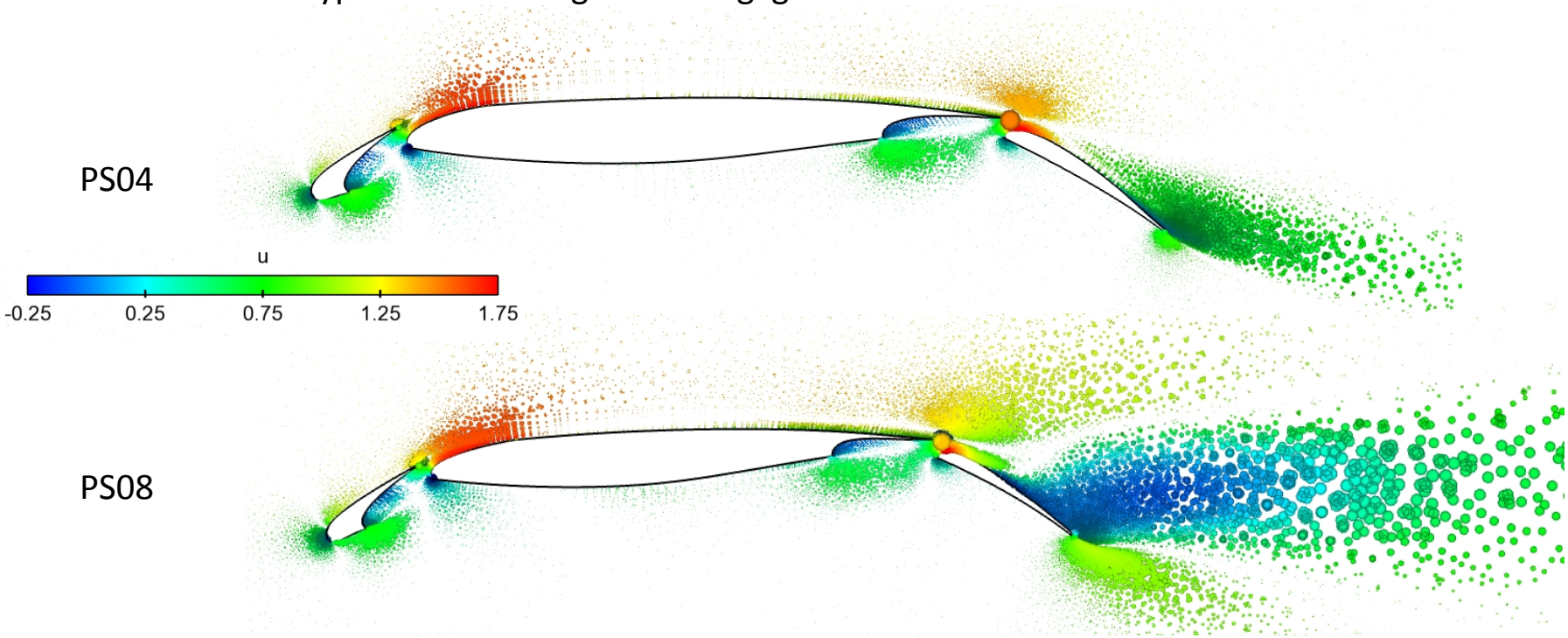






2D/3D Error Visualization

- Error bars are just one means of visualizing 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.

Conclusions – Error Analysis

- Error analyses from solution of Error Transport Equations (ETE) generally captured solution increments between coarse-fine and medium-fine meshes well
  - For Case 1, α=7, increments in C_p and velocity profiles often captured by ETE solution
  - Solution sequence for Case 1 α=16 not satisfactory, no assessment done
- Case 2 error predictions deemed reasonable
  - C_L, C_D errors well captured vs. experiment for attached flow cases
  - C_p errors generally small with CFD agreeing with test data
  - Error bars sometimes span difference between CFD and data
- Method can not account for changes in flow features due to mesh refinement
  - Attached vs. separated flow, failure to capture slat/main element wake, e.g.
- Analyses suggest discrepancies due to physical modeling, not grid
- Possible follow-on work:
  - Would like to revisit Case 1 with another mesh sequence for additional validation of error prediction
  - Application of ETE to time-averaged solutions for high α unsteady cases

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- ***Questions?***

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