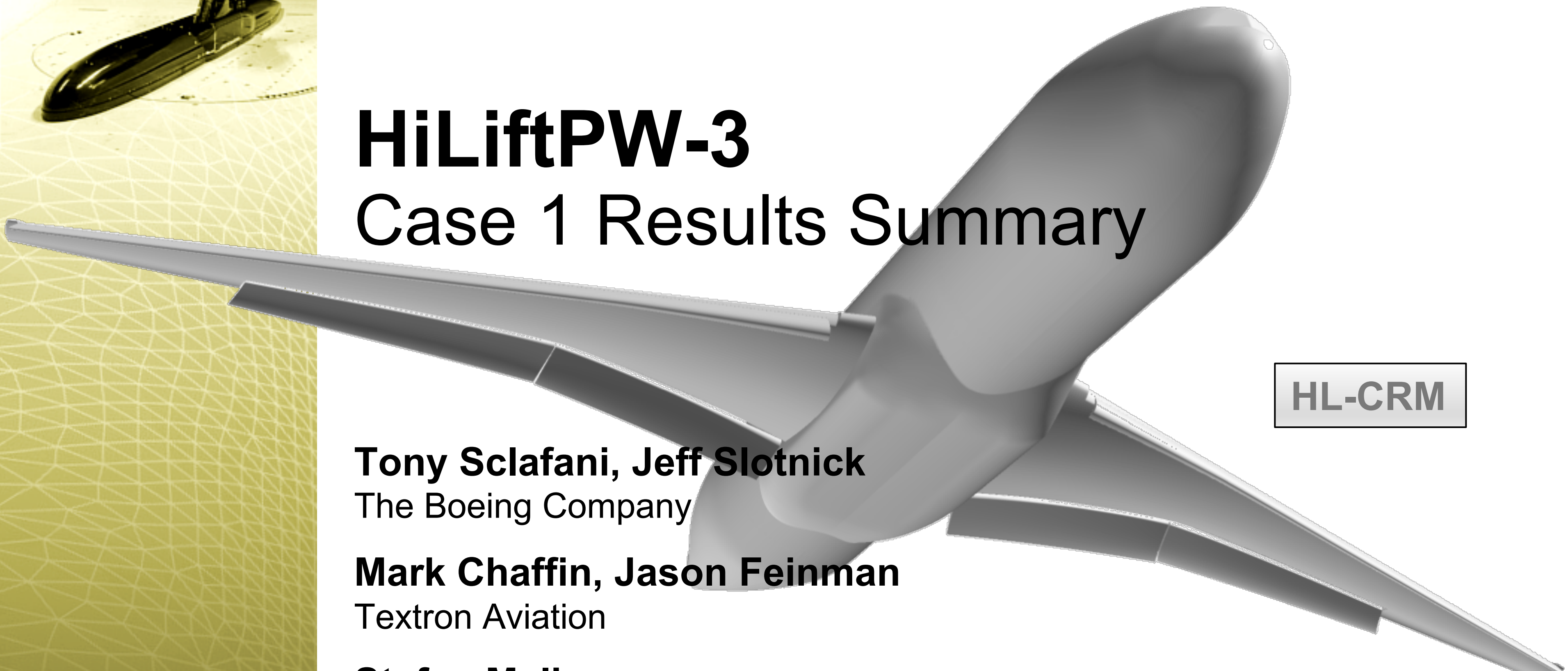


HiLiftPW-3

Case 1 Results Summary

HL-CRM

Tony Sclafani, Jeff Slotnick
The Boeing Company

Mark Chaffin, Jason Feinman
Textron Aviation

Stefan Melber
DLR, German Aerospace Center

3rd AIAA CFD High Lift Prediction Workshop

Denver, CO, USA

3-4 June 2017

Case 1: Grid Convergence Study

Outline

- Case Description
- Grid Families
- Participant List
- Results
  - Overview
  - Iterative Convergence
  - Lift, Drag and Pitching Moment
  - Pressures and Skin Friction
  - Velocity Profiles
- Conclusions

Case 1: Grid Convergence Study

CFD High Lift Prediction Workshop

Geometry and Requested Case

Flow solutions on a series of consistently refined fixed grids are requested to assess grid convergence. At a minimum, flow solutions should be provided for ***at least one family of coarse, medium, and fine workshop-provided meshes***. Providing the flow solution for the extra-fine mesh is optional.

Geometry

The **NASA High Lift Common Research Model (HL-CRM)** is a wing-body high lift system that will be studied in a nominal landing configuration (slat and flaps deployed at 30° and 37°, respectively) without nacelle, pylon, tail, or support brackets.

Case Parameters and Requirements

Case 1a: Full Chord Flap Gap (REQUESTED)

Mach Number	0.2
Alphas	8 and 16°
Reynolds Number based on MAC	3.26 million
Reference Static Temperature	518.67°R (=15.00°C=59.00°F)
Reference Static Pressure	760.21 mmHg (=14.700 PSI)
Mean Aerodynamic Chord (MAC)	275.8 inches full scale
Important Details:	• The intent here is to analyze the full-scale geometry at wind tunnel conditions. Instead of scaling the geometry down to 10% scale, we are analyzing the full-scale grid in a more viscous fluid. In other words, viscosity in this case is <u>not</u> sea level standard, but is scaled up appropriately, to achieve the desired Re of 3.26 million based on 275.8 inches for the full-scale model. • Run simulations FULLY TURBULENT. • This configuration is gapped approximately 1" full-scale between the inboard/outboard flaps and between inboard flap and side of body. • All simulations are "free air"; no wind tunnel walls or model support systems.

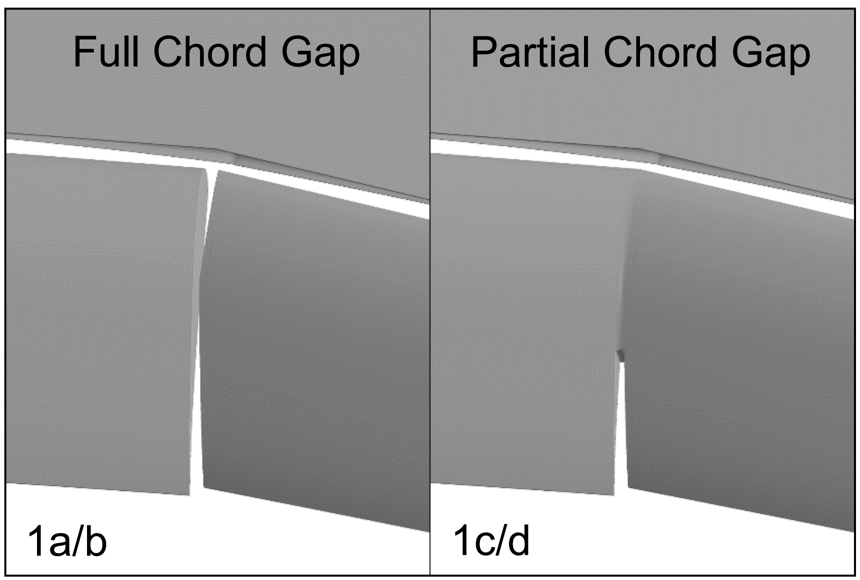
Case 1: Grid Convergence Study

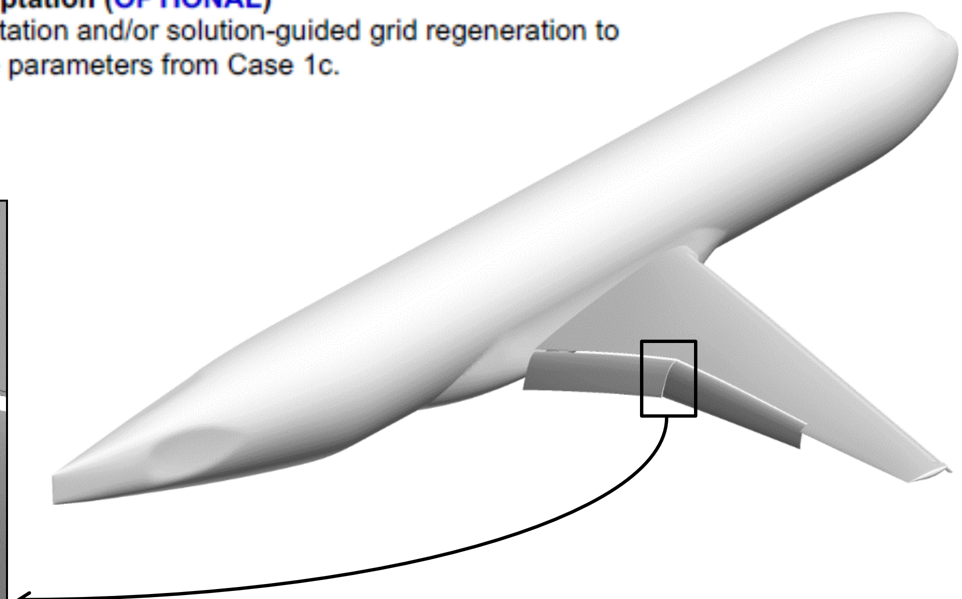
Optional Cases

Case 1b: Full Chord Flap Gap with Adaptation (OPTIONAL)
Use grid refinement based on automatic solution adaptation and/or solution-guided grid regeneration to perform the required grid convergence study using the parameters from Case 1a.

Case 1c: Partially-sealed Chord Flap Gap (OPTIONAL)
Using the flow conditions from Case 1a, provide flow solutions for the medium grid only with a partial chord seal between the inboard and outboard flaps, and between the inboard flap and side of body.

Case 1d: Partially-sealed Chord Flap Gap with Adaptation (OPTIONAL)
Use grid refinement based on automatic solution adaptation and/or solution-guided grid regeneration to perform the required grid convergence study using the parameters from Case 1c.

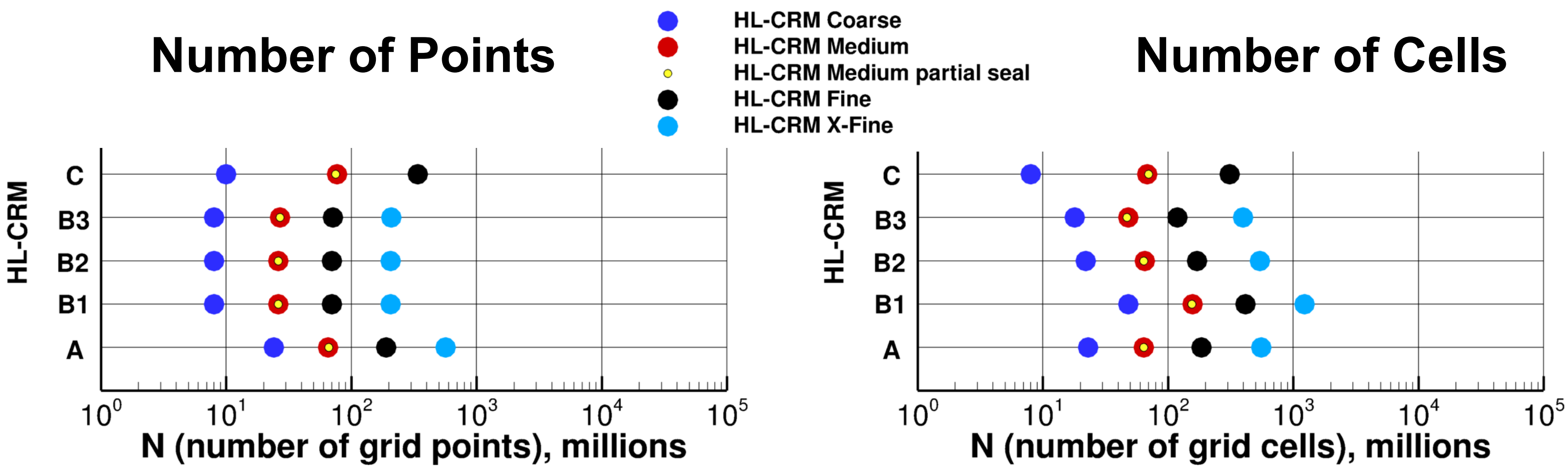




Case 1 Grid Families

Series	Type	Points (M)	Cells (M)	Developer	Tool
A	Overset	24, 65, 189, 565	23, 64, 185, 554	NASA Ames	ANSA+CGT
B1	Tetrahedral	8, 26, 70, 206	48, 157, 416, 1228	Pointwise	Pointwise
B2	Mixed (prism dominant)	8, 26, 70, 206	22, 65, 170, 541	Pointwise	Pointwise
B3	Mixed (hex dominant)	8, 27, 71, 208	18, 48, 119, 397	Pointwise	Pointwise
C	Structured point-matched	10, 77, 338	8, 68, 311	GridPro	GridPro

Blue=Coarse
Green=Medium
Black=Fine
Red=X-Fine



Case 1 Participants

29 Participants
46 Datasets
- Case 1a =46
- Case 1b = 2
- Case 1c = 10
- Case 1d = 2

CFD High Lift Prediction Workshop

Y Dataset Complete

I Dataset Incomplete

Detailed List

Item	PID	Author	Model	Code	1a	1b	1c	1d	Committee Grid	Participant Grid	Plot Symbol
1	001.1	Chen	SA	Mflow	I		I		B3		A solid
2	002.1	Ashton	SA	OpenFOAM	I					d-HLCRM	B solid
3	002.2	Ashton	SA	Star-CCM+	I					d-HLCRM	B dash
4	003.1	Zastawny	SST	Star-CCM+	y		y		B3		C solid
5	003.2	Zastawny	SA	Star-CCM+	y				B3		C dash
6	003.3	Zastawny	ke lagEB	Star-CCM+	y				B3		C dot-dash
7	004.1	Glasby	SA-neg	Kestrel/COFFE	I				B1		D solid
8	004.2	Eymann	SA	Kestrel	I					participant (?)	D dash
9	004.3	Nichols	BSL	Kestrel/KCFD	y				B2		D dot-dash
10	004.4	Nichols	SA	Kestrel/KCFD	y				B2		D dot-dot-dash
11	006.1	Edge	SA-RC-QCR	CFD++	y				B2		F solid
12	007.1	Michal	SA-QCR	GGNS	y	y	y	y	B1	special (a-	G solid
13	008.1	Yasuda	SA-noft2	Cflow	y	y	y	y	B3	n-HLCRM	H solid
14	011.1	Ito	SA-noft2-R	TAS	y				B3		K solid
15	011.2	Ito	SA-noft2-R-QCR2000	TAS	y				B3		K dash
16	012.1	Li	SA-QCR	CFD++	y		y			e2-HLCRM	L solid
17	012.2	Li	SA-RC-QCR	GGNS	I		y			e1-HLCRM	L dash
18	014.1	Lofthouse	SARC	Kestrel	y				B2		N solid
19	014.2	Lofthouse	SARC+DDES	Kestrel	y				B2		N dash
20	015.1	Wang	SA	TRIP	y					participant (?)	O solid
21	016.1	Pogosyan	RSM-SSG/LRR-w	LOGOS	y				B3		P solid
22	016.2	Pogosyan	SA	LOGOS	y				B3		P dash
23	016.3	Pogosyan	SST	LOGOS	y				B3		P dot-dash

Case 1 Participants

29 Participants
46 Datasets
- Case 1a =46
- Case 1b = 2
- Case 1c = 10
- Case 1d = 2

CFD High Lift Prediction Workshop

Y Dataset Complete

I Dataset Incomplete

Detailed List (continued)

Item	PID	Author	Model	Code	1a	1b	1c	1d	Committee Grid	Participant Grid	Plot Symbol
24	018.1	Moens	SA	elsA	I				B2		R solid
25	019.1	Scalabrin	SA	SU2	y				B3		S solid
26	020.1	Nichols	Wilcox2006	TENASI	I				B3		T solid
27	020.2	Nichols	Wilcox2006	TENASI	I					k-HLCRM	T dash
28	020.3	Nichols	SST+SAS	TENASI	I				B3		T dot-dash
29	020.4	Nichols	SST+SAS	TENASI	I					k-HLCRM	T dot-dot-dash
30	020.5	Nichols	SAS k-e	TENASI	I				B3		T long dash
31	020.6	Nichols	SAS k-e	TENASI	I					k-HLCRM	T dash 0.8
32	021.1	daSilva	SA	BRU3D	I					d-HLCRM	U solid
33	022.1	Pulliam	SA-RC-QCR2000	OVERFLOW	y		y		A		V solid
34	023.1	Yousuf	SA-RC-QCR	BCFD	y					e2-HLCRM	W solid
35	025.1	Cimpoeru	SST-V-sust	zCFD	y					participant (?)	Y solid
36	026.1	Rudnik	SA-neg	TAU	y					p-HLCRM	Z solid
37	028.1	O'Connell	LBM-VLES	PowerFLOW	I		I			participant (?)	a solid
38	030.1	Langlois	Wilcox88	Dragon	y				B2		b solid
39	030.2	Langlois	Wilcox88	Dragon	y		y			f-HLCRM	b dash
40	031.1	Brionnaud	WALE	XFlow	I					participant (?)	d solid
41	033.1	Jensen	SA-QCR2000	LAVA	y		y		A		f solid
42	034.1	Escobar	SA	SU2	I				B3		g solid
43	035.1	Wurst	SA-noft2	PHASTA	y				B1		h solid
44	036.1	Luo	SST	FUN3D	I				B1		m solid
45	039.1	Powell	SA	FUN3D	I				B2		q solid
46	040.1	Duque	SA-noft2	OVERFLOW	y				A		r solid

Case 1: Grid Convergence Study

CFD High Lift Prediction Workshop

Outline

- Case Description
- Grid Families
- Participant List
- Results
  - Overview
  - Iterative Convergence
  - Lift, Drag and Pitching Moment
  - Pressures and Skin Friction
  - Velocity Profiles
- Conclusions

Results Overview

CFD High Lift Prediction Workshop

Compare Iterative Convergence for Lift and Residual

Forces and Moments:

•Focus on lift prediction for Case 1a
•Plot grid convergence using $N^{-2/3}$
- ➢ grid convergence plots are used to visualize general trends only

•Compare grid convergence trends for various grid and turbulence model types
•Compare grid convergence trends between pre-defined grid family (global uniform refinement) and adapted meshes (targeted refinement)
•Compare increments due to flap gap

Pressures and Skin Friction:

•Focus on Medium Grid, α = 16° data at 3 span stations: η = 0.240, 0.552, 0.908

Velocity Profiles:

•Focus on Medium Grid, α = 16° data at 2 span stations: η = 0.240, 0.552

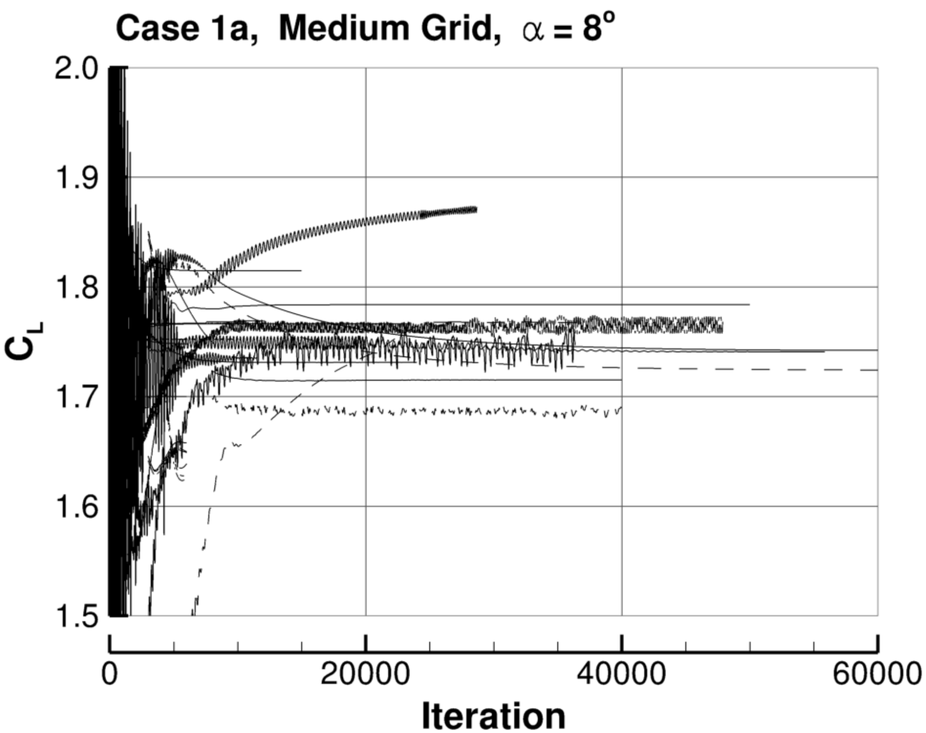
Case 1: Grid Convergence Study

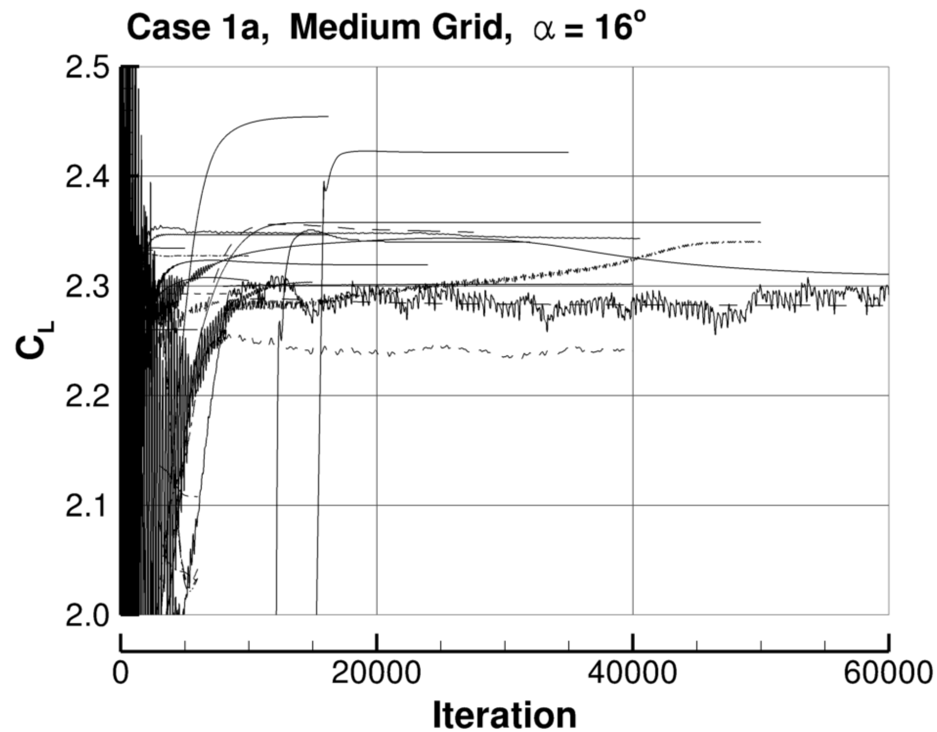
CFD High Lift Prediction Workshop

Outline

- Case Description
- Grid Families
- Participant List
- Results
  - Overview
  - Iterative Convergence
  - Lift, Drag and Pitching Moment
  - Pressures and Skin Friction
  - Velocity Profiles
- Conclusions

Lift Convergence



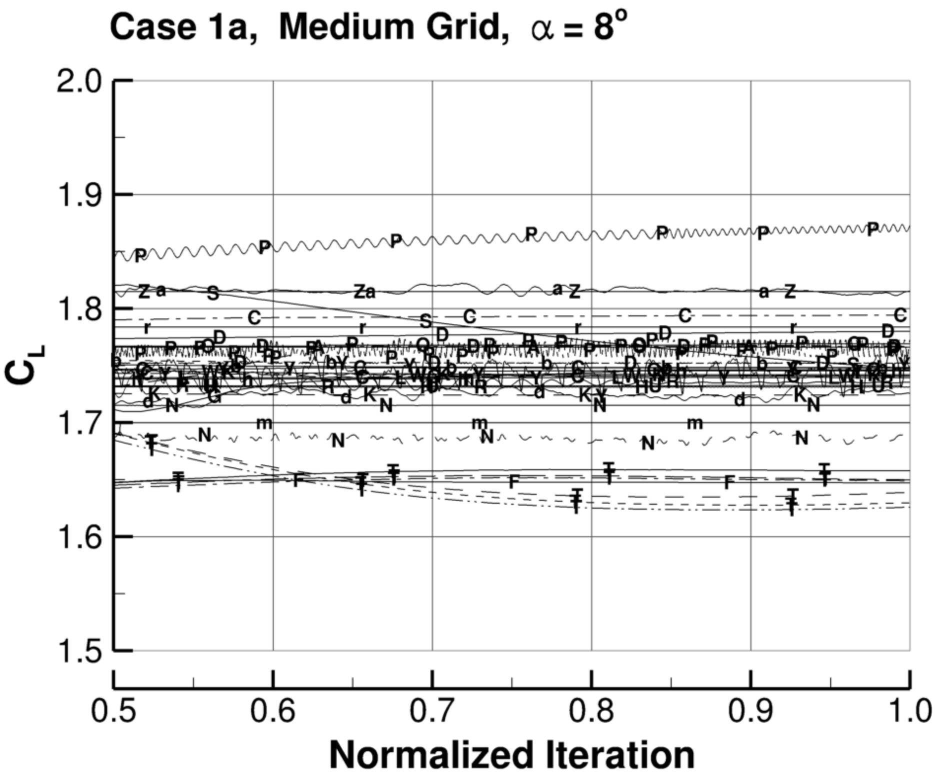


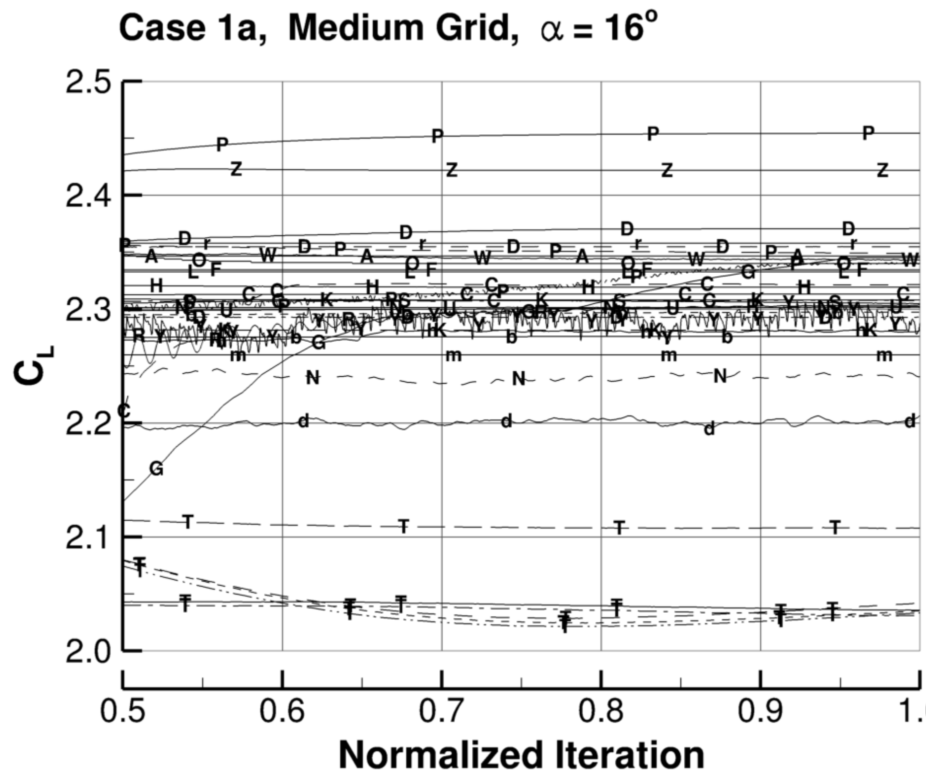
- Due to large variation in iteration, convergence data was normalized for comparison purposes.

$$\text{Normalized Iteration} = \frac{(Current\ Iteration - Min\ Iteration)}{(Max\ Iteration - Min\ Iteration)}$$

Normalized Lift Convergence

CFD High Lift Prediction Workshop

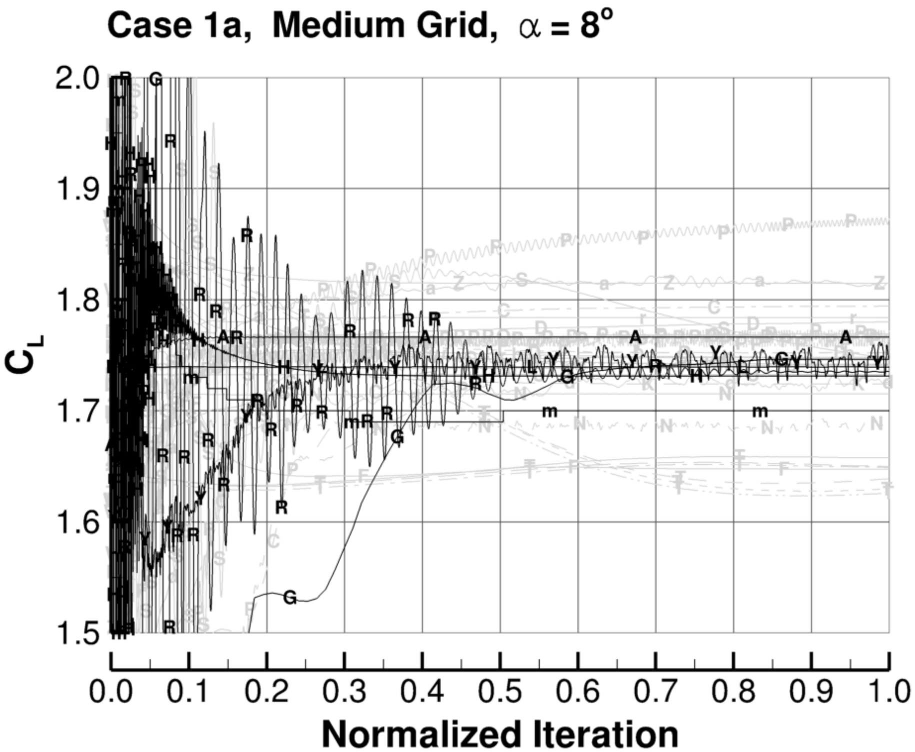


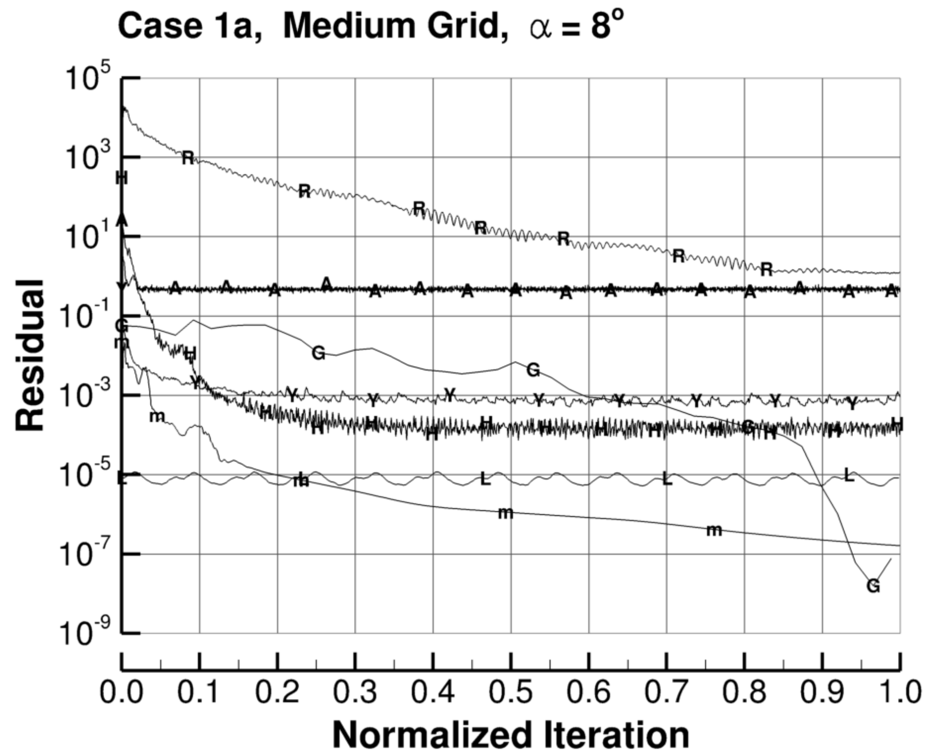


- About 90% of Case 1a data shown
- Lift levels appear to be converged to at least the second decimal place
- Dataset G and some of the T datasets stand-out at 16° as varying more in C_L over the second half of the run

Residual Convergence

CFD High Lift Prediction Workshop





- Based on the limited set of data submitted to date, there's a 1-to-3 order drop in residual for the Medium Grid run at 8° angle-of-attack
- Many of the solutions stop converging very early in the run

Case 1: Grid Convergence Study

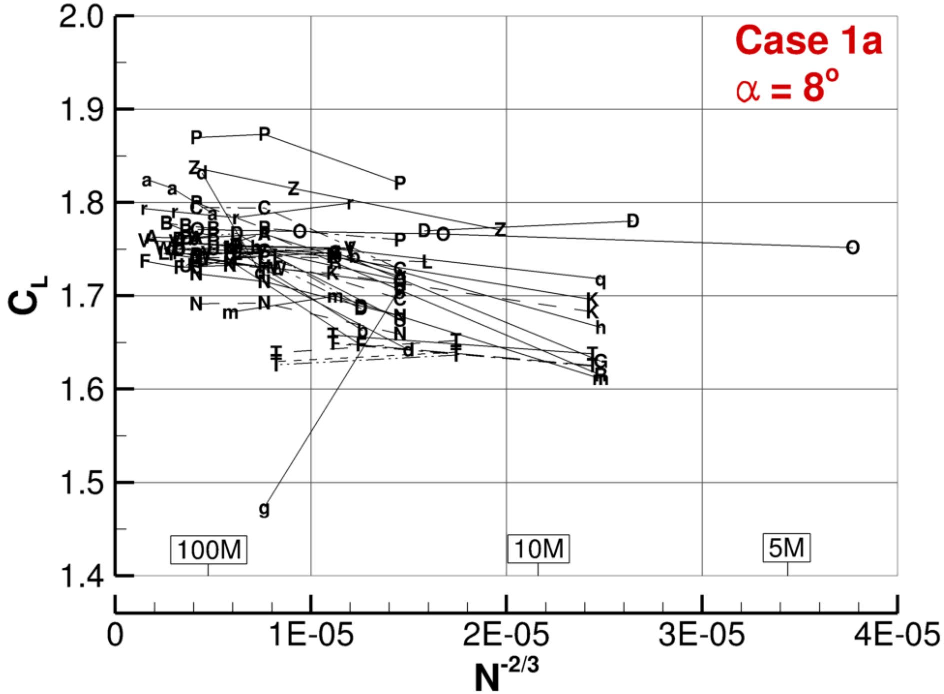
CFD High Lift Prediction Workshop

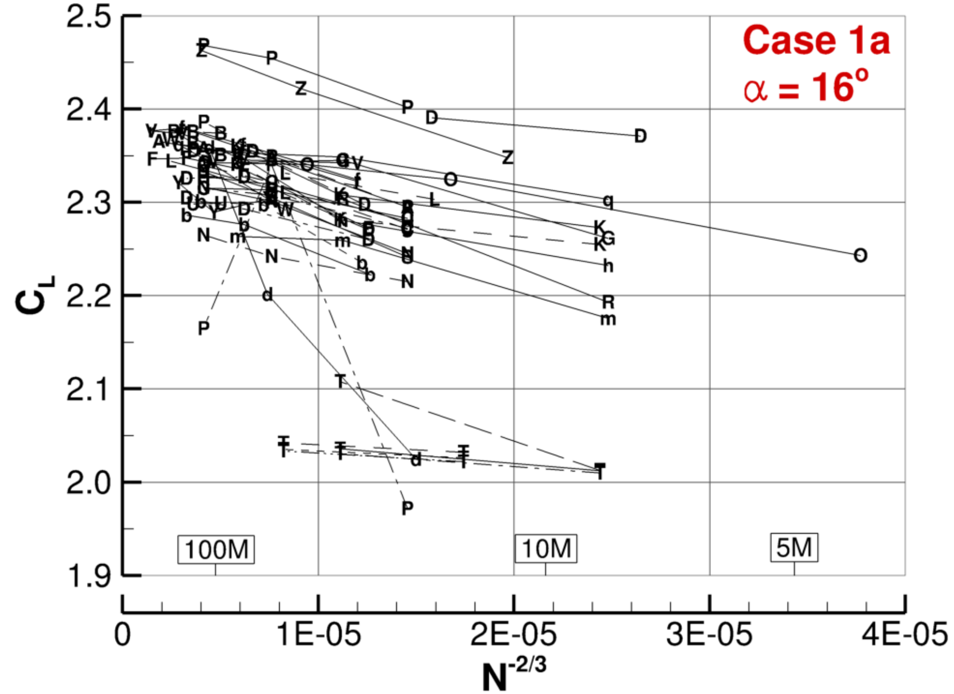
Outline

- Case Description
- Grid Families
- Participant List
- Results
  - Overview
  - Iterative Convergence
  - Lift, Drag and Pitching Moment
  - Pressures and Skin Friction
  - Velocity Profiles
- Conclusions

Lift – Case 1a

CFD High Lift Prediction Workshop

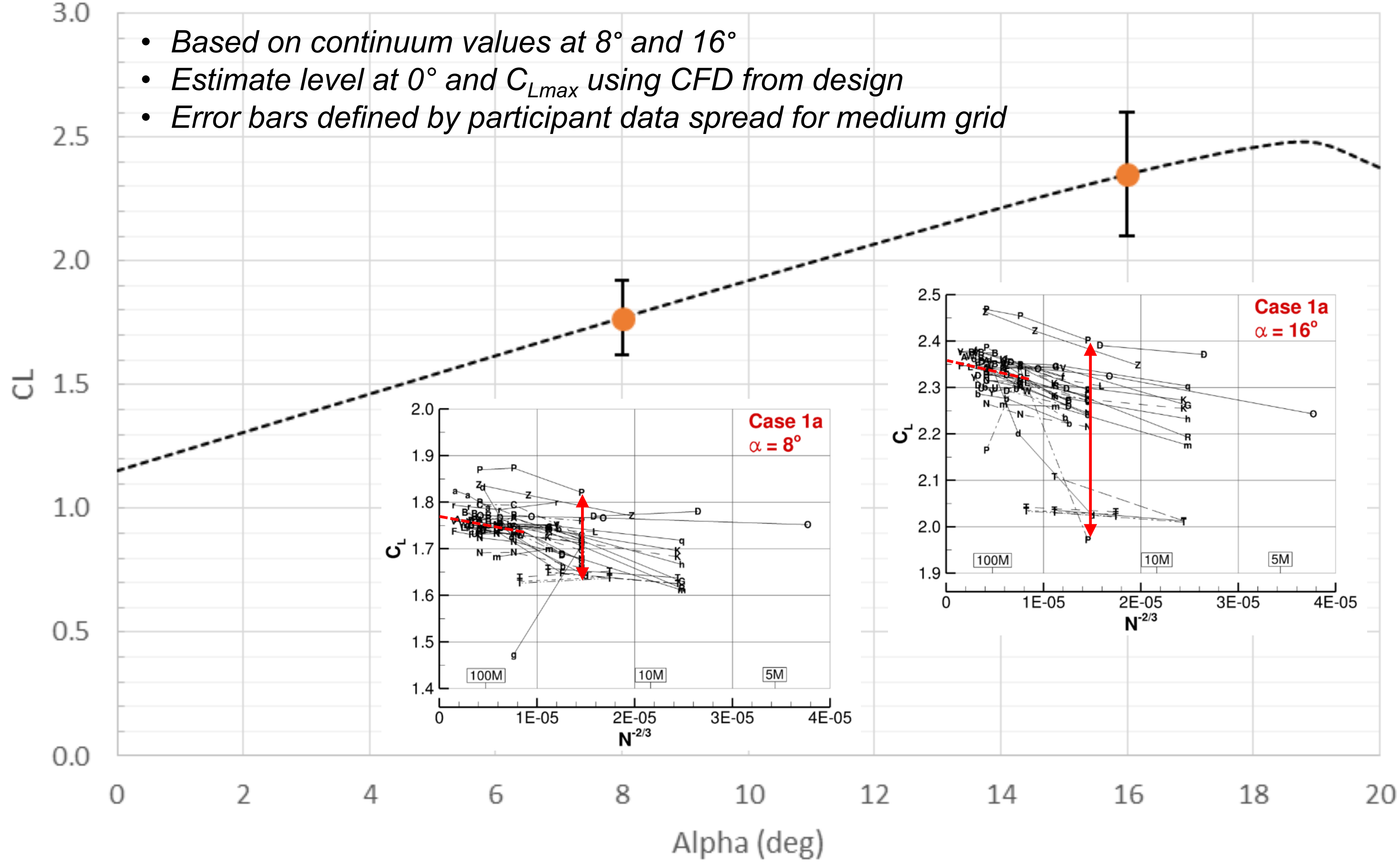




- Data show a general increase in lift with grid refinement
- There is a greater lift variation at higher alpha
- 16° plot shows larger slopes indicating greater sensitivity to grid refinement
- **Datasets P, T, Z, d, g have slopes and levels significantly different than most other datasets**

Note: The Z data are for a Reynolds number of 32.6 million instead of 3.26 million

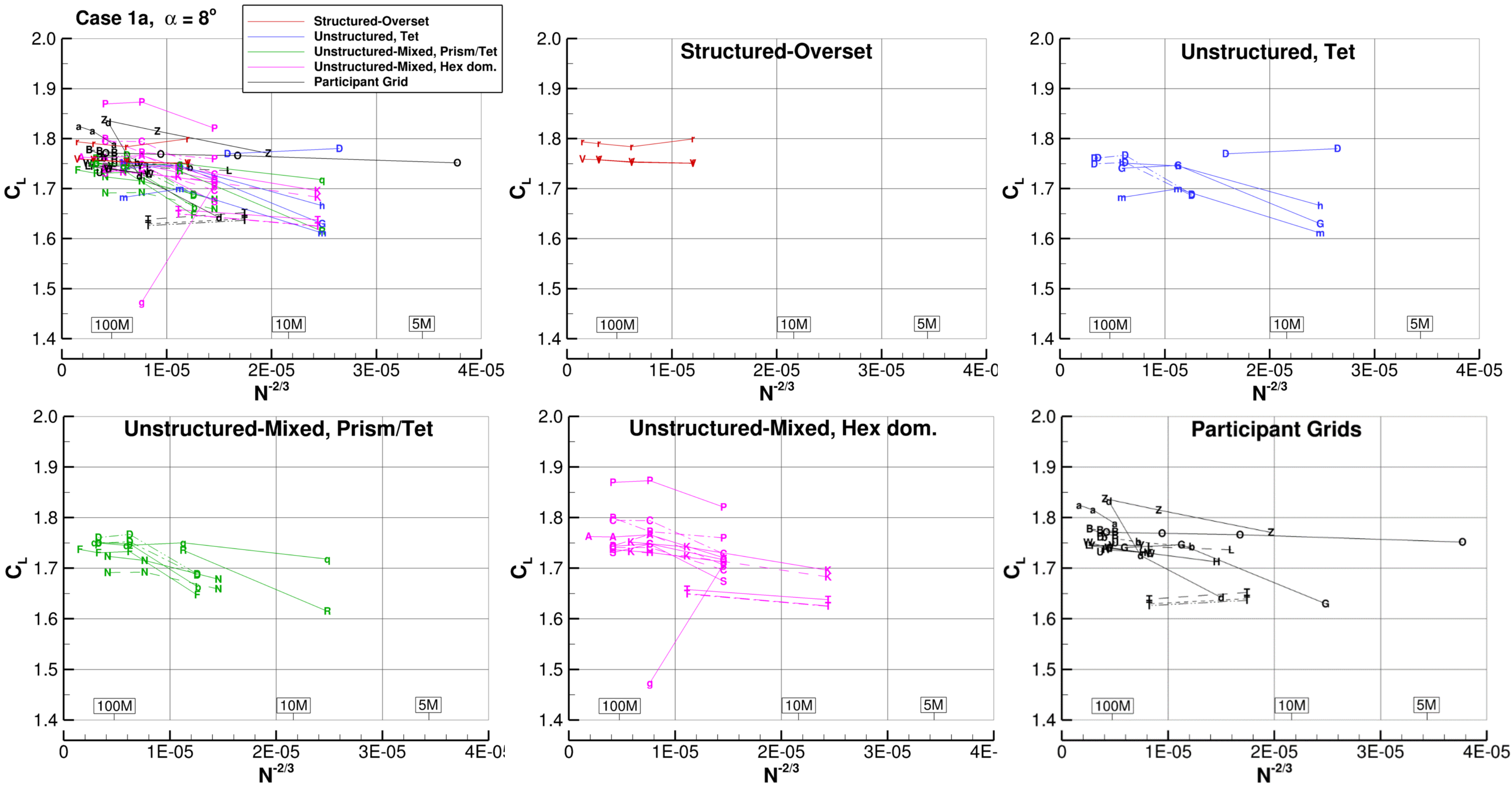
Notional HL-CRM Lift Curve



- The variation in C_L for the medium grid is significant at both angles-of-attack
- Spread at 8° is roughly 8% of C_{Lmax}

Case 1a Sorted by Grid Type: 8°

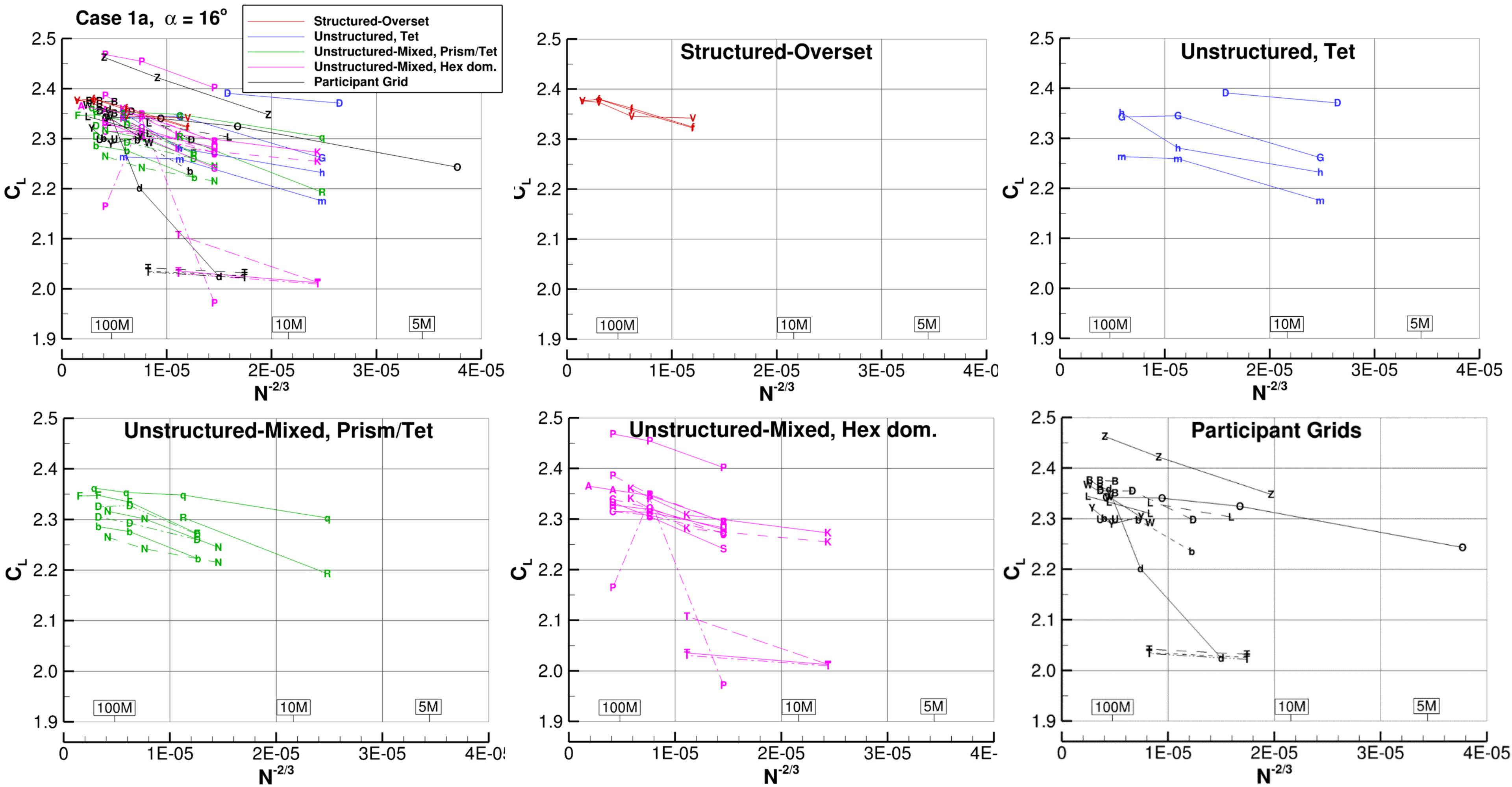
CFD High Lift Prediction Workshop



- With data plotted separately, there are no obvious differences in refinement trends due to grid type.

Case 1a Sorted by Grid Type: 16°

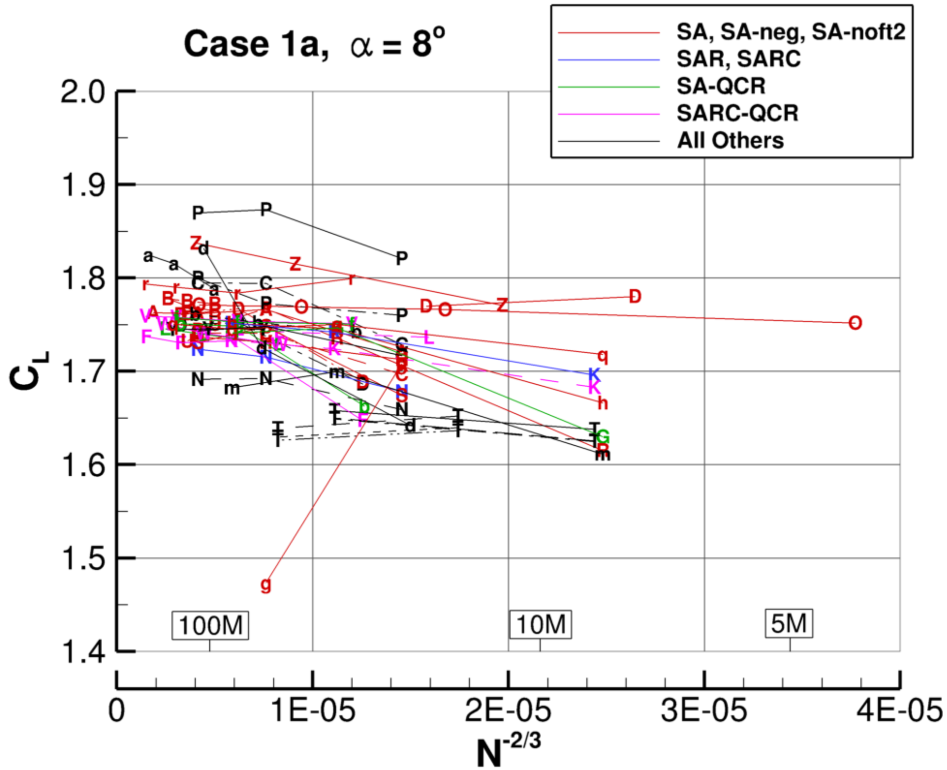
CFD High Lift Prediction Workshop

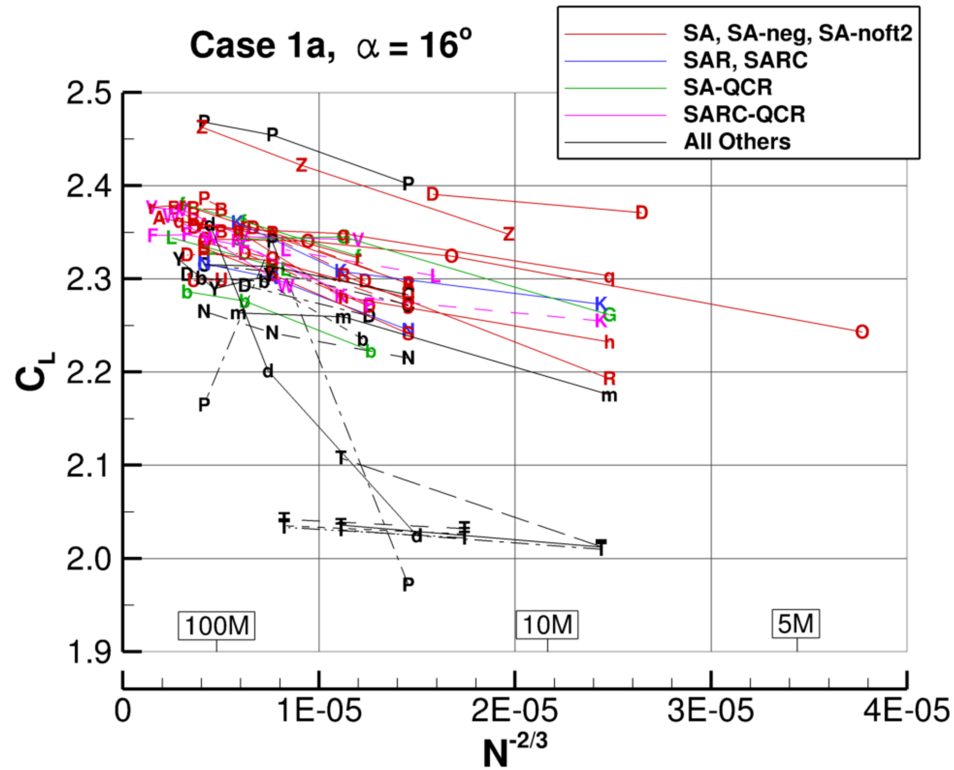


- With data plotted separately, there are no obvious differences in refinement trends due to grid type.

Case 1a Sorted by Turb Model

CFD High Lift Prediction Workshop

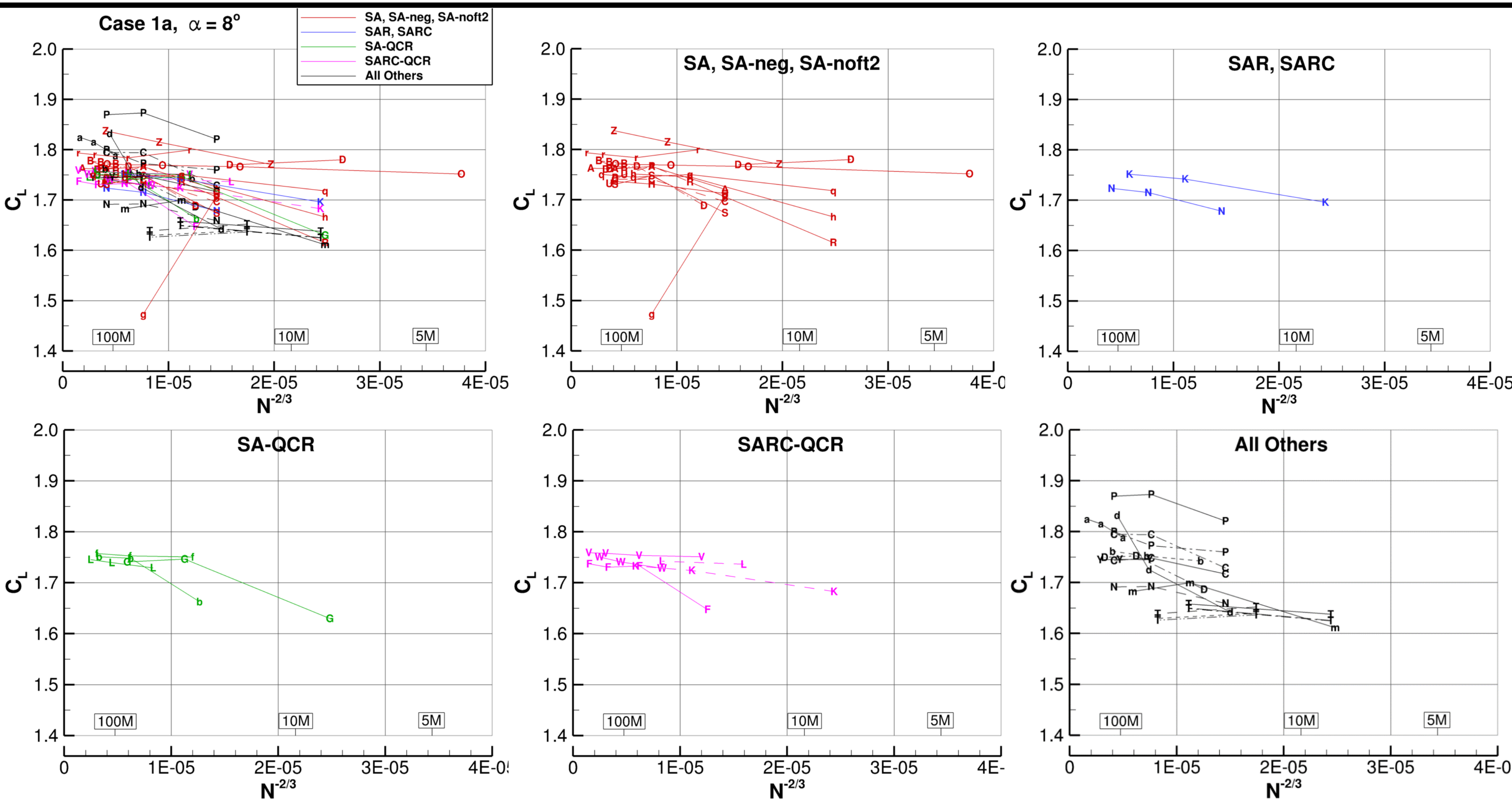




- The Spalart-Allmaras (SA) turbulence model was broken-out because it was used in 63% of the Case 1 datasets.
- Excluding datasets Z and g, the multi-colored SA results appear to be tightly bunched together and trending in a consistent manner.

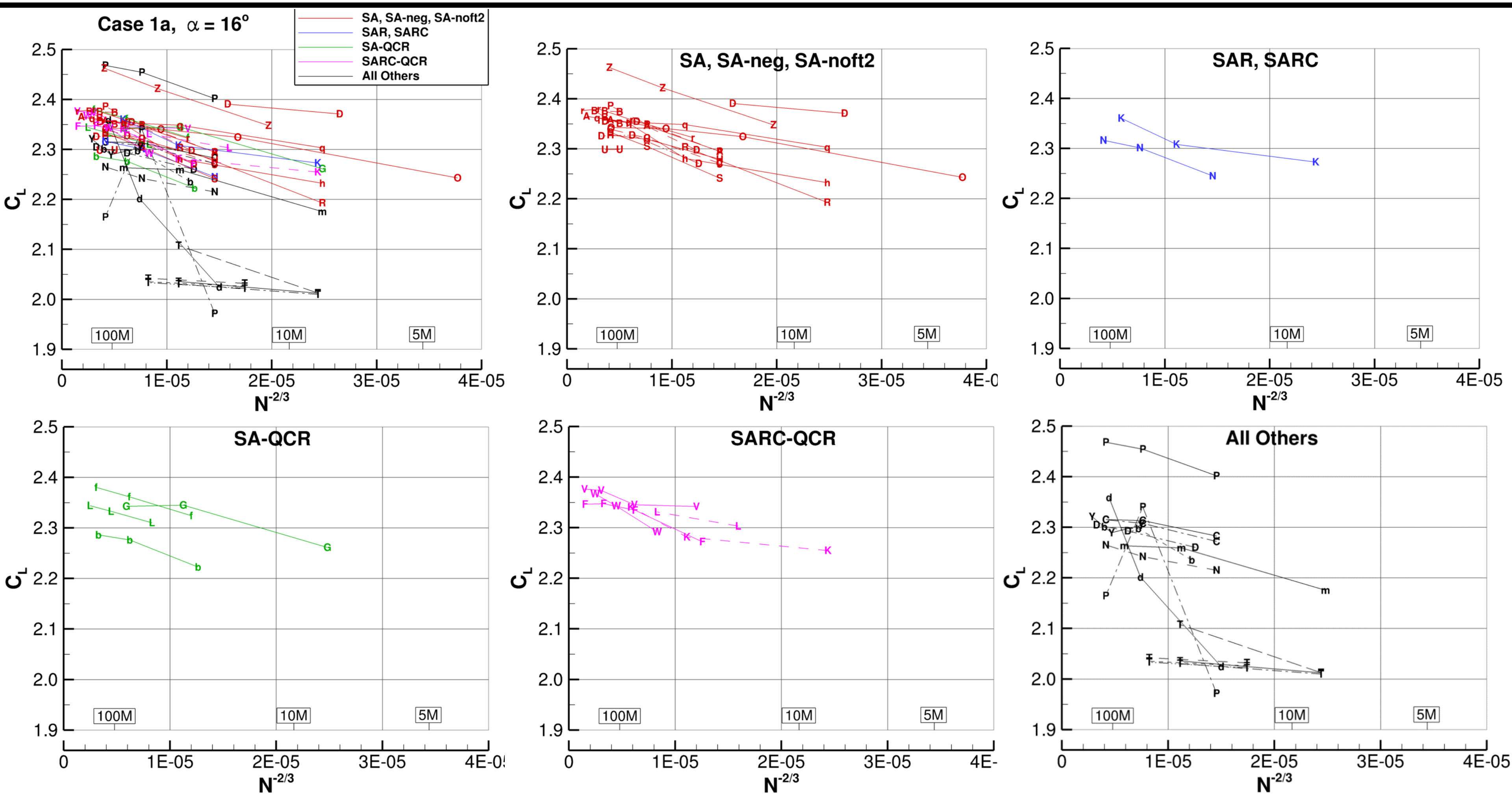
Case 1a Sorted by Turb Model: 8°

CFD High Lift Prediction Workshop



- Not clear what effect QCR and the Rotation (R) and Correction (C) terms have.
- “All Others” is made up of various TM types (including LBM), so it’s not surprising to see more C_L variation compared to just the SA results.

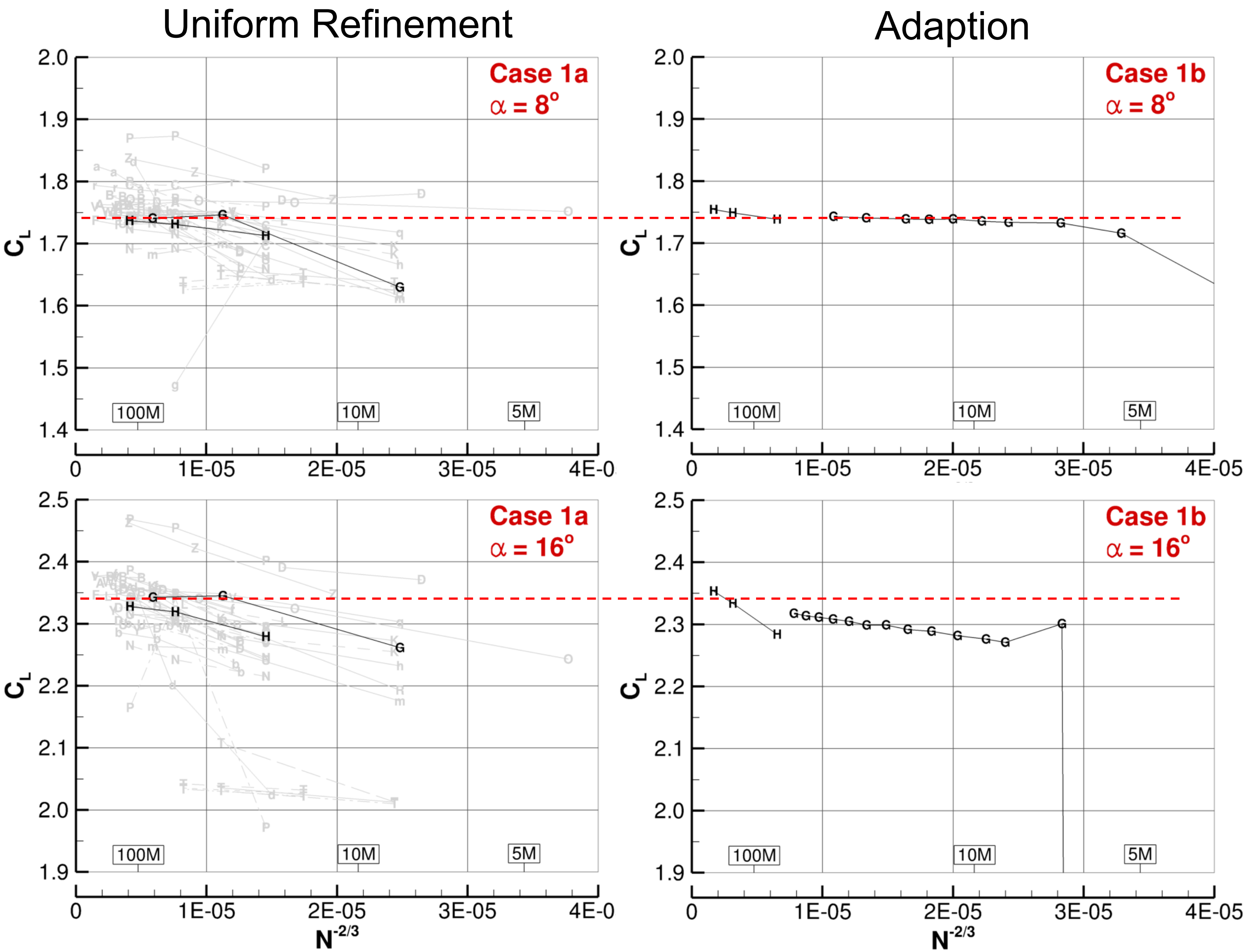
Case 1a Sorted by Turb Model: 16°



- Not clear what effect QCR and the Rotation (R) and Correction (C) terms have.
- “All Others” is made up of various TM types (including LBM), so it’s not surprising to see more C_L variation compared to just the SA results.

Uniform Refinement vs. Adaption

CFD High Lift Prediction Workshop

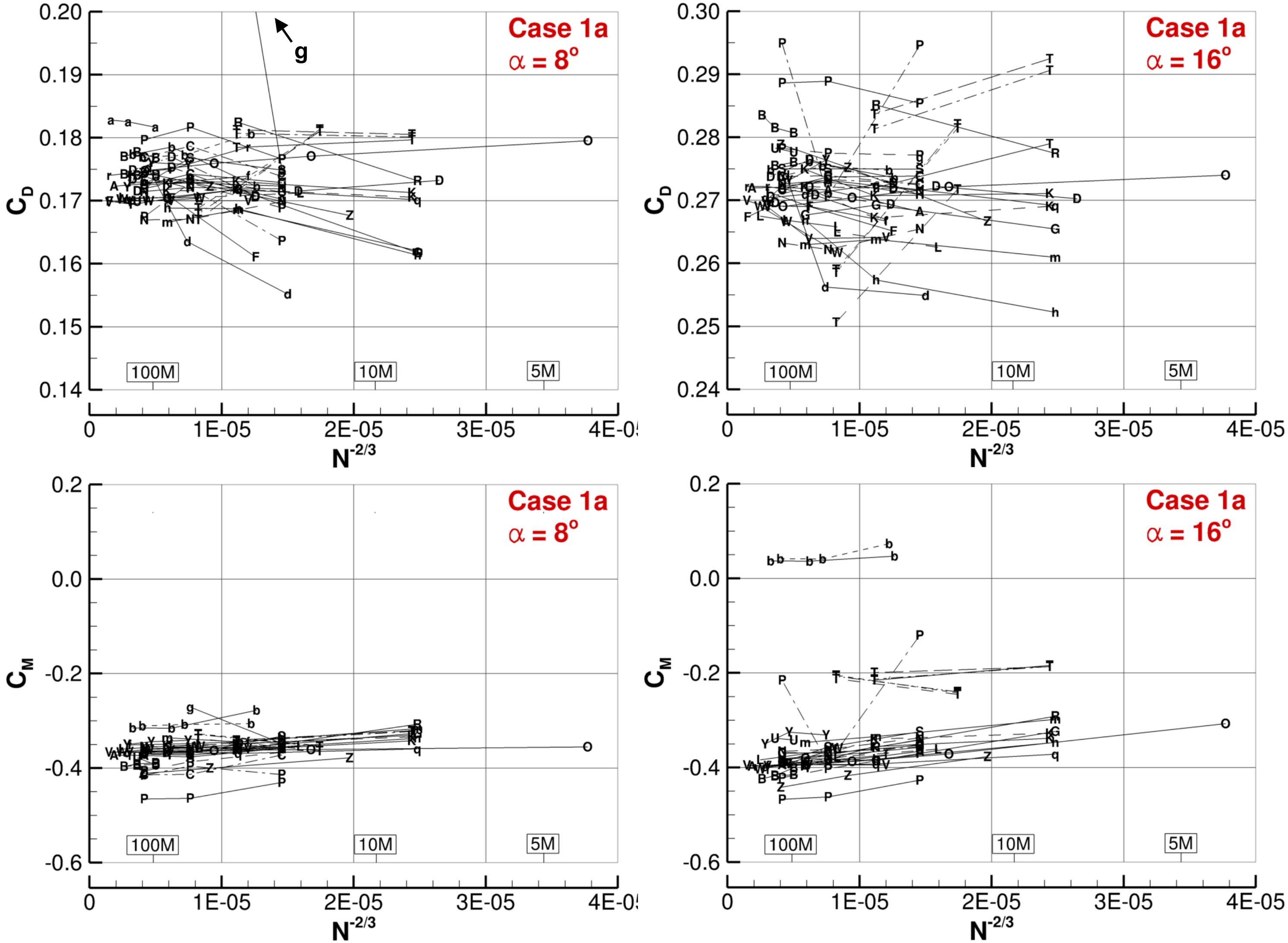


G data represent expected result at 8° where coarser adapted mesh produces similar lift level as finer uniformly refined mesh.

The 16° adapted mesh data does not converge as quickly as 8°.

Drag and Pitching Moment

CFD High Lift Prediction Workshop

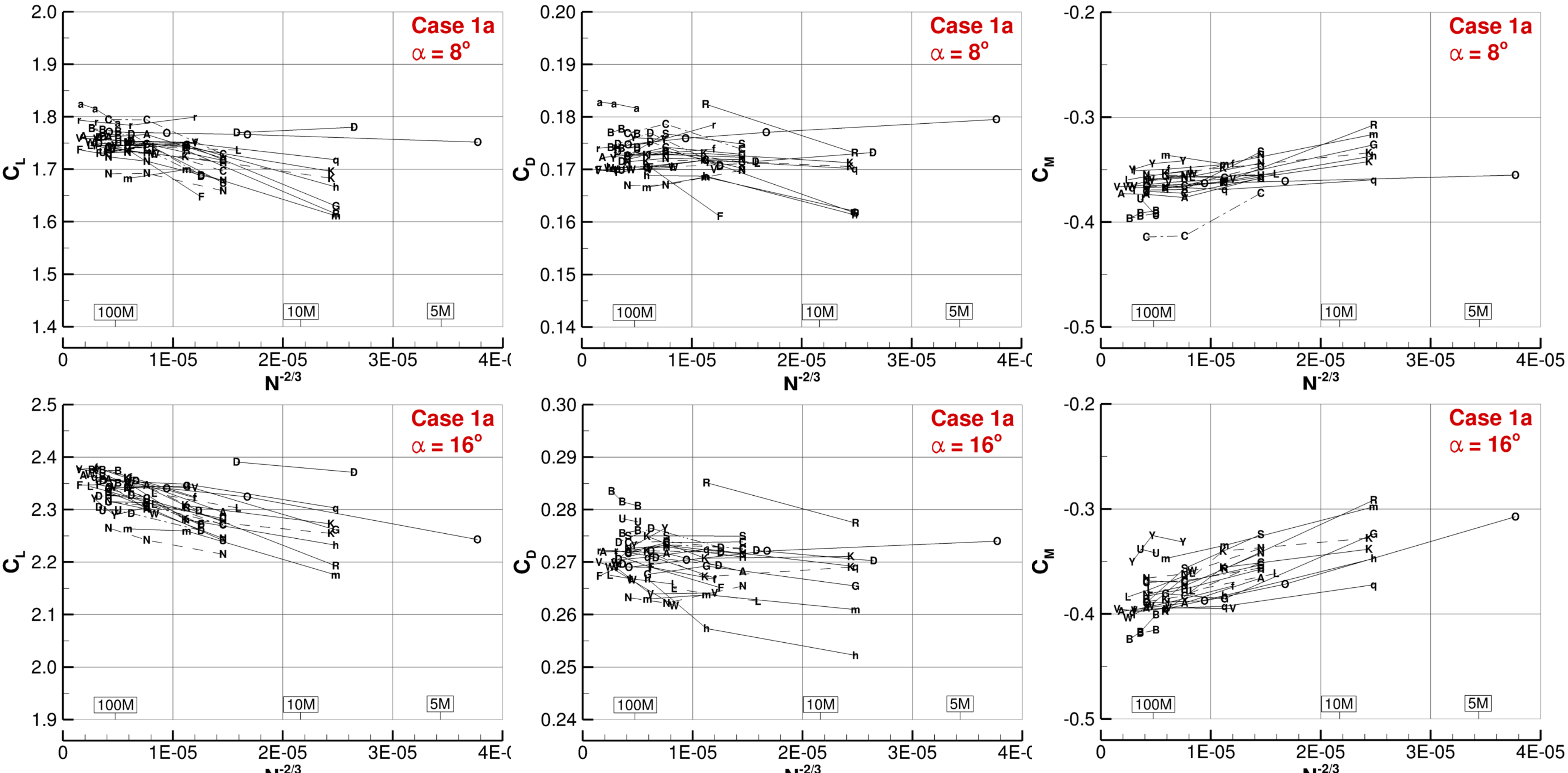


Considerable increase in drag variation at higher AOA.

The g dataset is an extreme outlier at 8°.

The b dataset is an extreme outlier for pitching moment.

Case 1a – Outliers Removed

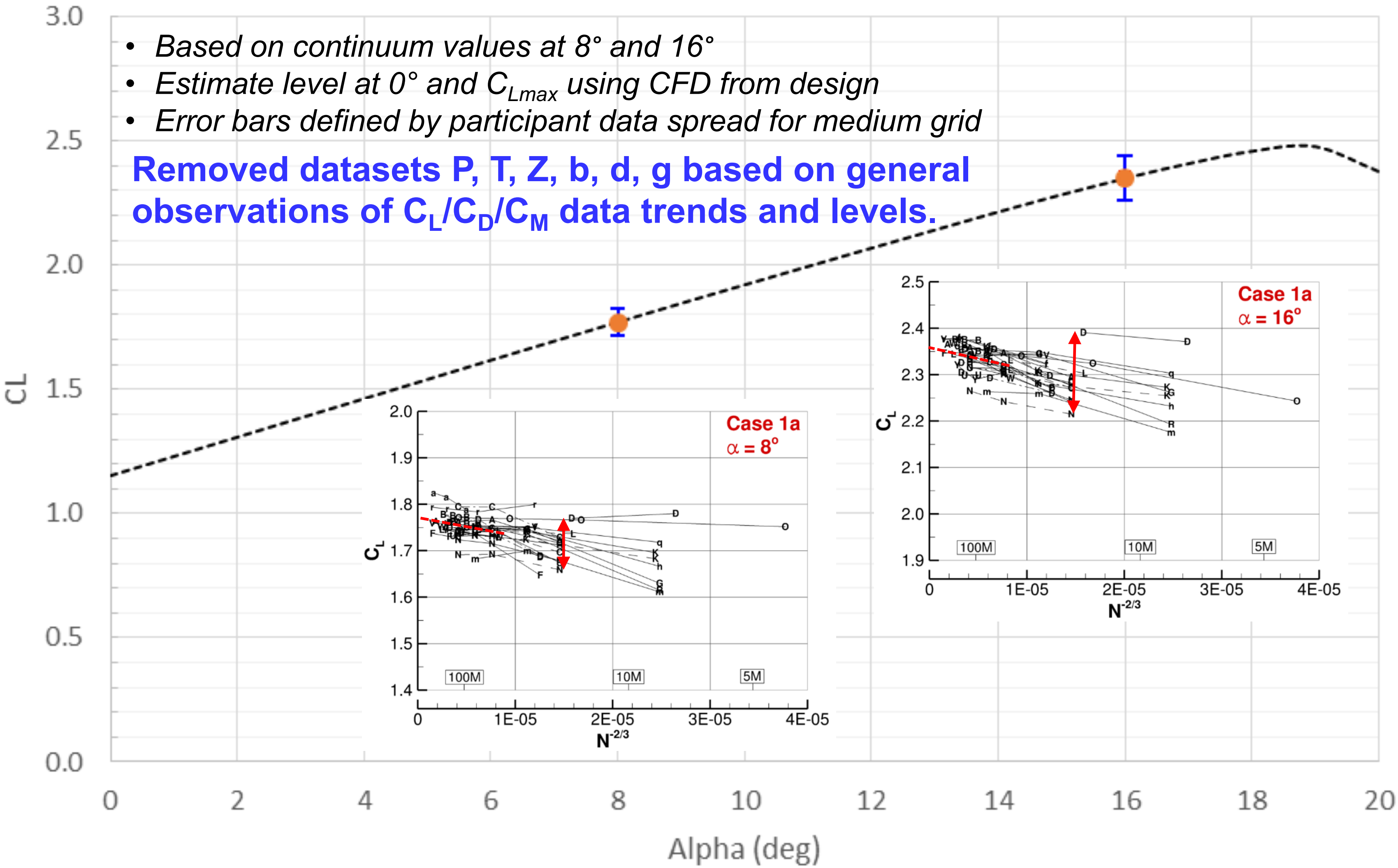


Removed datasets P, T, Z, b, d, g based on general observations of $C_L/C_D/C_M$ data trends and levels.

Note: The Z data are for a Reynolds number of 32.6 million instead of 3.26 million

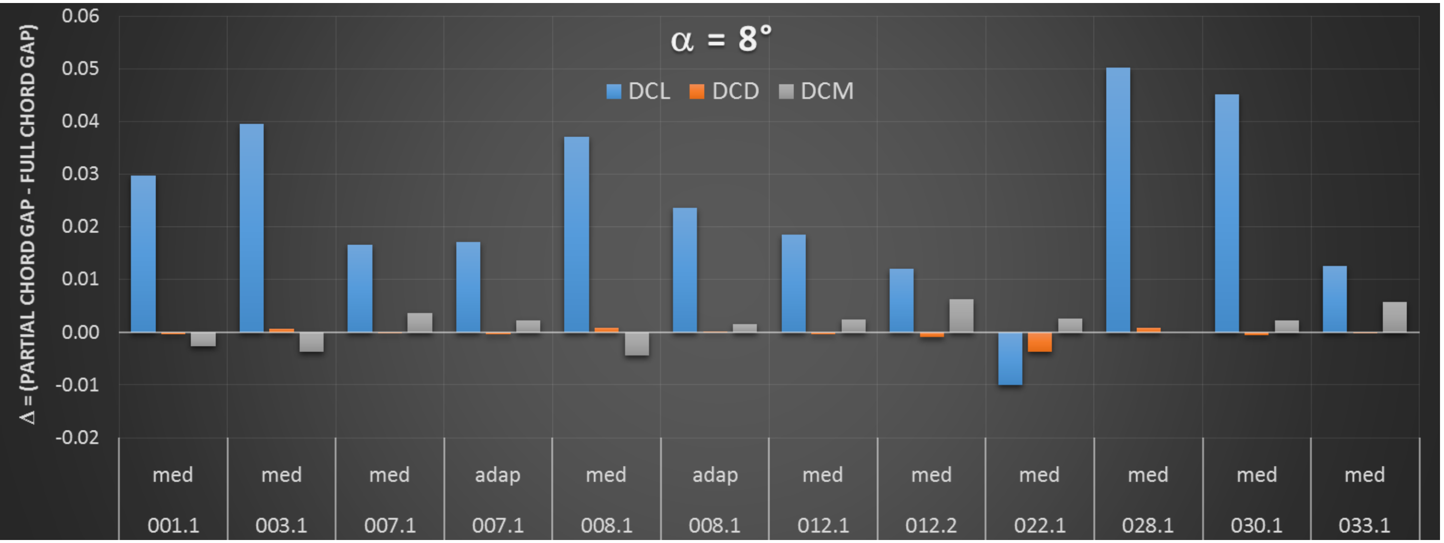
Notional HL-CRM Lift Curve

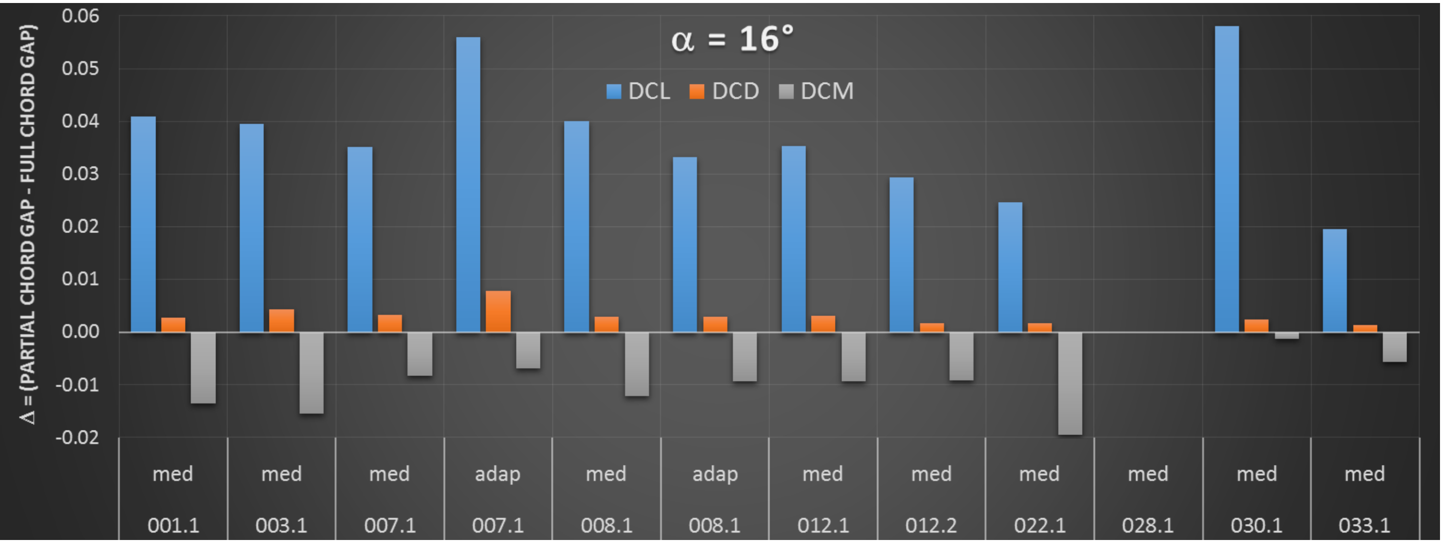
CFD High Lift Prediction Workshop



- With outliers removed, the variation in C_L for the medium grid level looks more promising

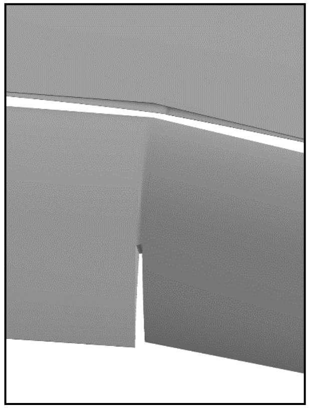
Effect of Flap Gap





Full Chord Gap

Partial Chord Gap



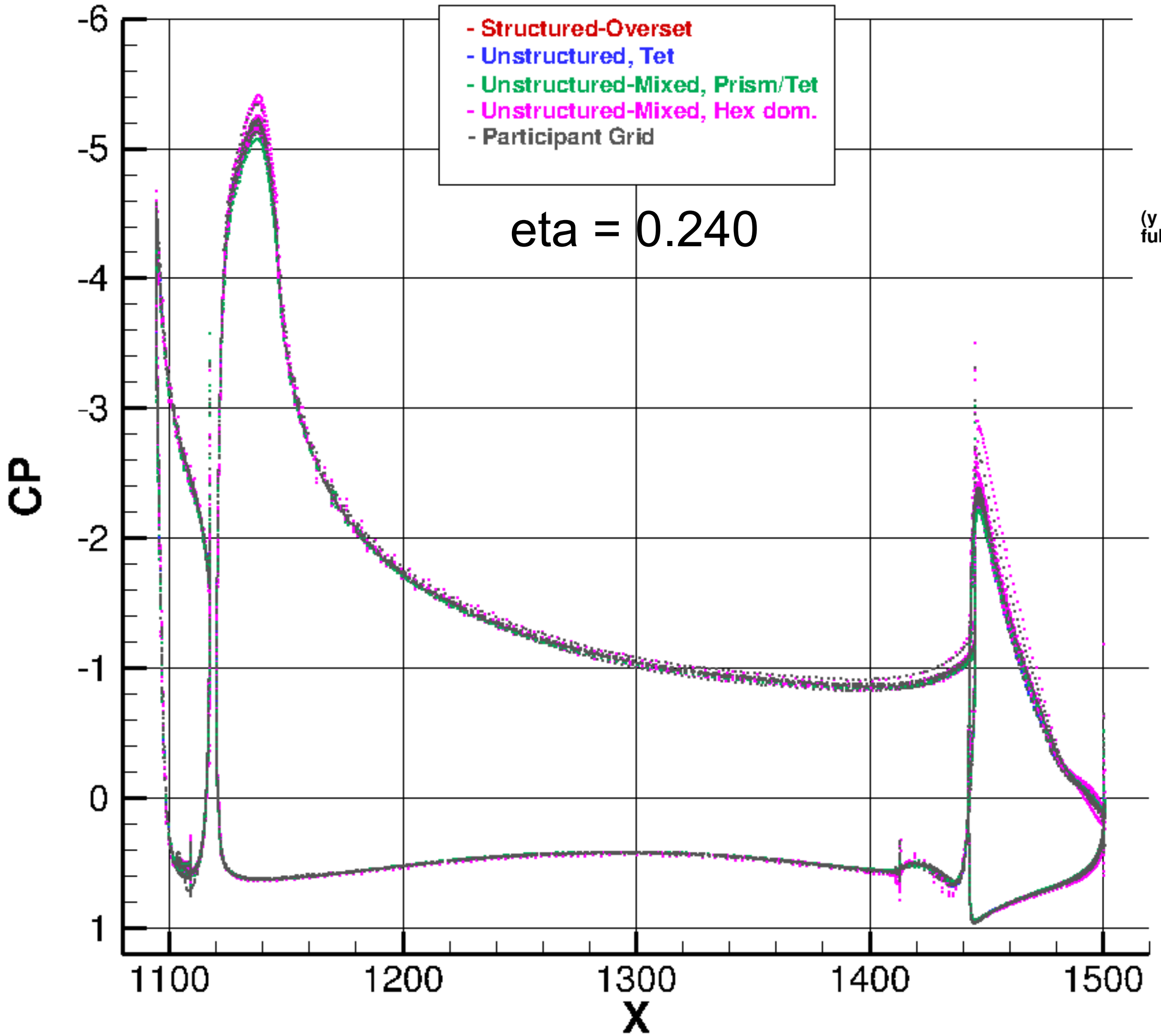
Case 1: Grid Convergence Study

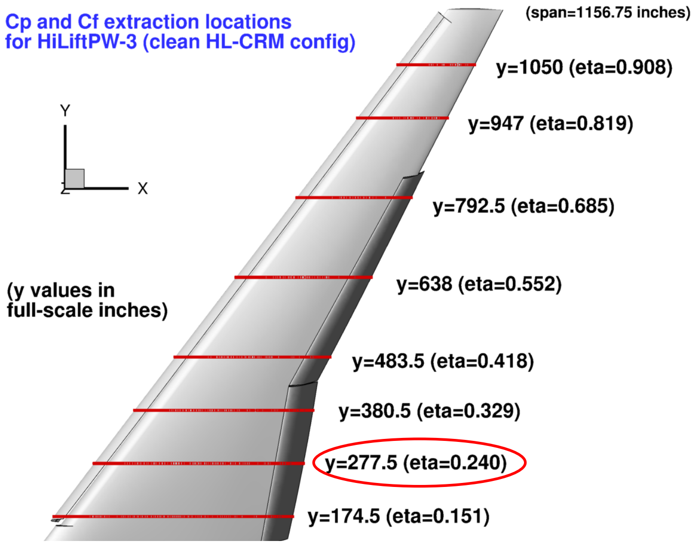
CFD High Lift Prediction Workshop

Outline

- Case Description
- Grid Families
- Participant List
- Results
  - Overview
  - Iterative Convergence
  - Lift, Drag and Pitching Moment
  - Pressures and Skin Friction
  - Velocity Profiles
- Conclusions

Pressure – Case 1a, Med, 16˚

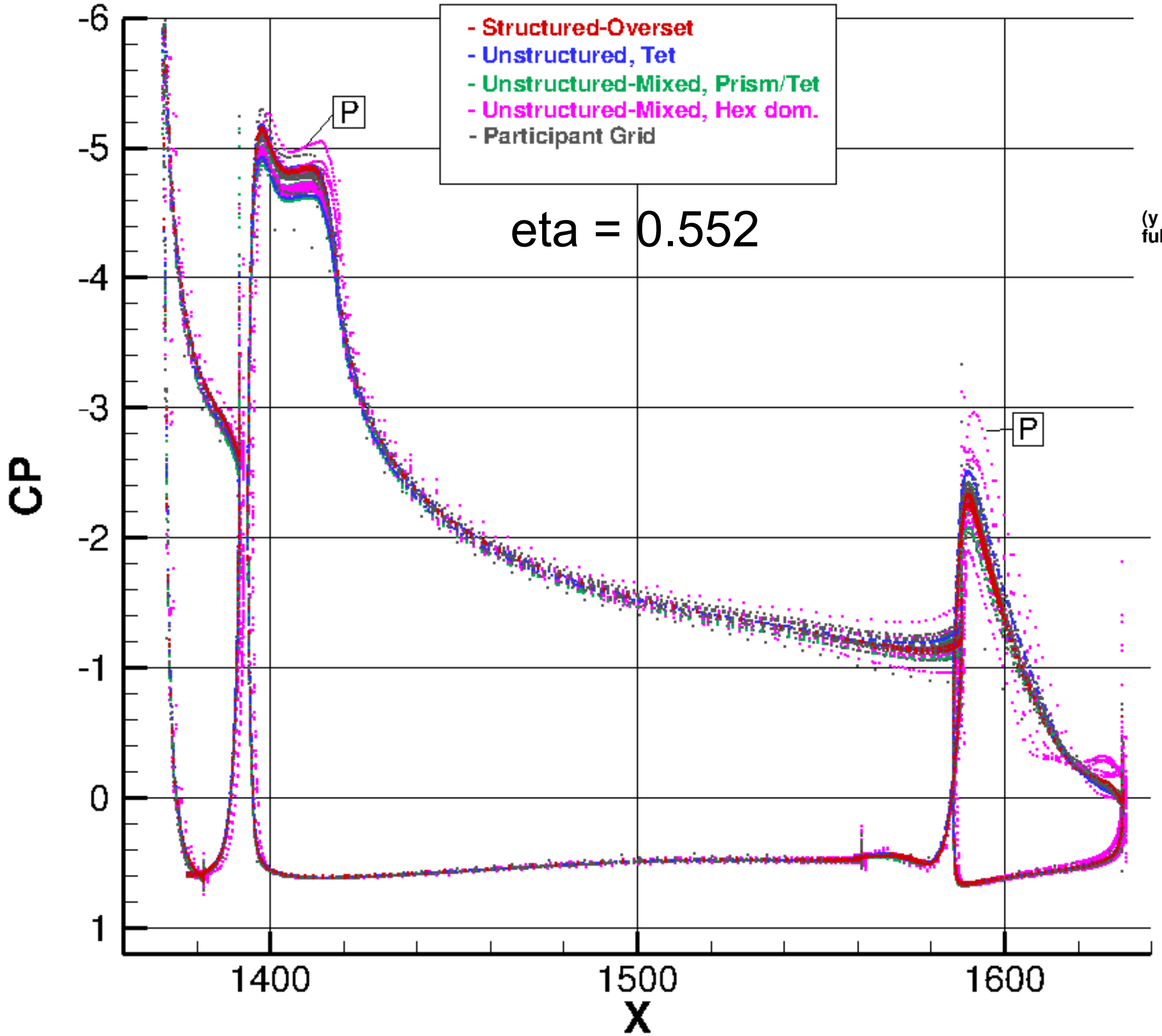


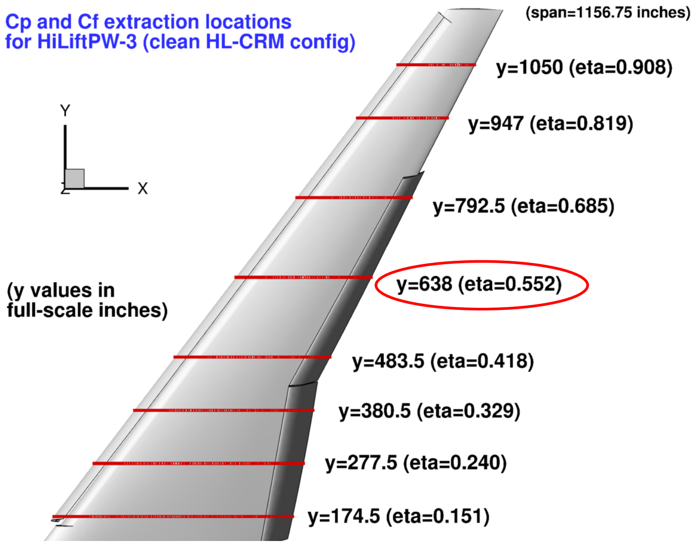


- Significant variation in wing minimum Cp levels
- Flap minimum Cp levels vary more than wing

Pressure – Case 1a, Med, 16˚

CFD High Lift Prediction Workshop

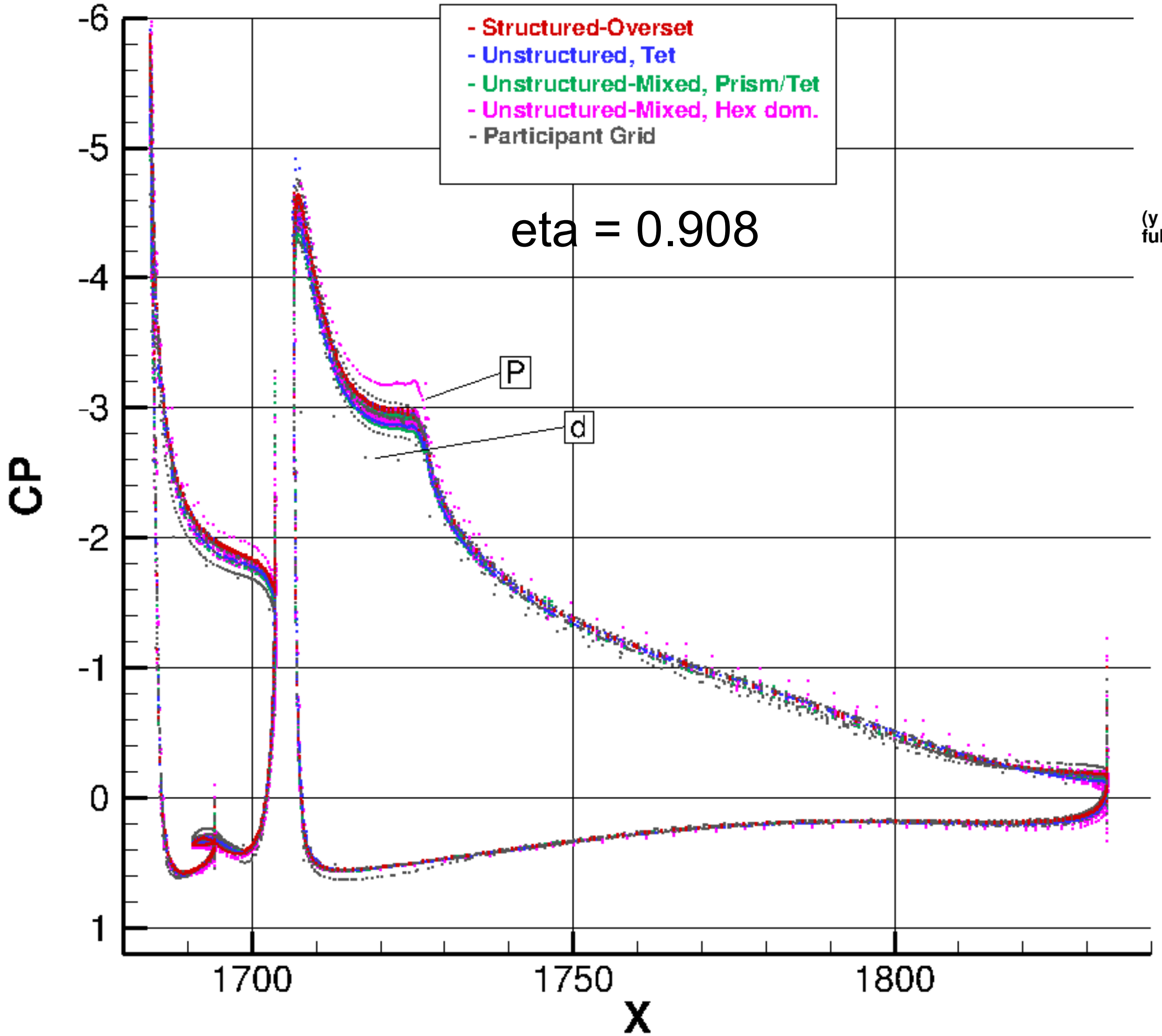


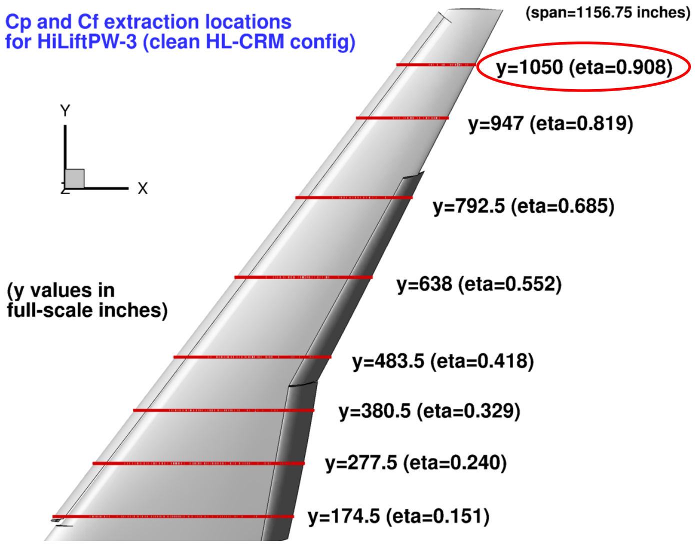


- Significant variation in wing minimum Cp levels
- Flap minimum Cp levels vary more than wing
- Dataset P predicts significantly higher flap suction pressure

Pressure – Case 1a, Med, 16˚

CFD High Lift Prediction Workshop

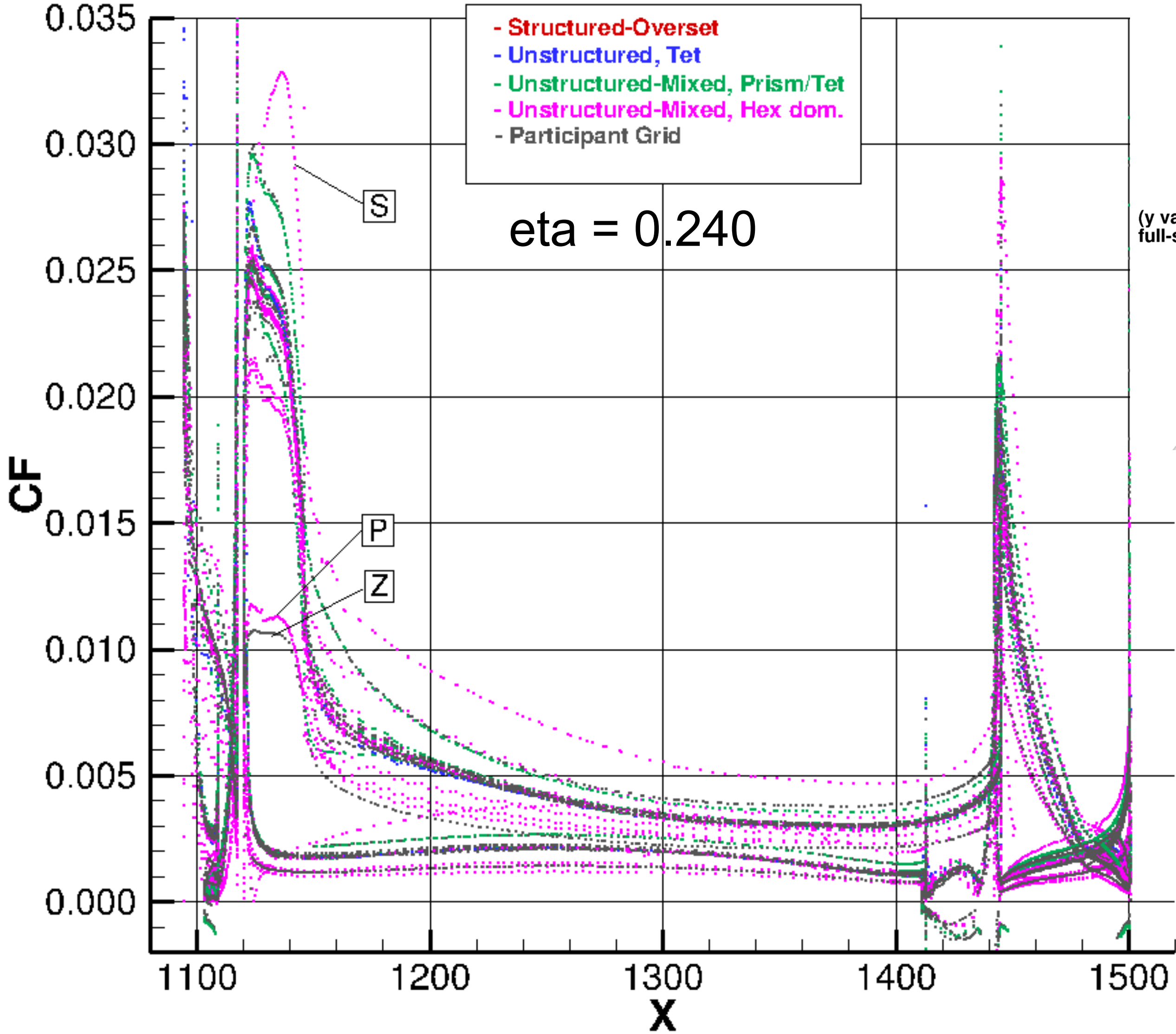


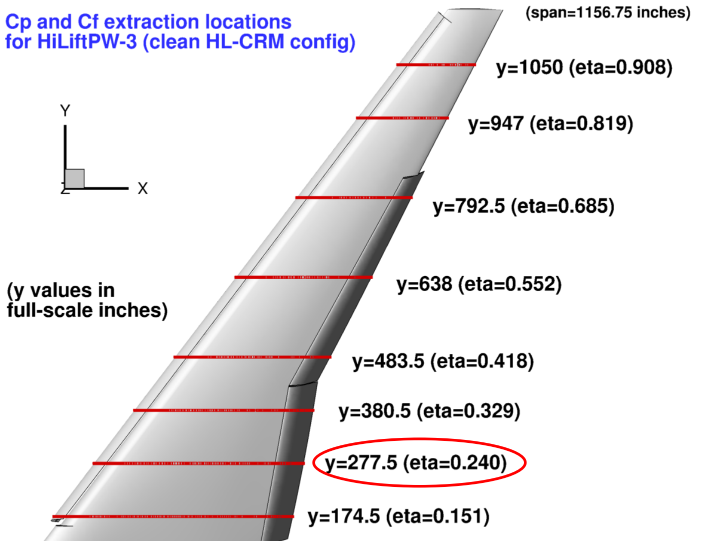


- Significant variation in wing minimum Cp levels
- Datasets d and P bracket all upper surface wing pressures

Skin Friction – Case 1a, Med, 16°

CFD High Lift Prediction Workshop

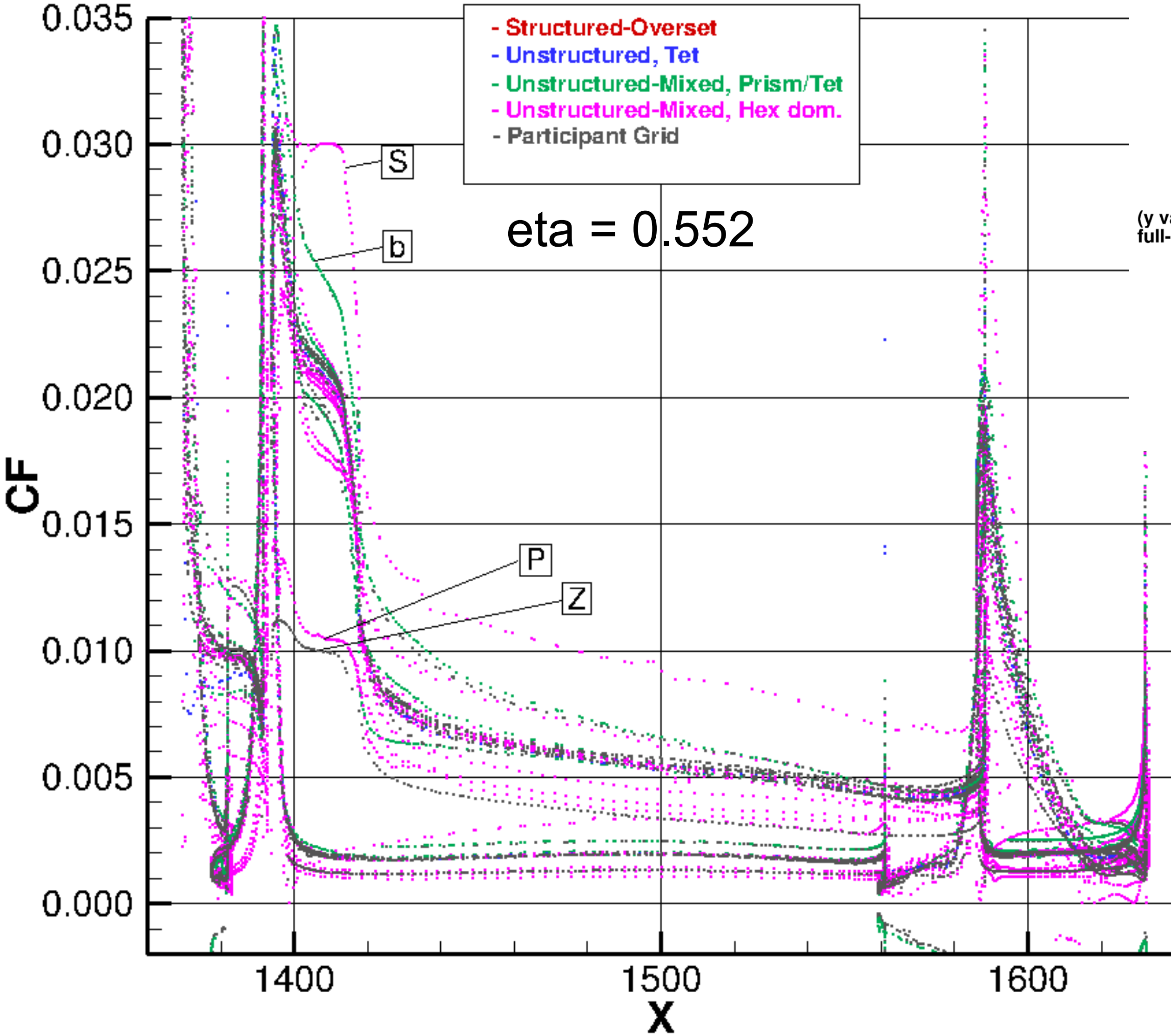


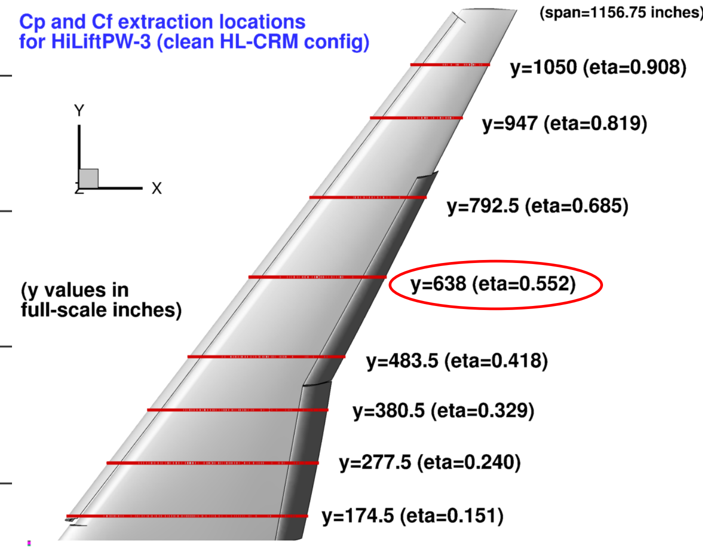


- Variation in skin friction is considerably larger than pressure variation
- Datasets Z, P and S represent the extremes for the wing

Note: The Z data are for a Reynolds number of 32.6 million instead of 3.26 million

Skin Friction – Case 1a, Med, 16°



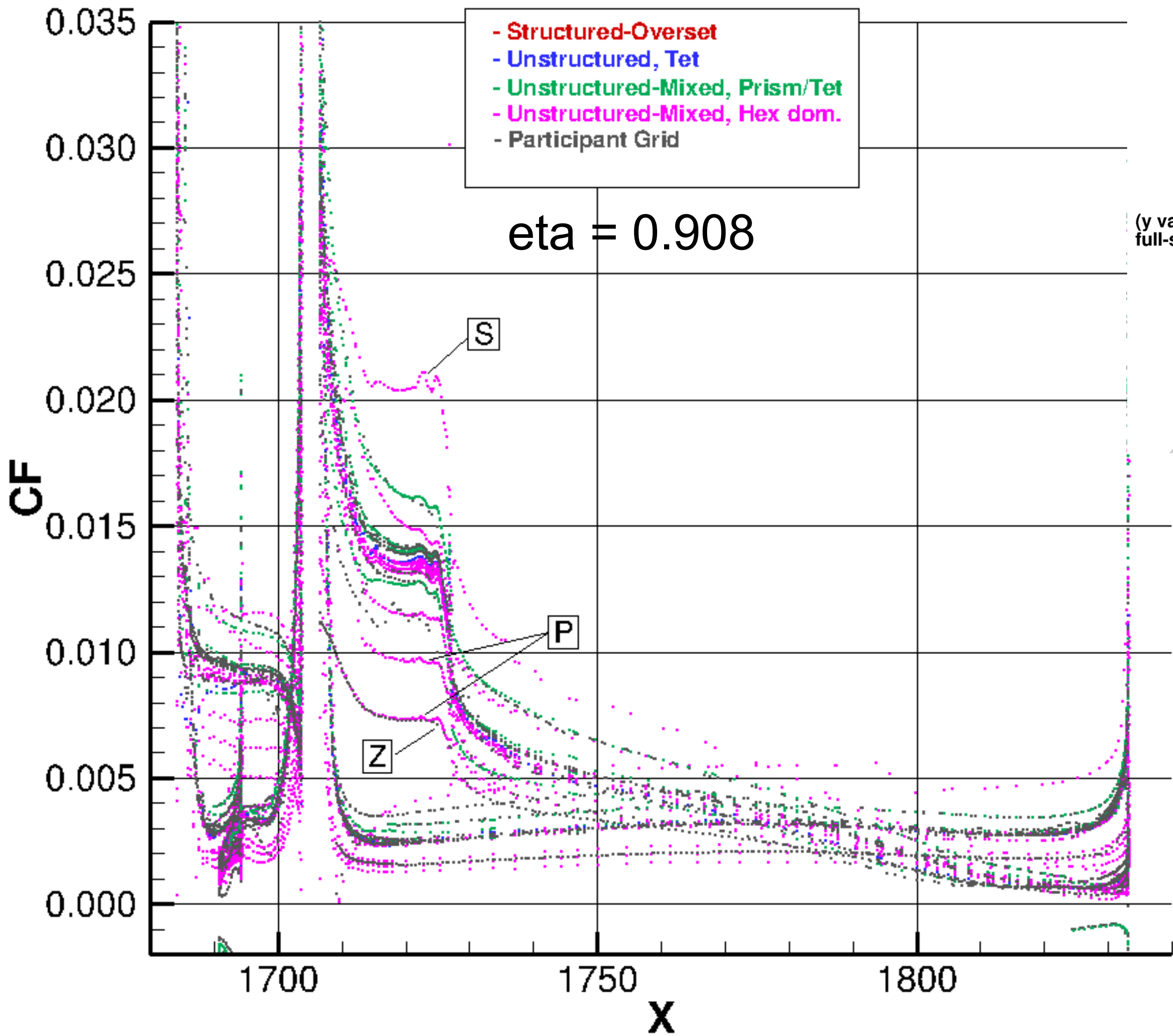


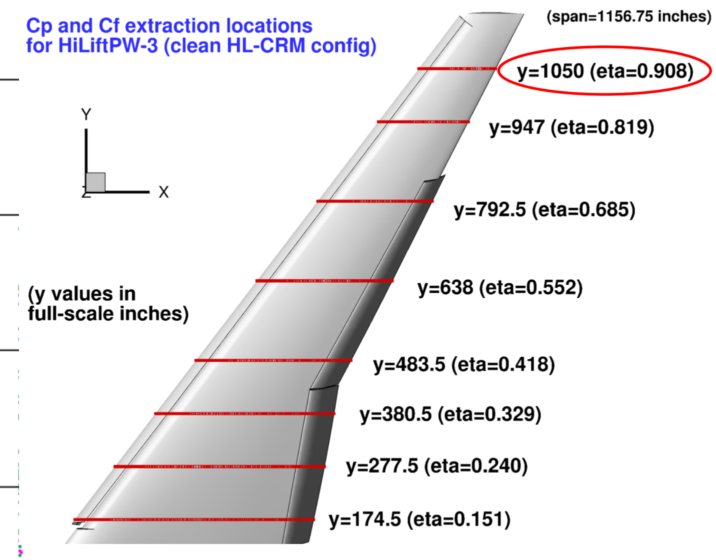
- Variation in skin friction is considerably larger than pressure variation
- Datasets Z, P, b and S represent the extremes for the wing

Note: The Z data are for a Reynolds number of 32.6 million instead of 3.26 million

Skin Friction – Case 1a, Med, 16°

CFD High Lift Prediction Workshop





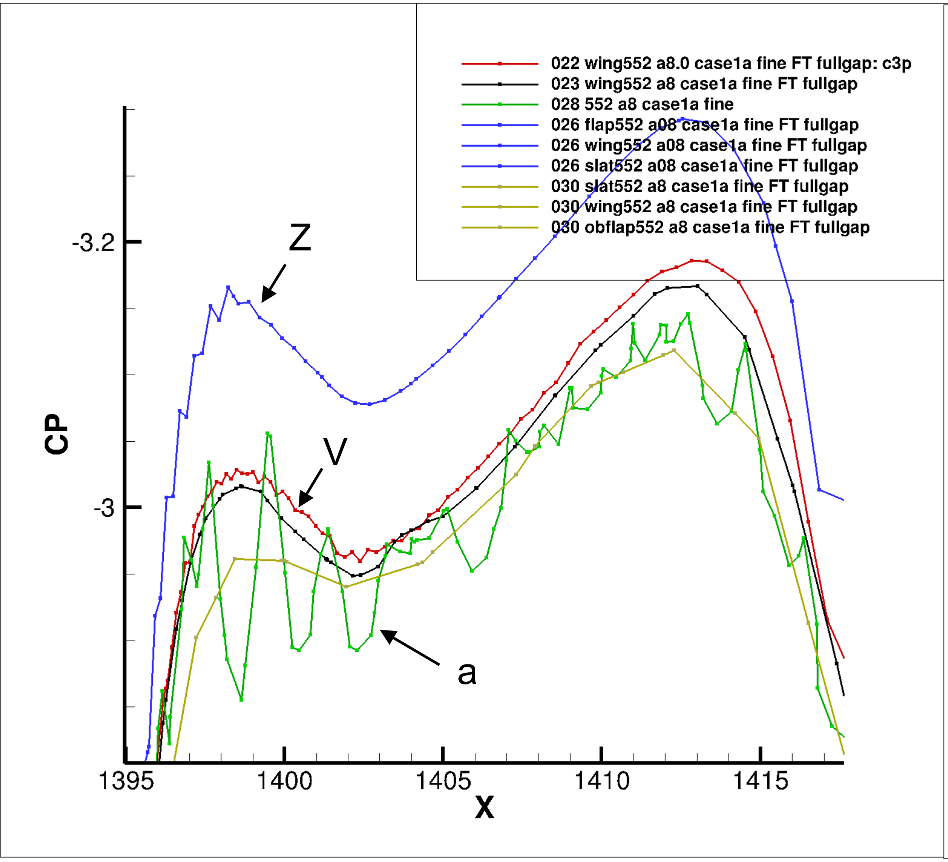
- Variation in skin friction is considerably larger than pressure variation
- Datasets Z, P and S represent the extremes for the wing

Note: The Z data are for a Reynolds number of 32.6 million instead of 3.26 million

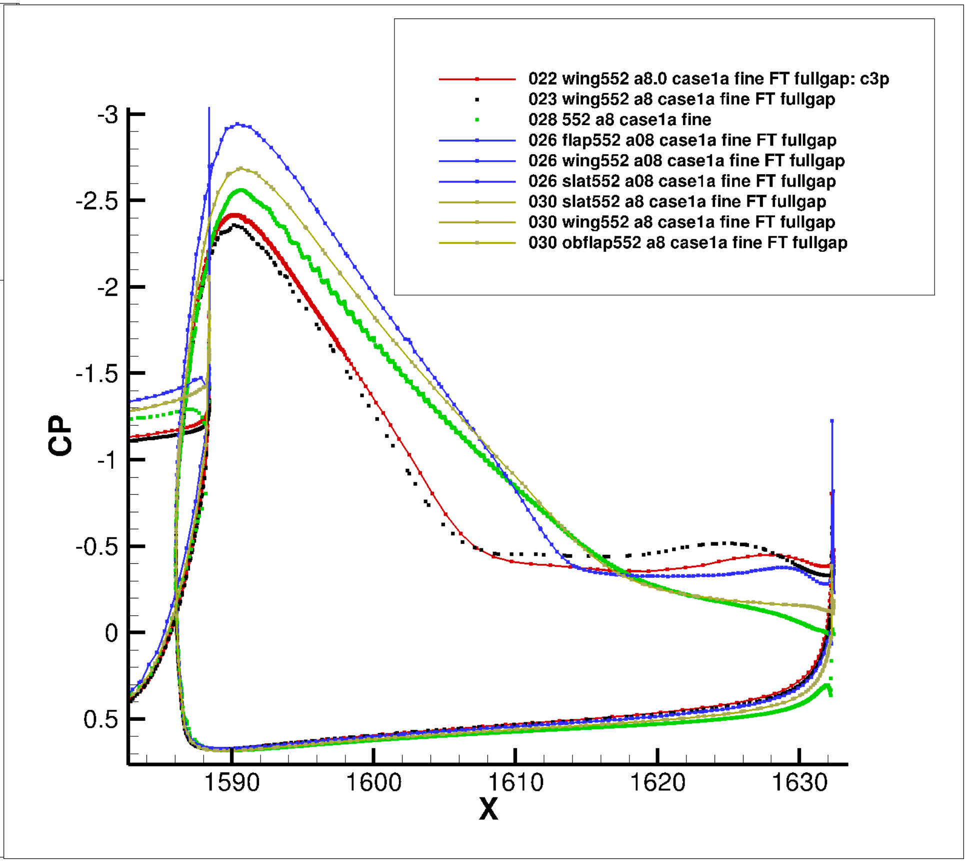
Case 1a, Fine, 8˚

CFD High Lift Prediction Workshop

Wing LE, Upper



Flap



- Irregular Cp distributions on wing and flap suggest surface curvature issues

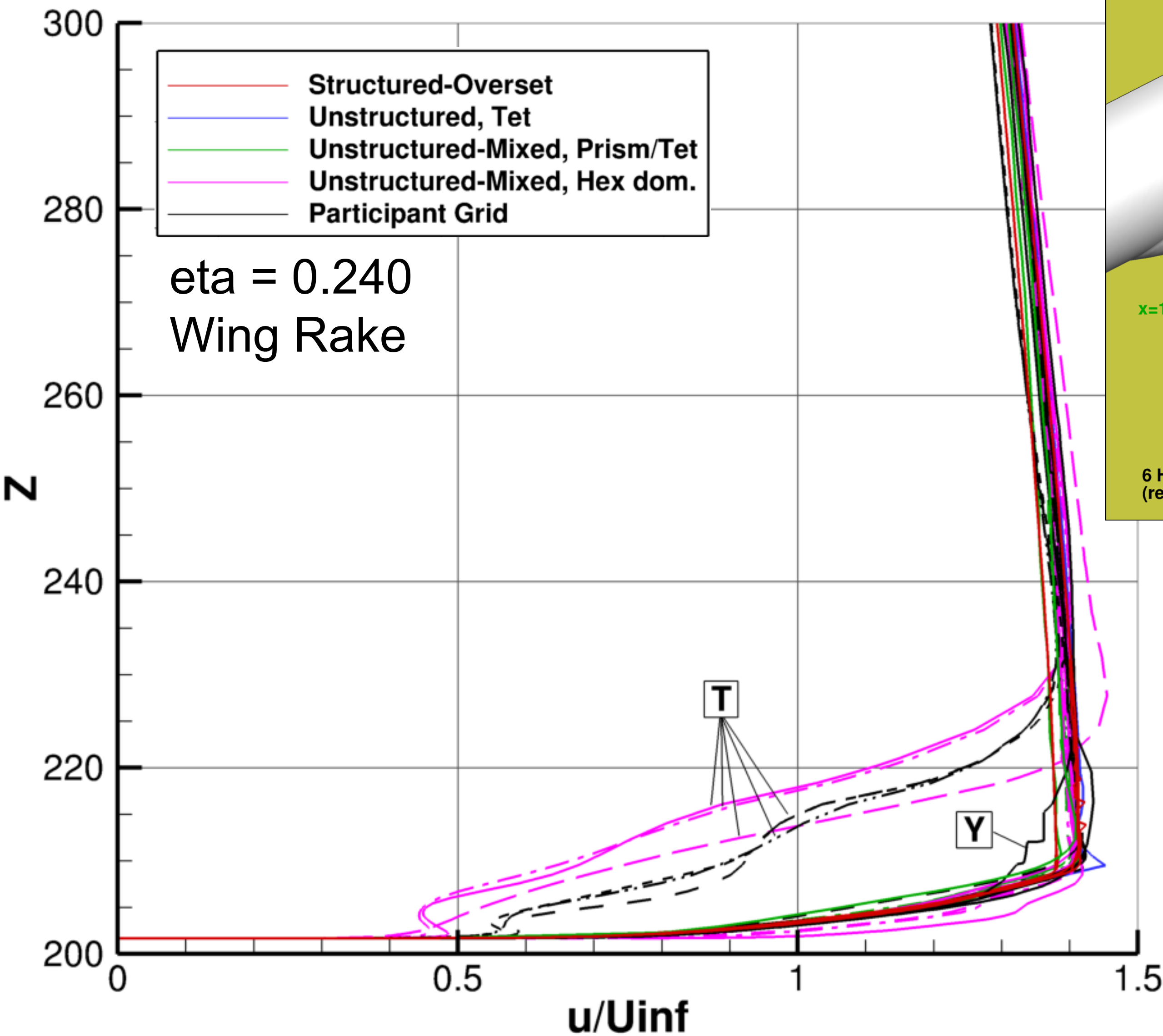
Case 1: Grid Convergence Study

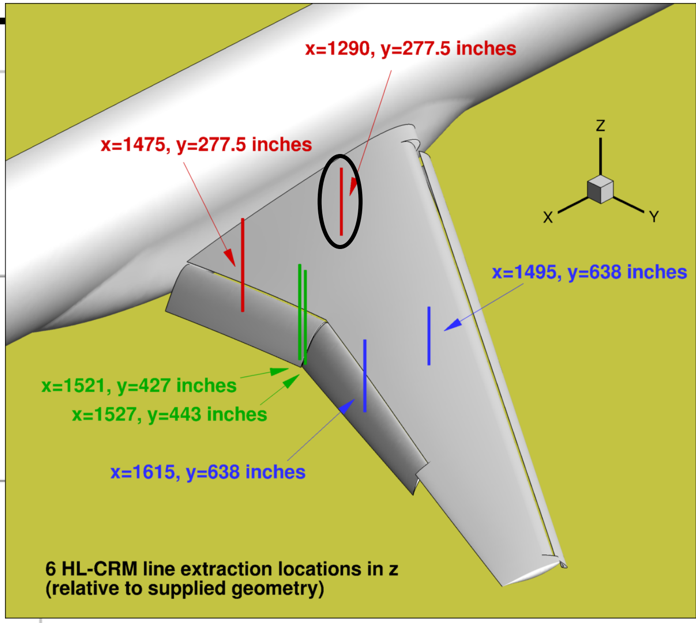
Outline

- Case Description
- Grid Families
- Participant List
- Results
  - Overview
  - Iterative Convergence
  - Lift, Drag and Pitching Moment
  - Pressures and Skin Friction
  - Velocity Profiles
- Conclusions

Vel Profile 1 – Case 1a, Med, 16°

CFD High Lift Prediction Workshop

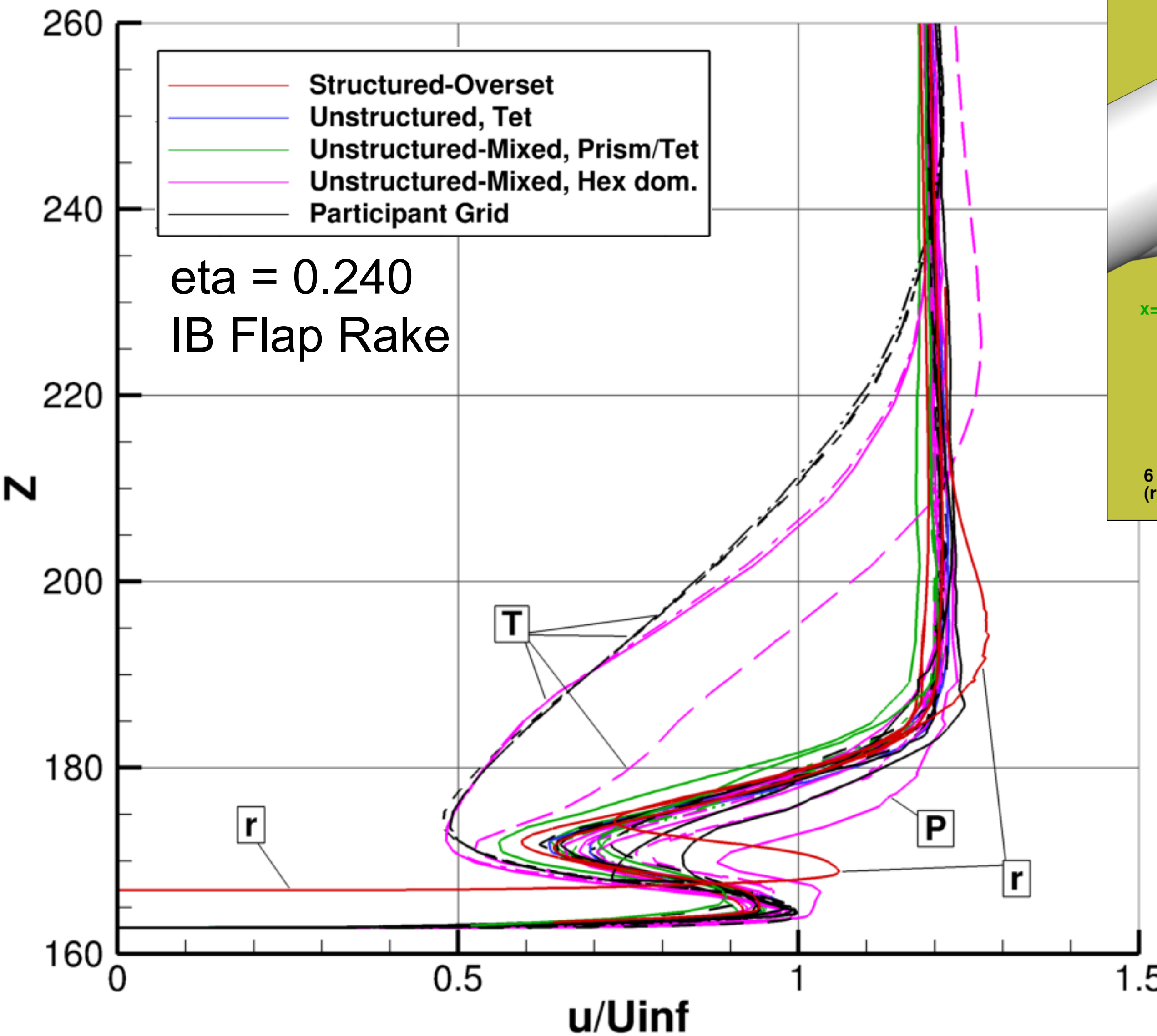


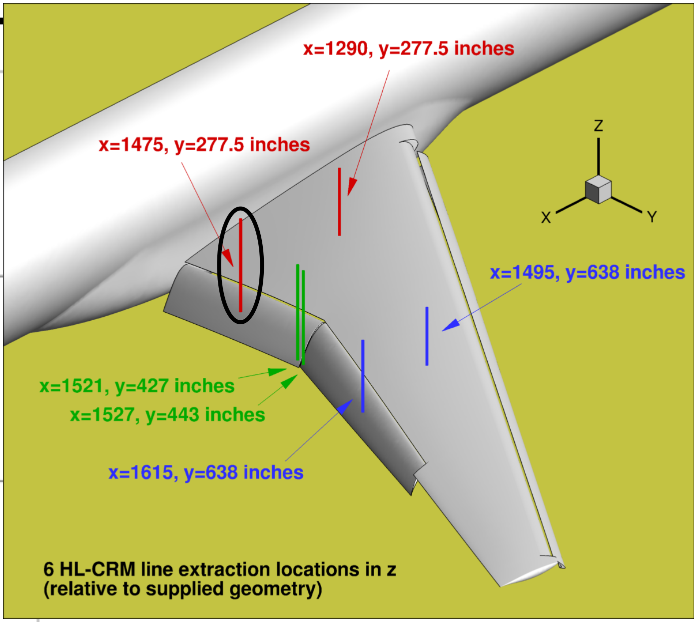


- Comparison covers 100” off surface (36% of Cref)
- Dataset T profiles show flow deceleration (slat wake?) near the surface where others do not

Vel Profile 2 – Case 1a, Med, 16°

CFD High Lift Prediction Workshop

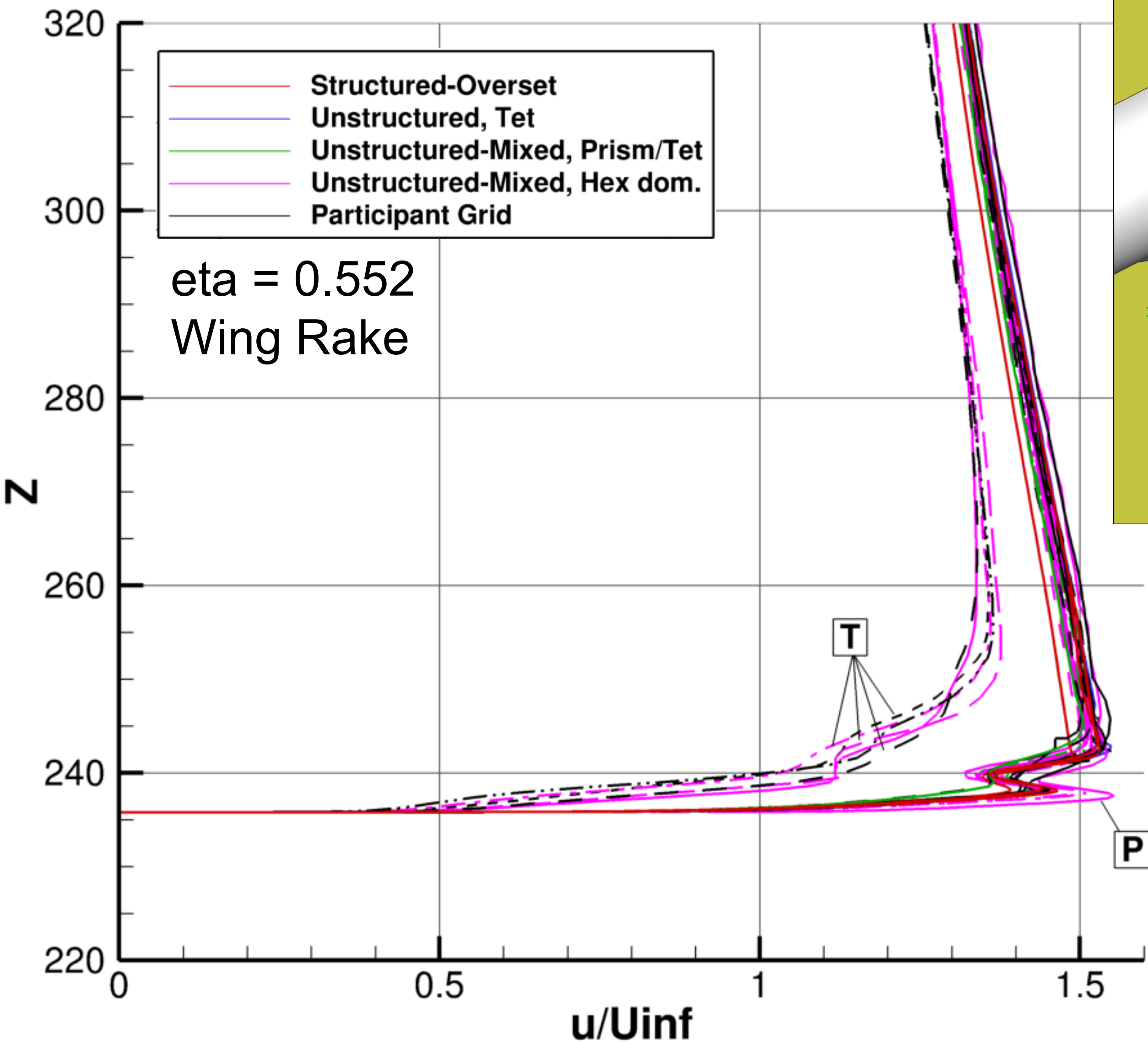


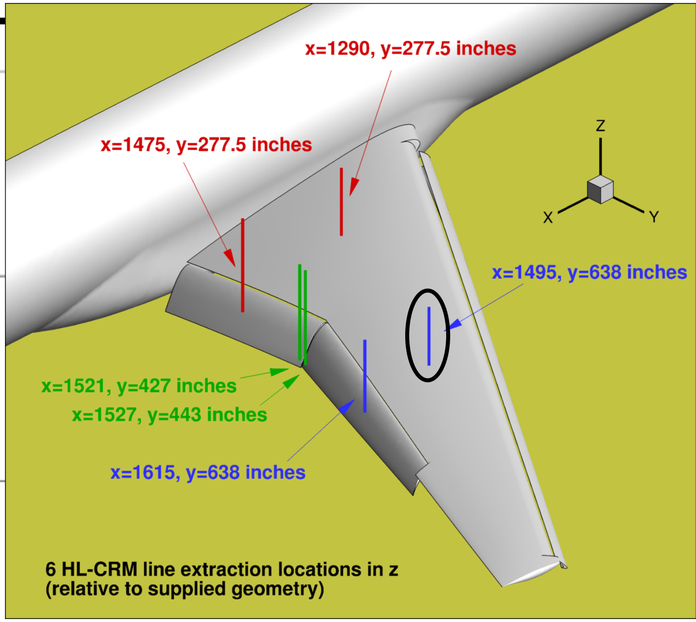


- Comparison covers 100" off surface (36% of Cref)
- Dataset r appears to be offset
- Datasets P and T represent wing BL and wake profile extremes

Vel Profile 5 – Case 1a, Med, 16°

CFD High Lift Prediction Workshop

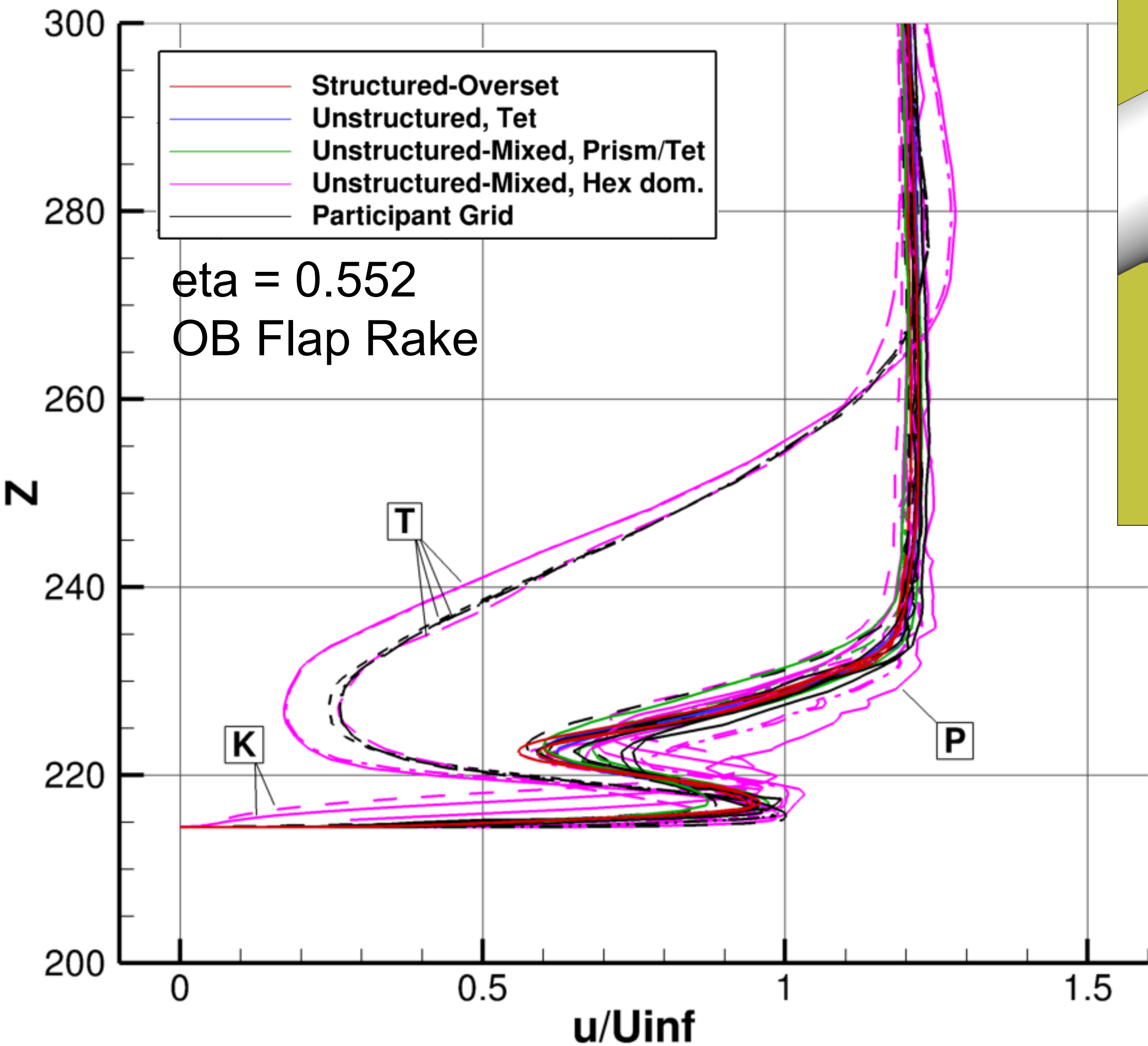


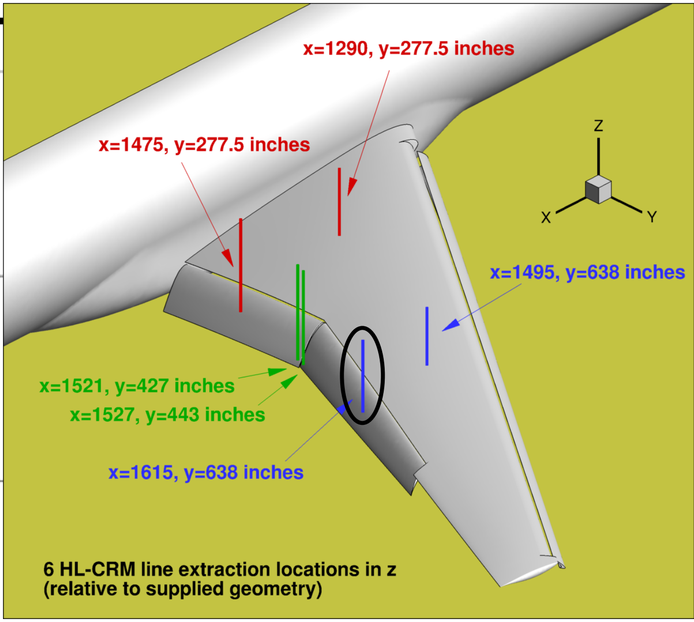


- Comparison covers 100” off surface (36% of Cref)
- Datasets P and T represent wing BL profile extremes

Vel Profile 6 – Case 1a, Med, 16˚

CFD High Lift Prediction Workshop

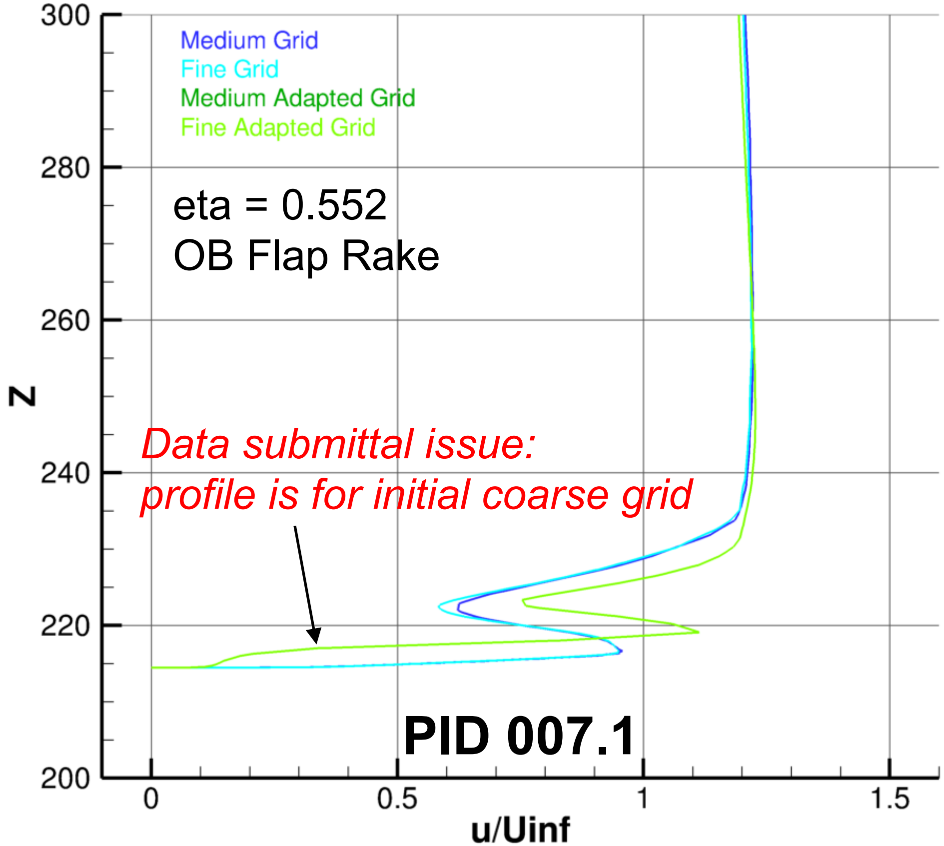


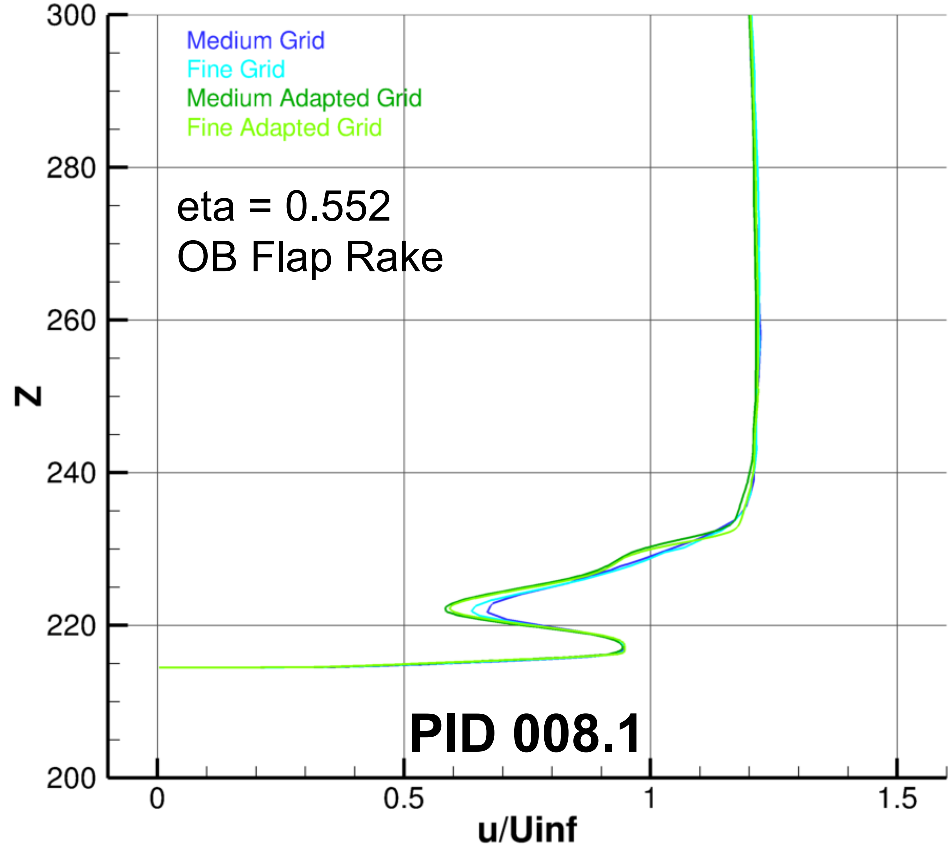


- Comparison covers 100" off surface (36% of Cref)
- Dataset K shows extreme flap BL profile near surface
- Datasets P and T represent profile extremes away from flap surface

Vel Profile 6 – Case 1a/b, 16°

CFD High Lift Prediction Workshop





007.1 Committee Grid → B1, Tetrahedral

- Nodes: 26M for Medium Grid
  70M for Fine Grid
- Cells: 157M for Medium Grid
  416M for Fine Grid

008.1 Committee Grid → B3, Mixed (hex)

- Nodes: 27M for Medium Grid
  71M for Fine Grid
- Cells: 48M for Medium Grid
  119M for Fine Grid

Conclusions

Lift convergence looks reasonable for most datasets

Grid Convergence Plots:

- Relatively large variation in lift level in the Medium Grid range
- Data scatter increases with angle-of-attack
- After removing outliers, lift variation improved substantially

$C_L/C_D/C_M$ increments due to partial chord flap seal are consistent

No clear data trends due to grid type or turbulence model

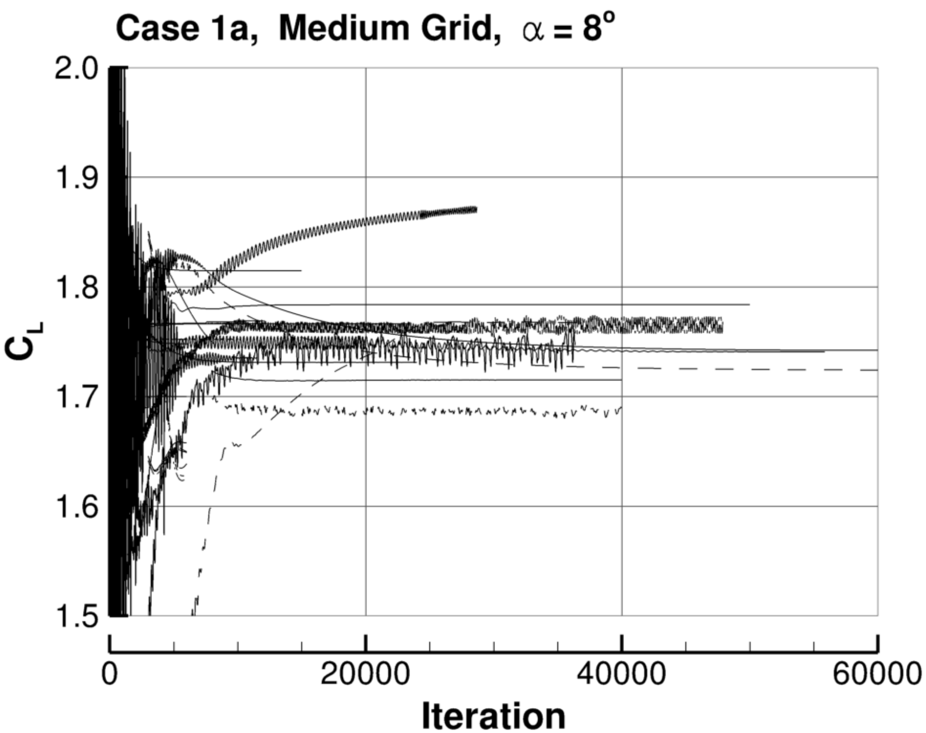
Pressure, skin friction and velocity data helpful in identifying potential outliers

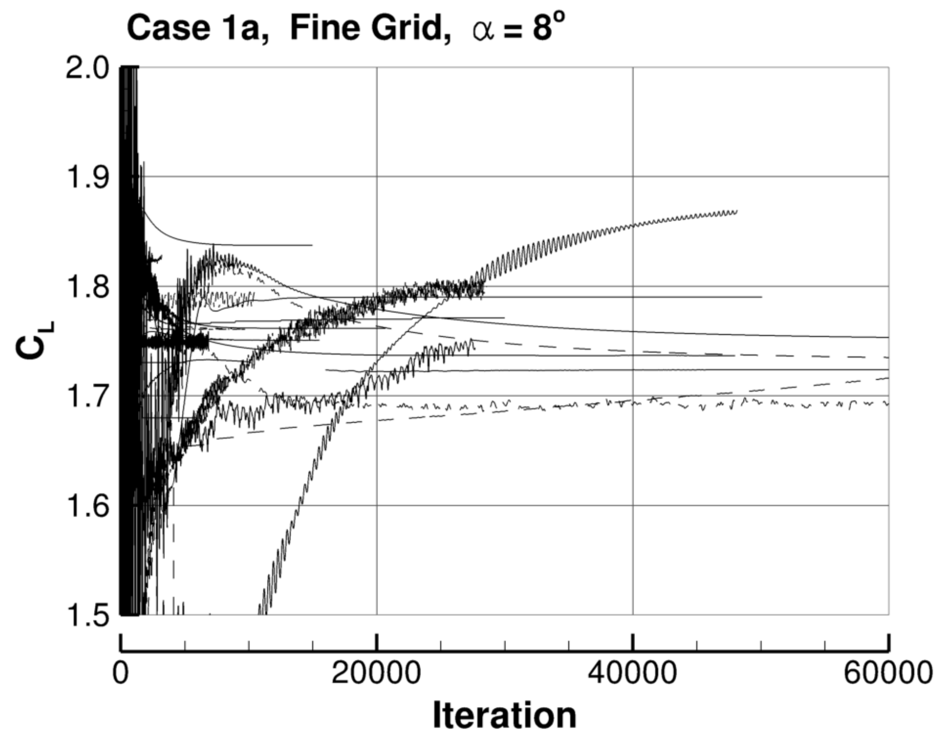
Irregular pressure distribution on wing and flap suggest surface curvature issues

Back-Up

Lift Convergence: Grid Effect

CFD High Lift Prediction Workshop

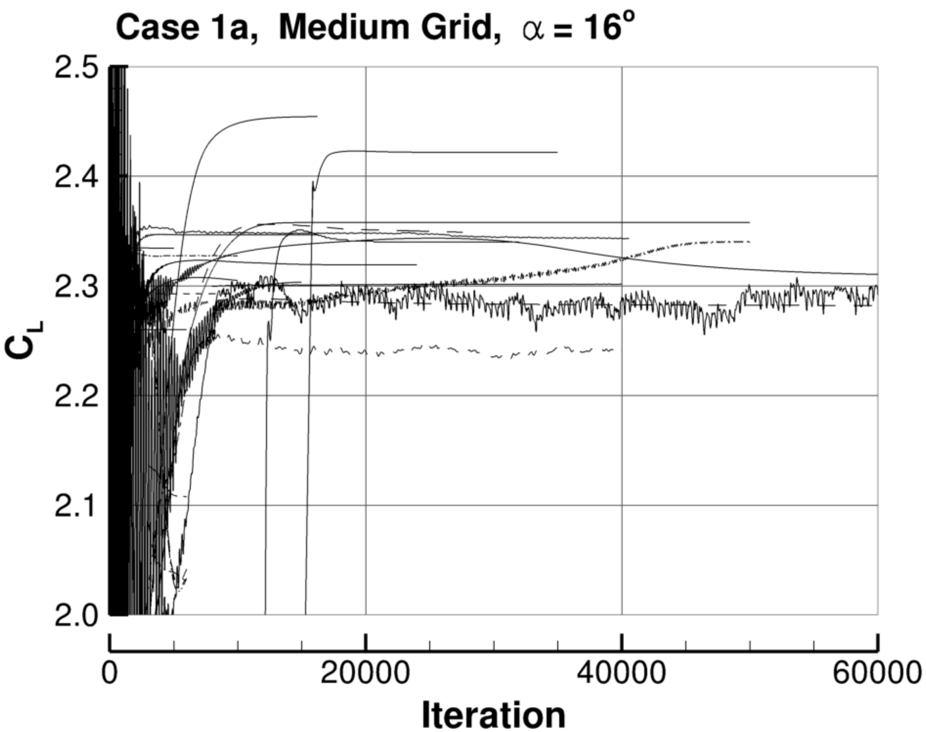


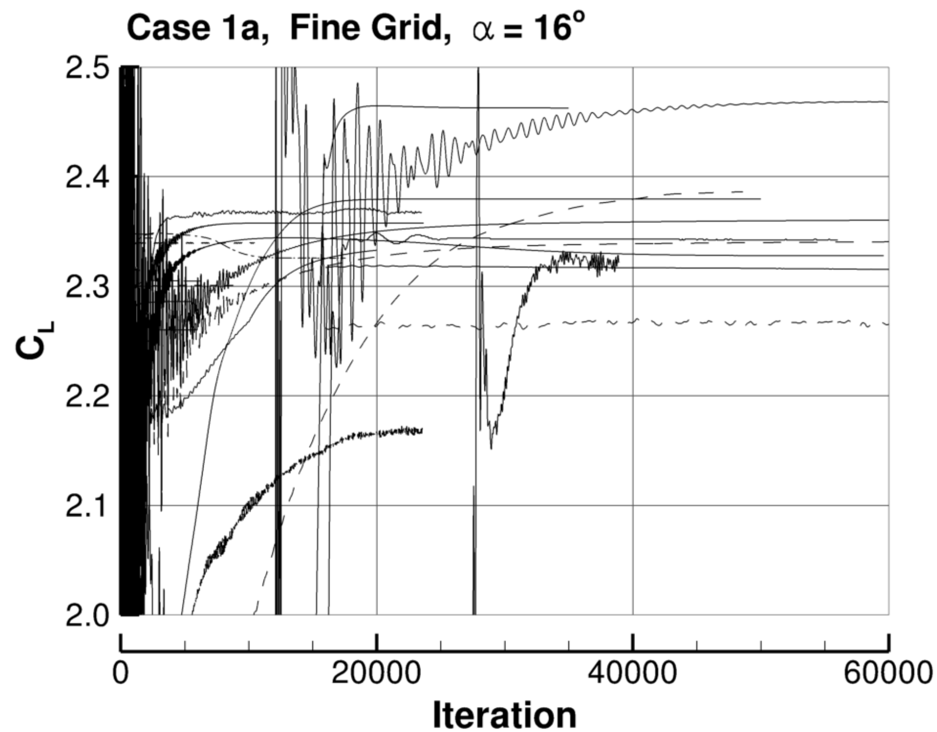


- Lift convergence at 8° looks similar for the Medium and Fine Grids
- Need to plot Normalized Iteration and include labels to comment further

Lift Convergence: Grid Effect

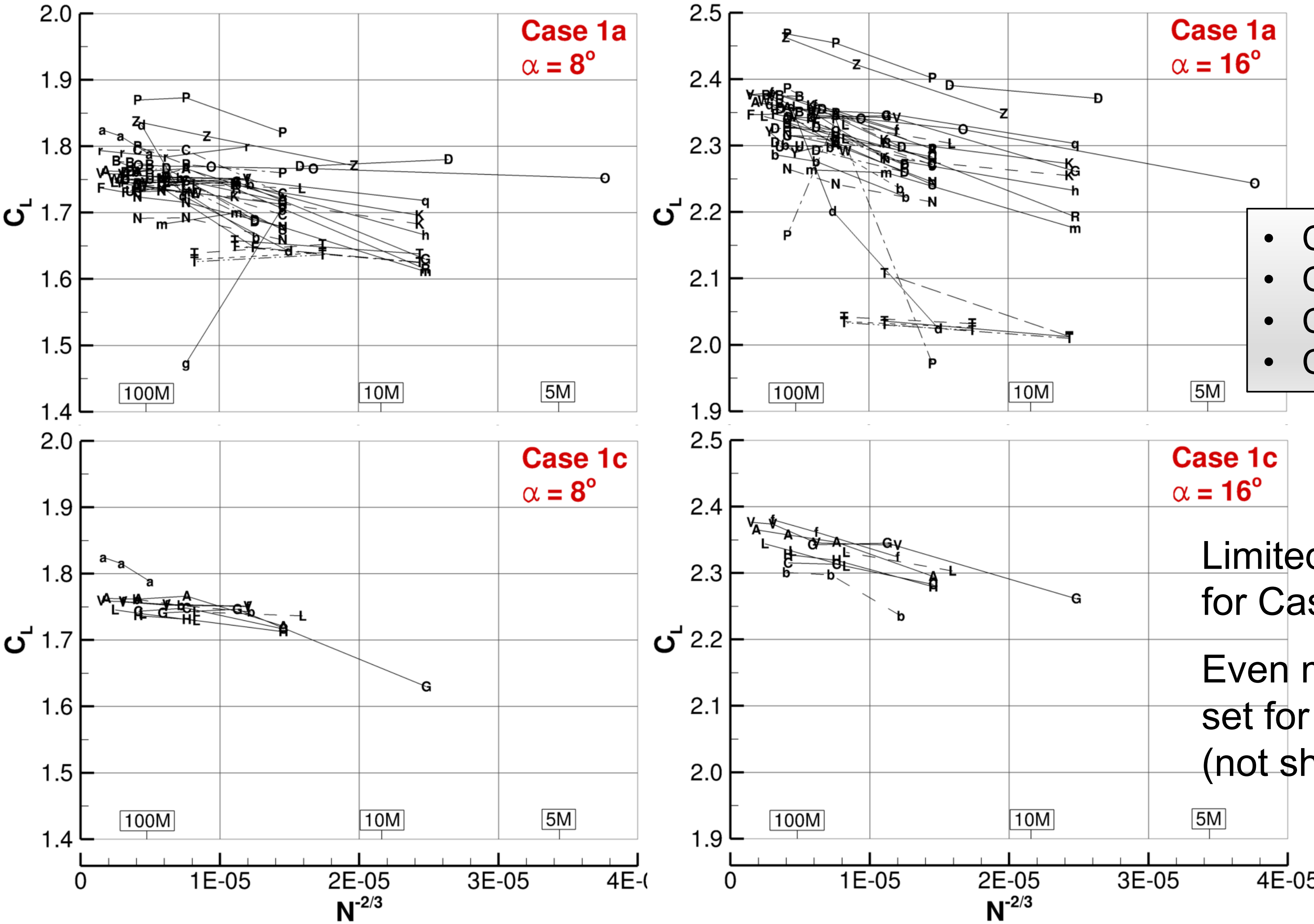
CFD High Lift Prediction Workshop





- Lift convergence at 16° looks similar for the Medium and Fine Grids
- Need to plot Normalized Iteration and include labels to comment further

Lift – Case 1a vs. 1c



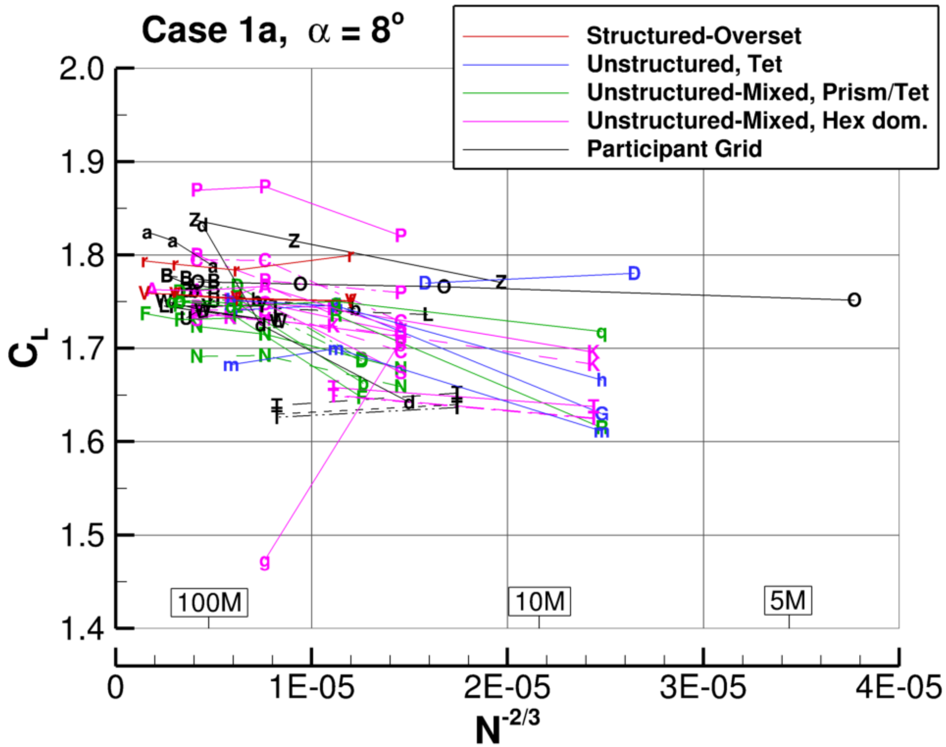
- Case 1a =46
- Case 1b = 2
- Case 1c = 10
- Case 1d = 2

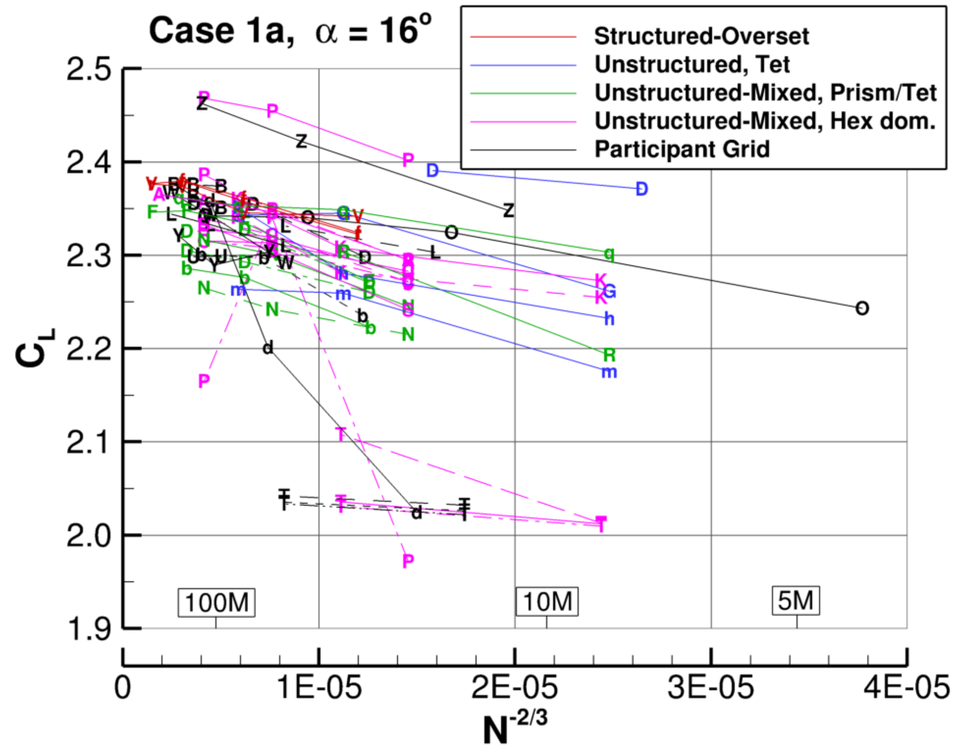
Limited set of data for Case 1c

Even more limited set for Case 1b/d (not shown)

Case 1a Sorted by Grid Type

CFD High Lift Prediction Workshop



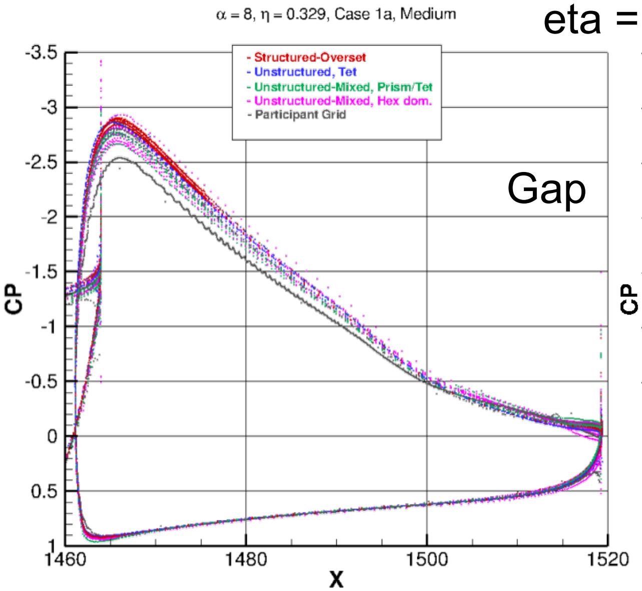


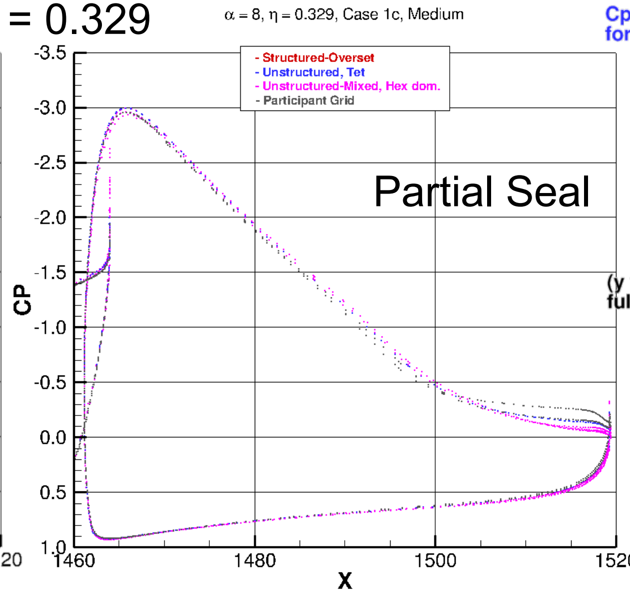
- Does not appear to be unique groupings or trends due to grid type

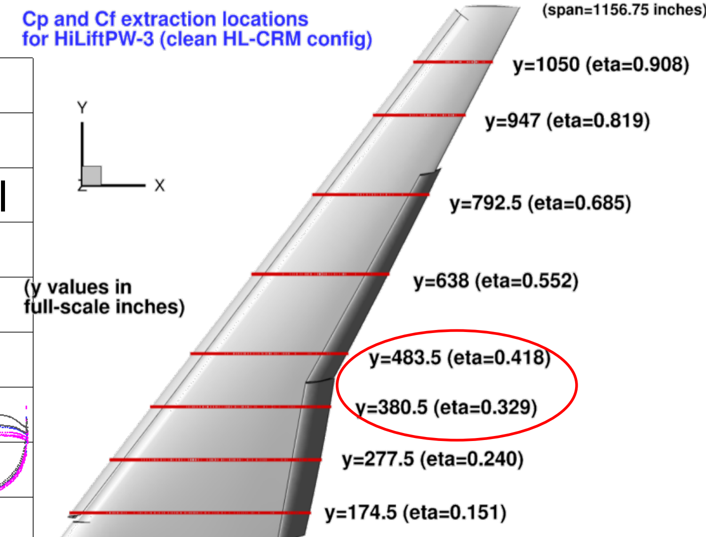
Flap Pressures – Case 1a, Med, 8°

CFD High Lift Prediction Workshop

eta = 0.329







eta = 0.418