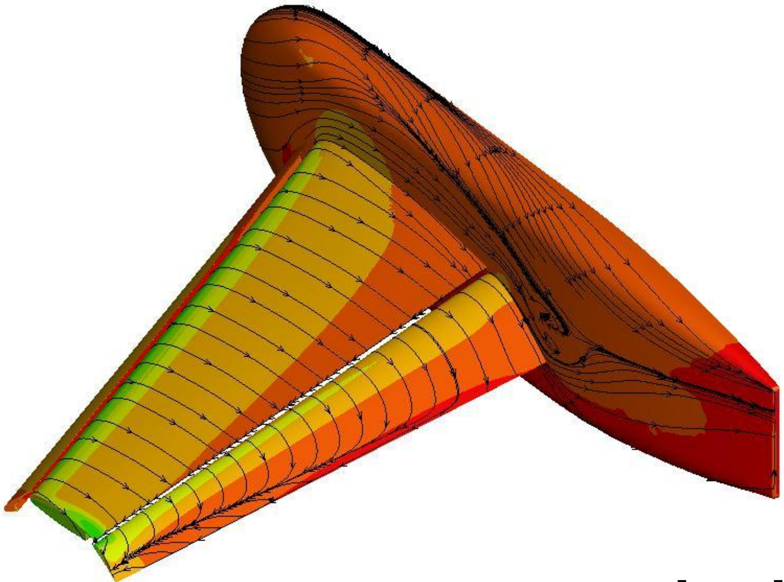


CFD High Lift Prediction Workshop

Workshop Summary

1st AIAA CFD High Lift Prediction Workshop (HiLiftPW-1)

Chris Rumsey (NASA LaRC) & Jeffrey Slotnick (Boeing)

Overview

- Open, two-day workshop focusing on CFD simulation using the NASA Trap Wing high-lift model
  – Held June 26-27, 2010, Chicago, IL
  – In conjunction with 28th AIAA Applied Aerodynamics Conference
  – Over 70 attendees
- Objectives:
  – Assess the numerical prediction capability (meshing, numerics, turbulence modeling, high-performance computing requirements, etc.) of current-generation CFD technology/codes for swept, medium/high-aspect ratio wings in landing/take-off (high-lift) configurations
  – Develop practical modeling guidelines for CFD prediction of high-lift flowfields
  – Advance the understanding of high-lift flow physics to enable development of more accurate prediction methods and tools
  – Enhance CFD prediction capability to enable practical high-lift aerodynamic design and optimization

HiLiftPW-1 Organizing Committee

CFD High Lift Prediction Workshop

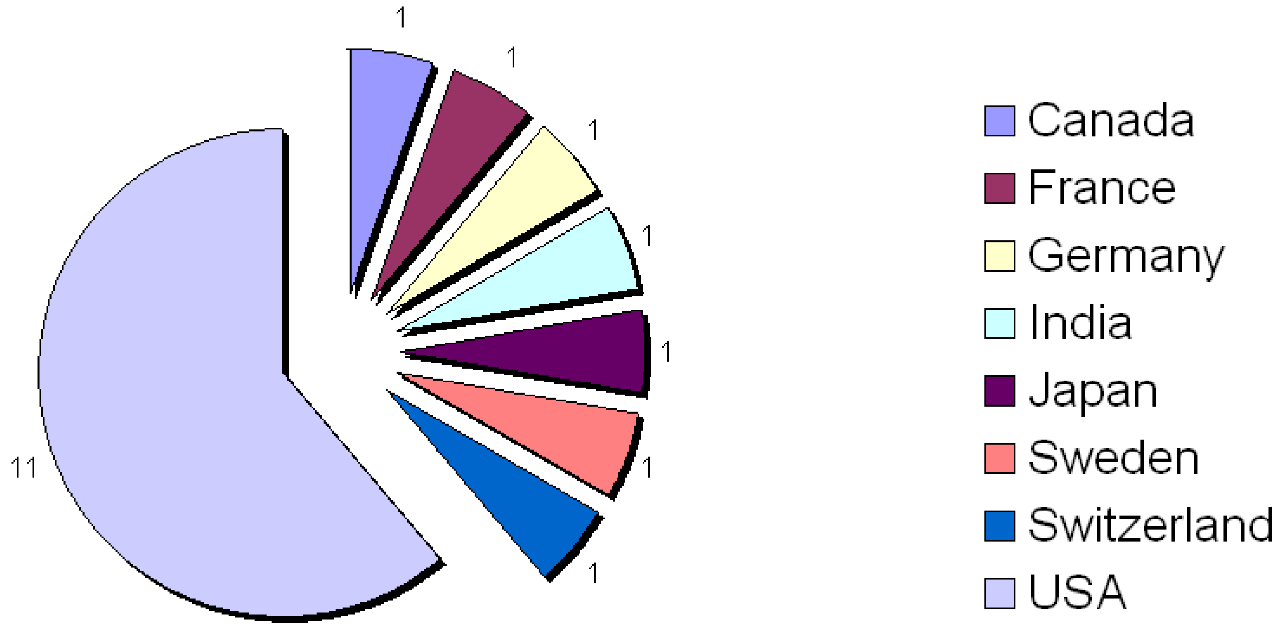
- **Jeffrey Slotnick (chair) and Tony Sclafani**
  The Boeing Company
- **Rob Lotz**
  CD-adapco
- **Mark Chaffin and David Levy***
  Cessna Aircraft Company
- **Ralf Rudnik**
  DLR – German Aerospace Center
- **Thomas Wayman**
  Gulfstream Aerospace Corporation
- **Bob Stuever and Chittur "Venkat" Venkatasubban**
  Hawker Beechcraft Corporation
- **Judi Hannon and Chris Rumsey**
  NASA Langley Research Center
- **Dimitri Mavriplis***
  University of Wyoming

*** also DPW organizing committee member**

Participant Statistics

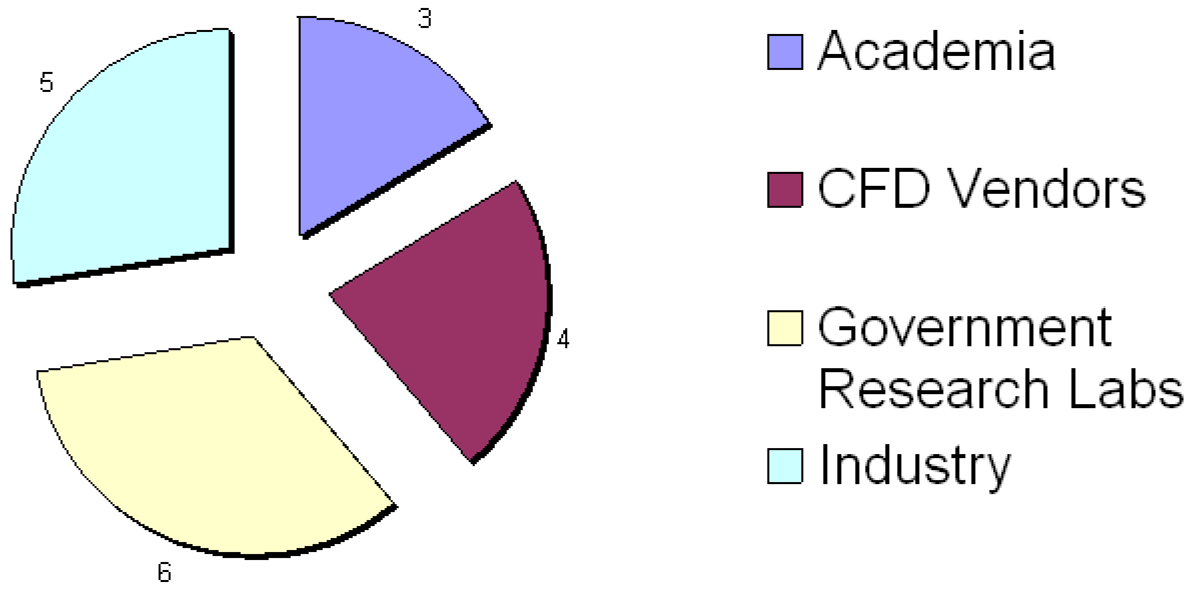
CFD High Lift Prediction Workshop

- **21** total participants (**35** total datasets)
- **18** individual organizations from **8** countries
- **~40%** non-US participation



Participant Statistics (2)

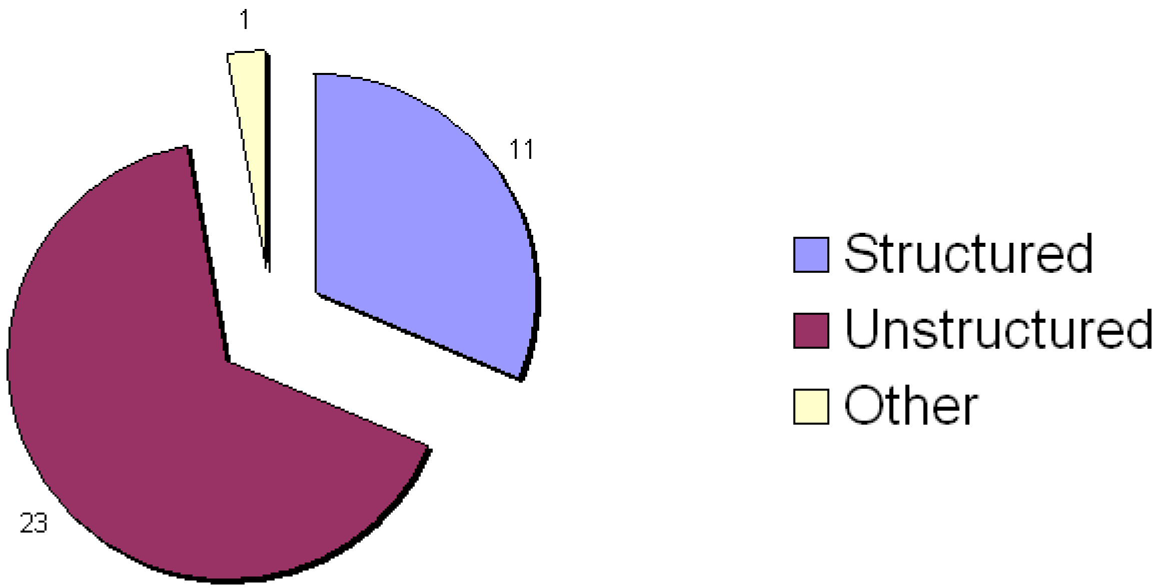
- Broad participation from aerospace community



Participant Statistics (3)

CFD High Lift Prediction Workshop

- Most participants used unstructured mesh CFD tools and processes



Trap Wing Geometry

- b/2 = 85.1”
- MAC = 39.6”
- AR = 4.56
- Λ_{le} = 33.9 deg
- $\Lambda_{c/4}$ = 30.0 deg
- taper ratio = 0.4

- original model was a horizontal tail (pre Trap Wing)

- 700 - 800 pressure orifices
- All pressure tubing runs through slat and flap brackets
- Standoff with labryinth seal
- Transition location was not fixed

Trap Wing Configuration

- Full-span flap configuration analyzed at 2 flap settings
- Differences between wind tunnel experiments and CFD:

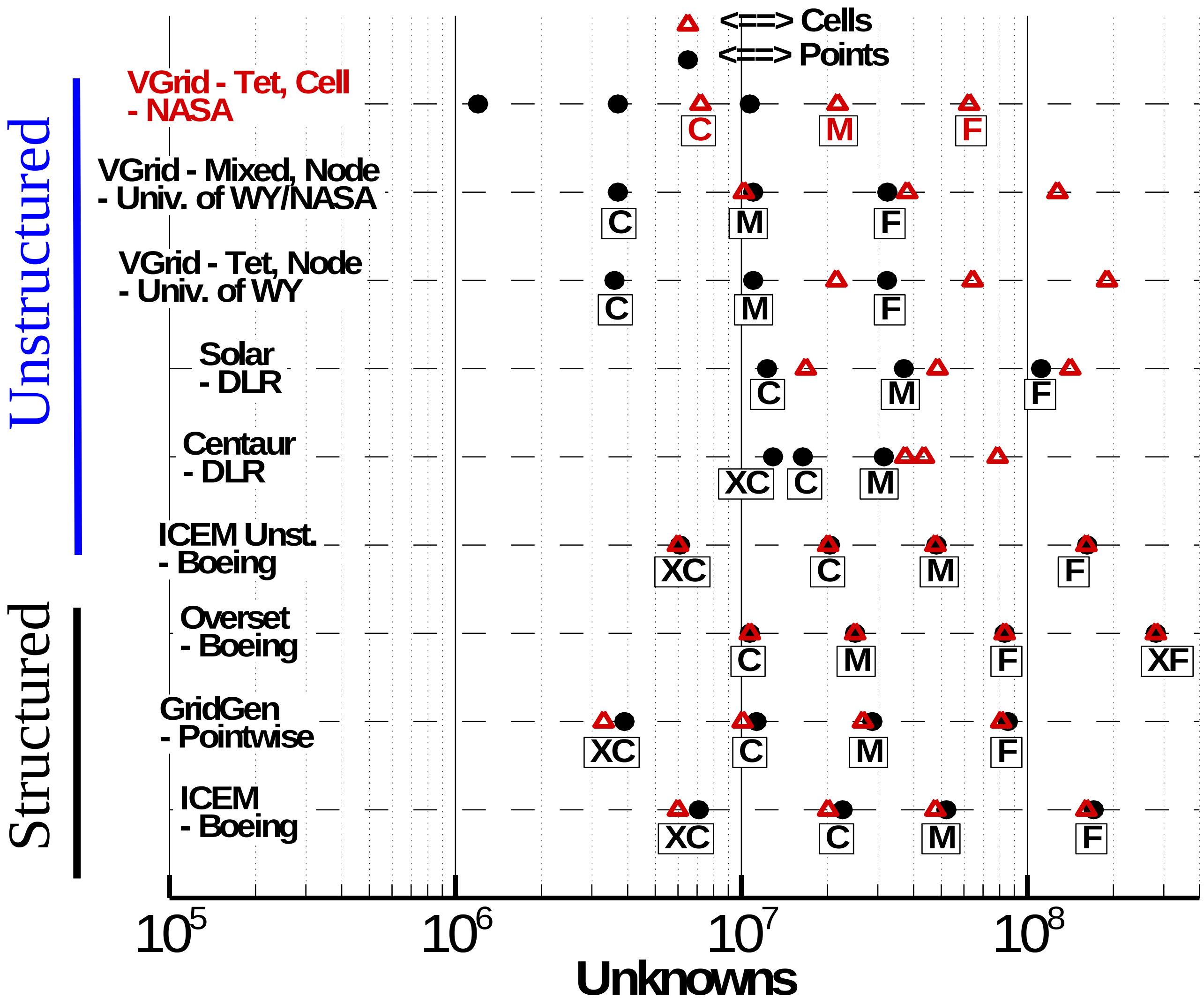
Experiments	CFD
Tunnel walls with correction to free air	Free air
Laminar/transitional/turbulent flow	Fully turbulent
Brackets	No brackets (except optional case 3)

Test Cases

- **Test Case 1 – Grid Convergence Study**
  - Trap Wing “Config 1” (Slat 30, Flap 25)
  - Mach = 0.2, α = 13 , 28
  - Re = 4.3M (based on MAC)
  - Tinf = 520°R
  - Coarse, Medium, Fine, Extra-Fine grids
- **Test Case 2 – Alpha Sweep, Flap Increments**
  - Trap Wing “Config 1” (Slat 30, Flap 25)
  - Trap Wing “Config 8” (Slat 30, Flap 20)
  - Mach = 0.2, α = 6 , 13 , 21 , 28 , 32 , 34 , 37
  - Medium Grid
- **Test Case 3 – Slat/Flap Support Effects**
  - Trap Wing “Config 1” (Slat 30, Flap 25)
  - Mach = 0.2, α = 13 , 28
  - Medium Grid

Blue = OPTIONAL

Grid Sizes



XC = extra-coarse
C = coarse
M = medium
F = fine
XF = extra-fine

(There were also other grids created by participants, not listed here)

Summary of Entries (35 total)

CFD High Lift Prediction Workshop

	001	002	003.01	003.02	004	005.01	005.02	006	007	008.01	008.02	008.03	009	010	011	012.01	012.02	013.01	013.02	013.03	014.01	014.02	014.03	015	016	017.01	017.02	017.03	017.04	018	019	020.01	020.02	021.01	021.02
Code	CFX	CFD++	OVER	OVER	HIFUN	FUN3D	NSU3D	FUN3D	TAU	TAU	TAU	TAU	POWER	EDGE	NSU3D	TAS	UPACS	CFD++	CFD++	CFD++	OVER	OVER	OVER	USM3D	FUN3D	FUN3D	CFL3D	CFL3D	CFL3D	ELSA	NSMB	USM3D	USM3D	NSU3D	NSU3D
Type	N	C	N	N	C	N	N	N	N	N	N	N	B	N	N	N	C	C	C	C	N	N	N	C	N	N	C	C	C	C	C	C	C	N	N
Grid	UX 9	UH	SX 3	SX 3	UH	UH 6	UH 6	UT 5	UH 8	UH 7	UH 7	UH 7	CB	UH 8	UH	UH	SX	UT 5	UT 5	UX 9	SX 3	SX 3	SX 3	UT 4	UT 5	UH 6	SX 1	SX 1	SX 2	SX 1	SX	UT 4	UT 4	UH 6	UH 6
Turb	SST*	KE*	SA	SA	SA	SA	SA	SA	SA	SA	SST	RSM	VLES	SA	SA	SA*	SA*	SA	KE*	KE*	SA	SA	SA	SA	SA	SA	SST	SA	SST	SA	SST	KO	KO*	SA	SST
Notes	Trans-ition model used			brackets off on bracket-like grid			Thin each direc						Trans-ition model used		Thin each direc			Used node-center grids	Used node-center grids		Roe	HLLC	Central				Thin each direc	Thin each direc	Thin each direc					Thin each direc	Thin each direc

N=node-centered
C=cell-centered
B=Boltzmann

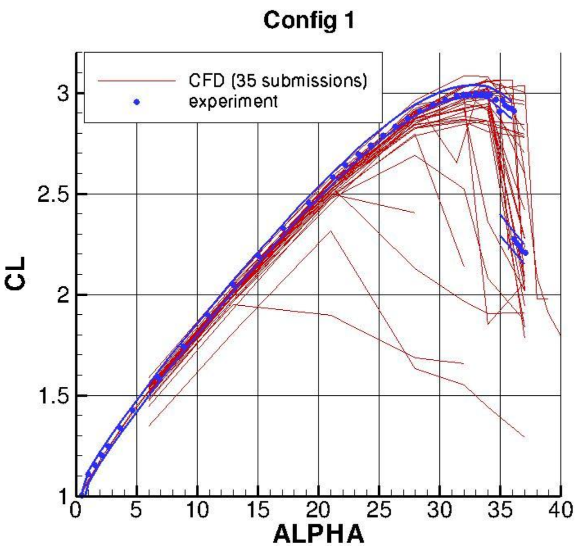
SX=Structured
UX=Unstructured hex
UT=Unstructured tet
UH=Unstructured hybrid
CB=Cartesian based

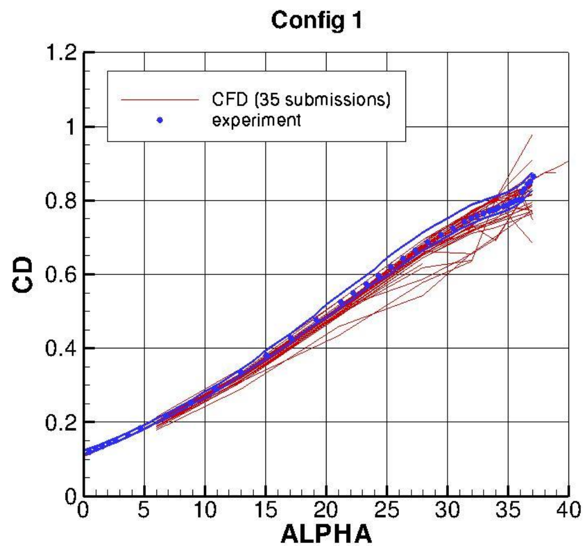
1=Str point-matched A
2=Str point-matched B
3=Str overset A
4=Unstr tet cell-center A
5=Unstr tet node-center A
6=Unstr hybrid (merged from 5)
7=Unstr hybrid node-center A
8=Unstr hybrid node-center B
9=Unst hex (from 1)

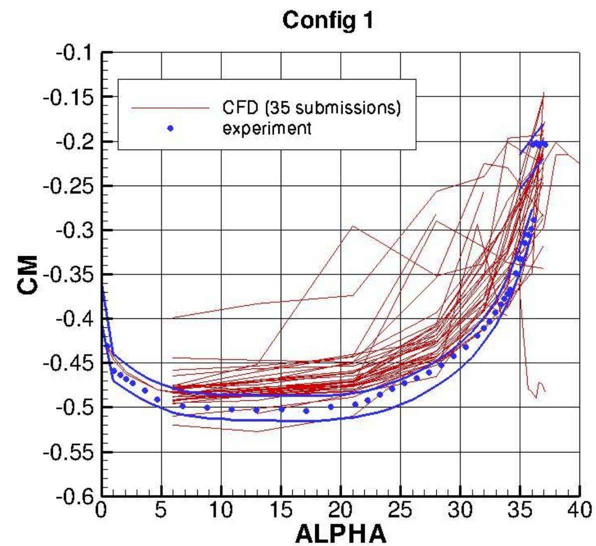
SA=Spalart-Allmaras
SST=Menter Shear Stress Transport
KE=K-Epsilon
VLES=Very Large Eddy Simulation
RSM=Reynolds Stress Model
KO=Wilcox K-Omega
* = modified in some way

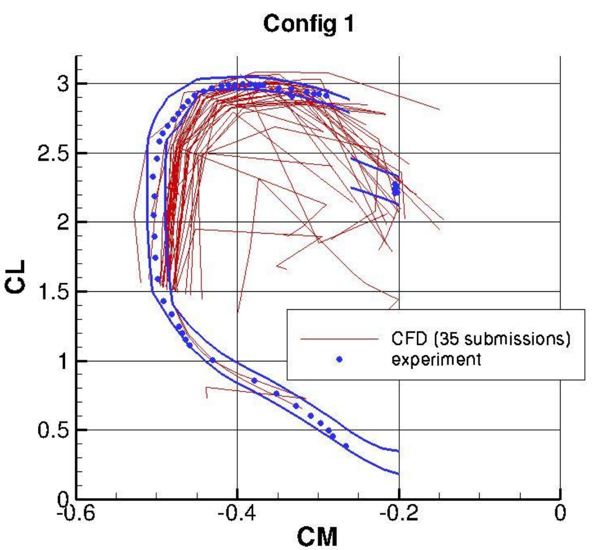
Overall View of CFD & Experiment

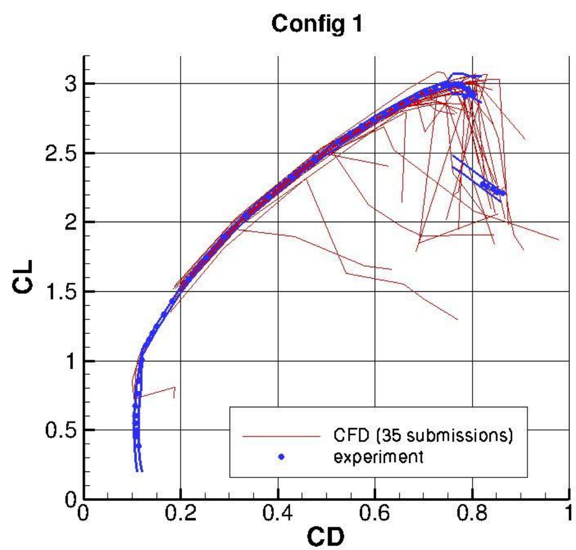
CFD High Lift Prediction Workshop







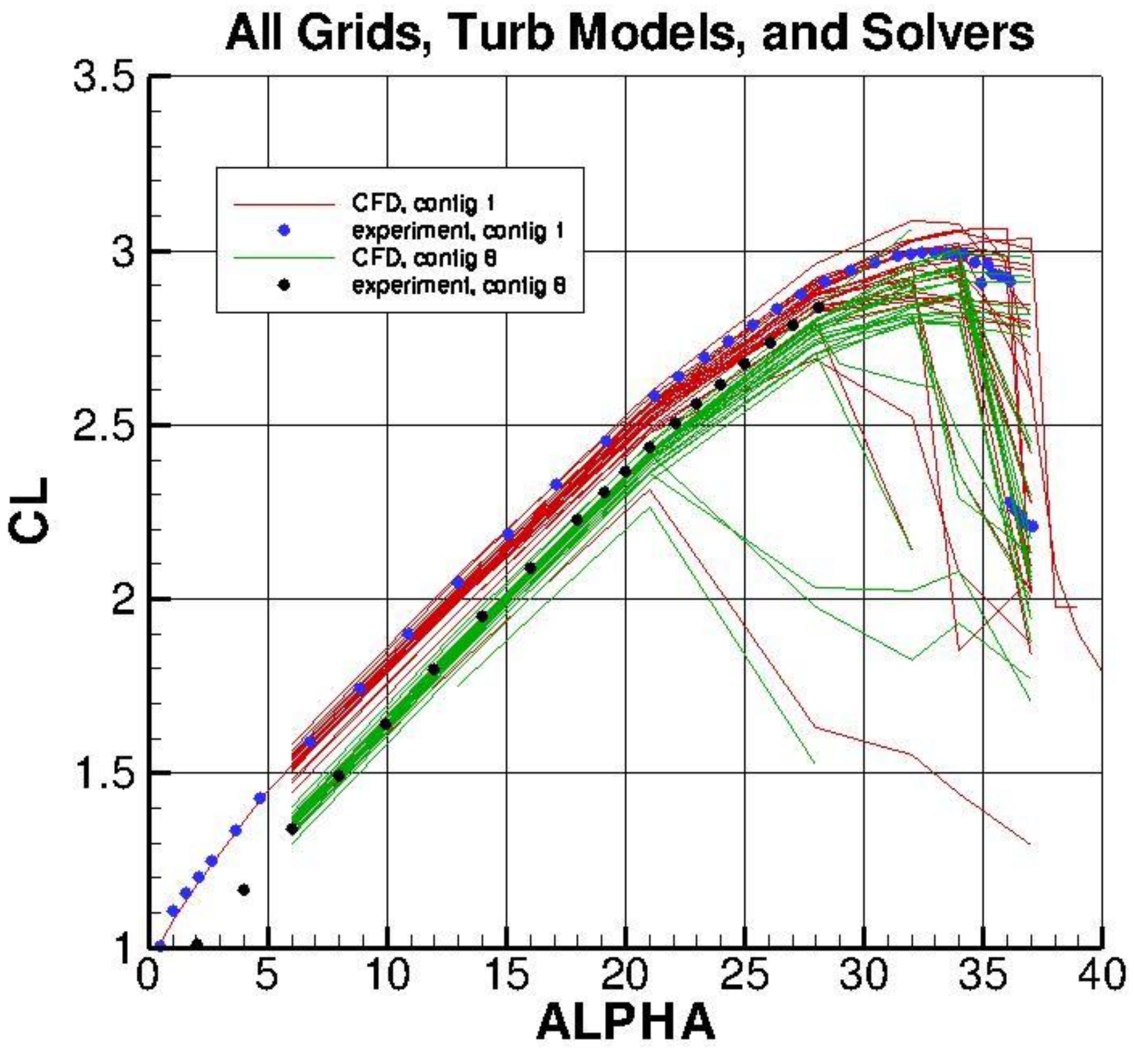




Collectively, CFD tended to yield too-low lift, too-low drag, too-high moment (on Medium-level grid)

Config 1 vs. Config 8

CFD High Lift Prediction Workshop

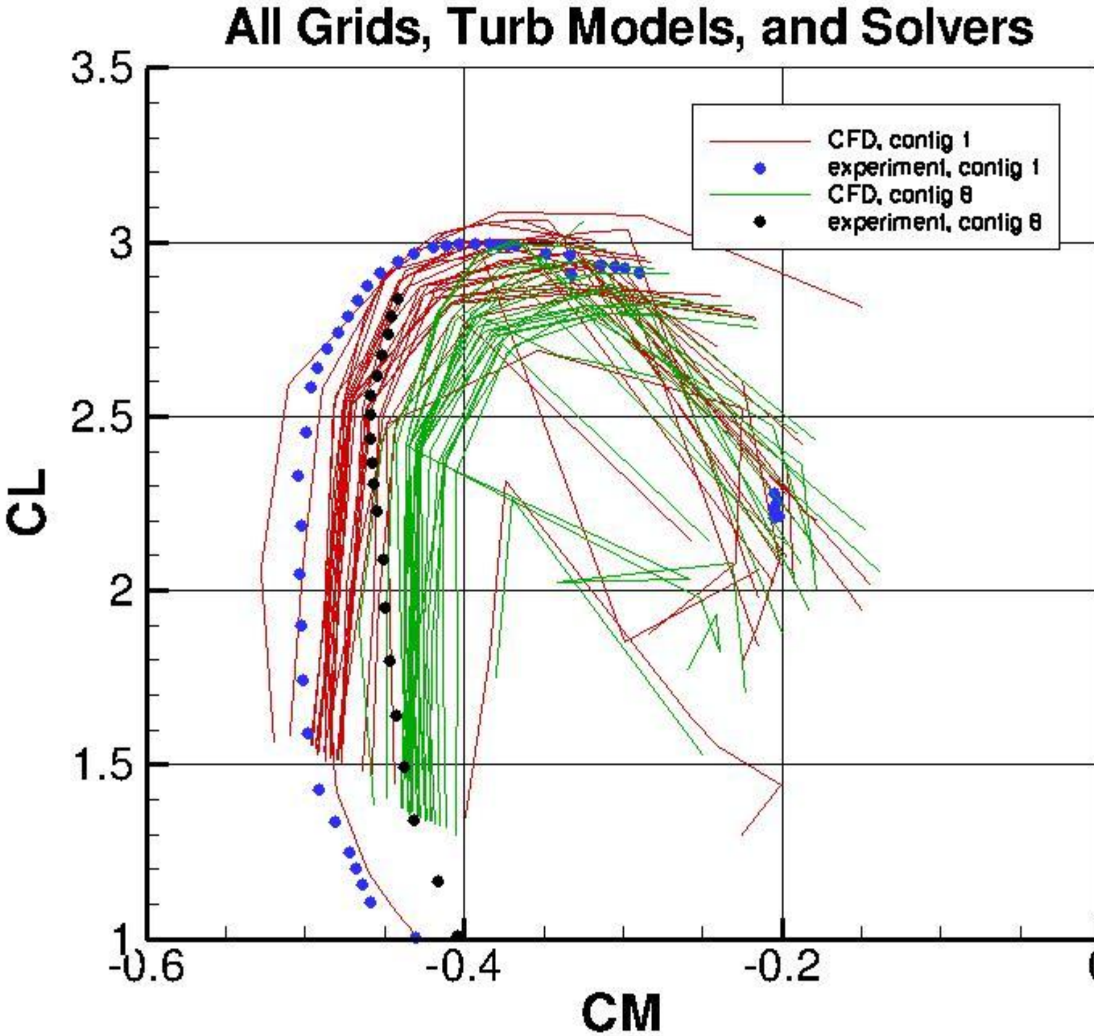


Recall that all comparisons between Config 1 and Config 8 were made using Medium-level grids only

(Only showing those who ran both configs)

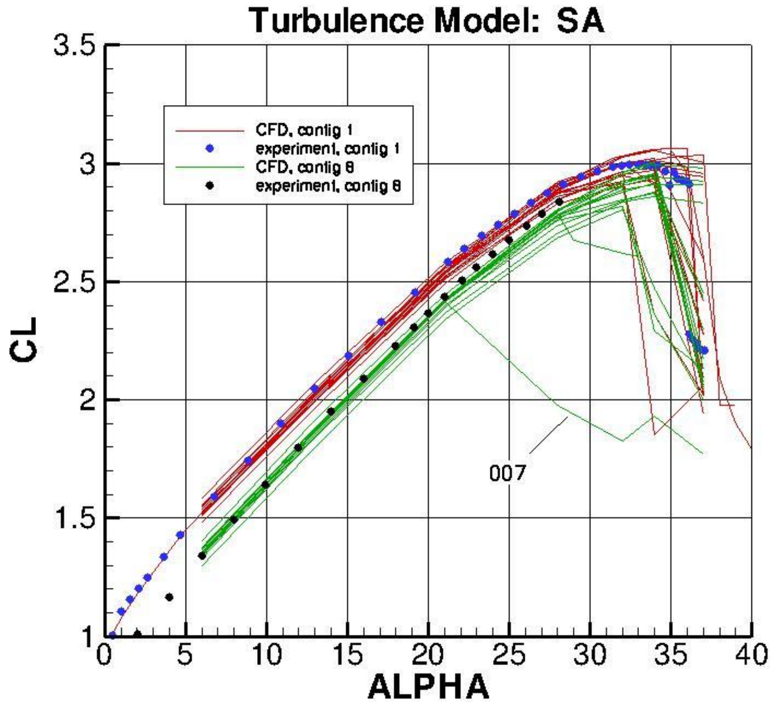
Config 1 vs. Config 8 (2)

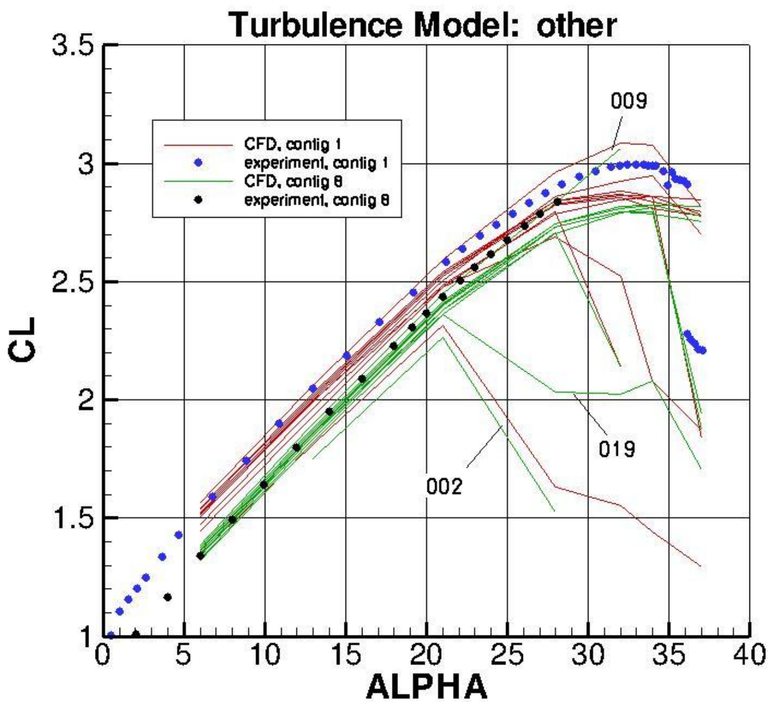
CFD High Lift Prediction Workshop



(Only showing those who ran both configs)

Config 1 vs. Config 8 (3)

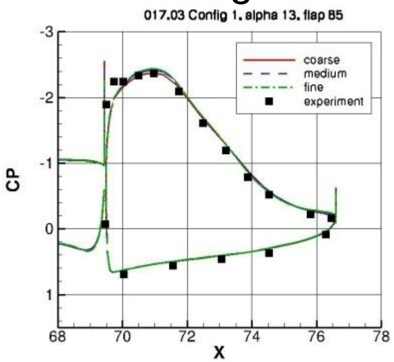




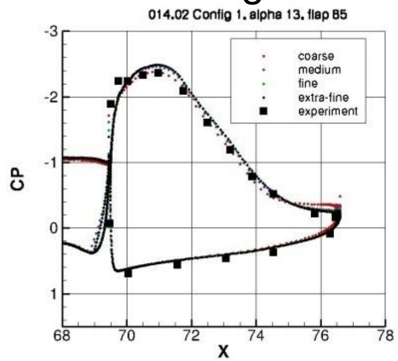
Except for 009 (lattice-Boltzmann LES-type), “other” turbulence models generally yielded lower lift than SA near CLmax

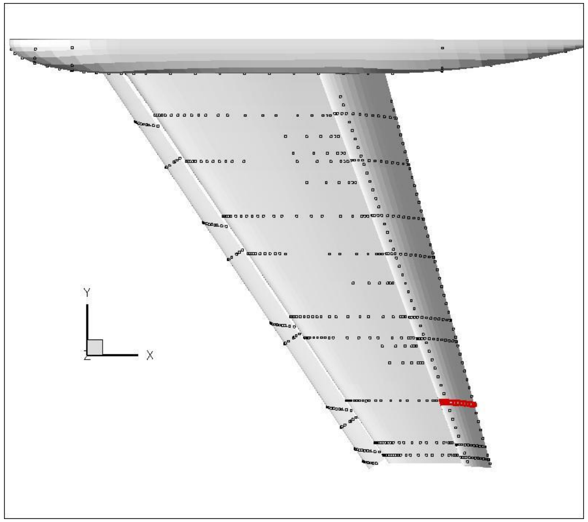
Example Cp Plots   Alpha=13, flap 85

SX1 grid

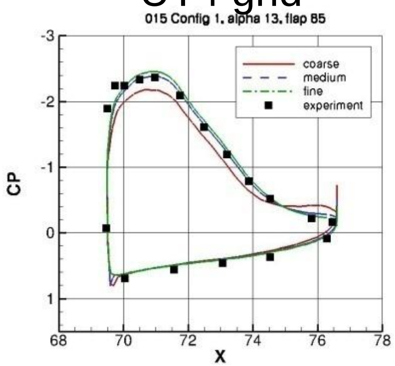


SX3 grid

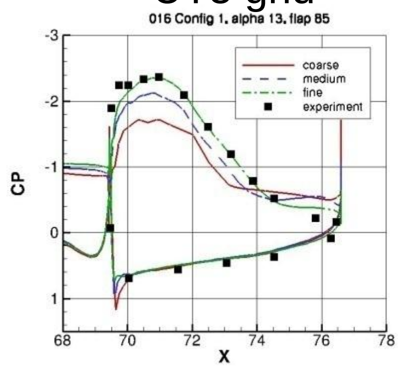




UT4 grid

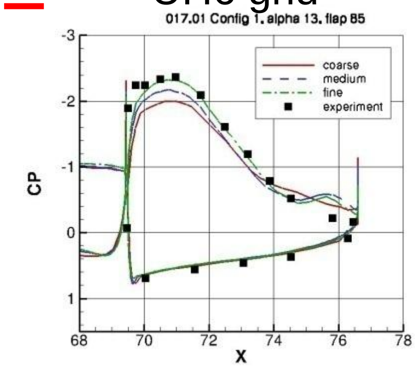


UT5 grid

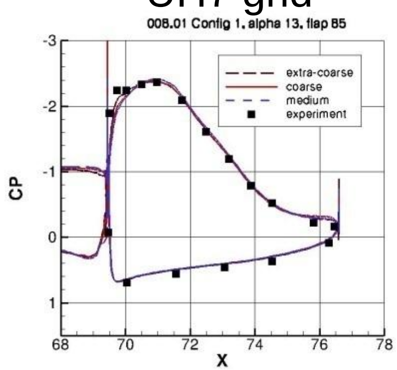


=

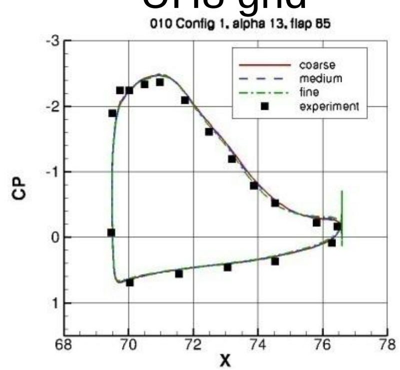
UH6 grid



UH7 grid



UH8 grid



Tet-based grids (row 2) tended to exhibit greater grid sensitivity

Flow Near Wingtip

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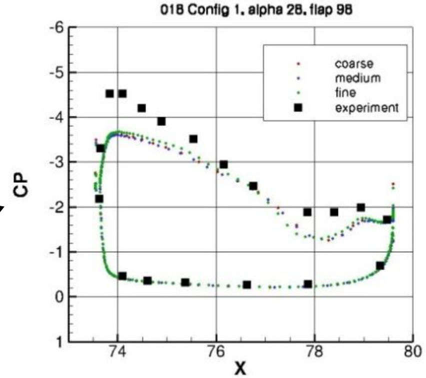
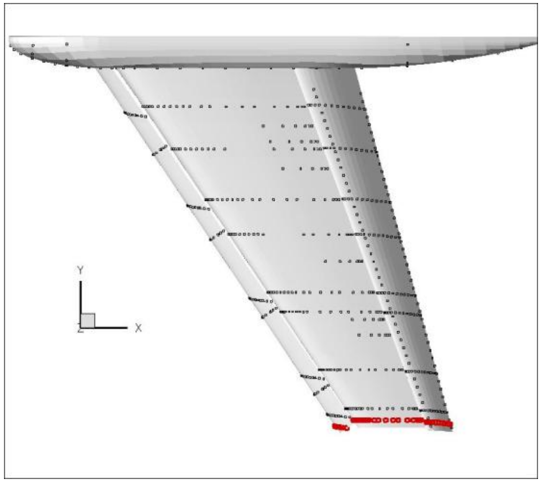
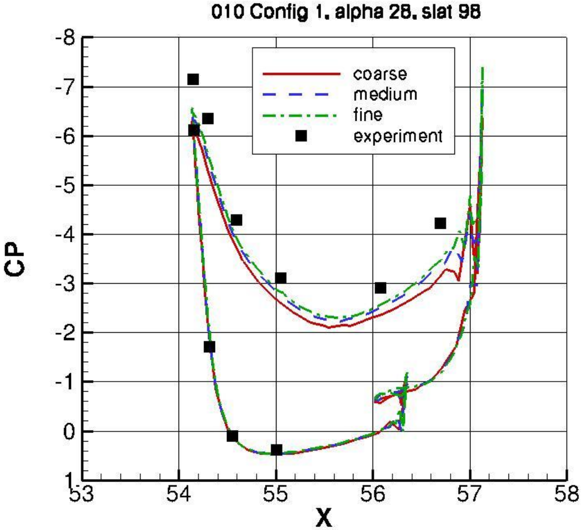
- Flow near wingtip was predicted poorly (in general)

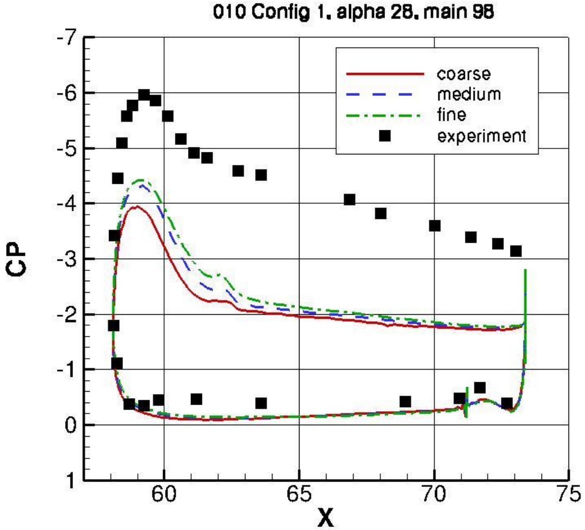
One of best results (flap)

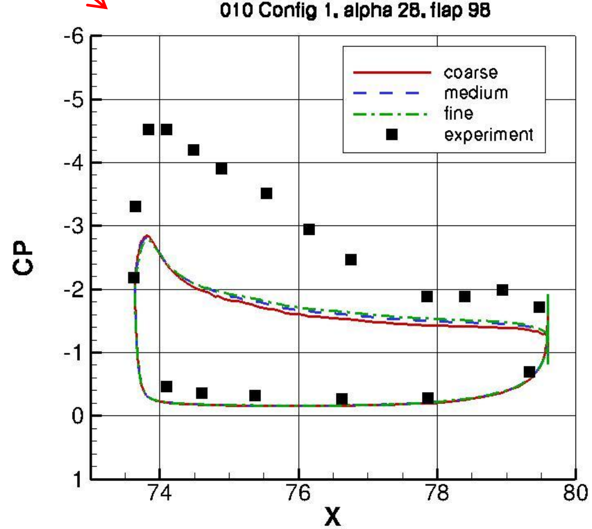




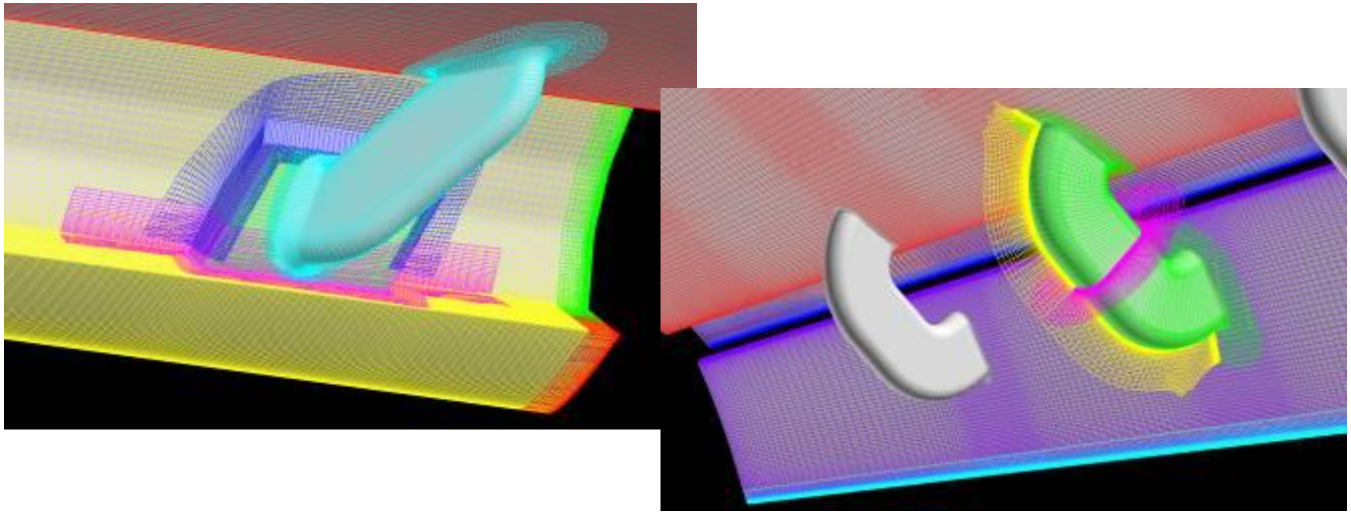
Example of the most common results:



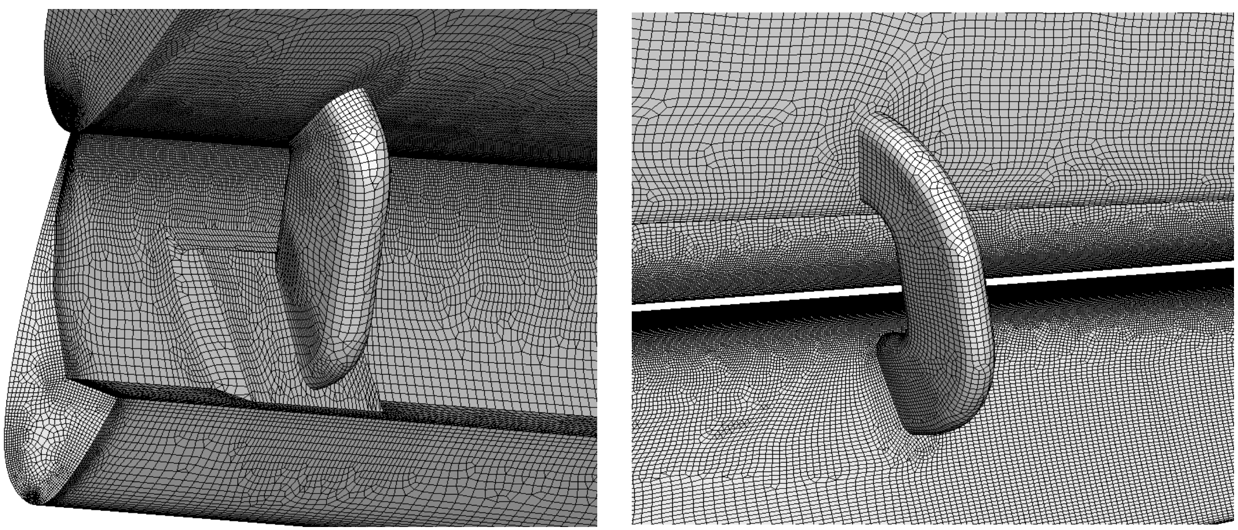




Brackets



CGT - Boeing

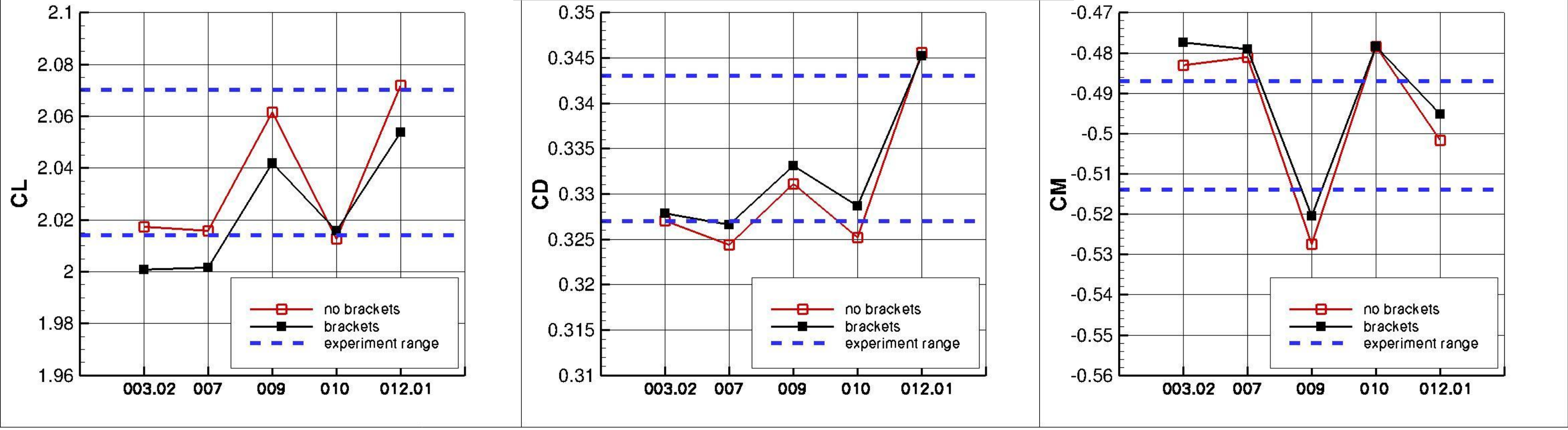


Solar - DLR

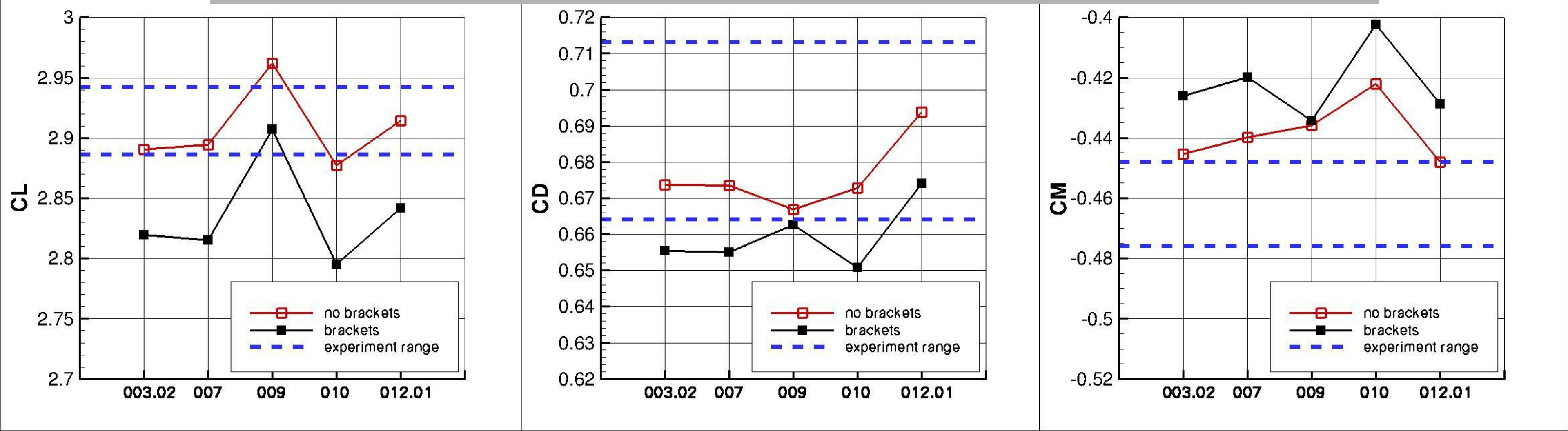
Effect of Brackets

CFD High Lift Prediction
Workshop

Alpha=13: minor effect



Alpha=28: trend away from exp on medium grids



Effect of Brackets (2)

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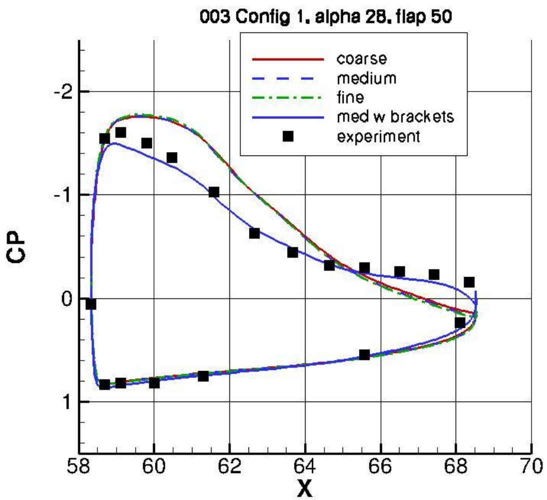
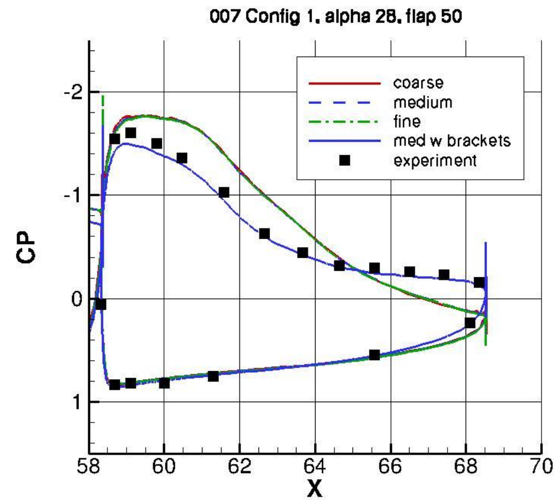
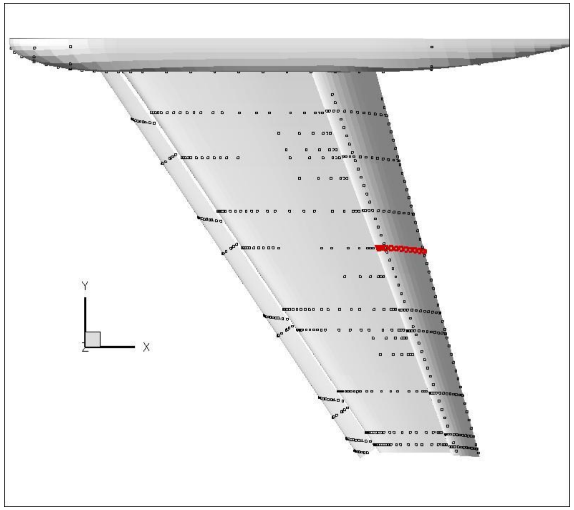
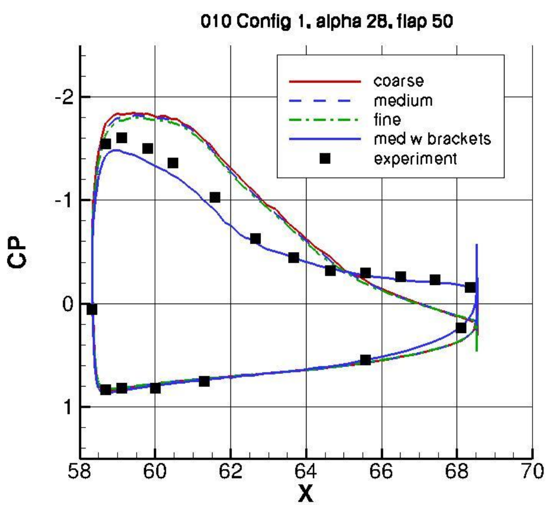
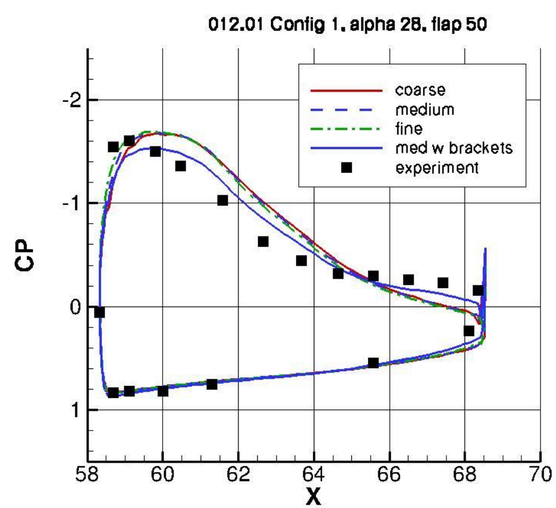
- Bracket effect can be seen at Cp station flap 50











Effect of Brackets (3)

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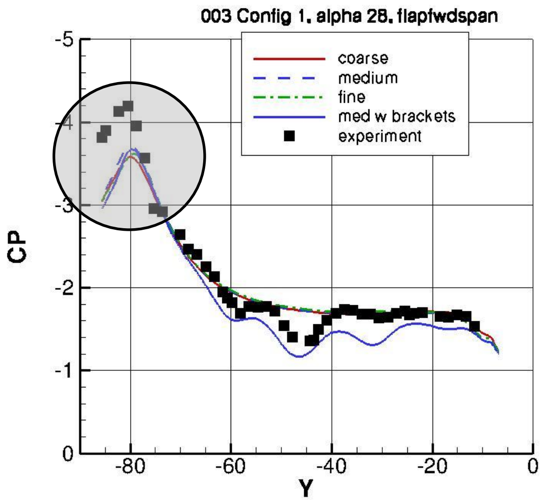
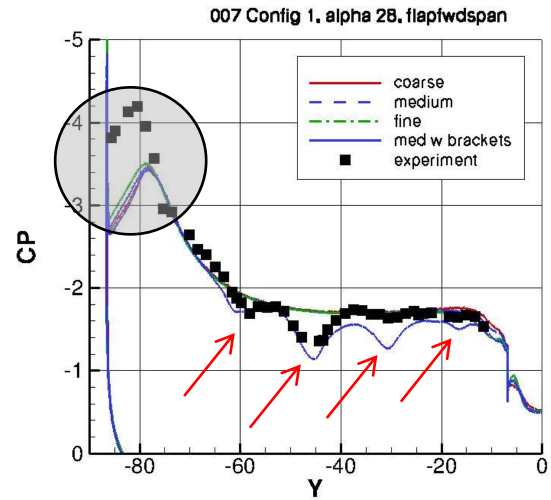
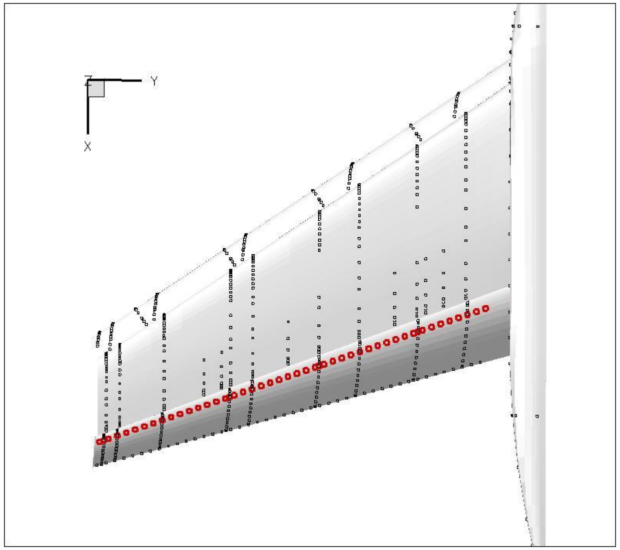
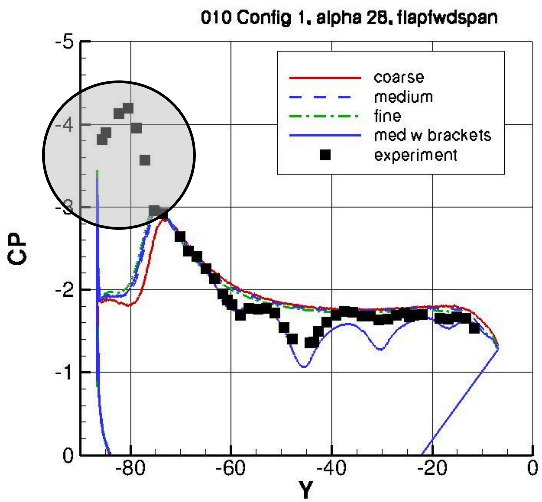
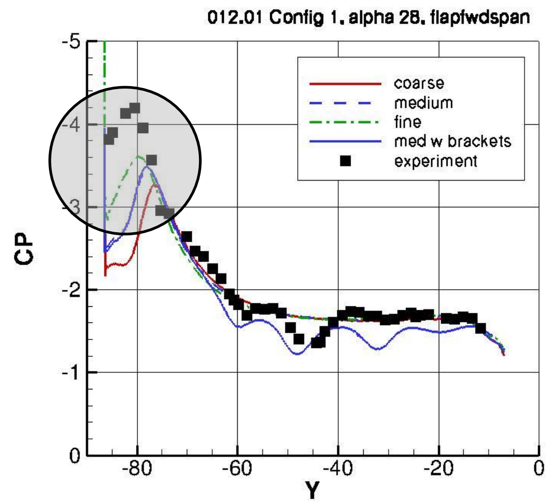
- Bracket effect can be seen (e.g.) at Cp station flapfwdspan
- This flap station also exhibits the poor tip comparisons





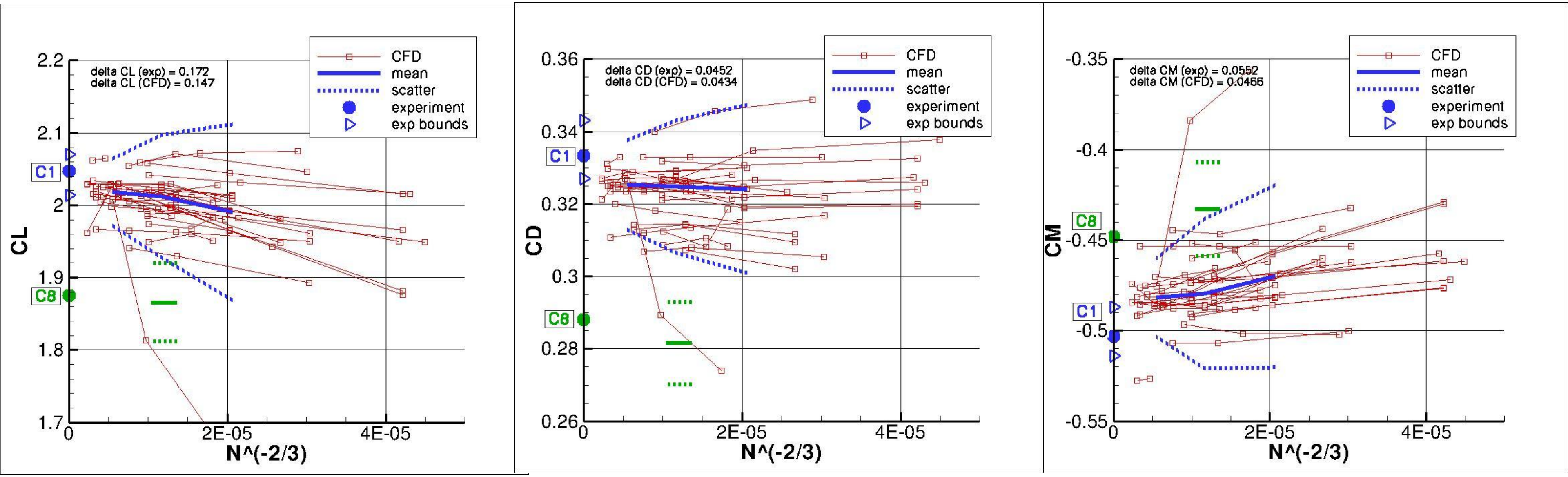






Statistical Analysis*

Alpha=13
all turbulence models



* Used basic methods applied to DPW series – see, e.g., AIAA 2010-4673: scatter limits = $\hat{\mu} \pm \sqrt{3}\hat{\sigma}$

(Exp bounds based on multiple tunnel entries were only established for C1)

Uncertainty bands converge with grid refinement; trend in correct direction toward experiment (higher lift, higher drag, lower moment)

Config effects somewhat under-predicted

Statistical Analysis (2)

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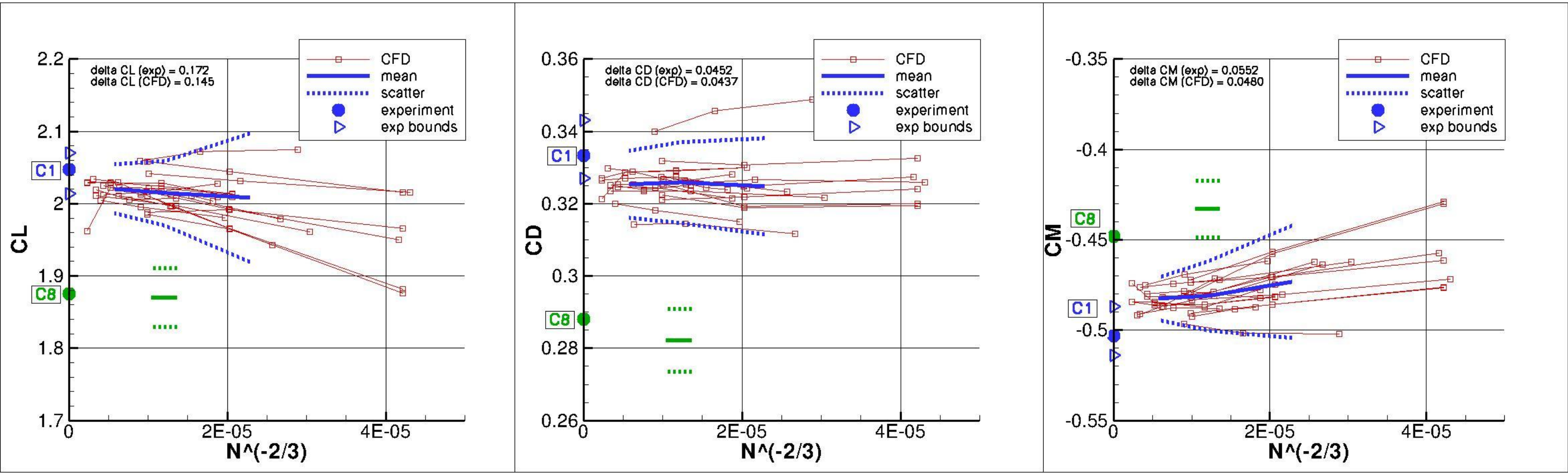
Alpha=13
SA only

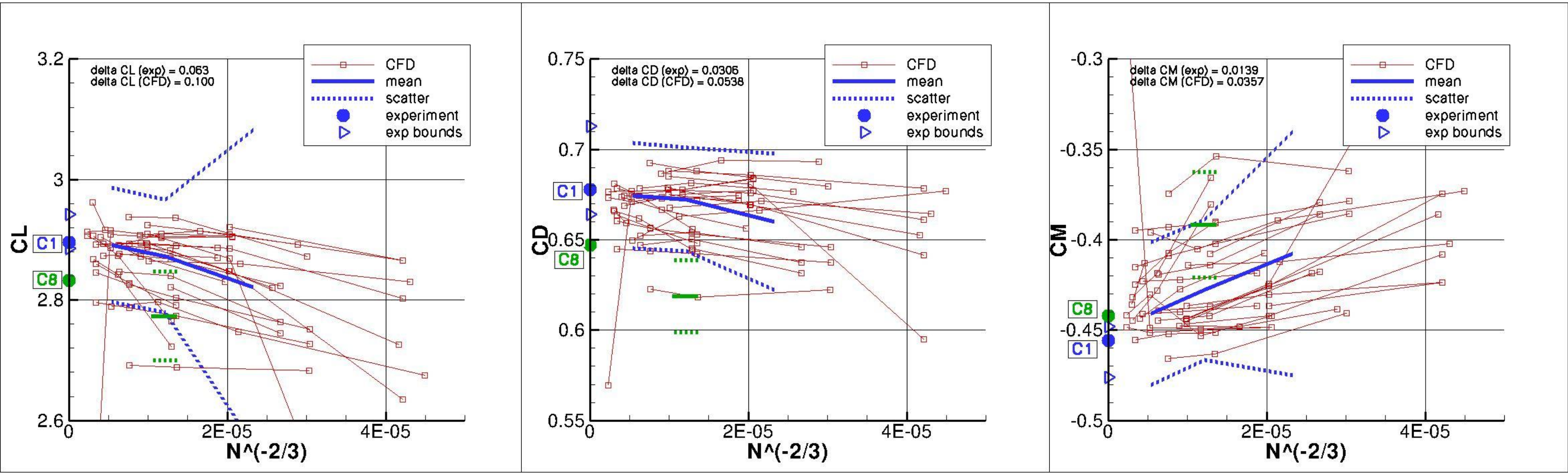


Uncertainty bands tighter

Config effects still somewhat under-predicted

Statistical Analysis (3)

Alpha=28
all models, outliers removed



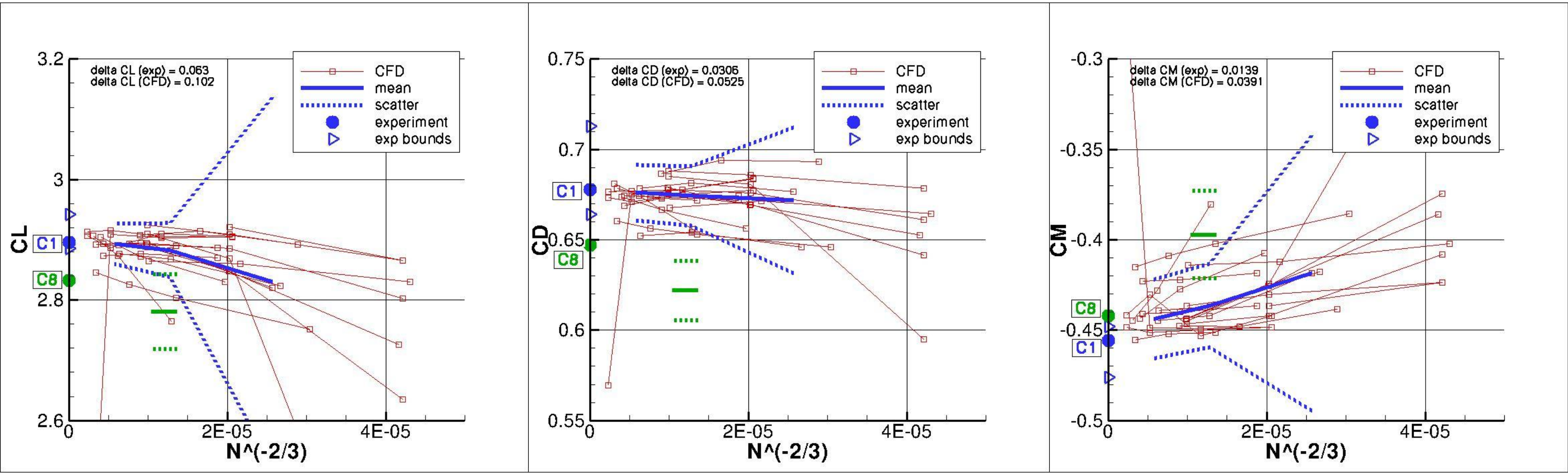
Uncertainty bands not converging between M and F grid levels

Config effects significantly over-predicted

Statistical Analysis (4)

CFD High Lift Prediction Workshop

Alpha=28
SA only, outliers removed



Uncertainty bands tighter; slightly converging between M and F levels

Config effects still over-predicted

Conclusions from Raw Data Analysis

CFD High Lift Prediction Workshop

- Effect of brackets
  - Only minor influence at alpha=13
  - Bigger influence at alpha=28, but collective trend is away from experiment
  - But only Medium-level grids were used – grid study needed
  - Brackets influence easy to see at some Cps stations
- Trends between configs 1 & 8
  - Statistically, deltas somewhat low at alpha=13
  - Deltas significantly high at alpha=28
  - Grid study needed for Config 8 to draw firmer conclusions
- Turbulence modeling
  - Collectively, SA appears to yield higher lift near CLmax than other models (grid studies needed near CLmax)
  - SST tended to over-predict separation on flap
  - CF data useful to note where "fully turbulent" turbulence models actually activate
- Cp levels were particularly missed by CFD near wingtip
  - Possible issues arising from neglecting viscous cross-derivative terms (thin-layer N-S)
  - Other reasons (grid? numerics? turbulence model?)
- Much more analysis of Cp and Cf data is possible

Conclusions from Statistical Analysis

- At alpha=13, only one “big” outlier – goes away on fine grid
  - Scatter converges with grid refinement
  - Scatter range of SA-only was tighter (dCL=0.07, dCD=185 cts)
- At alpha=28, a few “big” outliers
  - Scatter (with outliers removed) does not converge between M & F unless analyze SA-only
  - Scatter range of SA-only was tighter (dCL=0.07, dCD=308 cts)
- Collective is in fair agreement with experiment at alpha=13 & 28, taking into account repeatability bounds
  - But effects of brackets, transition, tunnel walls not accounted for
- CD coefficient of variation (fine grid):
  - 2.2-2.5% (all models) <- similar to DPW II, III, & IV
  - 1.3-1.6% (SA-only)
- CL coefficient of variation (fine grid):
  - 1.3-1.9% (all models)
  - 0.7-1.0% (SA-only)
- CM coefficient of variation (fine grid):
  - 2.6-5.2% (all models) <- DPW II & III was about 5%
  - 1.4-2.8% (SA-only)

Observations

- Many participants noted issue of CFD initial-condition-dependence at high alphas
  - Sometimes obtained massive separation if run from freestream
  - Good results if start from previous solution at lower angle of attack
- Overall, fine grid structured and unstructured results were comparable; i.e., grid type was not an issue
  - Tetrahedra-based unstructured grids tended to exhibit greater grid sensitivity than others on coarse grids
- Overall, CFD's CL on clean wing (no brackets) <u>should</u> be higher than exp data (with brackets), esp at high alpha
  - <u>Poor CFD results near wingtip</u> may be a major reason why this is not the case
  - <u>Including transition effects</u> is also likely to improve CFD results (increase lift)
  - Are wind-tunnel wall effects an issue near CLmax?

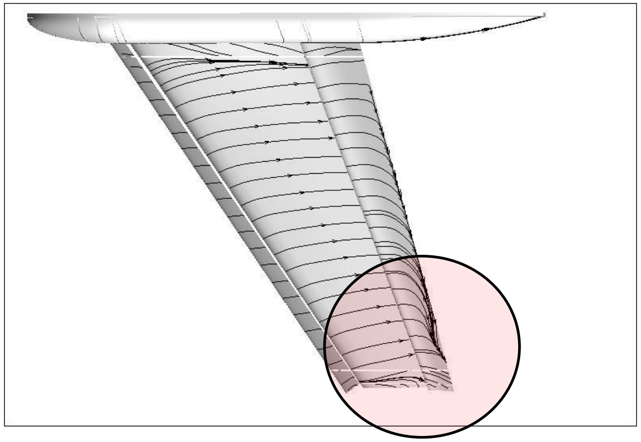
Thoughts / Recommendations

- Next time, collect iterative convergence histories for select cases
- Additional grid studies would be helpful
  - with brackets
  - config 8
  - near CLmax
- Address issue of thin-layer (no viscous cross-derivative terms) vs. full Navier-Stokes
  - Impact on tip flow and flap separation (see next page)
- Address issue of codes using different versions of a given turbulence model
- In retrospect, collecting Cps at so many cuts and for so many cases was a good idea
  - It was somewhat painful for the participants, but now we have a wealth of data for analysis that would have been extremely difficult to obtain otherwise

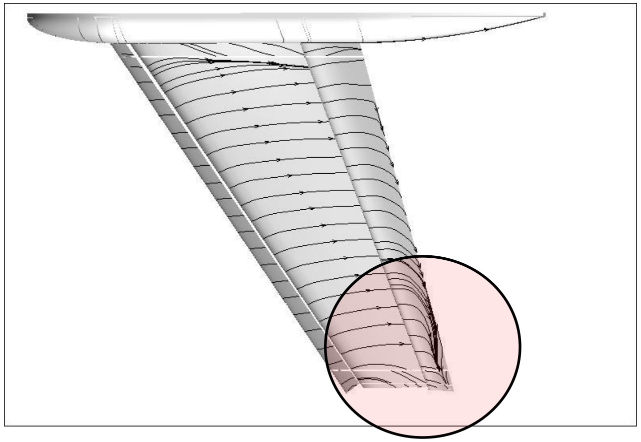
Effect of Thin Layer

- Post-workshop investigation by CFL3D (preliminary findings) - config 1, alpha=28

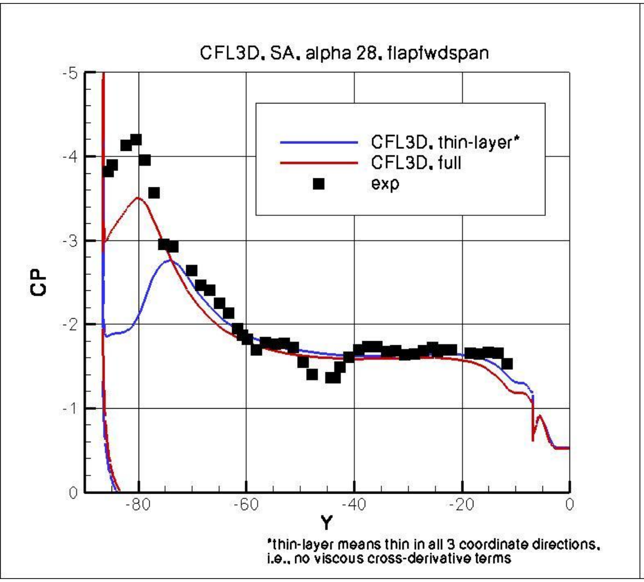
No viscous cross-derivative terms

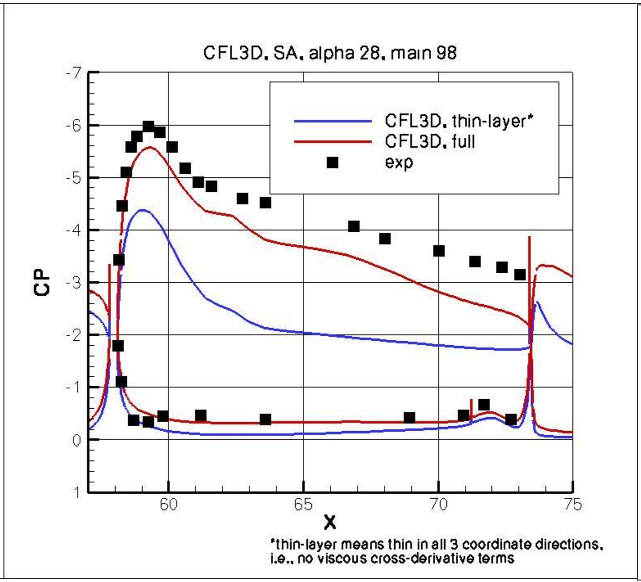


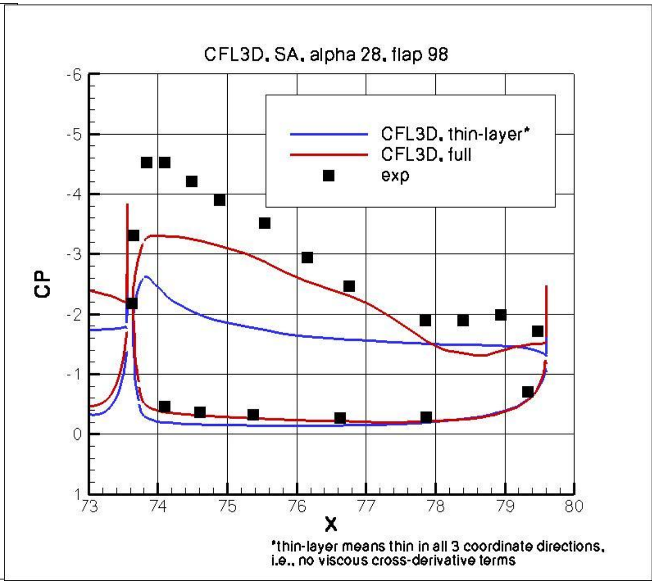
Full N-S



SX1 medium grid, SA model







Workshop Feedback

CFD High Lift Prediction Workshop

- “Kill free-air CFD and kill use of Thin-Layer approximation”
- “Always include brackets and wind tunnel walls, and solve only transient problems”
- “The lack of correlation between analytical and wind tunnel results appears to be solely due to what happens at the wing tip – we should consider more realistic wingtip geometry?”
- “Have a collaboration project between high-lift CFD and testing – Decide jointly what new, high-fidelity measurements are needed to validate CFD”
- “Re-test Trap Wing at higher Re?”
- “Allow participants time to remake new meshes based on the results of the workshop…”

Follow-on Work

- Participants can correct/resubmit data prior to 9/6/10
- 2 sessions at AIAA meeting in Orlando, Jan 2011
  - Summary papers by committee
  - Several participant papers
- Possible sessions at AIAA meeting in Hawaii, June 2011 – TBD
- Topics for HiLiftPW-2 are under consideration
  - Likely to be held in 2013 (to avoid conflicting with DPW-V in 2012)
  - Same configuration, but include transition, brackets, walls in CFD?
  - Different configuration is also possible (e.g., CRM with high-lift system)?
  - More focus on ability to capture wing tip region?
  - More focus near CLmax?
  - Investigate time-accuracy & hysteresis?
  - Develop methods for assessing adequacy of grid systems?
  - Will additional experimental data be necessary (e.g., velocity profiles)?