

Workshop Summary

Chris Rumsey

1st AIAA CFD High Lift Prediction Workshop

Chicago, Illinois

26-27 June 2010

Acknowledgments

- Summary evaluation plotting:
 - Mike Long (U Wyoming)
 - Tom Wayman (Gulfstream)
 - Bob Stuever (Hawker Beechcraft)

- Introduction
- Summary of entries
- Lift curve and polar plots
- Predicting deltas between Config 1 and 8
- Grid convergence behavior
- Surface pressure and skin friction
- Effect of brackets
- Other comparisons
- Statistical analysis
- Conclusions & recommendations

- Summary is preliminary
 - Participants can update their results after the workshop, if desired; deadline: Sept 6, 2010
- Looking for:
 - Overall collective results
 - Trends
 - Outliers

Mostly SA model, then SST



	0 0 1	0 0 2	0 0 3	0 0 3	0 0 4	0 0 5	0 0 5	0 0 6	0 0 7	0 0 8	0 0 8	0 0 9	0 1 0	0 1 1	0 1 2	0 1 2	0 1 3	0 1 3	0 1 4	0 1 4	0 1 4	0 1 5	0 1 6	0 1 7	0 1 7	0 1 7	0 1 8	0 1 9	0 2 0	0 2 0	0 2 1	0 2 1			
Code	C F X	C F D + +	O V E R	O V E R	H I F U N	F U N 3 D	N S U 3 D	F U N 3 D	T A U	T A U	T A U	T A U	P O W E R	E D G E	N S U 3 D	T A S	U P A C S	C F D + +	C F D + +	O V E R	O V E R	O V E R	U S M 3 D	F U N 3 D	F U N 3 D	C F L 3 D	C F L 3 D	C F L 3 D	E L S A	N S M B	U S M 3 D	U S M 3 D	N S U 3 D	N S U 3 D	
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	S S T *	K E *	S A	S A	S A	S A	S A	S A	S A	S A	S S T	R S M	V L E S	S A	S A	S A *	S A *	S A	K E *	K E *	S A	S A	S A	S A	S A	S A	S S T	S A	S S T	S A	S S T	K O	K O *	S A	S S T
Notes	Transition model used			brackets off on bracket-like grid			Thin each direc					Transition 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

Most used unstructured grids

	0 0 1	0 0 2	0 0 3	0 0 3	0 0 4	0 0 5	0 0 5	0 0 6	0 0 7	0 0 8	0 0 8	0 0 8	0 0 9	0 1 0	0 1 1	0 1 2	0 1 2	0 1 3	0 1 3	0 1 3	0 1 4	0 1 4	0 1 4	0 1 4	0 1 5	0 1 6	0 1 7	0 1 7	0 1 7	0 1 7	0 1 8	0 1 9	0 2 0	0 2 0	0 2 1	0 2 1	
Code	C F X	C F D +	O V E R	O V E R	H I F U N	F U N 3 D	N S U 3 D	F U N 3 D	T A U	T A U	T A U	T A U	P O W E R	E D G E	N S U 3 D	T A S	U P A C S	C F D +	C F D +	C F D +	O V E R	O V E R	O V E R	U S M 3 D	F U N 3 D	F U N 3 D	C F L 3 D	C F L 3 D	C F L 3 D	E L S A	N S M B	U S M 3 D	U S M 3 D	N S U 3 D	N S U 3 D		
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	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 1	UT 4	UT 4	UH 6	UH 6		
Turb	S S T *	K E *	S A	S A	S A	S A	S A	S A	S A	S A	S S T	R S M	V L E S	S A	S A	S A *	S A *	S A	S A	S A	S A	S A	S A	S A	S A	S A	S S T	S A	S A	S A	S A	S A	S A	S A	S A	S A	S A
Notes	Transition model used			brackets off on bracket-like grid			Thin each direc						Transition 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

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SX=Structured
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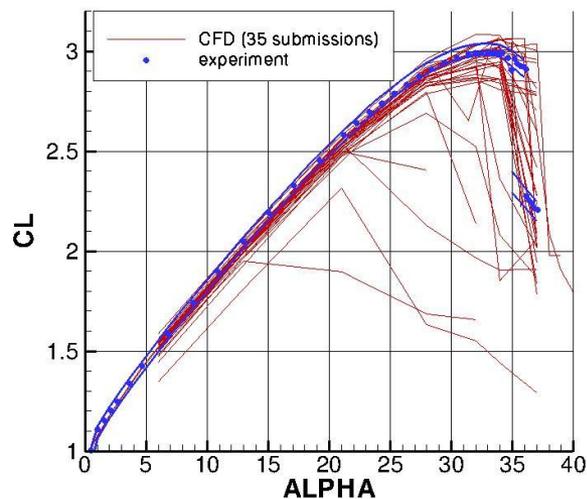
1=Str point-matched A
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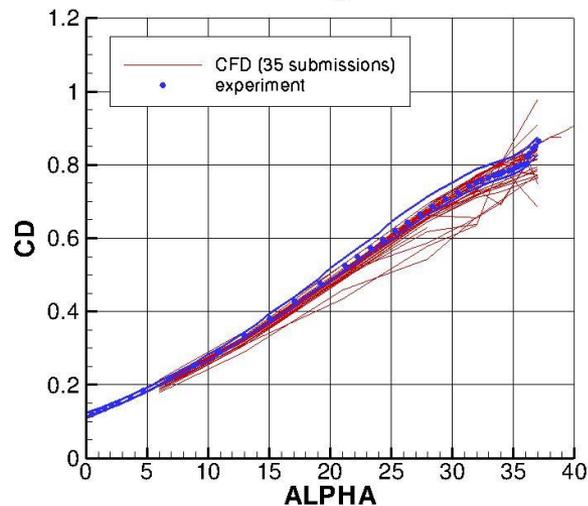
LIFT CURVE & POLAR PLOTS

Comparing to experimental bounds

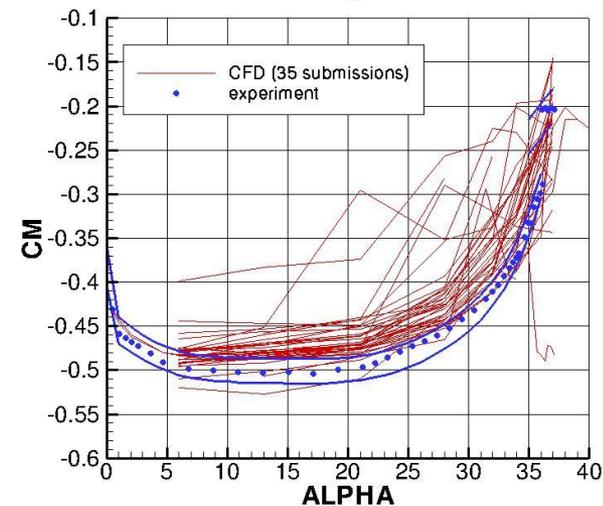
Config 1



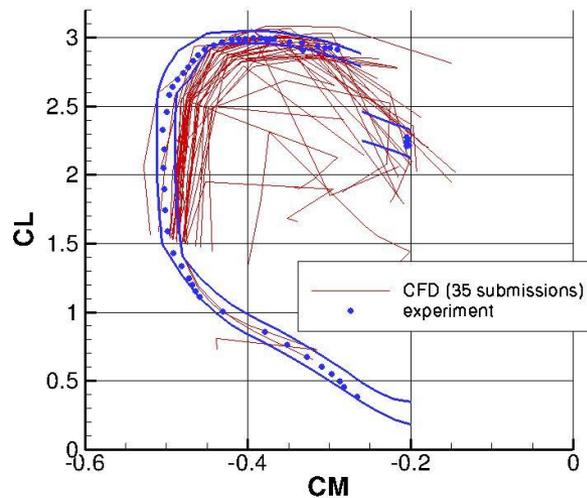
Config 1



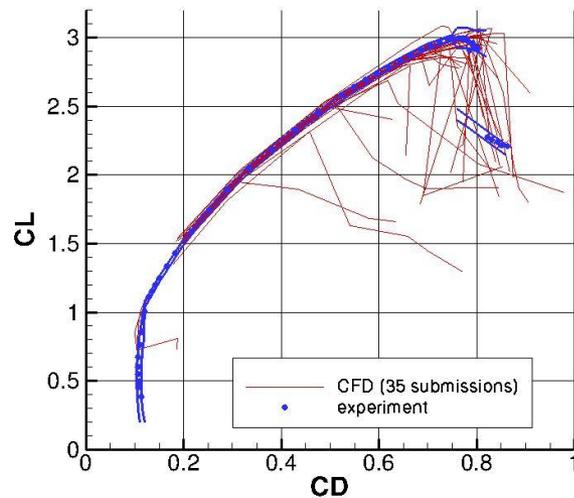
Config 1



Config 1

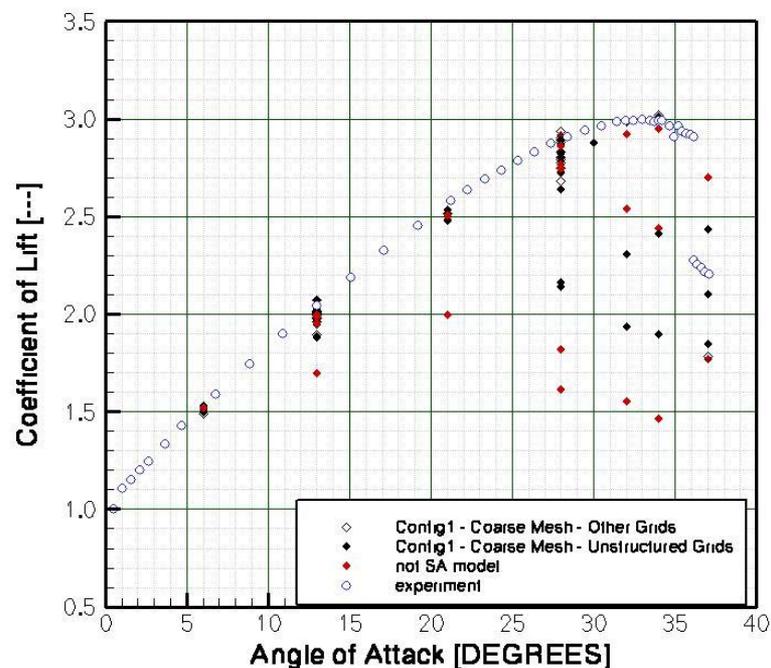
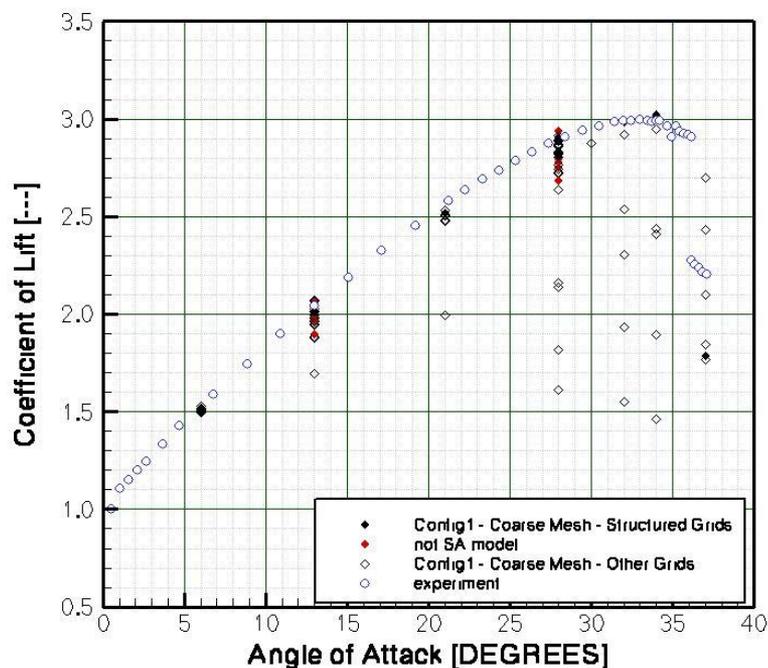


Config 1



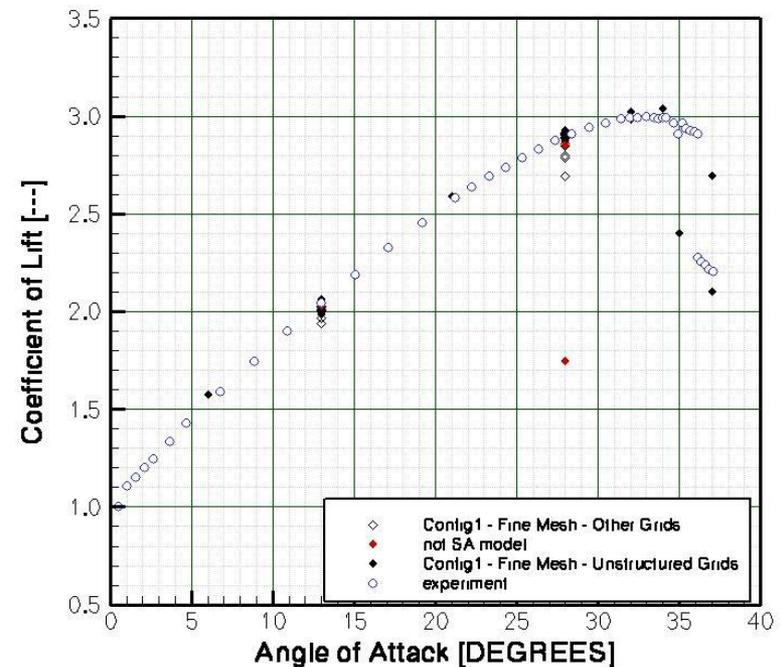
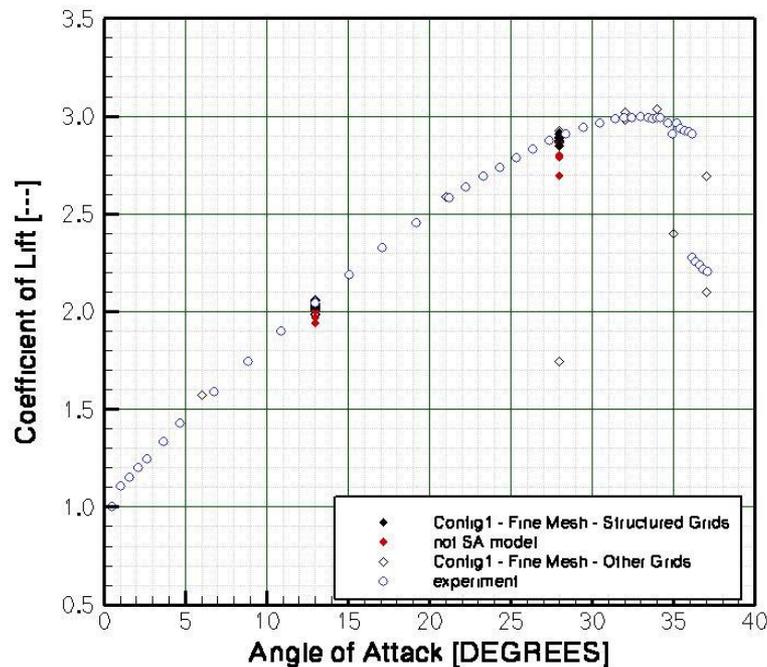
Collectively, CFD tended to yield too-low lift, too-low drag, too-high moment (on Medium-level grid)

Lift curve on coarse grids



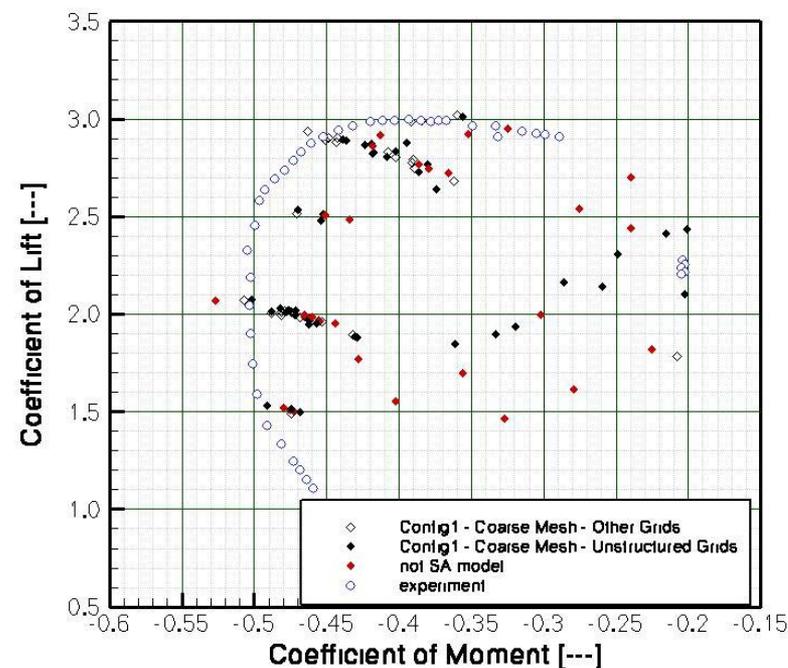
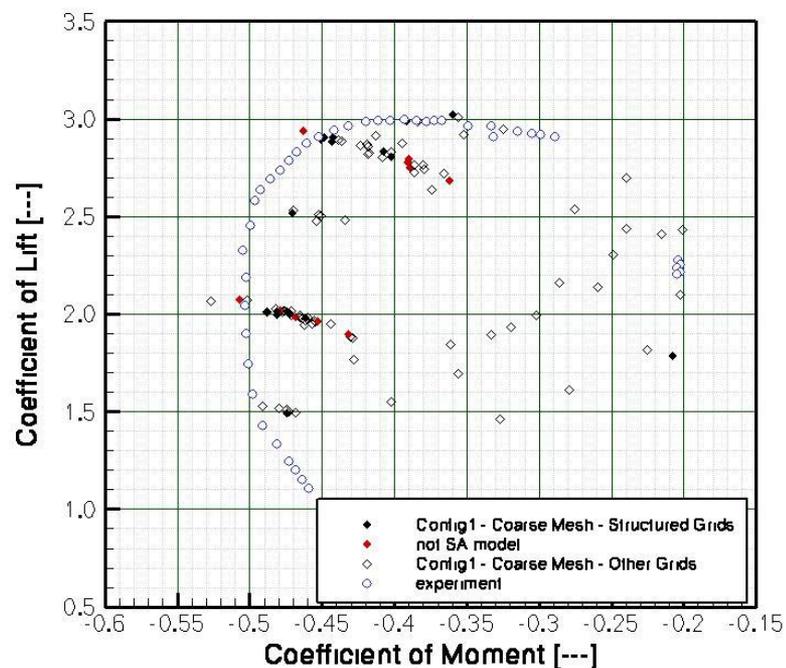
Structured grids yield less spread on coarse grids

Lift curve on fine grids



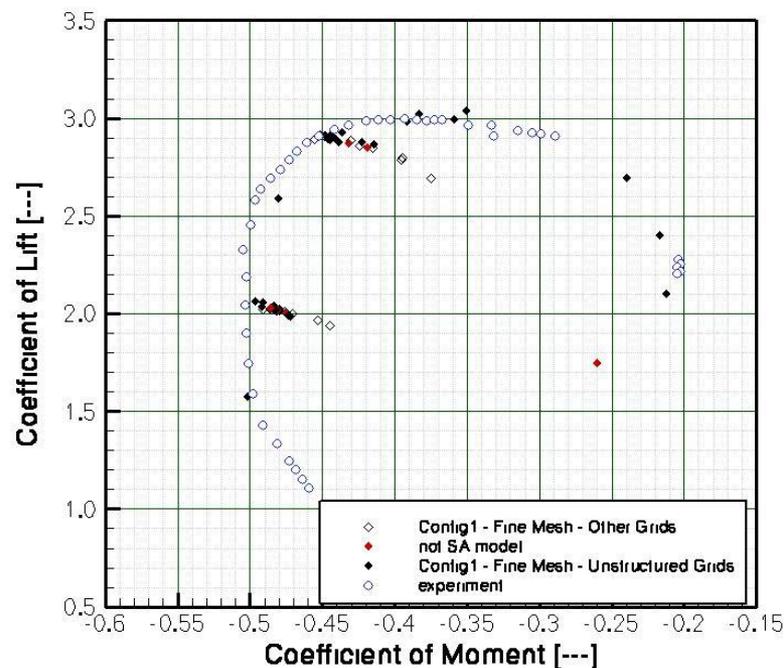
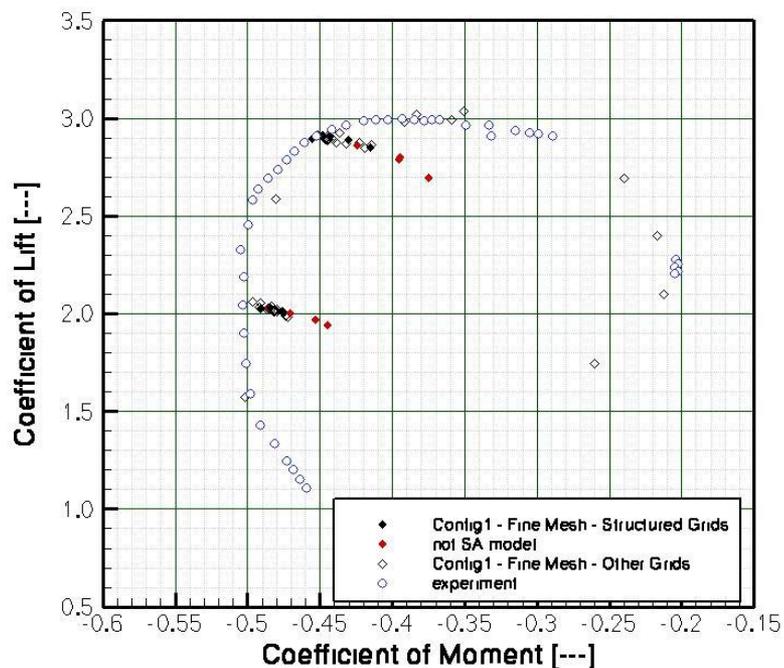
Both grid types similar spread on fine grids
(with same turbulence model)

Moment polar on coarse grids



Structured grids yield less spread on coarse grids

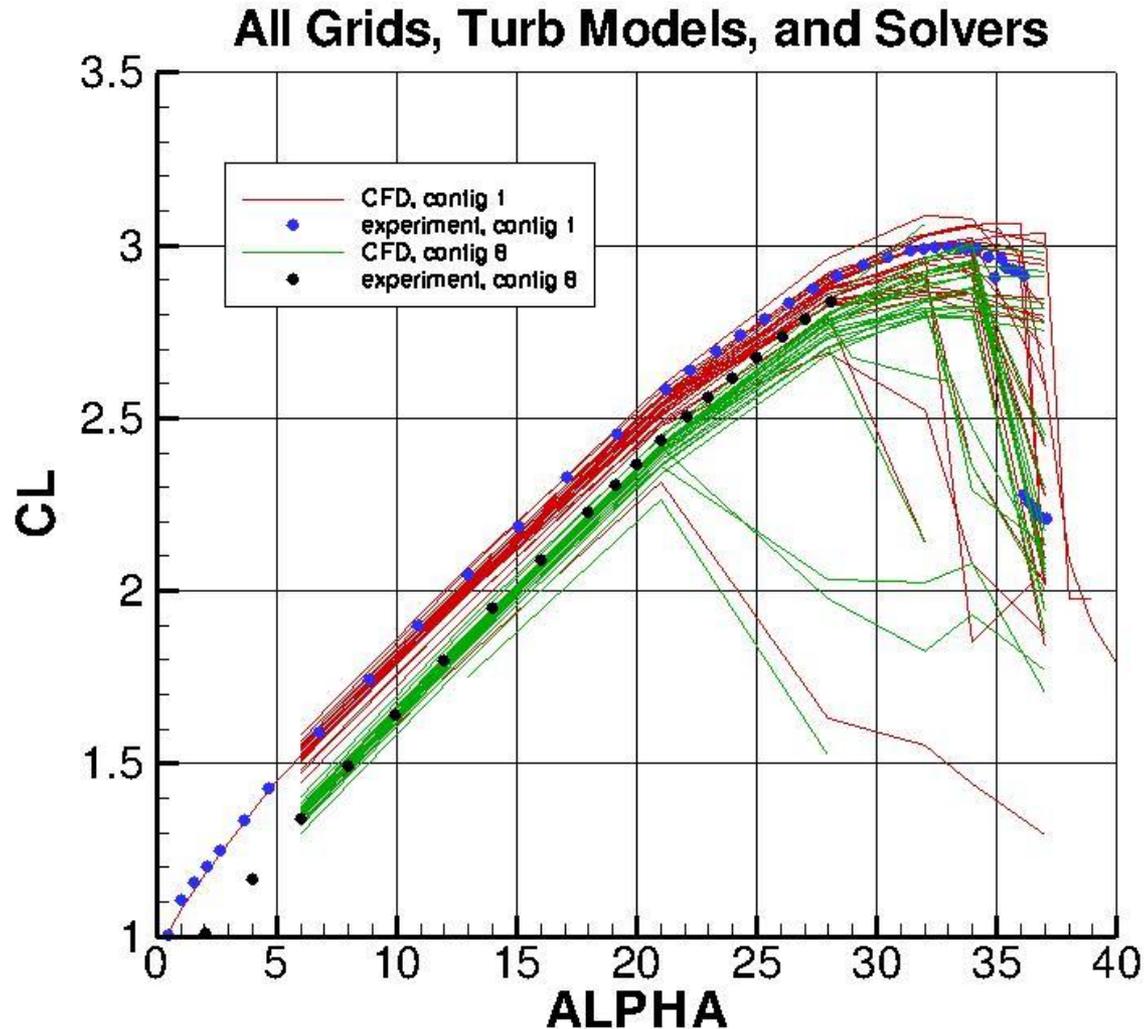
Moment polar on fine grids



Both grid types similar spread on fine grids
(with same turbulence model)

PREDICTING DELTAS BETWEEN CONFIG 1 & 8

Config 1 vs. config 8

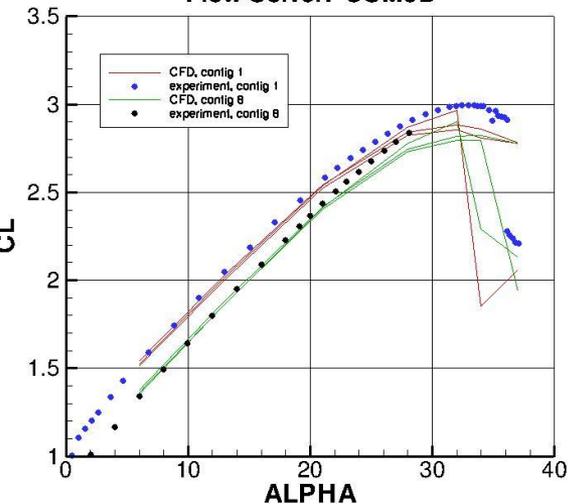


Recall that all comparisons between Config 1 and Config 8 were made using Medium-level grids only

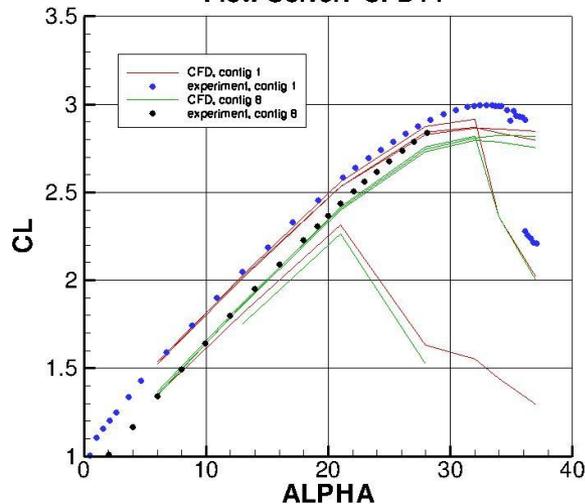
(Only showing those who ran both configs)

Config 1 vs. config 8

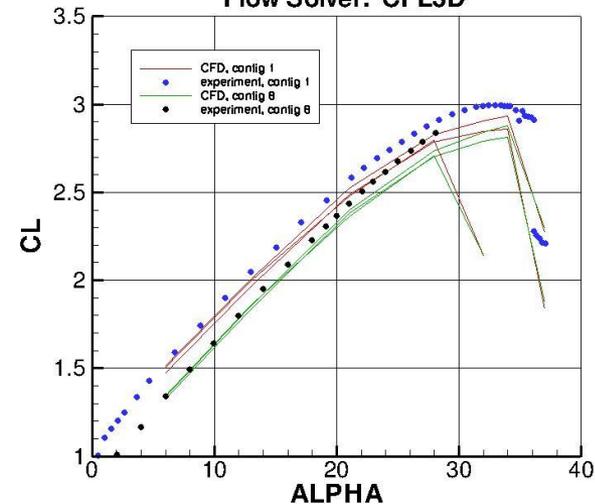
Flow Solver: USM3D



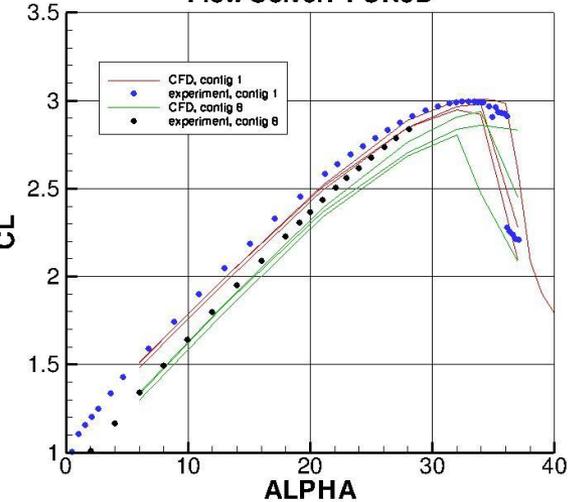
Flow Solver: CFD++



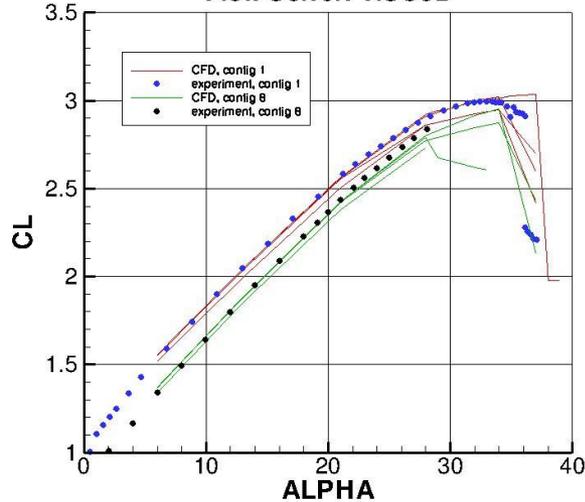
Flow Solver: CFL3D



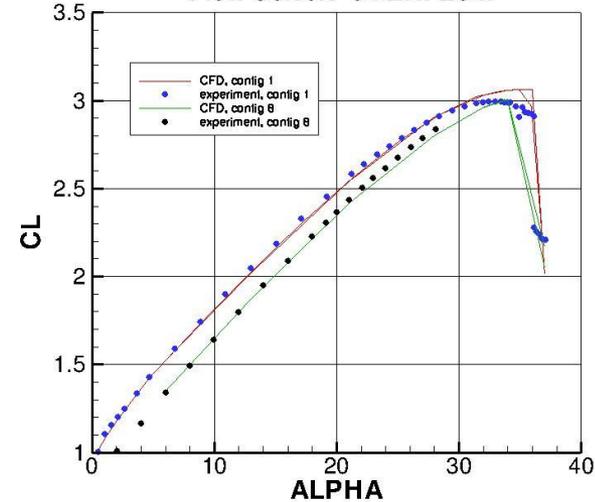
Flow Solver: FUN3D



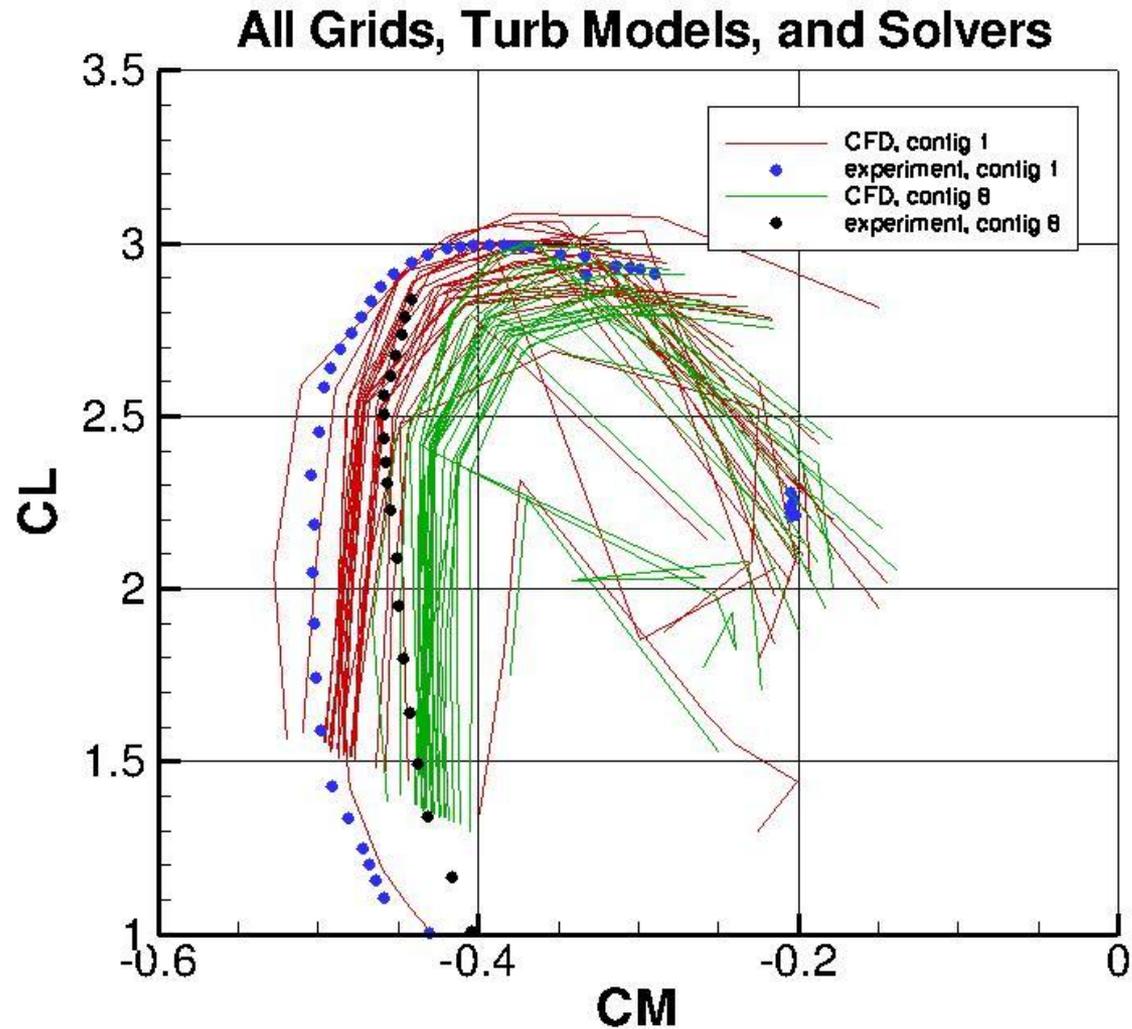
Flow Solver: NSU3D



Flow Solver: OVERFLOW

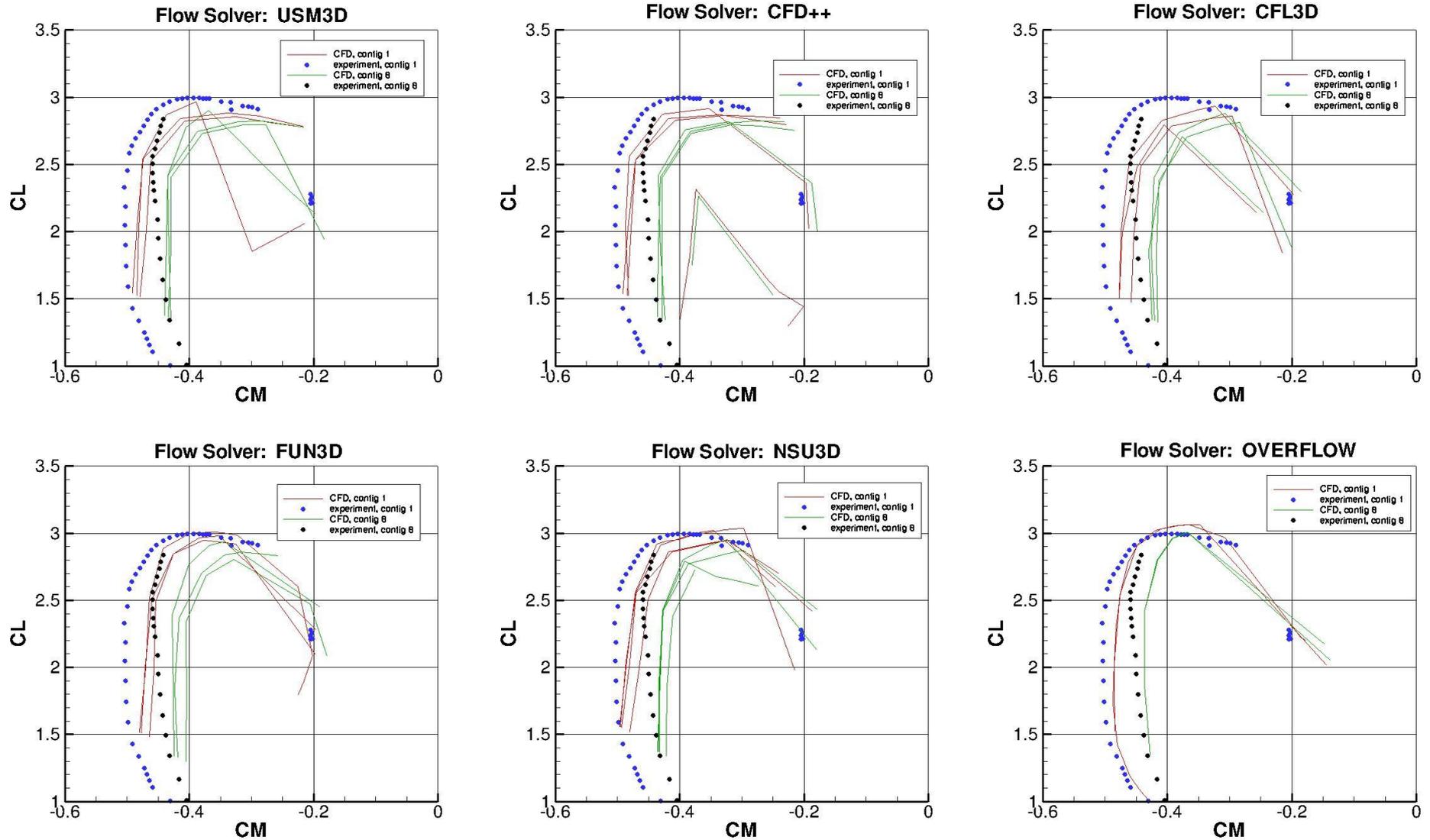


Config 1 vs. config 8

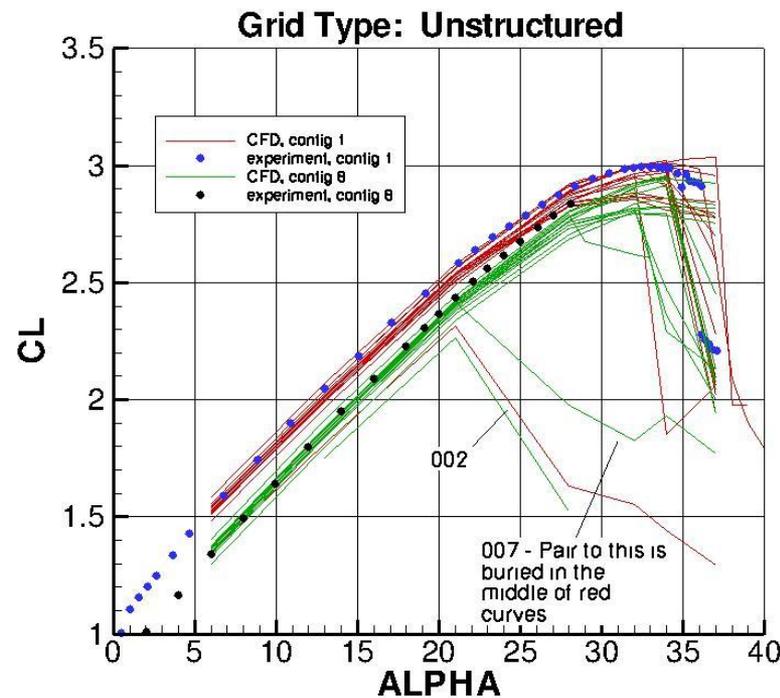
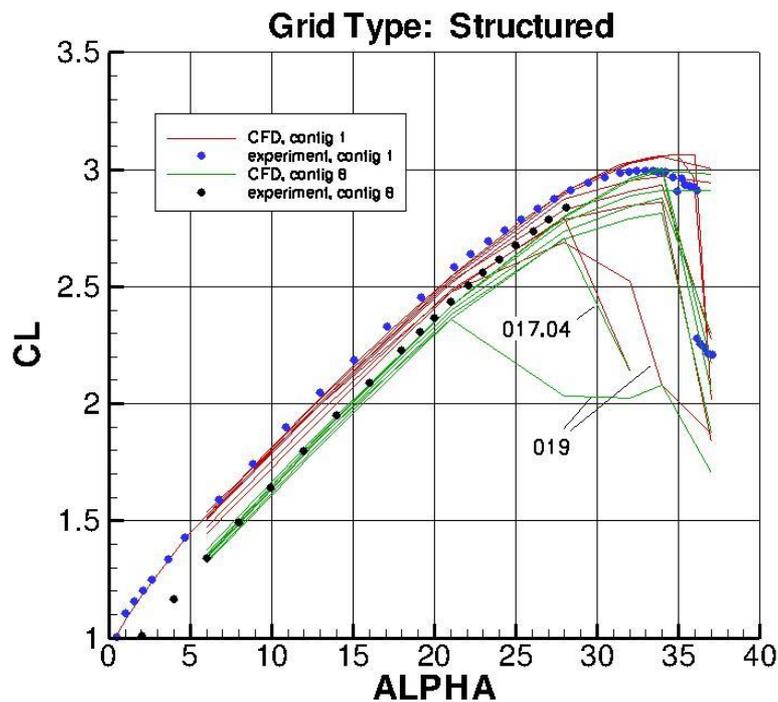


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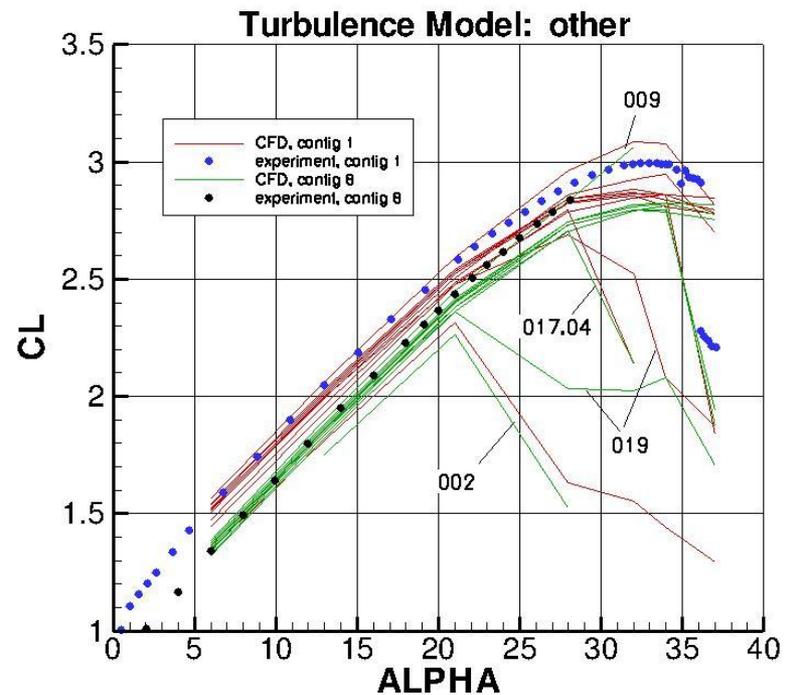
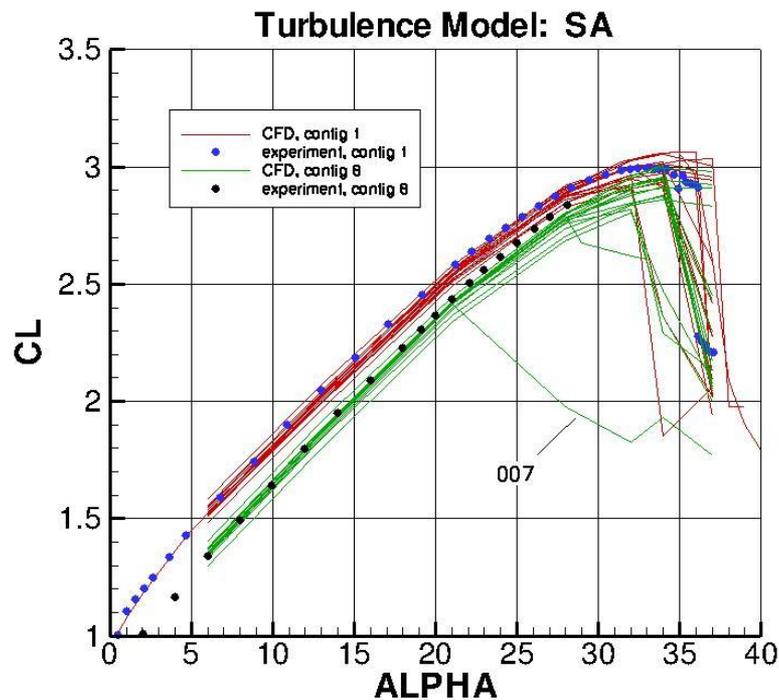
Config 1 vs. config 8



Config 1 vs. config 8



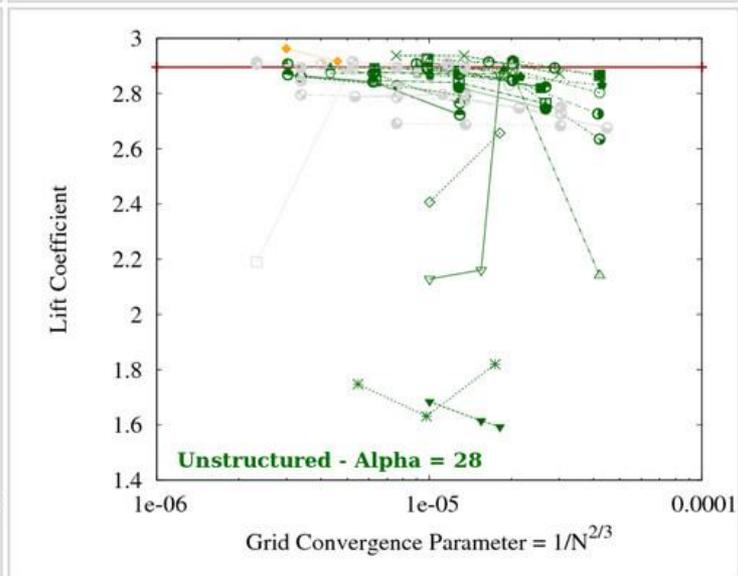
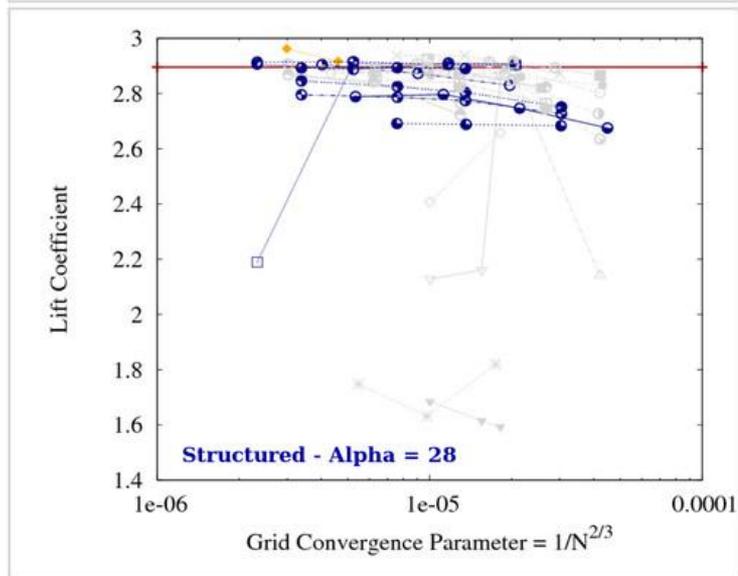
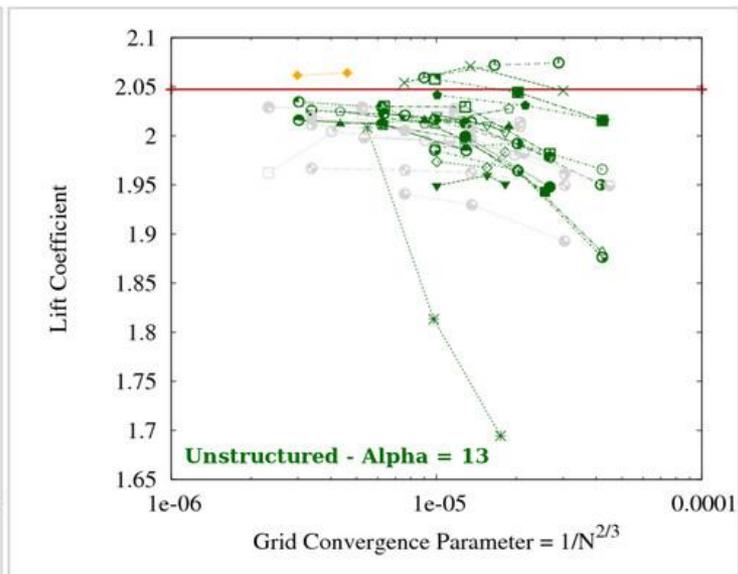
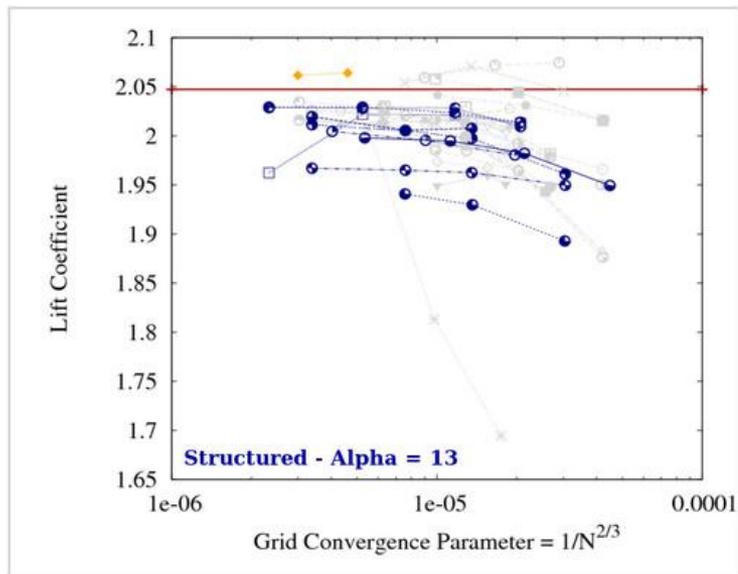
Config 1 vs. config 8



Except for 009, “other” models appear to yield lower lift than SA near CLmax

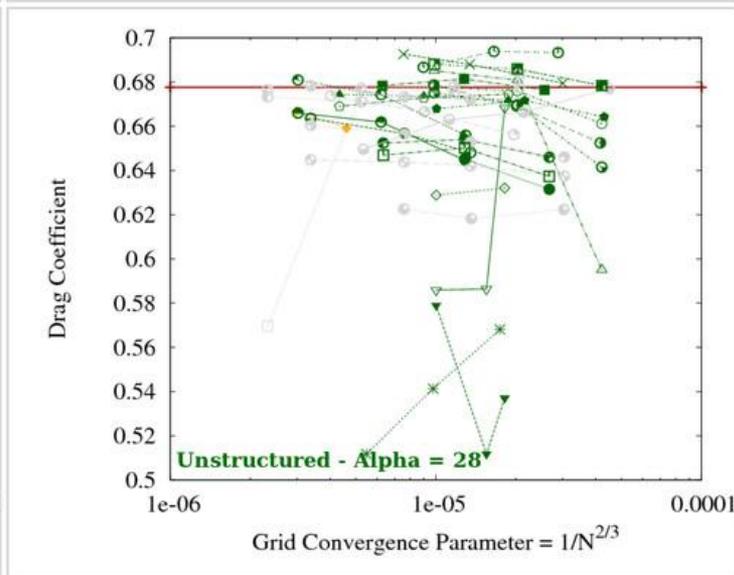
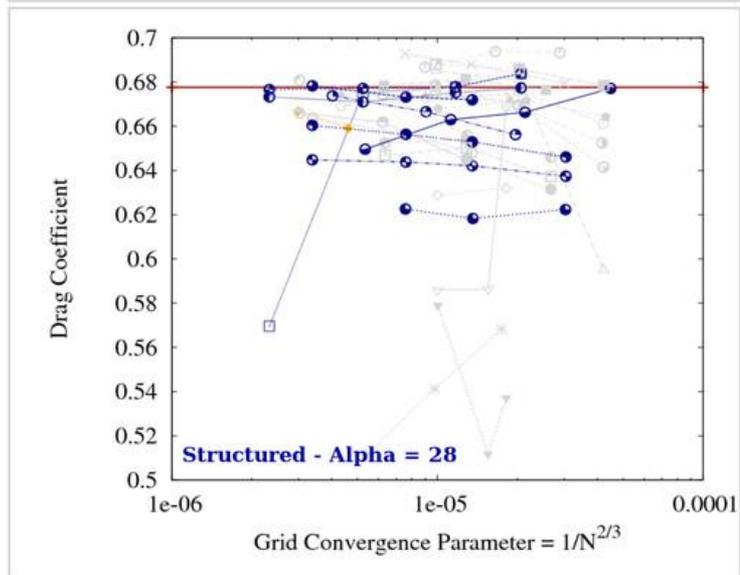
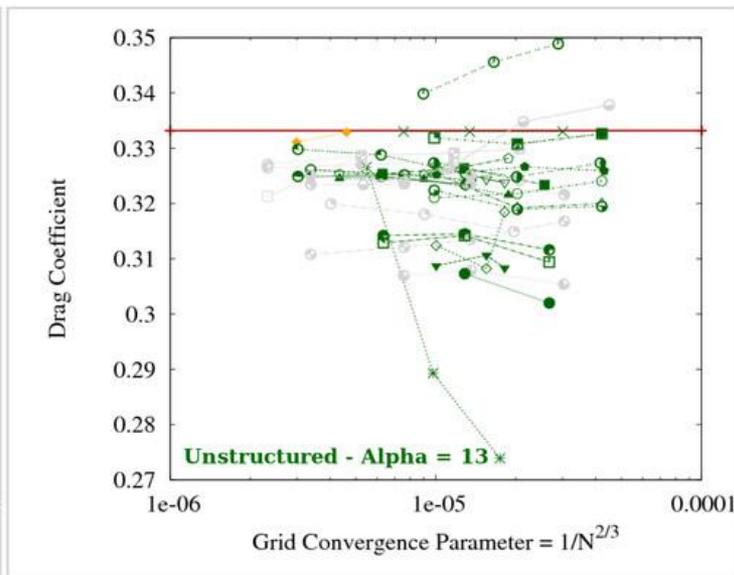
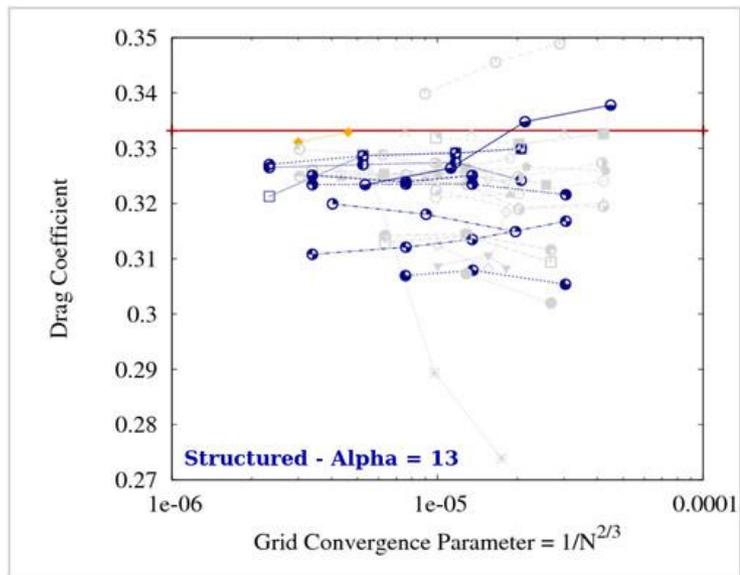
GRID CONVERGENCE BEHAVIOR

Structured vs. unstructured CL



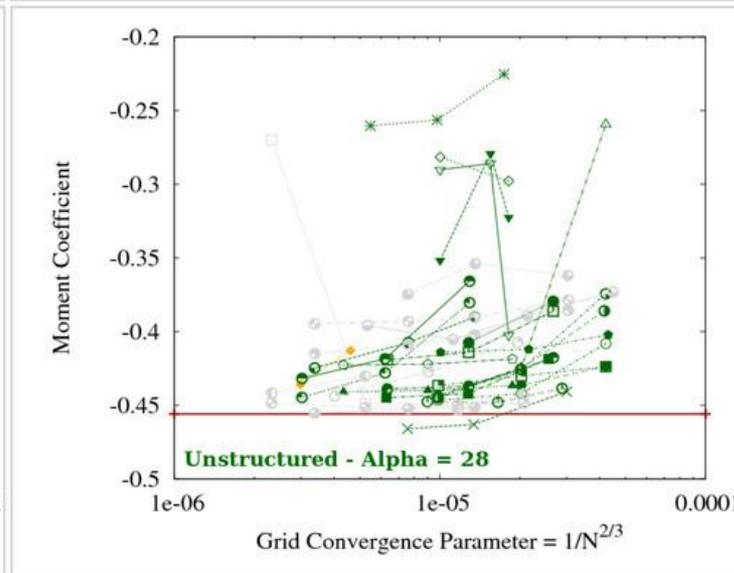
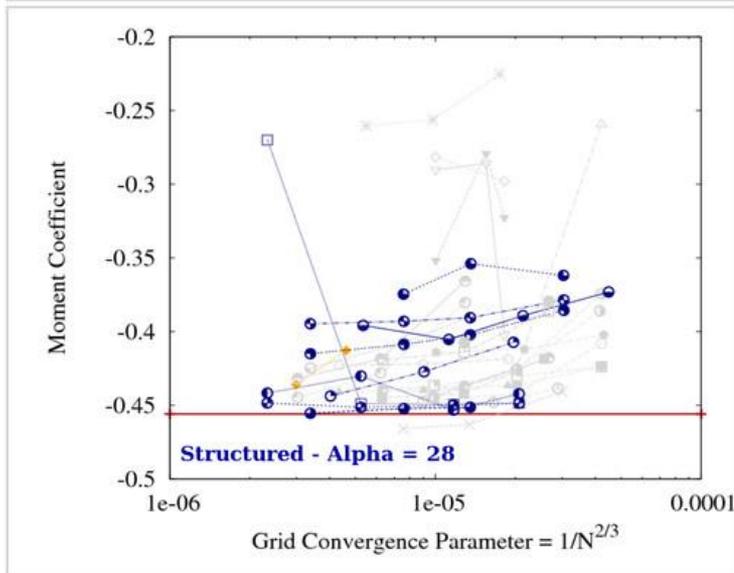
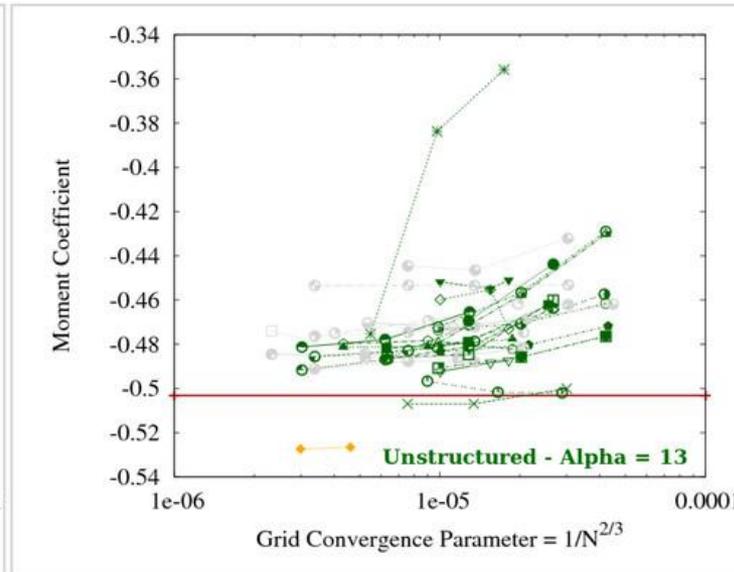
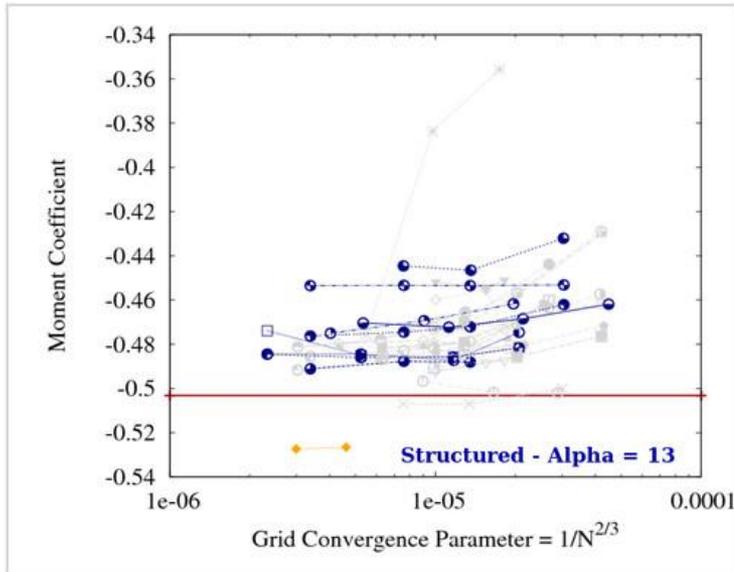
000-Exp	+
001	x
002	*
003.01	□
004	■
005.01	○
005.02	●
006	△
007	▲
008.01	▽
008.02	▼
008.03	◇
009	◆
010	⬠
011	⬢
012.01	⊖
012.02	⊗
013.01	⊙
013.02	⊚
013.03	⊛
014.01	⊜
014.02	⊝
015	⊞
016	⊠
017.01	⊡
017.02	⊣
017.03	⊥
017.04	⊦
018	⊧
019	⊨
020.01	⊩
020.02	⊪
021.01	⊫

Structured vs. unstructured CD



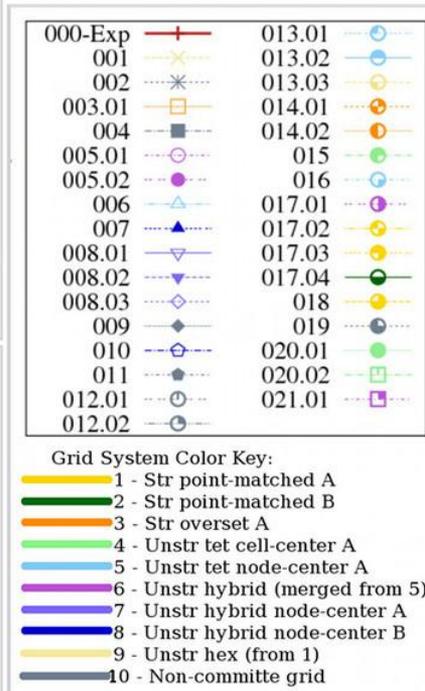
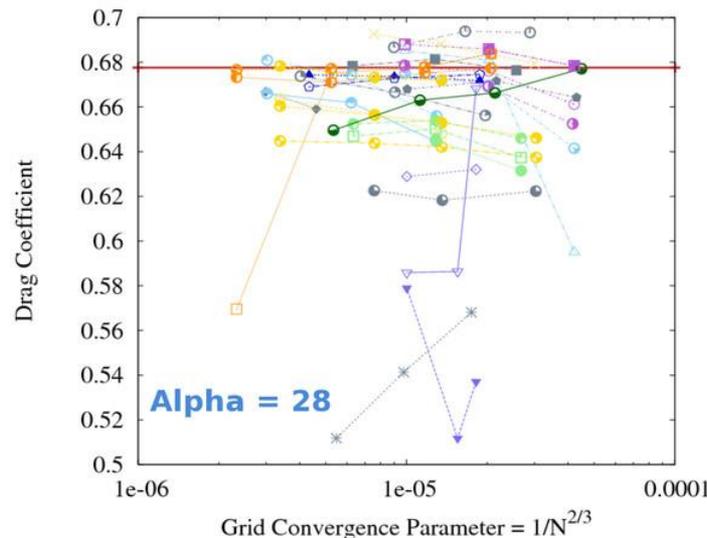
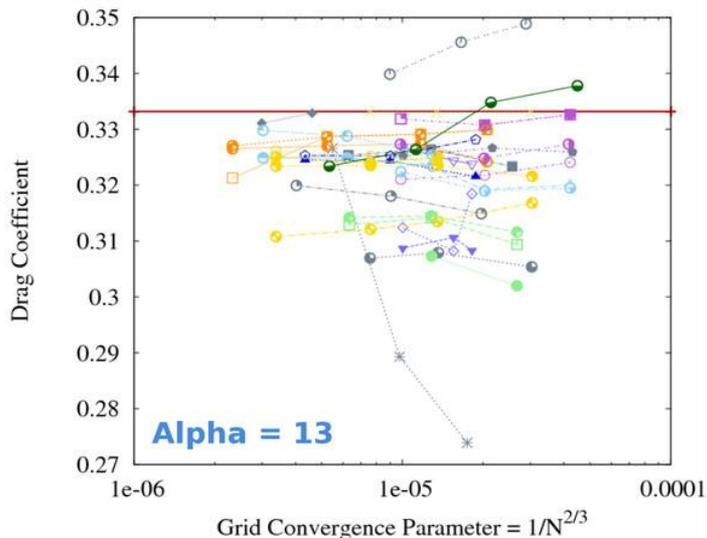
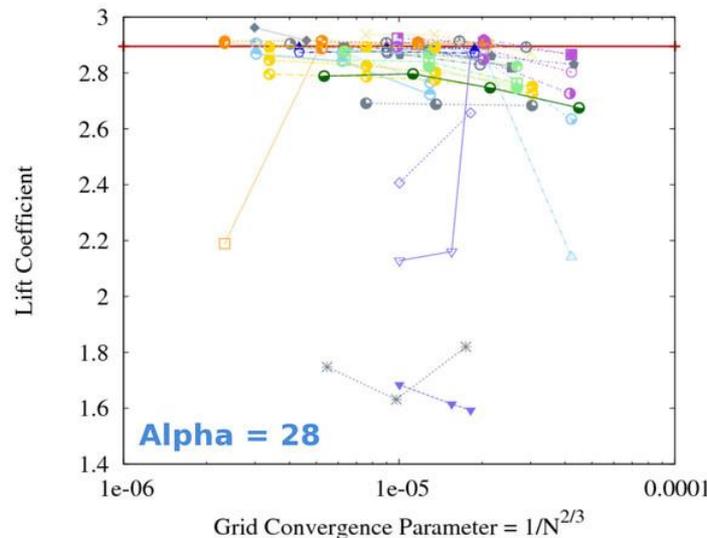
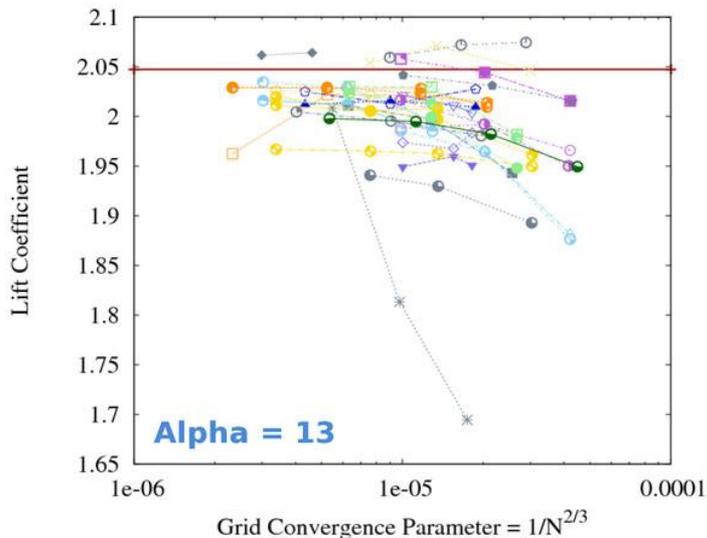
000-Exp	+
001	x
002	*
003.01	□
004	■
005.01	○
005.02	●
006	△
007	▲
008.01	▽
008.02	▼
008.03	◇
009	◆
010	◇
011	●
012.01	○
012.02	●
013.01	○
013.02	●
013.03	○
014.01	●
014.02	●
015	●
016	○
017.01	●
017.02	●
017.03	●
017.04	○
018	●
019	●
020.01	●
020.02	□
021.01	■

Structured vs. unstructured CM

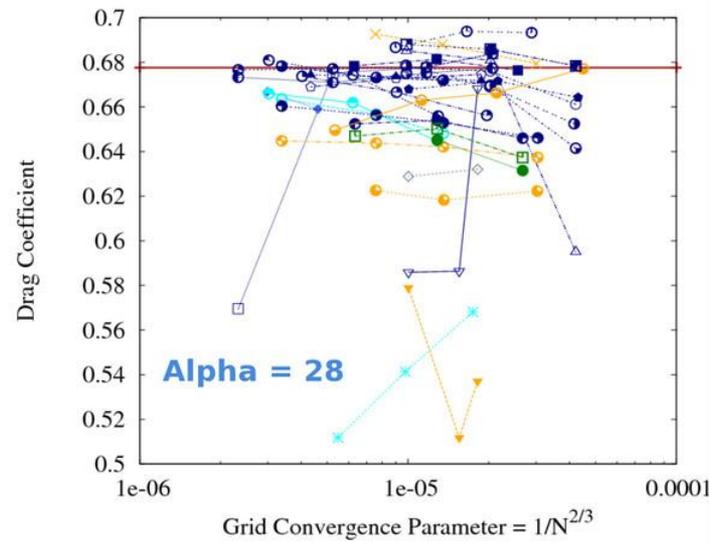
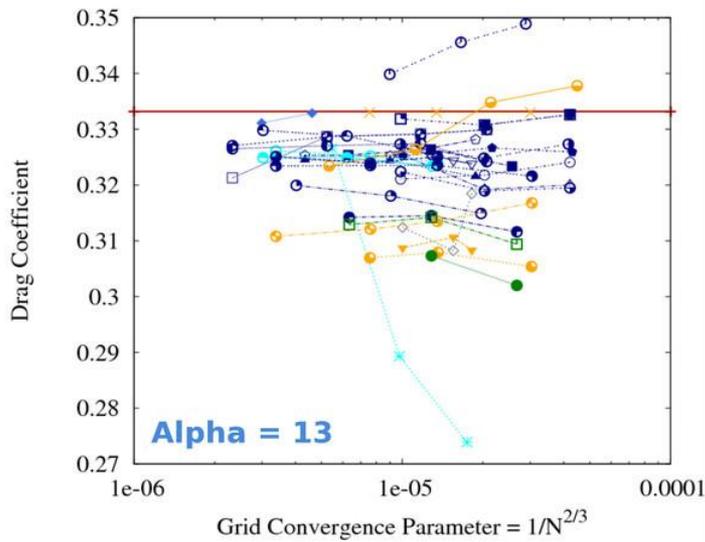
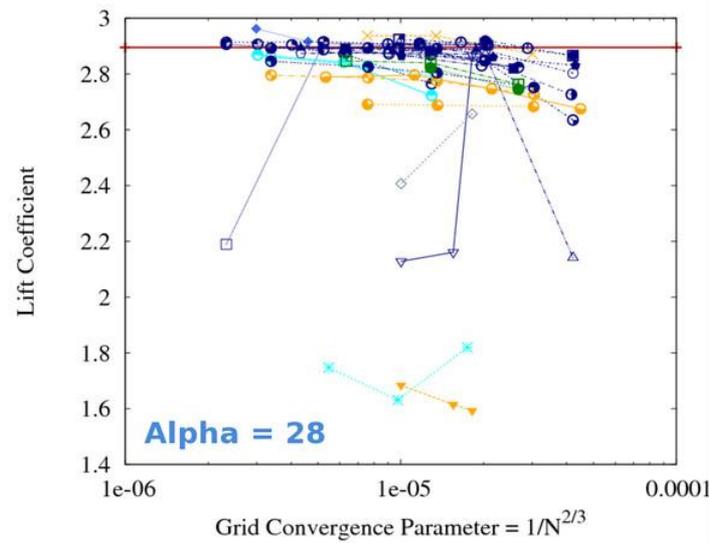
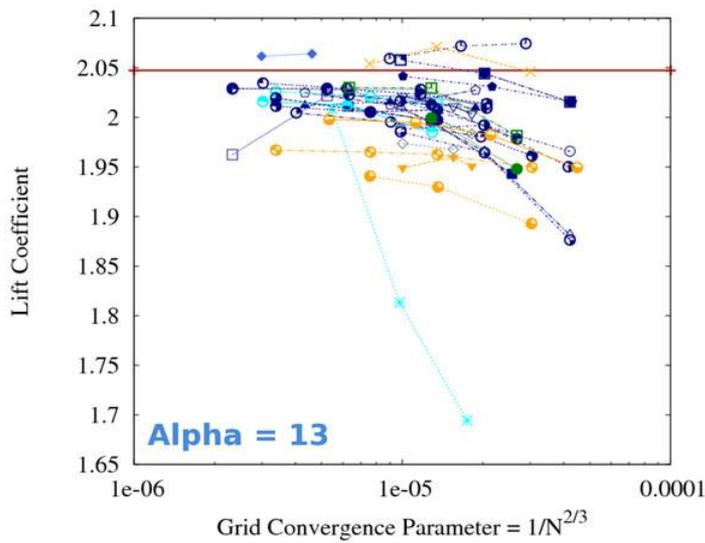


000-Exp	+
001	x
002	*
003.01	□
004	■
005.01	○
005.02	●
006	△
007	▲
008.01	▽
008.02	▼
008.03	◇
009	◆
010	◇
011	●
012.01	○
012.02	●
013.01	○
013.02	●
013.03	○
014.01	○
014.02	●
015	●
016	○
017.01	●
017.02	○
017.03	●
017.04	○
018	●
019	●
020.01	●
020.02	□
021.01	■

CL and CD by grid system



CL and CD by turbulence model



000-Exp	+	013.01	○
001	x	013.02	○
002	*	013.03	○
003.01	□	014.01	○
004	■	014.02	○
005.01	○	015	○
005.02	●	016	○
006	▲	017.01	○
007	◆	017.02	○
008.01	▽	017.03	○
008.02	∇	017.04	○
008.03	◇	018	○
009	◇	019	○
010	◇	020.01	○
011	◇	020.02	○
012.01	◇	021.01	○
012.02	◇		

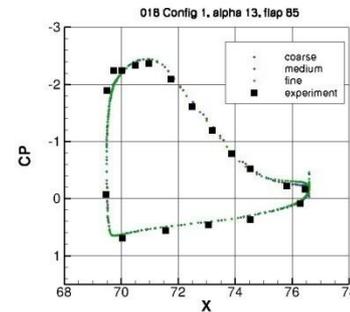
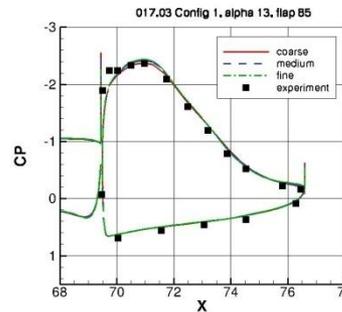
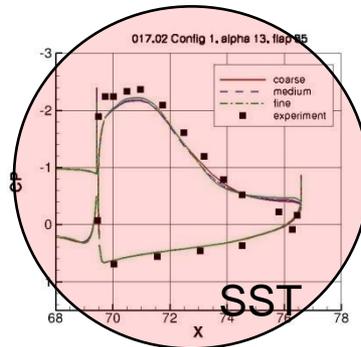
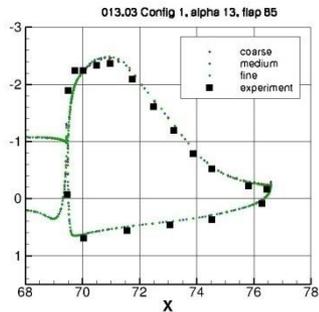
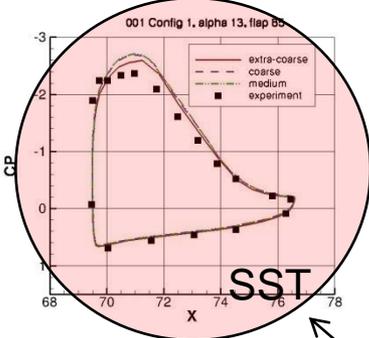
Color Key:

- Spalart-Allmaras
- Menter Shear Stress Transport
- K-Epsilon
- Very Large Eddy Simulation
- Reynolds Stress Model
- Wilcox K-Omega

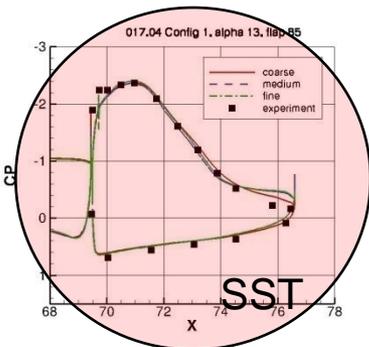
SURFACE PRESSURE & SKIN FRICTION

Cp, alpha=13, flap 85 (1)

SX1 & UX9

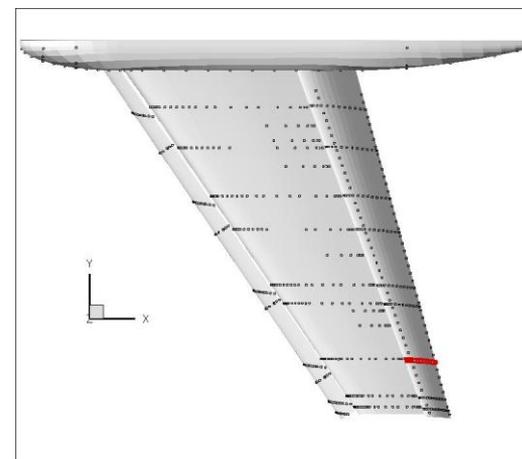


SX2

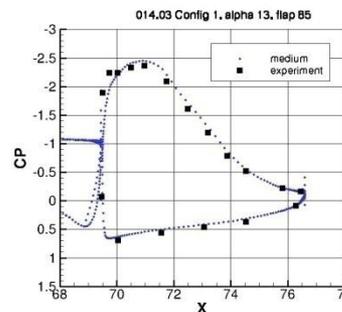
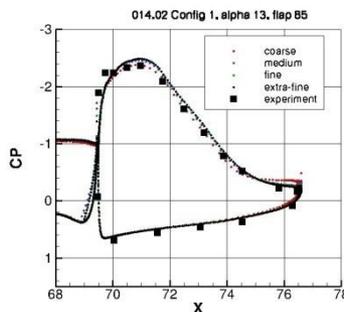
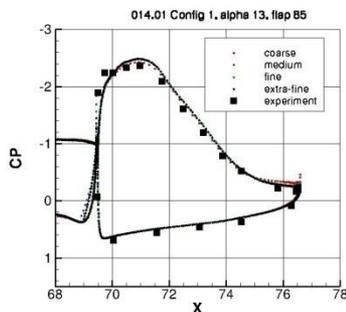
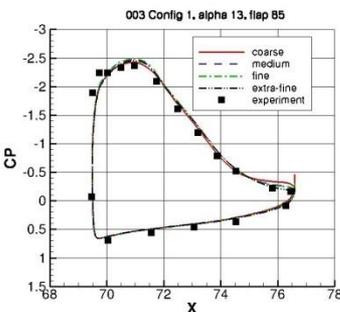


transition incl.

Red circles – SST
Yellow circles – most grid-sensitive

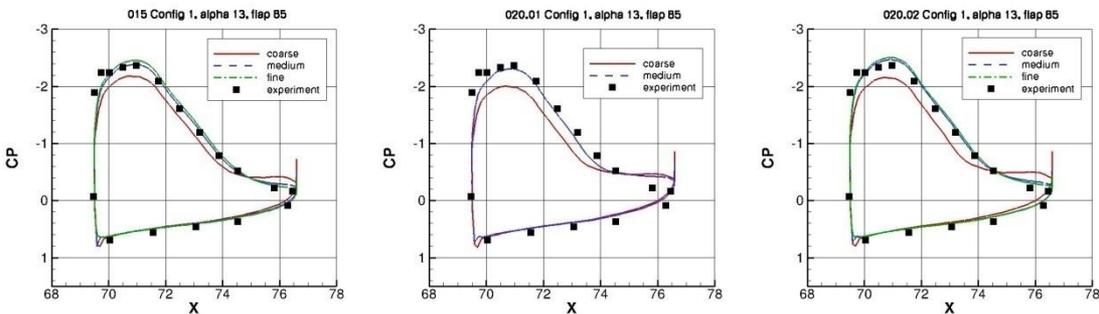


SX3

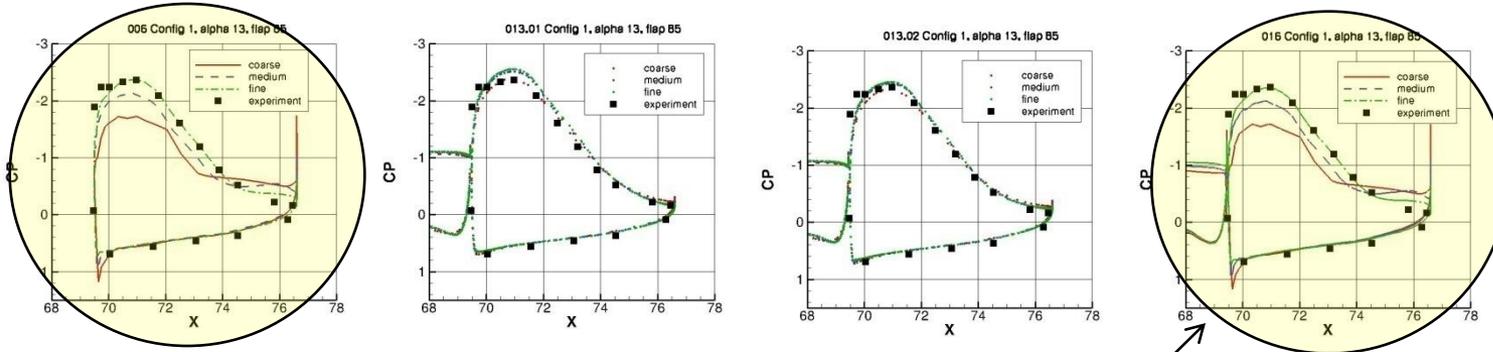


Cp, alpha=13, flap 85 (2)

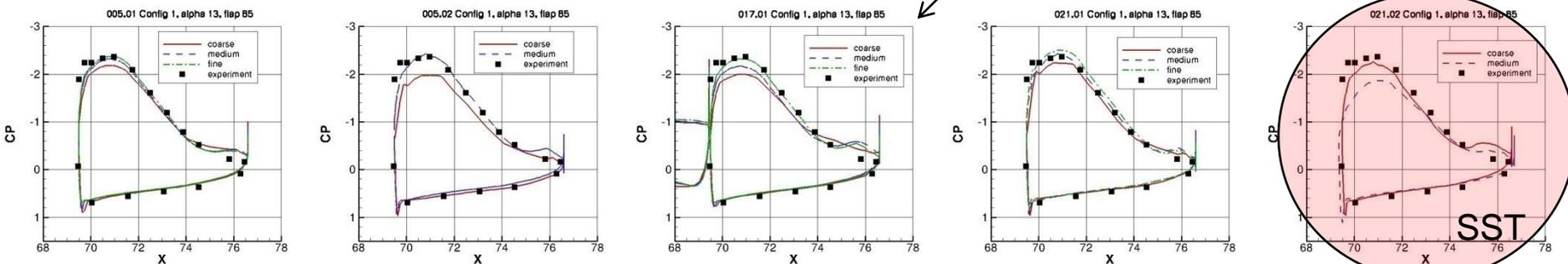
UT4



UT5

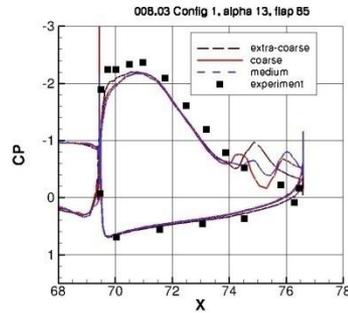
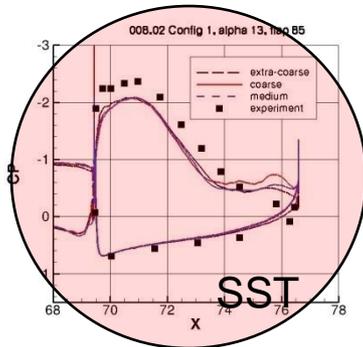
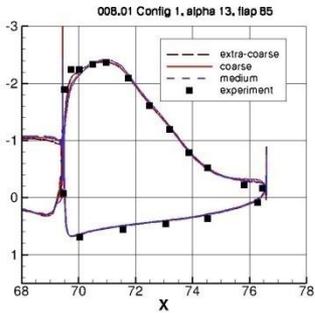


UH6

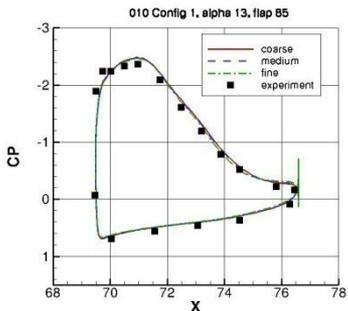
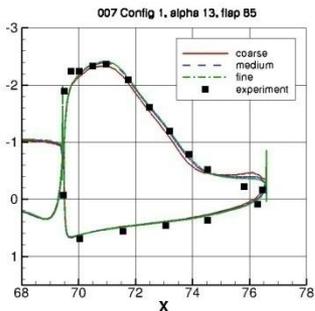


Cp, alpha=13, flap 85 (3)

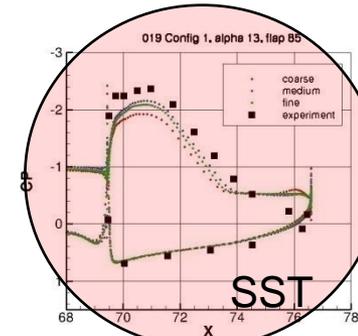
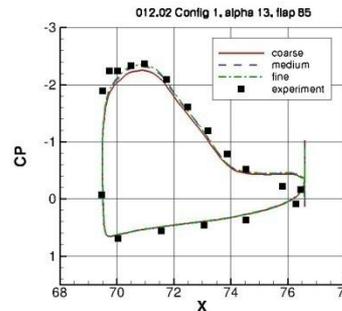
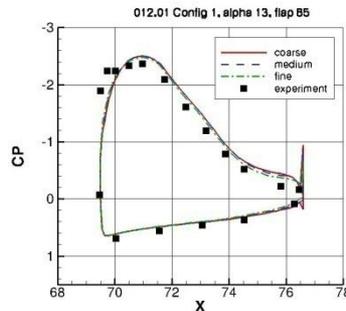
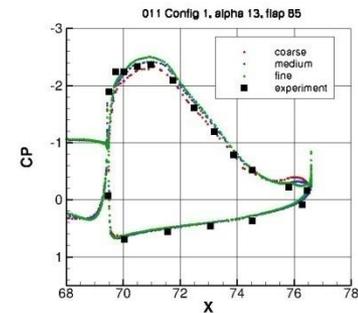
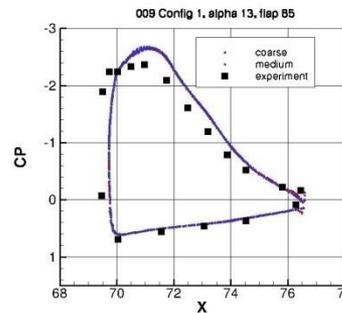
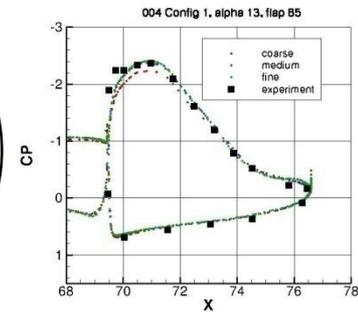
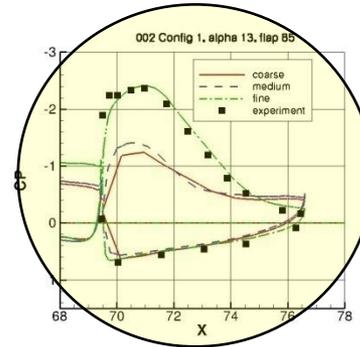
UH7



UH8



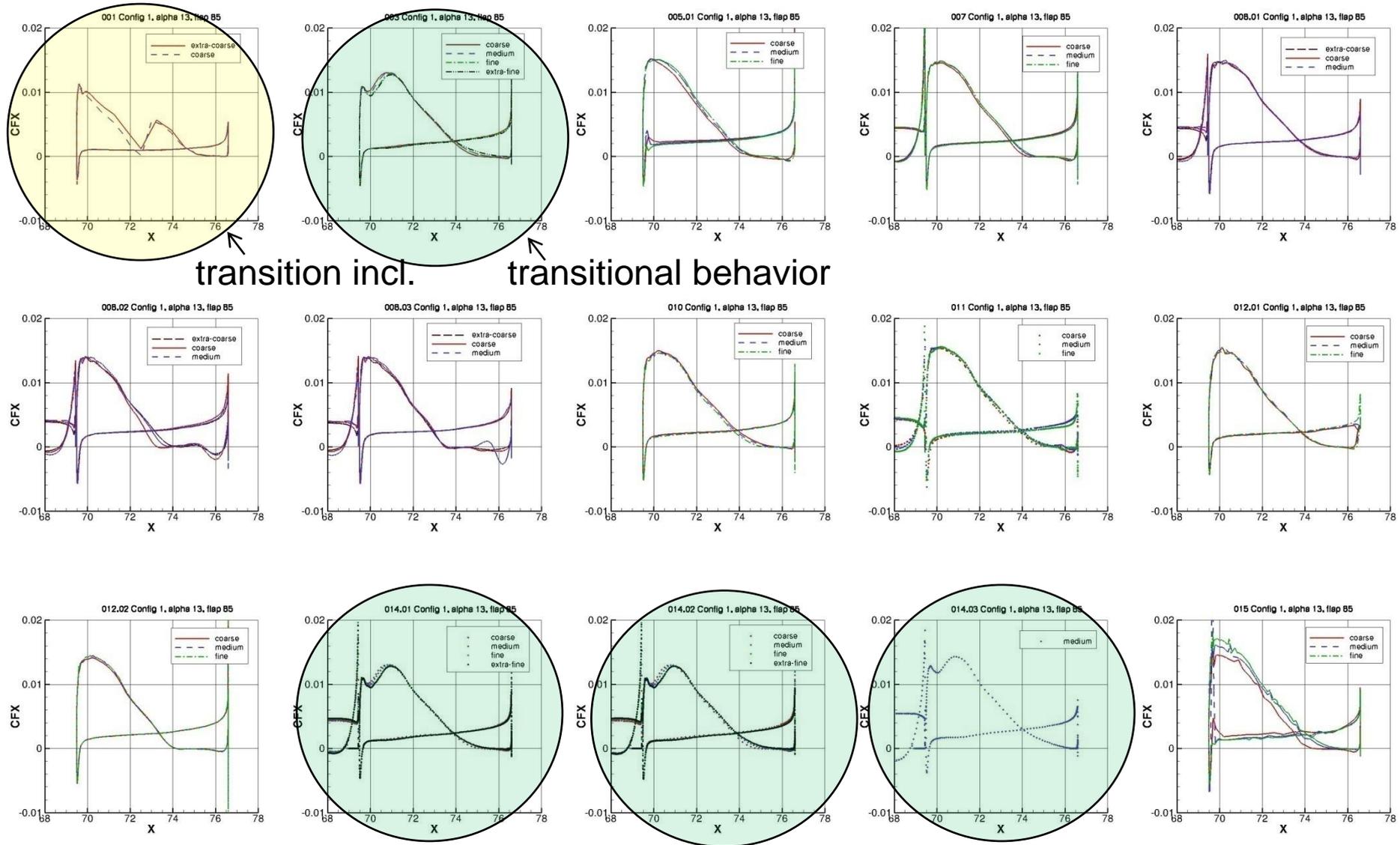
Others



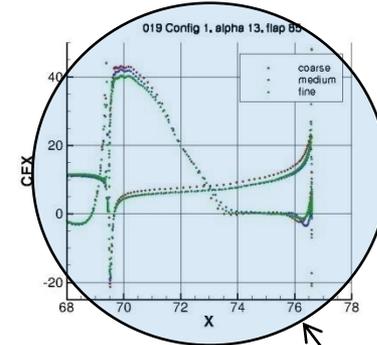
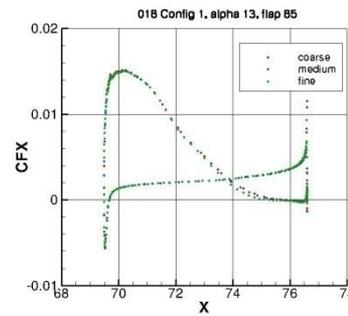
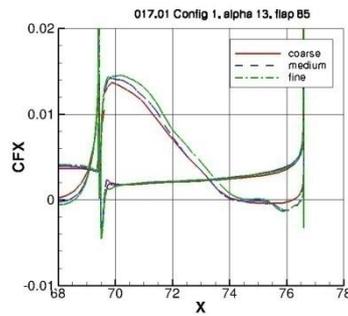
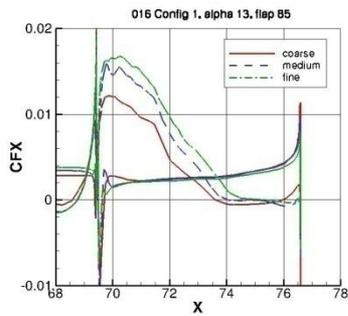
Cp, alpha=13, flap 85 (4)

- 5 out of 6 SSTs missed T.E. pressures at this station
- Among SA, 12 did well with T.E. pressures, 9 not as well
 - SA runs that missed T.E. more than others: 005.01, 005.02, 006, 007, 012.01, 012.02, 016, 017.01, 021.01
 - Reason(s) for differences not clear
- Most grid-sensitive:
 - 002, 006, 016
 - Jury out on 005.02, 014.03, 020.01, 021.02 (need Fine grid result)
 - Same grid UT5 (tets) more grid-sensitive than UH6 (merged into prisms in B.L.) when run in same code (FUN3D)
- Also looked at stations 17 (not shown)
 - All seem to get T.E. Cps on flap okay
 - Similar results (as flap 85) regarding grid sensitivity
 - Some participants get upper surface peak Cps worse than others
 - 007 and 019 exhibited odd-even decoupling on slat 17 (alpha=13)

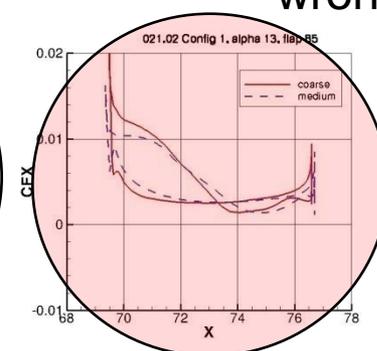
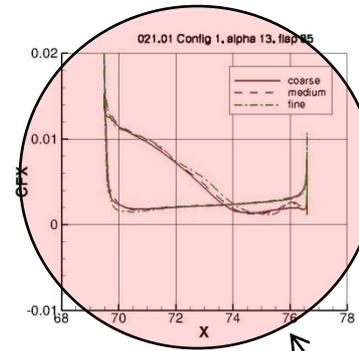
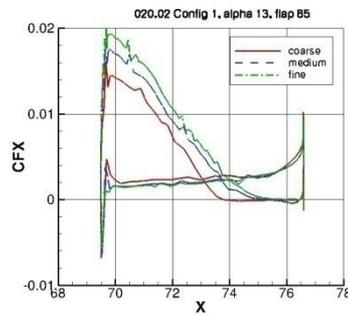
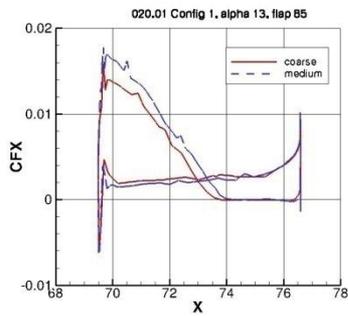
Cf, alpha=13, flap 85 (1)



Cf, alpha=13, flap 85 (2)



wrong levels



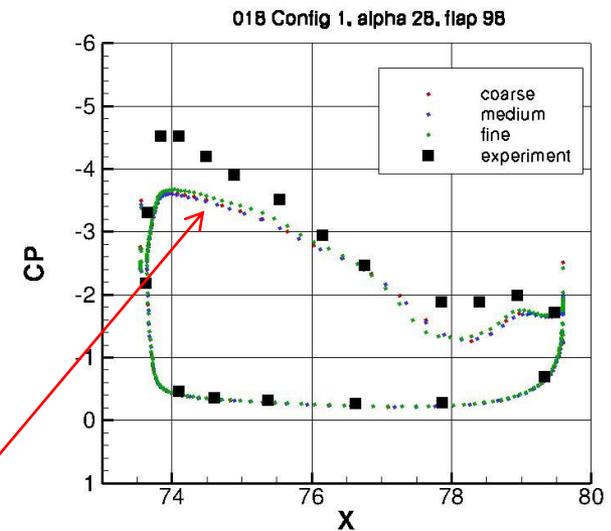
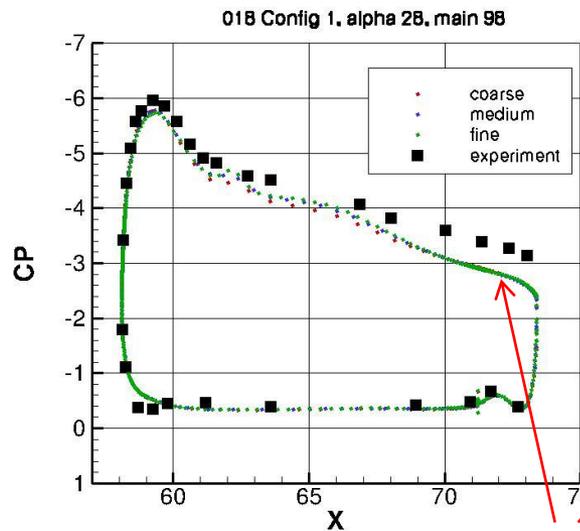
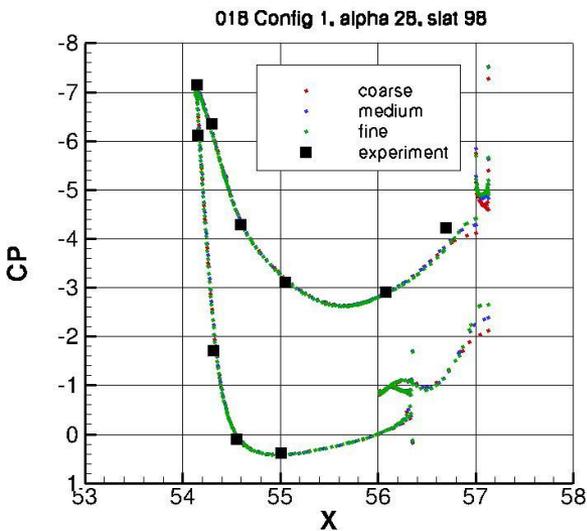
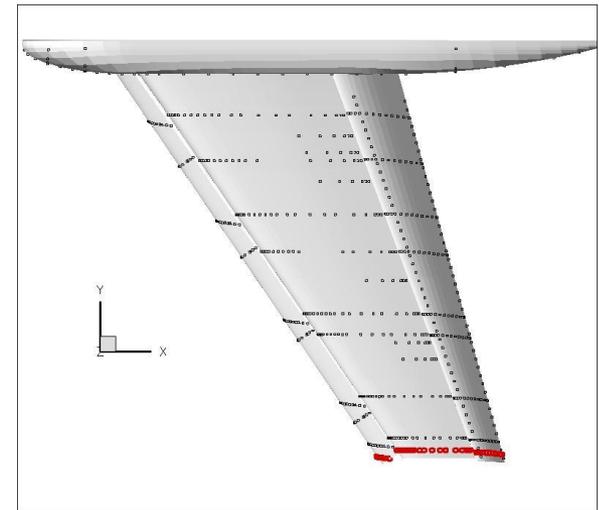
no separation

Cf, alpha=13, flap 85 (2)

- Cf not reported by all participants
- 001 has very different CF shape (transition incl. in model)
- OVERFLOW indicates transitional flow even though fully turbulent
 - This code used SA+fv3, a version known to have this tendency
- 019 reported incorrect CF levels
- Near flap T.E., 021.01 and 021.02 stand out from the others
 - All others predict upper surface T.E. separation or incipient separation
 - But participant showed separated streamlines in his talk

Flow near wingtip at alpha=28

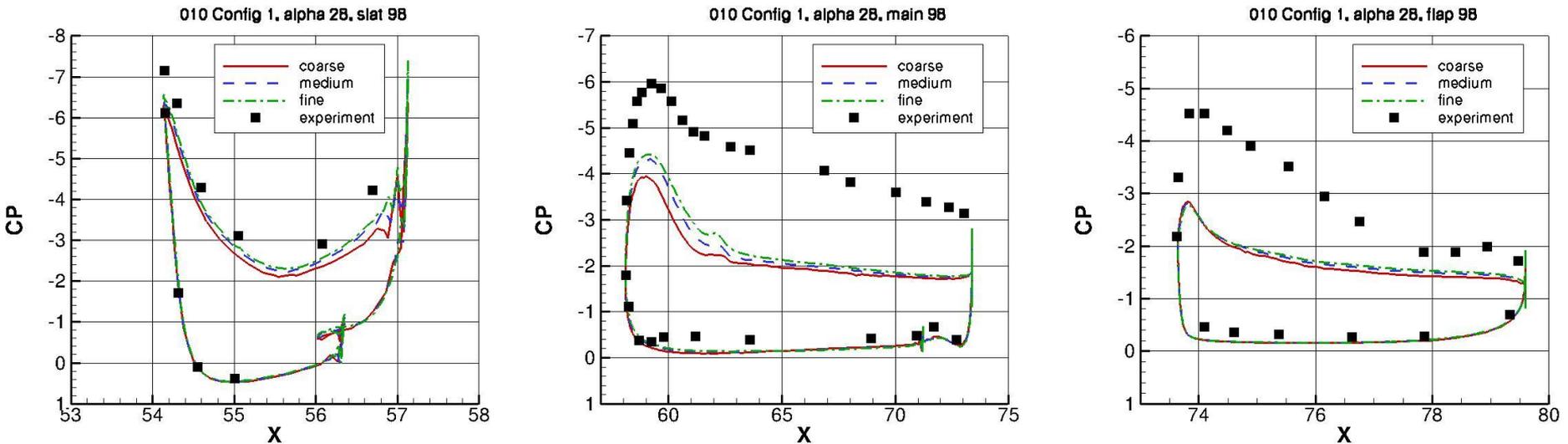
- All participants predicted flow near flap wingtip poorly (true at alpha=13 also)



This is an example of one of the best results

Flow near wingtip at alpha=28

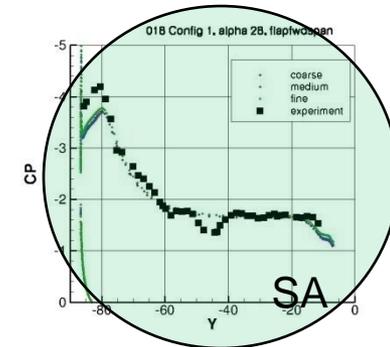
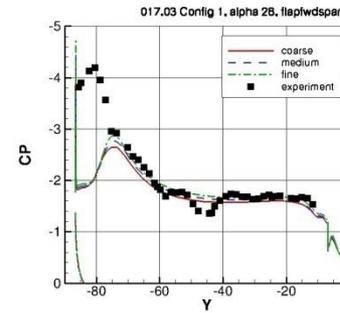
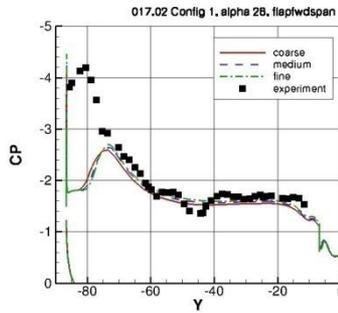
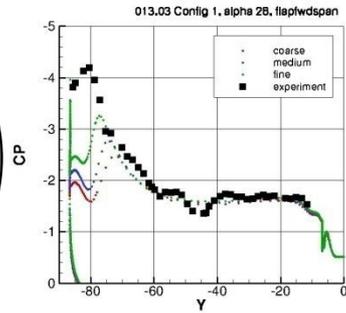
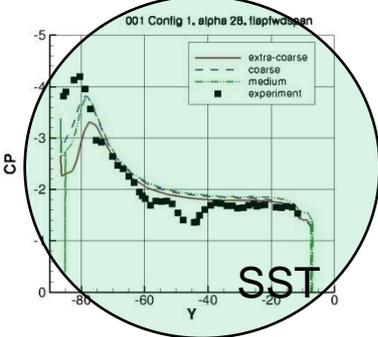
This is an example of the most common results (“Fair”)



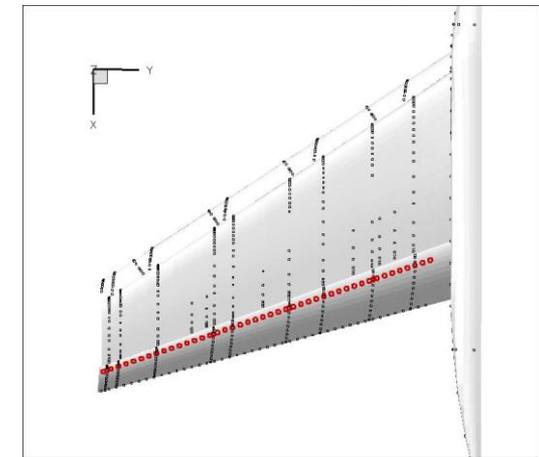
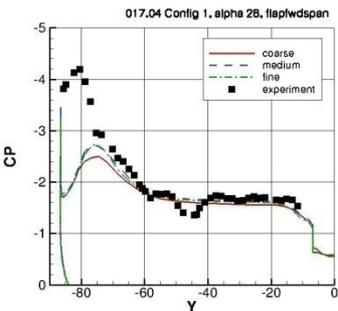
- Looking at spanwise flap stations is a good way to see the problem

Cp, alpha=28, flapfwdspan (1)

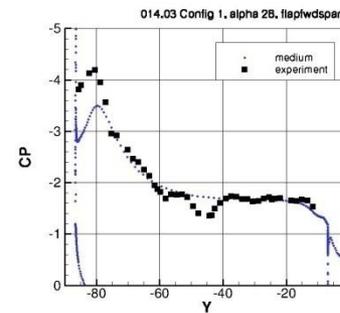
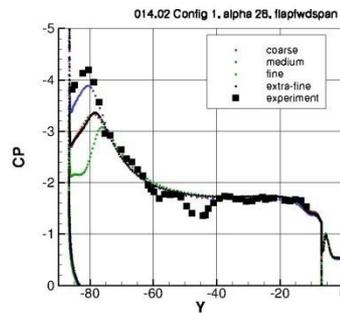
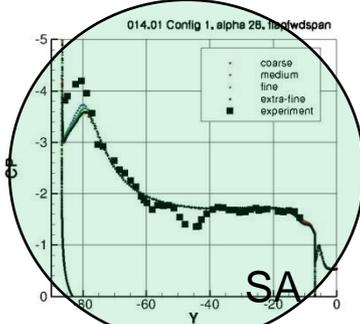
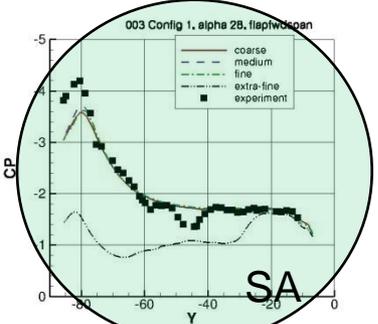
SX1 & UX9



SX2

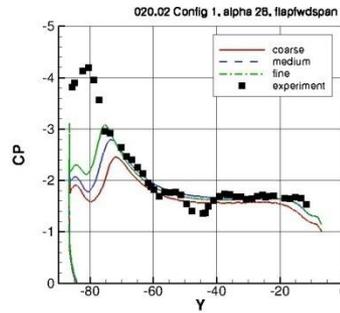
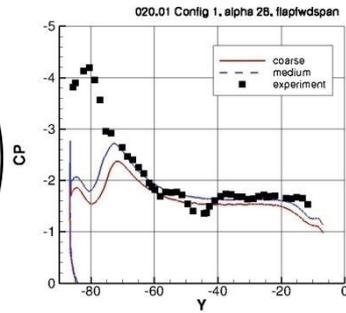
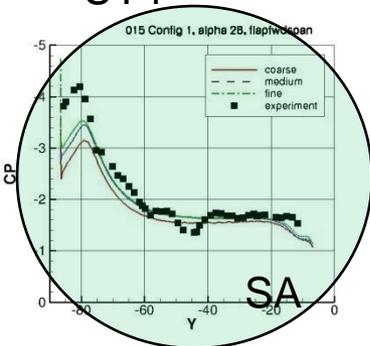


SX3

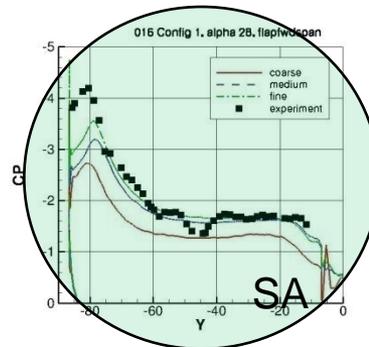
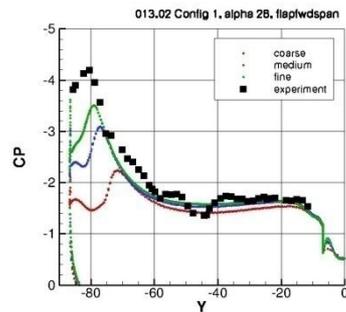
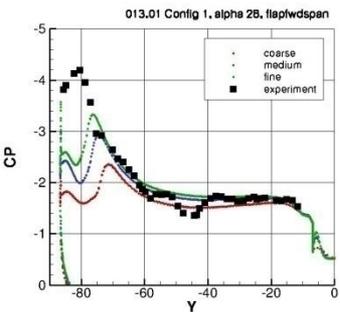


Cp, alpha=28, flapfwdspan (2)

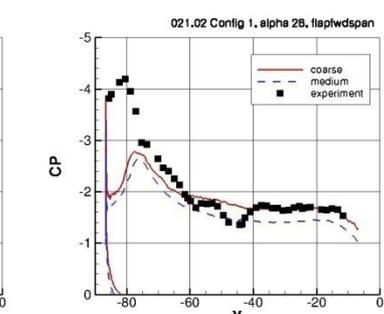
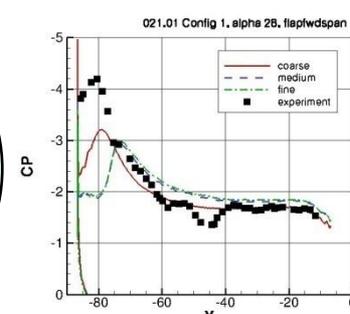
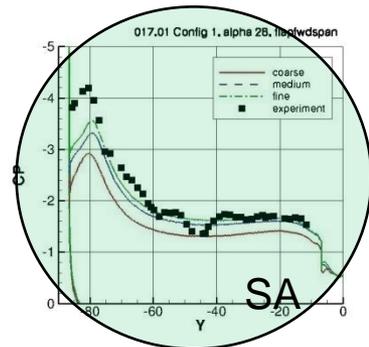
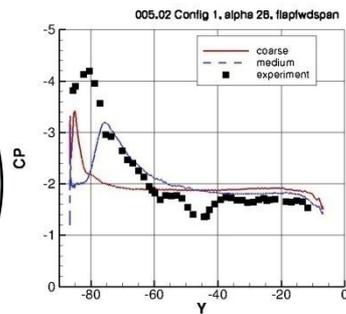
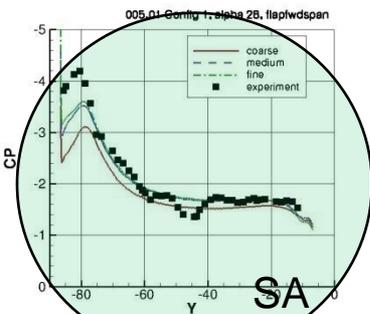
UT4



UT5

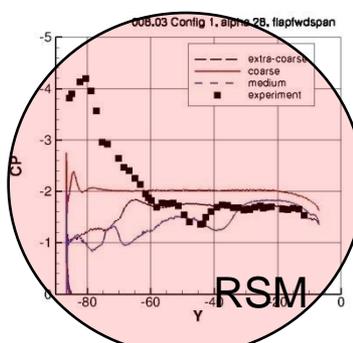
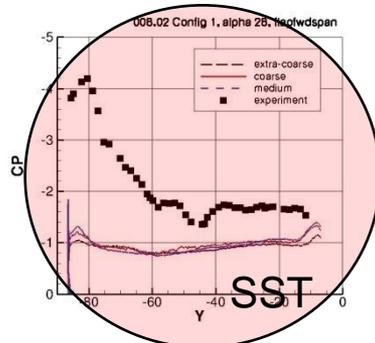
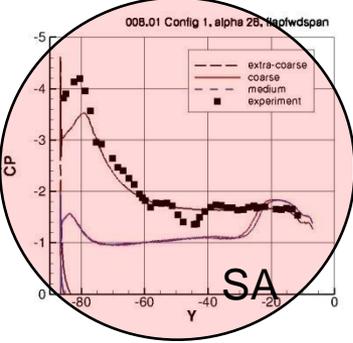


UH6

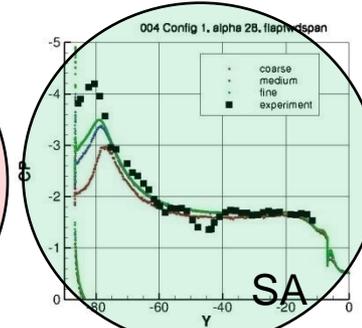
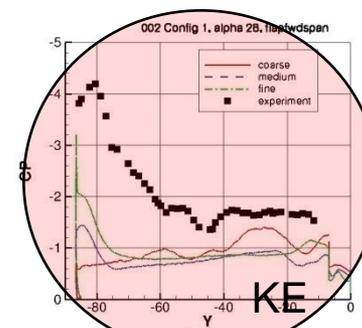


Cp, alpha=28, flapfwdspan (3)

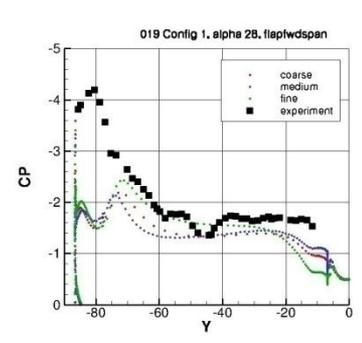
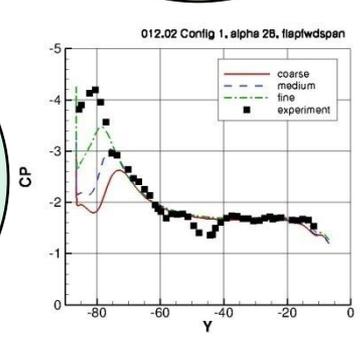
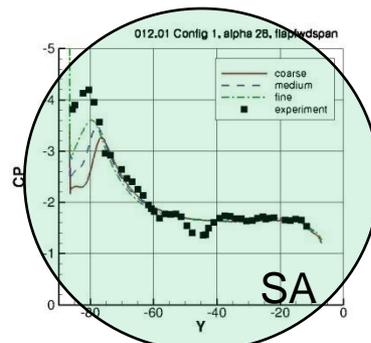
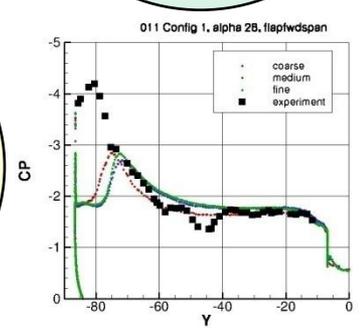
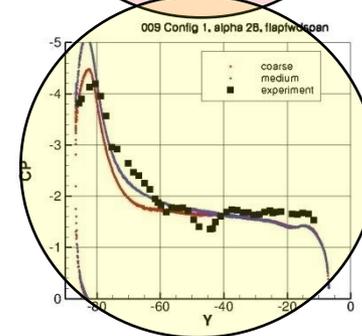
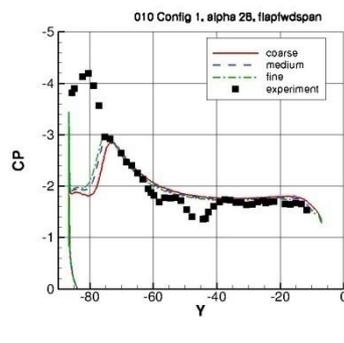
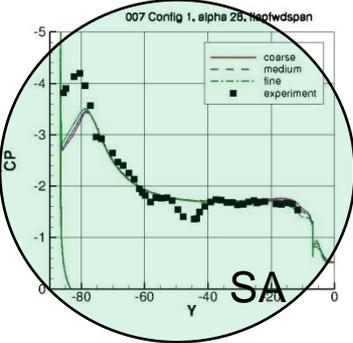
UH7



Others



UH8



Cp, alpha=28, flapfwdspan (4)

Subjective grouping:

(only listed here if 2 or more grid levels used)

- **Best:**
 - 003 (but not XF), 005.01, 014.01, 015, 018
- **Very good:**
 - 001, 004, 007, 012.01, 016, 017.01
- **Good:**
 - 009, 012.02, 013.01, 013.02, 013.03, 014.02
- **Fair:**
 - 005.02, 010, 011, 017.02, 017.03, 017.04, 019, 020.01, 020.02, 021.01, 021.02
- **Furthest from the data:**
 - 002, 008.01, 008.02, 008.03

—Other than grid UH7, the grid system does not seem to be the main key to success/failure

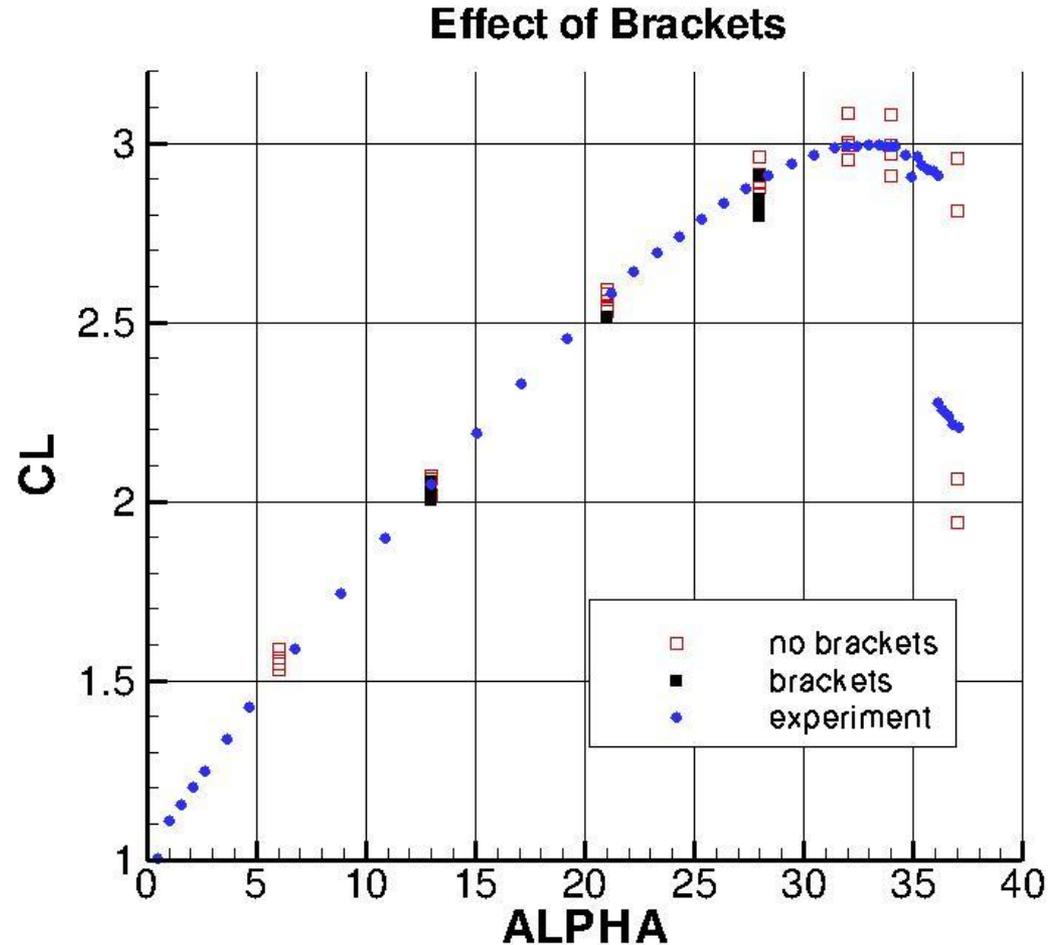
Some observations regarding tip flow

- Notes (based on flapfwdspan station only), accounting for trend near flap outboard tip as grid is refined:
 - Overset grid results among best (but there were inconsistencies)
 - TAU code with SA on UH8 grid good, but on UH7 among worst
 - Effect of grid? (more sensitive to ICs?)
 - USM3D on UT4 with SA good, but with k-omegas only fair
 - Effect of turbulence model?
 - SX1 grid with SA with ELSA among best, but with CFL3D only fair
 - Thin layer issue? Implementation difference?
 - UT5&UH6 grids with SA with FUN3D good, but NSU3D only fair
 - Thin layer issue? Implementation difference?
 - UH8 grid with SA with TAU good, but with EDGE only fair
 - Implementation difference?
 - 009 stands out at tip area

EFFECT OF BRACKETS

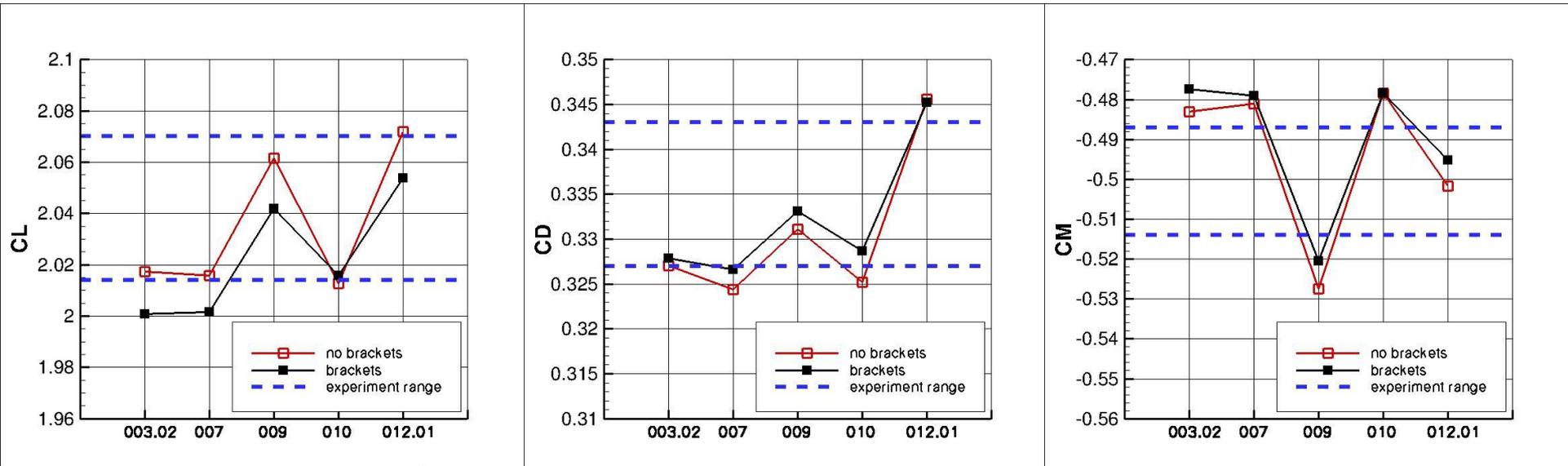
Effect of brackets

Trend with brackets:
slightly lower CL at
 $\alpha=13$, larger CL
drop at $\alpha=28$



Effect of brackets

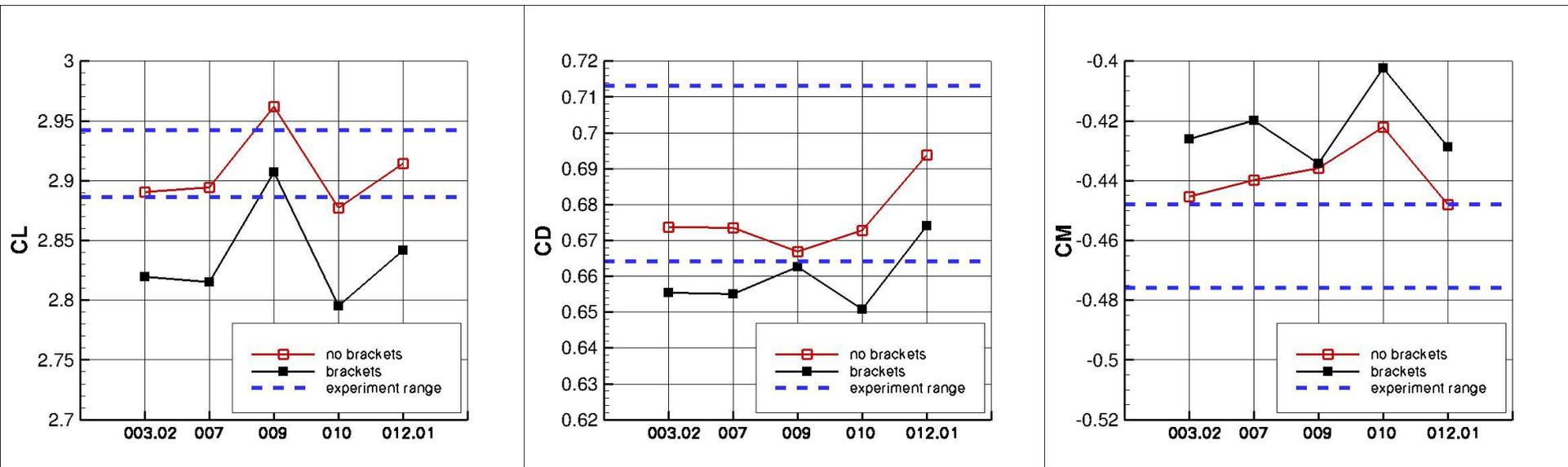
Alpha=13



Brackets have relatively minor effect:
typically slightly lower CL, higher CD,
higher CM

Effect of brackets

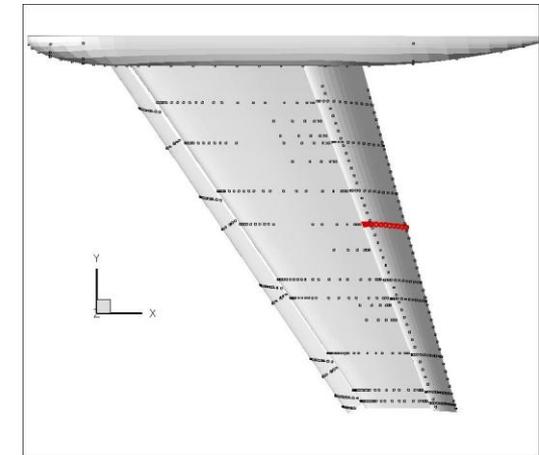
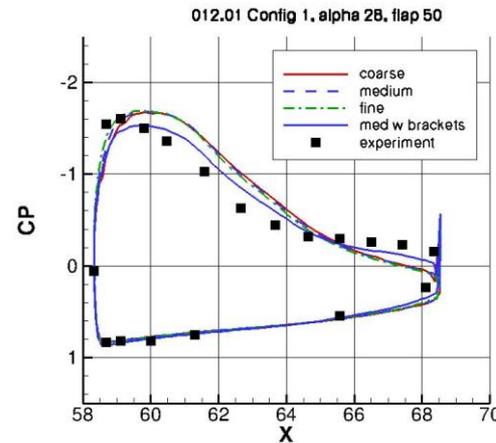
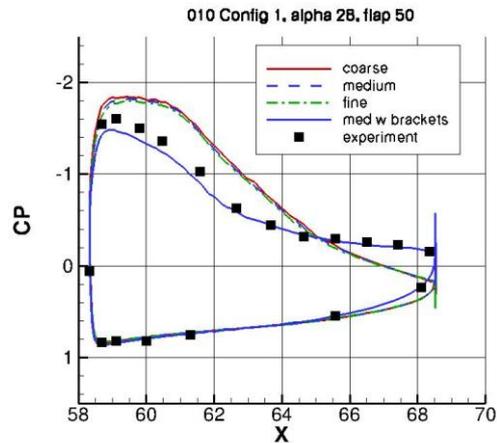
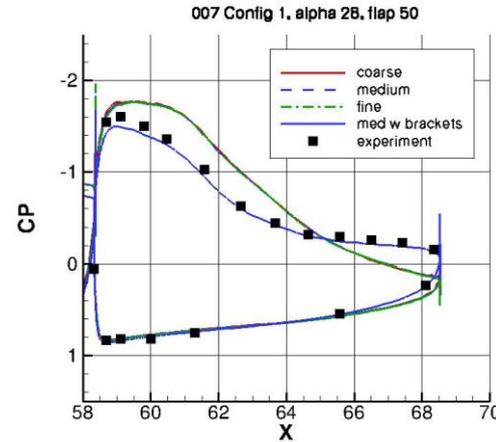
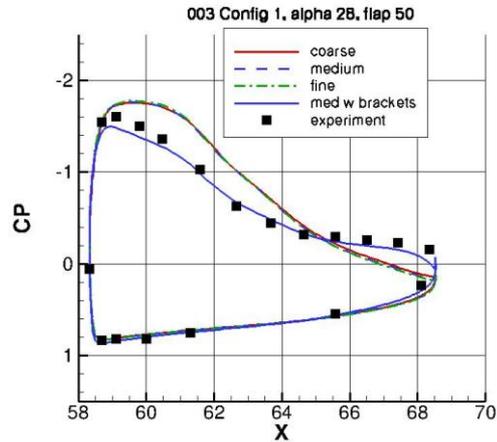
Alpha=28



Brackets have larger influence.
Collectively, CFD trend with brackets
is away from experiment (on Medium-
level grids) – grid study needed

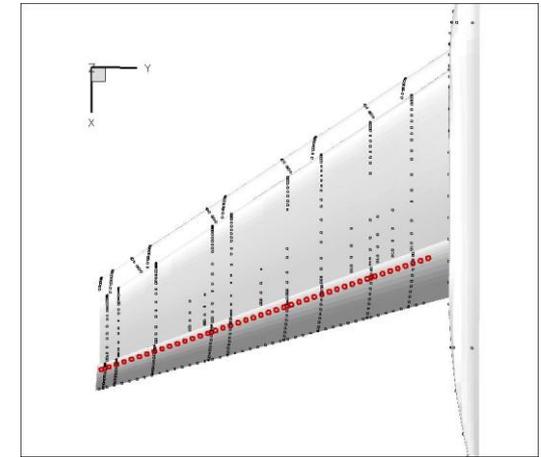
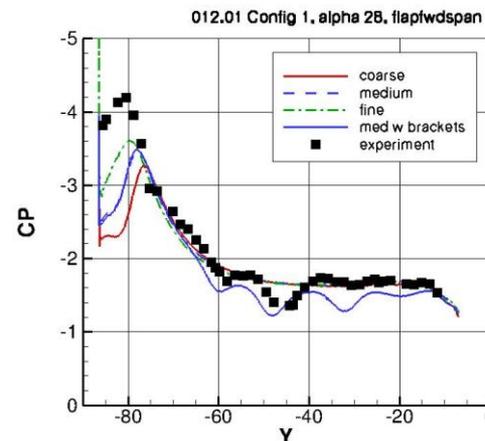
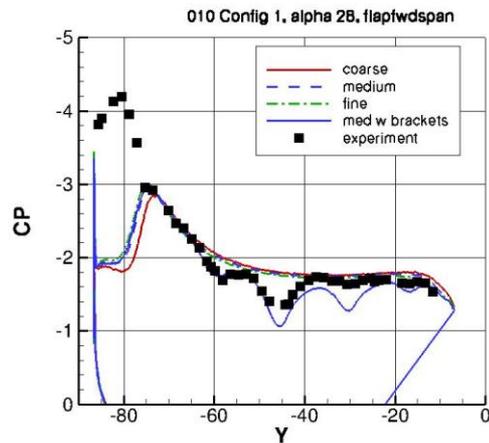
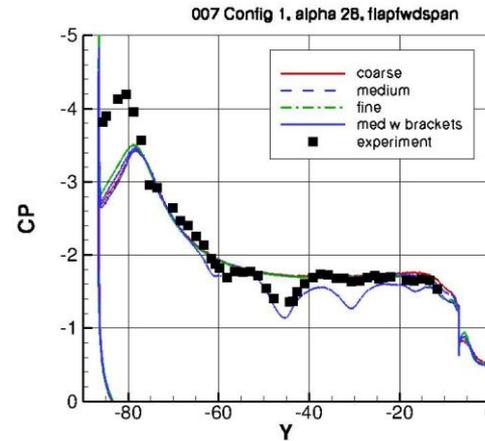
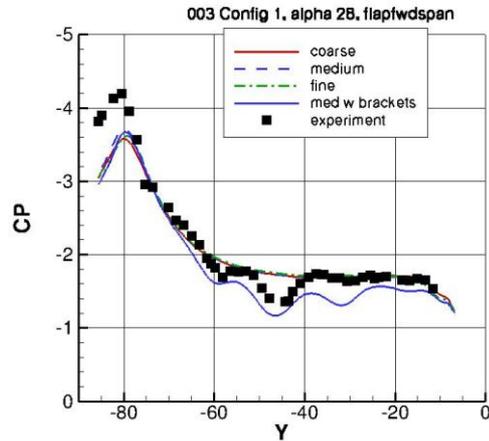
Effect of brackets

- Bracket effect can be seen at Cp station flap 50



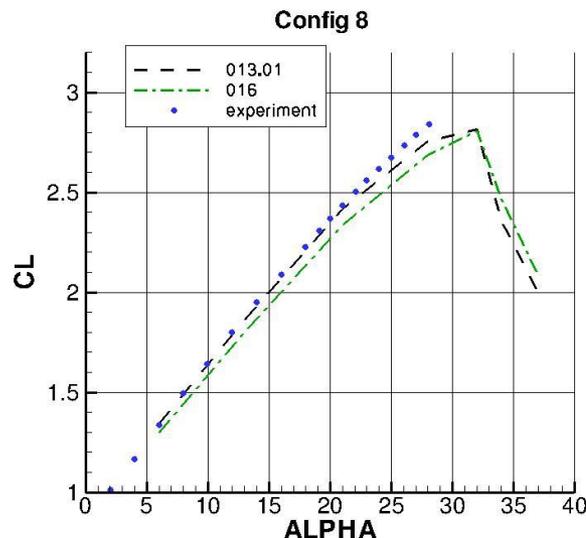
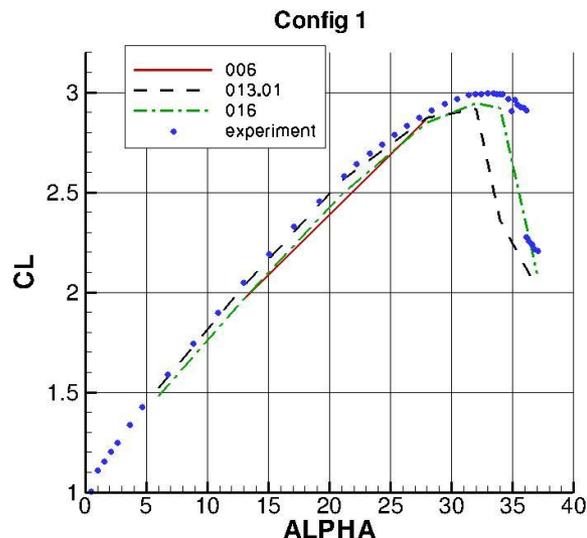
Effect of brackets

- Bracket effect can be seen at Cp station flapwdspan

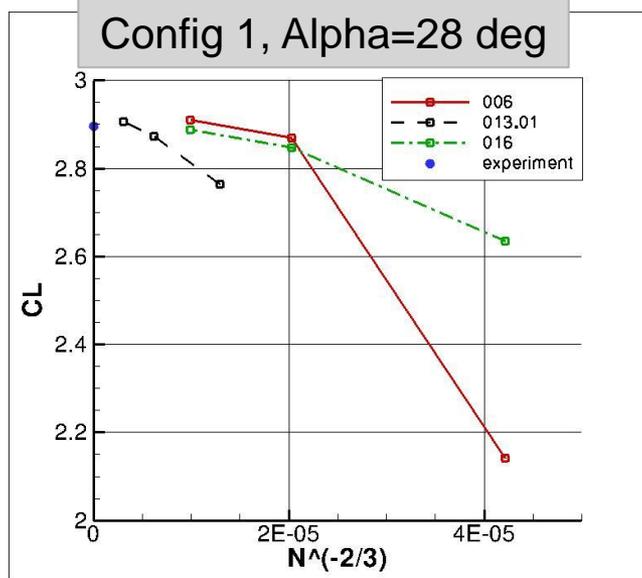
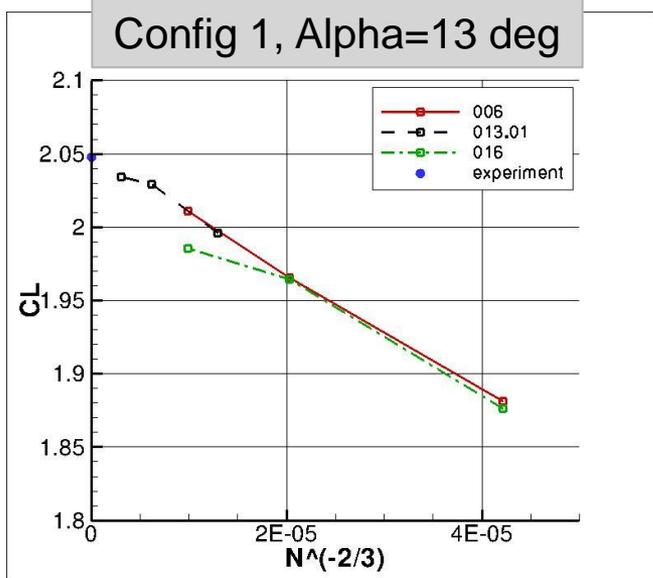


OTHER COMPARISONS

006 vs. 013.01 vs. 016



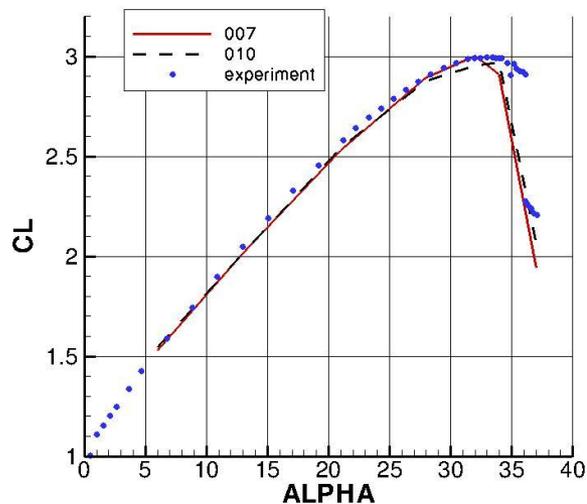
013.01 cell-center code, so approx 6x more resolution with same grid points for tets than 006 or 016 (node-center)



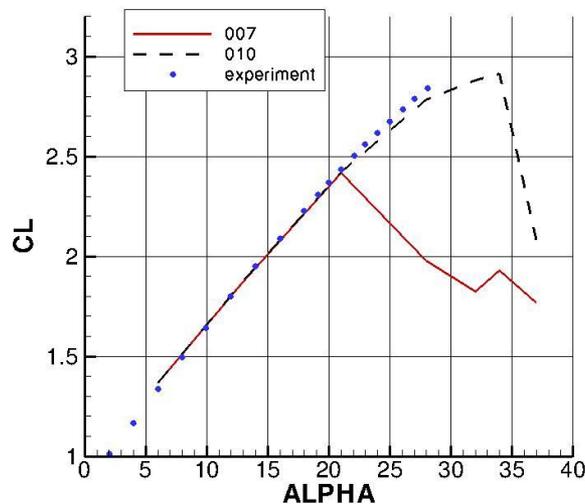
006 and 016 are same code: differences due to effect of ICs in 006?

007 vs. 010

Config 1

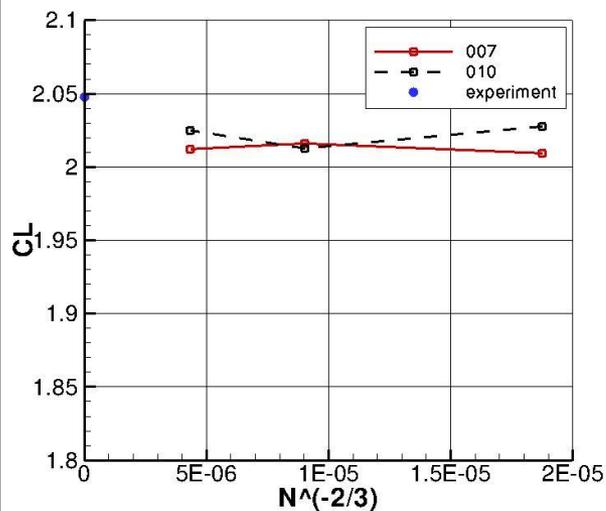


Config 8

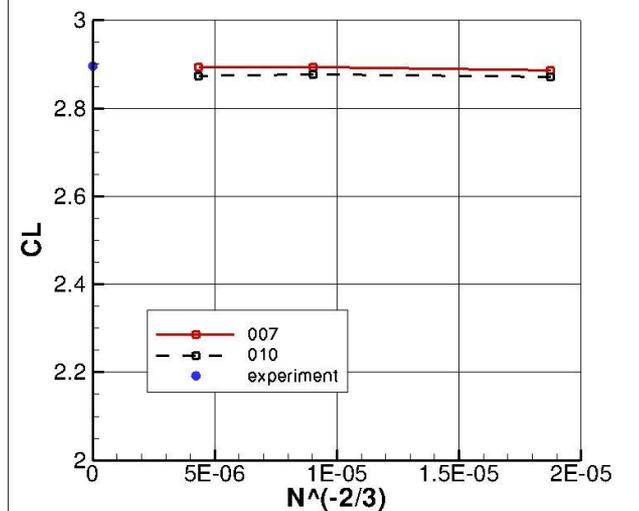


Similar results
except for Config
8 past alpha=21

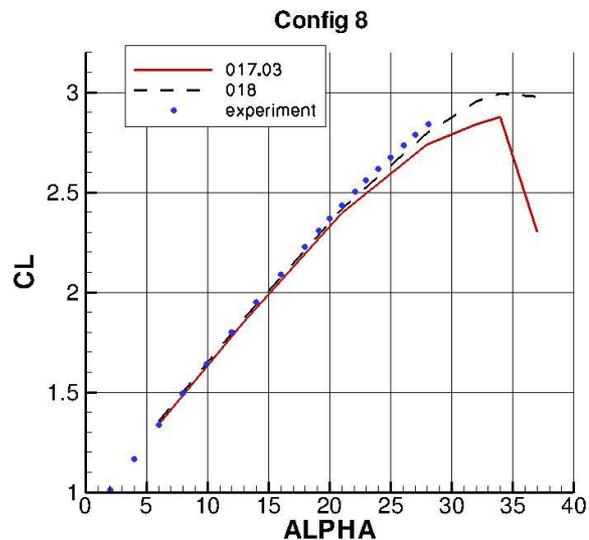
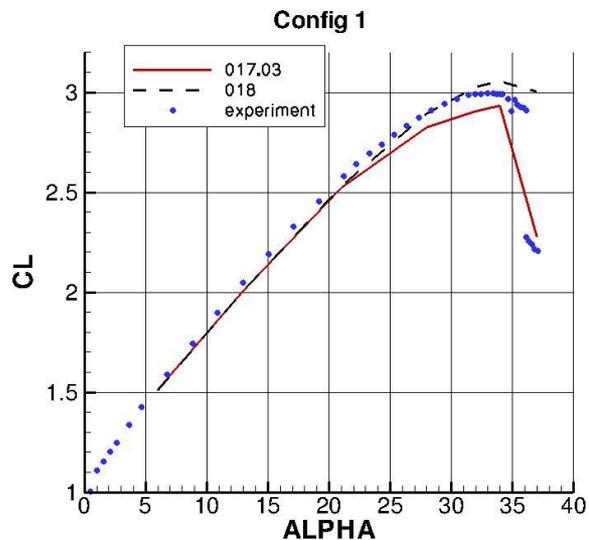
Config 1, Alpha=13 deg



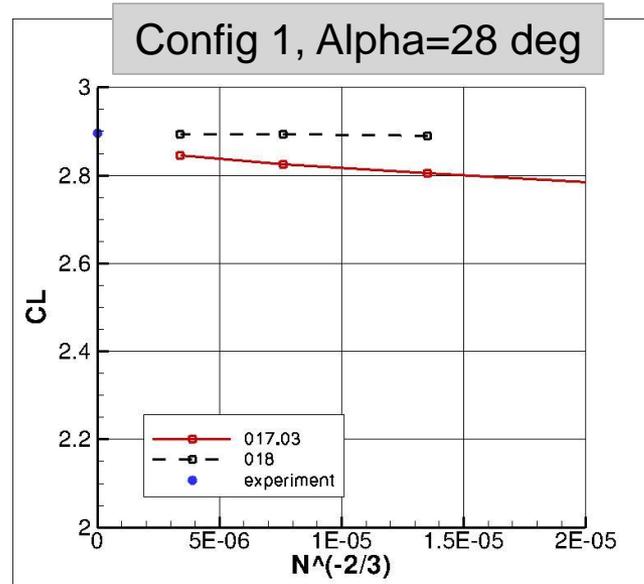
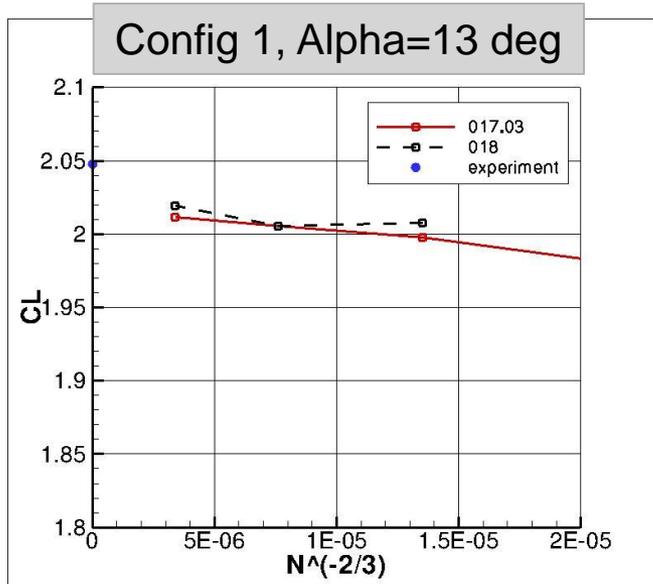
Config 1, Alpha=28 deg



017.03 vs. 018



Difference at higher alphas due to use of thin-layer in 017.03?



Same grid, code & turb, different people



	0 0 1	0 0 2	0 0 3	0 0 3	0 0 4	0 0 5	0 0 5	0 0 6	0 0 7	0 0 8	0 0 8	0 0 8	0 0 9	0 1 0	0 1 1	0 1 2	0 1 2	0 1 3	0 1 3	0 1 3	0 1 4	0 1 4	0 1 4	0 1 5	0 1 6	0 1 7	0 1 7	0 1 7	0 1 7	0 1 8	0 1 9	0 2 0	0 2 0	0 2 1	0 2 1		
Code	C F X	C F D + +	O V E R	O V E R	H I F U N	F U N 3 D	N S U 3 D	F U N 3 D	T A U	T A U	T A U	T A U	P O W E R	E D G E	N S U 3 D	T A S	U P A C S	C F D +	C F D +	C F D +	O V E R	O V E R	O V E R	U S M D	F U N 3 D	F U N 3 D	C F L L D	C F L L D	C F L L D	E L S A	N S M B	U S M 3 D	U S M 3 D	N S U 3 D	N S U 3 D		
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	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	S S T *	K E *	S A	S A	S A	S A	S A	S A	S A	S A	S T	S M	V L E S	S A	S A	S A	S A	K E *	K E *	S A	S A	S A	S A	S A	S A	S A	S A	S A	S A	S A	S A	S A	K O	K O	S A	S A	
Notes	Transition model used		brackets off on bracket-like grid			Thin each direc						Transition 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

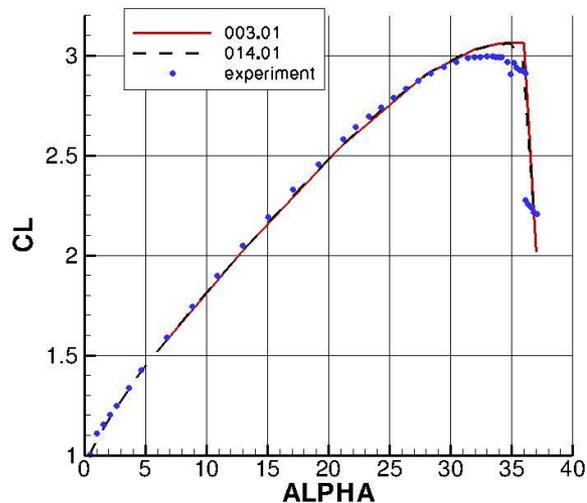
SX=Structured
UX=Unstructured hex
UT=Unstructured tet
UH=Unstructured hybrid
CB=Cartesian based

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)

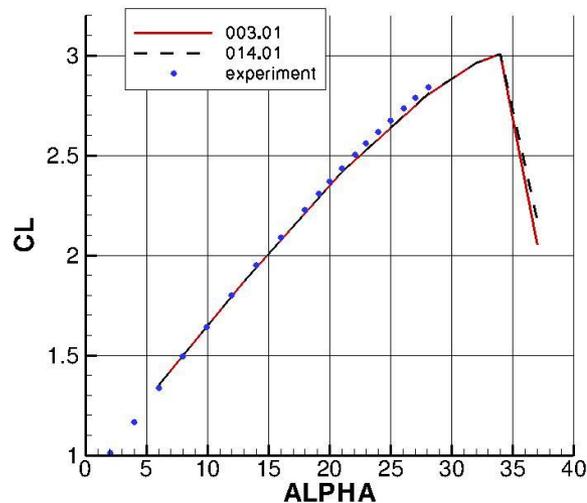
SA=Spalart-Allmaras
SST=Menter Shear Stress Transport
KE=K-Epsilon
VLES=Very Large Eddy Simulation
RSM=Reynolds Stress Model
KO=Wilcox K-Omega
* = modified in some way

003.01 vs. 014.01

Config 1

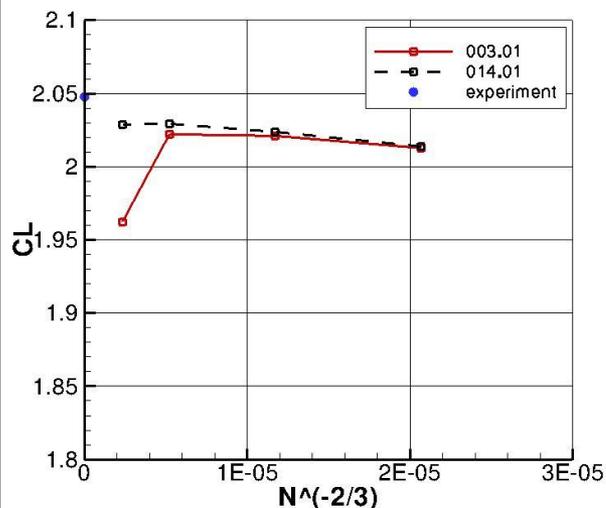


Config 8

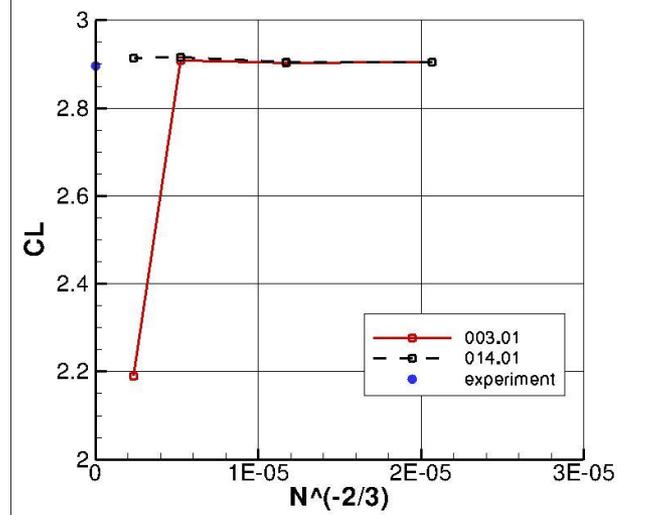


Nearly identical except on super-fine grid

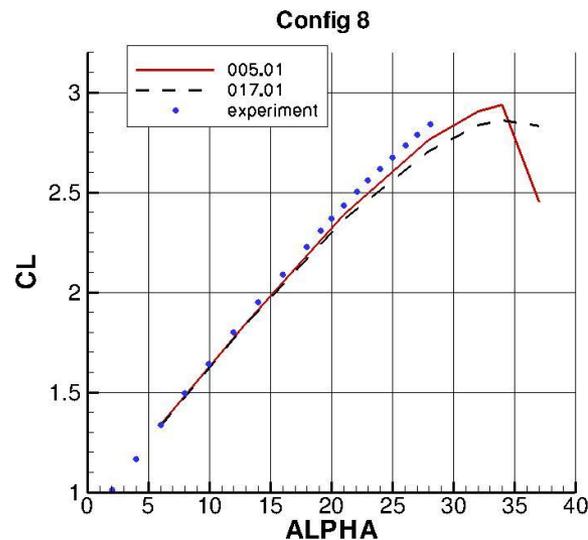
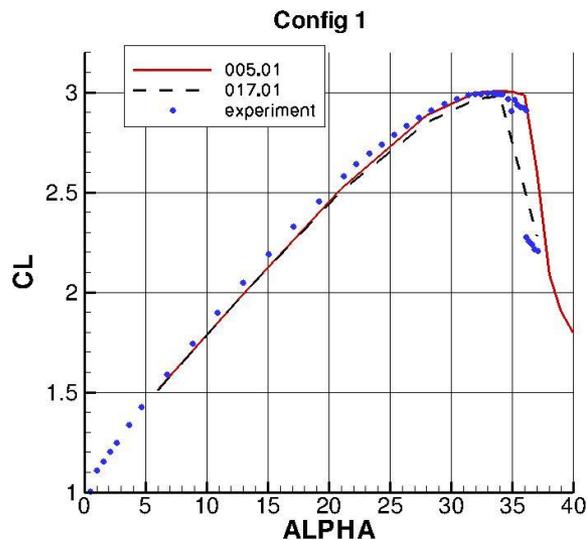
Config 1, Alpha=13 deg



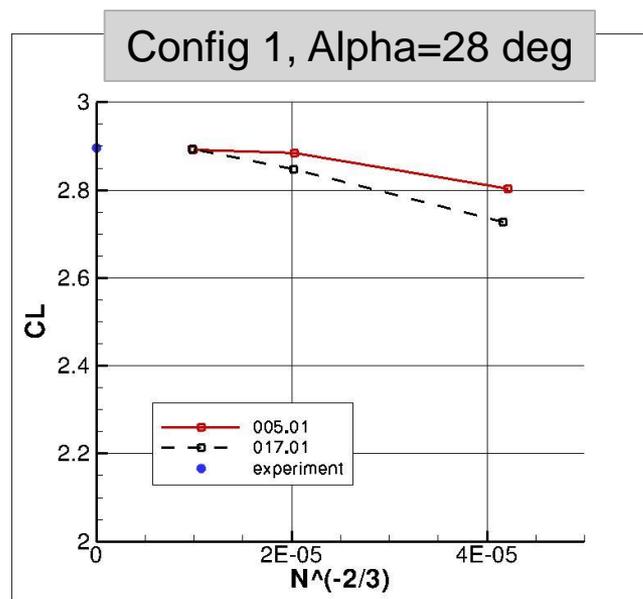
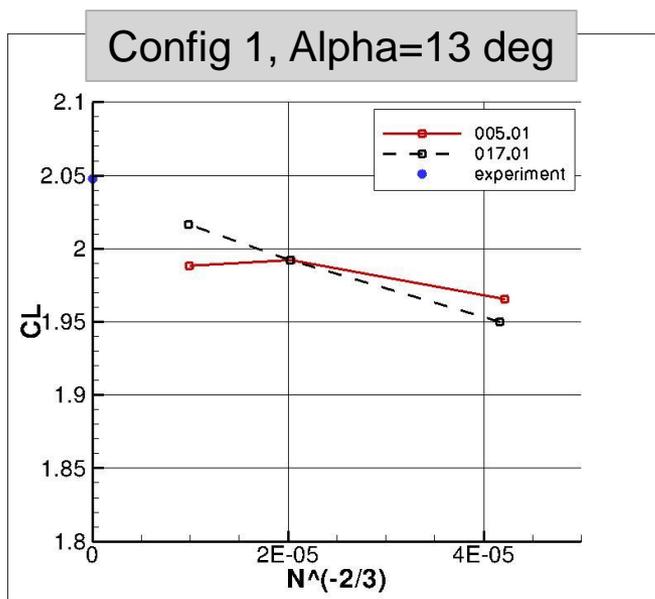
Config 1, Alpha=28 deg



005.01 vs. 017.01

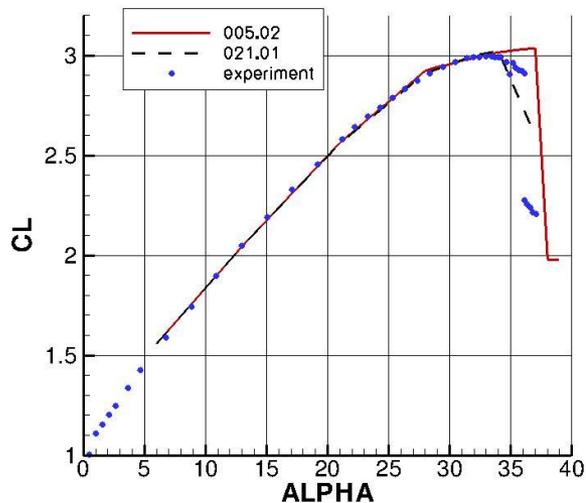


Differences due to use of limiter in 017.01?

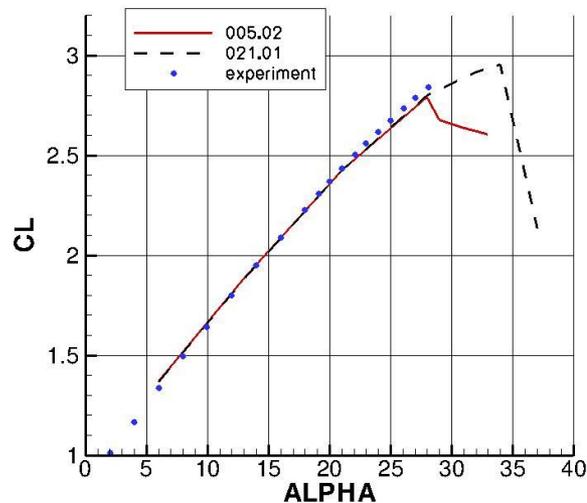


005.02 vs. 021.01

Config 1

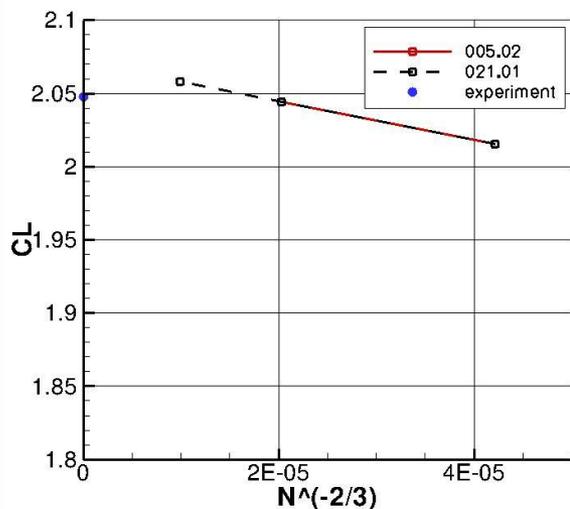


Config 8

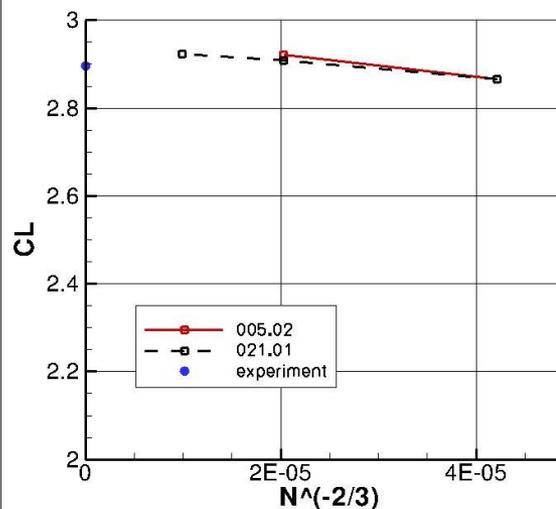


Nearly identical
except at highest
alphas

Config 1, Alpha=13 deg



Config 1, Alpha=28 deg



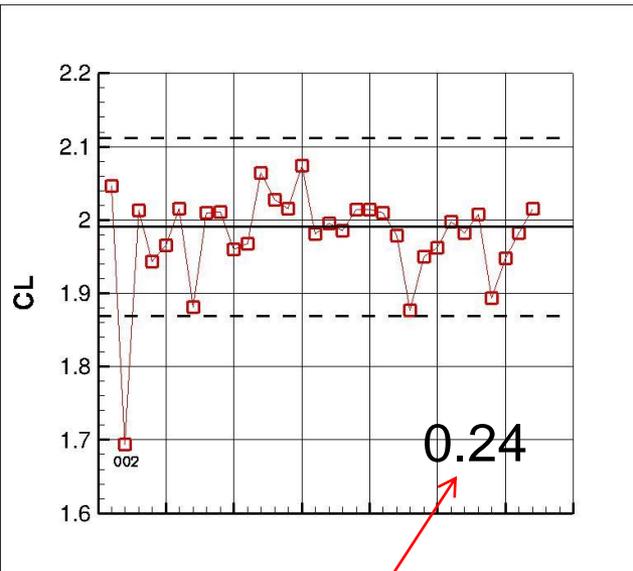
STATISTICAL ANALYSIS

- Used basic method from DPW (see AIAA 2010-4673)
- Limits $\hat{\mu} \pm K\hat{\sigma}$
 - $\hat{\mu}$ = median of sorted data
 - $\hat{\sigma}$ = sample standard deviation
 - $K = \sqrt{3}$ = coverage factor
- Coefficient of variation $Cv = \hat{\sigma} / \hat{\mu}$
- Analysis only done for alpha=13 & 28

Statistical analysis

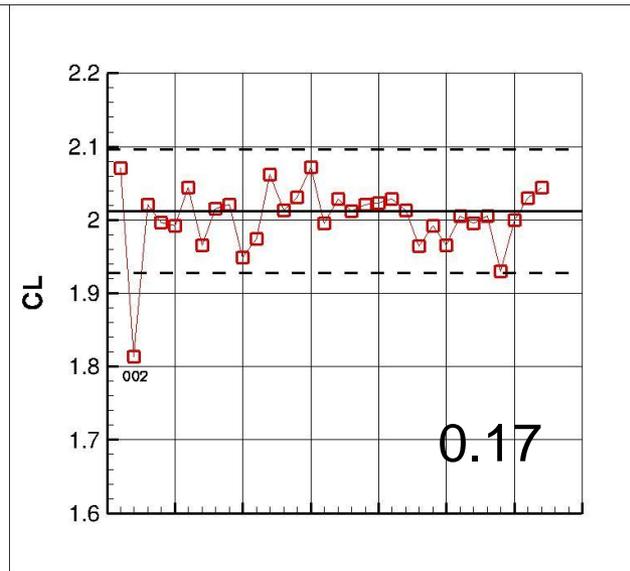
Alpha=13

Coarse



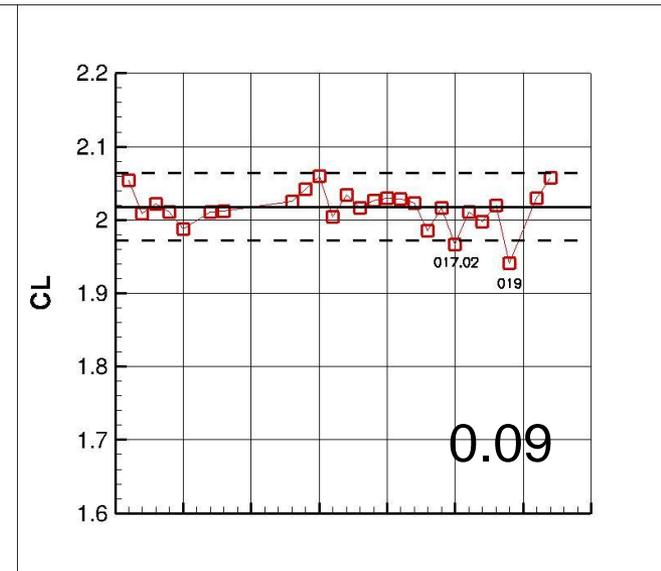
scatter range

Medium



Coefficient of variation on fine grid = 0.013

Fine



Scatter limits converging as grid is refined

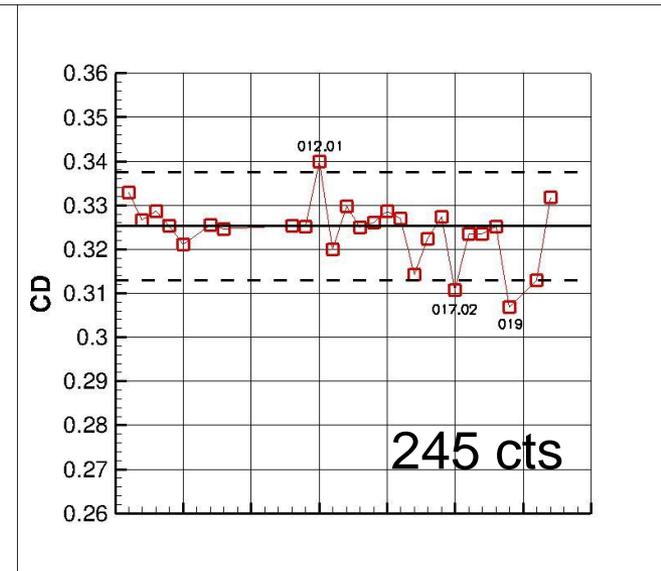
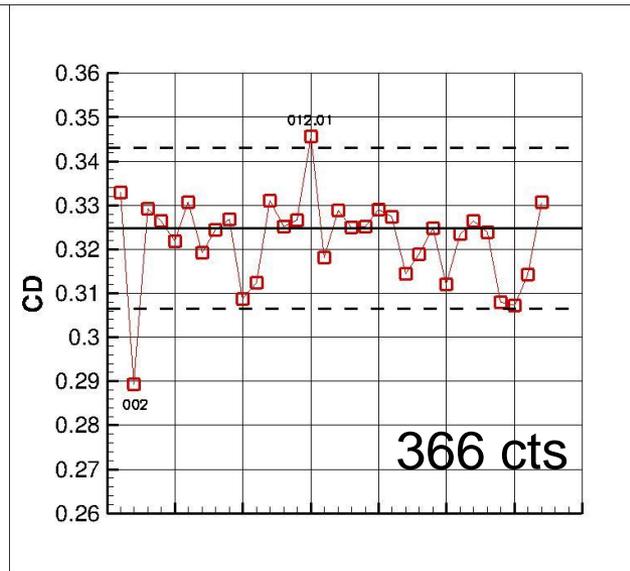
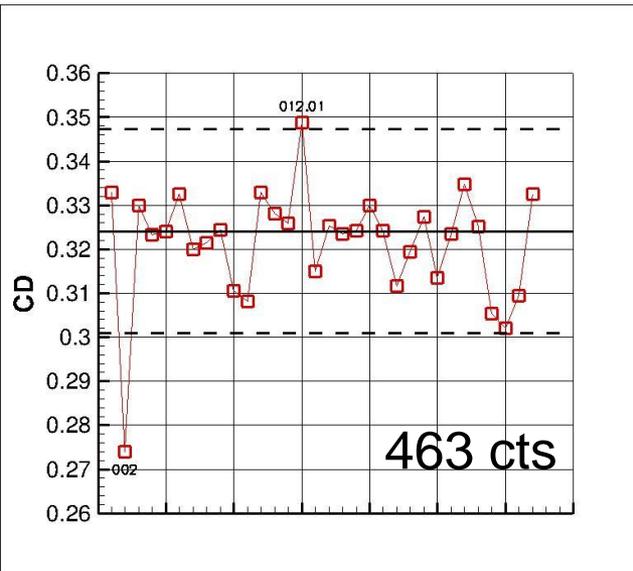
Statistical analysis

Alpha=13

Coarse

Medium

Fine



Coefficient of variation on fine grid = 0.022

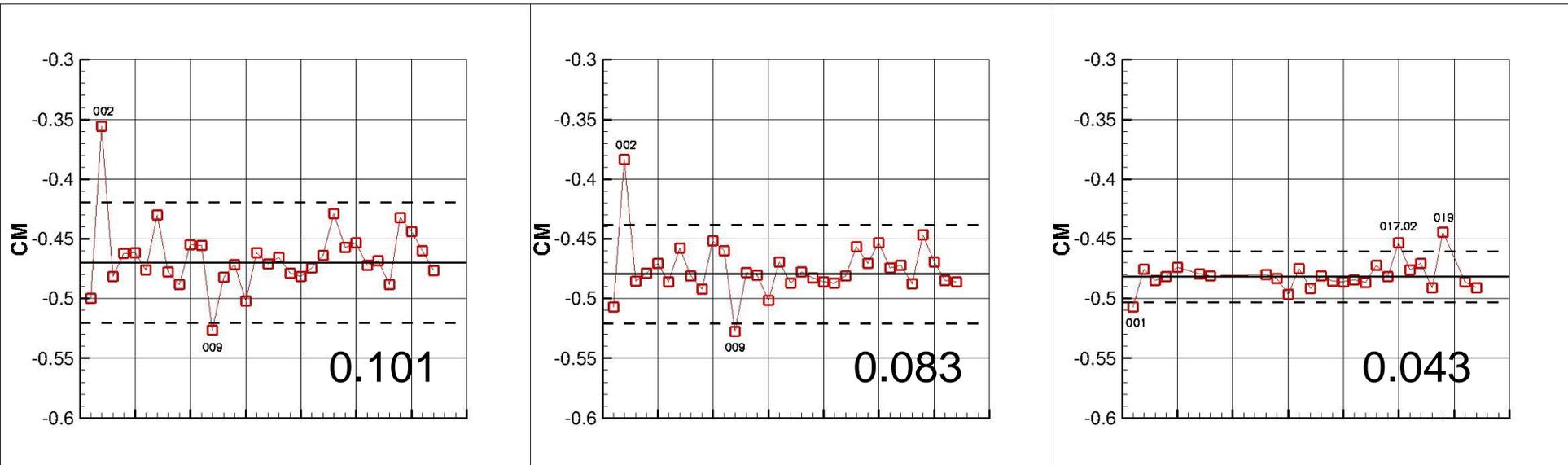
Statistical analysis

Alpha=13

Coarse

Medium

Fine



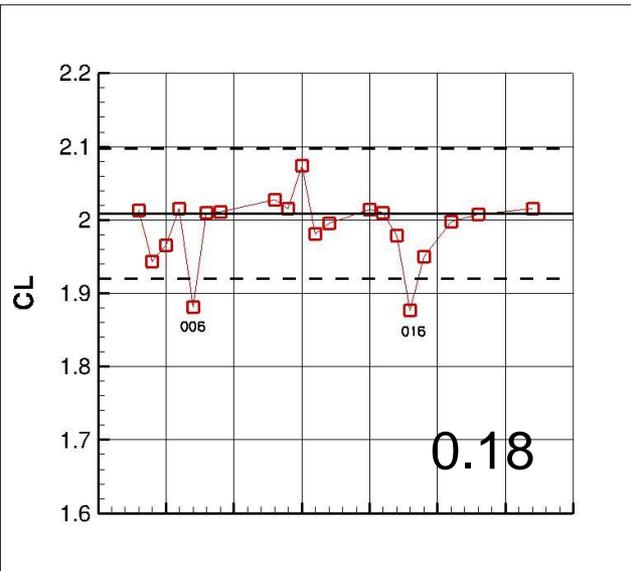
Coefficient of variation on fine grid = 0.026

002 is “big” outlier on C and M levels for CL, CD, CM
Participant 002 used k-epsilon based model on non-committee unstructured hybrid grid

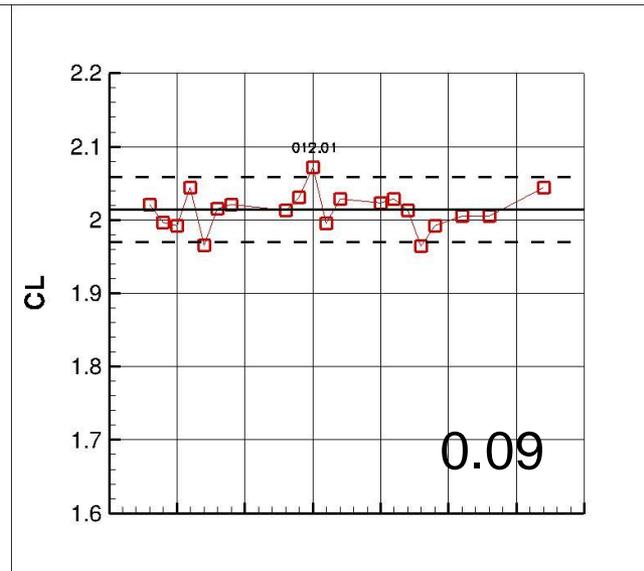
Statistical analysis

Alpha=13, SA only

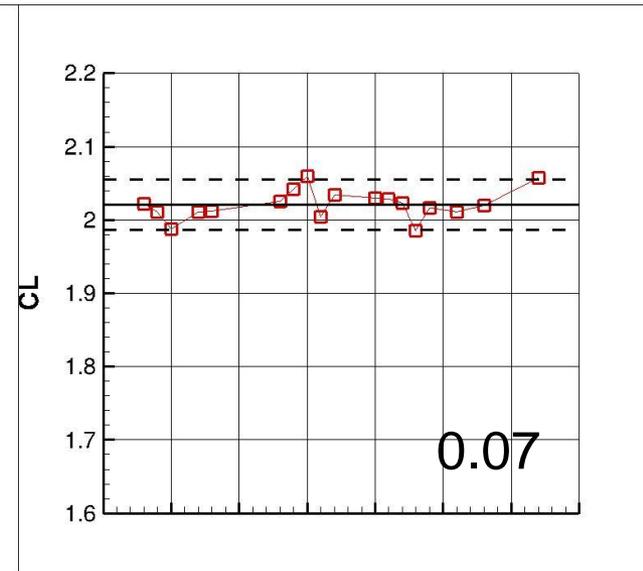
Coarse



Medium



Fine



Coefficient of variation on fine grid = 0.010

Scatter limits still converging with grid refinement; somewhat tighter

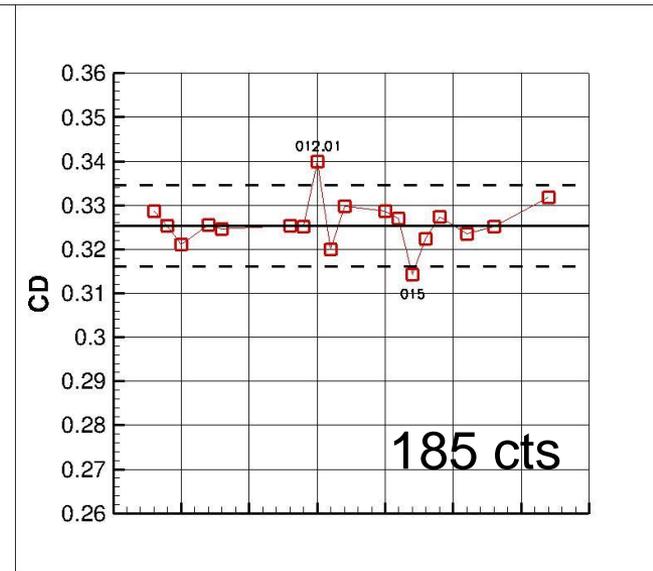
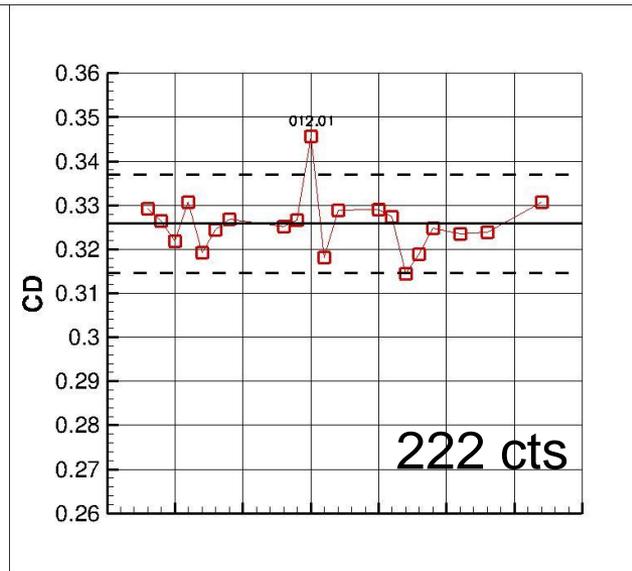
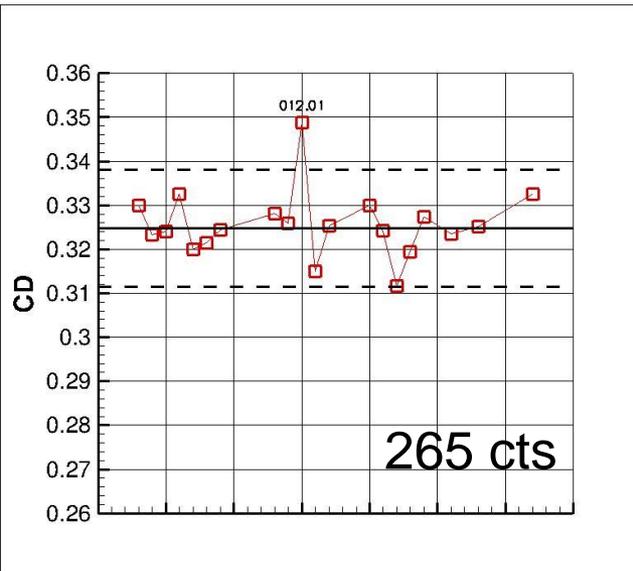
Statistical analysis

Alpha=13, SA only

Coarse

Medium

Fine



Coefficient of variation on fine grid = 0.016

012.01 has consistently high drag compared to SA collective

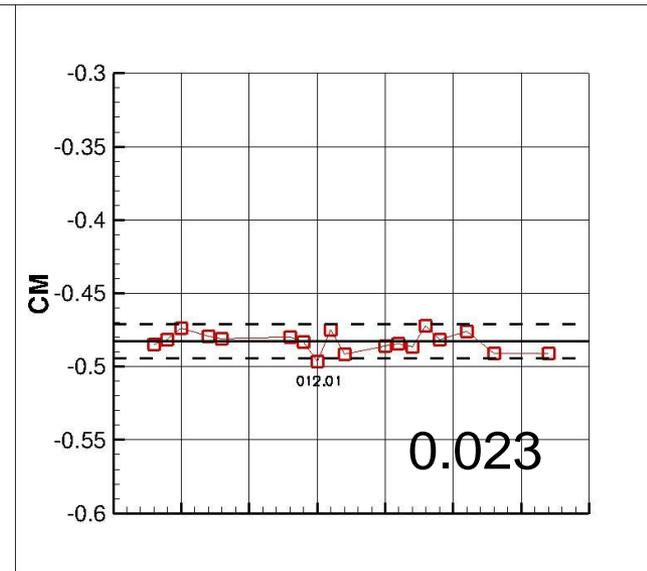
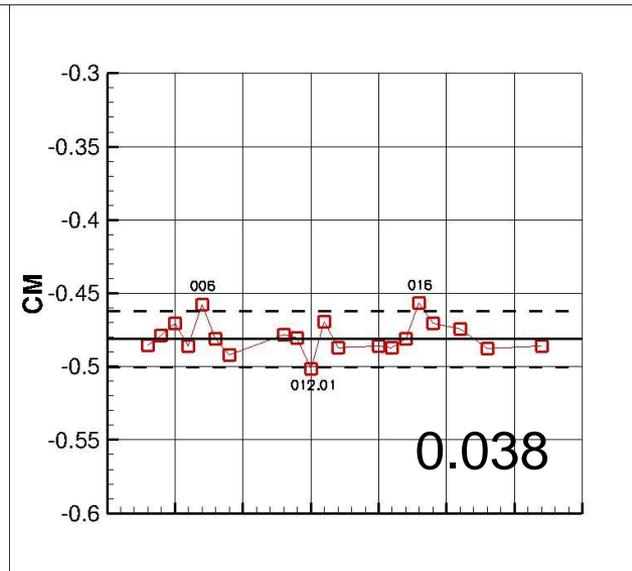
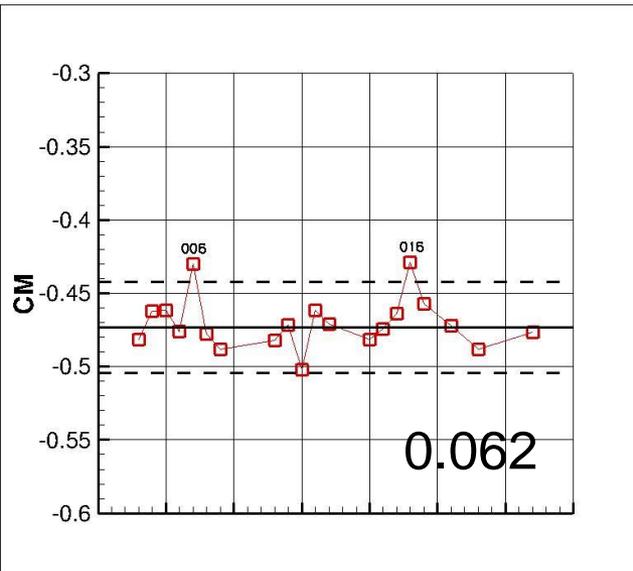
Statistical analysis

Alpha=13, SA only

Coarse

Medium

Fine



Coefficient of variation on fine grid = 0.014

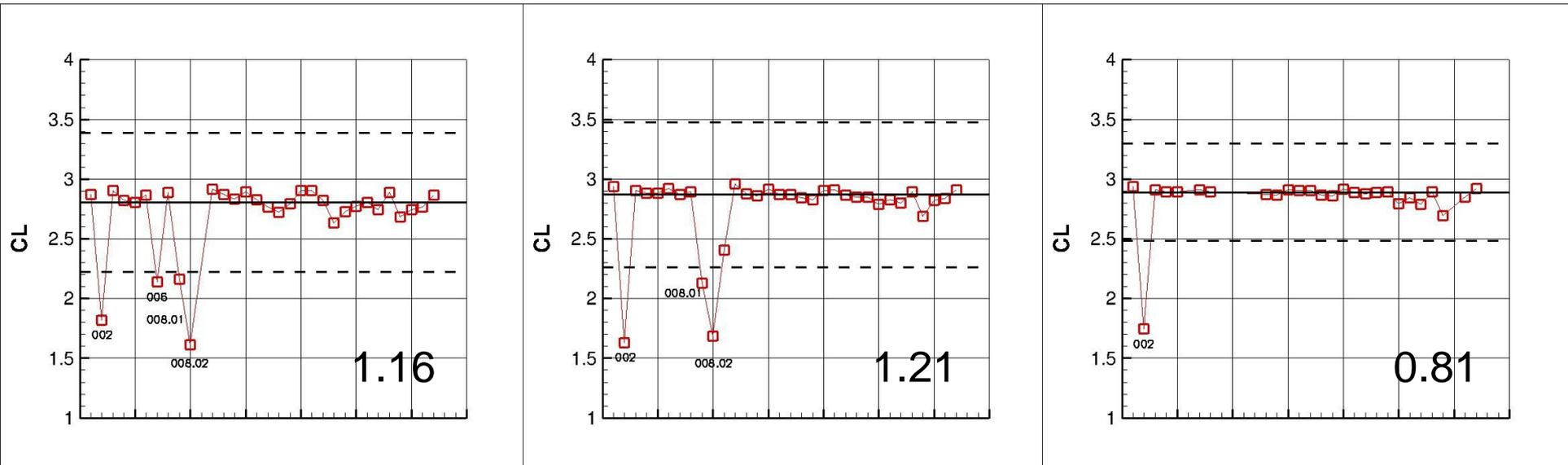
Statistical analysis

Alpha=28

Coarse

Medium

Fine



For alpha=28: 002, 008.xx are “big” outliers in most cases

002: k-epsilon model on non-committee unstructured hybrid grid

008: same code as 007, on unstructured hybrid node-centered A grids

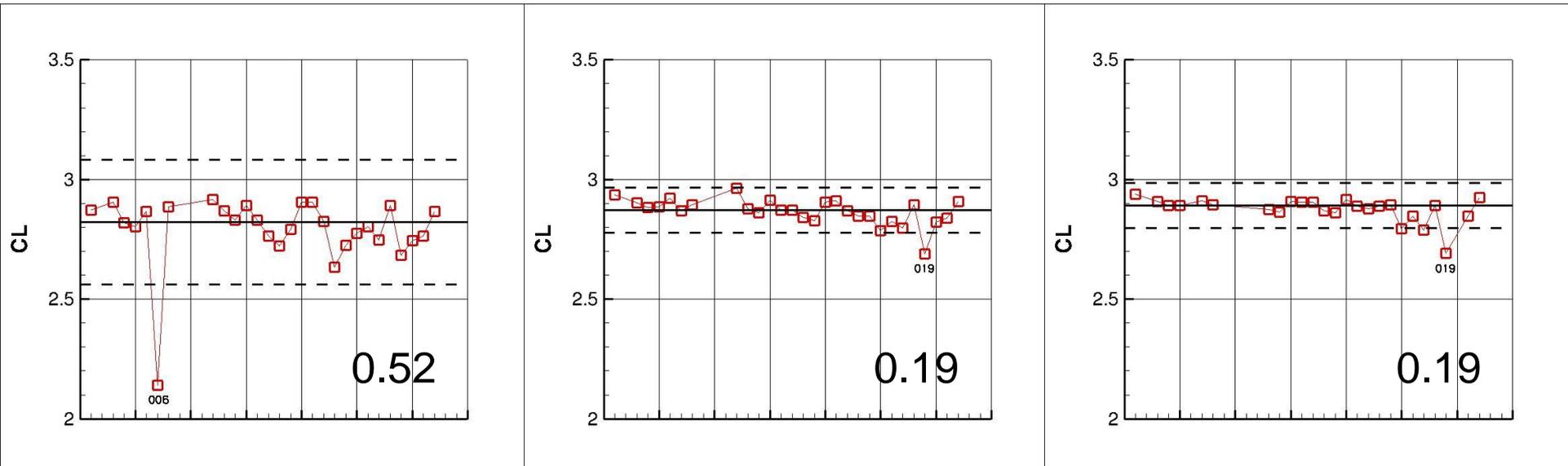
Statistical analysis

Alpha=28, with outliers 002 and 008.xx removed

Coarse

Medium

Fine



Coefficient of variation on fine grid = 0.019

Scatter limits not converging between medium & fine levels

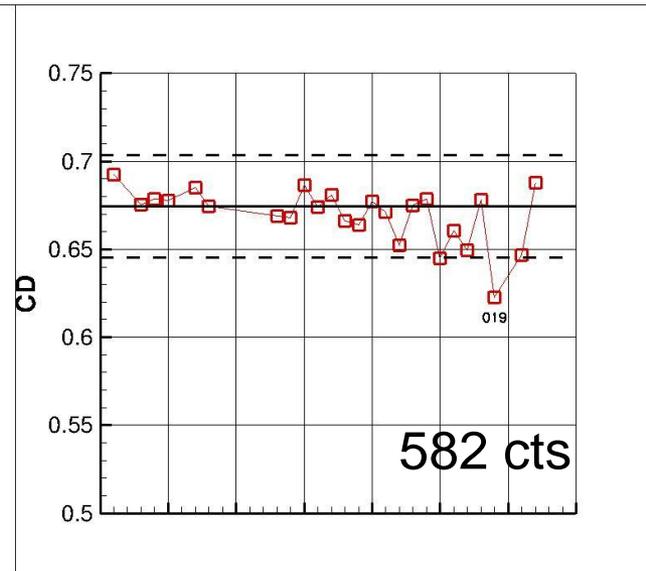
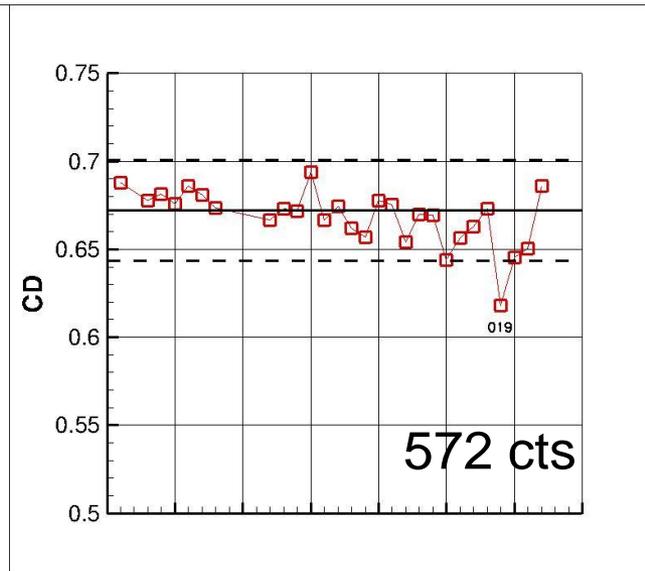
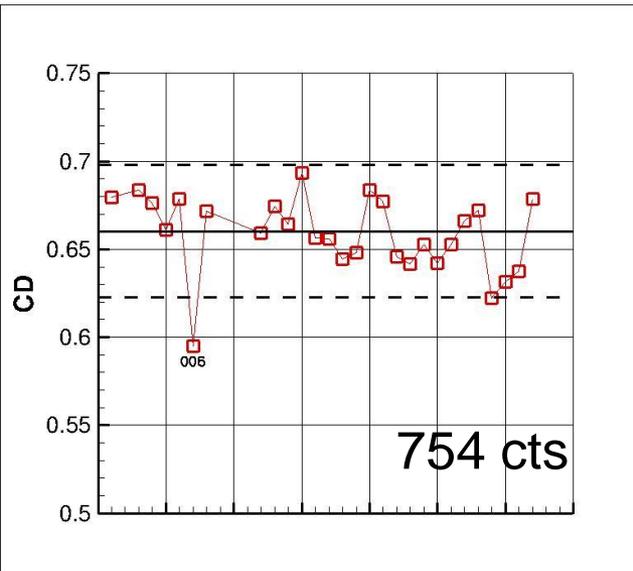
Statistical analysis

Alpha=28, with outliers 002 and 008.xx removed

Coarse

Medium

Fine



Coefficient of variation on fine grid = 0.025

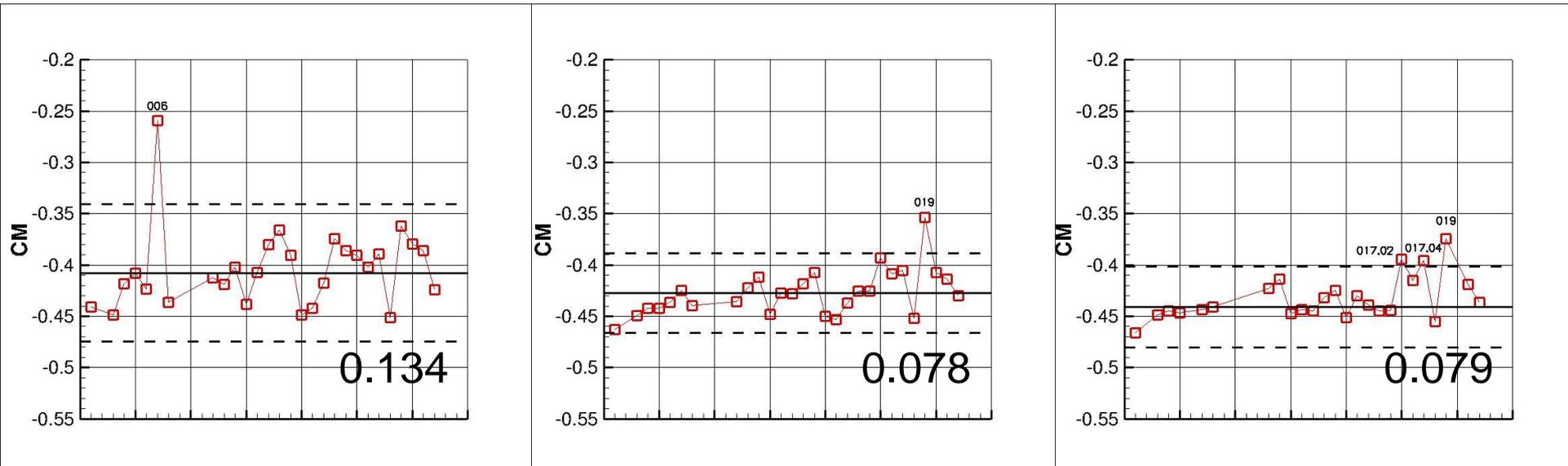
Statistical analysis

Alpha=28, with outliers 002 and 008.xx removed

Coarse

Medium

Fine



Coefficient of variation on fine grid = 0.052

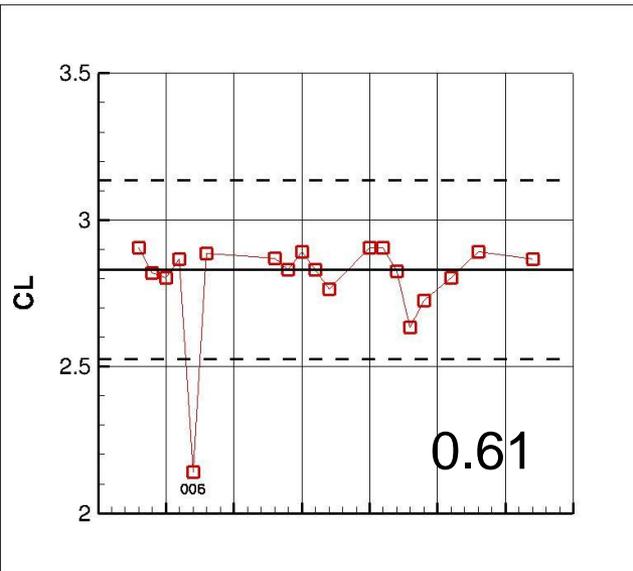
006: massively separated on C level... effect of ICs?

019: SST on non-committee structured multi-block grid

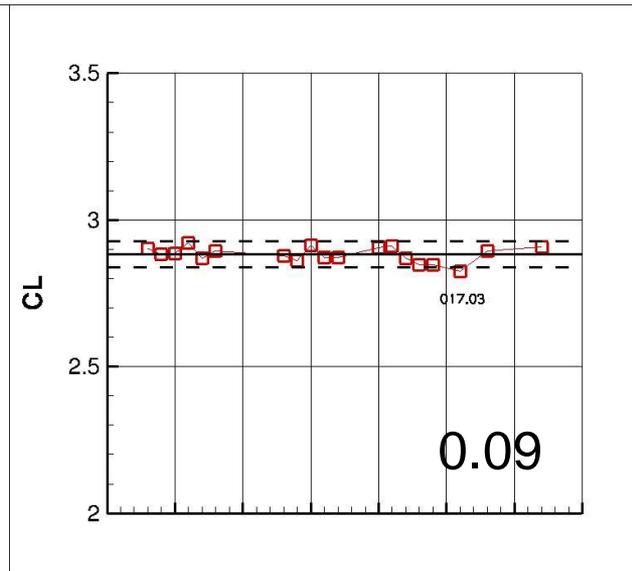
Statistical analysis

Alpha=28, with outliers 002 and 008.xx removed, and SA only

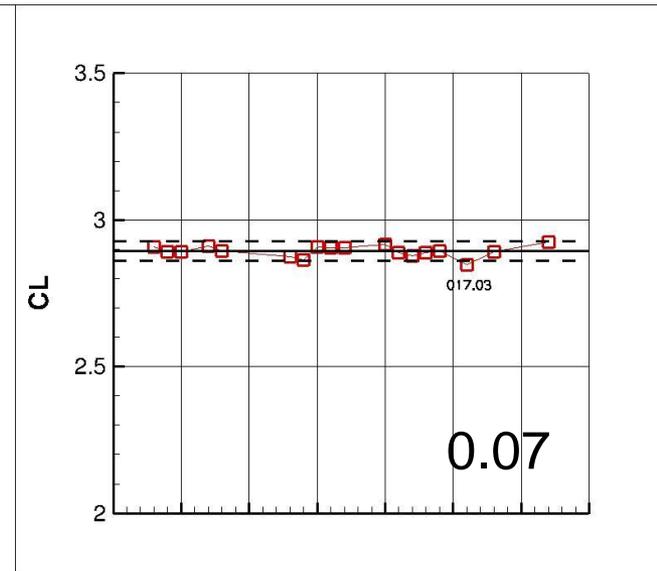
Coarse



Medium



Fine



Scatter limits converging

Coefficient of variation on fine grid = 0.007

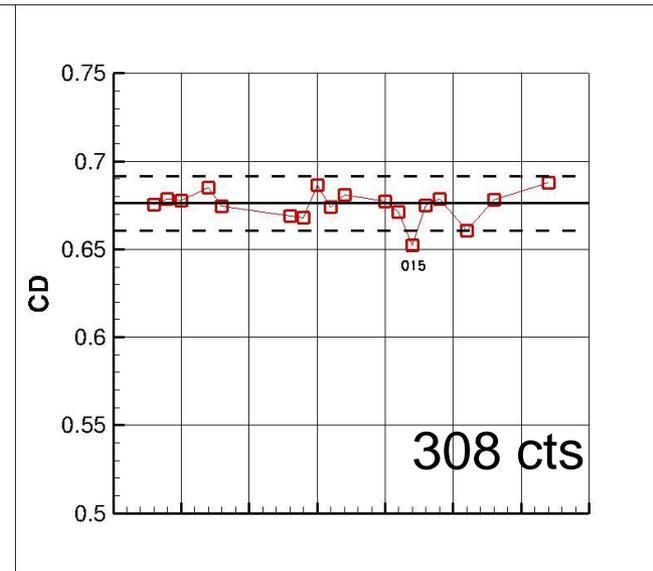
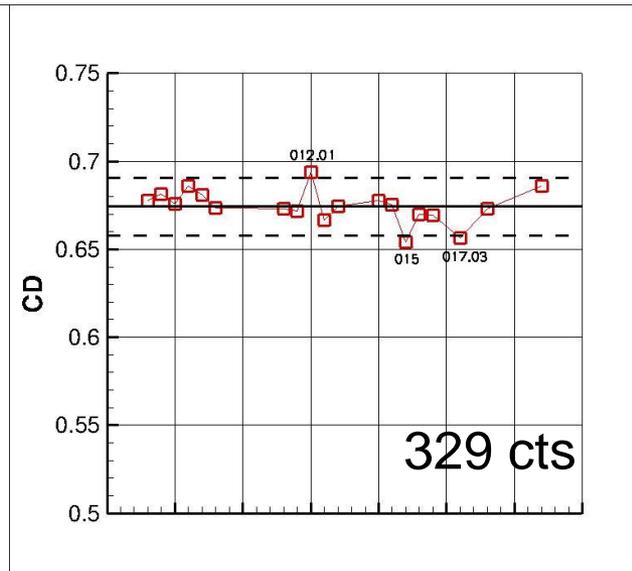
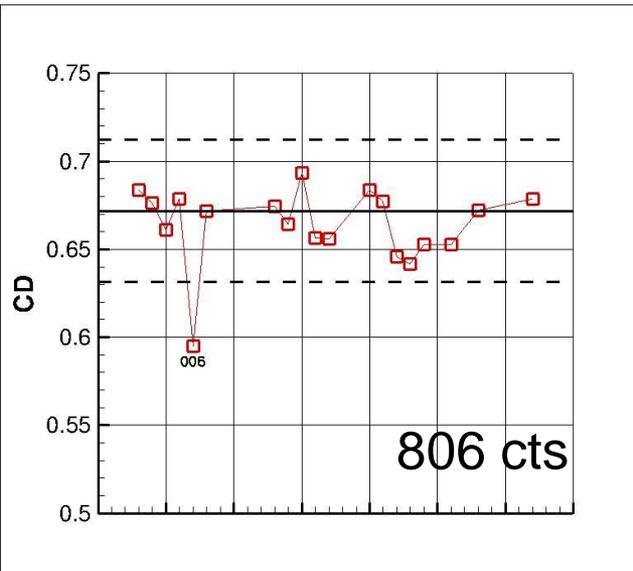
Statistical analysis

Alpha=28, with outliers 002 and 008.xx removed, and SA only

Coarse

Medium

Fine

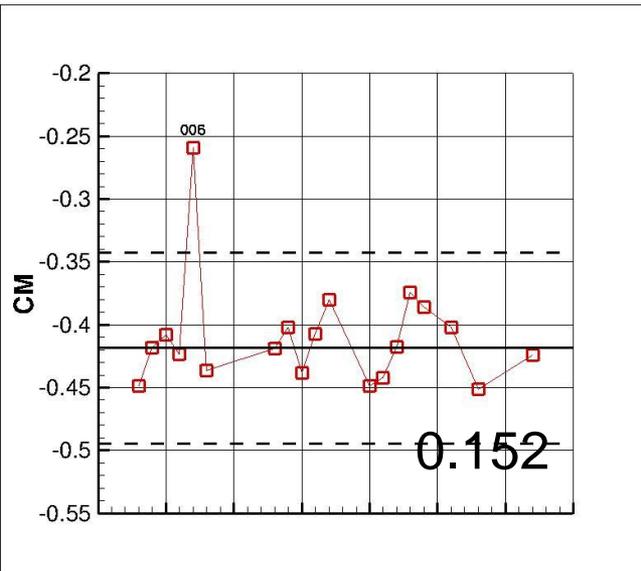


Coefficient of variation on fine grid = 0.013

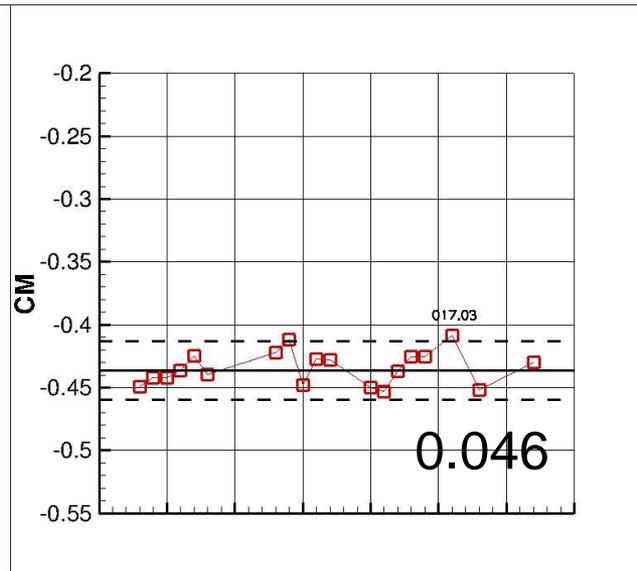
Statistical analysis

Alpha=28, with outliers 002 and 008.xx removed, and SA only

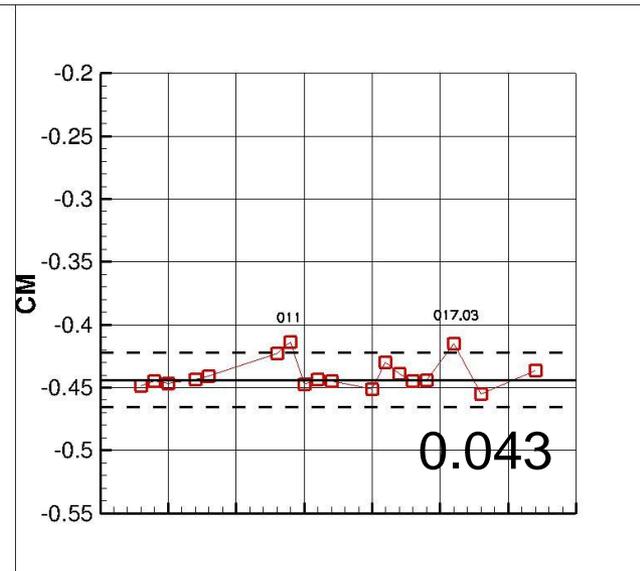
Coarse



Medium



Fine



Coefficient of variation on fine grid = 0.028

006: massively separated on C level... effect of ICs?

Coefficient of variation summary

Case	Turbulence	Cv for lift	Cv for drag	Cv for moment
DPW II & III	All models	n/a	0.02 – 0.025	0.045 – 0.06
DPW IV	All models	n/a	0.022	0.157
Alpha=13	All models	0.013	0.022	0.026
Alpha=28	All models	0.019	0.025	0.052
Alpha=13	SA model only	0.010	0.016	0.014
Alpha=28	SA model only	0.007	0.013	0.028

(“fine” grid, major outliers removed)

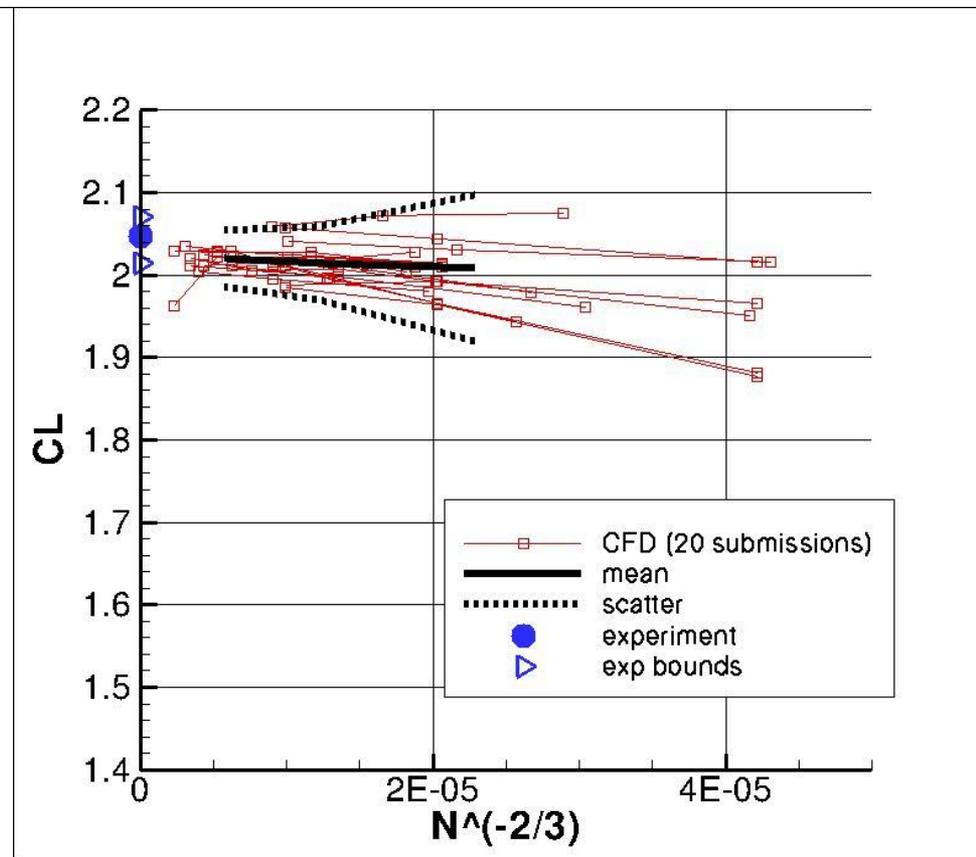
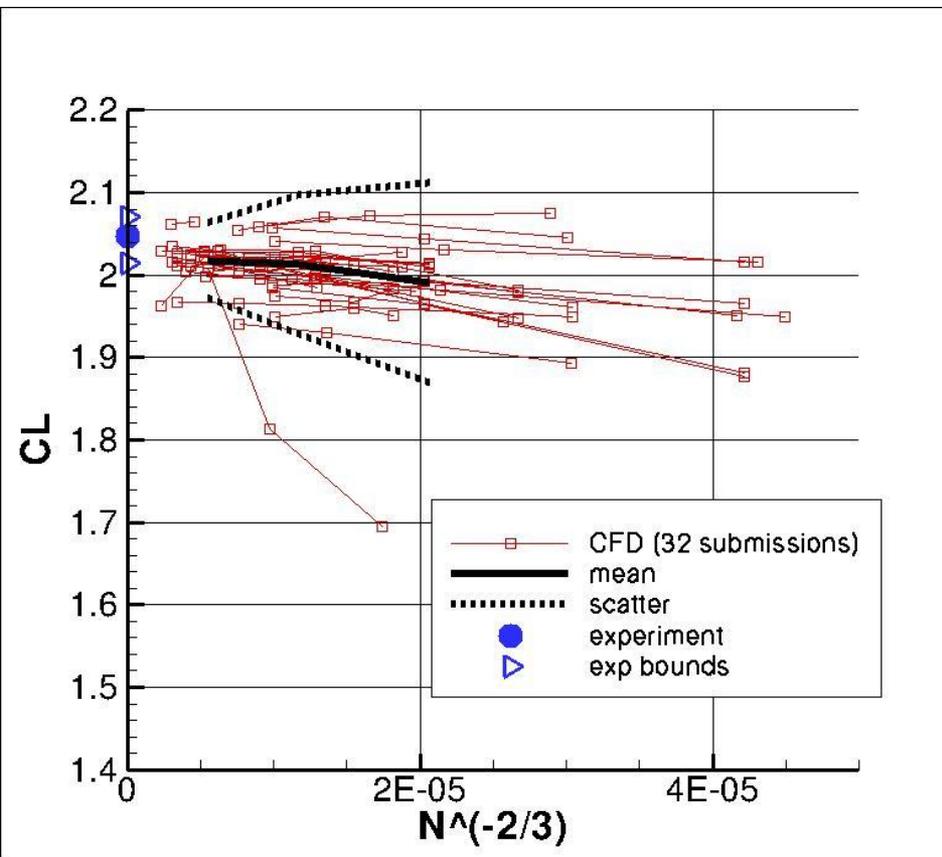
Statistical analysis

Alpha=13

Statistics include C-M-F data only (XC and XF not included)

All

SA only



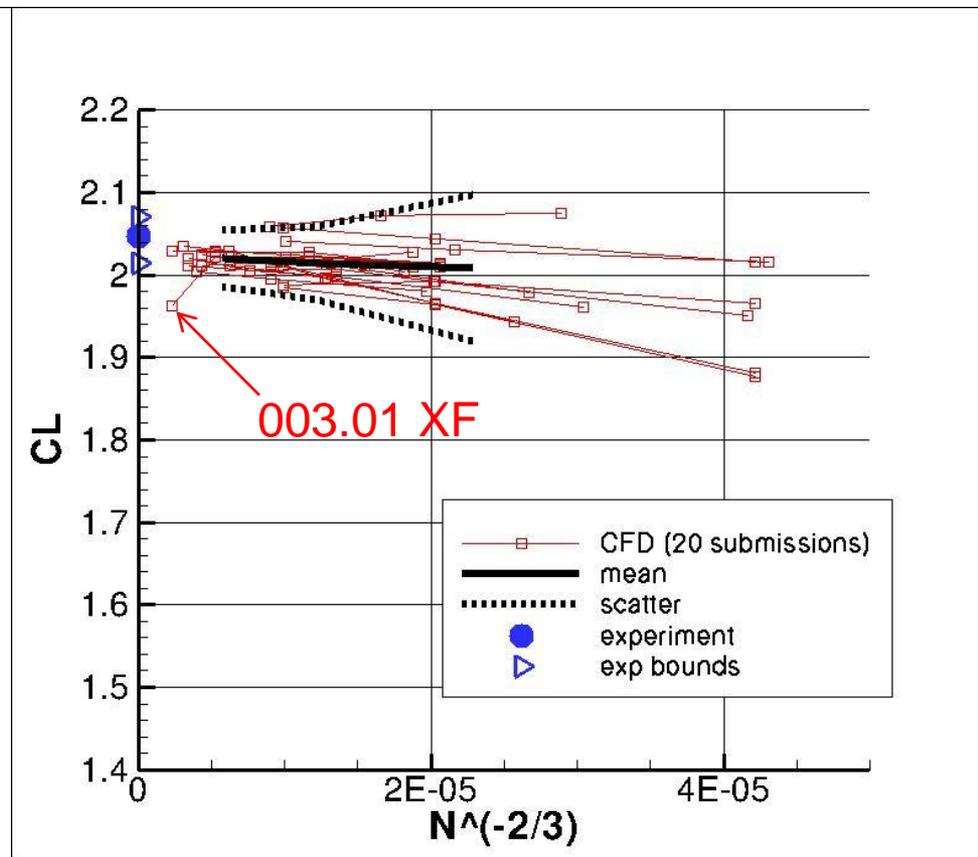
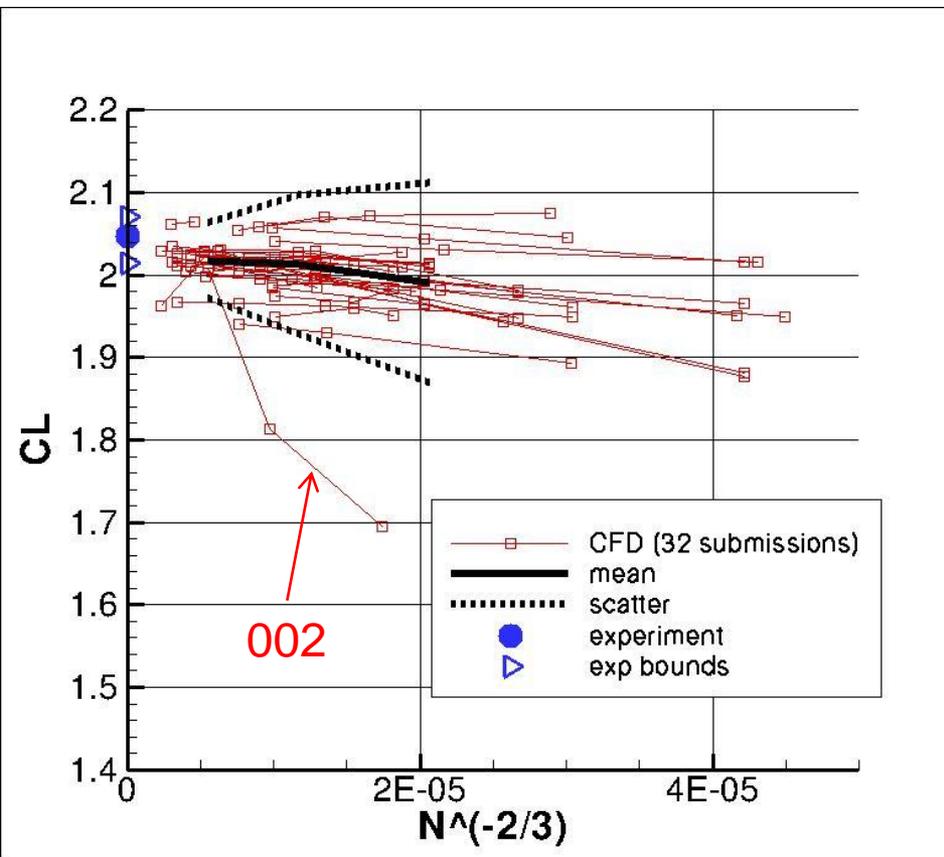
Statistical analysis

Alpha=13

Statistics include C-M-F data only (XC and XF not included)

All

SA only



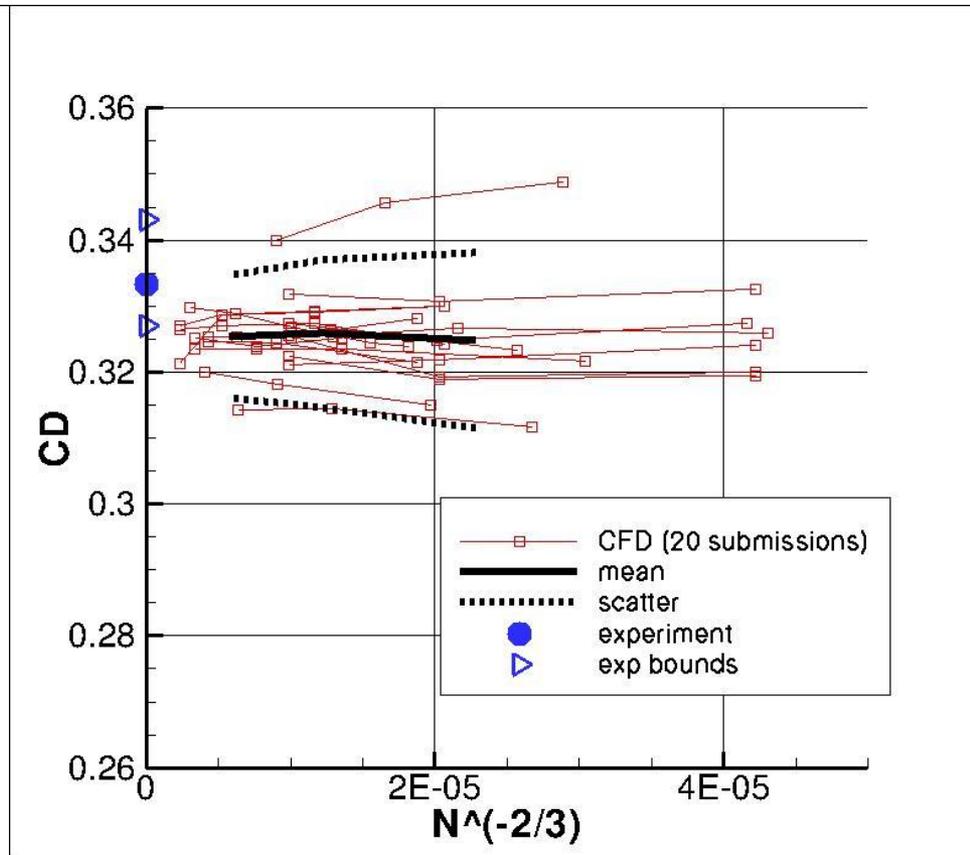
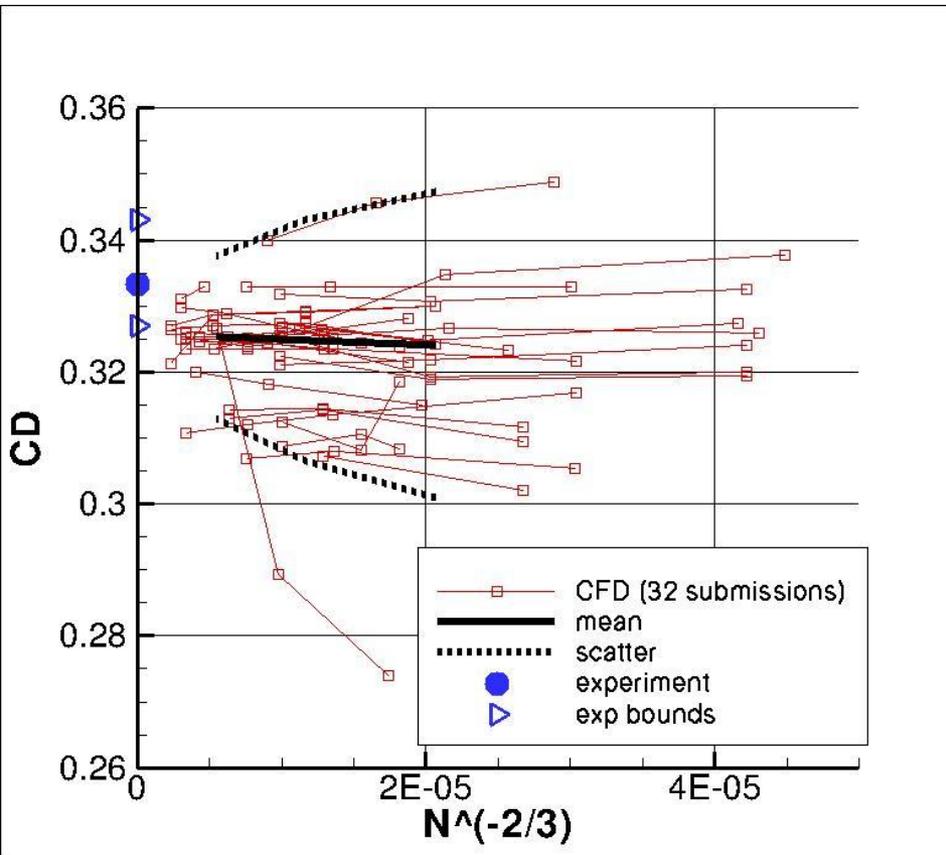
Statistical analysis

Alpha=13

Statistics include C-M-F data only (XC and XF not included)

All

SA only



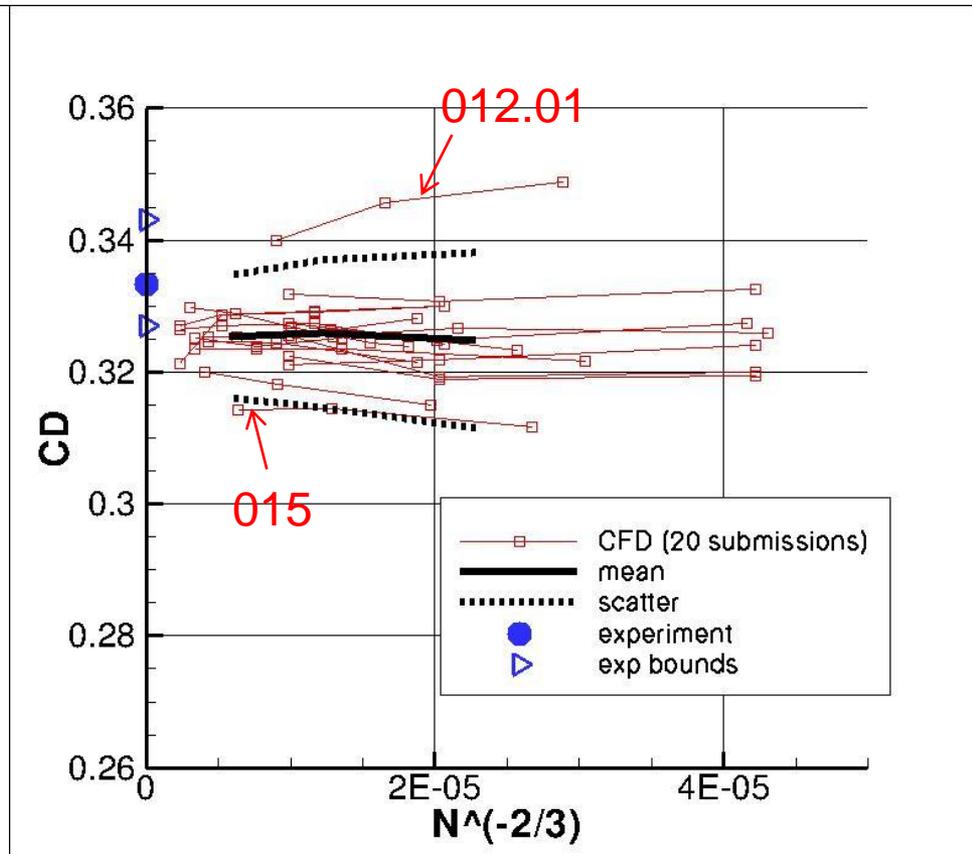
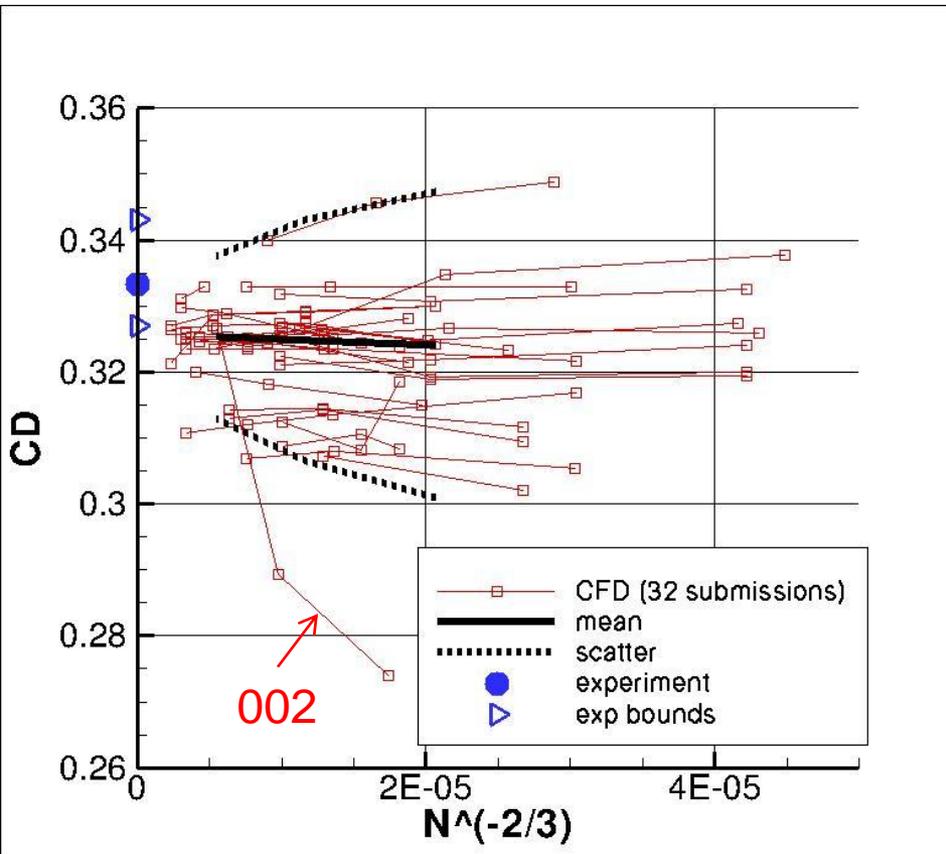
Statistical analysis

Alpha=13

Statistics include C-M-F data only (XC and XF not included)

All

SA only



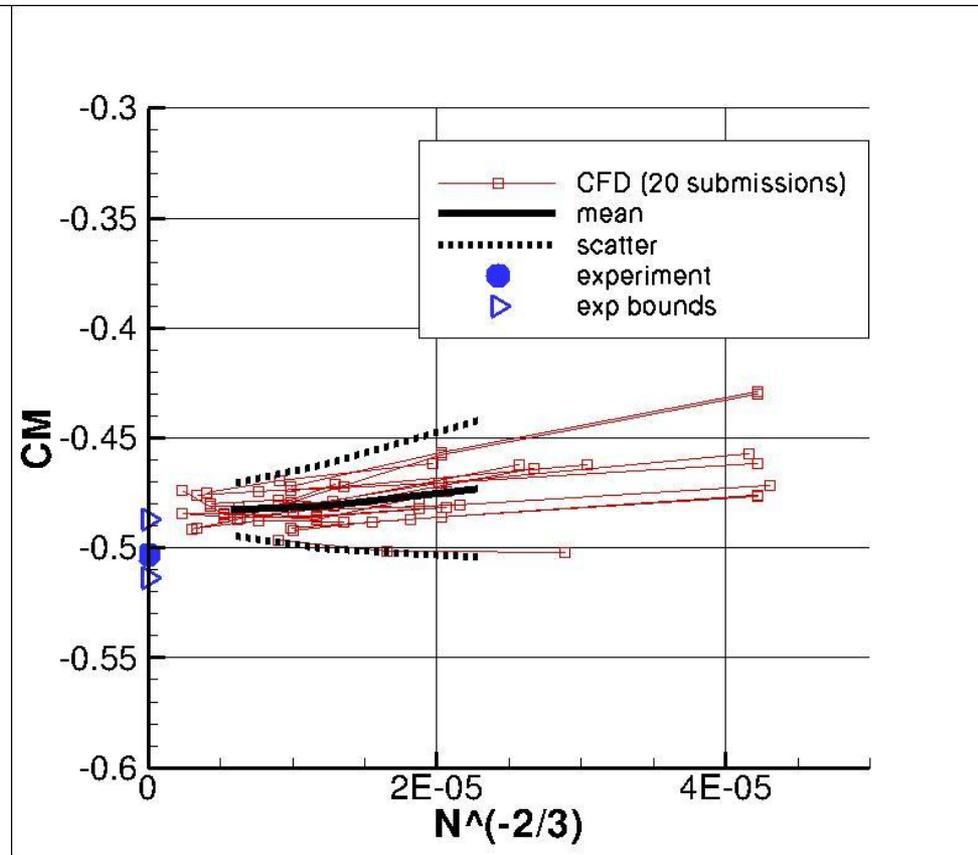
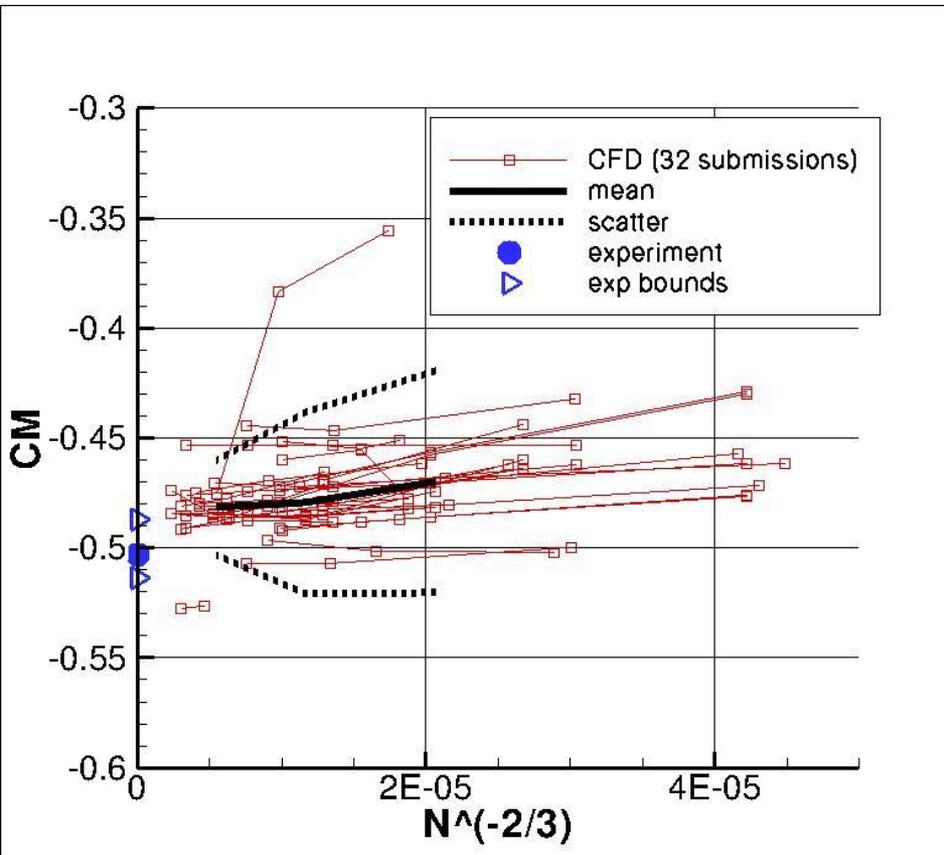
Statistical analysis

Alpha=13

Statistics include C-M-F data only (XC and XF not included)

All

SA only



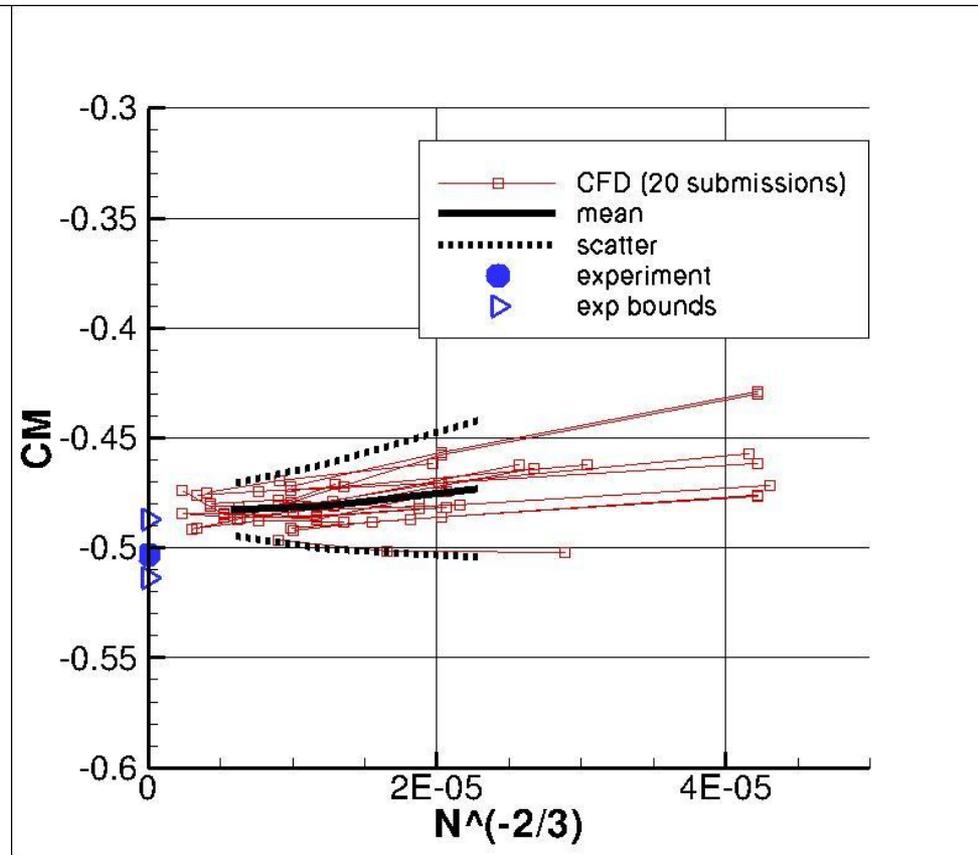
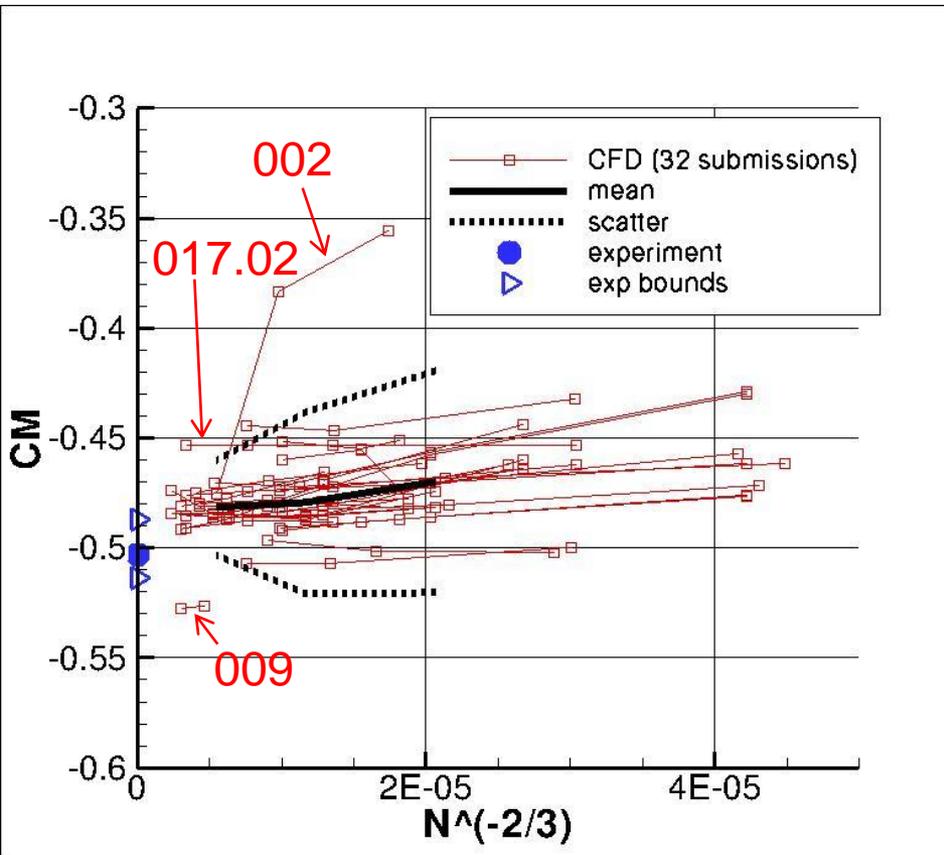
Statistical analysis

Alpha=13

Statistics include C-M-F data only (XC and XF not included)

All

SA only



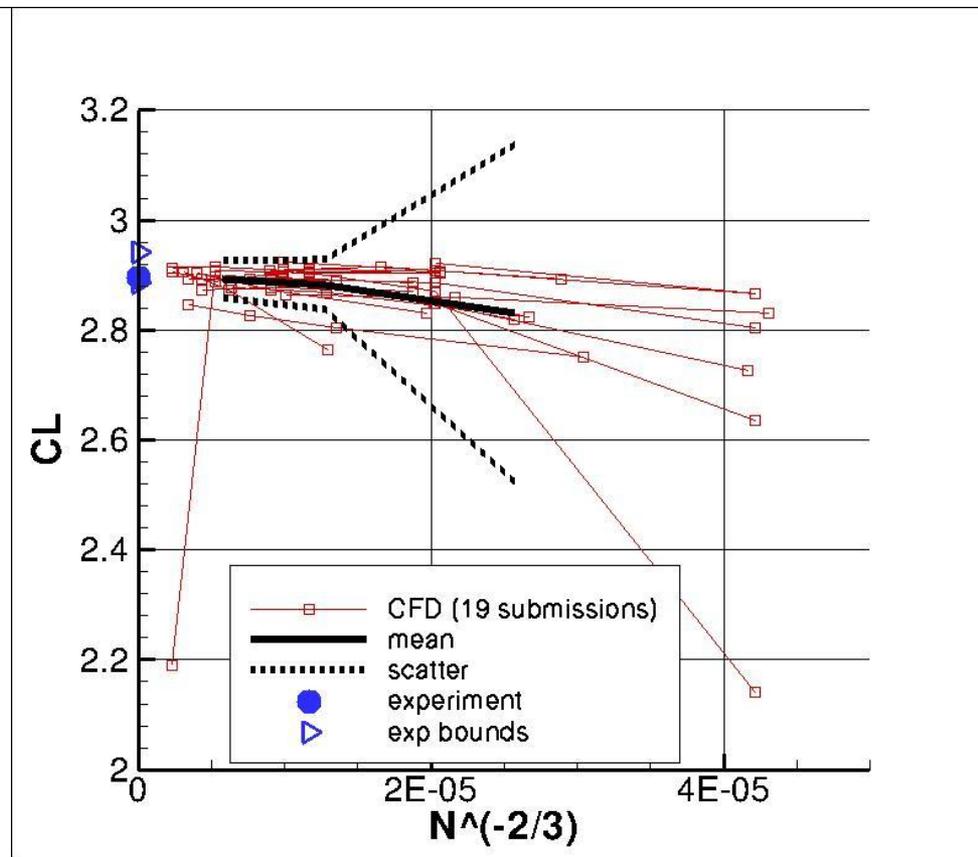
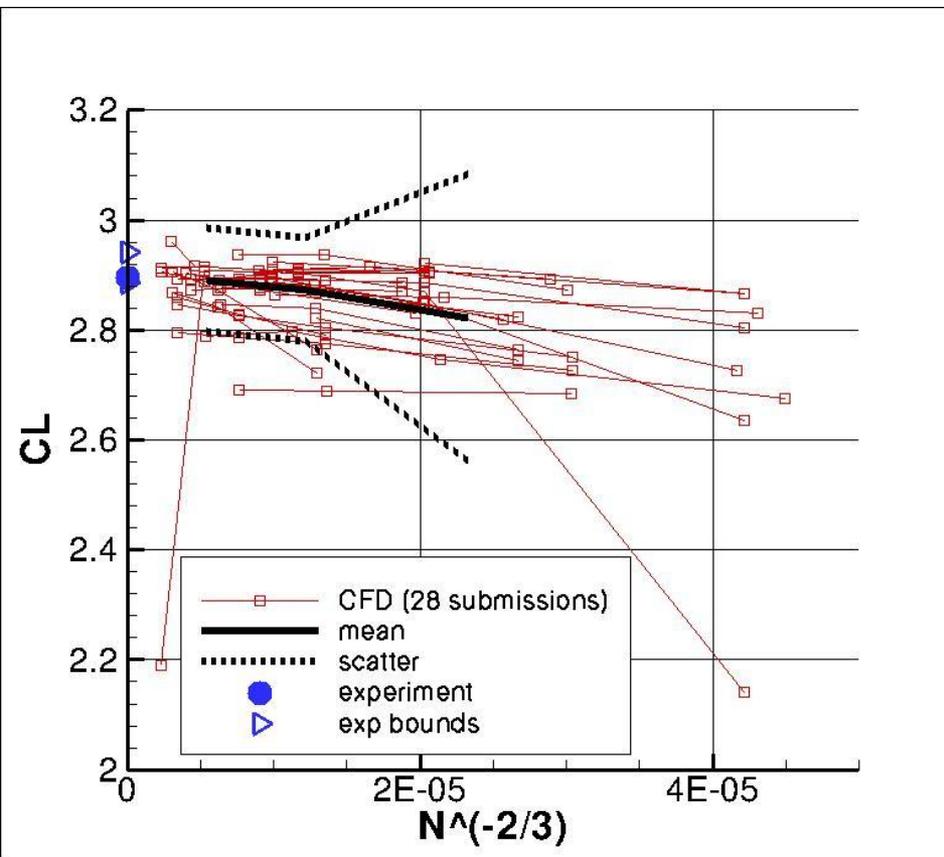
Statistical analysis

Alpha=28

Statistics include C-M-F data only (XC and XF not included)

All except outliers 002 & 008.xx

SA only (no 008.xx)



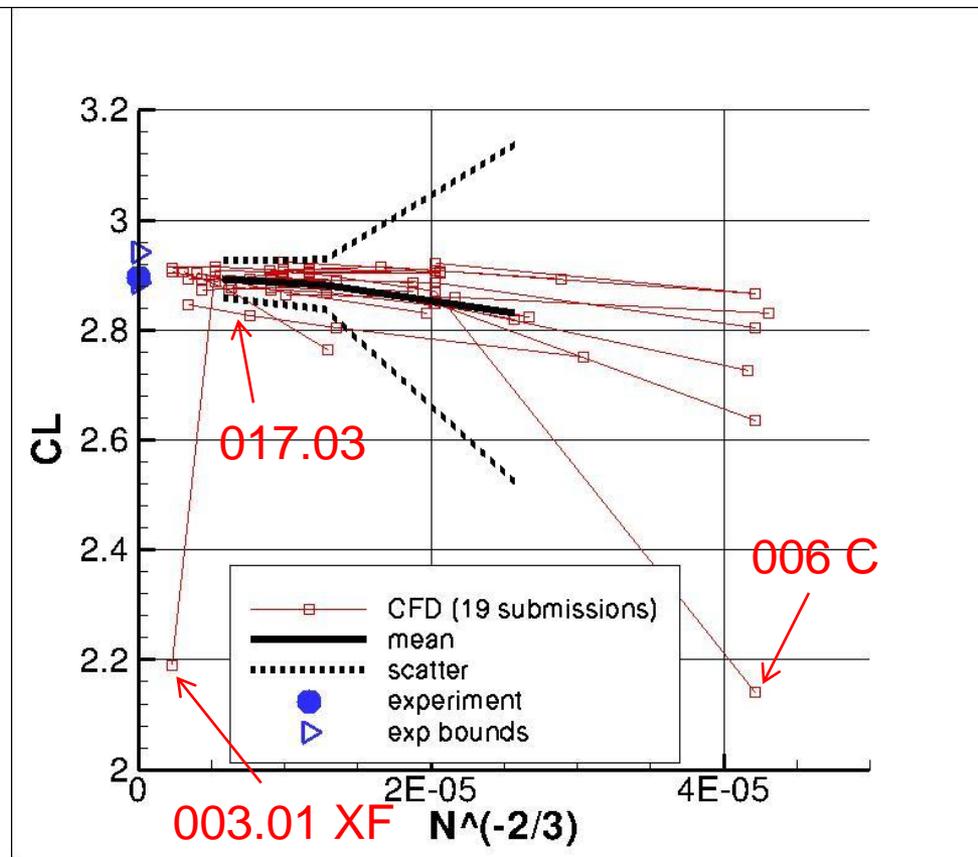
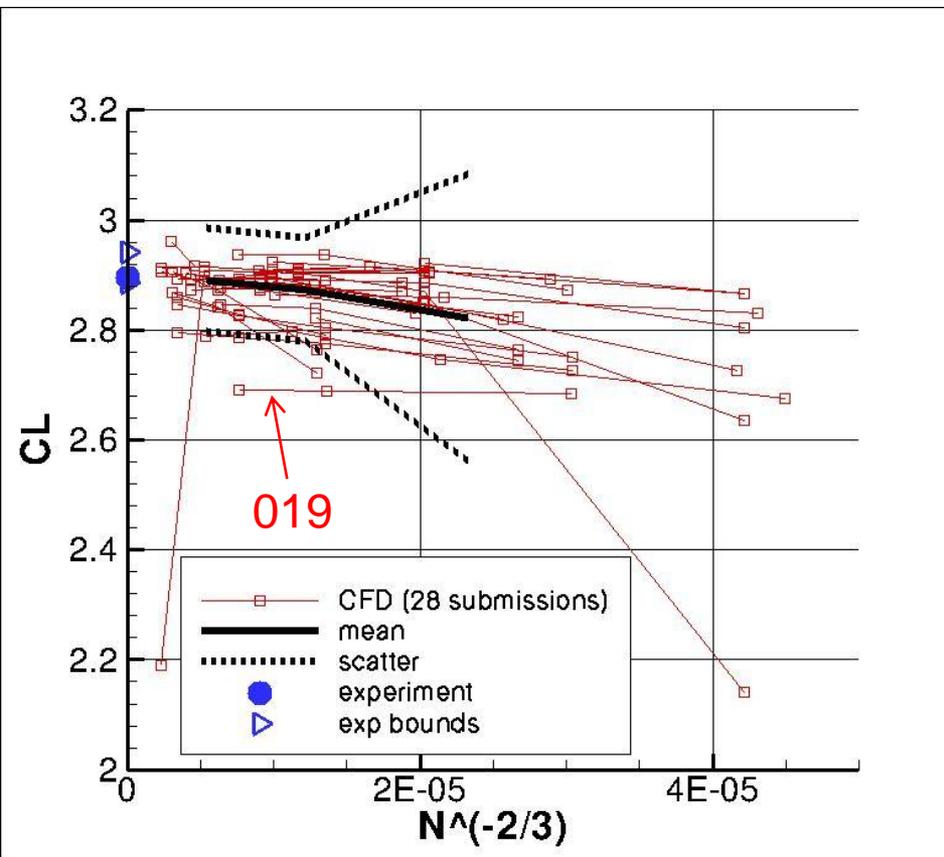
Statistical analysis

Alpha=28

Statistics include C-M-F data only (XC and XF not included)

All except outliers 002 & 008.xx

SA only (no 008.xx)



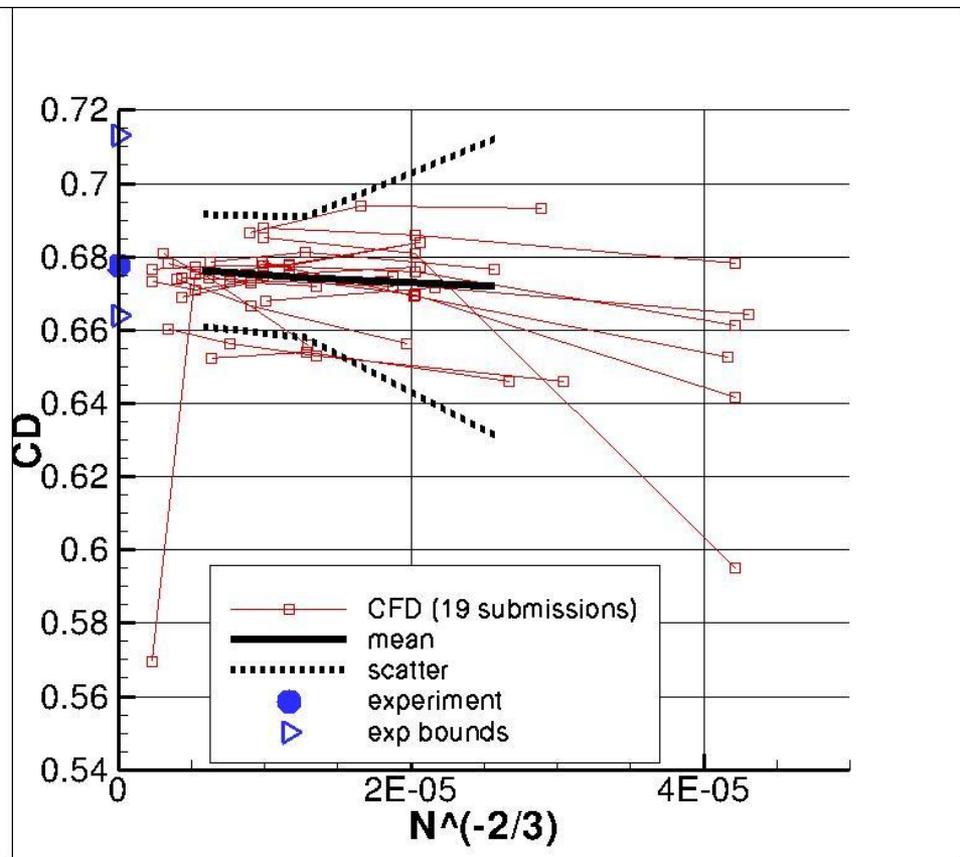
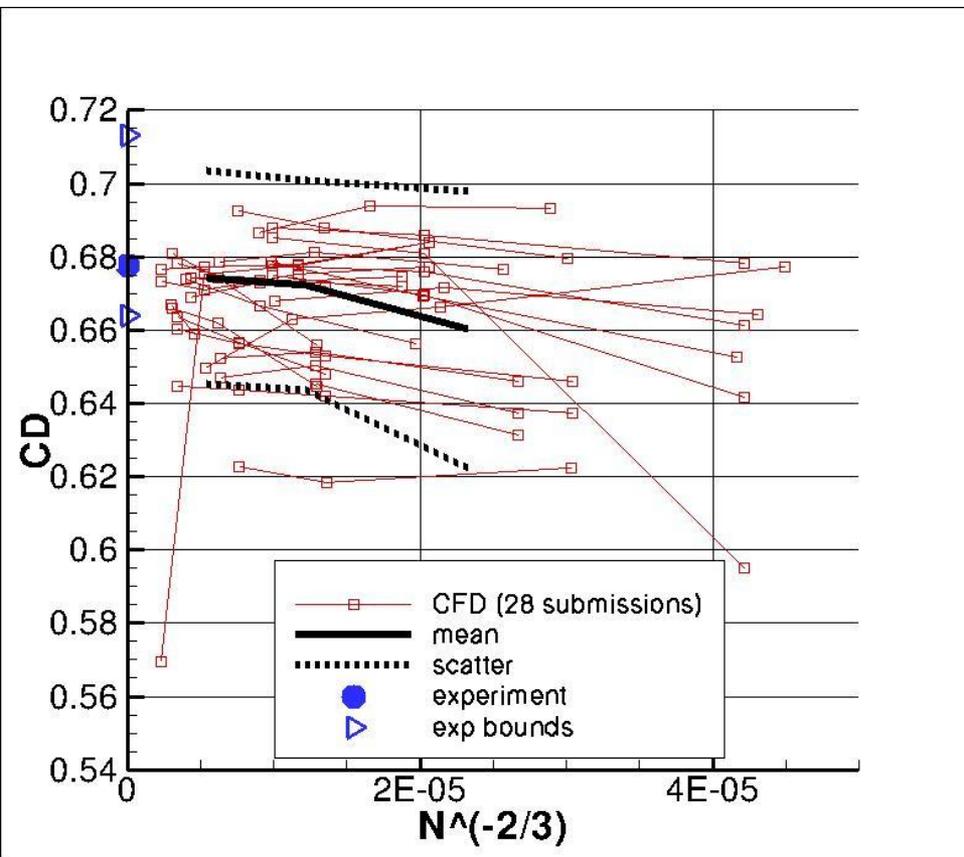
Statistical analysis

Alpha=28

Statistics include C-M-F data only (XC and XF not included)

All except outliers 002 & 008.xx

SA only (no 008.xx)



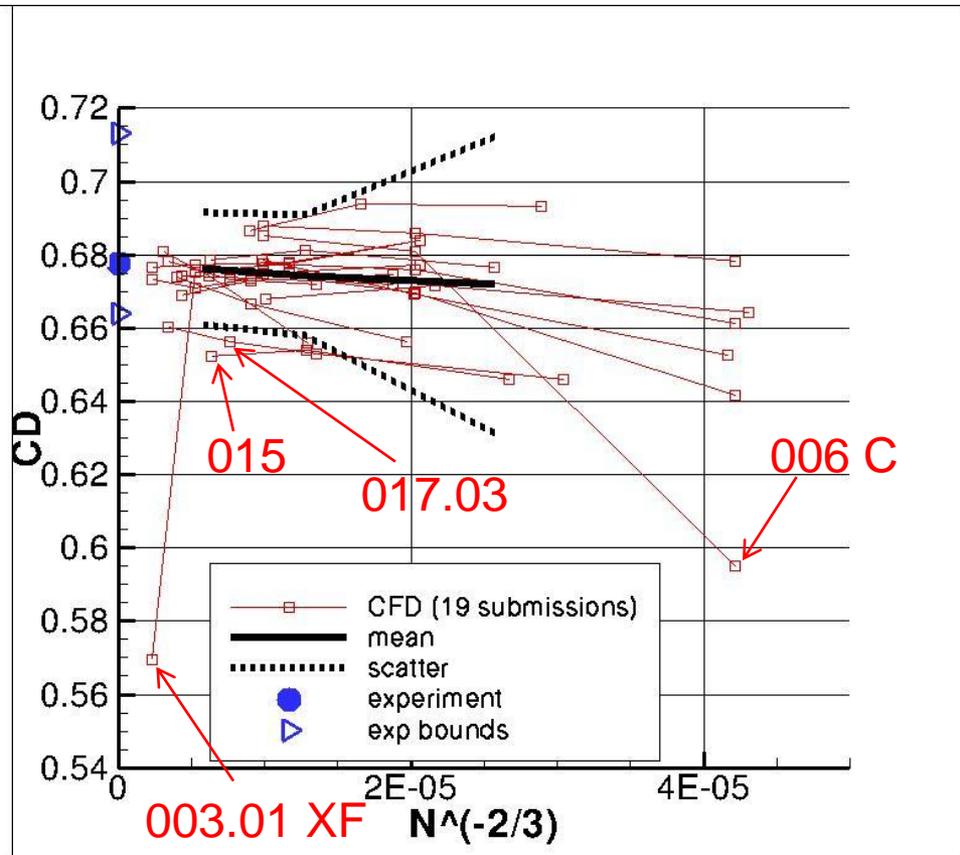
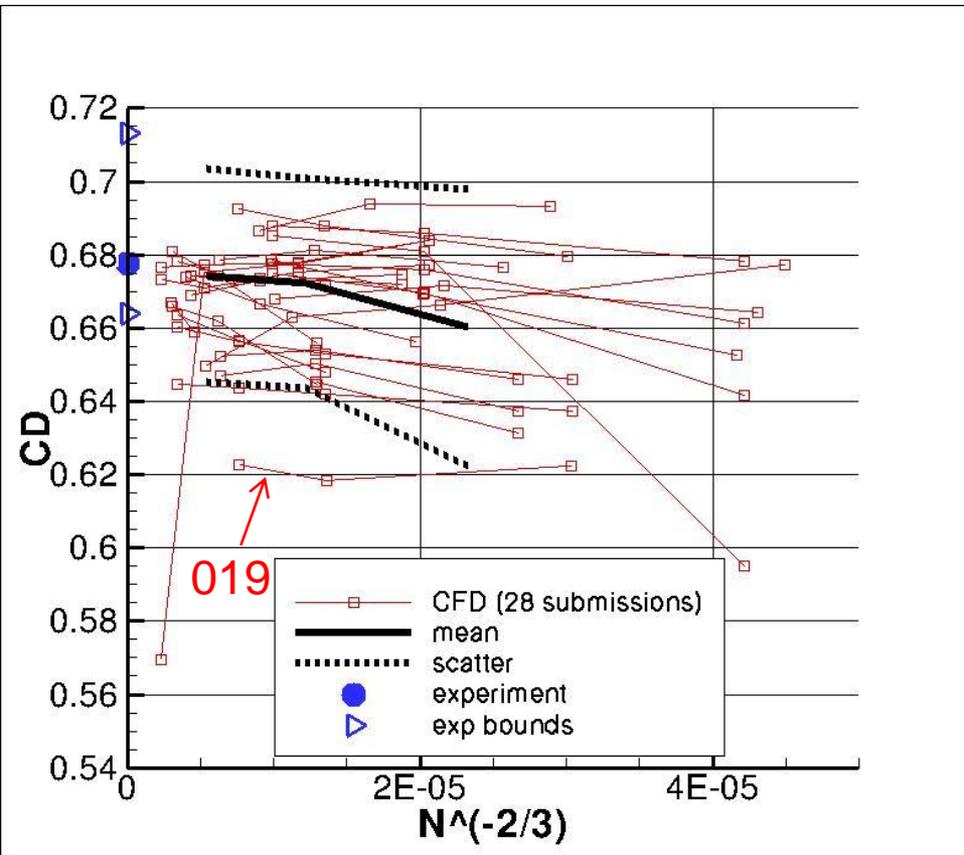
Statistical analysis

Alpha=28

Statistics include C-M-F data only (XC and XF not included)

All except outliers 002 & 008.xx

SA only (no 008.xx)



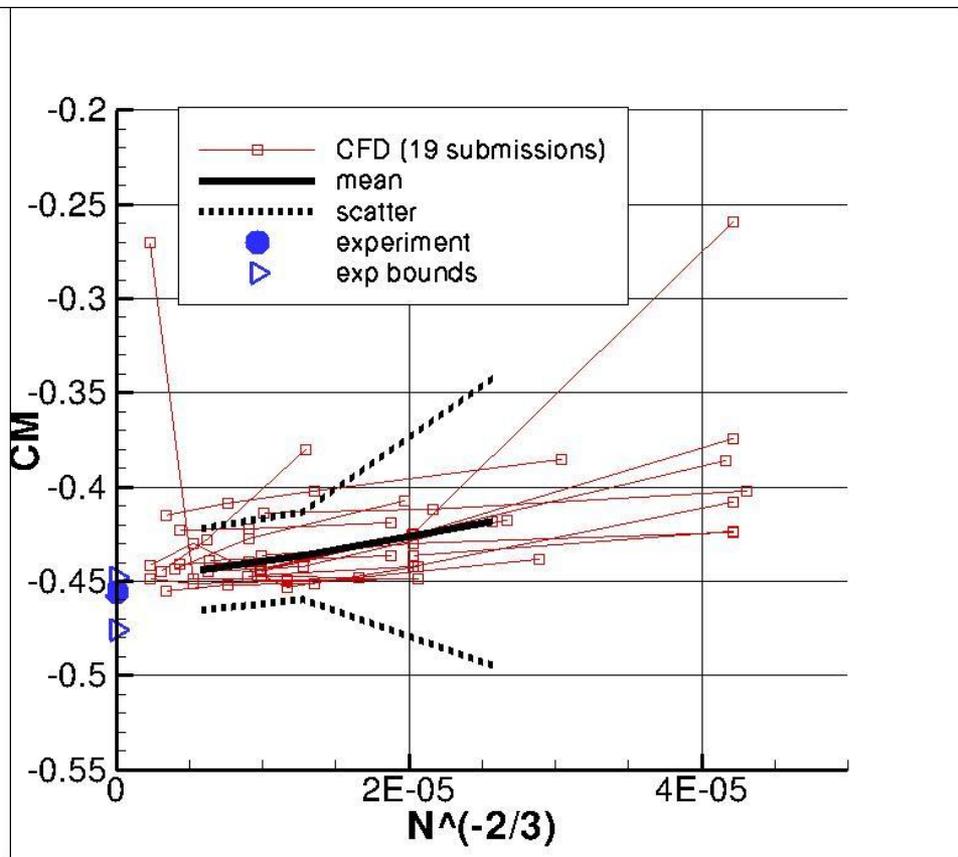
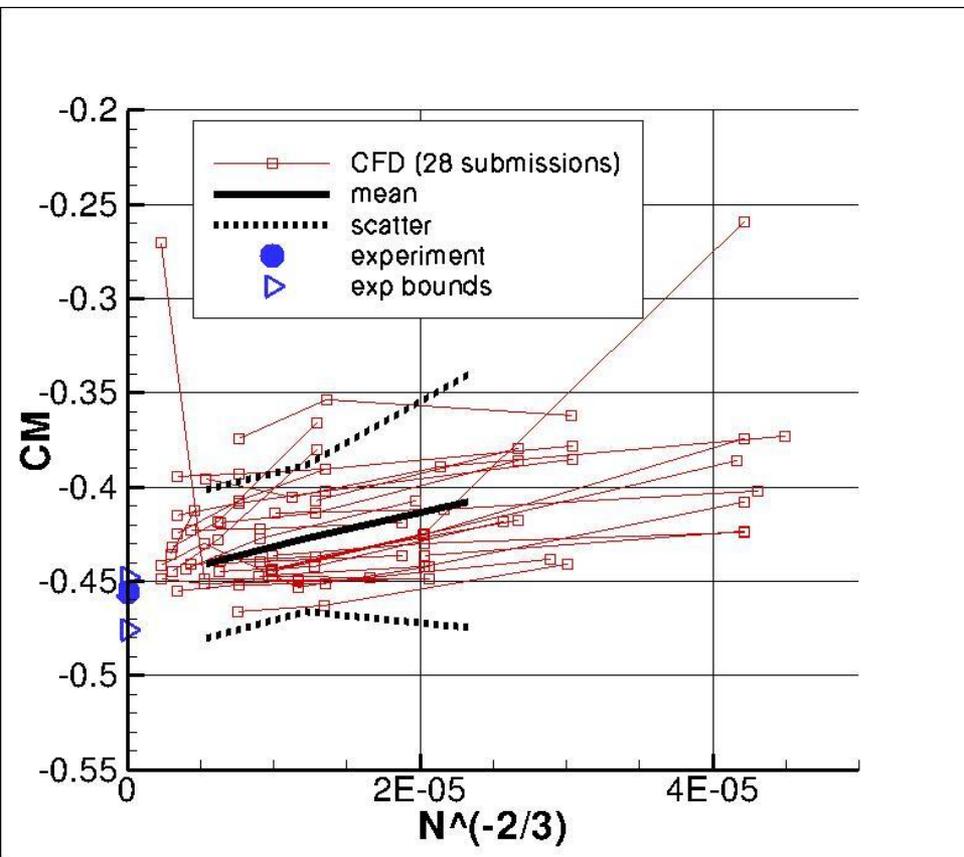
Statistical analysis

Alpha=28

Statistics include C-M-F data only (XC and XF not included)

All except outliers 002 & 008.xx

SA only (no 008.xx)



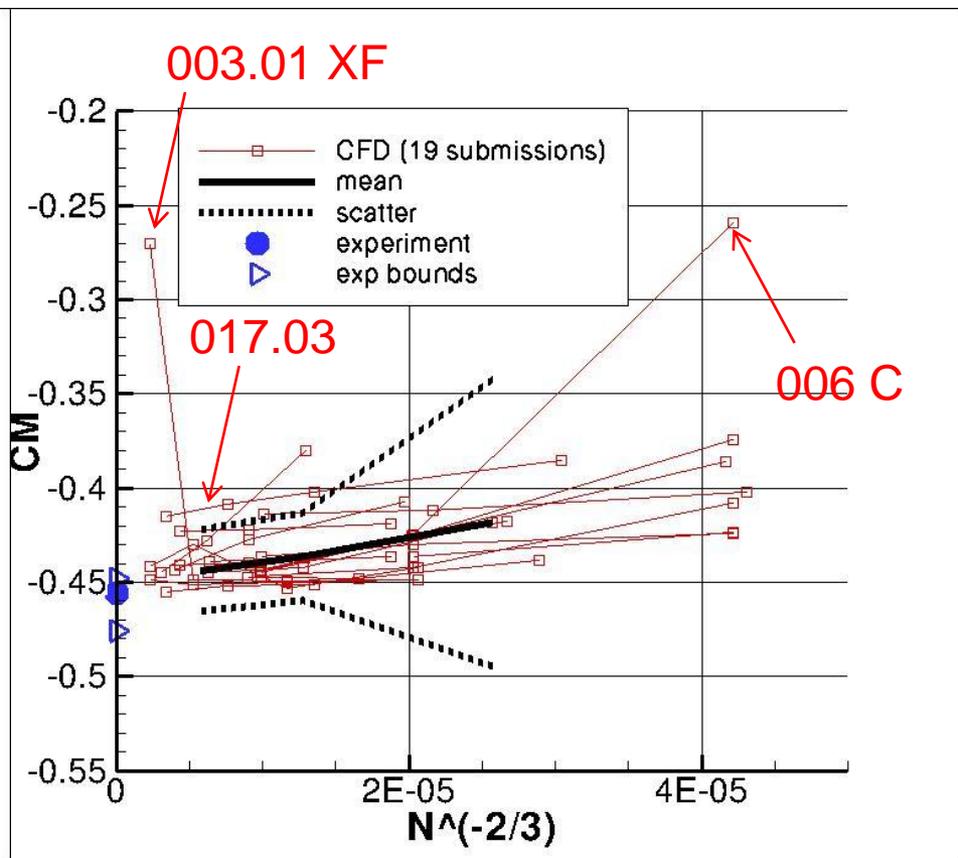
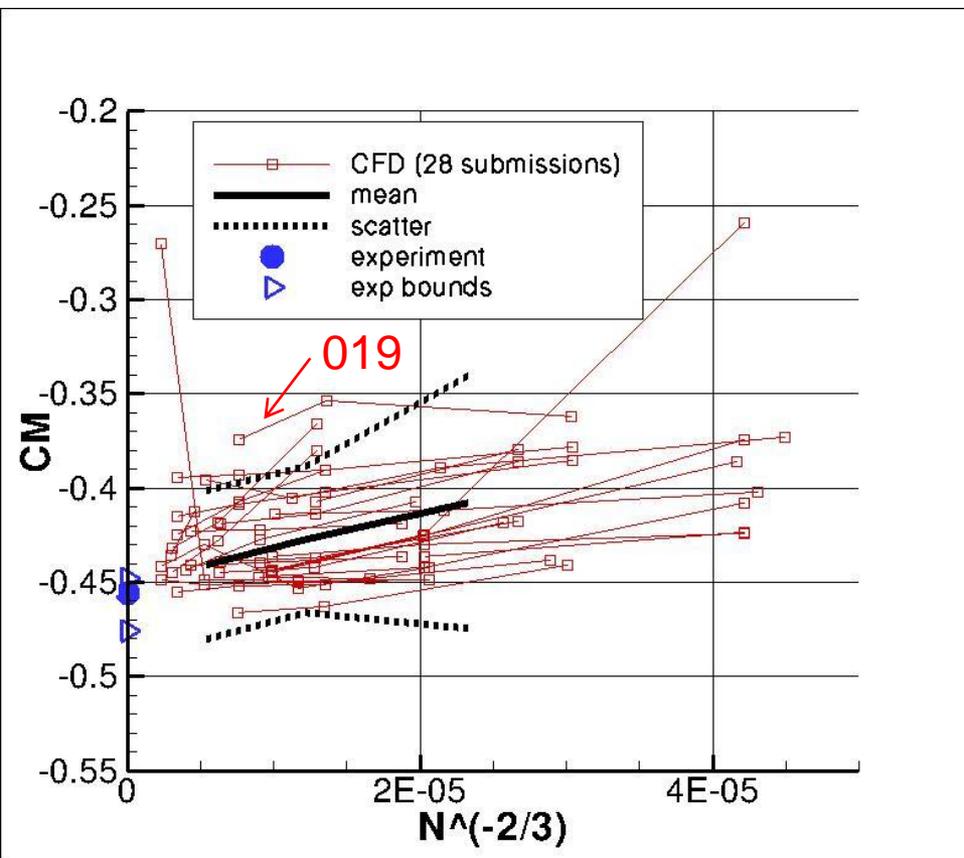
Statistical analysis

Alpha=28

Statistics include C-M-F data only (XC and XF not included)

All except outliers 002 & 008.xx

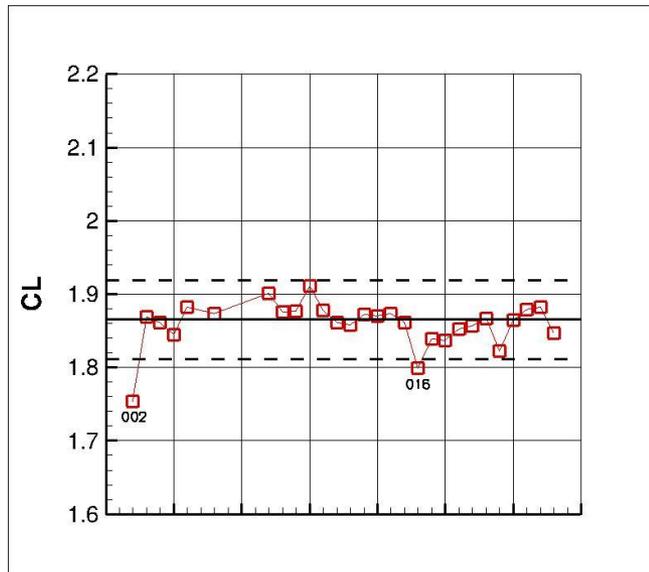
SA only (no 008.xx)



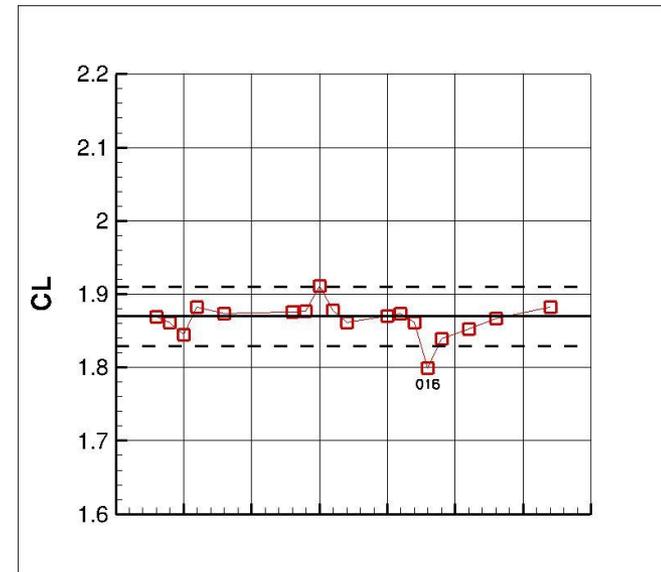
Statistical analysis

Configuration 8, Alpha=13 Medium grid

All



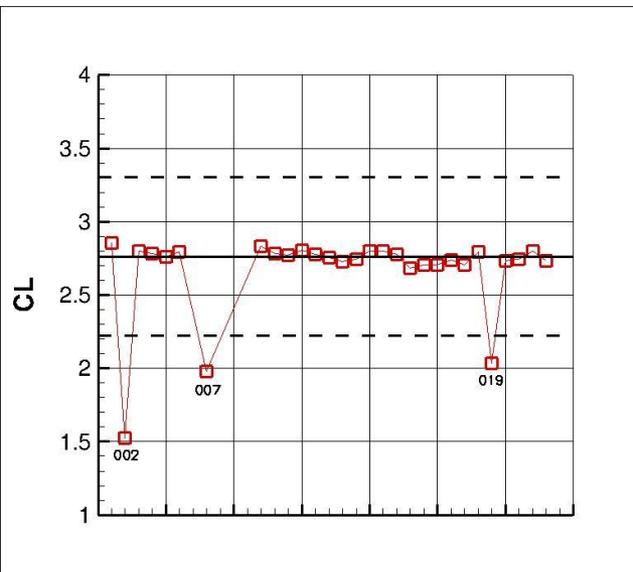
SA only



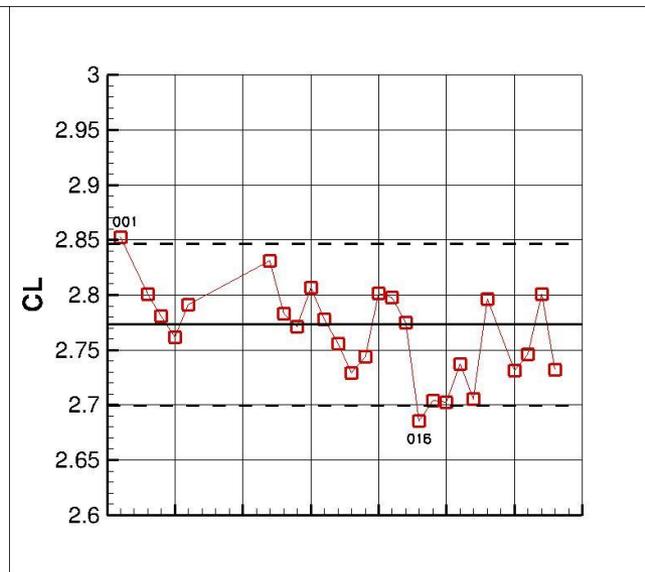
Statistical analysis

Configuration 8, Alpha=28 Medium grid

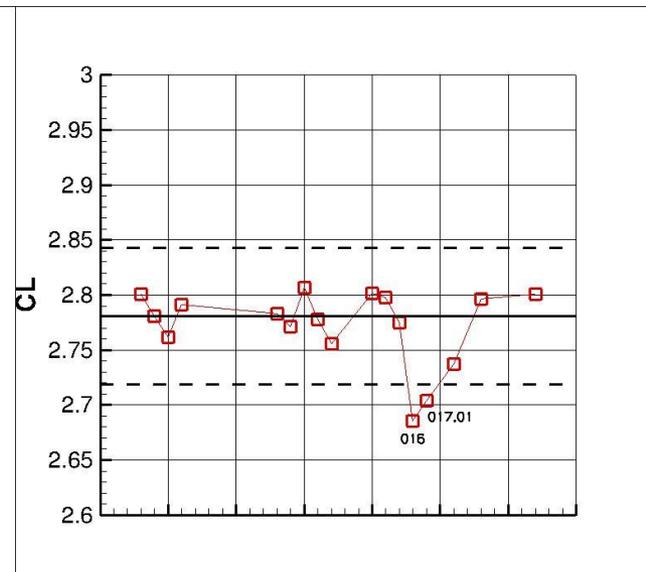
All



Outliers removed



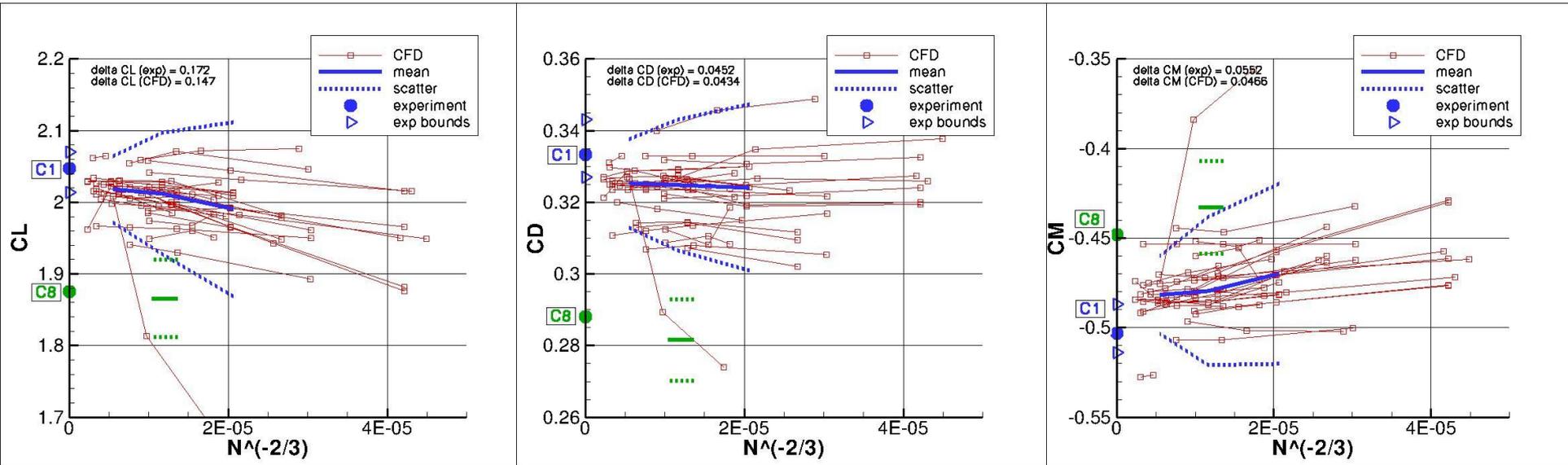
SA only



002, 007, and 019 are outliers at alpha=28
(002 and 019 were also outliers for config 1 at alpha=28)

Statistical analysis

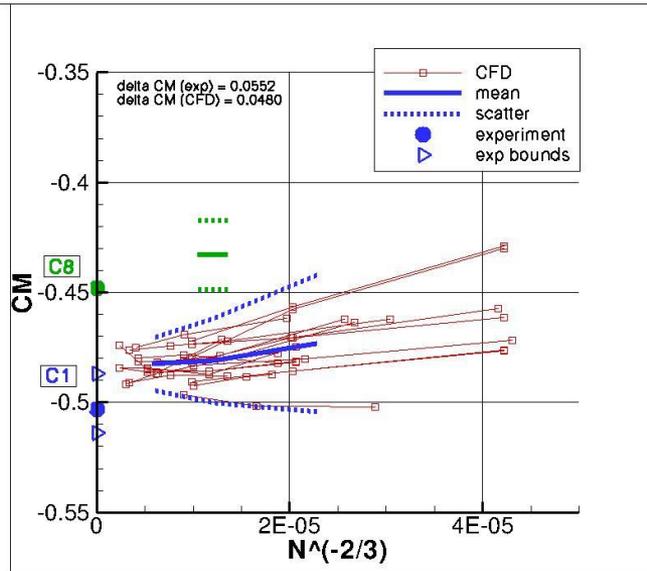
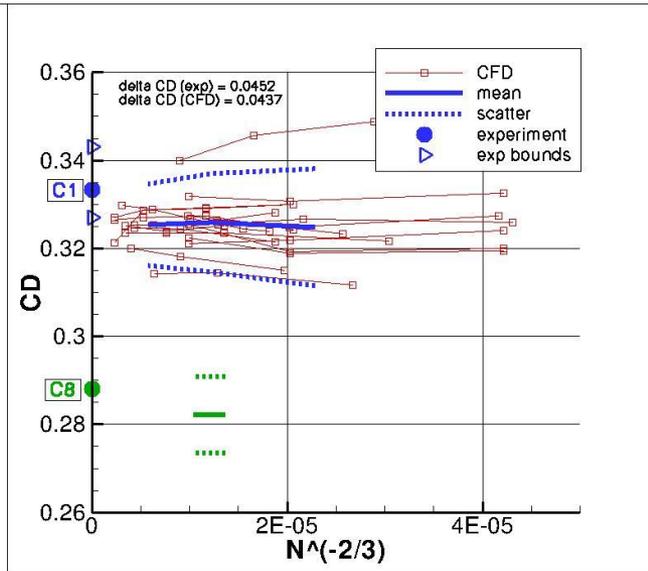
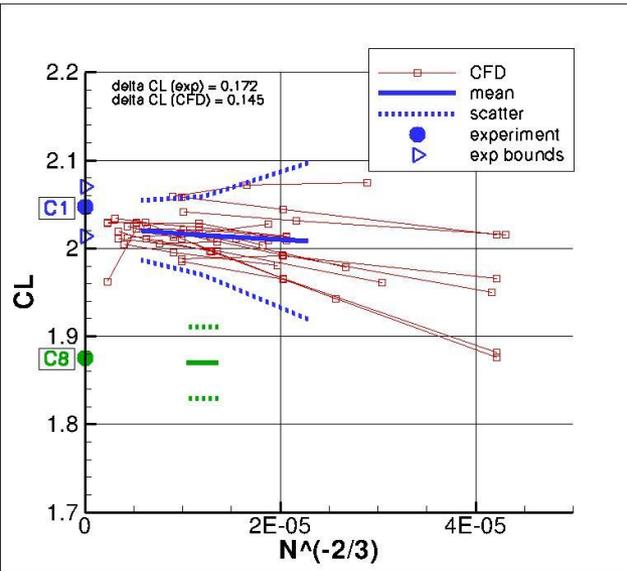
Predicting deltas between configs 1 and 8, Alpha=13



Grid study needed for config 8

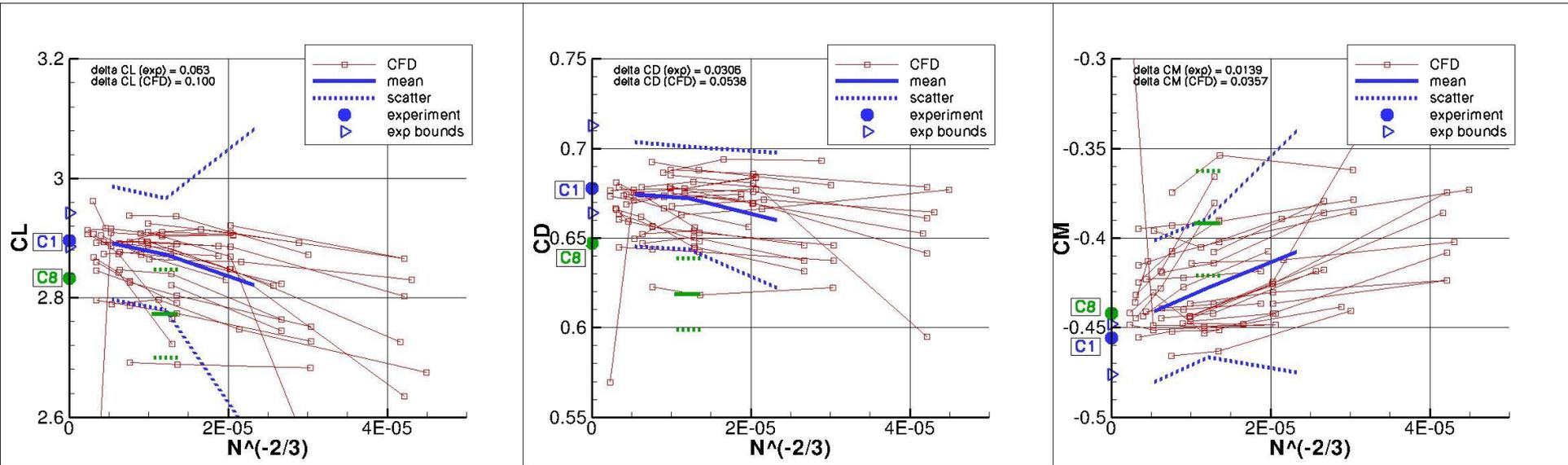
Statistical analysis

Predicting deltas between configs 1 and 8, Alpha=13 SA only



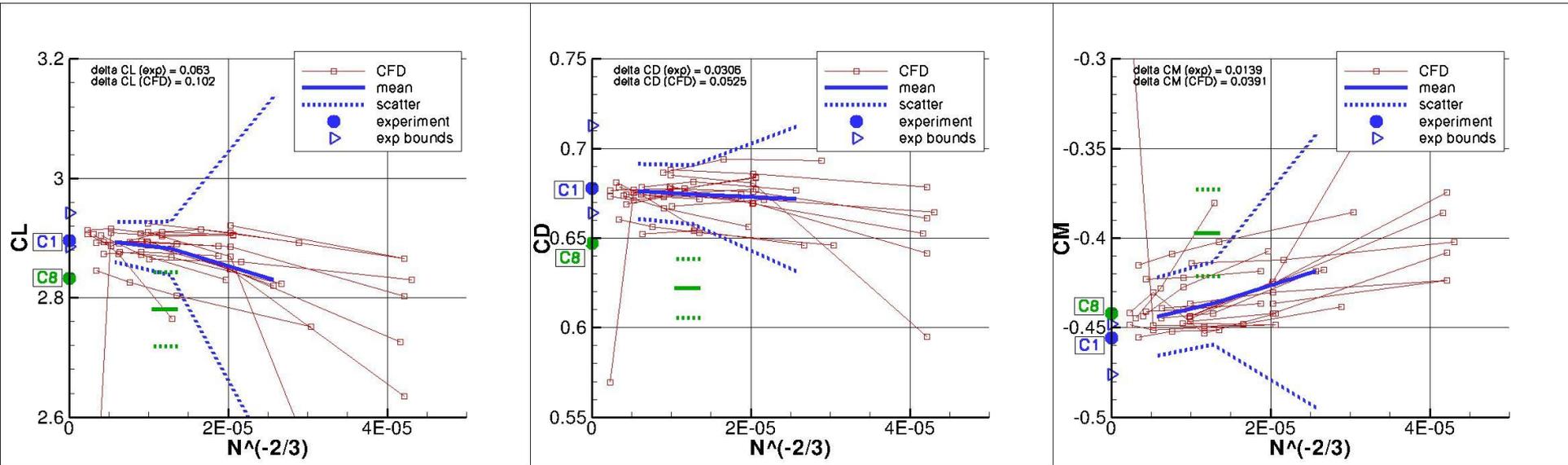
Statistical analysis

Predicting deltas between configs 1 and 8, Alpha=28
Outliers removed



Statistical analysis

Predicting deltas between configs 1 and 8, Alpha=28
Outliers removed, SA only



Conclusions (1)

- Effect of brackets
 - Only minor influence at $\alpha=13$
 - Collective trend is away from experiment at $\alpha=28$
 - But only Medium-level grids were used
 - Brackets influence seen 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
 - Collectively, SA appears to yield higher lift near CLmax than other models (grid studies needed near CLmax)

Conclusions (2)

- Surface pressures and skin friction
 - The spanwise rows of taps on the flap are very useful
 - CF data useful to note where “fully turbulent” turbulence models actually activate
 - SST tended to produce more separation than SA (at flap station 85, $\alpha=13$)
 - C_p particularly missed by CFD near wingtip on the flap
 - Possible issues arising from use of thin-layer N-S
 - Other CFD trends were noted
 - Much more analysis is possible
 - we have 29 cuts on all grids ($\alpha=13$ & 28) and at all angles of attack run (medium grid)

Conclusions (3)

- Statistical analysis
 - At alpha=13, scatter converges with grid refinement
 - Only one “big” outlier – goes away on fine grid
 - Scatter of SA-only is tighter: $\Delta CL=0.07$, $\Delta CD=185$ cts
 - At alpha=28, scatter does not converge between M & F unless analyze SA-only
 - A few “big” outliers
 - Scatter of SA-only (minus outliers): $\Delta CL=0.07$, $\Delta CD=308$ cts
 - Outliers also identified within SA-only group
 - 003.01 on XF grid is a big outlier – why?
 - Collective is in reasonable agreement with experiment at alpha=13 & 28, taking into account repeatability bounds
 - CD coefficient of variation (fine grid) similar to DPW if keep all models; smaller if only consider SA results

- Next time, collect iterative convergence histories for select cases
- Additional grid-convergence studies would be helpful
 - with brackets
 - config 8
 - near CLmax
- Issue of thin-layer vs. full Navier-Stokes?
- 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

- 006: missing many CP/CF cuts
- 009: missing bracket CP/CF cuts; also, slat & flap positioning appears to be incorrect in CP/CF extractions
- 010: wing component of forces/moments too low
- 014: CFs labeled incorrectly (already fixed)
- 019: CF values off by large factor (approx 2500x)
- 021: CF (flap showed no separation)