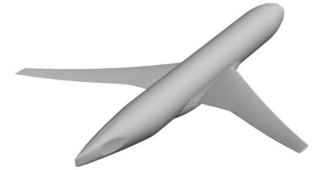
AIAA Applied Aerodynamics Technical Committee

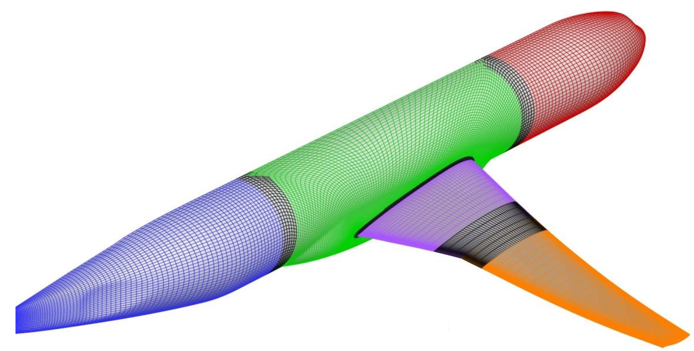


The CFD Drag Prediction Workshop Series: Summary and Retrospective

David W. Levy

Cessna Aircraft Company

and the DPW Organizing Committee



Jameson, Roe, van Leer Symposium *San Diego, CA* *22-23 June 2013*

DPW 5 Organizing Committee

David W. Levy and Kelly R. Laflin

Cessna Aircraft Company

Edward N. Tinoco, John C. Vassberg, Mori Mani, and Ben Rider

The Boeing Company: Seattle, Huntington Beach, and St. Louis

Christopher L. Rumsey, Richard A. Wahls, and Joseph H. Morrison

NASA Langley Research Center

Olaf P. Brodersen and Simone Crippa

DLR Institute of Aerodynamics and Flow Technology

Dimitri J. Mavriplis

University of Wyoming

Mitsuhiro Murayama

Japan Aerospace Exploration Agency

DPW Organizing Committee

Past Members

Shreekant Agrawal

The Boeing Company, Seattle

Steve Klausmeyer, Tom Zickuhr

Cessna Aircraft Company

Mike Hemsch, Shahyar Pirzadeh

NASA Langley Research Center

Bernhard Eisfeld, Mark Rakowitz

DLR Institute of Aerodynamics and Flow Technology

Rick Matus

Pointwise, Inc

Jean-Luc Godard

ONERA

Bastiaan Oskam

National Aerospace Laboratory

Outline of Presentation

- Introduction and Background
- Geometry Description
- Gridding Guidelines and Common Grids
- Participant and Test Case Descriptions
- Results and Discussion
- Conclusions

DPW Series Guidelines and Objectives

- Assess state-of-the-art CFD methods as a practical tool.
- Provide an impartial international forum.
- Promote balanced participation across academia, government labs, and industry.
- Use common public-domain subject geometries.
- Provide baseline grids to encourage participation and help reduce variability.
- Openly discuss areas needing added research and development.
- Conduct rigorous statistical analyses of CFD results.
- Schedule open-forum sessions to further engage interaction.
- Maintain a public-domain accessible database of geometries, grids, and results.
- Document workshop findings in open literature.

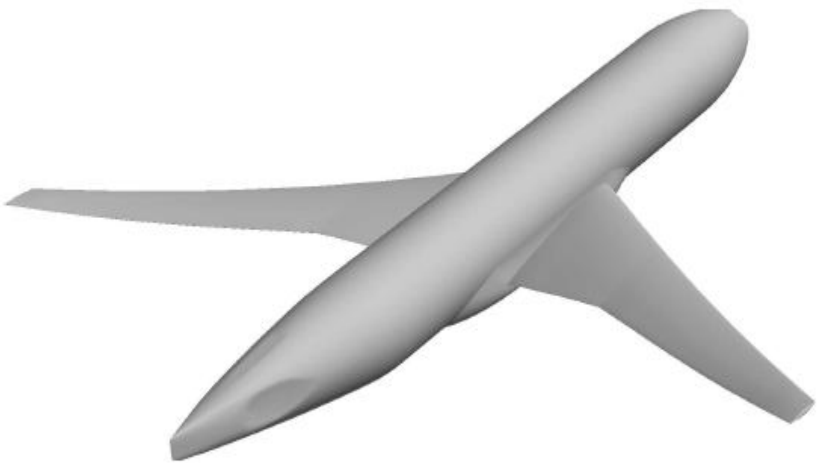
DPW Workshop Series

Note: All co-located with the AIAA Applied Aerodynamics Conference for that year

Year	Location	Configuration	Case Descriptions
2001	Anaheim, CA	DLR-F4 Wing-Body	Single Point Grid Refinement Study Drag Polar Drag Rise Curves at Constant C_L*
2003	Orlando, FL	DLR-F6 Wing-Body Wing-Body-Nacelle	Single Point Grid Refinement Study Drag Polar Boundary Layer Trip Study* Drag Rise Curves at Constant C_L*
2006	San Francisco, CA	DLR-F6 Wing-Body with and without FX2B fairing; W1/W2 Wing Alone	Single Point Grid Refinement Study Drag Polar Grid Convergence Study Drag Polar
2009	San Antonio, TX	NASA Common Research Model Wing-Body and Wing-Body-Tail	Grid Convergence Study Downwash Study Mach Sweep Study* Reynolds Number Study*
2012	New Orleans, LA	NASA Common Research Model Wing-Body	Common Grid Study Buffet Study Turbulence Model Verification*

*Optional Cases

NASA Common Research Model



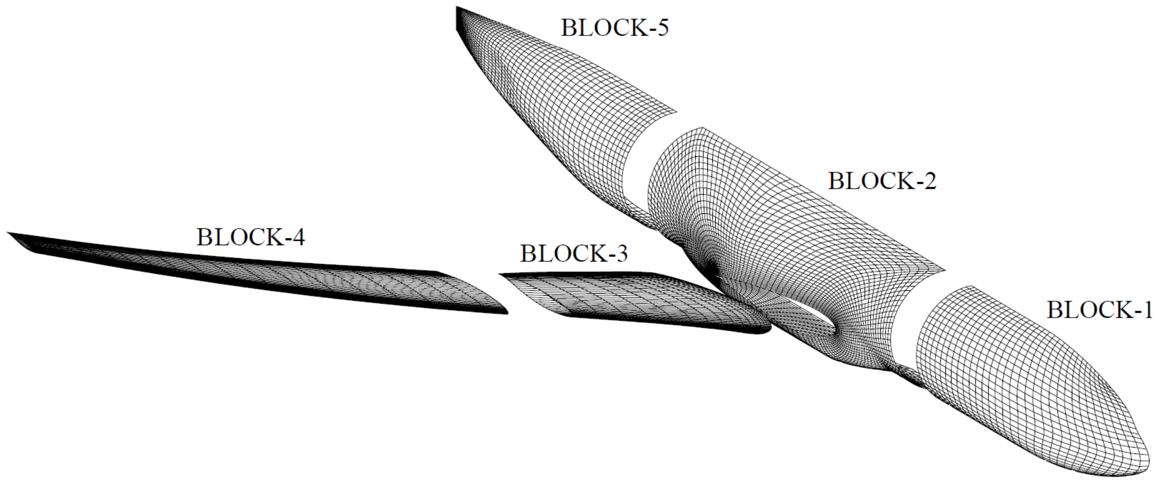
Horizontal tail and Nacelle available

- Developed by NASA Subsonic Fixed Wing Aero Technical Working Group with DPW Organizing Committee
- Modern transonic commercial transport airplane
- Design Condition: $M=0.85$, $C_L=0.50$, and $RE_{MAC}=40x10^6$
- Used in DPW 4 and 5

Gridding Guidelines (DPW 4-5)

1. Initial spacing normal to all viscous walls (RE Based on c_{ref}= 275.80”):
   a) coarse: $y^+ \sim 1.0$ Δy_1= 0.001478 (RE= 5M)
   b) medium: $y^+ \sim 2/3$ Δy_1= 0.000985 (RE= 5M), Δy_1= 0.000273 (RE= 20M)
   c) fine: $y^+ \sim 4/9$ Δy_1= 0.000657 (RE= 5M)
   d) extra-fine: $y^+ \sim 8/27$ Δy_1= 0.000438 (RE= 5M)
2. Recommended: generate grids with 2 cell layers of constant spacing normal to viscous walls
3. Total grid size to grow ~3X between each grid level for grid convergence cases
4. For structured meshes, this growth is ~1.5X in each coordinate direction
5. Grid convergence cases must maintain the same grid family between grid levels, i.e. maintain the same stretching factors, same topology, etc.
6. Growth rate of cell sizes in the viscous layer should be < 1.25.
7. Far field located at ~100c_{ref} for all grid levels.
8. For the Medium Baseline Grids:
   a) Chordwise spacing for wing and tail leading edge (LE) and trailing edge (TE) ~0.1% local chord.
   b) Wing and tail Spanwise spacing at root ~0.1% local semispan.
   c) Wing and tail Spanwise spacing at tip ~0.1% local semispan.
   d) Cell size near fuselage nose and after-body ~2.0% c_{ref}.

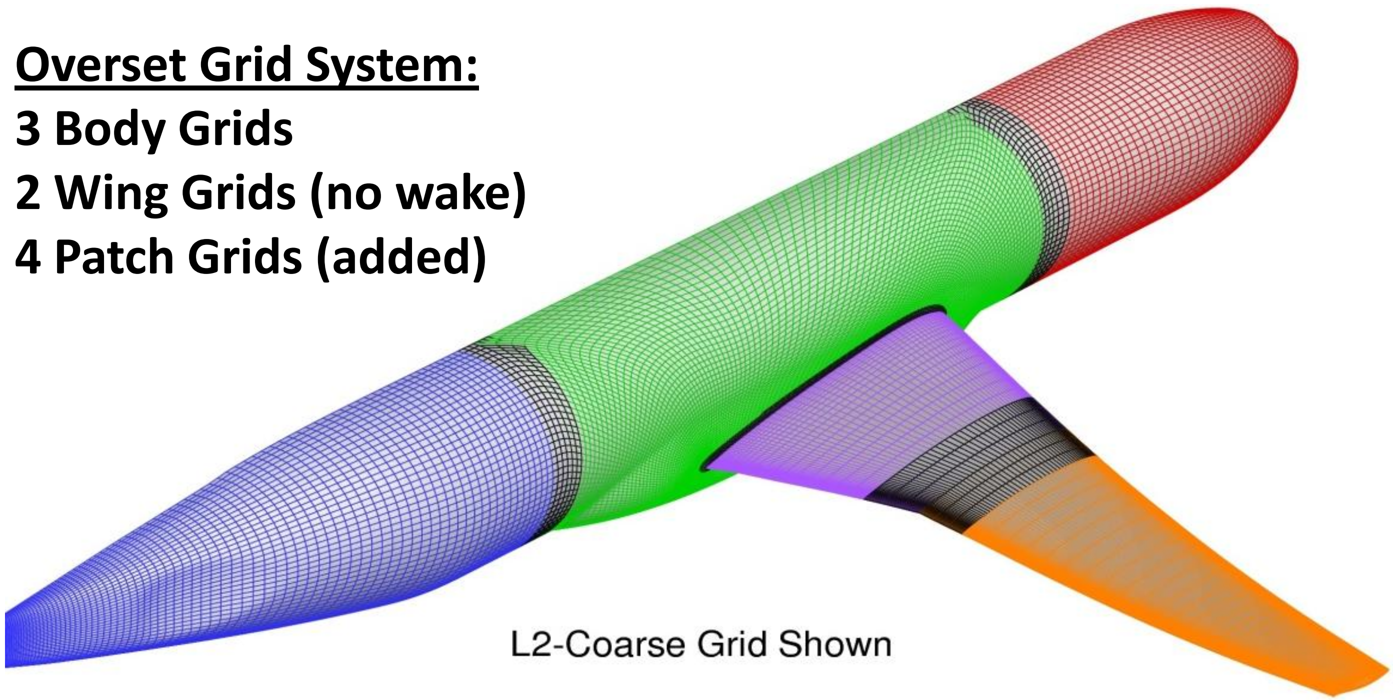
Multiblock Wing-Body Grid Family



- Finest grid (L6) developed first to extend into asymptotic range of grid convergence
- Coarsest grid (L1) multigrid capable to 3 levels
- Six grid size levels in total: L1-L6

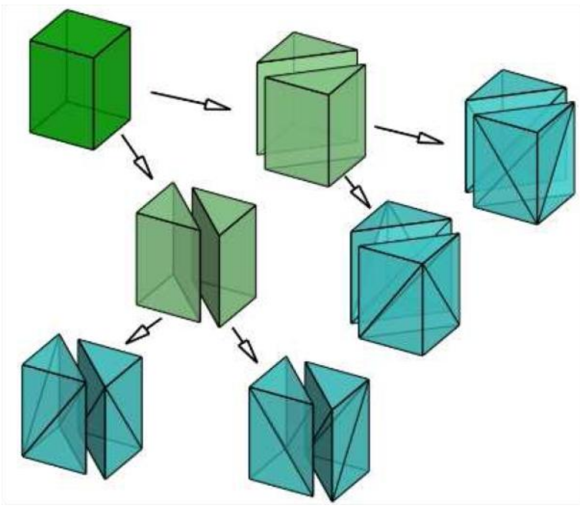
Overset Grids

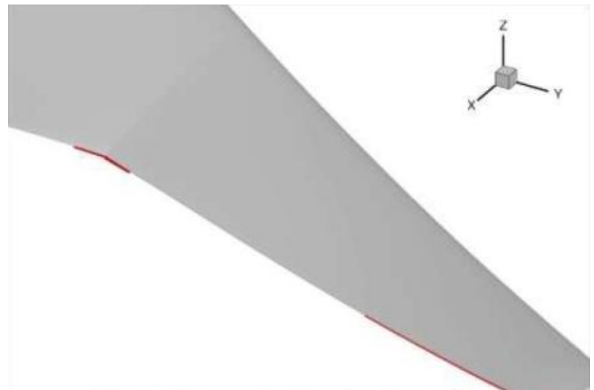
<u>Overset Grid System:</u>
3 Body Grids
2 Wing Grids (no wake)
4 Patch Grids (added)

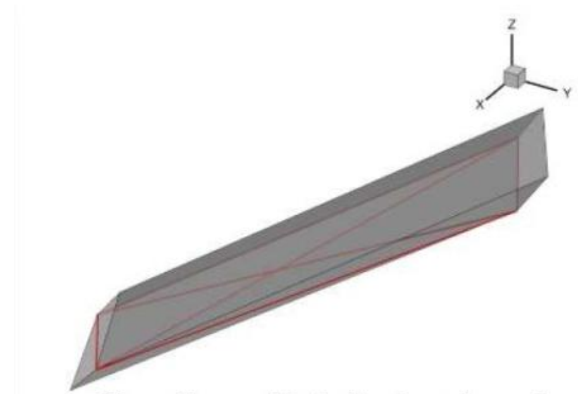


- Main blocks same as MB grids
- Patch grids are point-matched

Unstructured Grids







- Use exact same cloud of points from MB/Overset families
- Hex, prism, and hybrid tet/prism types
- Each hex => 2 prisms; each prism => 3 tets
- Negative volume issues
- Sequences available for cell- or node-based schemes

Common Grid Family Metrics

				Multiblock Structured		Overset	Unstr. Hex	Unstr. Prism	Unstr. Hybrid		
Level	**Name**	**Label**	$\Delta_1 y^+$	**Cells**	**Nodes**	**Nodes**	**Cells**	**Cells**	**Tets**	**Prism**	**Tot. Cells**
1	Tiny	T	2.00	0.64	0.66	0.8	0.64	1.3	2.6	0.43	3.0
2	Coarse	C	1.33	2.2	2.2	2.5	2.2	4.3	8.6	1.4	10.0
3	**Medium**	**M**	**1.00**	**5.1**	**5.2**	**5.7**	**5.1**	**10.2**	**20.8**	**3.3**	**24.1**
4	Fine	F	0.67	17.3	17.4	18.6	17.3	34.5	69.7	11.3	81.0
5	Extra Fine	X	0.50	40.9	41.2	43.3	40.9	81.8	166.1	26.4	192.5
6	Super Fine	S	0.33	138.0	138.8	143.5	138.0	---	---	---	---

Note: All cell/node counts in millions

Participant Descriptions

- **57 Data Total Data Submittals**
- **22 Teams/Organizations**
  - 10 N. America, 5 Europe, 6 Asia, 1 S. America
  - 9 Government, 5 Industry, 6 Academia, 2 Commercial
  - 1 for Case 3 only
- **Grid Types:**
  - 5 Overset (4 Teams)
  - 7 Structured Multi-block (5 Teams)
  - 25 Unstructured (13 Teams: 14 Hex, 7 Hybrid, 4 Prism)
  - 20 Custom (7 Teams: 6 Overset, 2 MB, 2 Hex, 8 Hybrid, 2 Tet)
- **Turbulence Models:**
  - 38 SA (all types), 13 SST (all types), 4 Goldberg R_T, 1 EARSM, 1 Lag-RST

Case 1 and 2 Participant Data Key

Team	ID	Name	Organization	Code	Misc Solver	Grid Type	Turbulence Model
1	A	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central	Overset	SA-Ia
	B	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central	Overset	SA-Ia w/ RC
	C	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central	Custom (Overset)	SA-Ia
	D	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central / QCR	Custom (Overset)	SA-Ia
	E	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central	Custom (Overset)	SA-Ia w/ RC
	F	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central / QCR	Custom (Overset)	SA-Ia w/ RC
	G	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central	Custom (Overset)	SA-Ia w/ RC
	H	Sclafani	Boeing (Huntington)	OVERFLOW v2.2c	Central / QCR	Custom (Overset)	SA-Ia w/ RC
2	I	Chen	CADRC	MFlow	Upwind	Hex	SA
	J	Chen	CARDC	MFlow	Upwind	Hybrid	SA
3	K	GariÈpy	EcolePolytechMontreal	Fluent V13	Upwind	Prism	SA
	L	GariÈpy	EcolePolytechMontreal	Fluent V13	Upwind	Custom (Hex)	SA
4	M	Scalabrin	Embraer	CFD++	Upwind	Hex	RT
	N	Scalabrin	Embraer	CFD++	Upwind	Hex	SST
	O	Scalabrin	Embraer	CFD++	Upwind	Hybrid	RT
	P	Scalabrin	Embraer	CFD++	Upwind	Hybrid	SST
	Q	Scalabrin	Embraer	CFD++	Upwind	Prism	RT
	R	Scalabrin	Embraer	CFD++	Upwind	Prism	SST
	S	Scalabrin	Embraer	CFD++	Upwind	Custom (Hybrid)	RT
	T	Scalabrin	Embraer	CFD++	Upwind	Custom (Hybrid)	SST
5	U	Eliasson	FOI	EDGE	Central	Hex	EARSM
	V	Eliasson	FOI	EDGE	Central	Hex	SA
	W	Eliasson	FOI	EDGE	Central	Hex	SST
6	X	Powell	Gulfstream *	FUN3D	Upwind Roe	Hybrid	SA
7	Y	Balakrishnan	Indian Inst. Science	HiFUN	Upwind	Hex	SA
8	Z	Hashimoto	JAXA *	FaSTAR	Upwind	Hex	SA-noft2-R
	2	Hashimoto	JAXA	FaSTAR	Upwind	Custom (Hex)	SA-noft2-R
9	3	Yamamoto	JAXA *	UPACS	Upwind	Multi-block	SA-noft2-R (Crot=1)
	4	Yamamoto	JAXA *	UPACS	Upwind	Multi-block	SST-V

* Data Resubmitted After Workshop ** Cases Added After Workshop

Case 1 and 2 Participant Data Key

Team	ID	Name	Organization	Code	Misc Solver	Grid Type	Turbulence Model
10	**5**	Olson	NASA Ames *	overflow2.2e_LRS	Central/matrix	Overset	Lag RST
11	**6**	Park	NASA Langley	FUN3D v12.2	Upwind Roe	Hybrid	SA
	7	Park	NASA Langley	CFL3D v6.6	Upwind Roe	Multi-block	SA
12	**8**	Cai	NPU China *	ExStream	Upwind	Overset	SST
13	**9**	Hue	ONERA	elsA	Central	Multi-block	SA
14	**a**	Coder	Penn St. U	OVERFLOW 2.2c	Upwind	Overset	SA-fv3
15	**b**	Osusky	U. Toronto *	Diablo	Scalar	Multi-block	SA
	d	Osusky	U. Toronto *	Diablo	Matrix	Multi-block	SA
16	**e**	Levy	Cessna Aircraft Co. *	NSU3D	Central/matrix	Hybrid	SA
	f	Levy	Cessna Aircraft Co.	FUN3D	Upwind Roe	Hybrid	SA
17	**g**	Crippa	DLR	TAU	Matrix	Hex	SA
	h	Crippa	DLR	TAU	Matrix	Hex	SST
18	**k**	Moitra	CRL_INDIA	CFD++	Upwind	Prism	SA-RC
19	**m**	Winkler	Boeing (St. Louis)	BCFD	Upwind HLLE	Hex	SA
	n	Winkler	Boeing (St. Louis)	BCFD	Upwind HLLE	Hex	SST-V
	q	Winkler	Boeing (St. Louis)	BCFD	Upwind HLLE	Hex	SA
	r	Winkler	Boeing (St. Louis)	BCFD	Upwind HLLE	Hex	SST-V
20	**t**	Temmerman	NUMECA	FINE/Open	Cell Centered	Multi-block	SA
21	α	Brodersen	DLR	TAU	Diss 1	Custom (Hybrid)	SA
	β	Brodersen	DLR	TAU	Diss 3	Custom (Hybrid)	SA
	δ	Brodersen	DLR	TAU	Diss 1	Custom (Hyb w/Hex-Wake)	SA
	γ	Brodersen	DLR	TAU	Diss 3	Custom (Hyb w/Hex-Wake)	SA
	λ	Brodersen	DLR	TAU	Diss 1	Custom (Hyb w/Hex-Wake)	Menter SST
	π	Brodersen	DLR	TAU	Diss 3	Custom (Hyb w/Hex-Wake)	Menter SST
6	ξ	Powell	Gulfstream **	FUN3D	Upwind Roe	Custom (Tet)	SA
	ψ	Powell	Gulfstream **	USM3D	Upwind Roe	Custom (Tet)	SA
9	σ	Yamamoto	JAXA **	UPACS	Upwind Roe	Custom (MB)	SA-noft2-R (Crot=1)
	ϖ	Yamamoto	JAXA **	UPACS	Upwind Roe	Custom (MB)	SST-V

* Data Resubmitted After Workshop

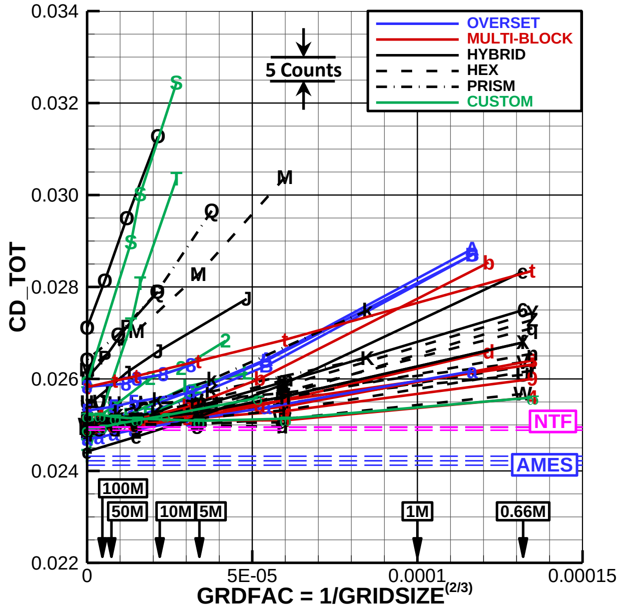
** Cases Added After Workshop

Case 1: Grid Convergence Study

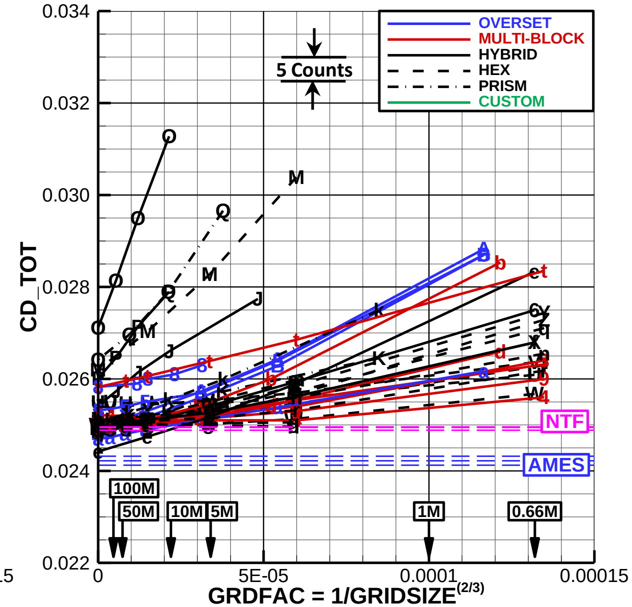
- NASA Common Research Model, Wing-Body
- Mach=0.85, C_L=0.500±0.001
- Grid Resolution Level:
  - 1) Tiny 2) Coarse 3) Medium,
  - 4) Fine 5) Extra-Fine 6) Super-Fine
- Chord Reynolds Number: $5x10^6$

Richardson Extrapolation: CD_TOT

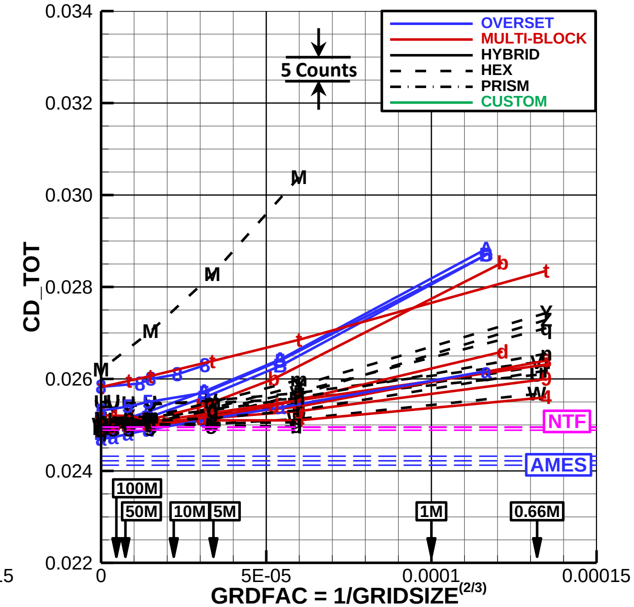
Wind Tunnel Results shown for Reference Only



All Grids



Common Grids Only

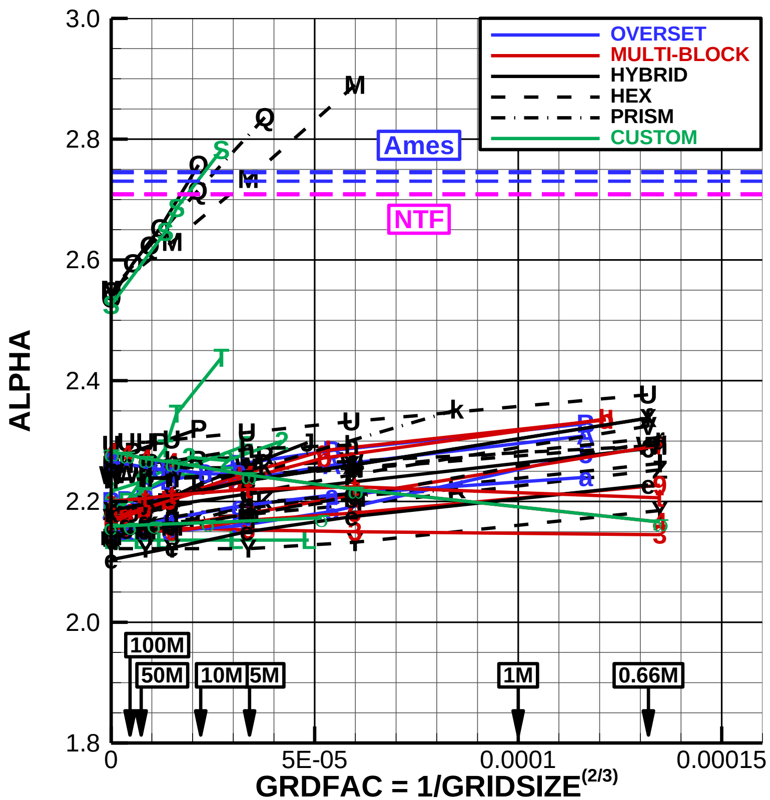


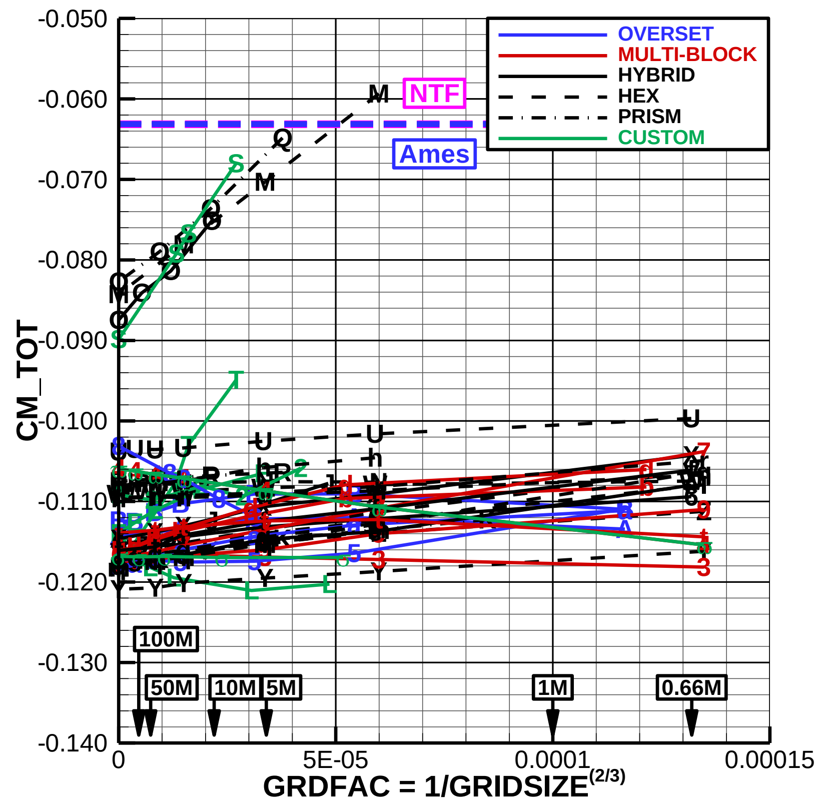
Common Hex Grids Only

Richardson Extrapolation:

ALPHA and CM_TOT

Wind Tunnel Results shown for Reference Only





Wind Tunnel Data

Rivers, M. and Dittberner, A., "Experimental Investigations of the NASA Common Research Model in the NASA Langley National Transonic Facility and NASA Ames 11-Ft Transonic Wind Tunnel (Invited)," AIAA Paper 2011-1126, presented at the 49th Aerospace Sciences Meeting, Orlando, FL, Jan 2011

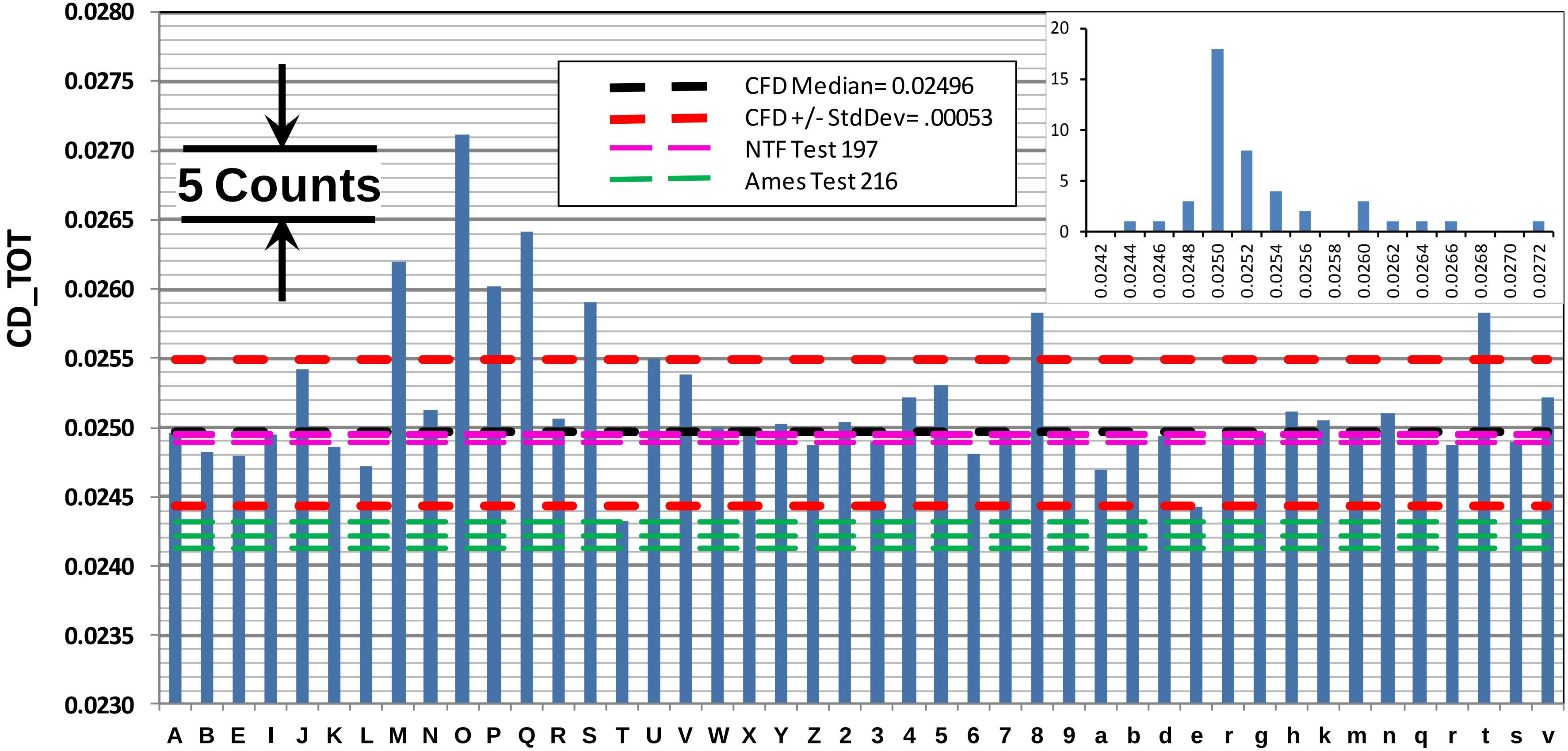
Wind Tunnel	CFD
Walls	Free Air
Support System (Sting)	Free Air
Laminar/Turbulent (Tripped)	"Fully" Turbulent (usually)
Aeroelastic Deformation	Rigid 1g Shape
Measurement Uncertainty	Numerical Uncertainty & Error
Corrections for known effects	No Corrections

- Should we compare to Wind Tunnel Data?
  - Wind Tunnel and CFD measure/compute different things!
- Data are included for reference only

http://commonresearchmodel.larc.nasa.gov/

Continuum Drag Extrapolation

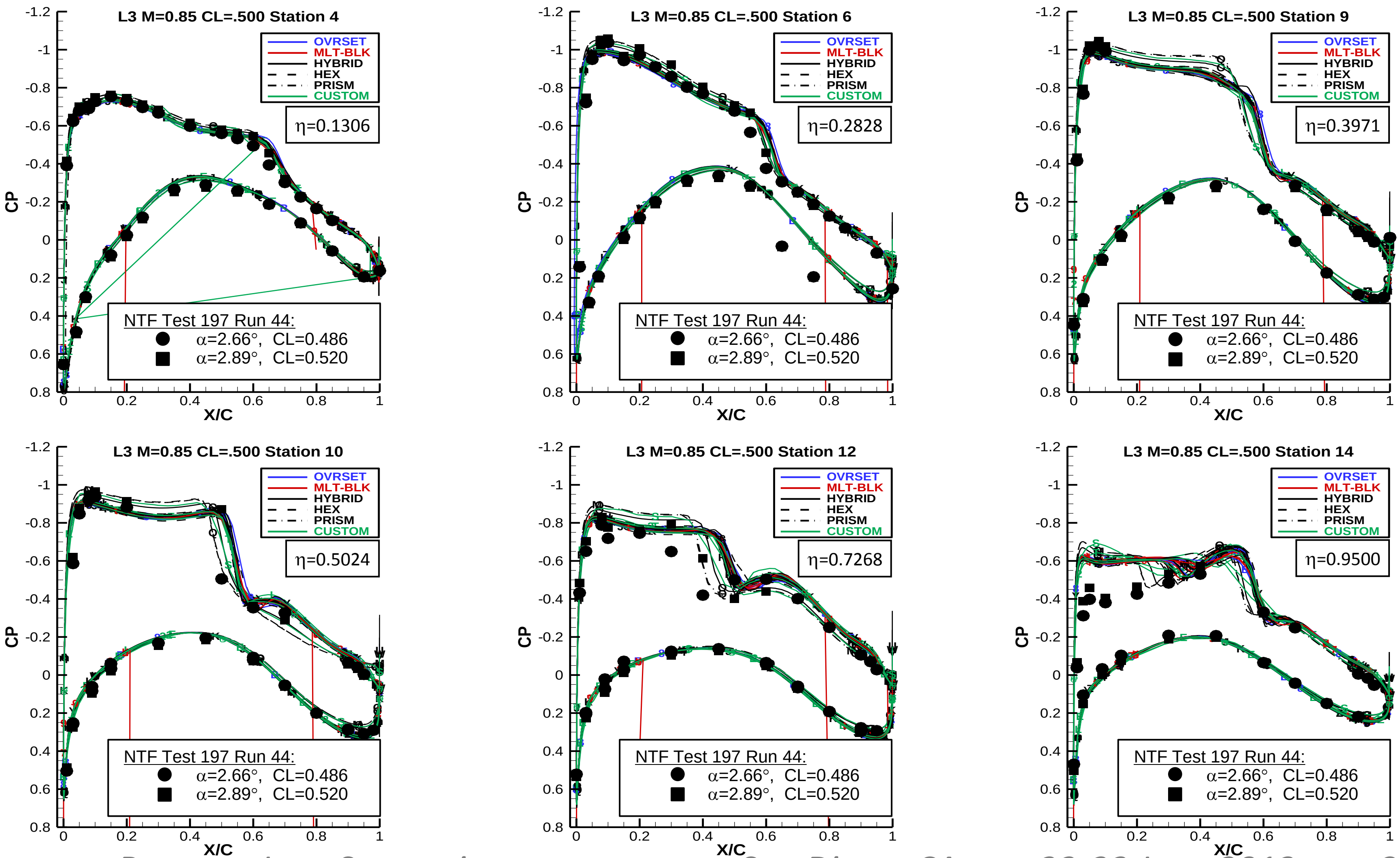
Wind Tunnel Results shown for Reference Only



Richardson Extrapolation Conclusions

- Most results are monotonically decreasing
- Some are nonlinear
  - Convergence issues
  - Flow-feature changes (SOB or TE Separation)
- Scatter is reduced somewhat for Common Grids
  - Scatter still large for coarser grids
  - Best for Hex-based, including Structured, Overset, and Unstructured

Wing Pressures: Spanwise Trends



Case 1 Discussion

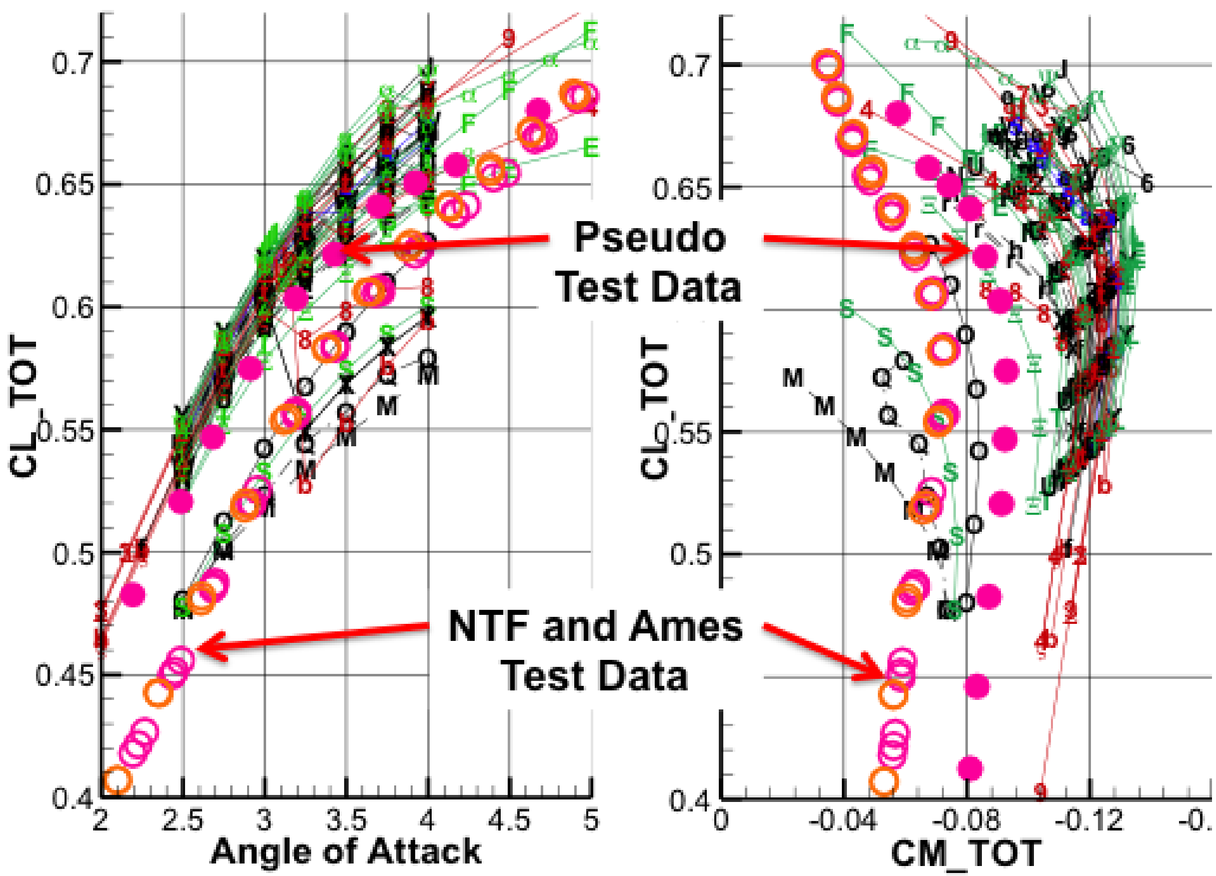
- Still a lot of scatter!
- No clear break-outs with grid type or turbulence model
  - Some Turb. Models are outliers
  - Trends are still hard to isolate due to small sample sizes
- Agreement with experiment on CD_TOT is better than for ALPHA and CM_TOT
  - Wing aeroelastic effects are likely part of this
  - Spread in CD_TOT is similar for wind tunnel and CFD scatter
- Scatter is reduced somewhat for Common Grids
  - Statistics did not change significantly
  - Best for Hex-based, including Structured, Overset, and Unstructured
  - Discretization and Turbulence Modeling is still a major contributor
- Agreement in pressure data with experiment deteriorates at outboard stations, likely due to aeroelastic effects
- Variations in pressure data with grid level hard to discern due to reduced number of data sets

Case 2 Buffet Study:

- NASA Common Research Model, Wing-Body
- Mach=0.85:
  - α=2.50°, 2.75°, 3.00°, 3.25°, 3.50°, 3.75°, 4.00°
- Grid Resolution Level:
  - 3) Medium (5.2M Nodes)
- Chord Reynolds Number: 5×10^6

CL_TOT and CM_TOT by Grid Type

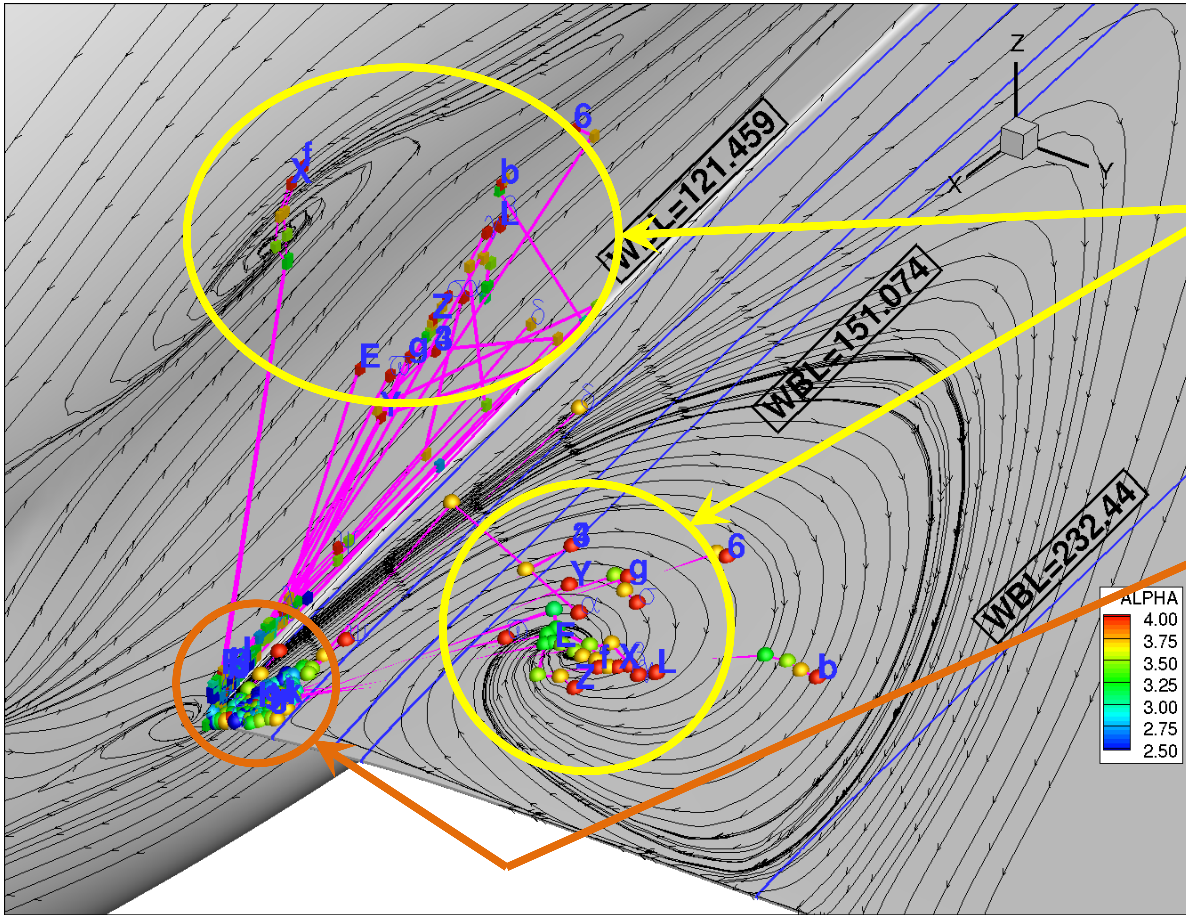
Case 2 – All Solutions



Psuedo Test Data accounts for Aeroelastic Wing Twist

Some data show early lift break at low α

Wing SOB TE Separation Bubble



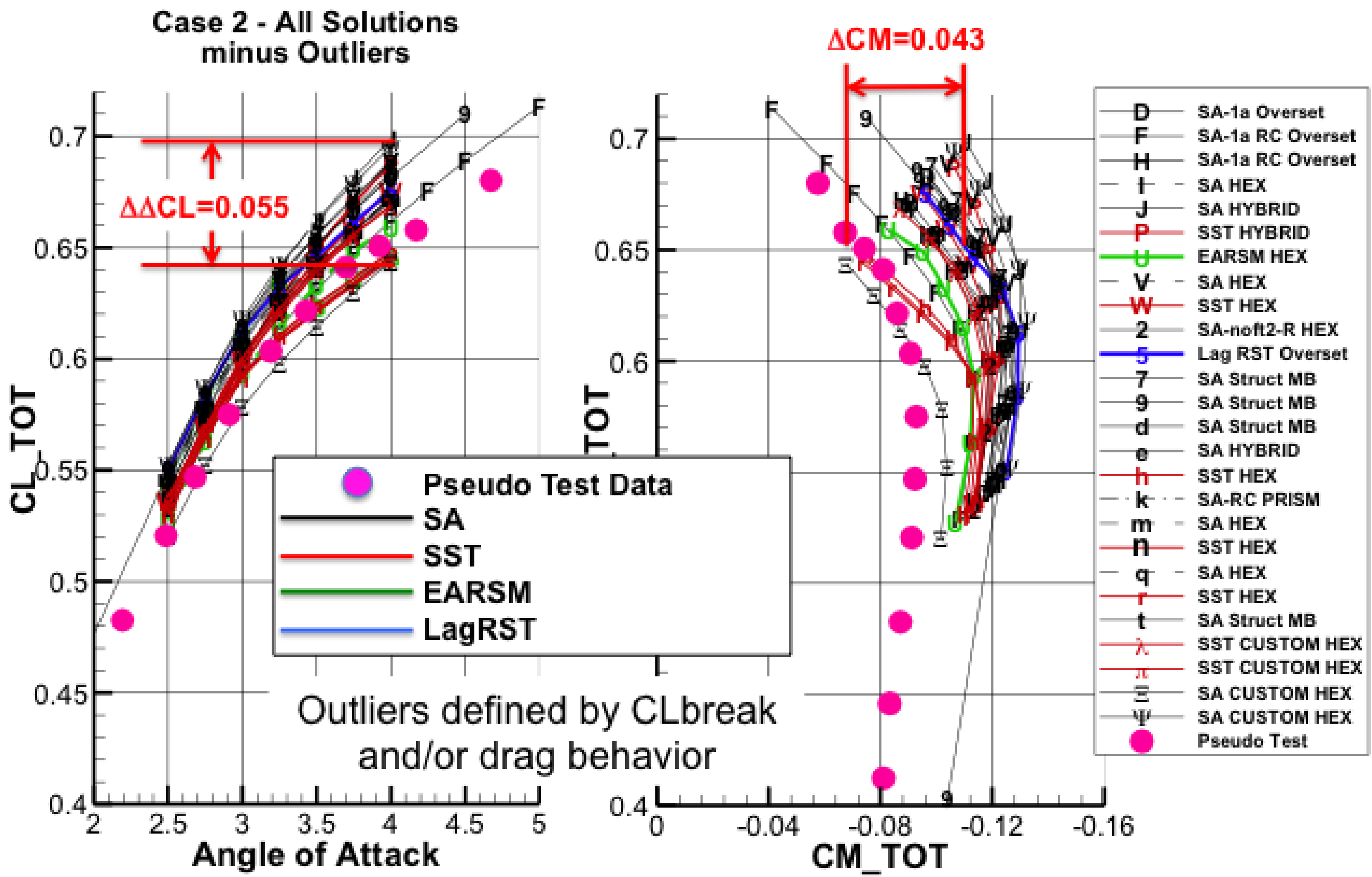
Some solutions had large SOB bubble which occurred for α=3.00 °-3.50°

Majority did not

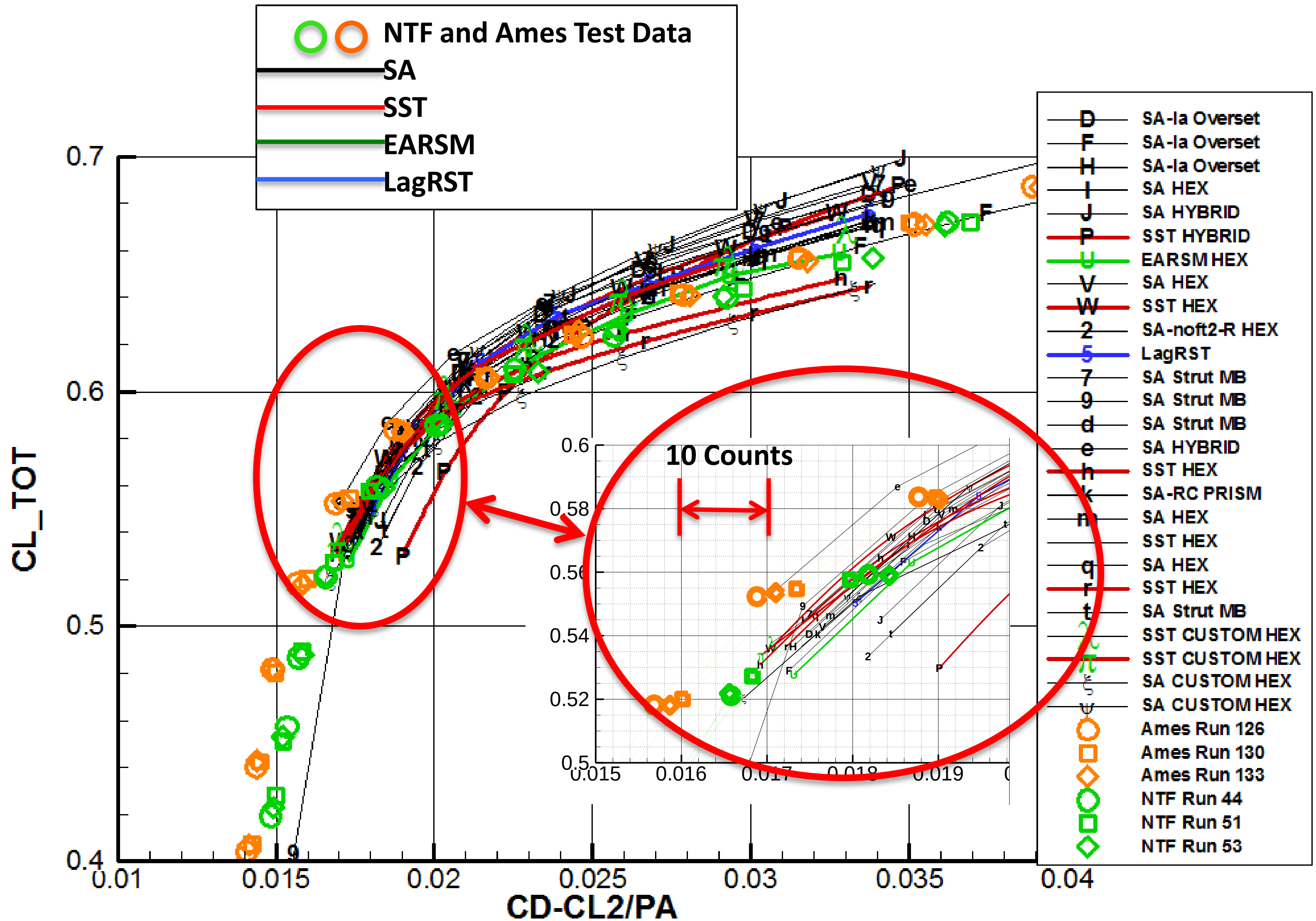
Caused early lift break at low alpha

Streamlines shown are example from dataset "f" at α=3.50°

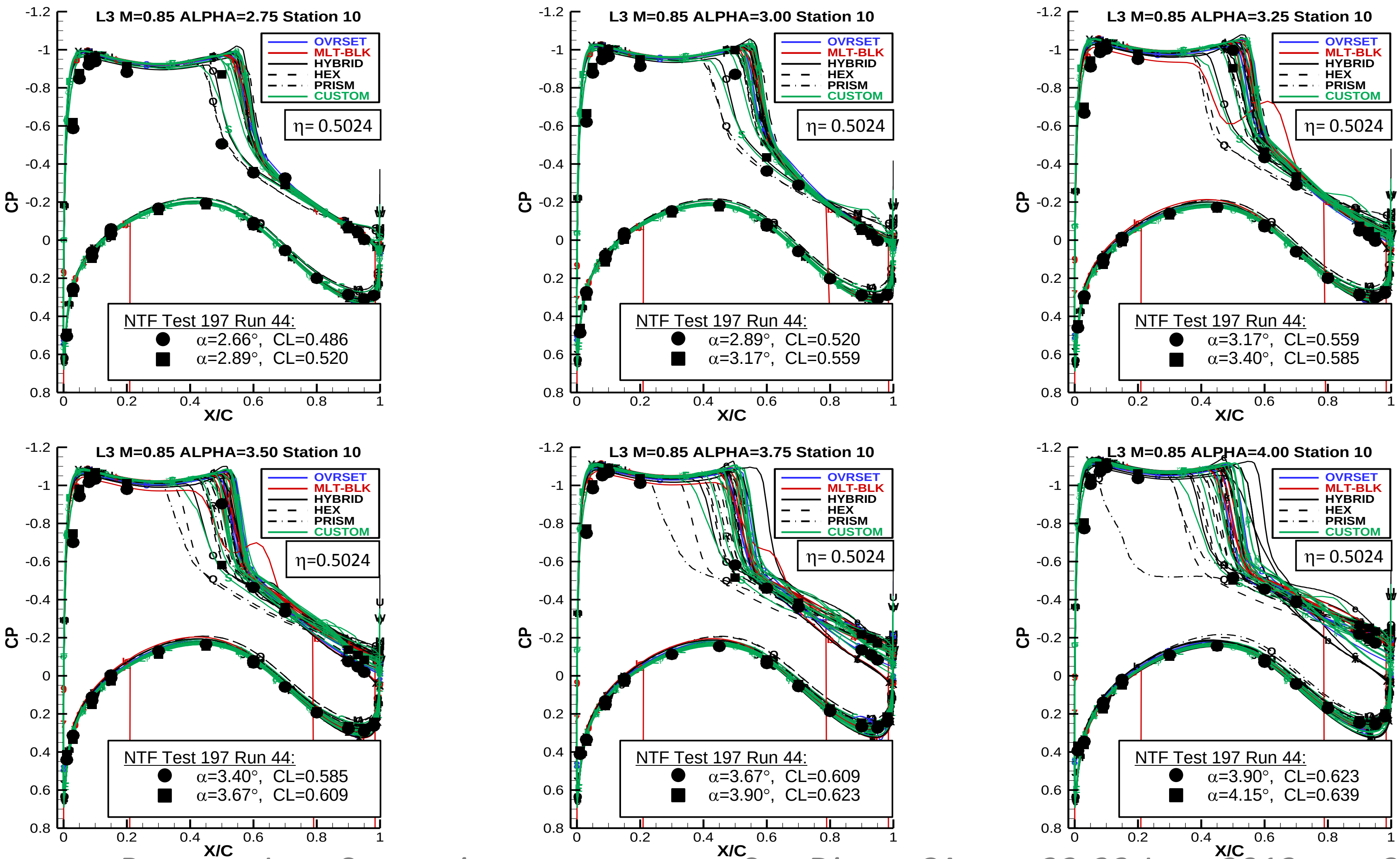
CL_TOT and CM_TOT: Outliers Removed



Idealized Profile Drag



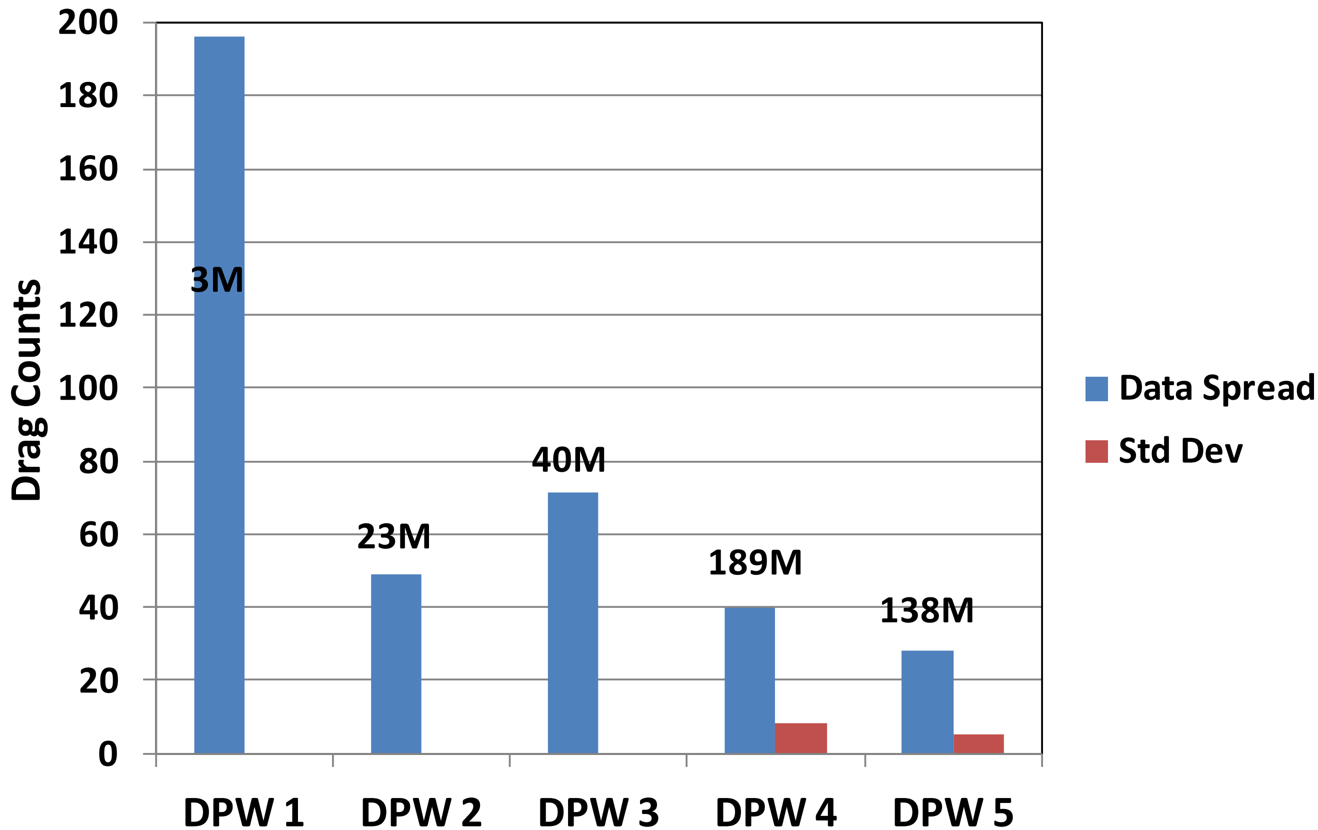
Wing Pressures: Alpha Sweep



Case 2 Discussion

- No clear break-outs with grid type or turbulence model (except for some outliers – Goldberg R_T)
- For all solutions minus outliers
  - Relatively tight forces and moment at α=2.5°, more spread at α=4.0°
- C_L is too high and C_M predicted too negative
  - Is it CFD, test, geometry, etc.?
- Steady aeroelastic effects are significant
  - Contributes to C_L, C_M errors, but not only factor
- High α data characterized by significant shock induced separation
  - Is the real flow steady at these conditions?
  - Is RANS adequate or do we need URANS or DES?
- Large variation in shock location at high α

DPW Series Trend



Yes, we are improving, but more needs to be done

General Conclusions

- Very successful workshop: ***Thanks to Participants***
- Still more variation than desired
  - Some improvement from DPW-IV: We are getting better
  - Mixed results from common grid study
- Drag comparisons to wind tunnel generally favorable
  - Not clear that we *should* agree
- Force/Moment predictions better at low α
  - Less separation, but bigger spread at α=4.0°
- Pressures consistent with Force/Moments
  - Poorer correlation outboard points to aeroelastic effects
  - Wide variation in α for shock separation
- Large variations in separation prediction
  - SOB Separation => Outliers

Further Study

- Check SOB/TE separation with wind tunnel data
  - Is flow visualization data available?
- Include static aeroelastics in CFD
  - Needed to match wind tunnel data
- Include boundary layer transition model
  - Forced/Free
- Unsteady RANS?
  - Will only help if flow is unsteady
- LES/DES?
  - DES only helps for off-body separation
  - LES (beyond current SOA?)