Overview of the AIAA CFD Drag Prediction Workshop Series

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NASA

RAeS Conference on
Aerodynamic Drag Prediction and Reduction: Capabilities and Future Requirements

23-24 October, 2007
London, United Kingdom

Outline

- Background
- DPW Results
- Concluding Remarks

DPW Organizing Committee

- Membership Organizations (varied over time)
  - AIAA Headquarters & APA TC, USA
  - DLR, Germany
  - ETW, Germany
  - NASA, USA
  - NLR, The Netherlands
  - ONERA, France
  - Pointwise, USA
  - Raytheon-Beechcraft, USA
  - Textron-Cessna, USA
  - The Boeing Company, USA
  - University of Wyoming, USA

DPW Objectives

- To assess state-of-the-art CFD methods as practical aerodynamic tools for prediction of forces & moments on industry-relevant geometries, with a focus on drag
  - Use a statistical framework to assess the results
- To provide an impartial international forum for evaluating the effectiveness of CFD NS solvers
  - Promote balanced participation across academia, government labs, and industry
  - Schedule open-forum sessions to further engage interaction among all interested parties
- To identify areas needing additional research and development

DPW Principles

- Use public-domain subject geometries
  - Industry-relevant, yet simple enough to permit high-fidelity computations
  - Provide baseline grids to encourage participation and help reduce variability of CFD results

- Maintain a public-domain accessible database of geometries, grids, and results
  - Document workshop findings; disseminate through publications and presentations

DPW Timeline

- Origins in AIAA Applied Aero TC ~1999
  - Technical Subcommittee on Drag Reduction/Prediction
- DPW-I: Anaheim CA, June 2001
  - 18 Participants, 55 Attendees
  - Spawned a Session at Reno 2002
- DPW-II: Orlando FL, June 2003
  - 22 Participants, 80 Attendees
  - Spawned 2 Sessions at Reno 2004
- DPW-III: San Francisco CA, June 2006
  - 15 Participants, 65 Attendees
  - Spawned a Session at Reno 2007
  - Spawned a Pre-DPW-III Session - Toronto 2005

DPW Test Case Overview

- DPW-I: Anaheim CA, June 2001
  - DLR-F4 Commercial Transport Wing/Body
  - Cruise Polar, Drag Rise
  - Experimental Data Available; 3 facilities

- DPW-II: Orlando FL, June 2003
  - DLR-F6 Commercial Transport Wing/Body + Pylon/Nacelle
  - Cruise Polar, Drag Rise, plus (large) component increment
  - Experimental Data Available; 1 facility

- DPW-III: San Francisco CA, June 2006
  - DLR-F6 Commercial Transport Wing/Body + FX2B Fairing
  - Wing Alone Cases
  - Cruise Polar, Drag Rise, plus (small) component increment
  - Blind - No Experimental Data at Time of Workshop

DPW-I Results from 2 Summary Papers

AIAA 2002-0841
Summary of Data from the First
AIAA CFD Drag Prediction Workshop

David W. Levy (Cessna), plus organizing committee

AIAA 2002-0842
Statistical Analysis of CFD Solutions from the
Drag Prediction Workshop

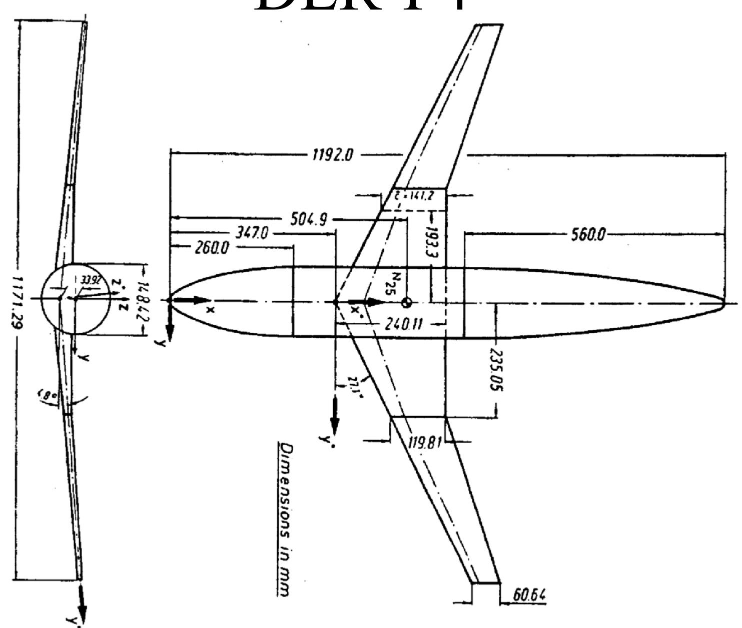
Michael J. Hemsch (NASA)

DPW-I Test Cases

<u>**Required:**</u> $Rn_c = 3 \times 10^6$

- <u>**Case 1:**</u> M_∞ =0.75, C_L= 0.500 ± 0.005
- <u>**Case 2:**</u> M_∞ =0.75, α= -3°, -2°, -1°, 0°, 1°, 2°

DLR-F4



<u>**Optional:**</u>

- <u>**Cases 3:**</u> M_∞ sweep, C_L= .500
- <u>**Cases 4:**</u> M_∞ sweep, C_L= .400, .600

Standard Grids Supplied

Participant and Methods Summary

- 18 participants, 14 codes
- 35 Case 1, 28 Case 2, 10 Case 3, 9 Case 4
- Grid types:

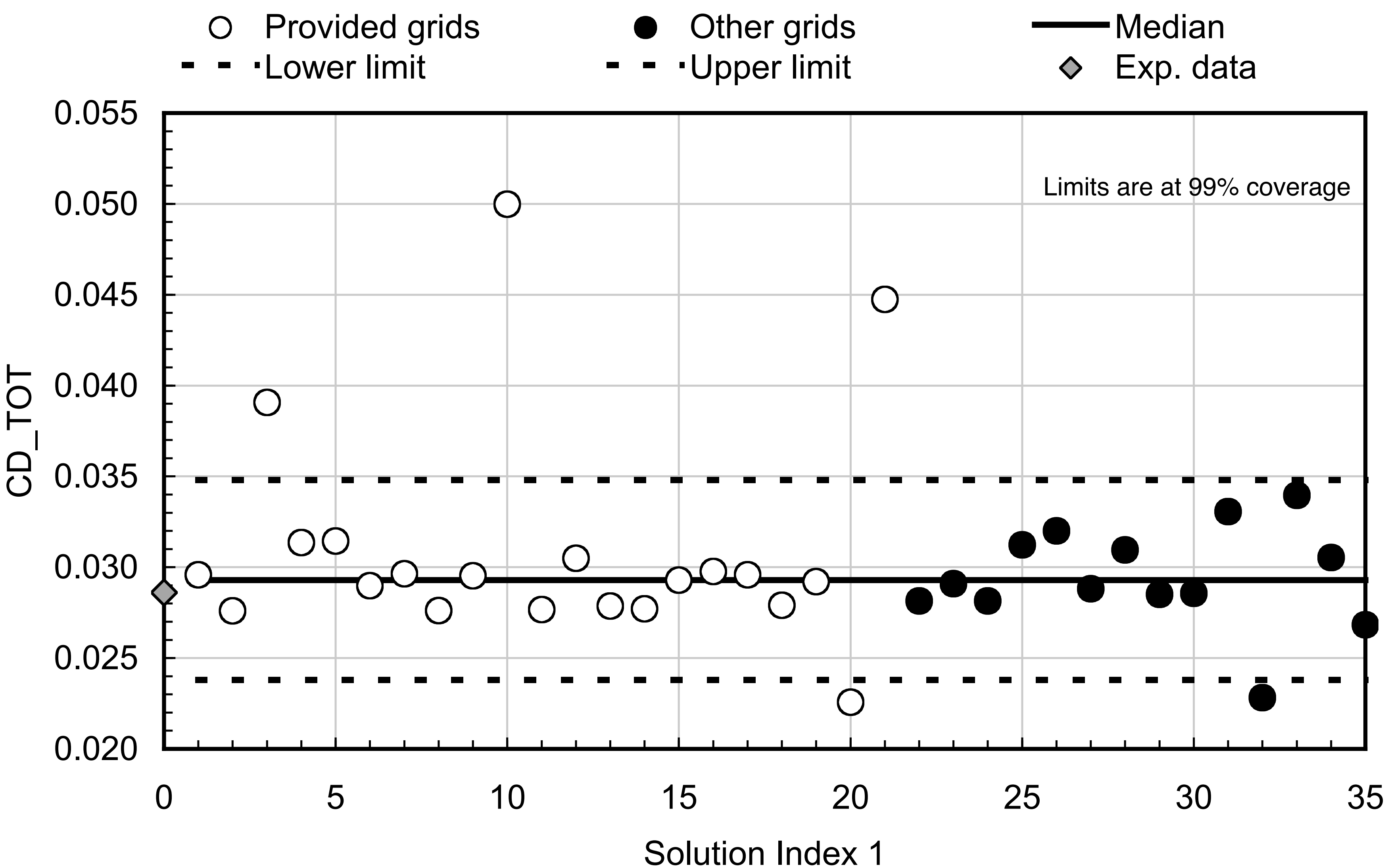
Blk. Str.	Unstructured	Overset	Cartesian
8	7	2	1

- 8 turbulence models (3 main types):

Spalart-Allmaras	k-ω	k-ε	other
14	10	2	2

There can be various forms , versions, or implementations of a given model

Case 1- Total Drag Variation



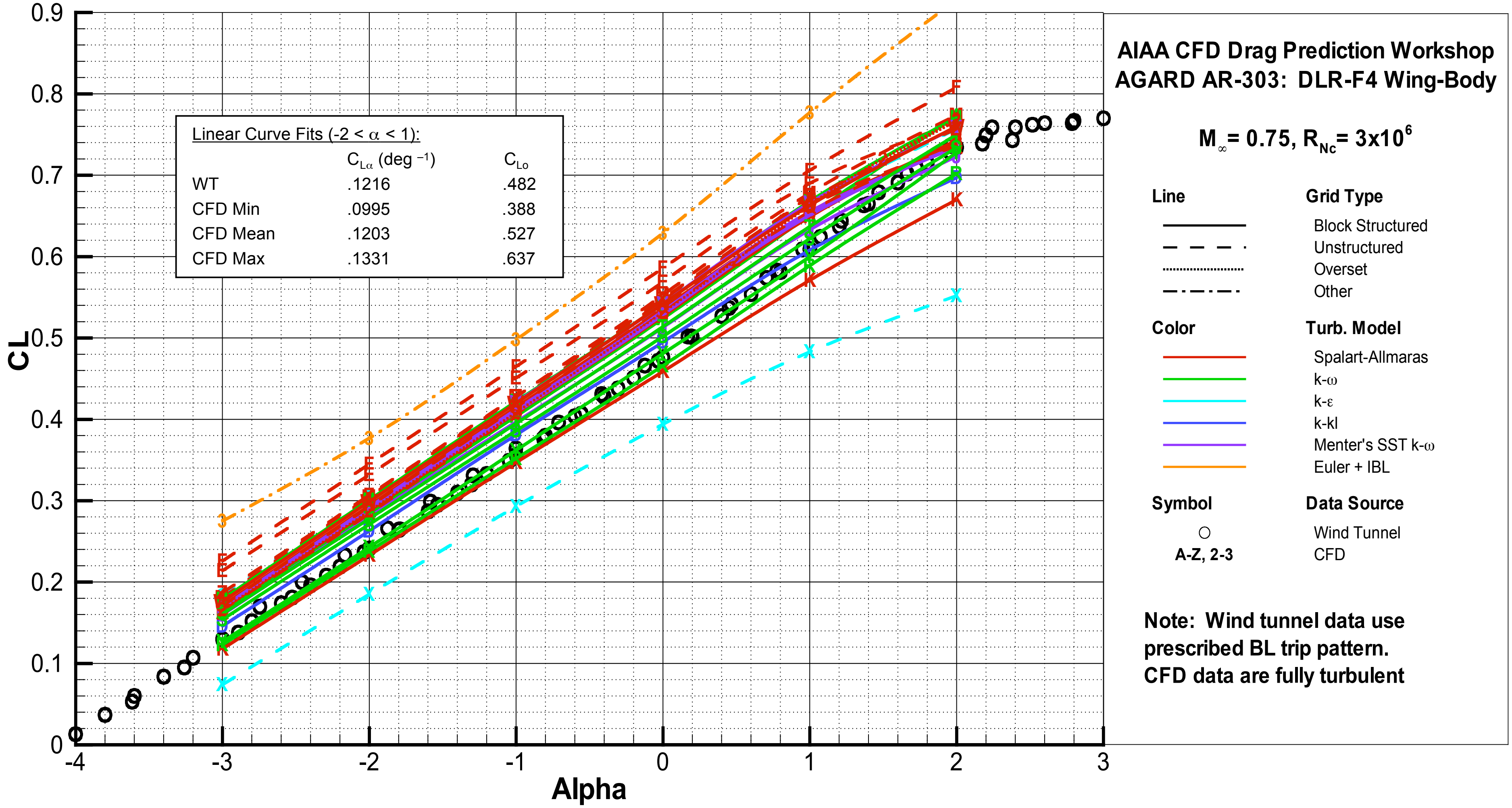
Case 1- Drag Component Variation

Drag Statistics Summary
w/o outliers

	CD_PR	CD_SF	CD_TOT	Exp.
Location $\hat{\mu} = \tilde{x}$	166.2	133.9	292.9	286
Dispersion $\hat{\sigma} = 1.483\sqrt{\frac{n}{n-1}}MAD$	13.5	15.3	21.4	4

Case 2: Lift Curve

$M_\infty = .75, Rn_c = 3x10^6$

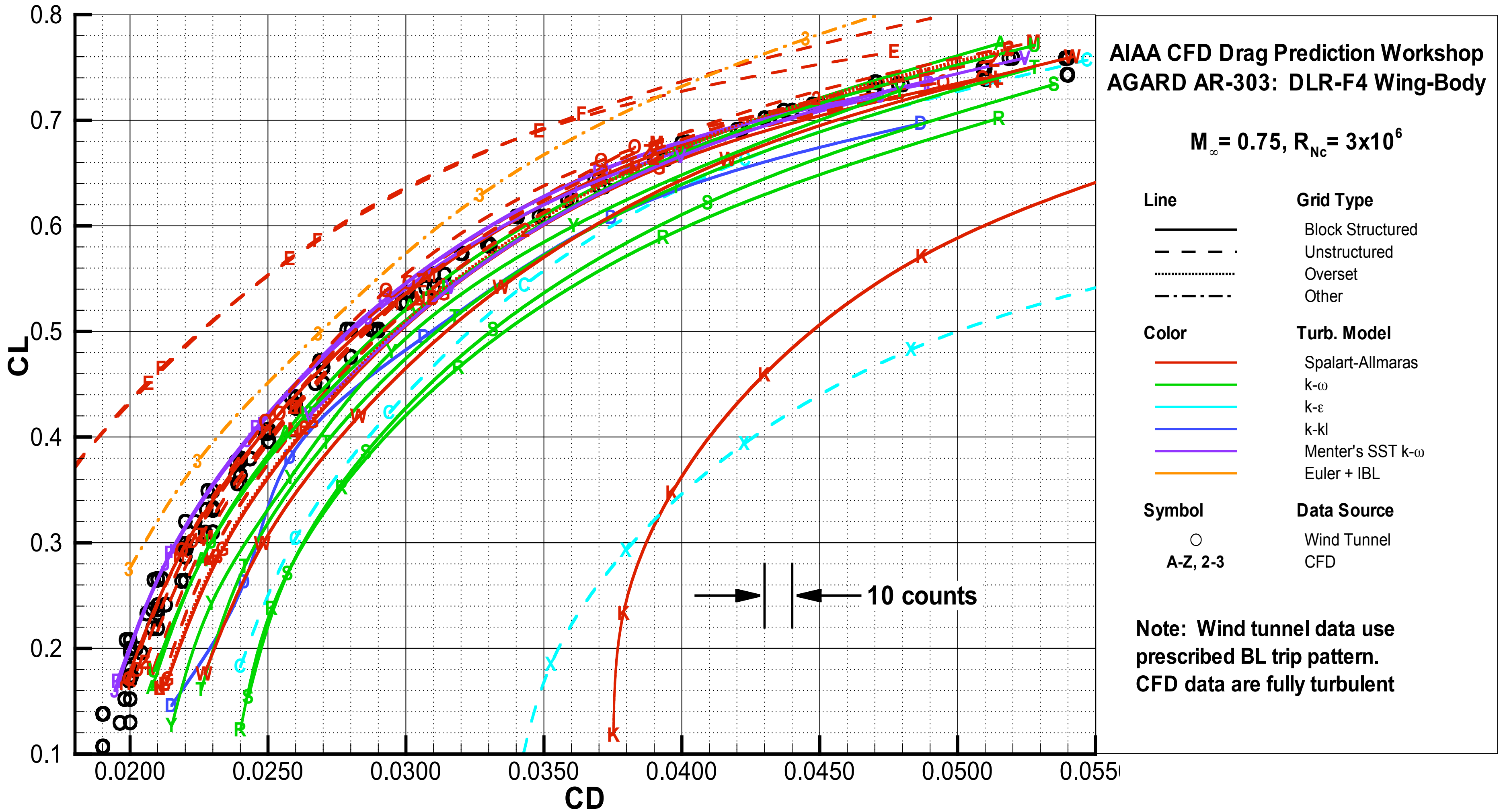


Linear Curve Fits (-2 < α < 1):

	$C_{L\alpha}$ (deg $^{-1}$)	C_{Lo}
WT	.1216	.482
CFD Min	.0995	.388
CFD Mean	.1203	.527
CFD Max	.1331	.637

Case 2: Drag Polar

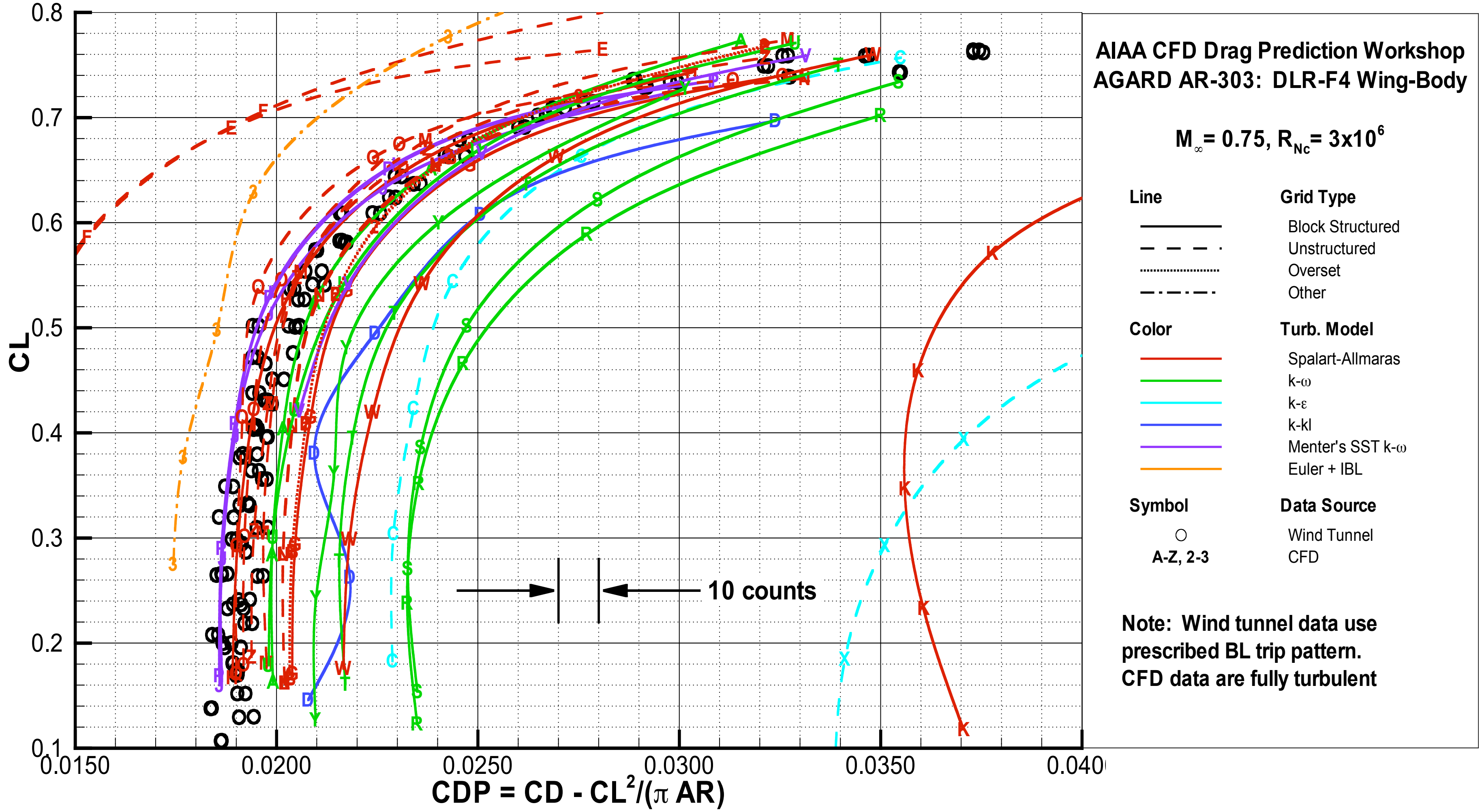
$M_\infty = .75, Rn_c = 3x10^6$



Drag Prediction Workshop

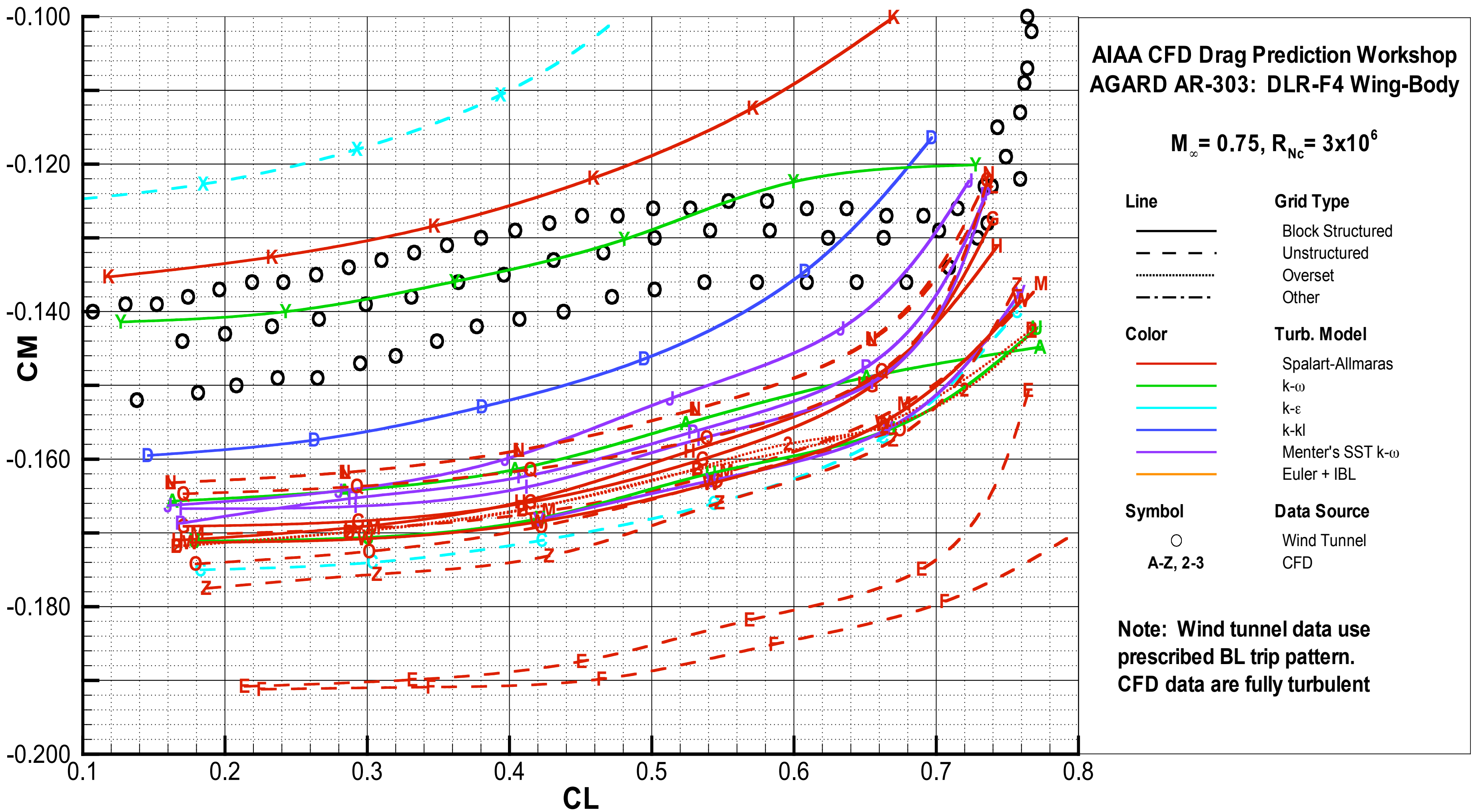
Case 2: Idealized Profile Drag

$M_\infty = .75, Rn_c = 3x10^6$



Case 2: Pitching Moment

$M_\infty = .75,\ Rn_c = 3x10^6$

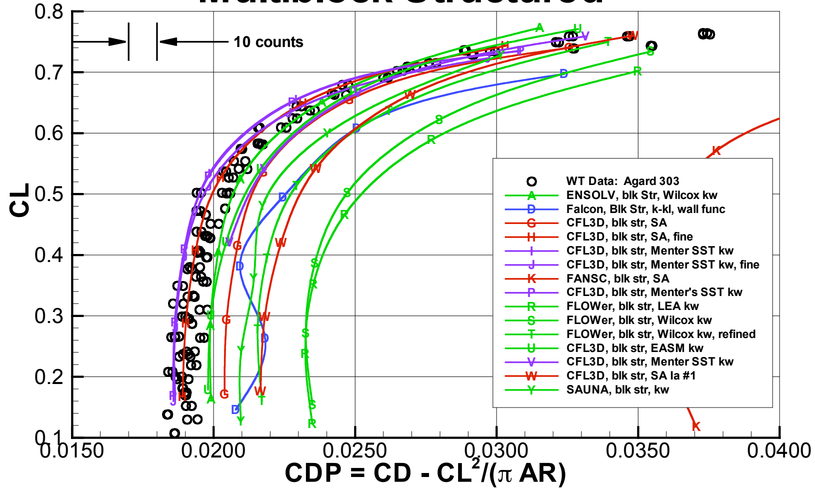


Drag Prediction Workshop

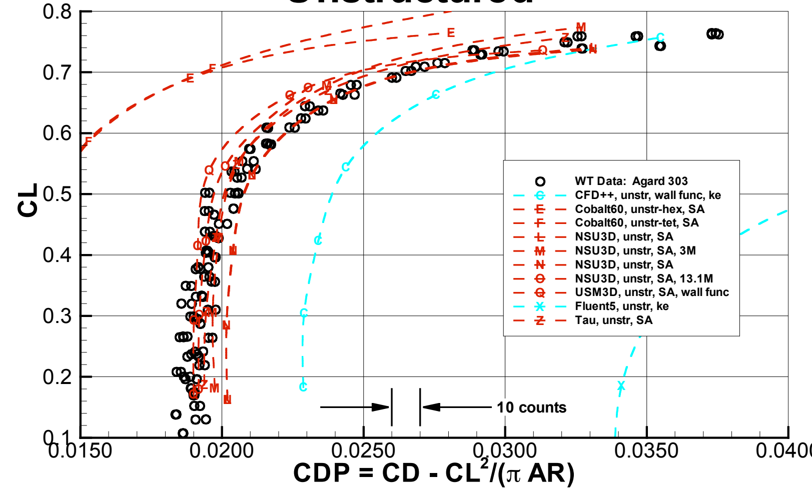
Trends by Grid Type

$M_\infty = .75,\ R_{Nc} = 3x10^6$

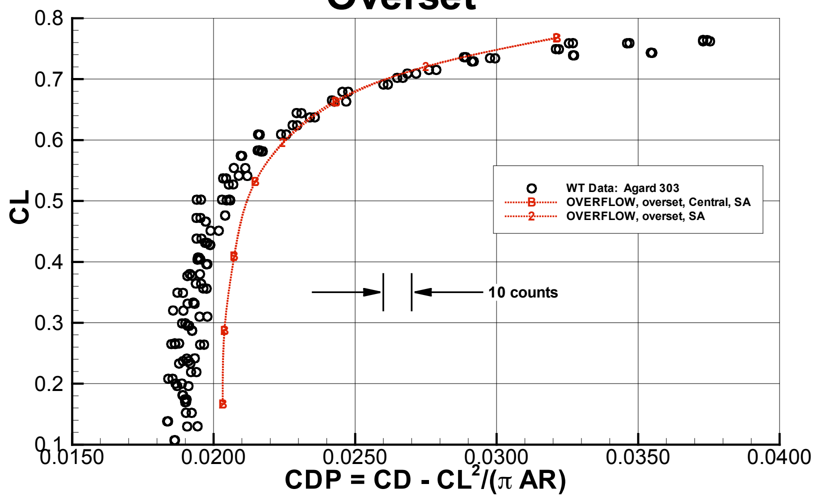
Multiblock Structured



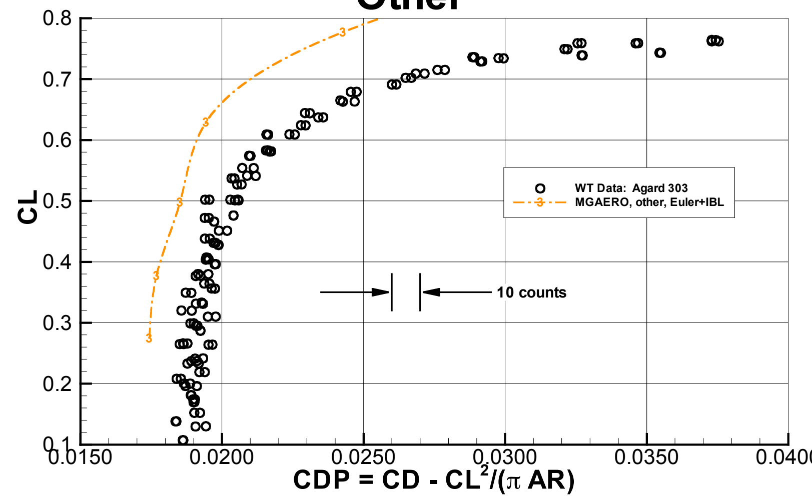
Unstructured



Overset



Other

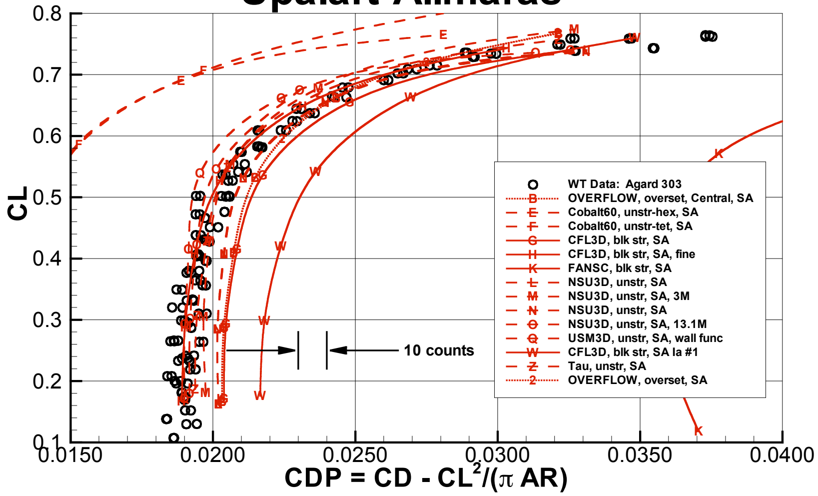


Drag Prediction Workshop

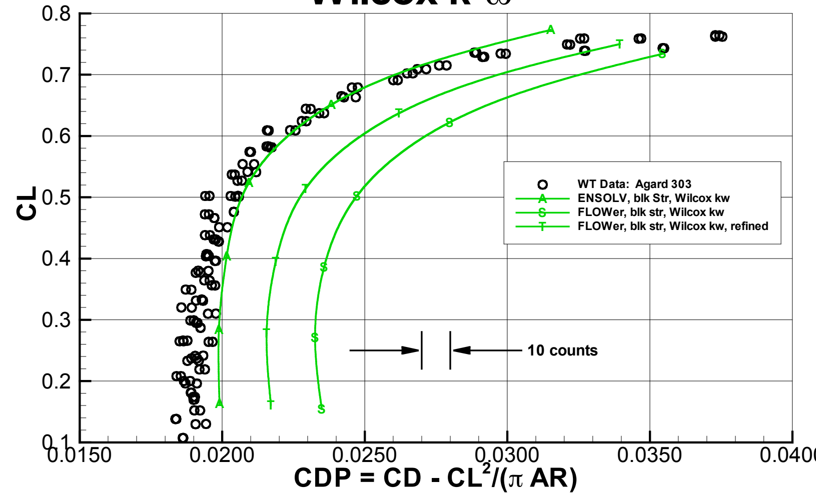
Trends by Turbulence Model

$M_{\infty} = .75,\ R_{Nc} = 3x10^{6}$

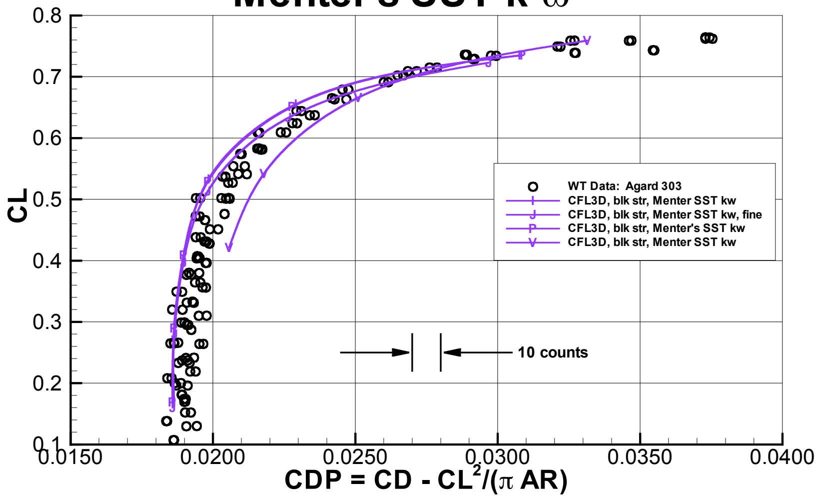
Spalart-Allmaras



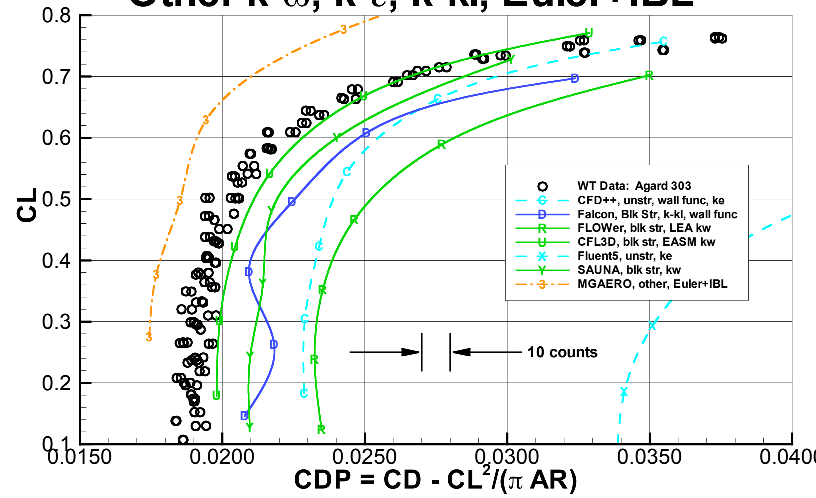
Wilcox k-ω



Menter's SST k-ω



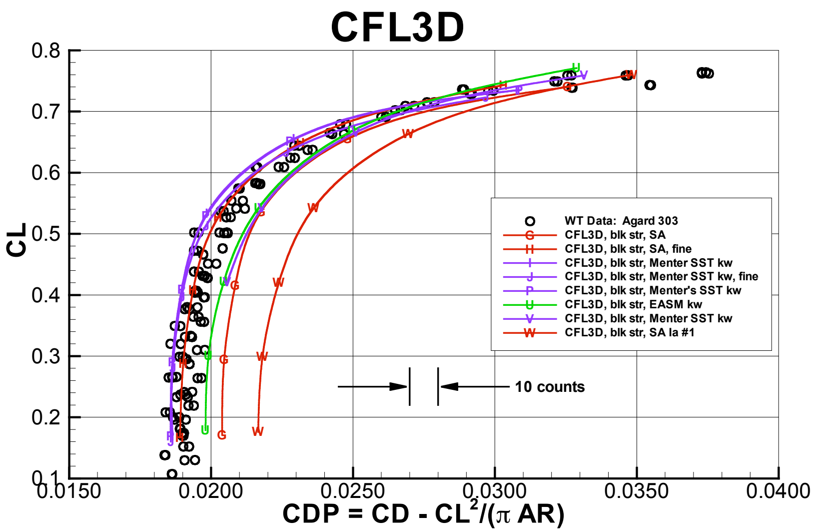
Other k-ω, k-ε, k-kl, Euler+IBL

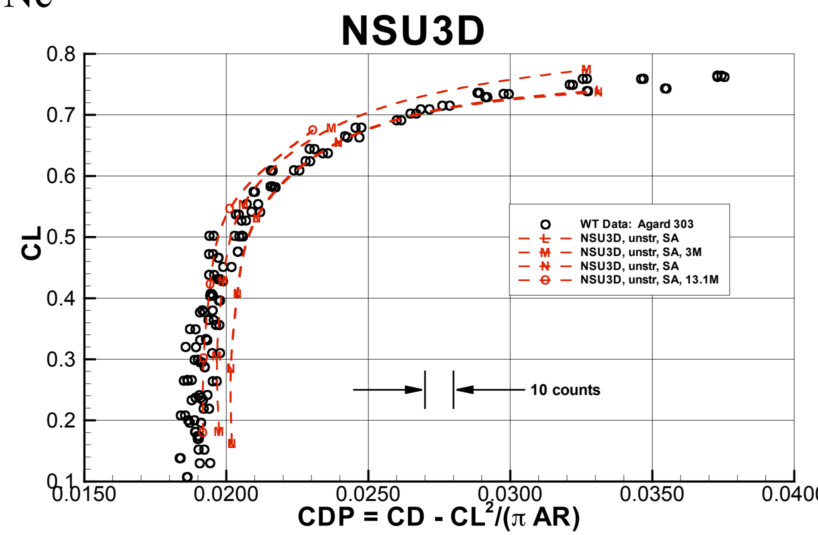


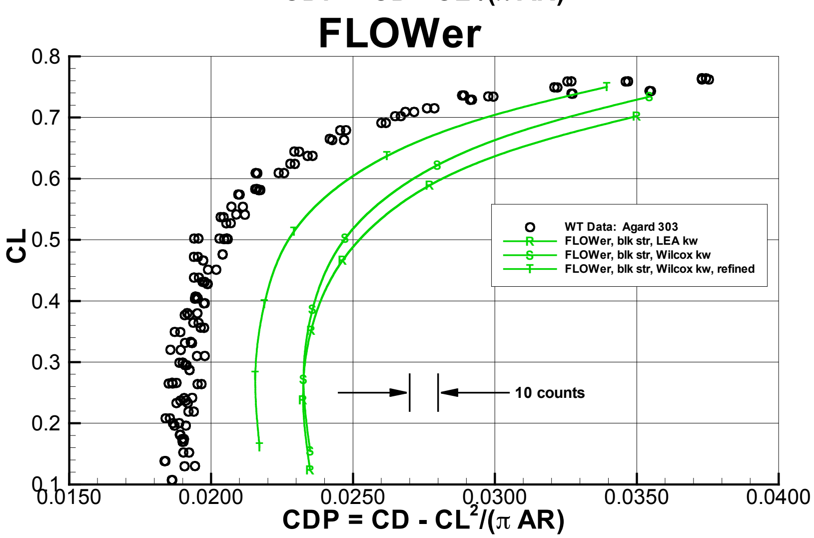
Drag Prediction Workshop

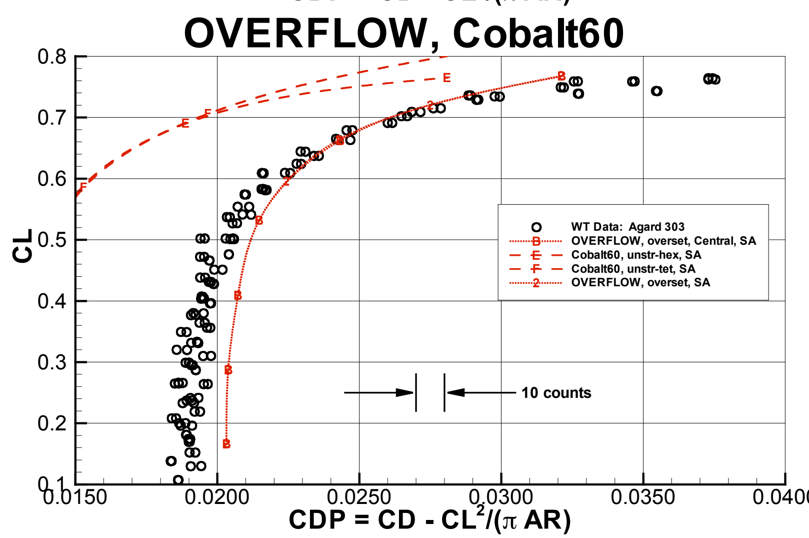
Trends by Code

$M_\infty = .75,\ R_{Nc} = 3x10^6$



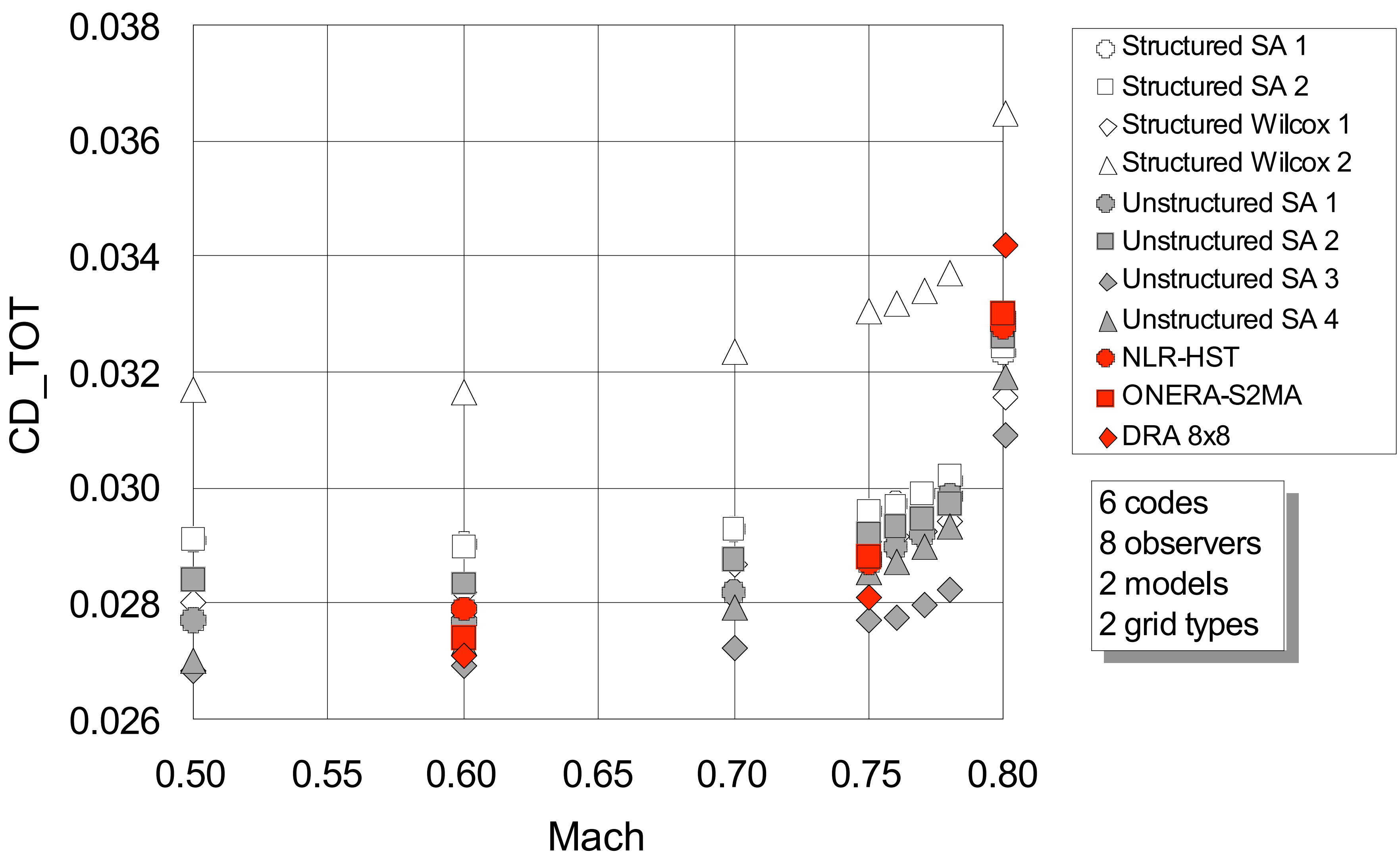






Drag Prediction Workshop

Case 3 -Drag rise curves for CL=0.5



6 codes
8 observers
2 models
2 grid types

DPW-I Recollections

- Scatter amongst CFD solutions at cruise significantly higher than anyone anticipated
  - Pockets of separated flow a leading cause
- Hard to isolate and quantify effects causing variability
  - Turb model, grid, code, transition, geometry (some simplified)
- Problematic grids - okay for one code, not another
- Comparison with experiment became a much larger focus that anticipated
  - CFD C_L generally too high at a given α
  - CFD C_M generally more nose-down
  - CFD C_{Dmin} generally higher than experiment (expected)
    - Boundary layer transition modeling/fixing vs experiment

DPW-II Results in 2 Summary Papers

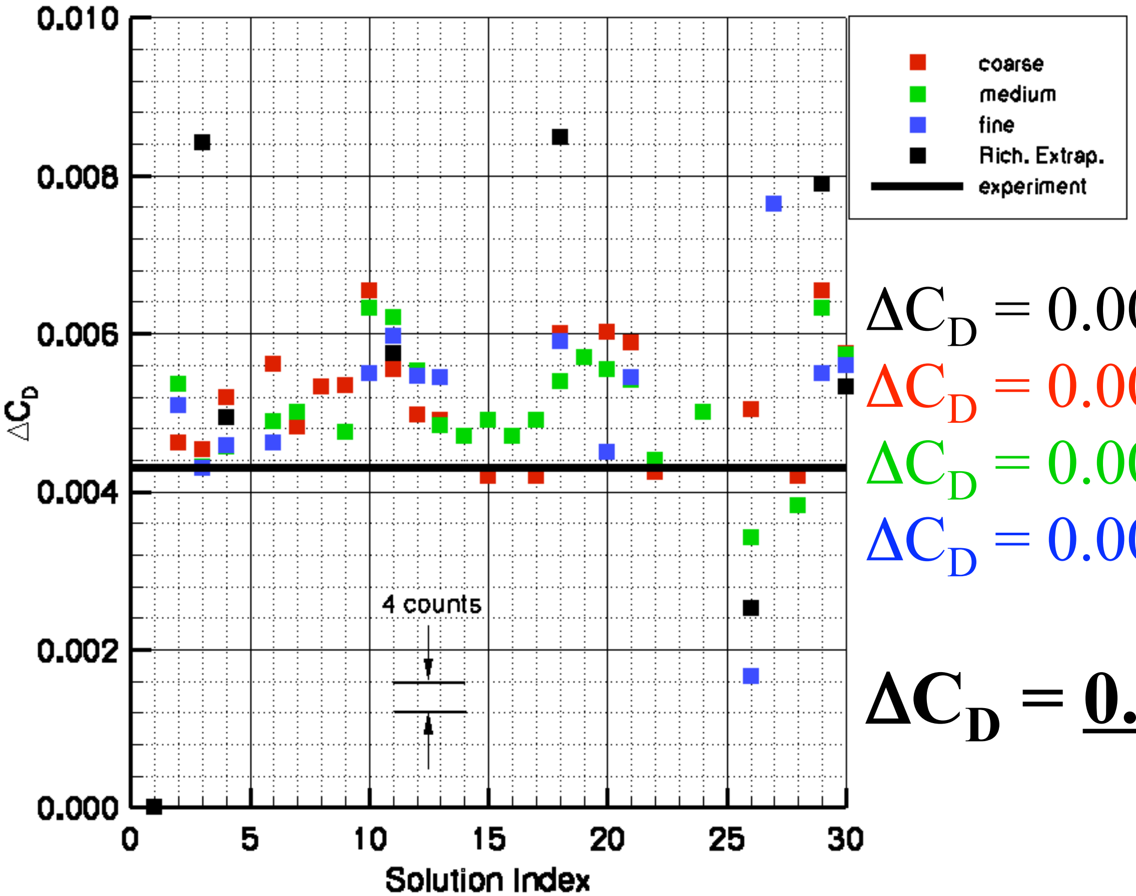
AIAA 2004-0555
Summary of Data from the Second AIAA CFD Drag Prediction Workshop
Kelly R. Laflin (Cessna), plus organizing committee

AIAA 2004-0556
Statistical Analysis of CFD Solutions from the 2nd Drag Prediction Workshop
Michael J. Hemsch, Joseph H. Morrison (NASA)

DPW-II Large Increment Example

Grid/Richardson Extrapolation Issue

Delta Drag



$\Delta C_D = 0.00433$

$\Delta C_D = 0.00538$

$\Delta C_D = 0.00515$

$\Delta C_D = 0.00513$

$\Delta C_D =$ **0.00619** !?!

Case 1

DPW-II Recollections

- Results in general vary similar to DPW-I
- Grid convergence study envisioned, but provided grids proved insufficient (Richardson extrapolation issue)
- Compared to DPW-I, large reduction in overall spread, but dispersion of the core essentially unchanged
- Configuration Increment (pylon/nacelle) much larger than typically explored by with detailed CFD studies
- Increments more forgiving that absolutes (canceling errors)

DPW-III Results from 2 Summary Papers

AIAA 2007-0260
Summary of the
Third AIAA CFD Drag Prediction Workshop
John C. Vassberg (Boeing), plus organizing committee

AIAA 2007-0254
Statistical Analysis of CFD Solutions from the
Third AIAA Drag Prediction Workshop
Joseph H. Morrison, and Michael J. Hemsch (NASA)

DPW-III Approach - some differences

- Provide Blind Test Cases
  - CFD Data Submissions Before WT Test
  - Follow-Up With Experimental Tests
- Utilize Simpler Geometries
  - Wing/Body and Wing-Alone Configurations
- Vary Complexity of Flowfield Physics
  - Reduce Trailing-Edge Separation Tendency
  - Remove Side-of-Body Separation Bubble
  - Fully-Attached Flow on Wing-Alone Cases

DPW-III Test Cases

Case 1: DLR-F6 WB with and without FX2B Fairing

Fixed-C_L Single Point Grid Sensitivity Study on Three Grids

- $Mach = 0.75$, $C_L = 0.5$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.75$, $Re = 5$ million,
  $\alpha = [-3.0°, -2.0°, -1.0°, -0.5°, 0.0°, 0.5°, 1.0°, 1.5°]$.

Case 2: DPW-W1/W2 Wing-Alone

Fixed-α Single Point Grid Sensitivity Study on Four Grids

- $Mach = 0.76$, $\alpha = 0.5°$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.76$, $Re = 5$ million,
  $\alpha = [-1.0°, 0.0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°]$.

Case 1: Baseline Grids

avg medium grid size has increased from 3.2 to 5.4 to 7.8 million points from DPW 1 to 3

Table I: Case 1 DLR-F6/FX2B Grids - Number of Grid Points.

		DLR-F6			FX2B			
Family	Type	Fine	Medium	Coarse	Fine	Medium	Coarse	Usage
Tinoco	MB	27,185,664	8,080,896	2,298,880	27,185,664	8,080,896	2,298,880	A-C,G-J
SAUNA	MB	9,761,201	4,731,073	2,551,989	9,761,201	4,731,073	2,551,989	D
Extruded	MB	28,367,120	9,343,009	2,996,626	28,367,120	9,329,185	3,028,420	E
Gridgen	MB	27,982,776	8,927,196	2,739,621	27,982,776	9,138,772	2,842,878	F,T
Sclafani	OS	26,892,352	7,985,236	2,387,918	26,969,192	8,020,348	2,395,170	K-M,U
DLR	HY	8,535,263	5,102,446	2,464,385	10,305,876	6,111,664	2,873,102	N
ANSYS	HY	18,120,772	8,038,922	3,059,189	20,472,520	8,272,308	3,163,605	O
LaRC	UH	40,014,934	14,298,135	5,354,214	41,069,036	14,598,610	5,618,073	P,Q
AFLR	UN	11,374,451	3,792,485	1,492,082	11,849,212	3,178,559	1,640,590	R,S,Y
Embraer	UN	24,030,000	8,320,000	3,550,000	24,030,000	8,320,000	3,550,000	V
STAR	UN	-	12,377,058	-	21,509,137	12,469,599	8,421,799	W
USM3D	UN	-	-	-	-	-	-	X
TAS	UN	17,535,215	9,431,154	5,399,929	17,219,535	9,481,477	5,422,128	Z

Case 1: Submissions

Table III: Case 1 Submissions.

Tag	Code	Grid Type	Grid Family	Turbulence Model	Submitter
A	PAB3D	Multiblock	Tinoco	Girimaji EASM	ASM Elmiligui
B	PAB3D	Multiblock	Tinoco	K-Epsilon	ASM Elmiligui
C	PAB3D	Multiblock	Tinoco	SZL EASM	ASM Elmiligui
D	STAR-CCM+	Multiblock	SAUNA	Wilcox K-Omega	QinetiQ Milne
E	UPACS	Multiblock	Extruded	Modified SA	JAXA Murayama
F	UPACS	Multiblock	Gridgen	Modified SA	JAXA Murayama
G	CFL3D-Thin	Multiblock	Tinoco	SA	Boeing Tinoco
H	CFL3D-Thin	Multiblock	Tinoco	SST	Boeing Tinoco
I	CFL3D-Full	Multiblock	Tinoco	SA	Boeing Tinoco
J	CFL3D-Full	Multiblock	Tinoco	SST	Boeing Tinoco
K	CFL3D-Full	Overset	Sclafani	SST	LaRC Rumsey
L	CFL3D-Thin	Overset	Sclafani	SST	LaRC Rumsey
M	Overflow	Overset	Sclafani	SA	Boeing Sclafani

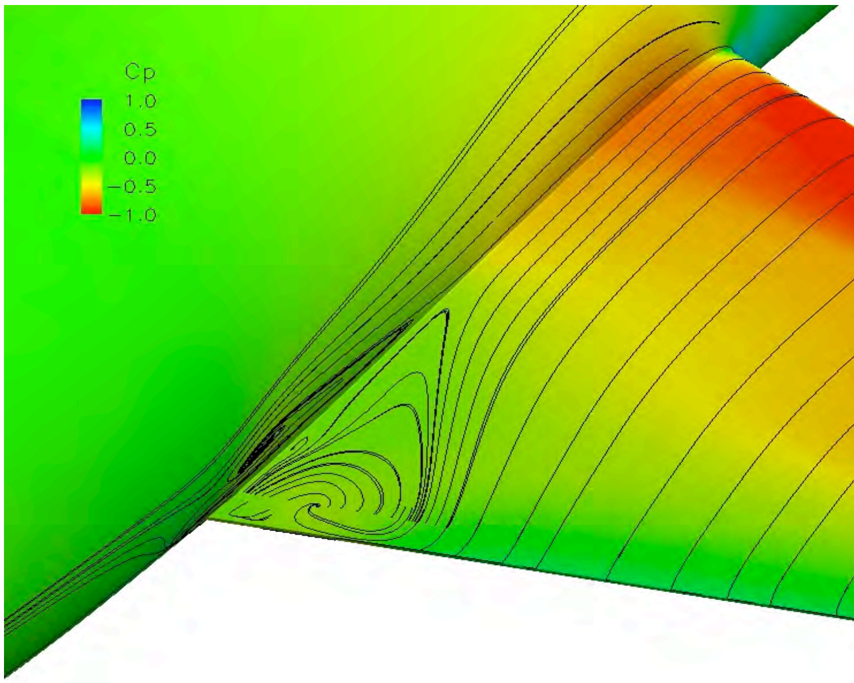
Case 1: Submissions (cont.)

Table III: Case 1 Submissions.

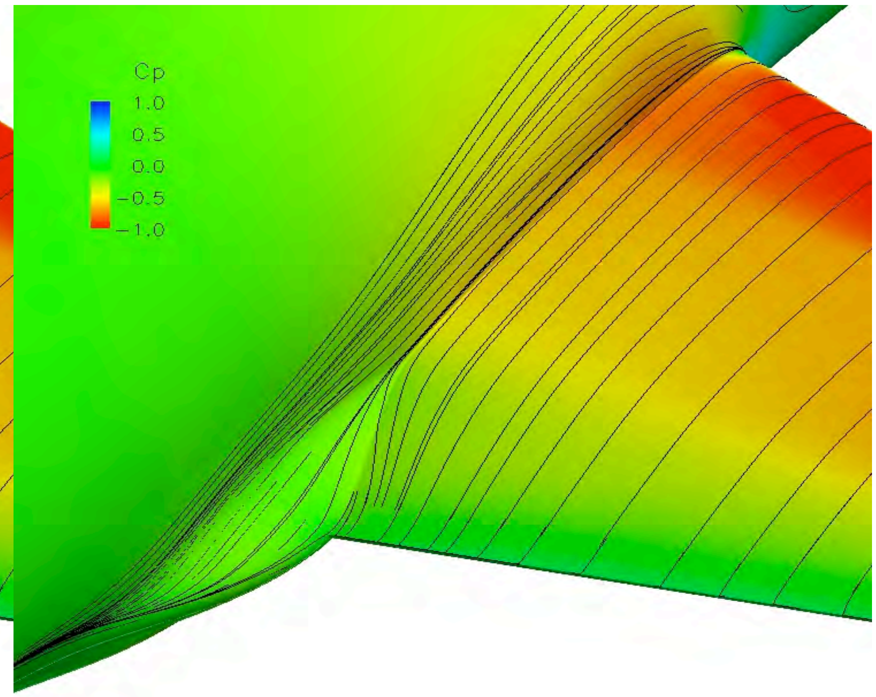
Tag	Code	Grid Type	Grid Family	Turbulence Model	Submitter
N	TAU	Hybrid	DLR	SA Edwards	DLR Brodersen
O	Edge	Hybrid	ANSYS CFX	Hellsten EARSM	FOI Eliason
P	FUN3D	Unstructured	LaRC Nodal	SA	LaRC Lee-Rausch
Q	NSU3D	Hybrid	LaRC Mixed	SA	UWy Mavriplis
R	CFD++	Hybrid	AFLR	SA	Boeing Venkat
S	BCFD	Hybrid	AFLR	SA	Boeing Winkler
T	UPACS	Multiblock	Gridgen	SST	JAXA Murayama
U	OVERFLOW	Overset	Sclafani	SST	LaRC Rumsey
V	FLUENT	Unstructured	Embraer	K-Epsilon	Fluent Scheidigger
W	STAR-CCM+	Unstructured	STAR	SST	CD-Adapco Vaughn
X	USM3D	Unstructured	USM3D	SA/WF	Raytheon Venkat
Y	BCFD	Hybrid	AFLR	SST	Boeing Winkler
Z	TAS	Unstructured	TAS	Modified SA	JAXA Murayama

Surface Streamlines – Side of Body Flow

Medium Grid, Mach = 0.75, C_L = 0.50, R_N = 5.0 million, Fully Turbulent, SA



DLR-F6

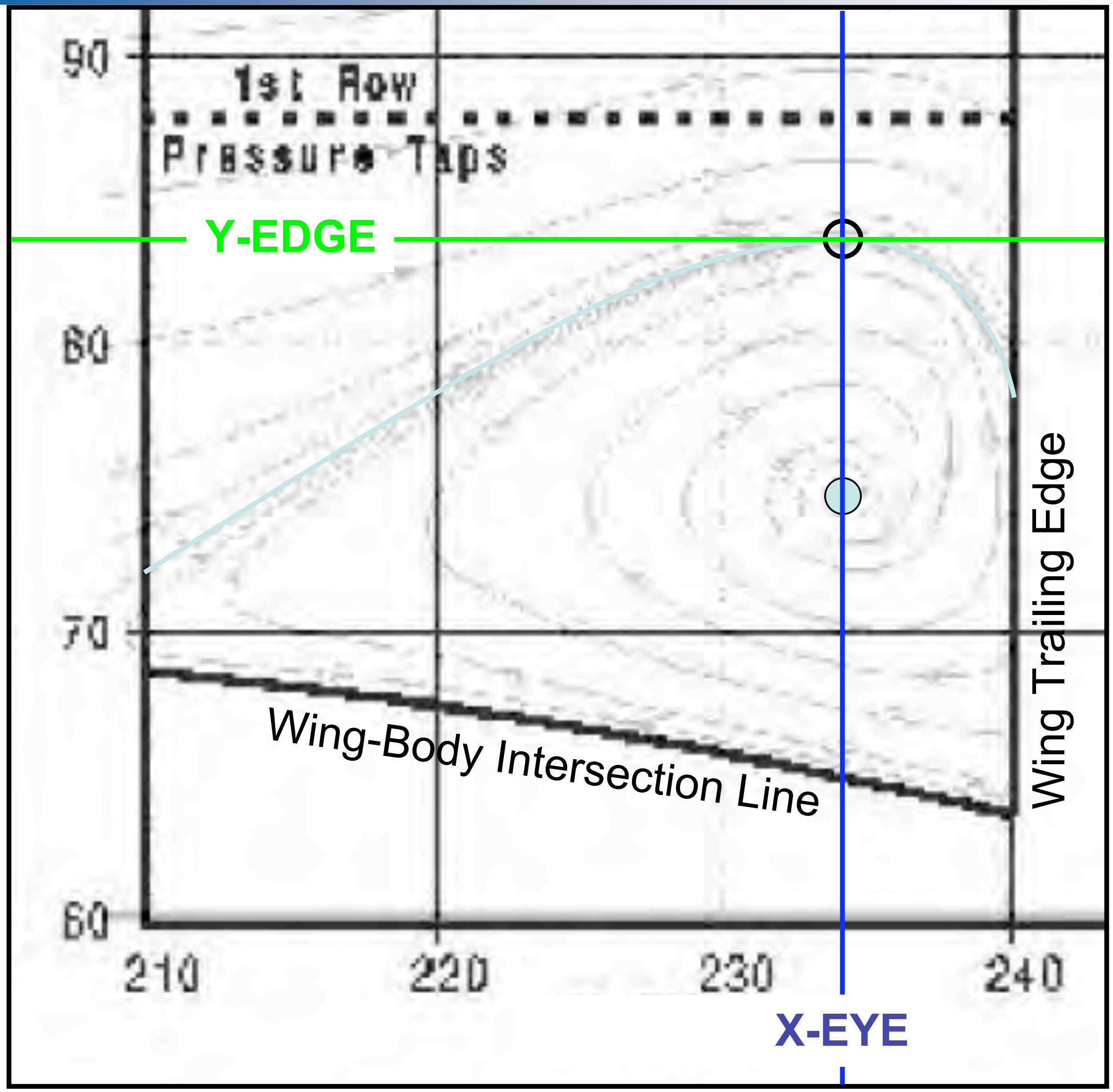


DLR-F6 with FX2B

DLR-F6 Wing-Body

Surface Streamlines – Side of Body Flow Definitions

V_∞ →



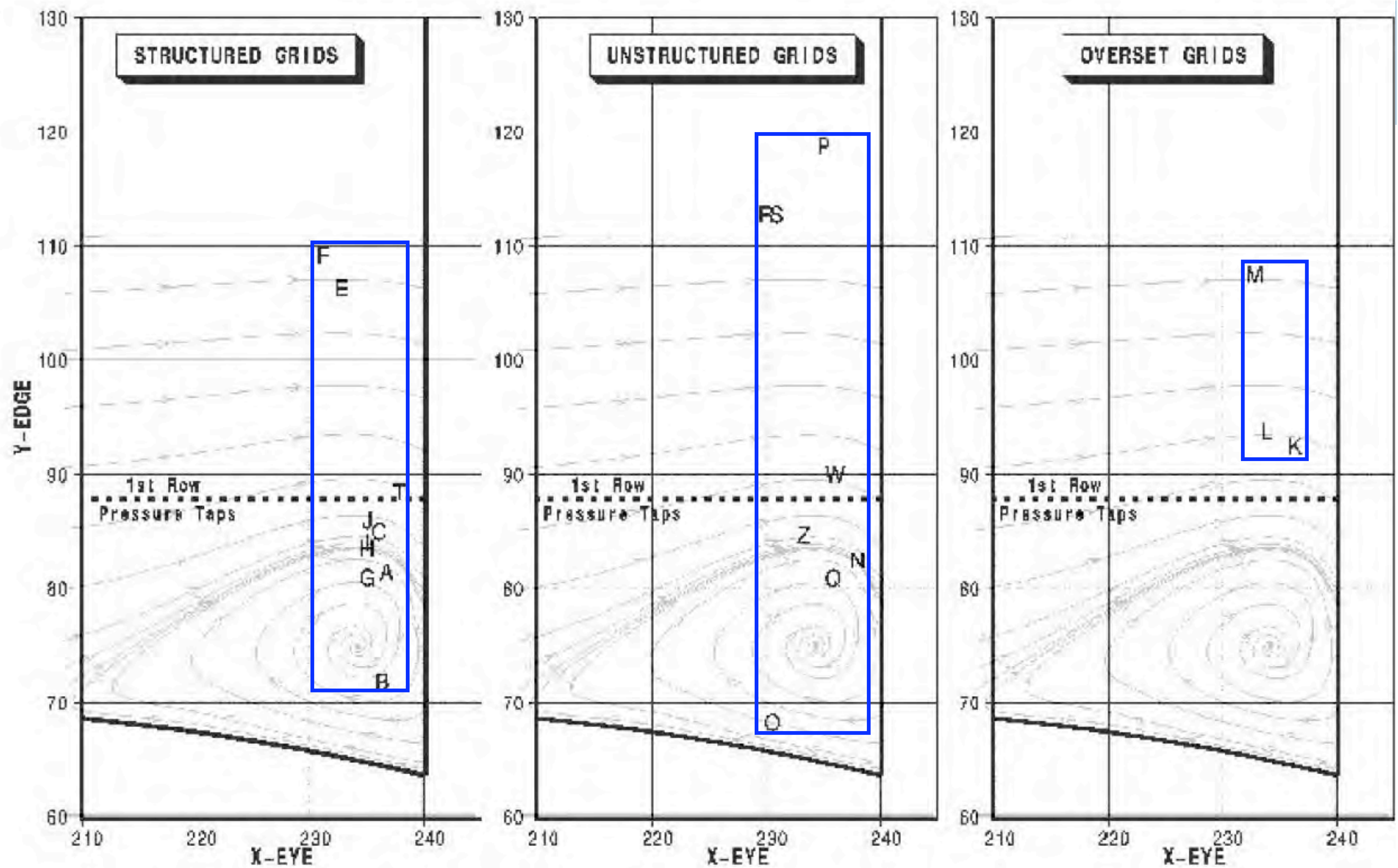


Figure 7. Case 1 Side-of-Body Separation Bubble Characteristics of the Baseline DLR-F6.

DPW-III Test Cases

Case 1: DLR-F6 WB with and without FX2B Fairing

Fixed-C_L Single Point Grid Sensitivity Study on Three Grids

- $Mach = 0.75$, $C_L = 0.5$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.75$, $Re = 5$ million,
  $\alpha = [-3.0°, -2.0°, -1.0°, -0.5°, 0.0°, 0.5°, 1.0°, 1.5°]$.

Case 2: DPW-W1/W2 Wing-Alone

Fixed-α Single Point Grid Sensitivity Study on Four Grids

- $Mach = 0.76$, $\alpha = 0.5°$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.76$, $Re = 5$ million,
  $\alpha = [-1.0°, 0.0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°]$.

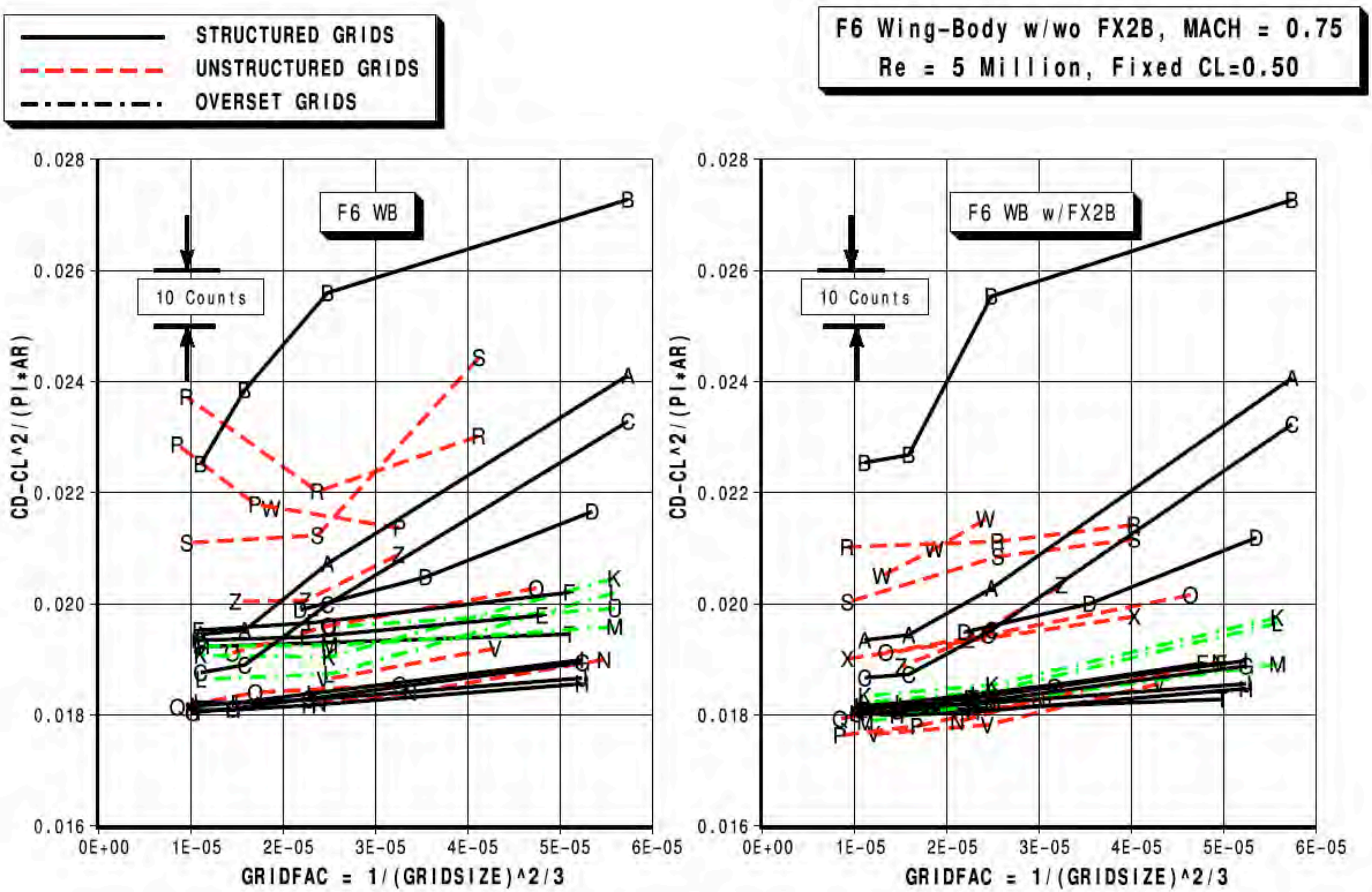
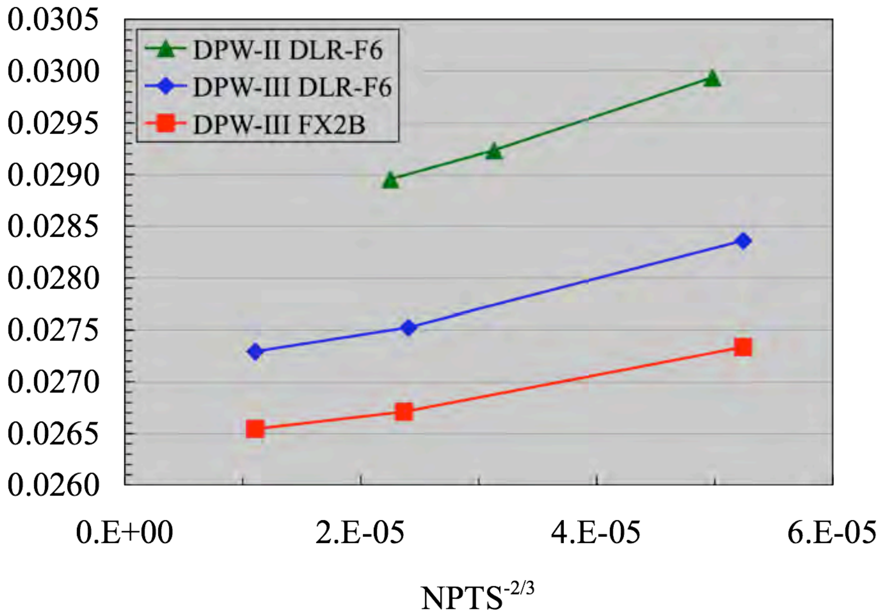


Figure 3. Case 1 Grid Sensitivity on Idealized Profile Drag: $M = 0.75$, $C_L = 0.5$, $Re = 5$ *million*.

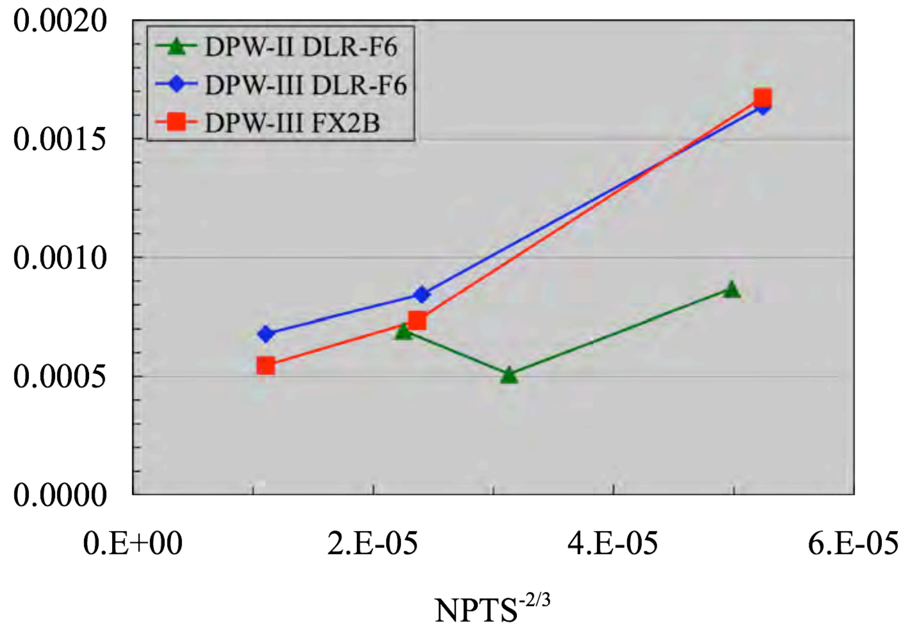
Case 1 Core Solutions (CD)

Total Drag Coefficient

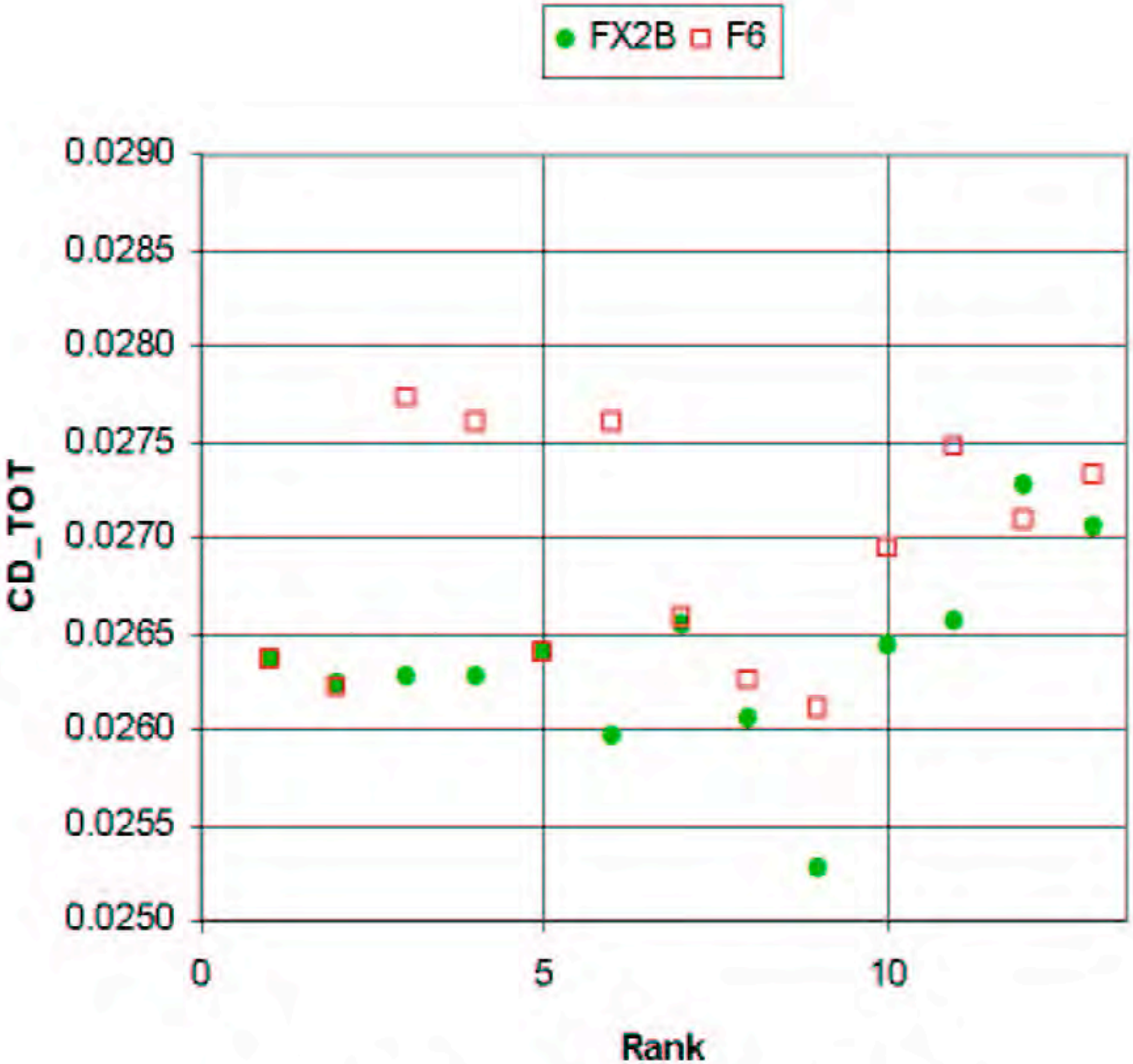
Median



Standard Deviation



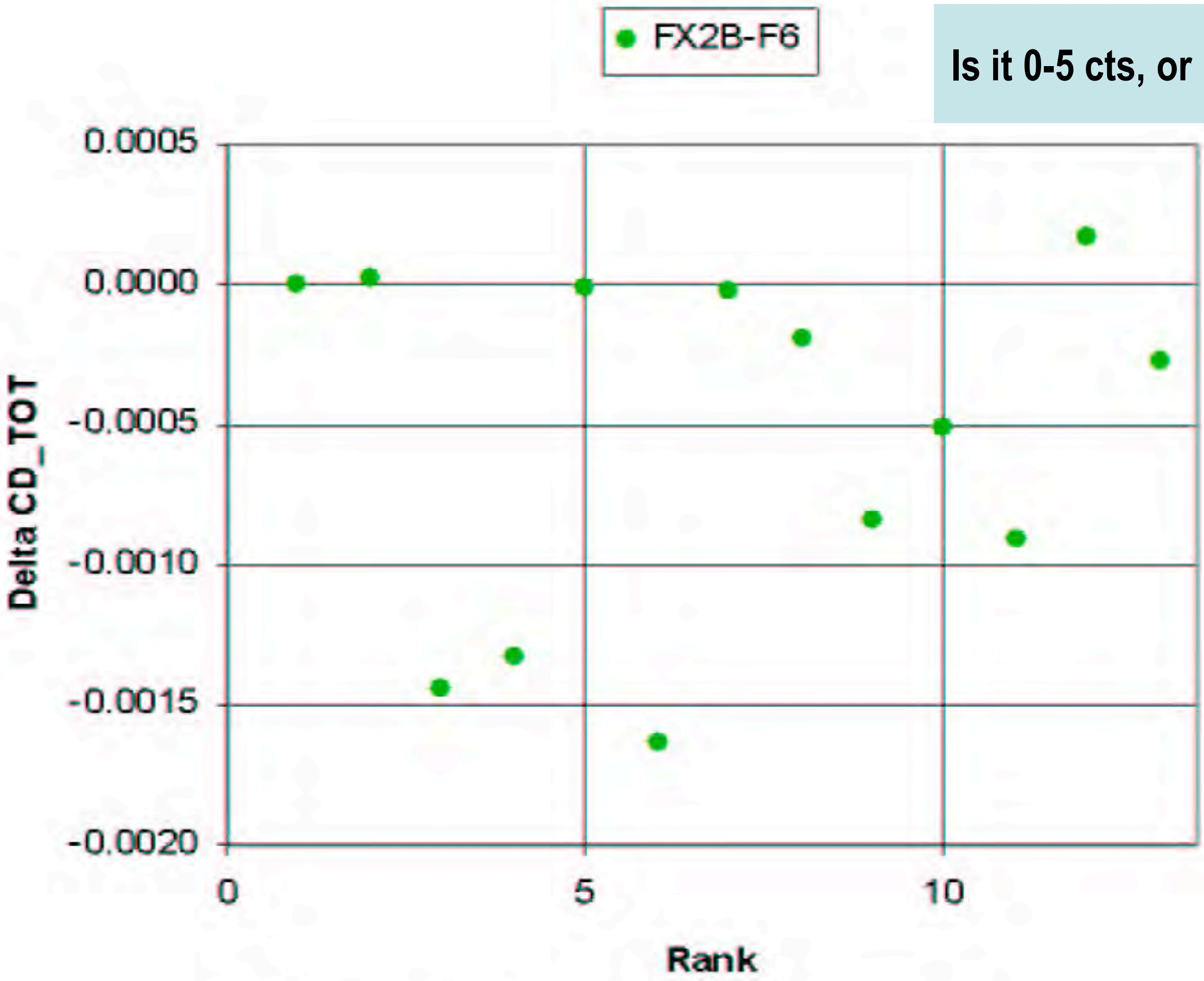
Statistical Analysis w/o Outliers



$$F6: \quad Avg.C_D = 0.02690, \quad \sigma = 0.00060, \quad min = 0.02612, \quad max = 0.02772,$$

$$FX2B: \quad Avg.C_D = 0.02636, \quad \sigma = 0.00049, \quad min = 0.02527, \quad max = 0.02727.$$

Delta Drag w/o Outliers



Is it 0-5 cts, or 5-15?

DPW-III Test Cases

Case 1: DLR-F6 WB with and without FX2B Fairing

Fixed-C_L Single Point Grid Sensitivity Study on Three Grids

- $Mach = 0.75$, $C_L = 0.5$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.75$, $Re = 5$ million,
  $\alpha = [-3.0°, -2.0°, -1.0°, -0.5°, 0.0°, 0.5°, 1.0°, 1.5°]$.

Case 2: DPW-W1/W2 Wing-Alone

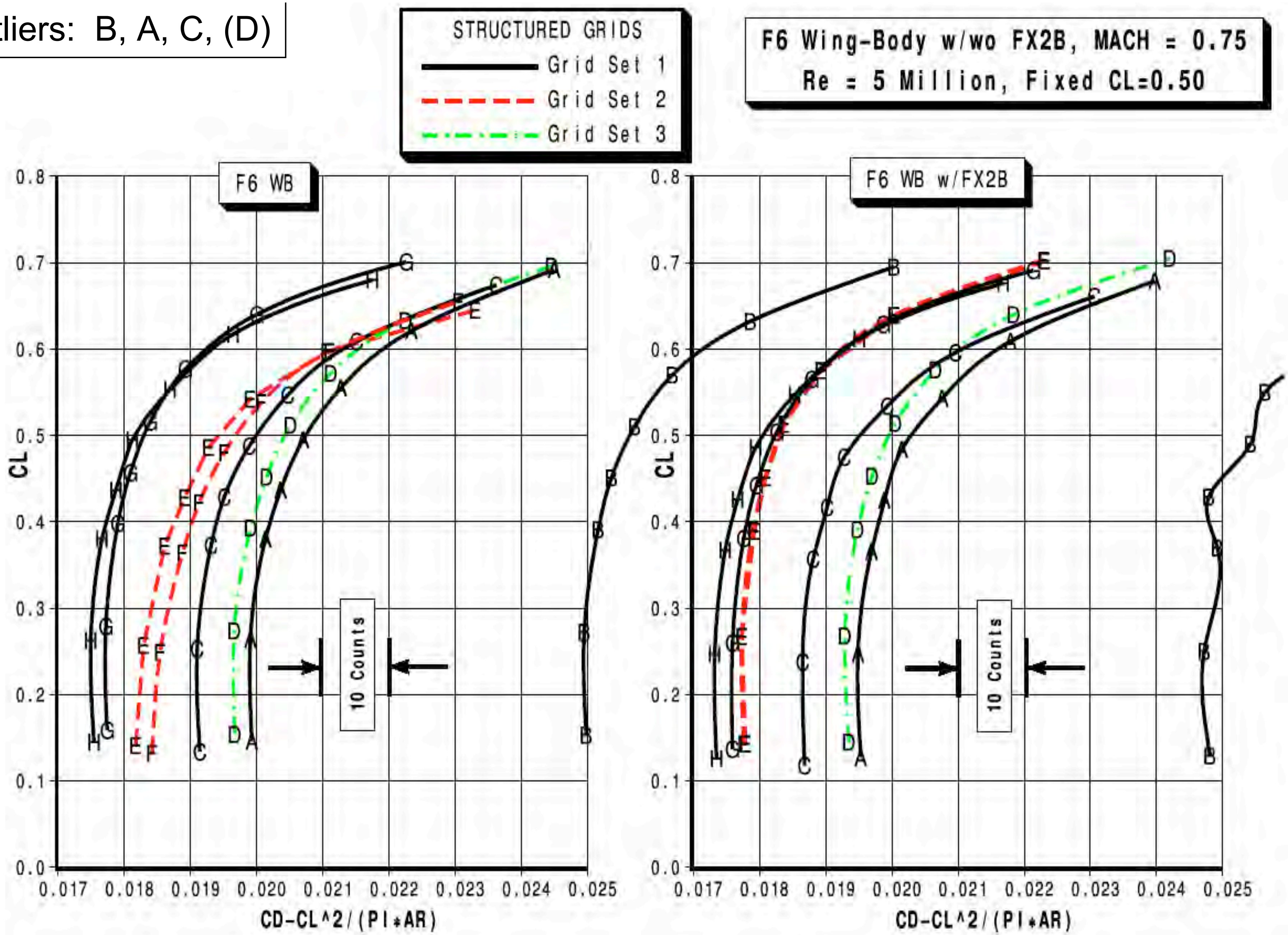
Fixed-α Single Point Grid Sensitivity Study on Four Grids

- $Mach = 0.76$, $\alpha = 0.5°$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.76$, $Re = 5$ million,
  $\alpha = [-1.0°, 0.0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°]$.

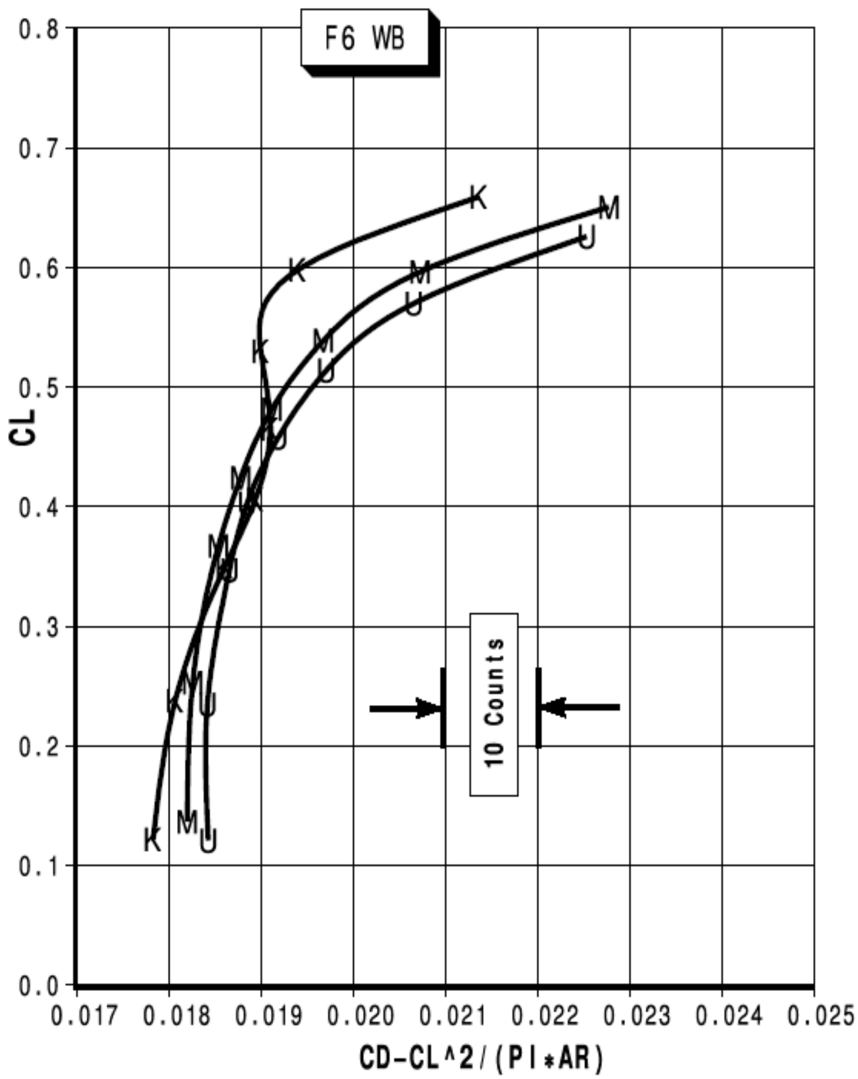
Outliers: B, A, C, (D)

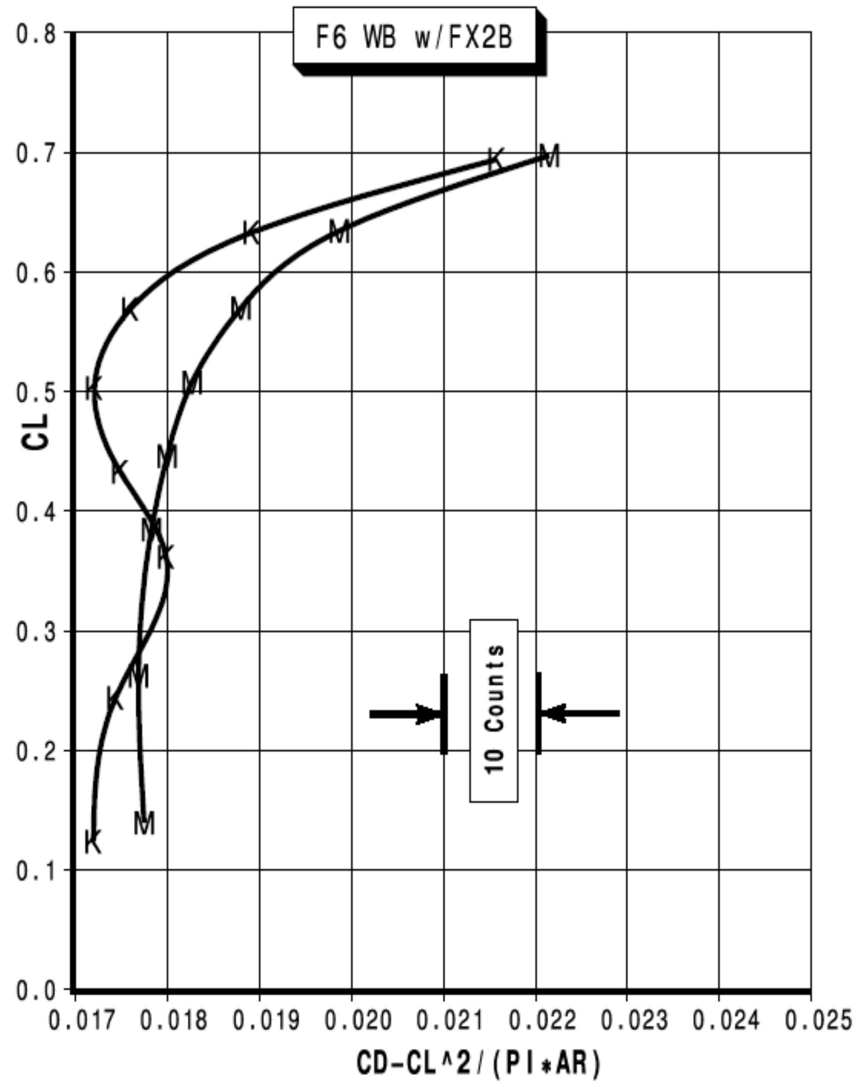


Drag Prediction Workshop

OVERSET GRIDS

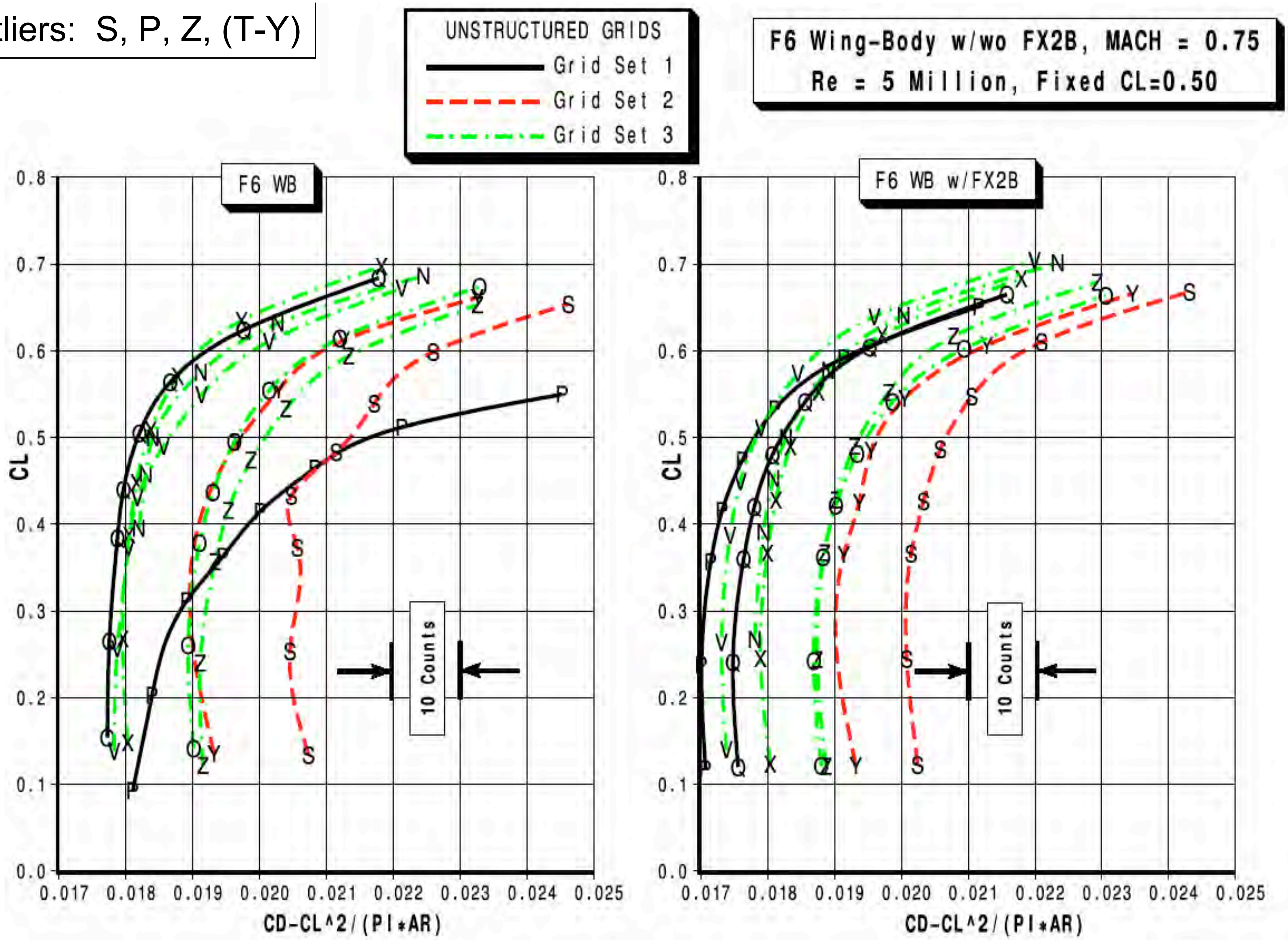
F6 Wing-Body w/wo FX2B, MACH = 0.75
Re = 5 Million, Fixed CL=0.50



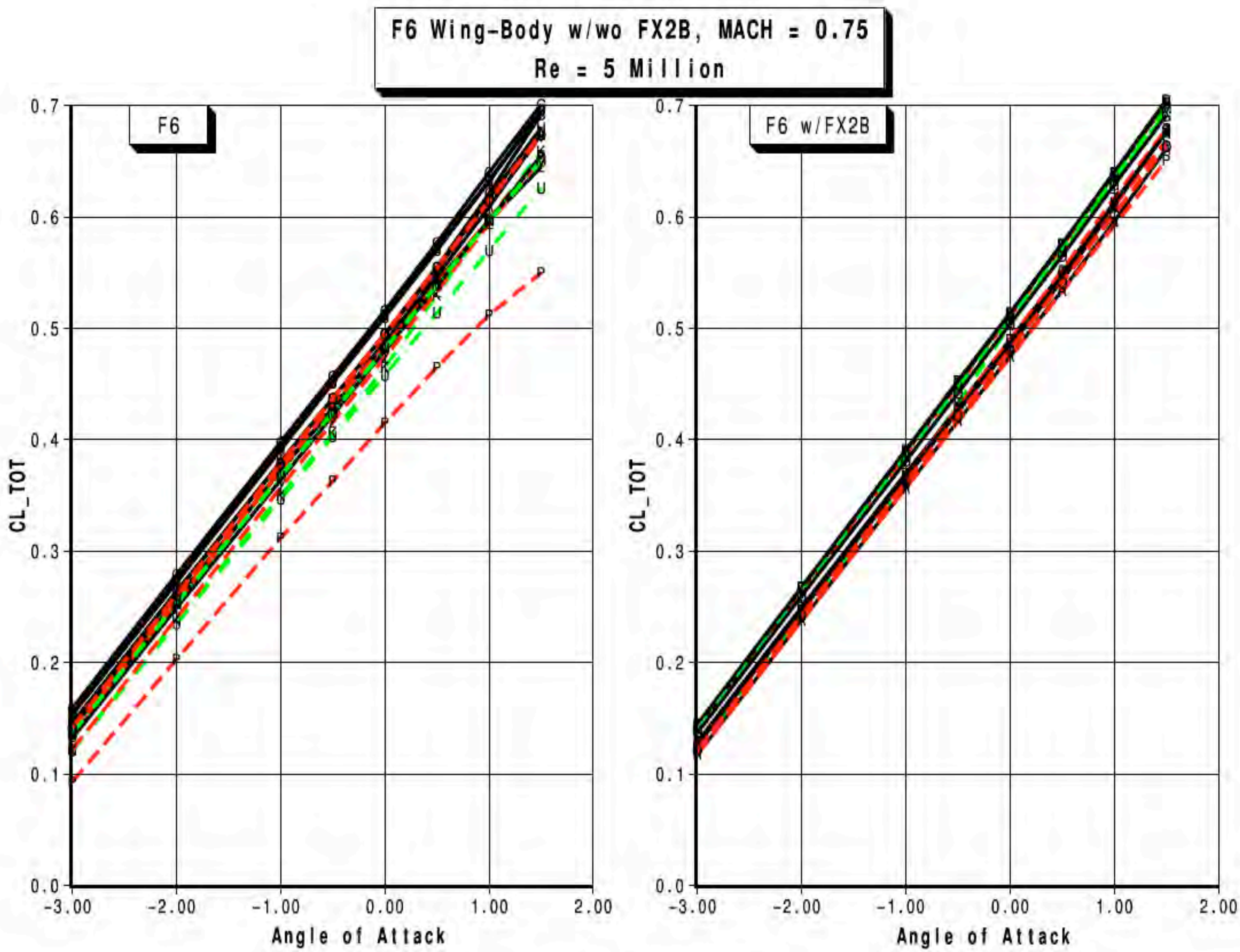


Drag Prediction Workshop

Outliers: S, P, Z, (T-Y)



Drag Prediction Workshop



F6 Wing-Body w/wo FX2B, MACH = 0.75
Re = 5 Million
F6
F6 w/FX2B
CL_TOT
Angle of Attack
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
-3.00
-2.00
-1.00
0.00
1.00
2.00

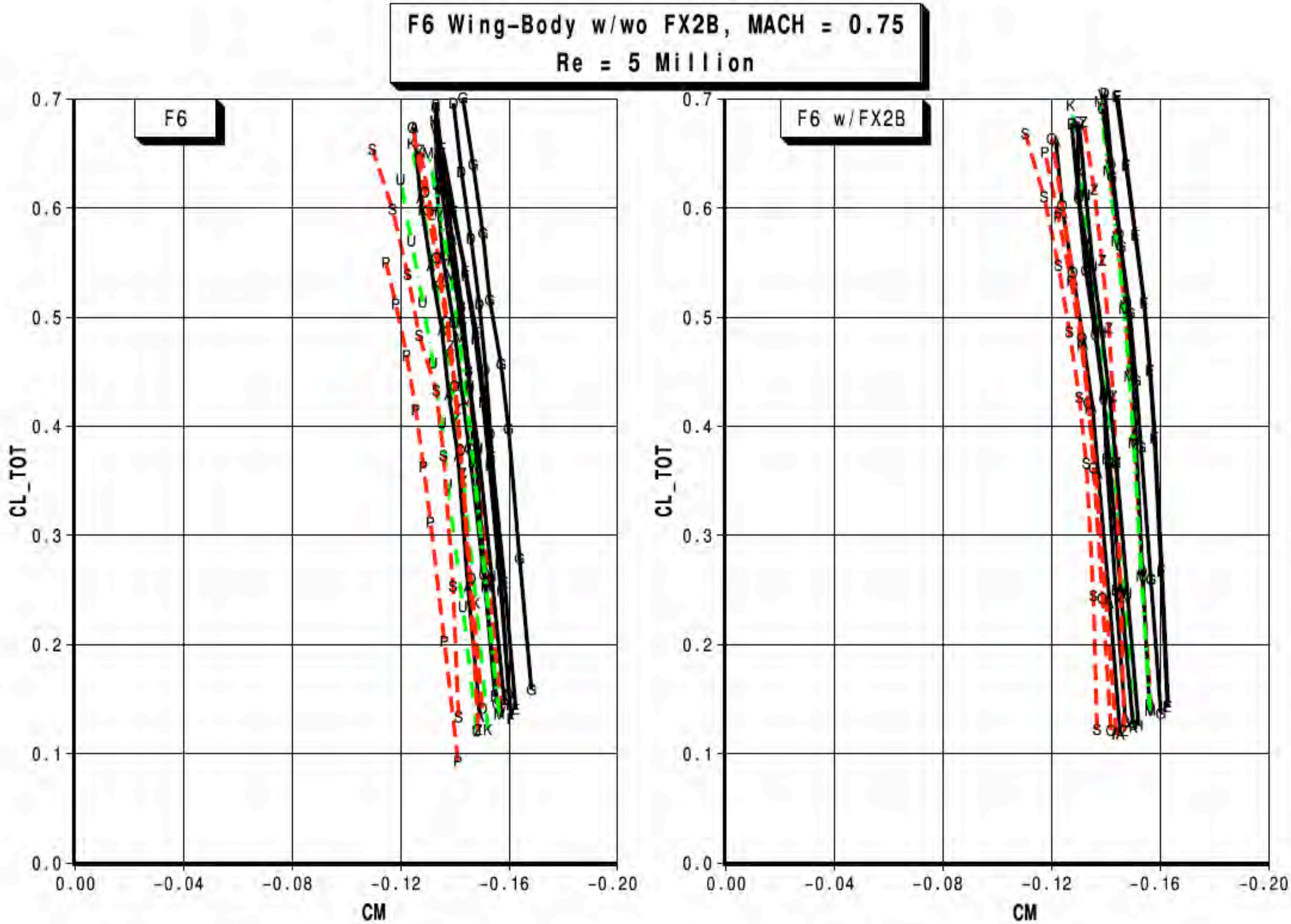


Figure 18. Case 1 Pitching Moment Curves.

Case 1: Conclusions

- Comparison of Aggregate Results
  - Highlights Room for Improvement
- Results on Medium Meshes
  - Scatter of Drag Levels is Large (~25%)
- Results Extrapolated to Continuum
  - Scatter Reduces, Especially for FX2B
  - Scatter Reduces Significantly w/o Outliers (σ ~ 2%)

DPW-III Test Cases

Case 1: DLR-F6 WB with and without FX2B Fairing

Fixed-C_L Single Point Grid Sensitivity Study on Three Grids

- $Mach = 0.75$, $C_L = 0.5$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.75$, $Re = 5$ million,
  $\alpha = [-3.0°, -2.0°, -1.0°, -0.5°, 0.0°, 0.5°, 1.0°, 1.5°]$.

Case 2: DPW-W1/W2 Wing-Alone

Fixed-α Single Point Grid Sensitivity Study on Four Grids

- $Mach = 0.76$, $\alpha = 0.5°$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.76$, $Re = 5$ million,
  $\alpha = [-1.0°, 0.0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°]$.

Case 2: Baseline Grids and Submissions

Table II: Case 2 DPW-W1/W2 Grids - Number of Grid Points.

	DPW-W1				DPW-W2			
Family	Extra-Fine	Fine	Medium	Coarse	Extra-Fine	Fine	Medium	Coarse
Tinoco	14,811,489	8,620,123	4,204,203	1,602,651	14,811,489	8,620,123	4,204,203	1,602,651
Sclafani	55,014,321	16,265,909	4,856,149	1,442,285	55,014,321	16,265,909	4,856,149	1,442,285
DLR	17,053,510	10,150,588	5,288,507	2,174,364	16,631,805	9,910,645	5,030,379	1,928,405
LaRC	36,956,019	11,492,625	4,495,117	1,818,508	38,462,630	11,903,329	4,658,853	1,882,672
Raytheon	12,748,678	6,138,245	2,417,082	983,633	12,419,567	5,963,713	2,325,884	947,409
JFLO	-	-	-	-	-	-	-	-

Table VII: Case 2 Submissions.

Tag	Code	Grid Type	Grid Family	Turbulence Model	Submitter
1	FLUENT	Multiblock	Tinoco	K-Epsilon	Fluent Scheidigger
2	CFL3D-Thin	Multiblock	Tinoco	SA	Boeing Tinoco
3	CFL3D-Thin	Multiblock	Tinoco	SST	Boeing Tinoco
4	OVERFLOW	Overset	Sclafani	SA	Boeing Sclafani
5	TAU	Hybrid	DLR	SA Edwards	DLR Brodersen
6	FUN3D	Unstructured	LaRC Nodal	SA	LaRC Lee-Rausch
7	NSU3D	Hybrid	LaRC Mixed	SA	UWy Mavriplis
8	NSU3D	Unstructured	Raytheon	SA	Cessna Zickuhr
9	FLOWer	Multiblock	Tinoco	RSM	DLR Eisfeld
10	FLOWer	Multiblock	Tinoco	SST	DLR Raddatz
11	TAI	Multiblock	JFLO C-H	BL	TAI Tarhan

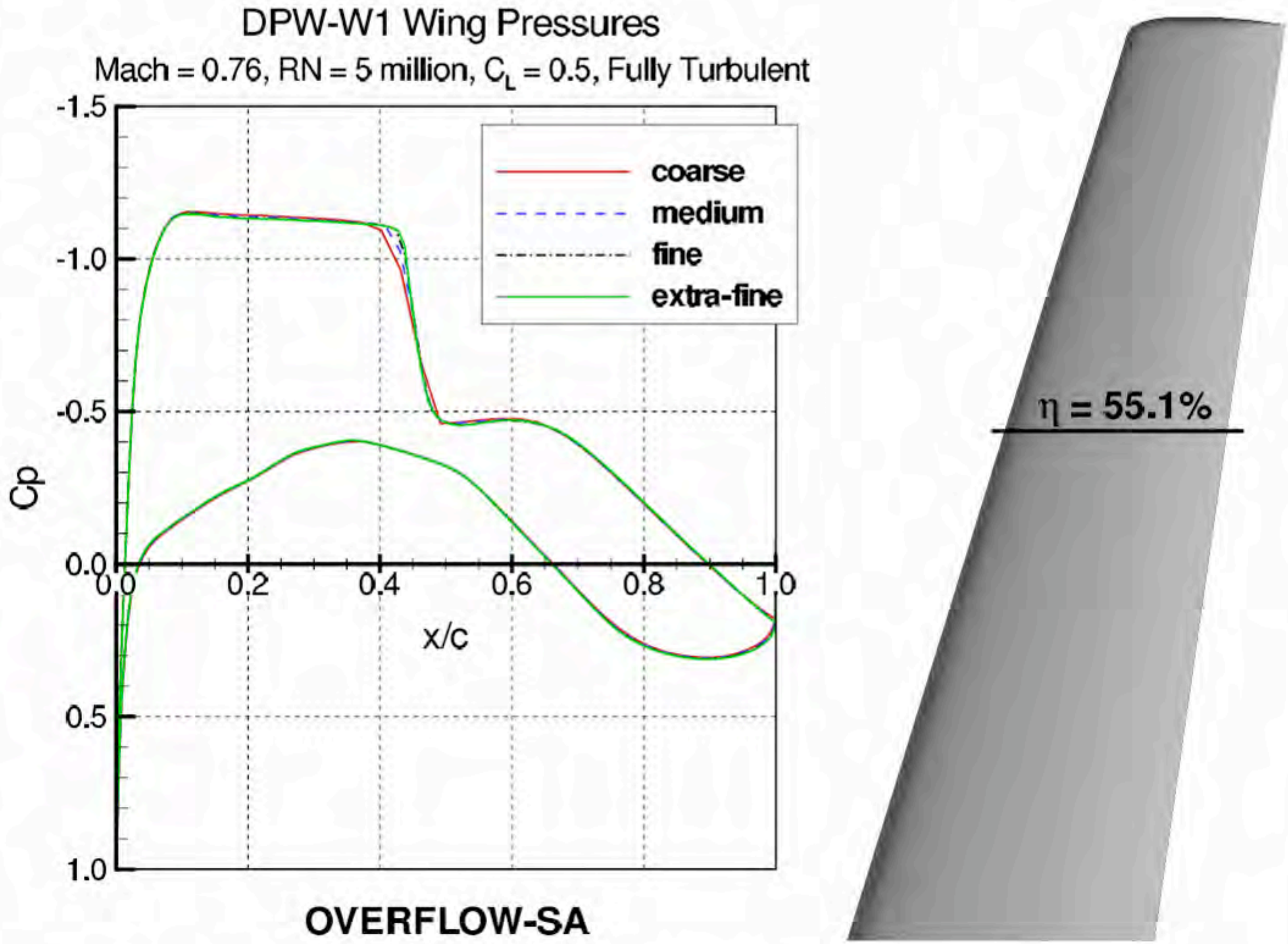


Figure 20. Case 2 W1 Pressure Distributions: $M = 0.76$, $C_L = 0.5$, $Re = 5$ *million*.

DPW-III Test Cases

Case 1: DLR-F6 WB with and without FX2B Fairing

Fixed-C_L Single Point Grid Sensitivity Study on Three Grids

- $Mach = 0.75$, $C_L = 0.5$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.75$, $Re = 5$ million,
  $\alpha = [-3.0°, -2.0°, -1.0°, -0.5°, 0.0°, 0.5°, 1.0°, 1.5°]$.

Case 2: DPW-W1/W2 Wing-Alone

Fixed-α Single Point Grid Sensitivity Study on Four Grids

- $Mach = 0.76$, $\alpha = 0.5°$, $Re = 5$ million.

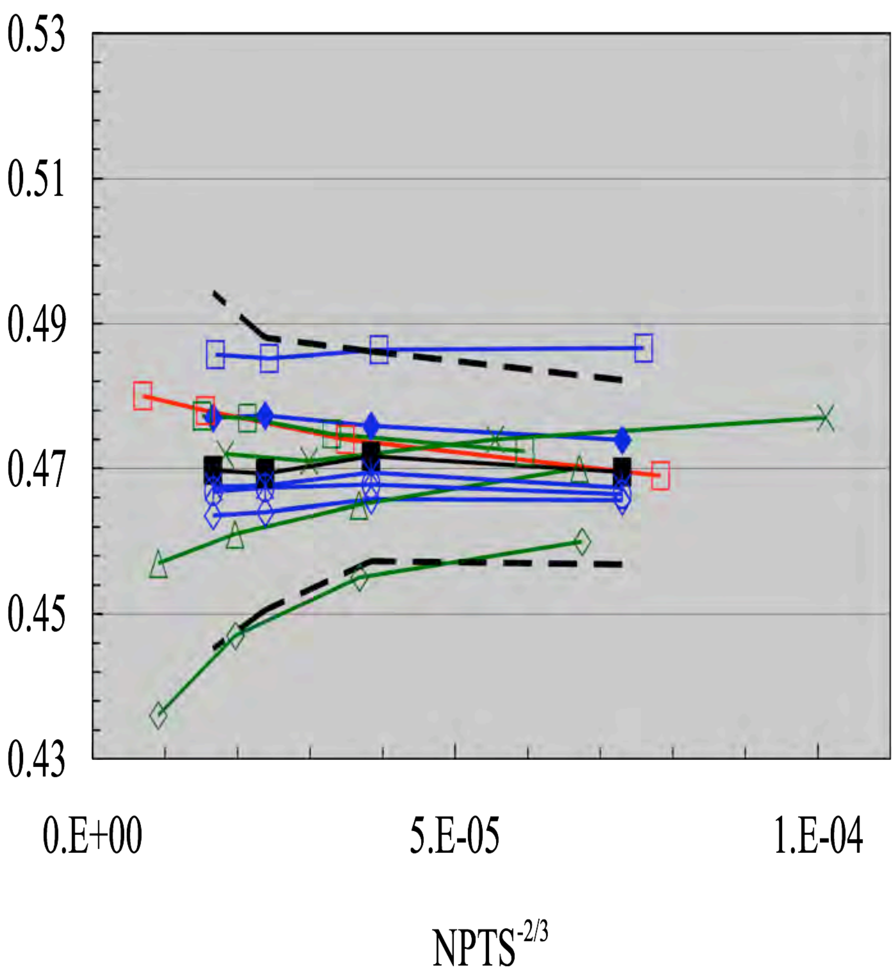
Drag Polar on Medium Grid

- $Mach = 0.76$, $Re = 5$ million,
  $\alpha = [-1.0°, 0.0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°]$.

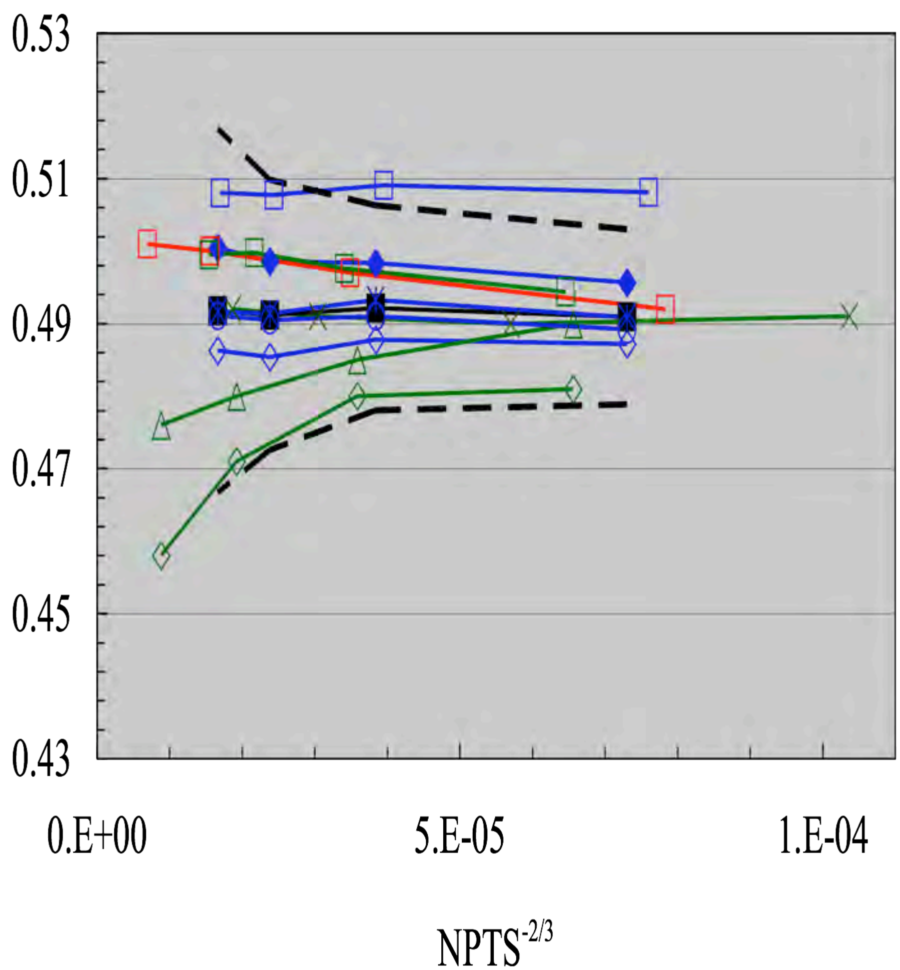
Case 2 Nested Solutions (CL)

Lift Coefficient

DPW-W1

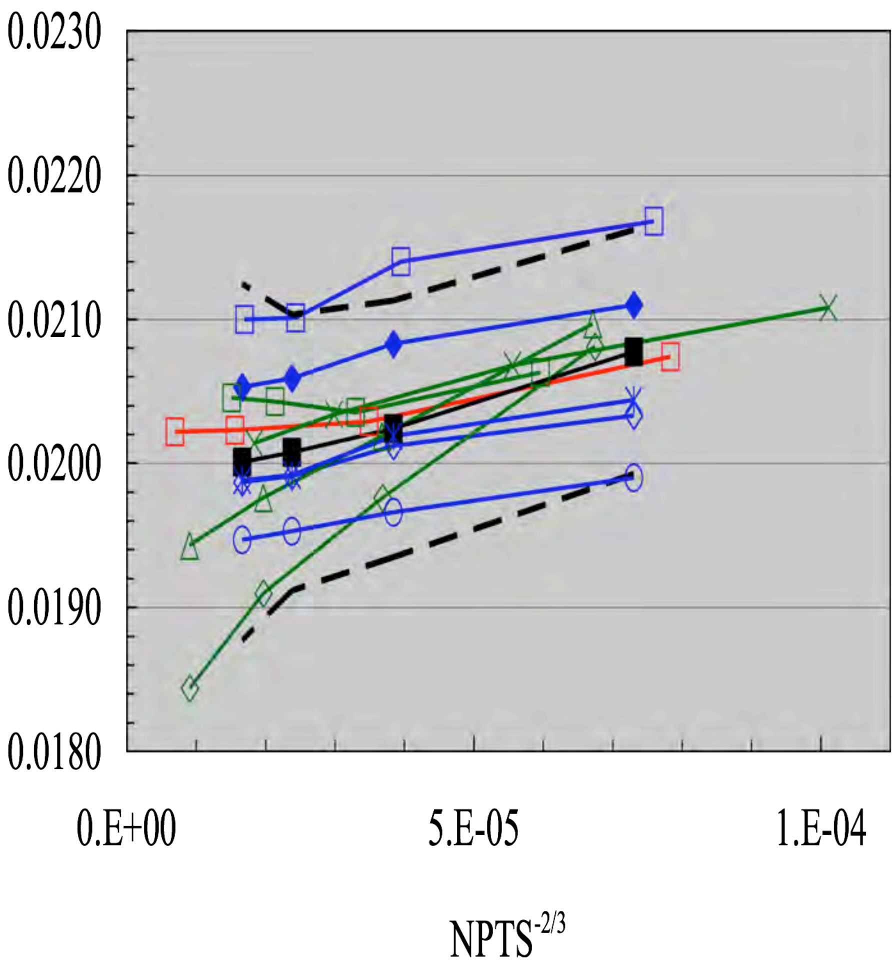


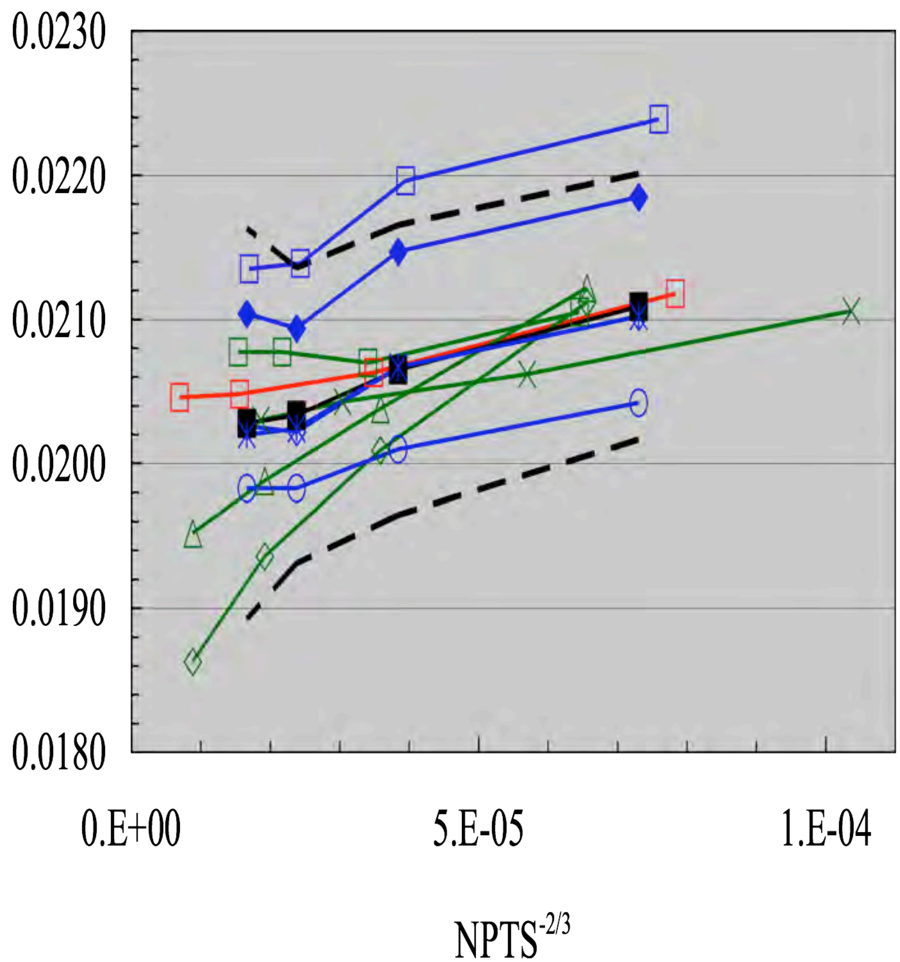
DPW-W2



Case 2 Nested Solutions (CD)

DPW-W1 **Total Drag Coefficient** DPW-W2



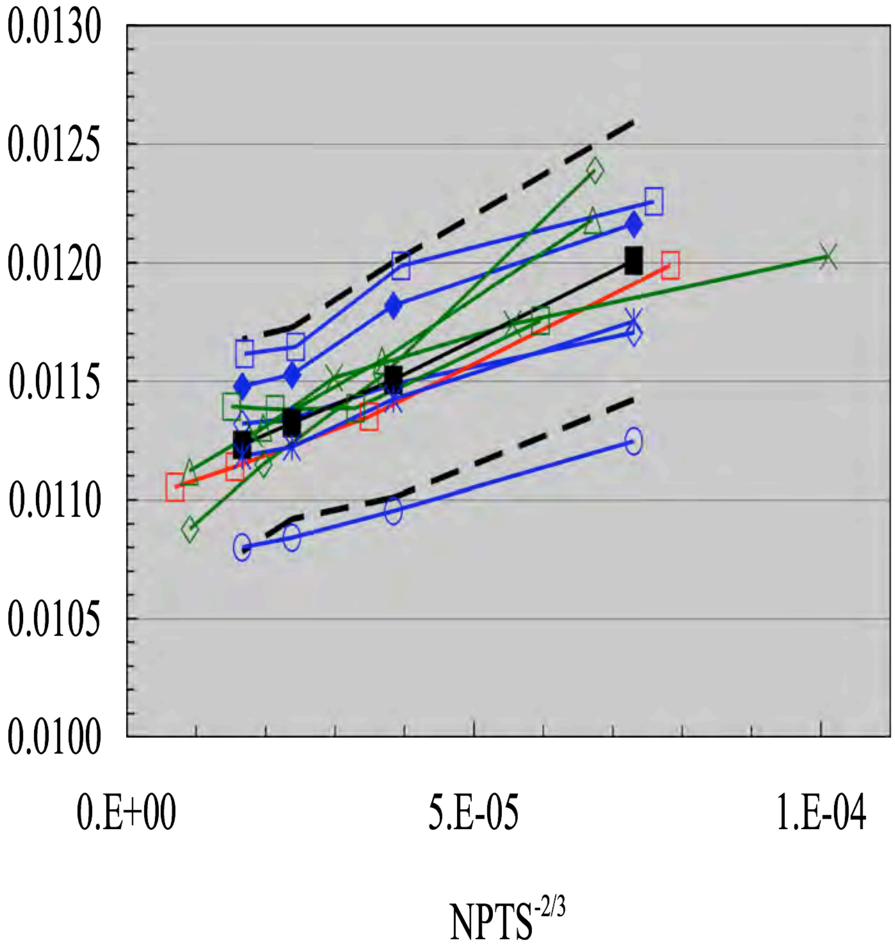


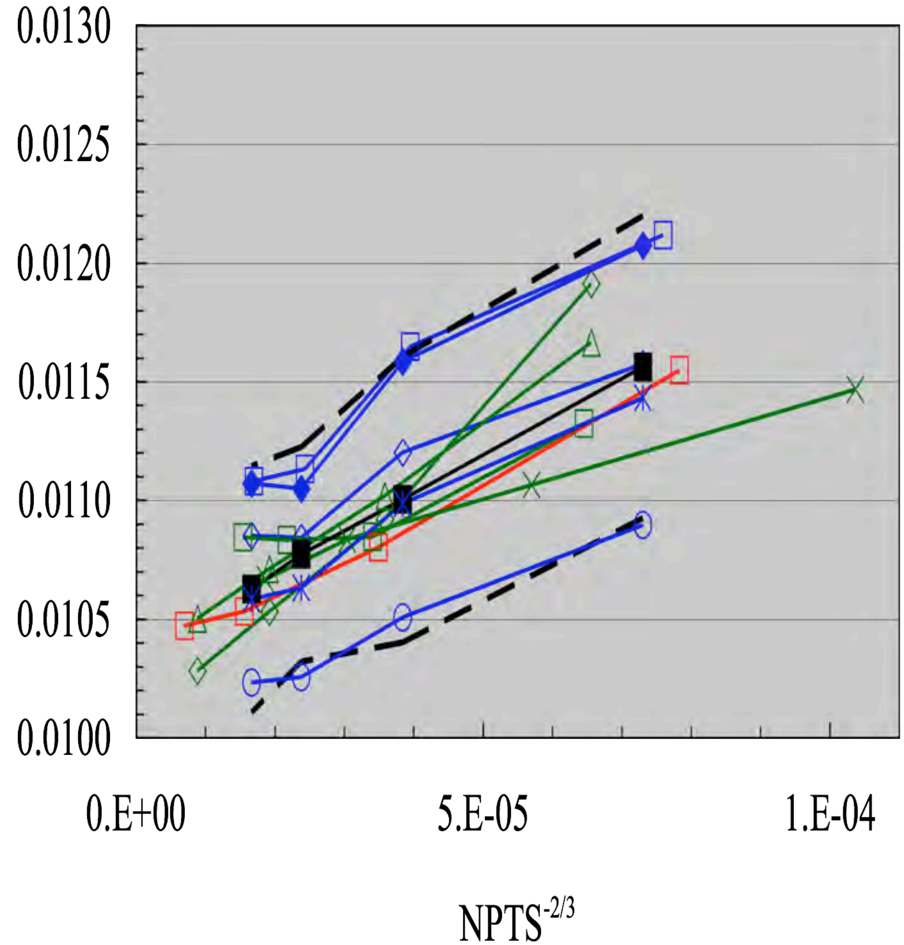
Case 2 Nested Solutions (CDP)

DPW-W1

Idealized Profile Drag Coefficient
$C_D - C_L^2 / (\pi\ AR)$

DPW-W2

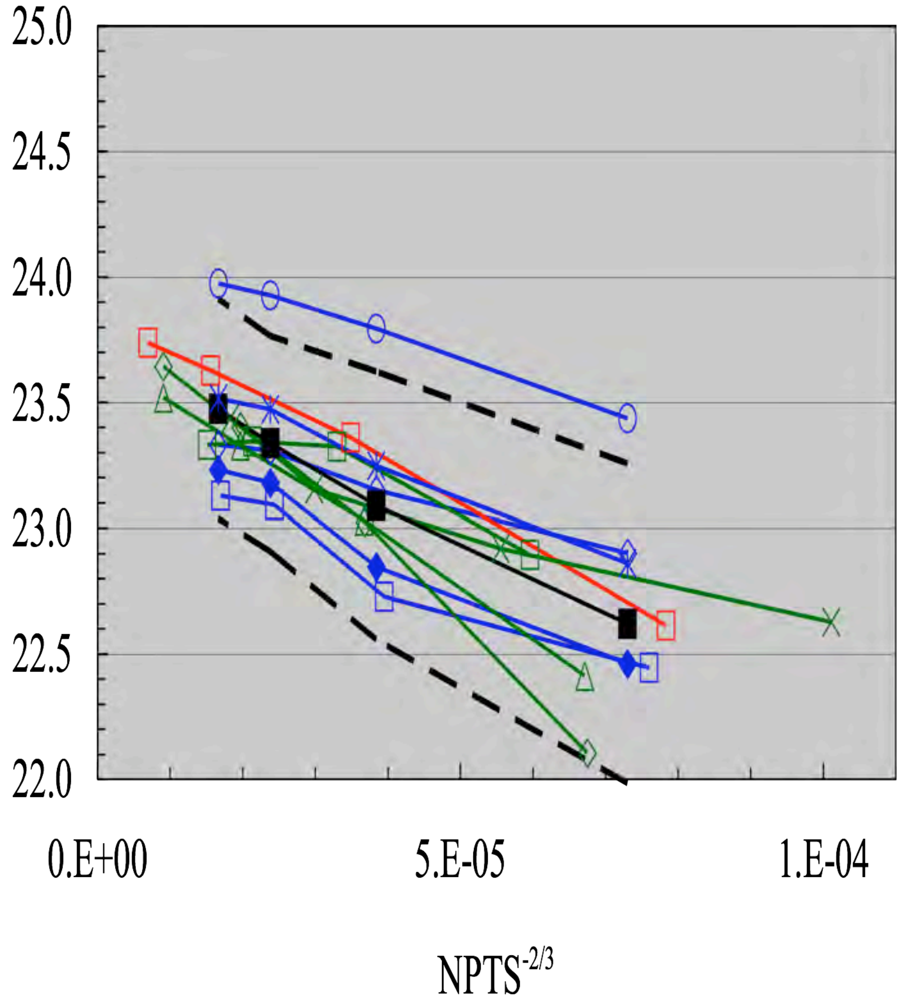


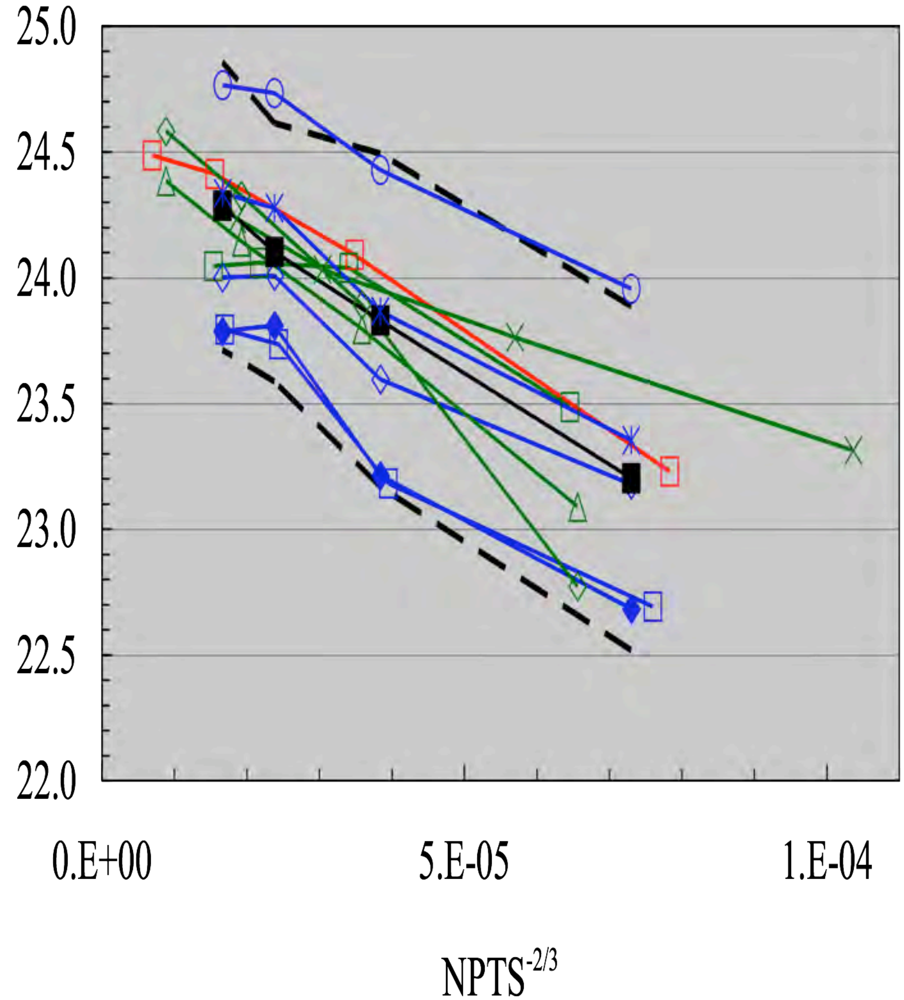


Drag Prediction Workshop

Case 2 Nested Solutions (L/D)

DPW-W1 **Lift-to-Drag Ratio** **DPW-W2**





Drag Prediction Workshop

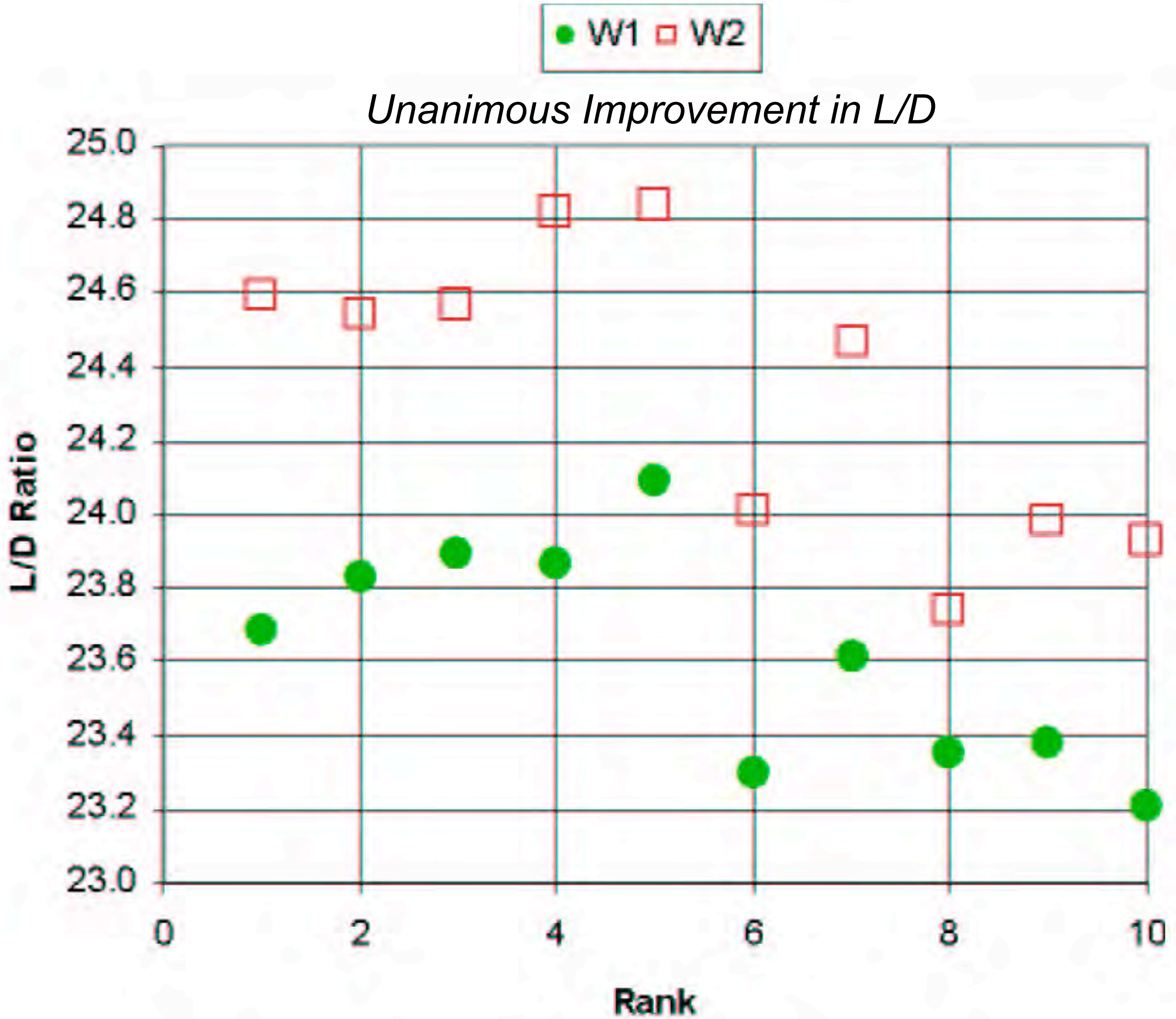


Figure 30. Case 2 Ranked Continuum Lift-to-Drag Ratio.

DPW-III Test Cases

Case 1: DLR-F6 WB with and without FX2B Fairing

Fixed-C_L Single Point Grid Sensitivity Study on Three Grids

- $Mach = 0.75$, $C_L = 0.5$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.75$, $Re = 5$ million,
  $\alpha = [-3.0°, -2.0°, -1.0°, -0.5°, 0.0°, 0.5°, 1.0°, 1.5°]$.

Case 2: DPW-W1/W2 Wing-Alone

Fixed-α Single Point Grid Sensitivity Study on Four Grids

- $Mach = 0.76$, $\alpha = 0.5°$, $Re = 5$ million.

Drag Polar on Medium Grid

- $Mach = 0.76$, $Re = 5$ million,
  $\alpha = [-1.0°, 0.0°, 0.5°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°]$.

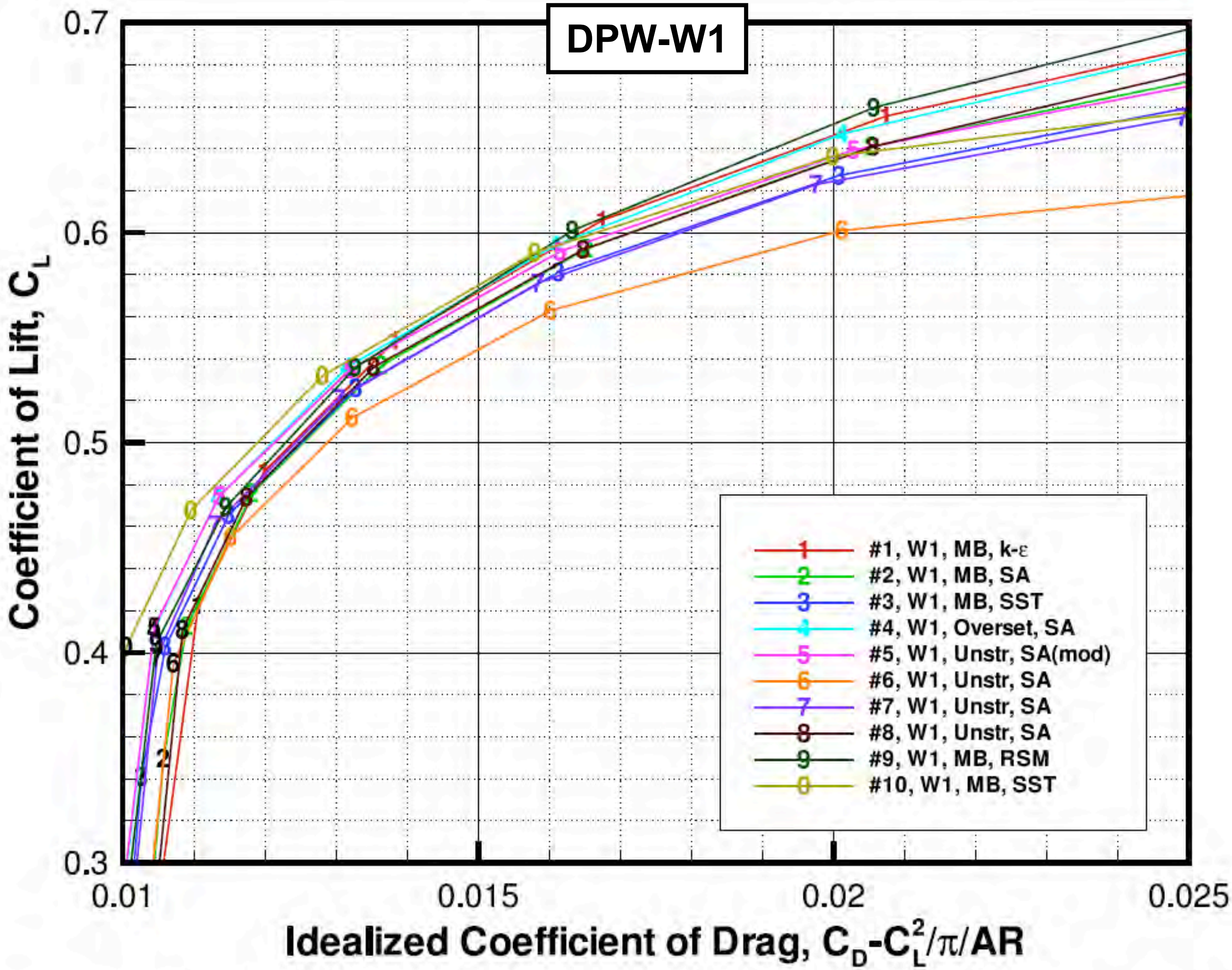


Figure 31. Case 2 W1 Idealized Profile Drag Polar: $M = 0.76$, $Re = 5$ *million*, **Medium Mesh.**

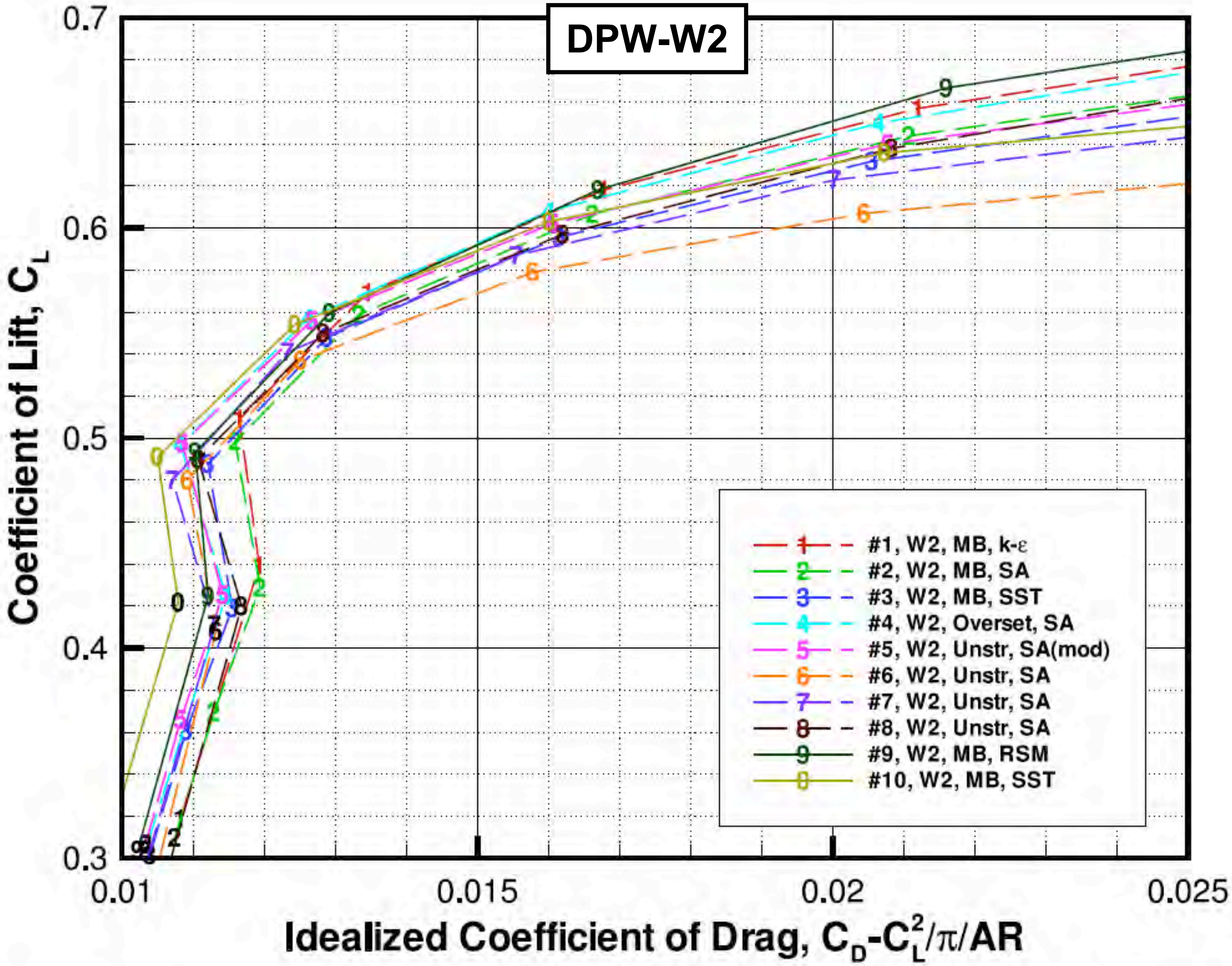


Figure 32. Case 2 W2 Idealized Profile Drag Polar: $M = 0.76$, $Re = 5$ *million*, Medium Mesh.

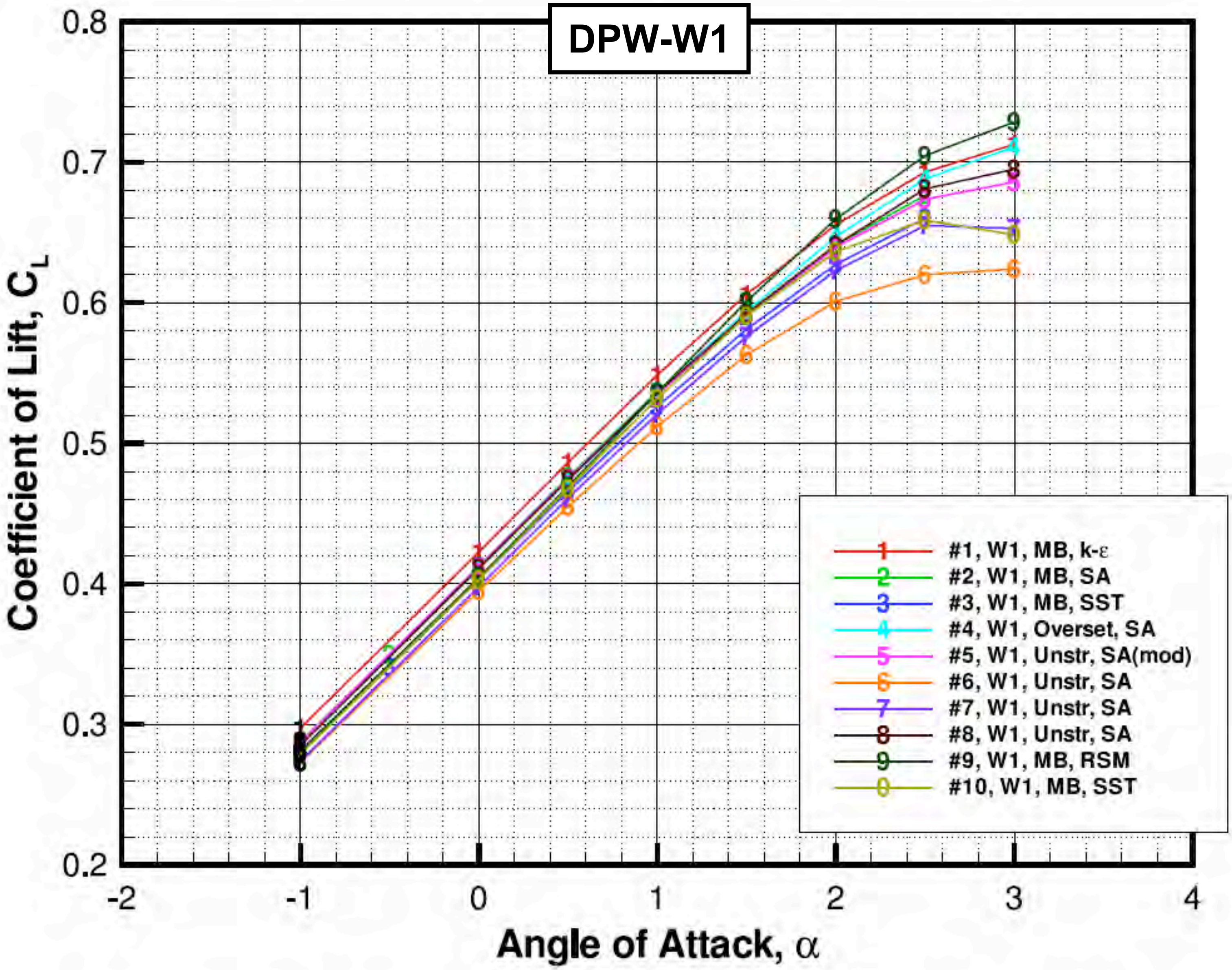


Figure 33. Case 2 W1 C_L-α Curves: $M = 0.76$, $Re = 5\ million$, **Medium Mesh.**

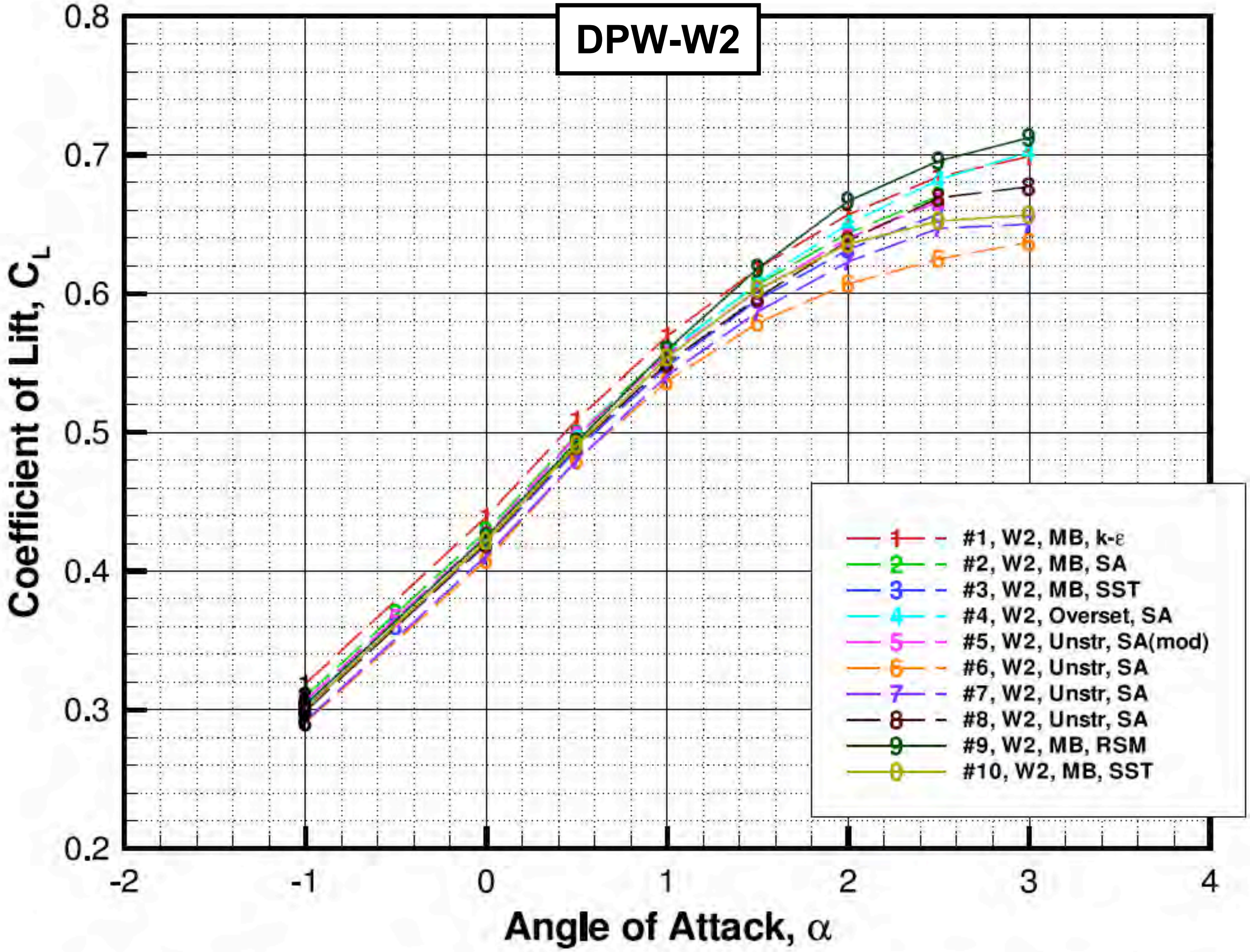


Figure 34. Case 2 W2 C_L-α Curves: $M = 0.76$, $Re = 5\ million$, Medium Mesh.

Drag Prediction Workshop

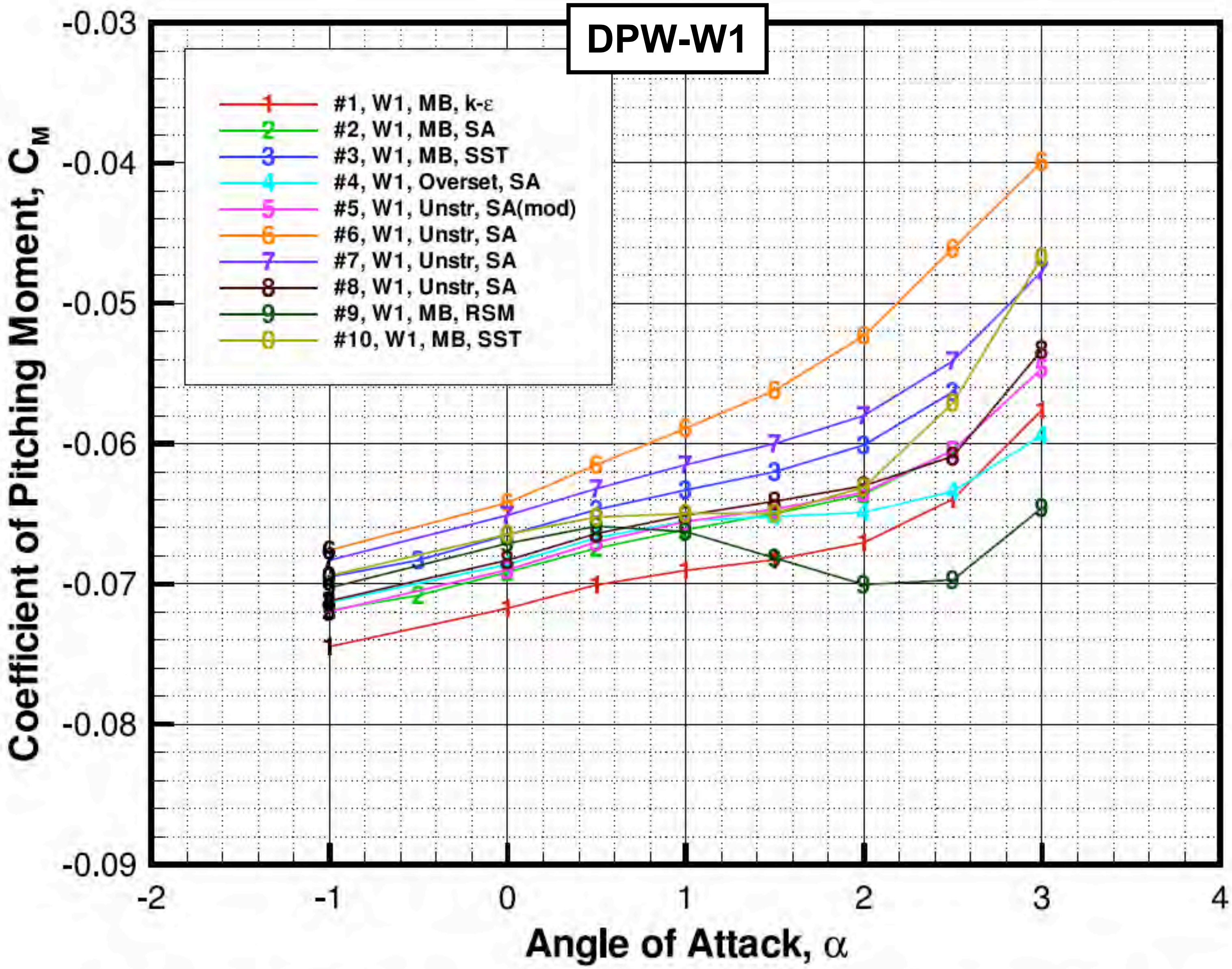


Figure 35. Case 2 W1 C_M-α Curves: $M = 0.76$, $Re = 5\ million$, **Medium Mesh.**

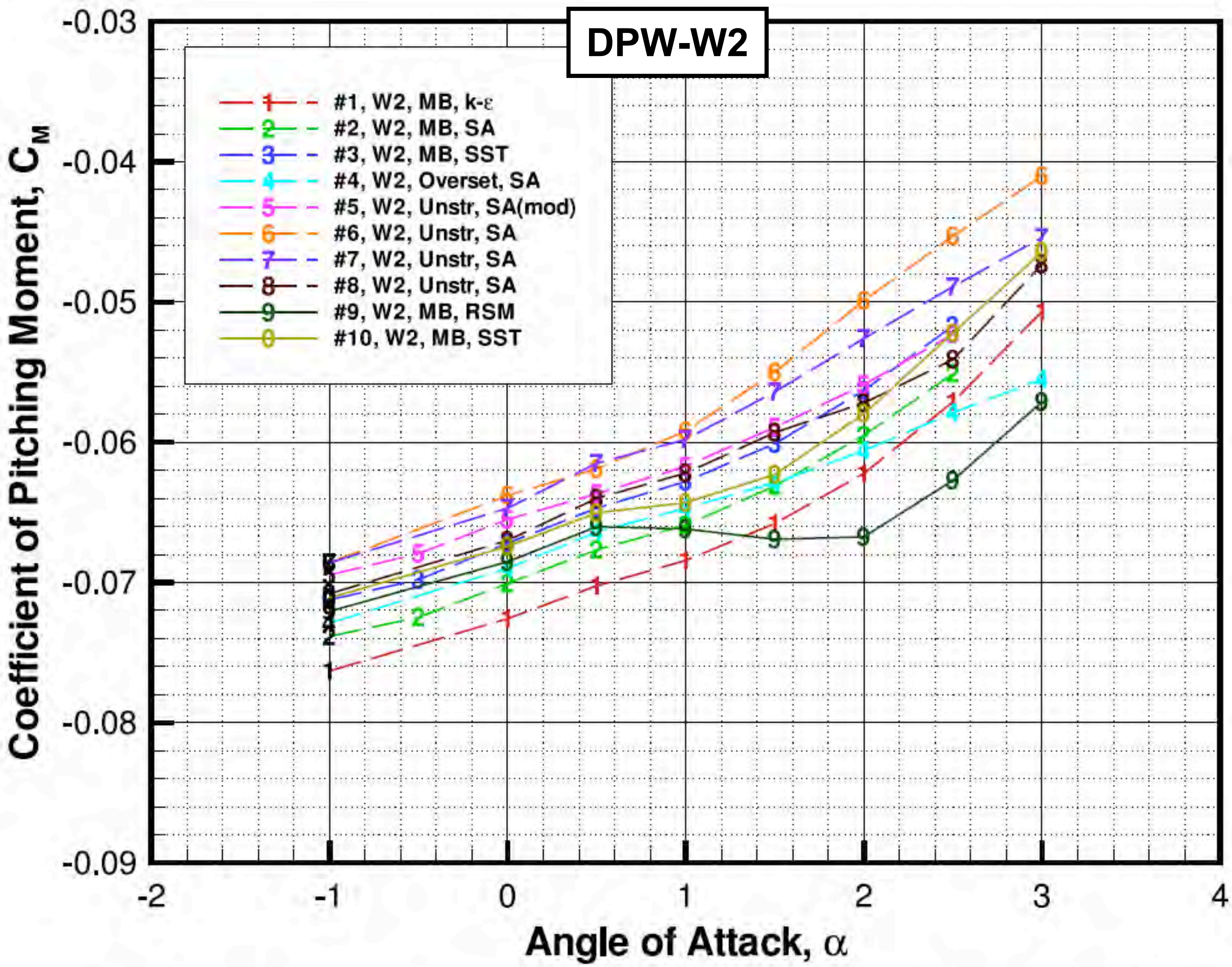


Figure 36. Case 2 W2 C_M-α Curves: $M = 0.76$, $Re = 5$ *million*, Medium Mesh.

Case 2: Conclusions

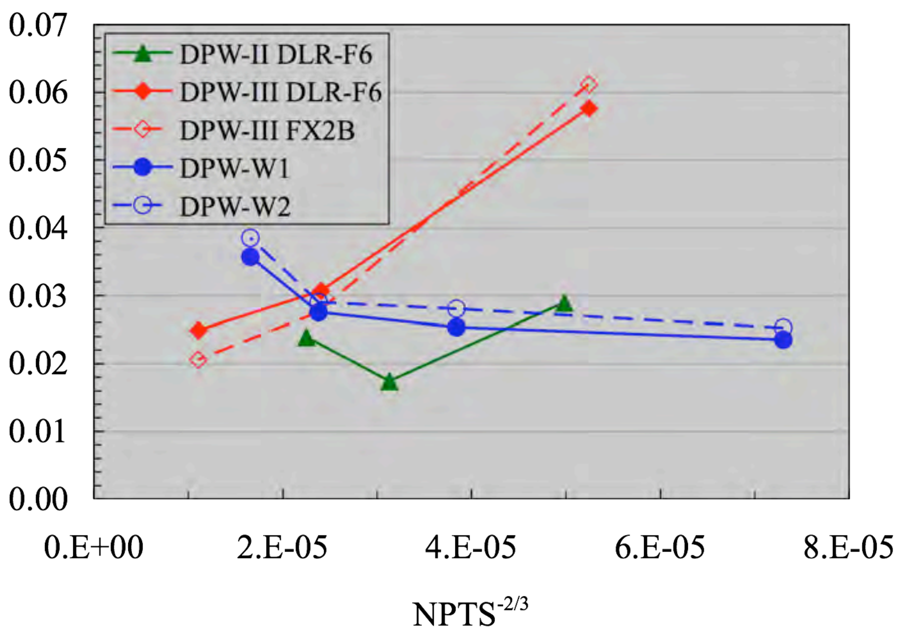
- Fixed-Alpha Grid-Convergence Study
  - Lift & Drag Scatter ~10%
  - L/D & CDP Scatter ~5% (~3% omitting one sol'n)
  - Scatter Approximately Constant w/ Grid Resolution

- Results Extrapolated to Continuum
  - Scatter Reduces, But Only Very Slightly

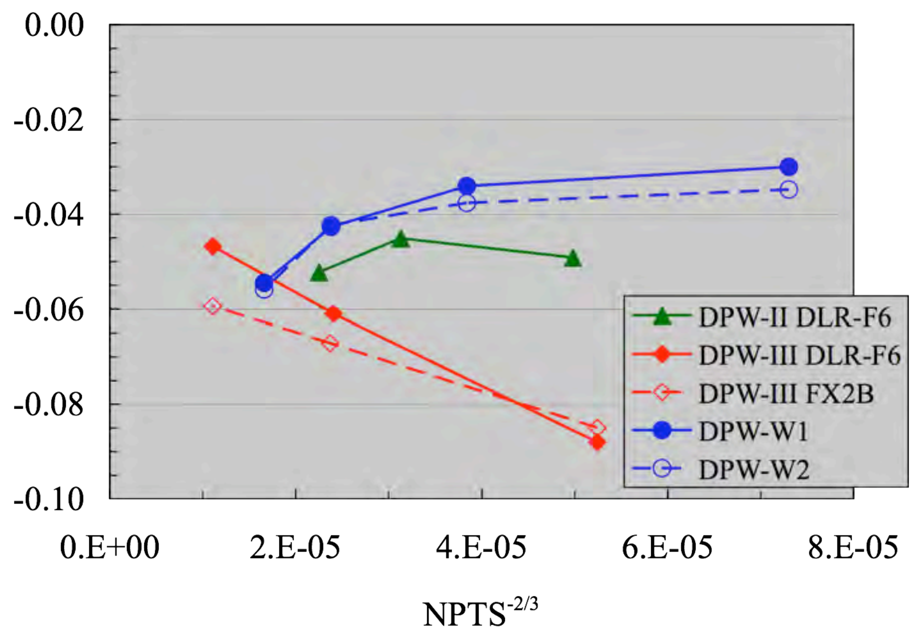
Some Comparisons of DPW2 and DPW3

$C_v = \sigma / \mu$

Total Drag Coefficient



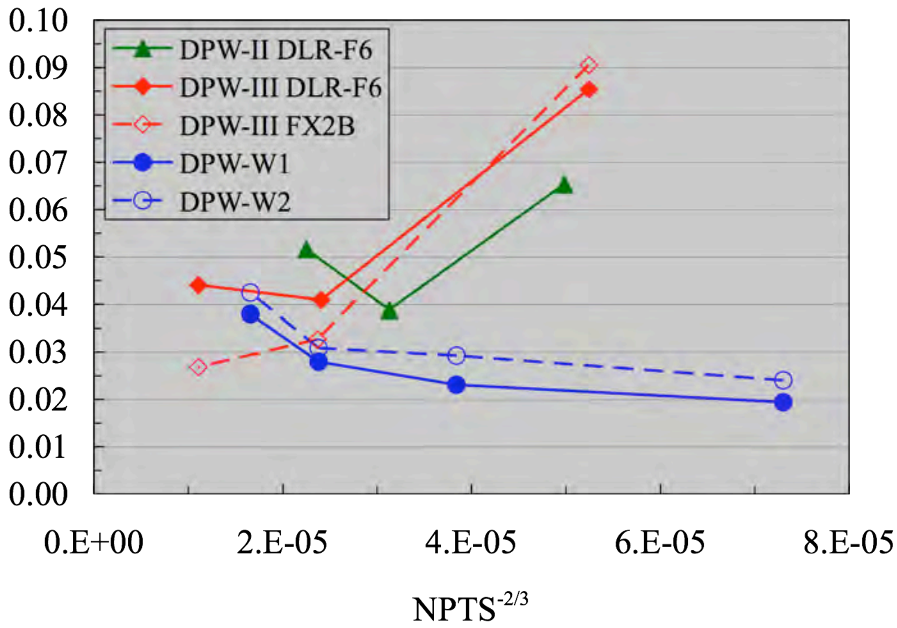
Pitching Moment Coefficient



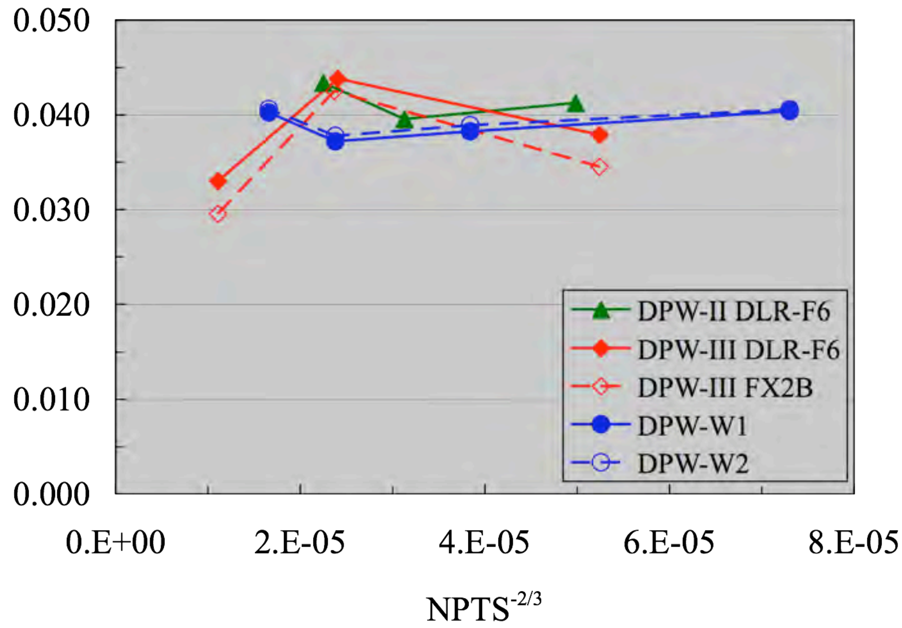
Some Comparisons of DPW2 and DPW3

$C_v = \sigma / \mu$

Pressure Drag Coefficient



Skin Friction Drag Coefficient

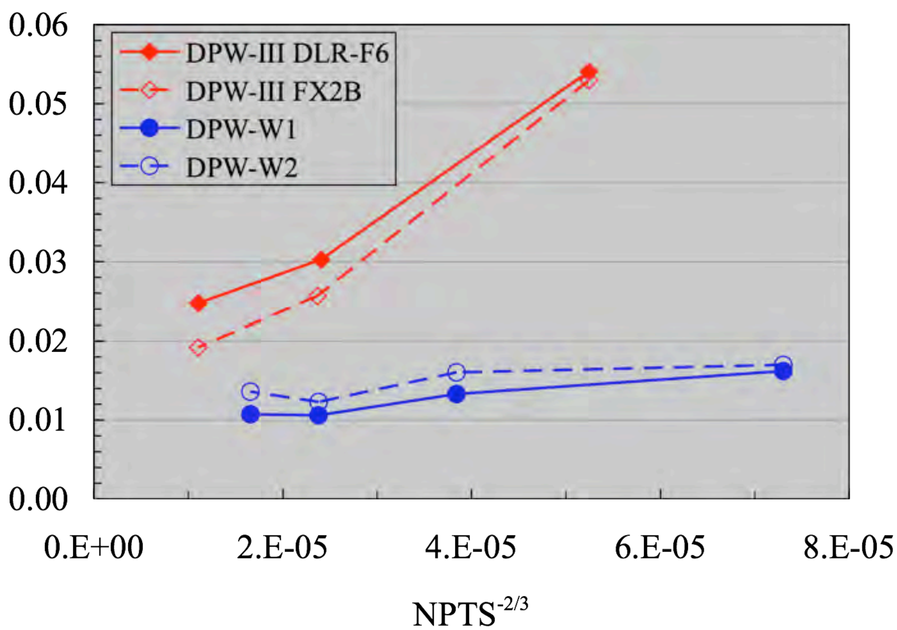


Drag Prediction Workshop

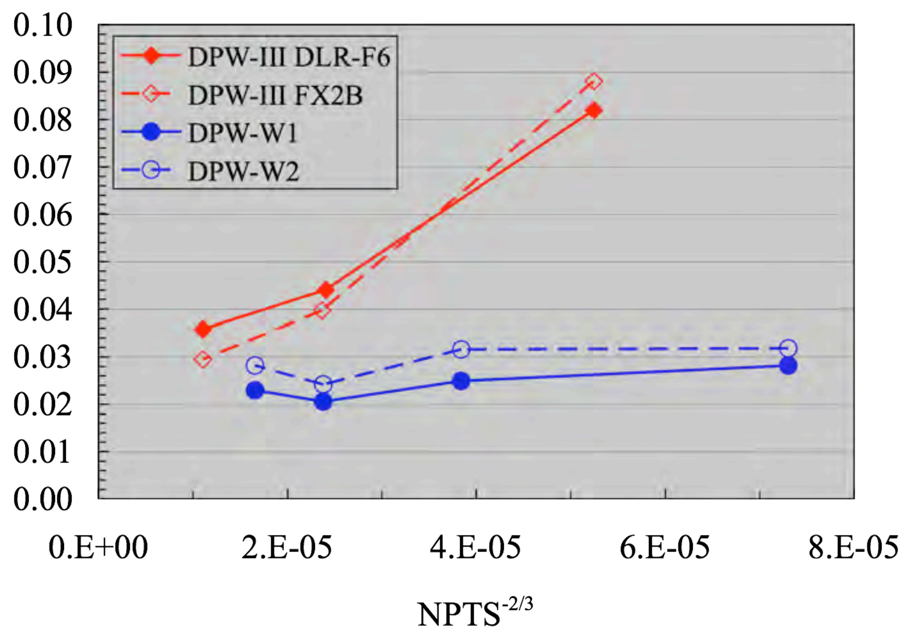
Some Comparisons of DPW2 and DPW3

$C_v = \sigma / \mu$

Lift-to-Drag Ratio



Idealized Profile Drag Coefficient

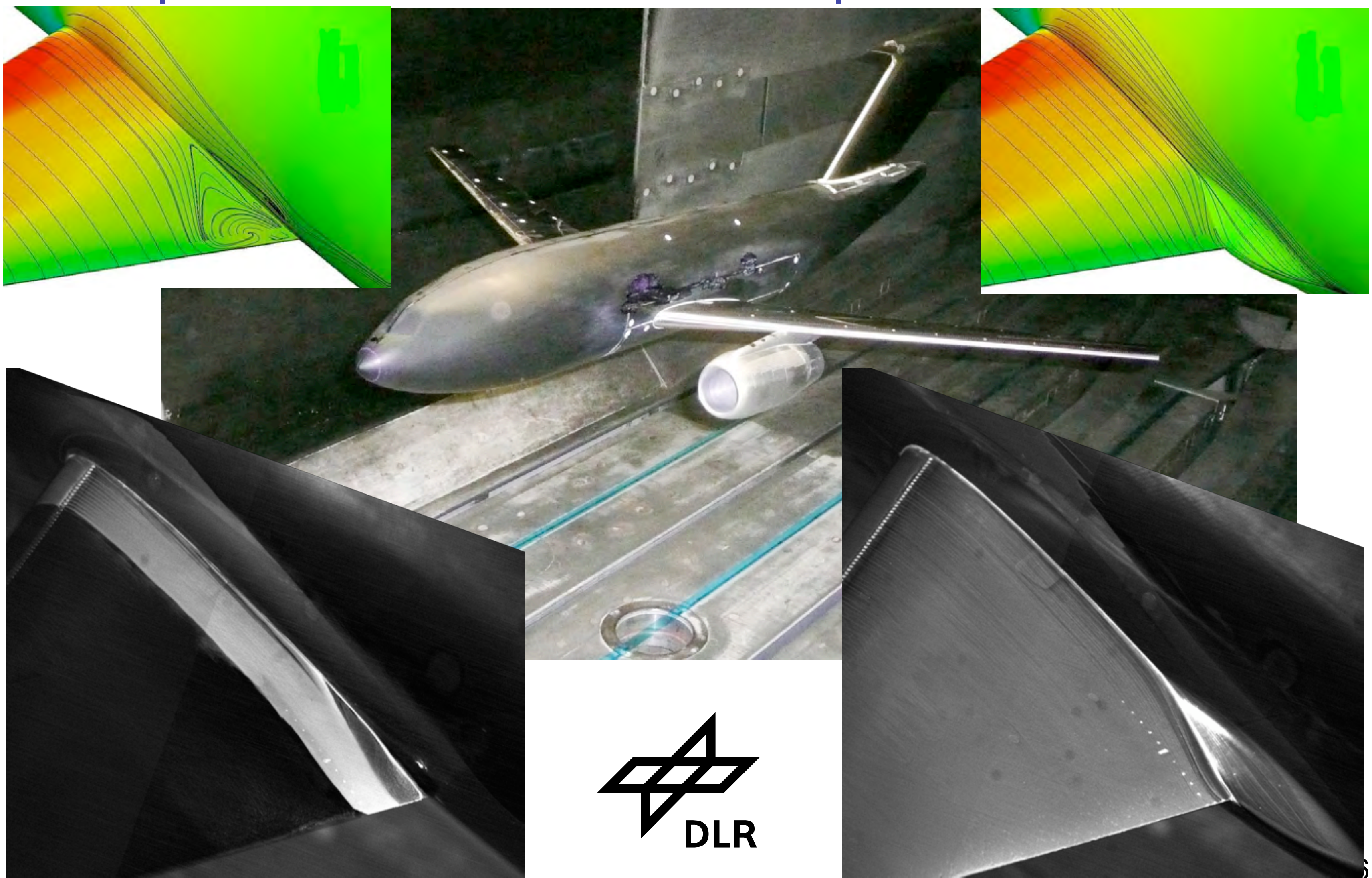


DPW3 Observations

- The Good News:
  - **DPW-3 was a blind test, i.e. no experimental data existed to "guide" solutions. The results were about as good for the blind test as for DPW-2.**
  - **DLR-F6 and FX2B demonstrated a monotonic decrease in variation with increasing grid resolution.**
  - **DPW-W1 and DPW-W2 demonstrated a nearly grid independent variation for total drag when the lift component was appropriately accounted for.**
- The Less Good News:
  - Have not demonstrated convergence of medians, spread or core interval for F6/FX2B despite increased grid sizes
  - DLR-F6 variation has not improved from DPW-2
  - Variation on the attached flow FX2B configuration is approximately the same as variation on the separated flow DLR-F6 configuration
  - After 3 drag prediction workshops, grids remain a leading order issue

DPW3 Test Completed; Report August 2008

NTF CFD Validation Test of the DLR F6 Commercial Aircraft Configuration
Experimental Results at Rn 5m for Comparison to AIAA DPW3



DLR

Concluding Remarks

- To assess state-of-the-art CFD methods as practical aerodynamic tools for prediction of forces & moments on industry-relevant geometries, with a focus on drag
  - Use a statistical framework to assess the results
- RANS is a practical aerodynamic tool - a practical approximation
  - But to the community at large (including bosses), the DPWs have demonstrated that quality CFD is not a simple, turn-key operation; increments better than absolutes
- Consistently predicting (across methods) flow separation onset and progression is still a tough problem
- Grid generation/Solution convergence is a consistent problem
  - highlighted in each DPW
- Statistical framework provides a unique perspective on results, and help further the discussion on uncertainty quantification

Concluding Remarks

- To provide an impartial international forum for evaluating the effectiveness of CFD NS solvers
  - Promote balanced participation across academia, government labs, and industry
  - Schedule open-forum sessions to further engage interaction among all interested parties
- Broad participation across the world
  - The workshops and the follow-up sessions
- Open geometry and common challenges enable the lively, educational discussions and debates
- Interest in continuing this type of activity/forum

Concluding Remarks

- To identify areas needing additional research and development
- Isolating cause and effect, quantifying uncertainty
  - numerics, physics, geometry (and user)
  - Modern Design of Experiments (MDOE)
  - numerical error estimation techniques
- Grids, grids, grids …. Convergence …
  - A specific challenge is nested unstructured grids
  - Generate families of grids, rather than individual grids
  - Solution adaptive grids
- Improved turbulence models ?? Probably
  - Near (to long) term, RANS will be the primary practical high fidelity CFD method
- Establish best practices and use them
  - General or code/organization specific?