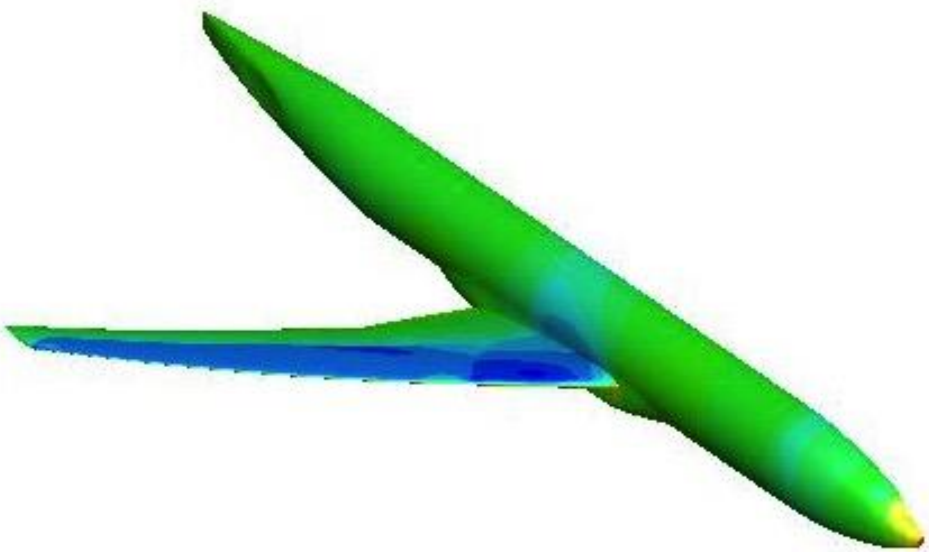
DPW 7 Summary of Participant Data



- Edward N. Tinoco and the DPW Organizing Committee

Outline:

- Introduction and Participant Data
- Case 1: Grid Convergence Study
- Case 2: Angle of Attack Sweep
- Case 3: Reynolds Number Sweep
- Case 4: Grid Adaptation
- Case 5: Beyond RANS
- Case 6: Coupled Aero-Structural Simulation
- Observations/Issues

Should We Compare to Wind Tunnel?

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

- Wind Tunnel and CFD measure/compute different things!
- Neither produces free-air absolute values!
- This CRM model
  - Tested in 3 different wind tunnels
  - Several repeats in each facility.
  - High degree of consistency among data – Excellent for increments
  - Data are included for reference

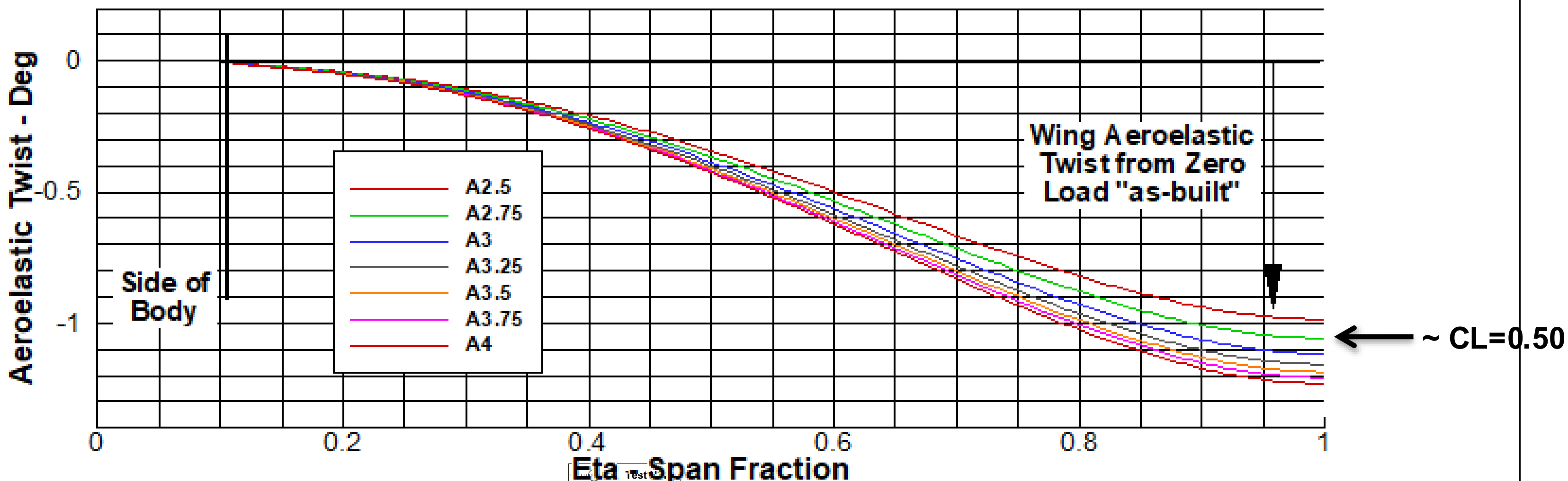
Question about mounting system corrections to CRM experimental data

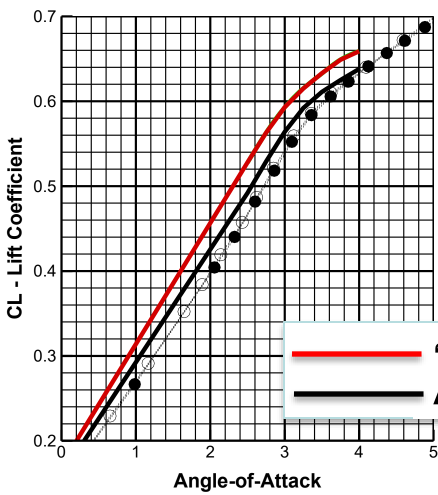
Table S-III-1. Corrections for Aeroelastic Twist and USS.

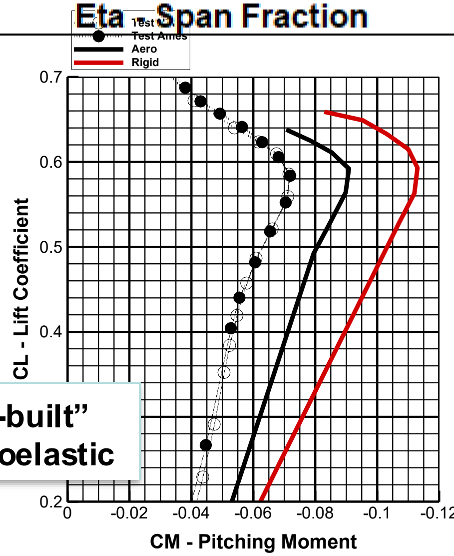
Correction for	δCL	δCD	δCM	Add to	Source
Aeroelastic Twist	–0.0360	0.0	0.0300	WB; DPW-IV, -V WBT; DPW-IV	Refs. 1&2
USS	–0.0030	–0.0025	0.0050	WB; All DPWs	Ref. 3
USS	–0.0270	–0.0025	0.0457	WBT; DPW-IV	Refs. 1&2
USS	–0.0030	–0.0025	0.0050	WBNP; DPW-VI	Ref. 3

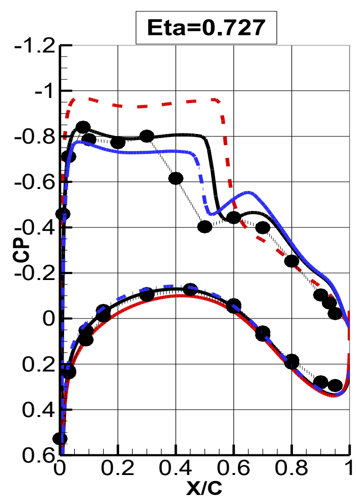
1. Rivers, M. and Hunter, C., "Support System Effects on the NASA Common Research Model," AIAA Paper 2012-707, January 2012.
2. Rivers, M., Hunter, C., and Campbell, R., "Further Investigation of the Support System Effects and Wing Twist on the NASA Common Research Model," AIAA Paper 2012-3209, June 2012.
3. Tinoco, Edward N., "An Evaluation and Recommendations for Further CFD Research Based on the NASA Common Research Model (CRM) Analysis from the AIAA Drag Prediction Workshop (DPW) Series," NASA/CR-2019-220284

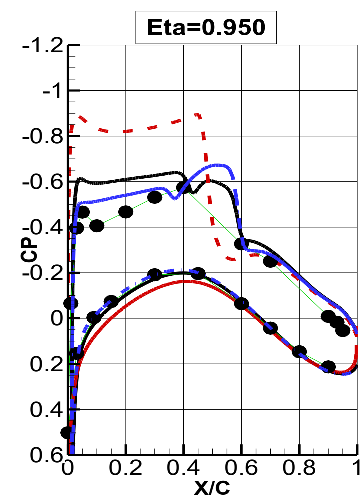
CRM geometry for DPW7 includes the static aeroelastic twist and deformation experienced by the model at different angles of attack











Participant Data:

- **30 Total Data Submittals**
- **18 Teams/Organizations**
  - 6 N. America, 7 Europe, 4 Asia
  - 7 Government, 2 Industry, 1 Academia, 5 Commercial
  - 2 for Case 5 only, 1 for Case 6 only
- **Grid Types:**
  - 16 Unstructured (x Teams)
  - 3 Overset (x Teams)
  - 3 Structured Multi-block (x Teams)
  - 1 Custom Cartesian (x Teams)
- **Turbulence Models:**
  - 14 SA-QCR (all types), 7 SA w/oQCR, 4 SST, 2 EARSM, 1 SSG/LRR, 1 AMM-QCR, 1 RSM-ln(w)

Outline:

- Participant Data
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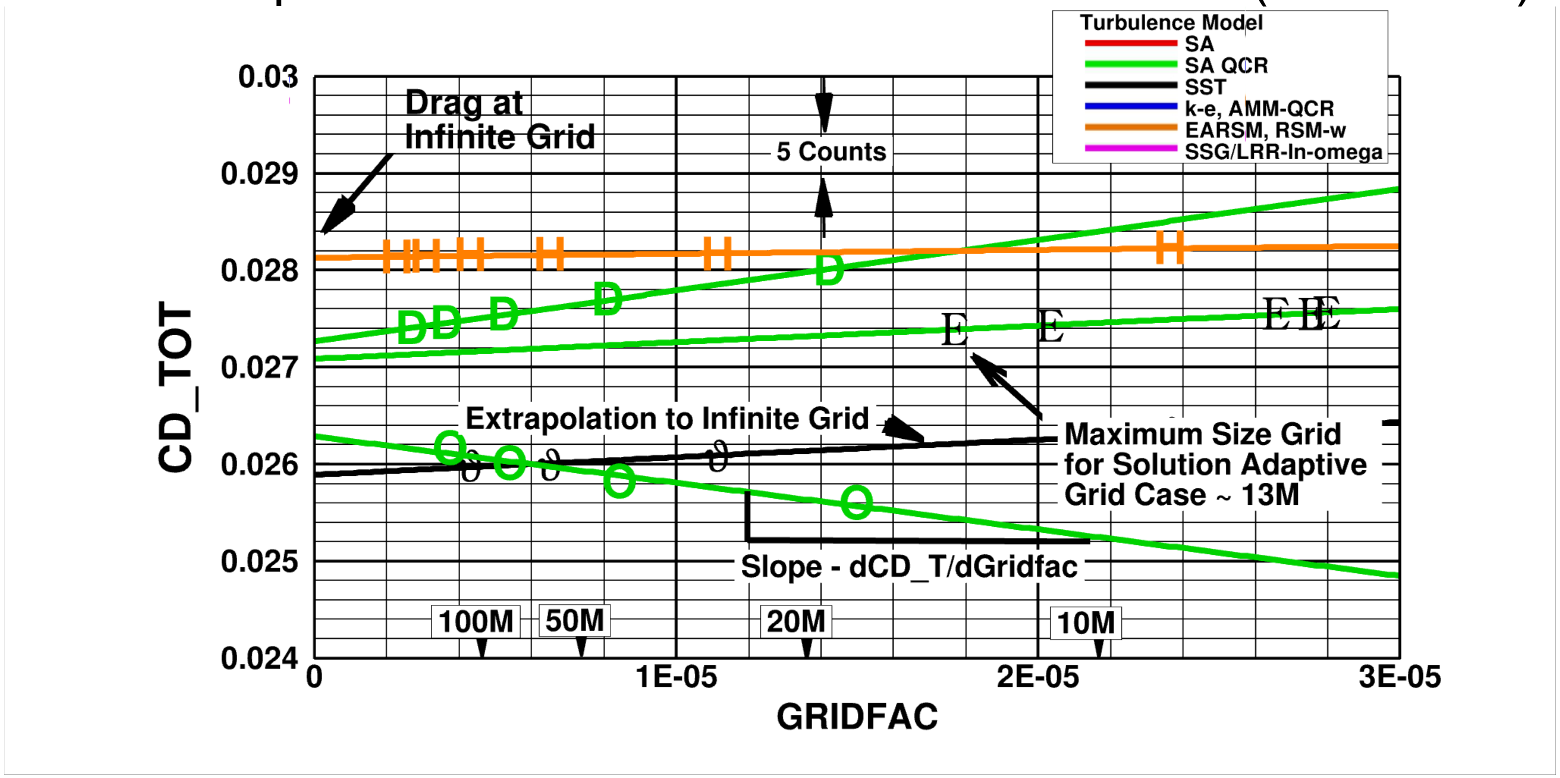
Case 1: Grid Convergence Study

- Grid Convergence Study
- NASA Common Research Model -
- Mach=0.85, C_L=0.580±0.001
- Chord Reynolds Number: 20×10^6 , 5×10^6 Optional
- Grid Resolution Level:
  - 1) Tiny 2) Coarse 3) Medium,
  - 4) Fine 5) Extra-Fine 6) Super-Fine
- Reynolds Number Effect on Forces and Moments

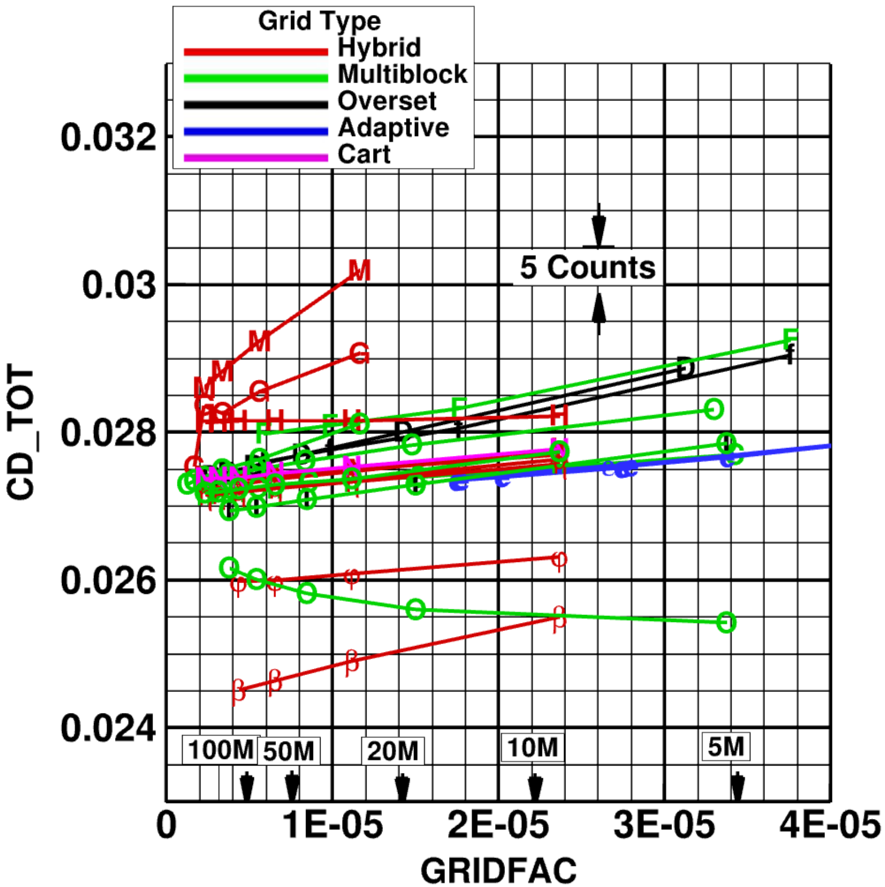
Grid Convergence?

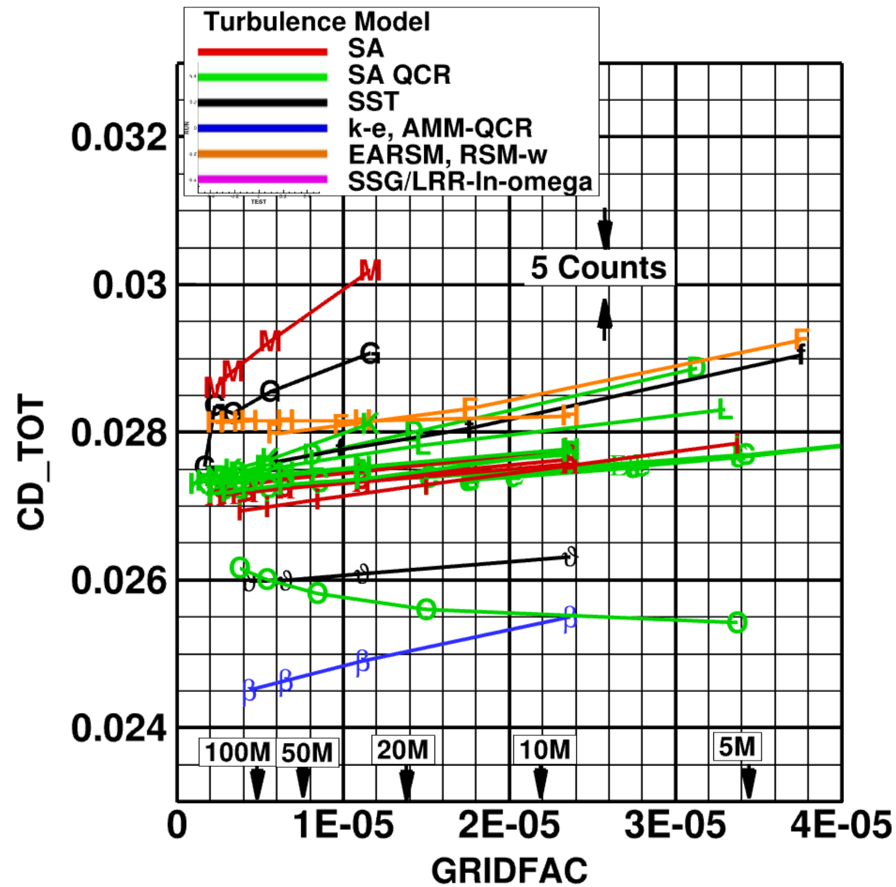
Richardson Extrapolation:

- Standard 2nd order least squares fit
- For 2nd order codes, should be linear vs. Grid_Factor = $N^{-2/3}$
- Y-intercept estimates theoretical infinite resolution (continuum) result

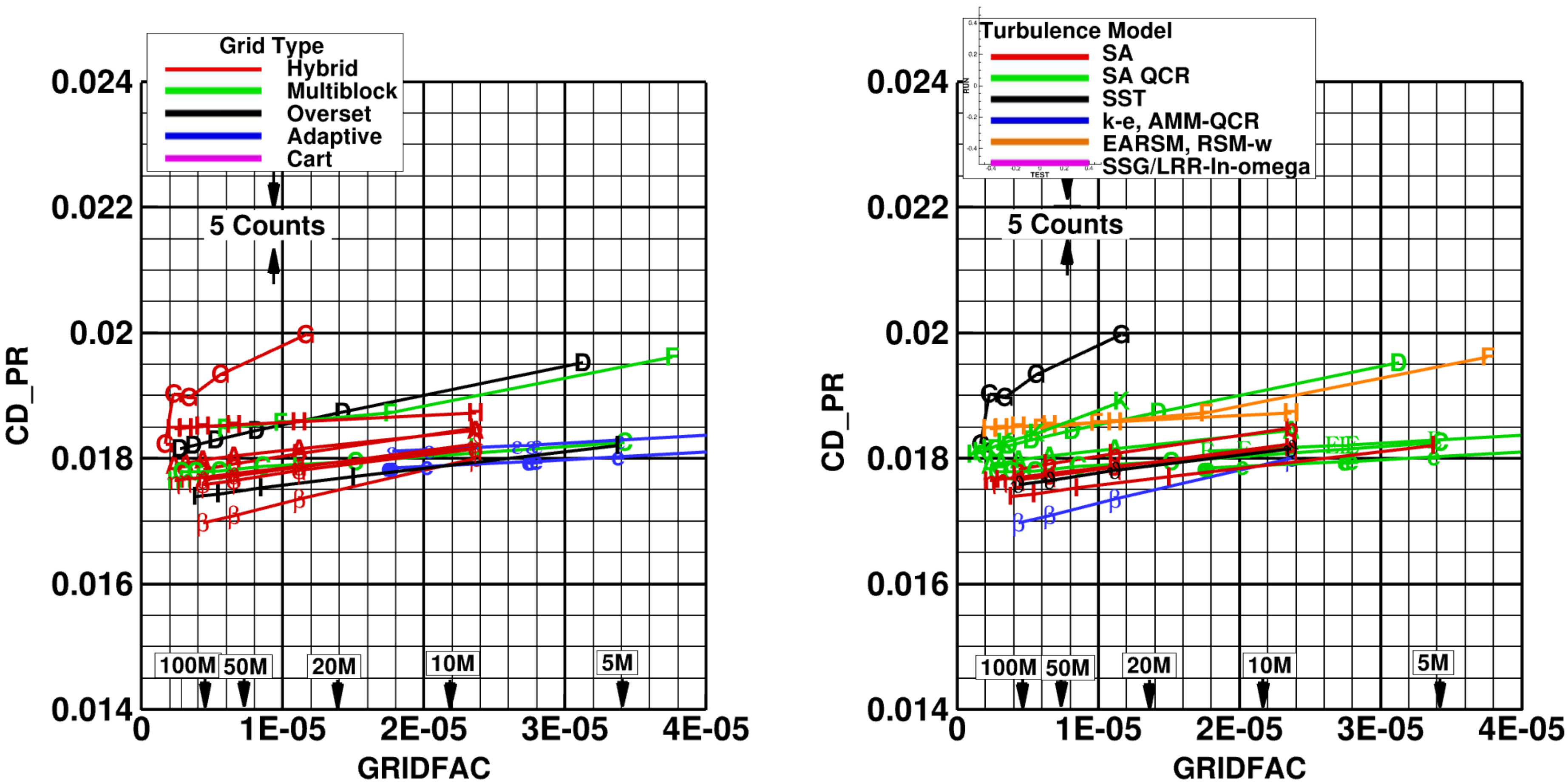


Case 1: CD_T (Total) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 20M

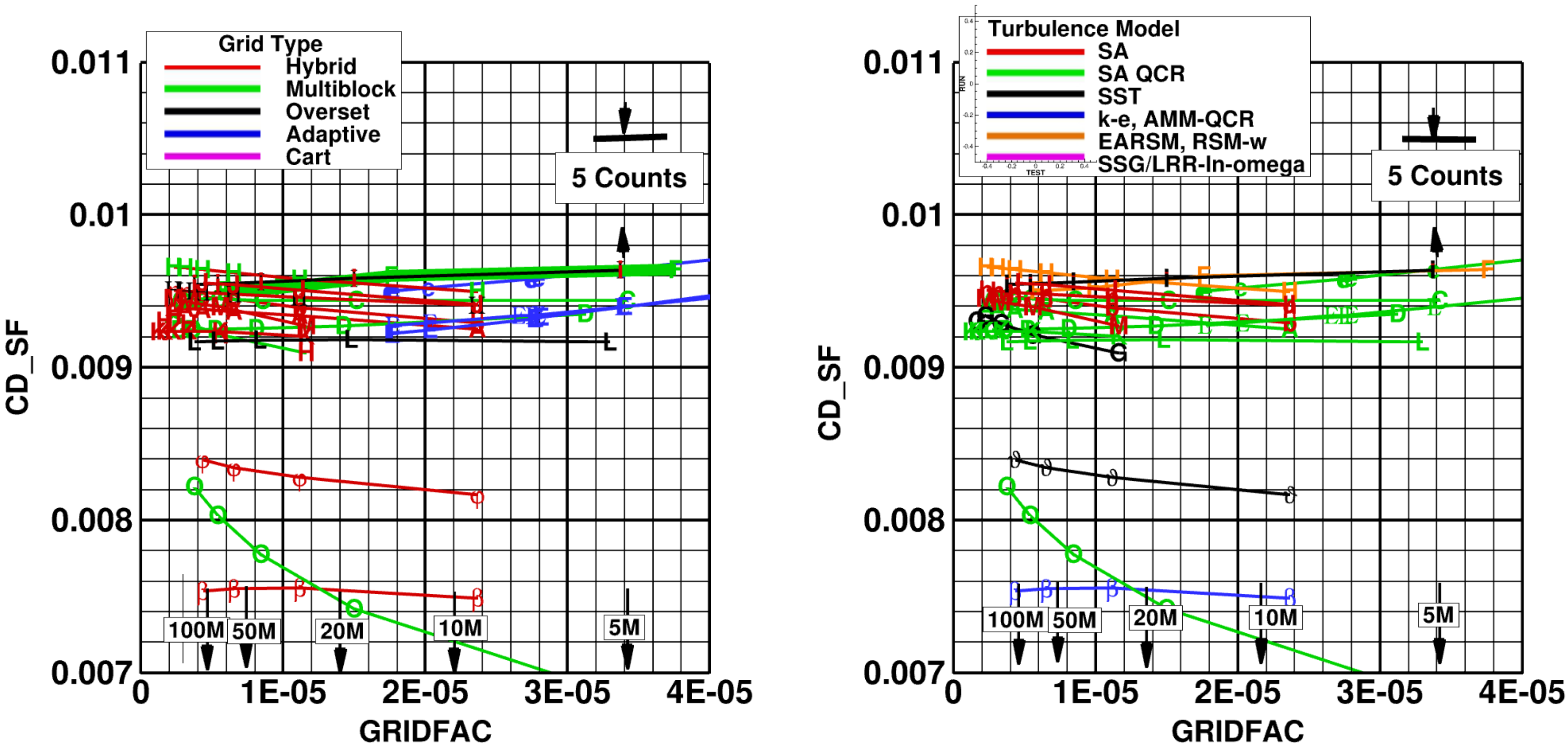




Case 1: CD_PR (Pressure Drag) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 20M



Case 1: CD_SF (Skin Friction) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 20M



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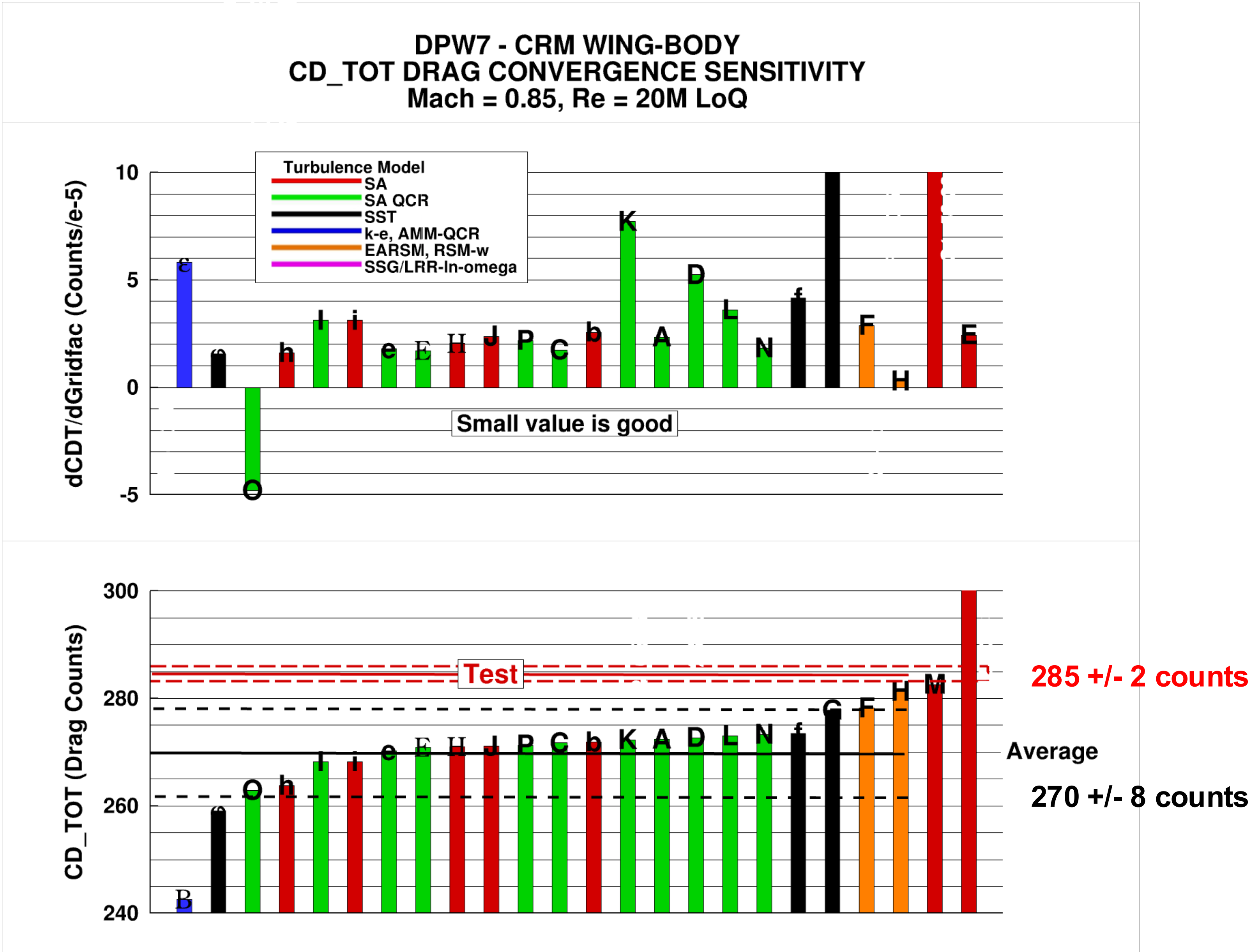
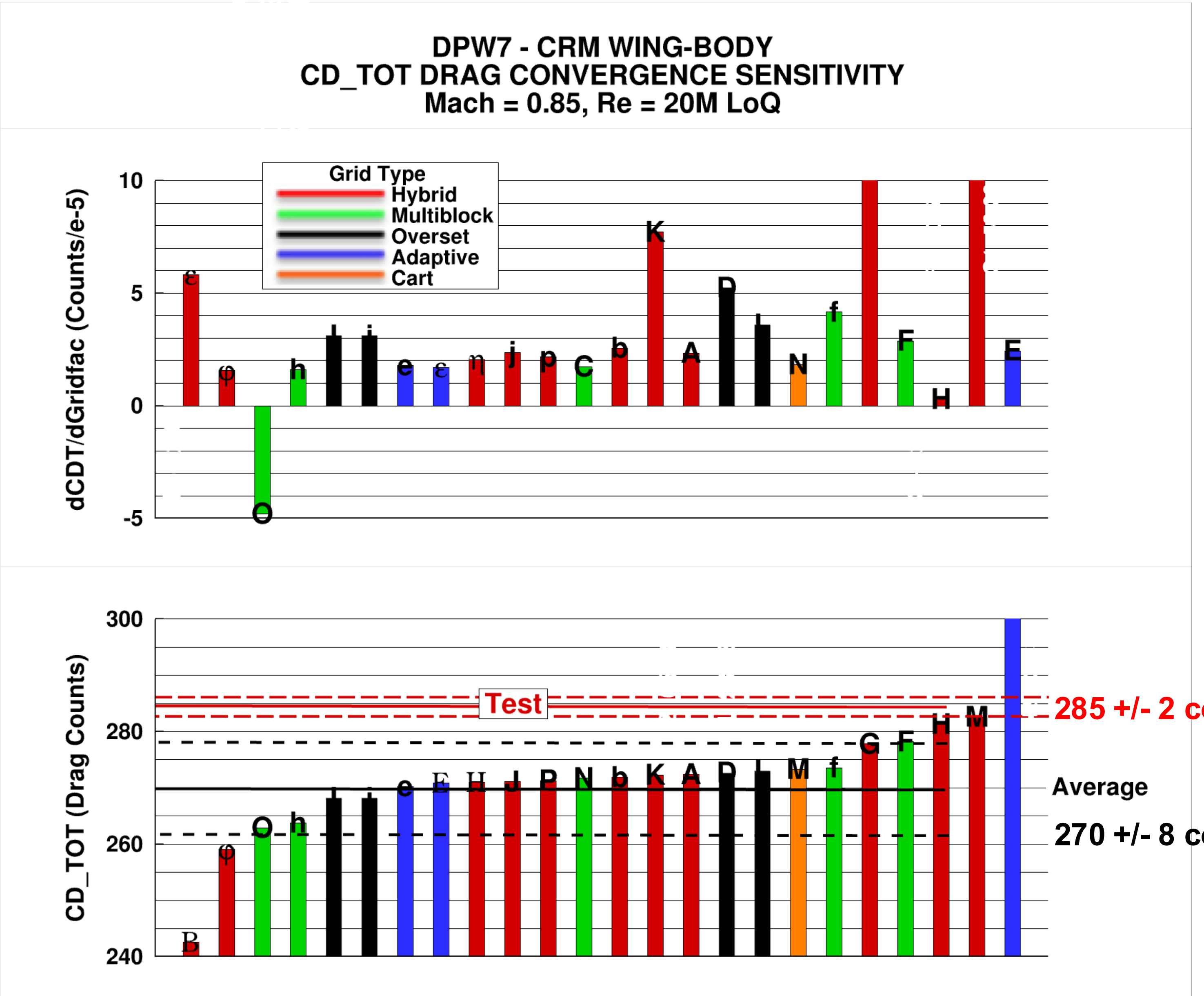
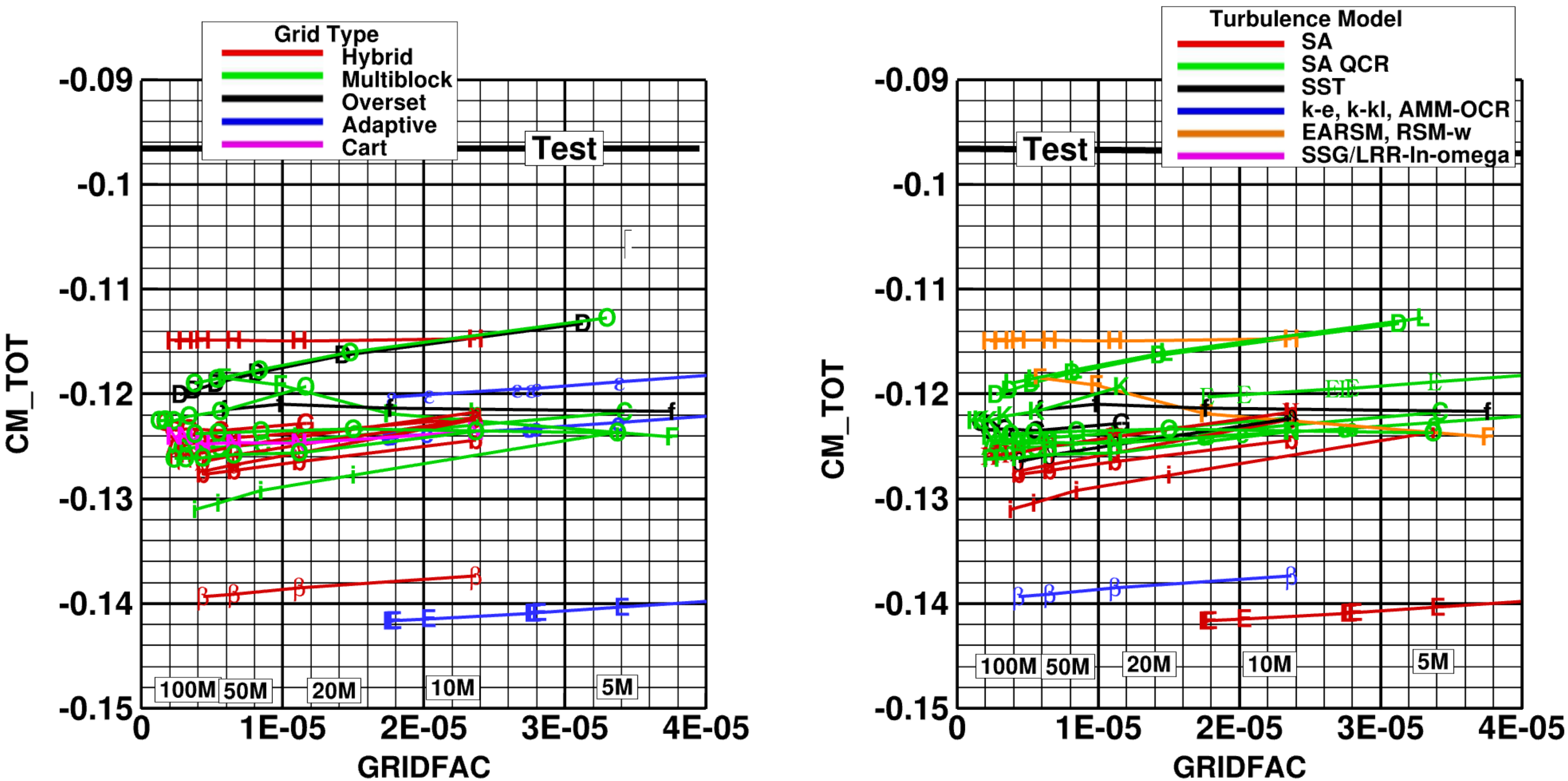



DPW7 - CRM WING-BODY
CD_TOT DRAG CONVERGENCE SENSITIVITY
Mach = 0.85, Re = 20M LoQ
Grid Type
Hybrid
Multiblock
Overset
Adaptive
Cart
dCDT/dGridfac (Counts/e-5)
10
5
0
-5
CD_TOT (Drag Counts)
300
280
260
240
Test
285 +/- 2 counts
Average
270 +/- 8 counts

Case 1: CM_T Grid Convergence
Mach = 0.85, CL = 0.58
Re = 20M



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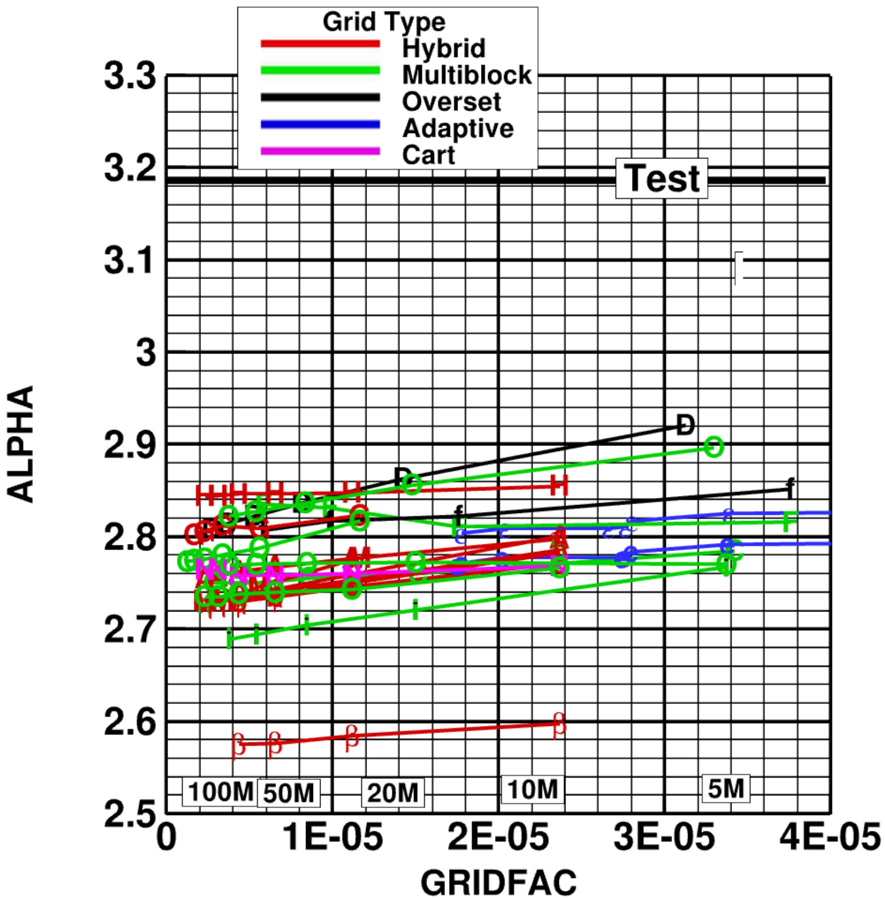
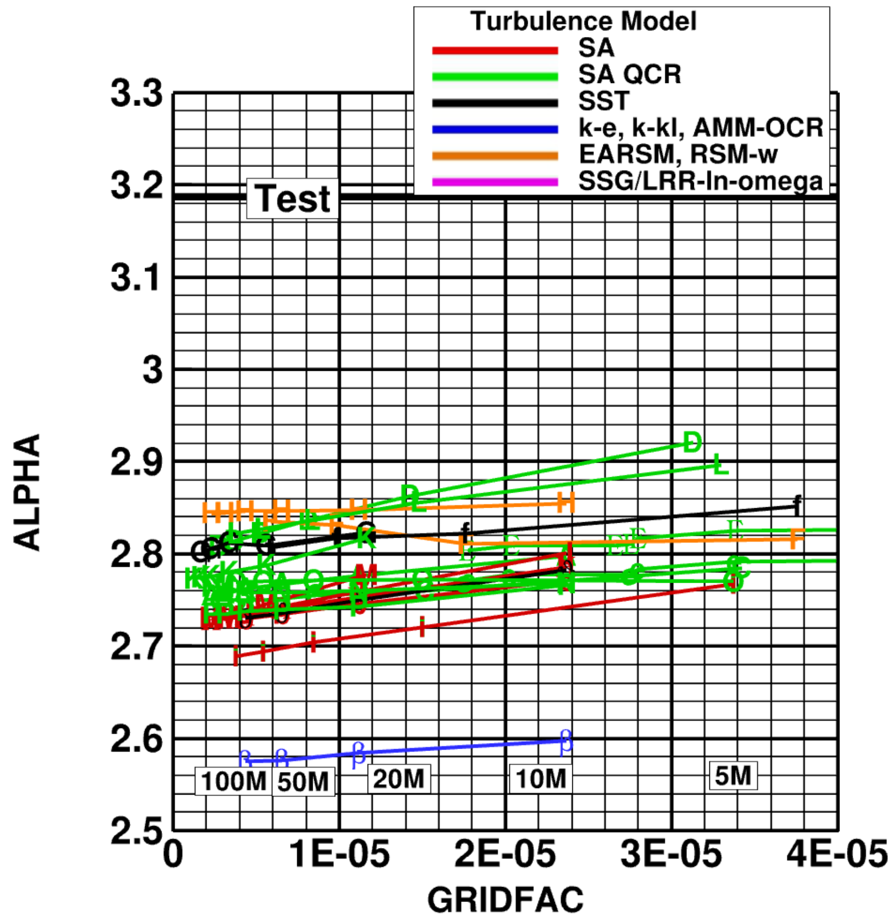
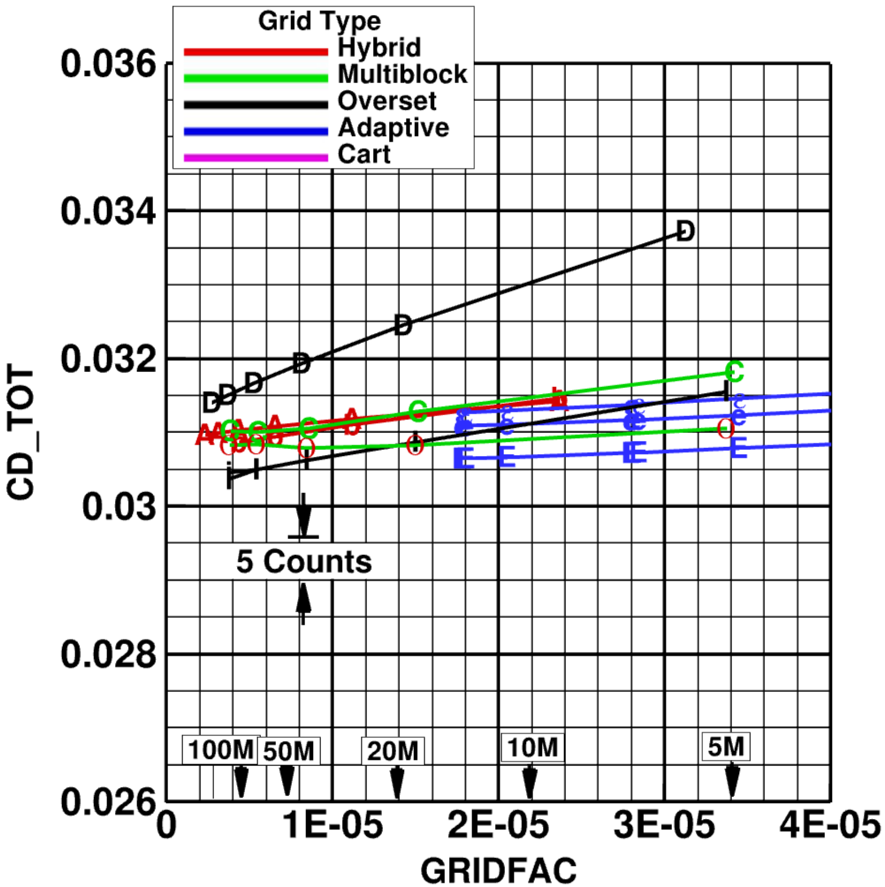
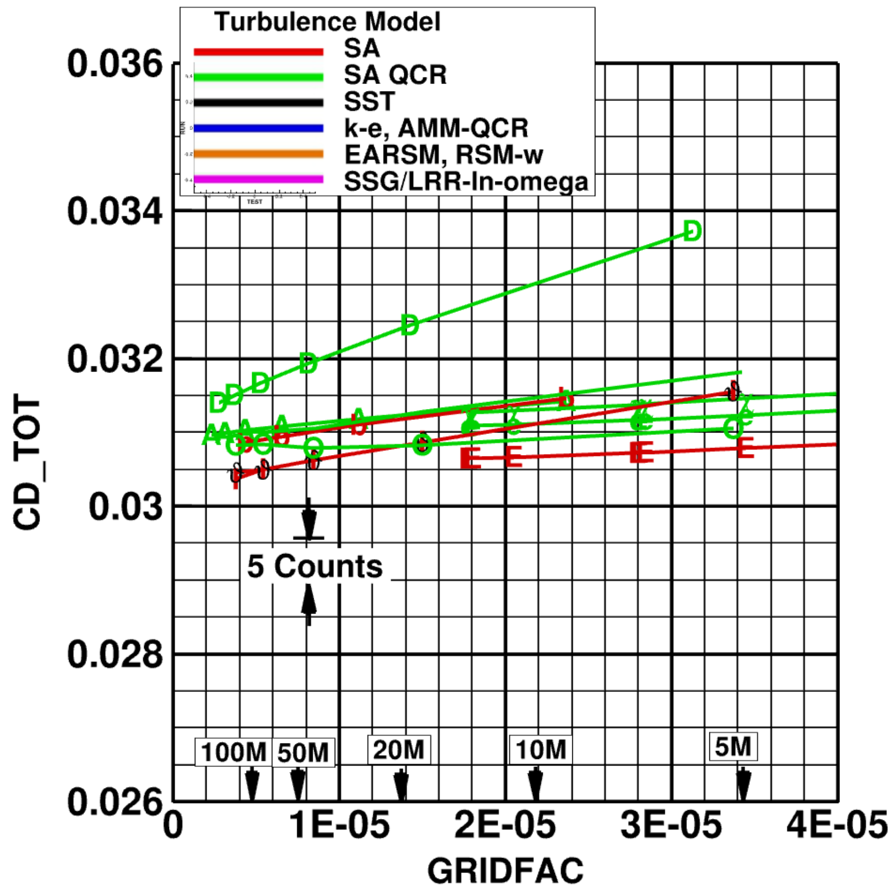
Case 1: AOA Grid Convergence
Mach = 0.85, CL = 0.58
Re = 20M

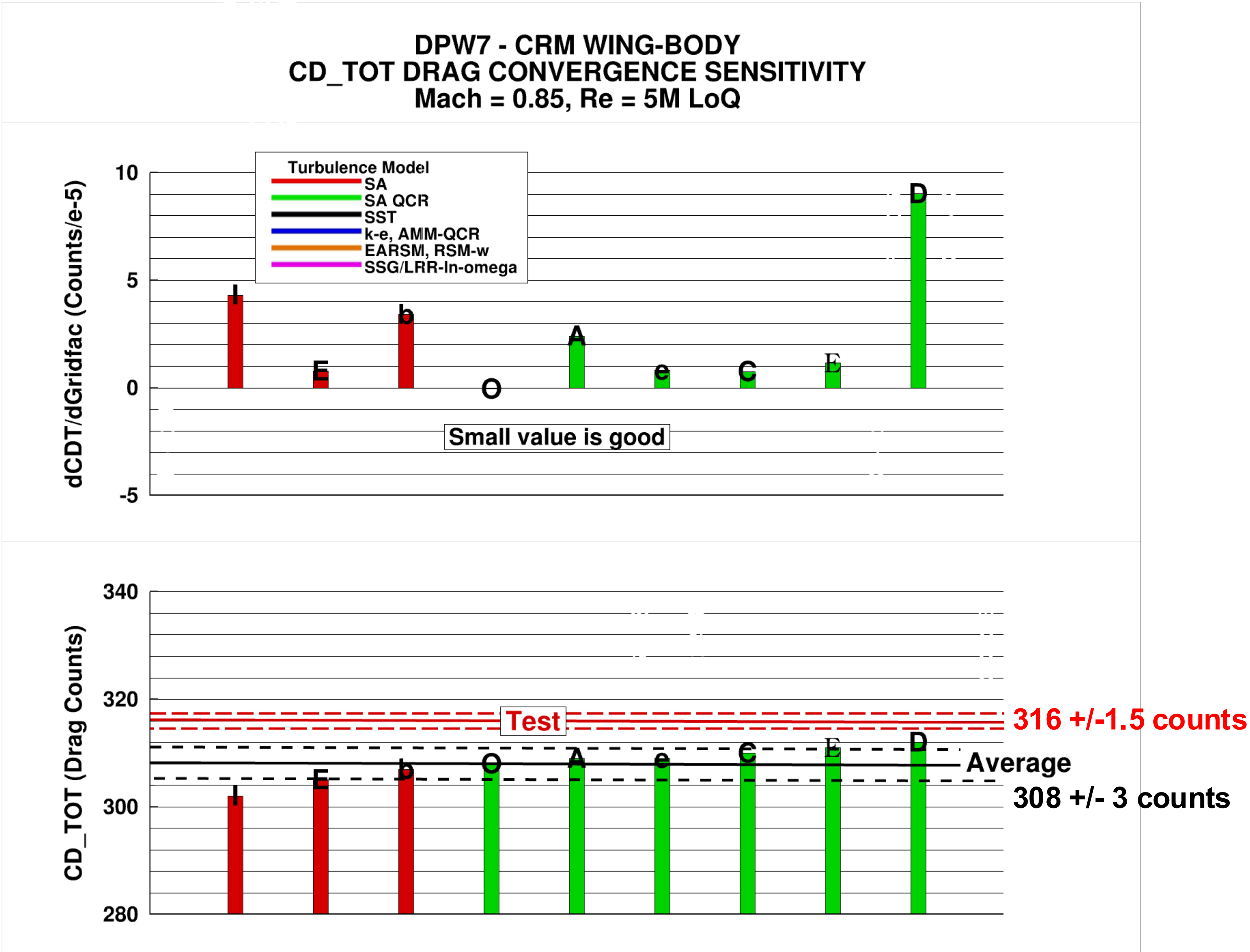


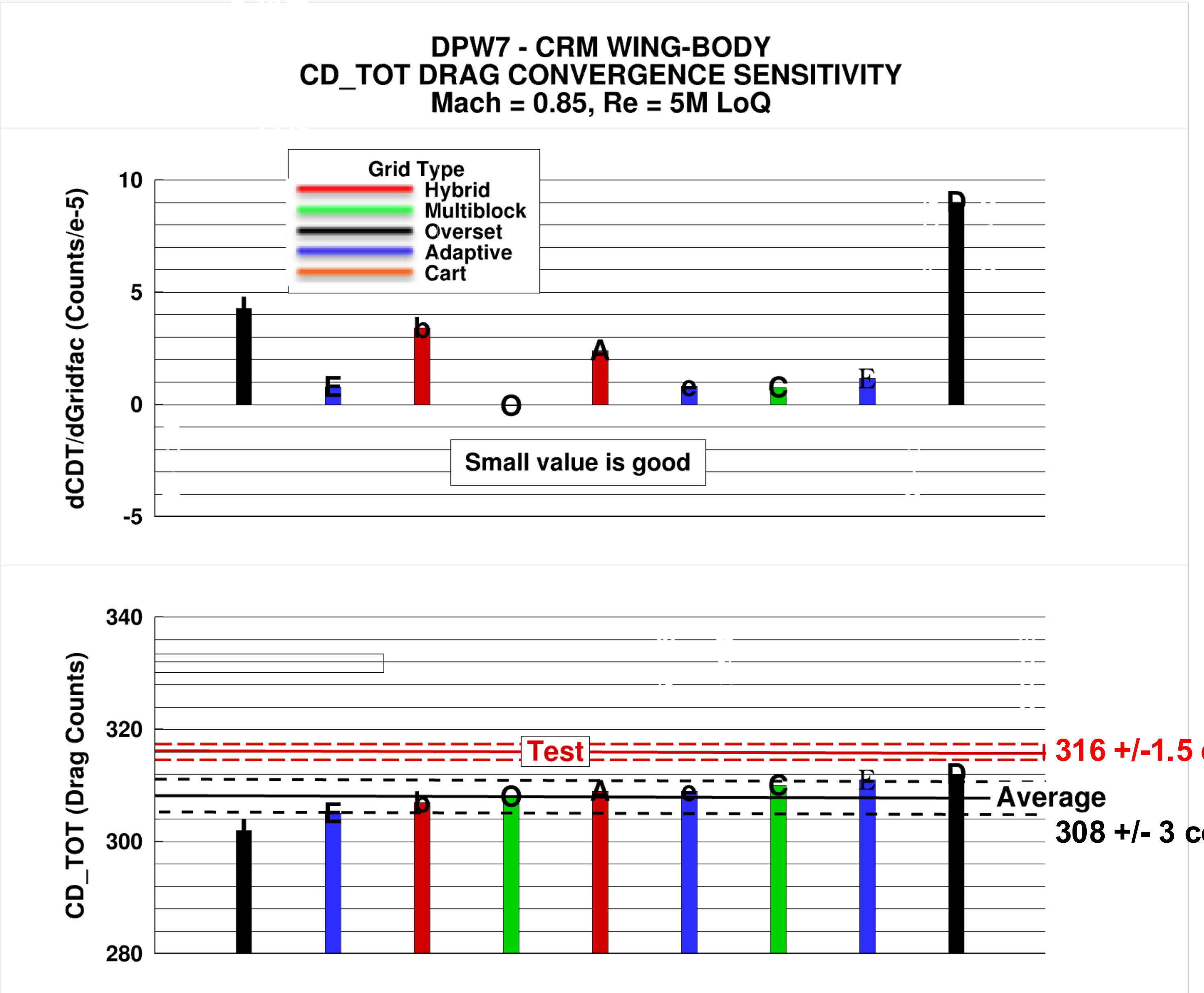


Case 1: CD_T (Total) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 5M

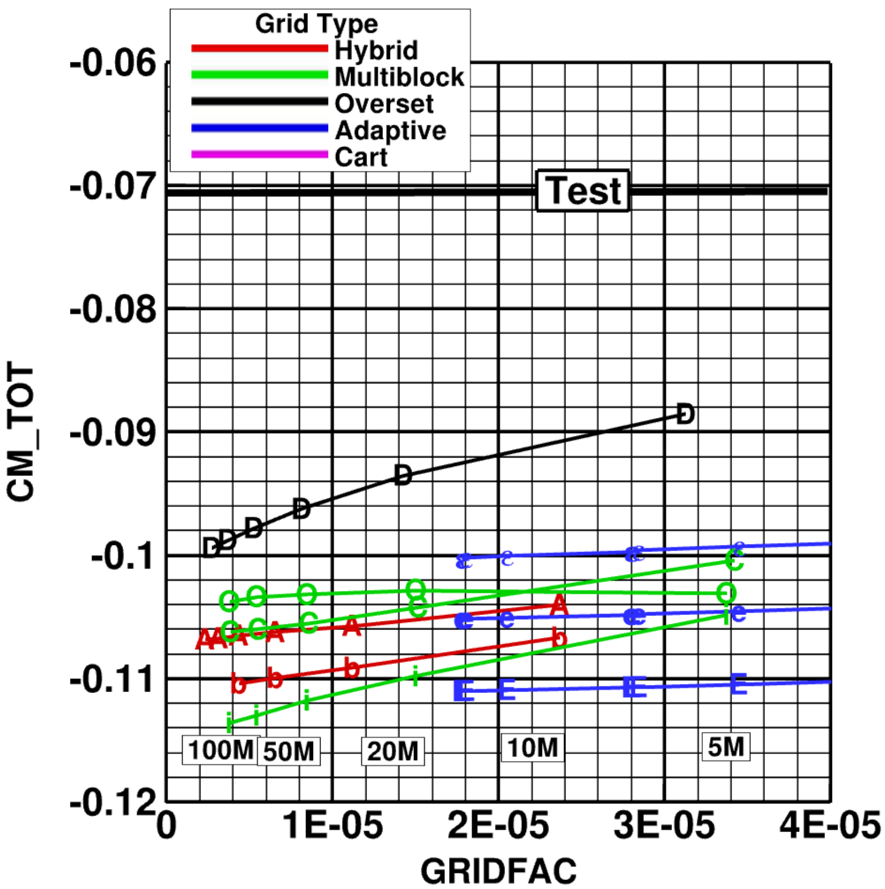


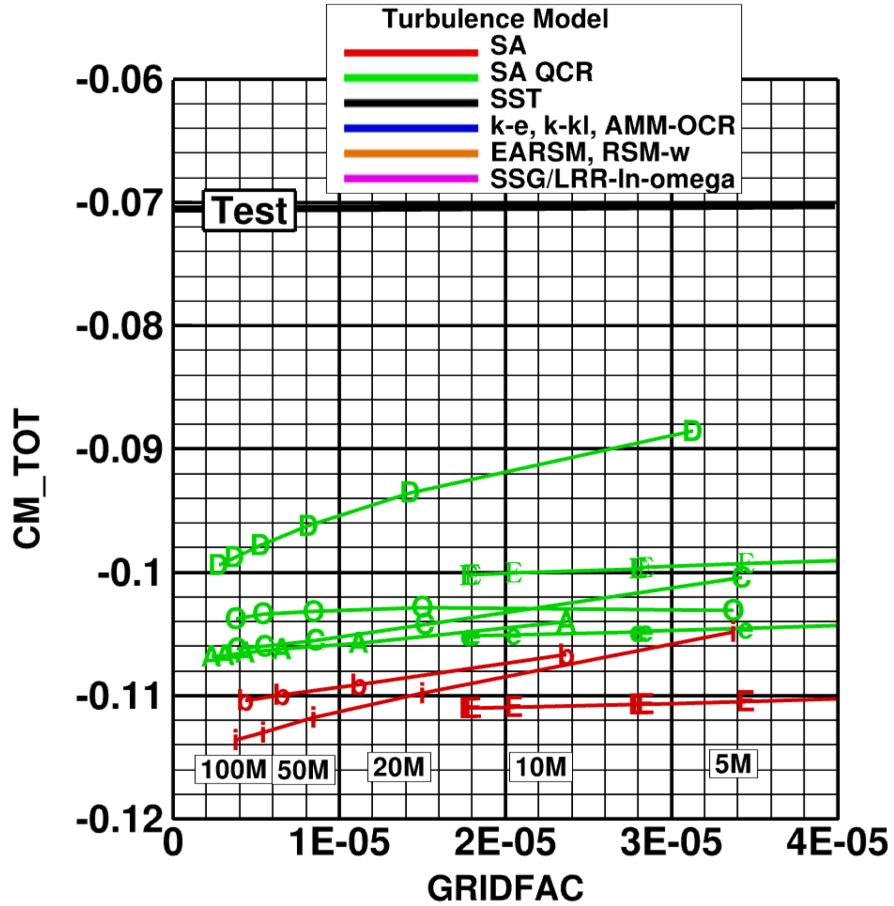



DPW7 - CRM WING-BODY
CD_TOT DRAG CONVERGENCE SENSITIVITY
Mach = 0.85, Re = 5M LoQ
Turbulence Model
SA
SA QCR
SST
k-e, AMM-QCR
EARSM, RSM-w
SSG/LRR-ln-omega
dCDT/dGridfac (Counts/e-5)
10
5
0
-5
Small value is good
I
E
b
O
A
e
C
D
CD_TOT (Drag Counts)
340
320
300
280
Test
316 +/-1.5 counts
Average
308 +/- 3 counts

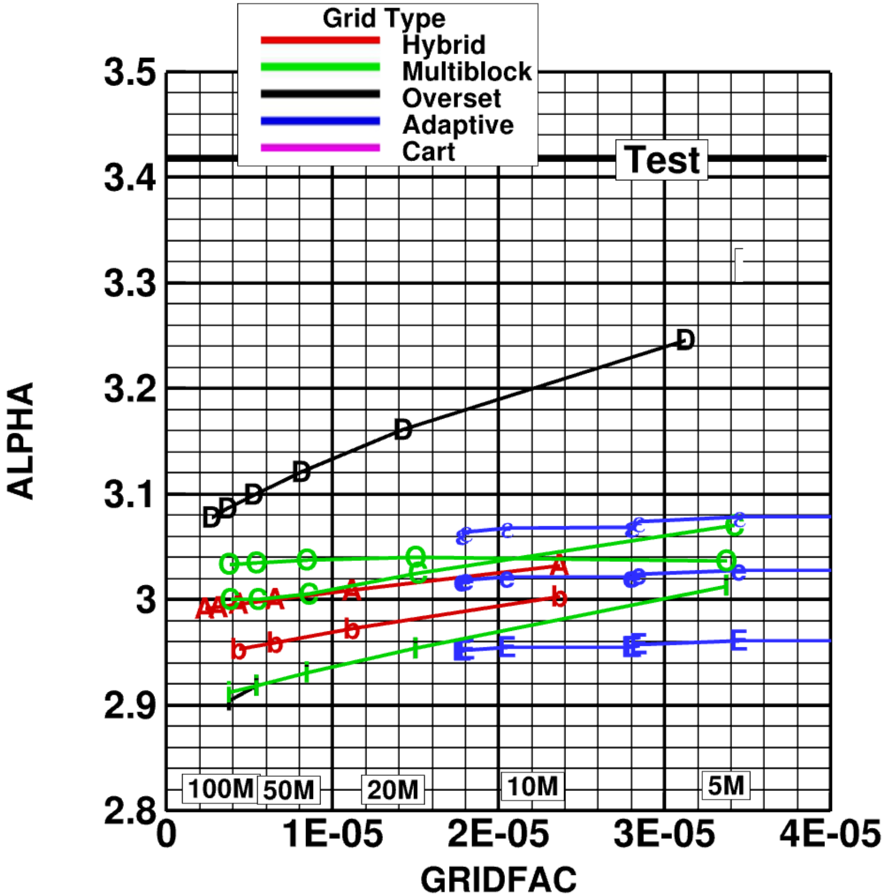

DPW7 - CRM WING-BODY
CD_TOT DRAG CONVERGENCE SENSITIVITY
Mach = 0.85, Re = 5M LoQ
Grid Type
Hybrid
Multiblock
Overset
Adaptive
Cart
dCDT/dGridfac (Counts/e-5)
10
5
0
-5
Small value is good
CD_TOT (Drag Counts)
340
320
300
280
Test
316 +/-1.5 counts
Average
308 +/- 3 counts

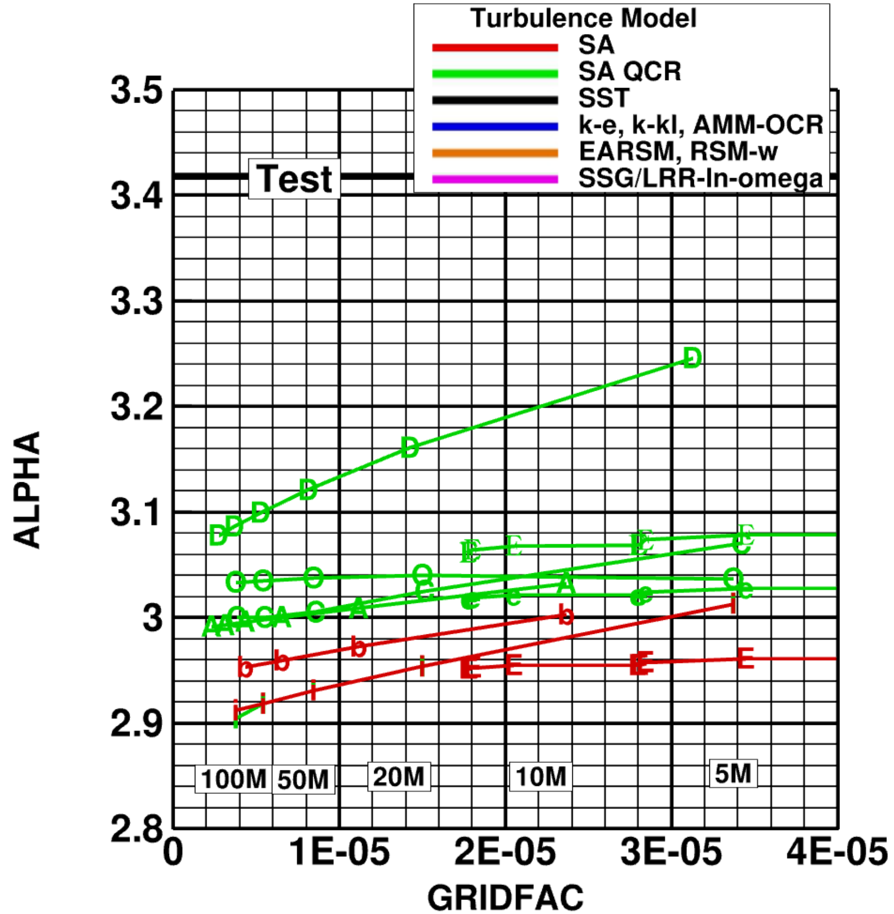
Case 1: CM_T Grid Convergence
Mach = 0.85, CL = 0.58
Re = 5M





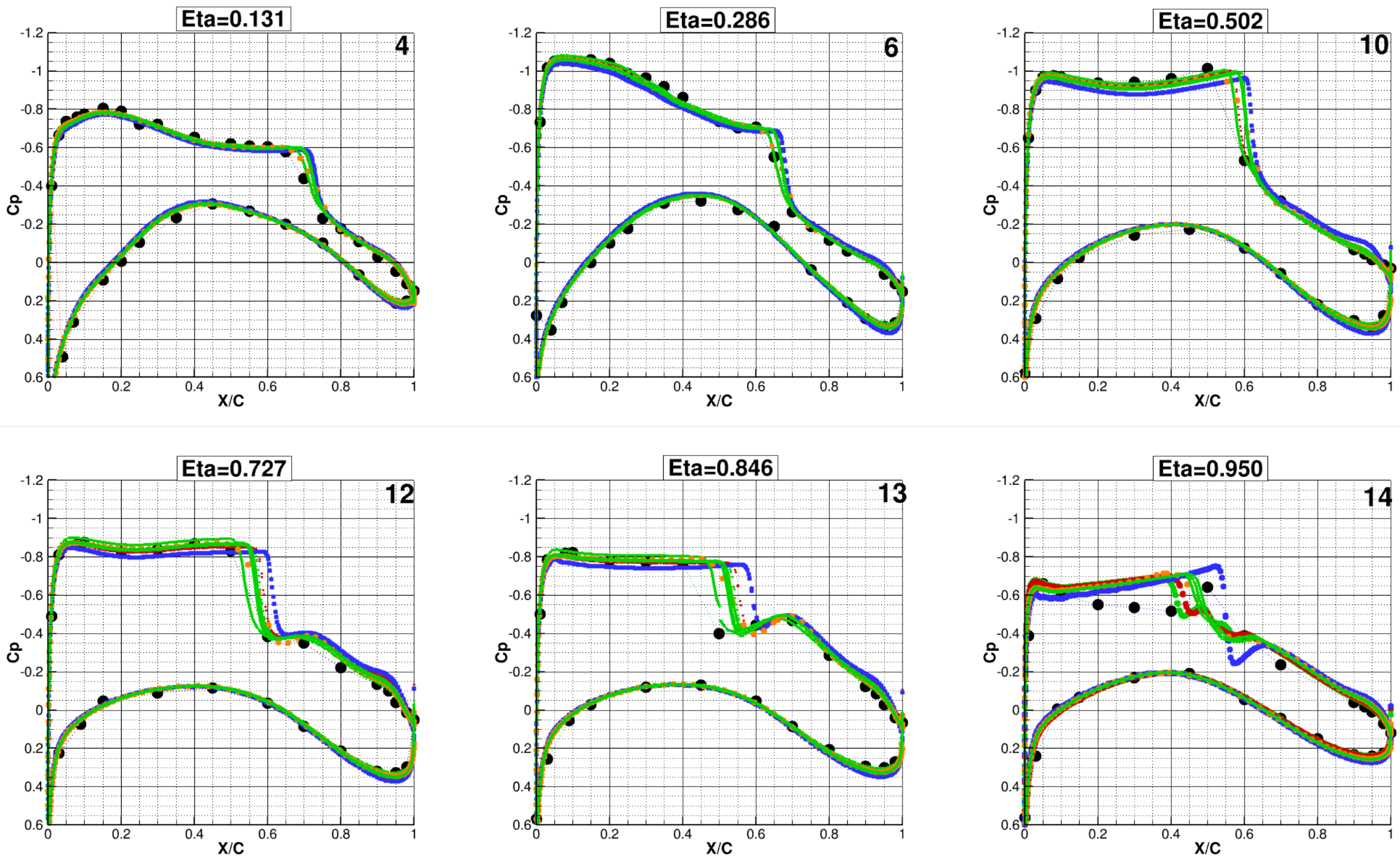
Case 1: AOA Grid Convergence
Mach = 0.85, CL = 0.58
Re = 5M

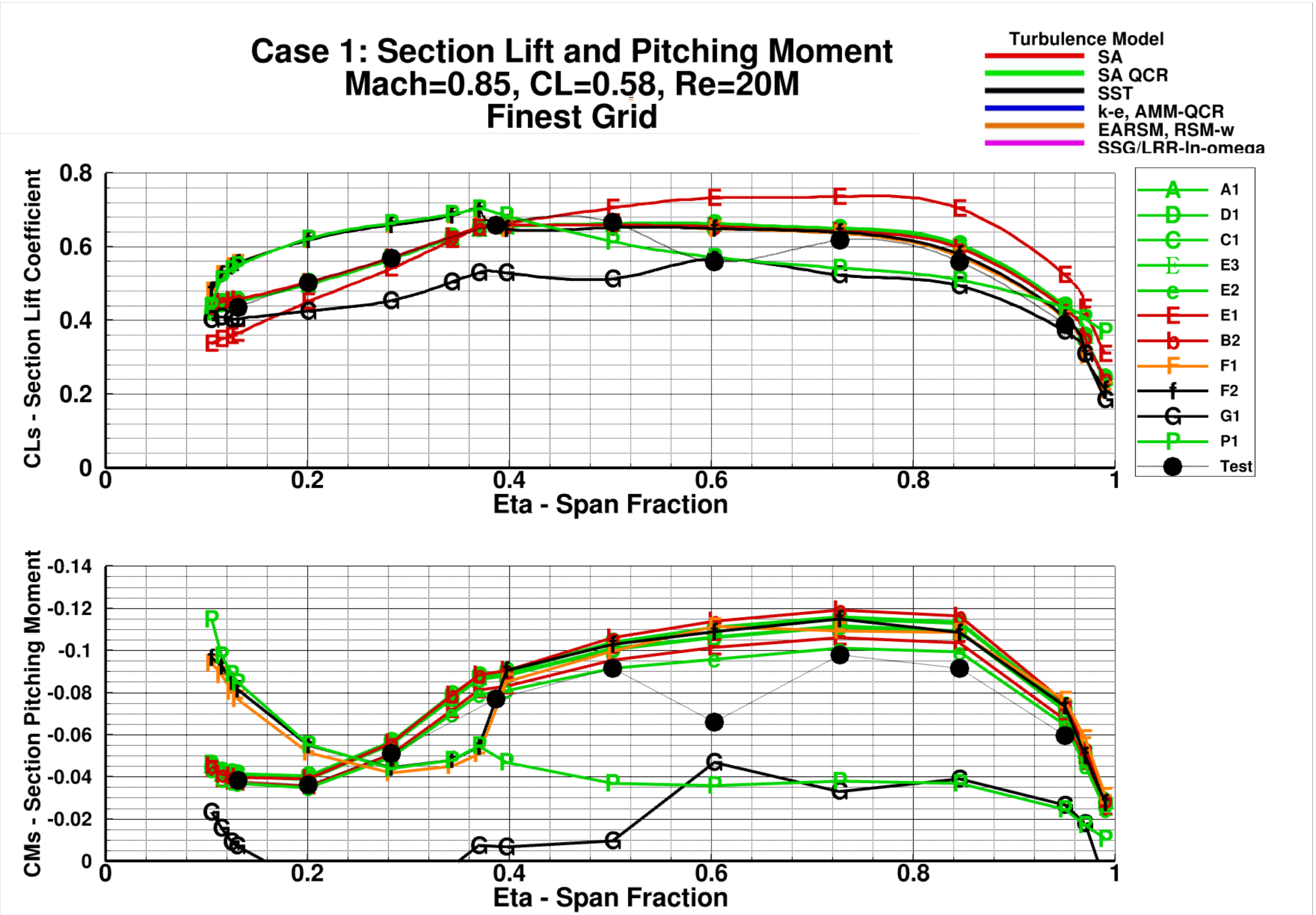




Case 1: Wing-Body Wing Pressue Distributions
Finest Grid
M=0.85, CL=0.58, Re=20M

Turbulence Model
- SA
- SA QCR
- SST
- k-e, AMM-OCR
- EARSM, RSM-w
- SSG/LRR-ln-omega




Case 1: Section Lift and Pitching Moment
Mach=0.85, CL=0.58, Re=20M
Finest Grid
Turbulence Model
SA
SA QCR
SST
k-e, AMM-QCR
EARSM, RSM-w
SSG/LRR-ln-omega
A1
D1
C1
E3
E2
E1
B2
F1
F2
G1
P1
Test
CLs - Section Lift Coefficient
Eta - Span Fraction
CMs - Section Pitching Moment
Eta - Span Fraction

Case 1 - Observations

- With very few exceptions solutions showed very good linear Richardson extrapolation.
- No clear break-outs with grid type or turbulence model AT THIS (ATTACHED FLOW) CONDITION!
- Excessive aft-loading on outboard wing sections contributes to too negative section pitching moments and excessive section lift (see Case 2).

Outline:

- Participant Data
- Case 1: Grid Convergence Study
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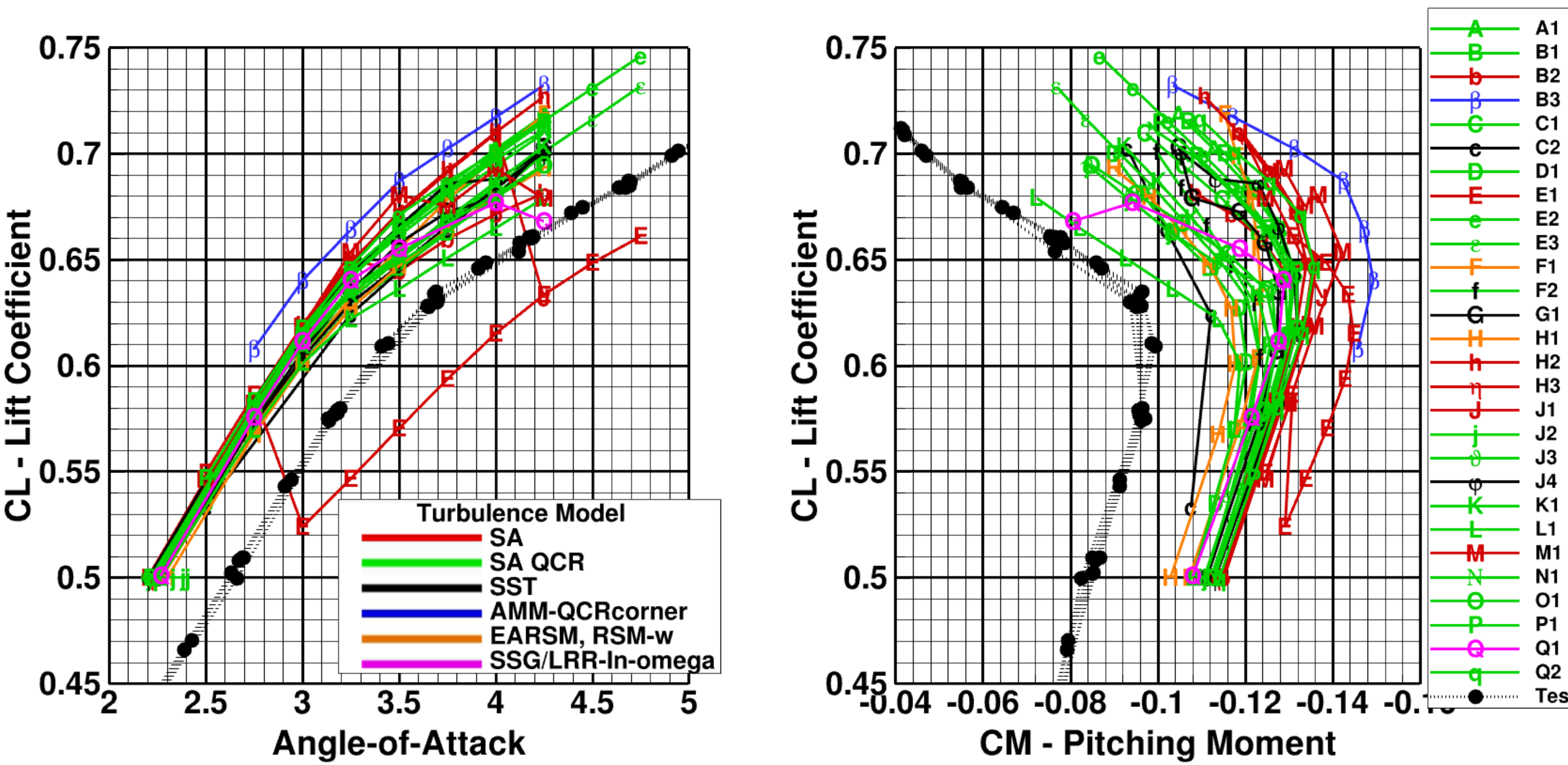
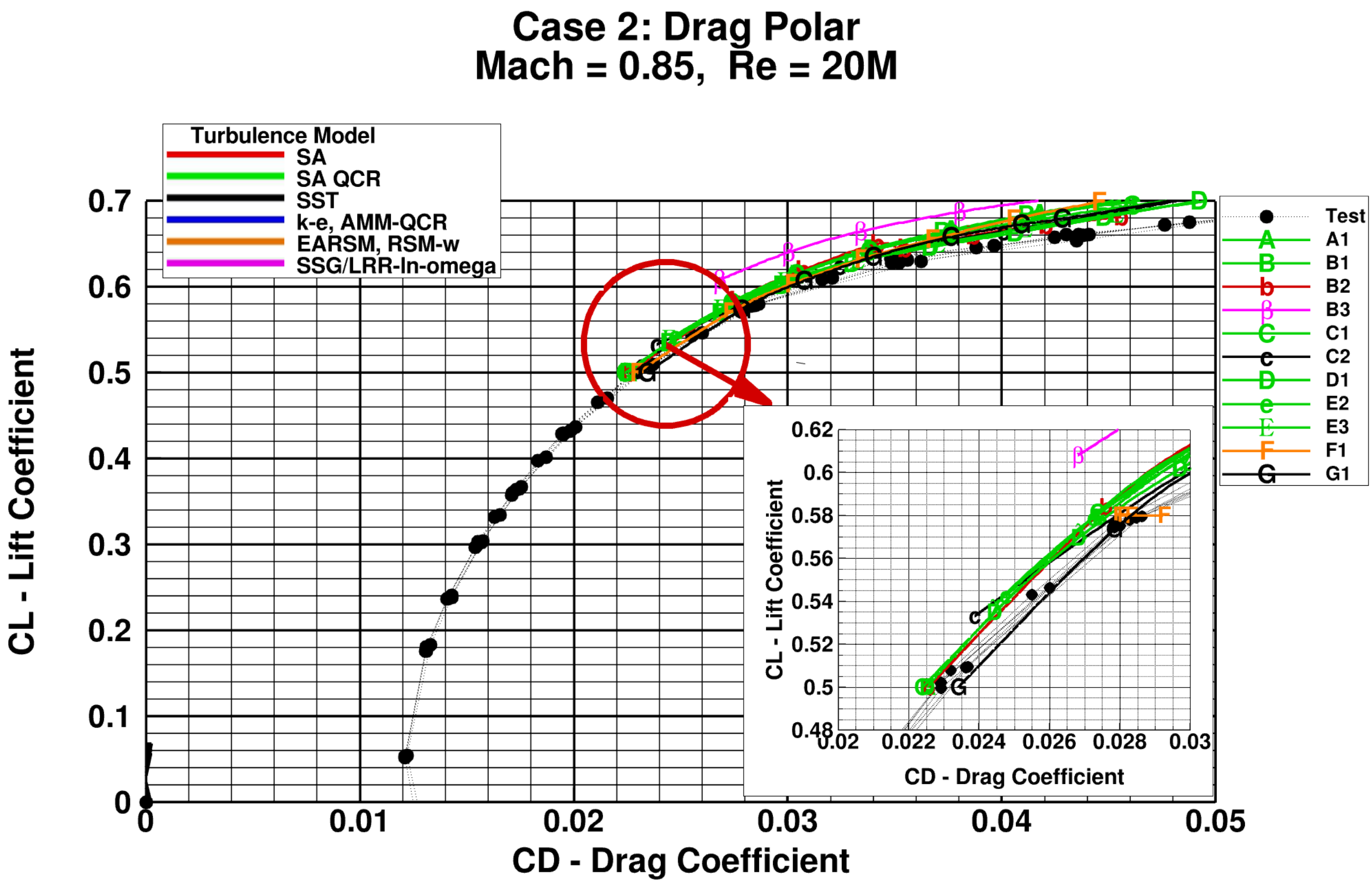
Case 2: Angle of Attack Sweep

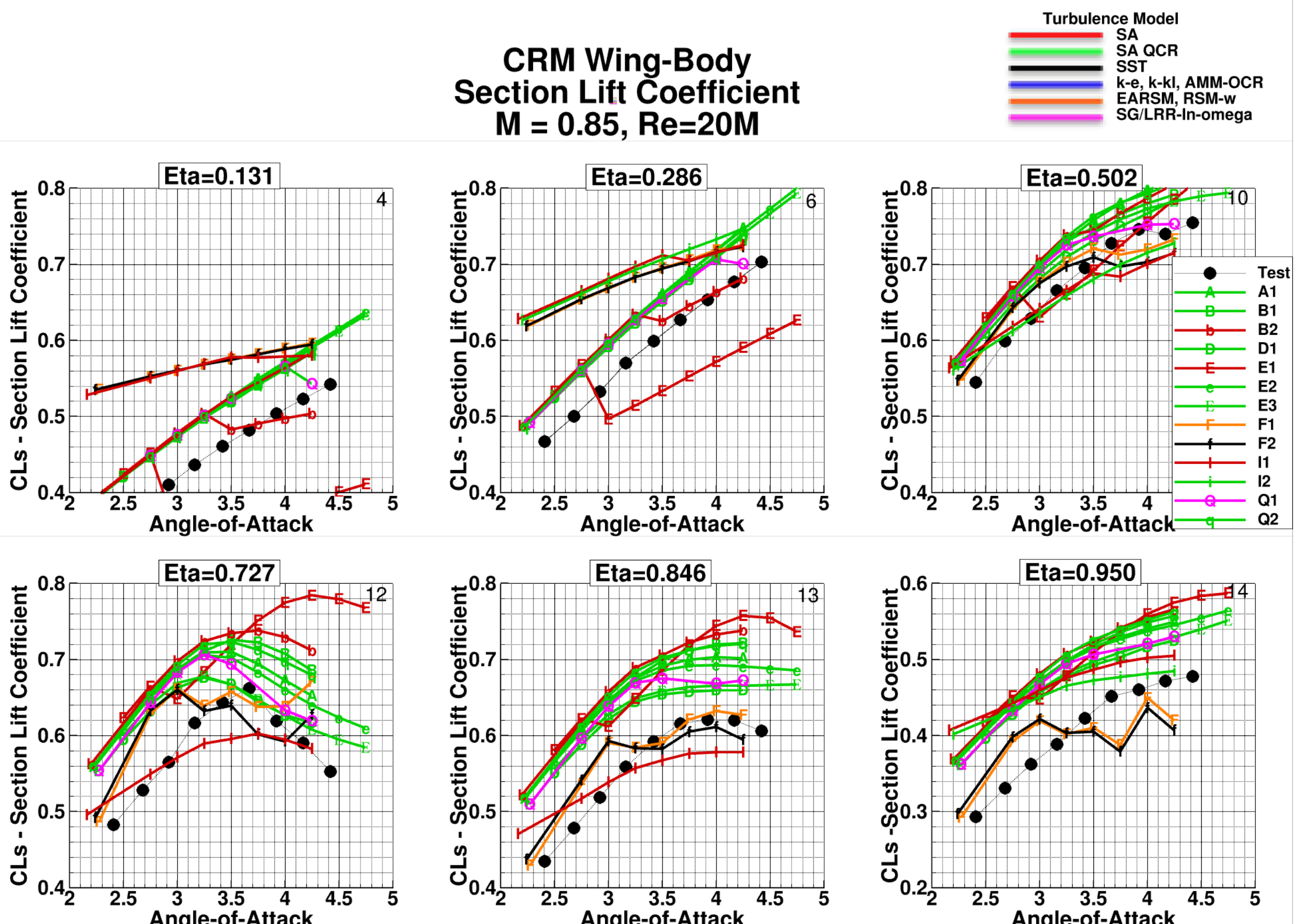
- NASA Common Research Model, Wing-Body
- Mach=0.85:
  - α=2.75 °, 3.00 °, 3.25 °, 3.50 °, 3.75 °, 4.00 °, 4.25°,
- Grid Resolution Level:
  - 3) Medium,
- Chord Reynolds Number: $20x10^6$, $5x10^6$ Optional
- Measured Static Aero-Elastic Wing Deformation at each angle of attack

Case 2: Lift and Pitching Moment
Mach = 0.85, Re=20M

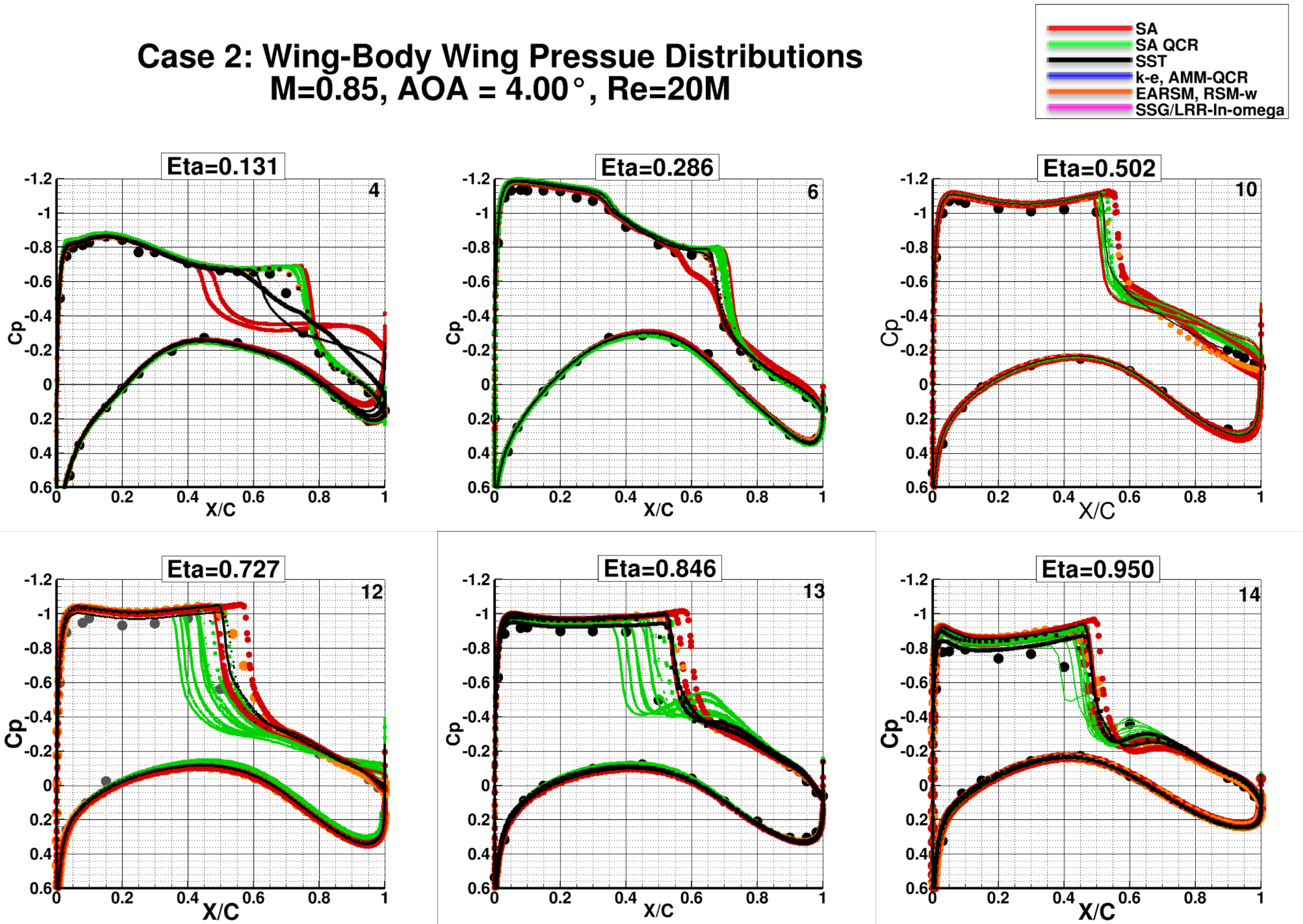



Case 2: Drag Polar
Mach = 0.85, Re = 20M
Turbulence Model
SA
SA QCR
SST
k-e, AMM-QCR
EARSM, RSM-w
SSG/LRR-ln-omega
Test
A1
B1
B2
B3
C1
C2
D1
E2
E3
F1
G1
CL - Lift Coefficient
CD - Drag Coefficient
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.01
0.02
0.03
0.04
0.05
0.48
0.5
0.52
0.54
0.56
0.58
0.6
0.62
0.022
0.024
0.026
0.028
0.03

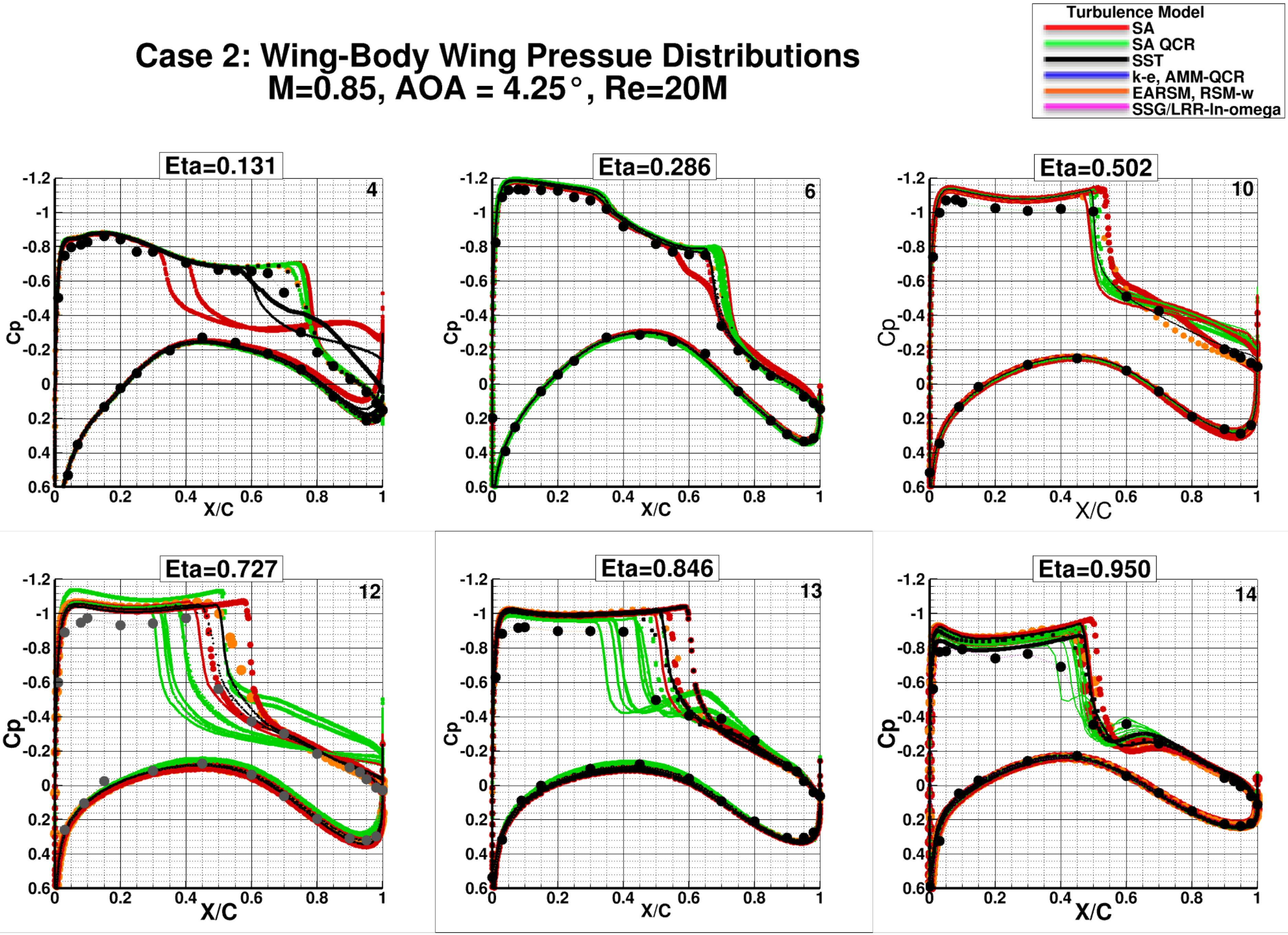
CRM Wing-Body
Section Lift Coefficient
M = 0.85, Re=20M



Case 2: Wing-Body Wing Pressue Distributions
M=0.85, AOA = 4.00°, Re=20M



Case 2: Wing-Body Wing Pressue Distributions
M=0.85, AOA = 4.25°, Re=20M



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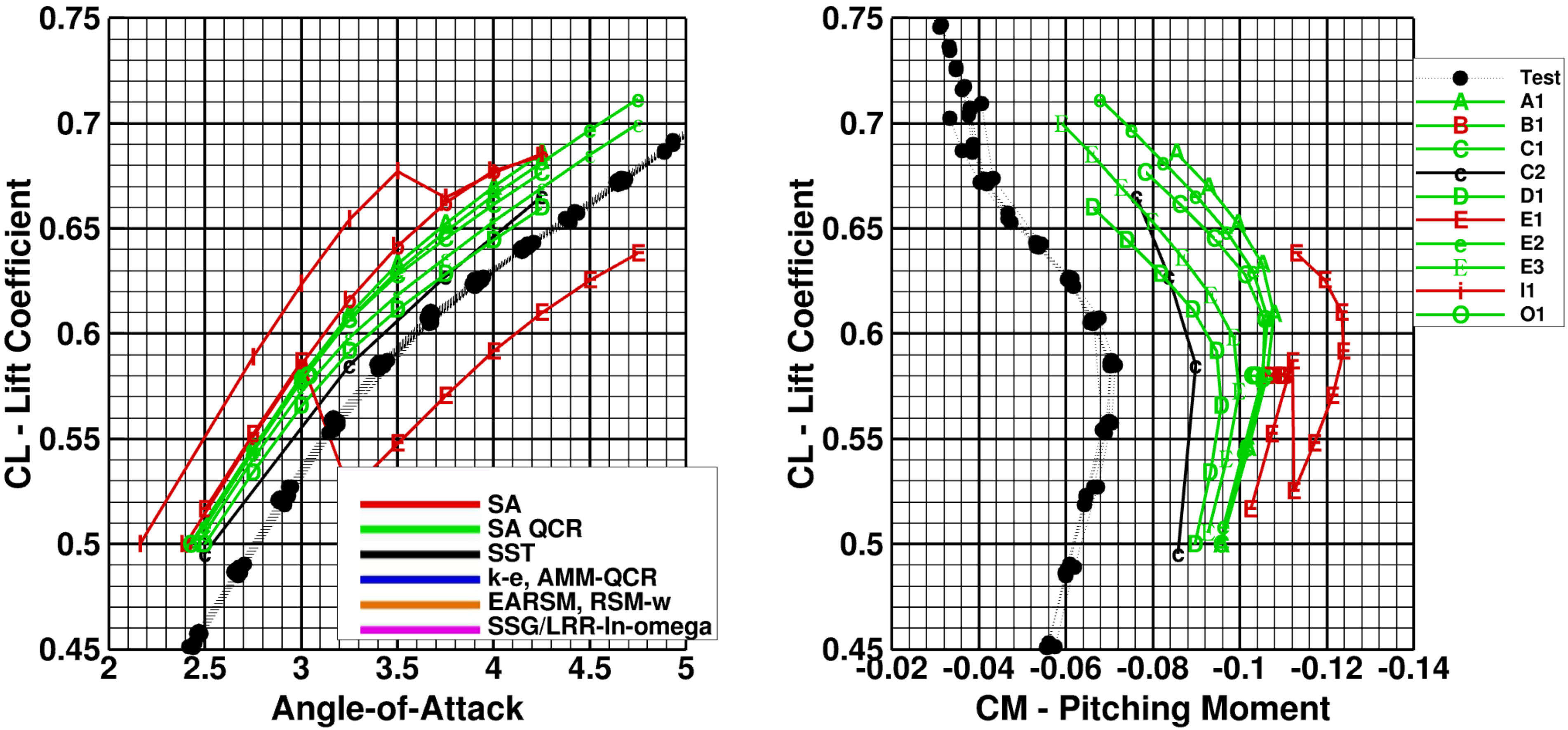
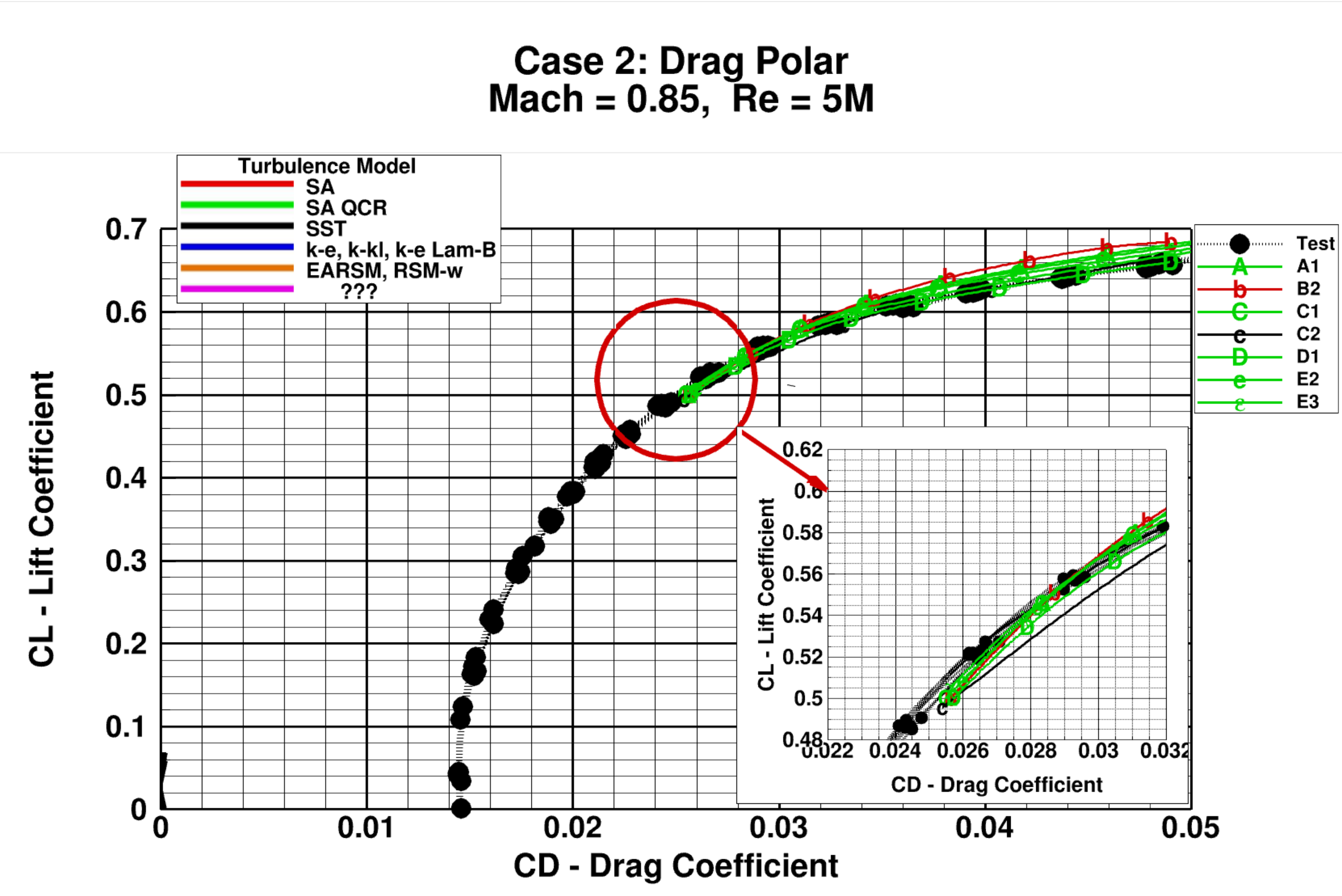
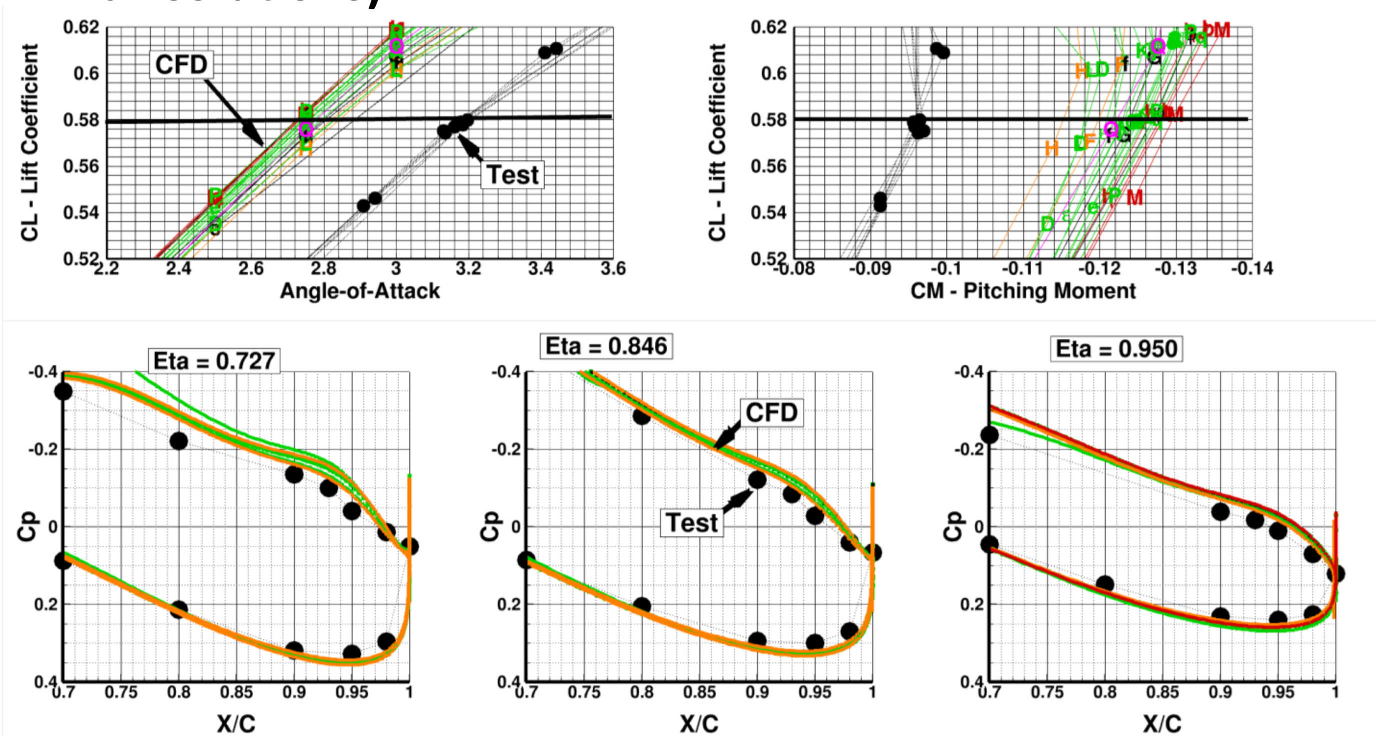
Case 2: Lift and Pitching Moment
Mach = 0.85, Re=5M




Case 2: Drag Polar
Mach = 0.85, Re = 5M
Turbulence Model
SA
SA QCR
SST
k-e, k-kl, k-e Lam-B
EARSM, RSM-w
???
Test
A1
B2
C1
C2
D1
E2
E3
CL - Lift Coefficient
CD - Drag Coefficient
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.02
0.03
0.04
0.05
0.62
0.58
0.56
0.54
0.52
0.48
0.022
0.024
0.026
0.028
0.032

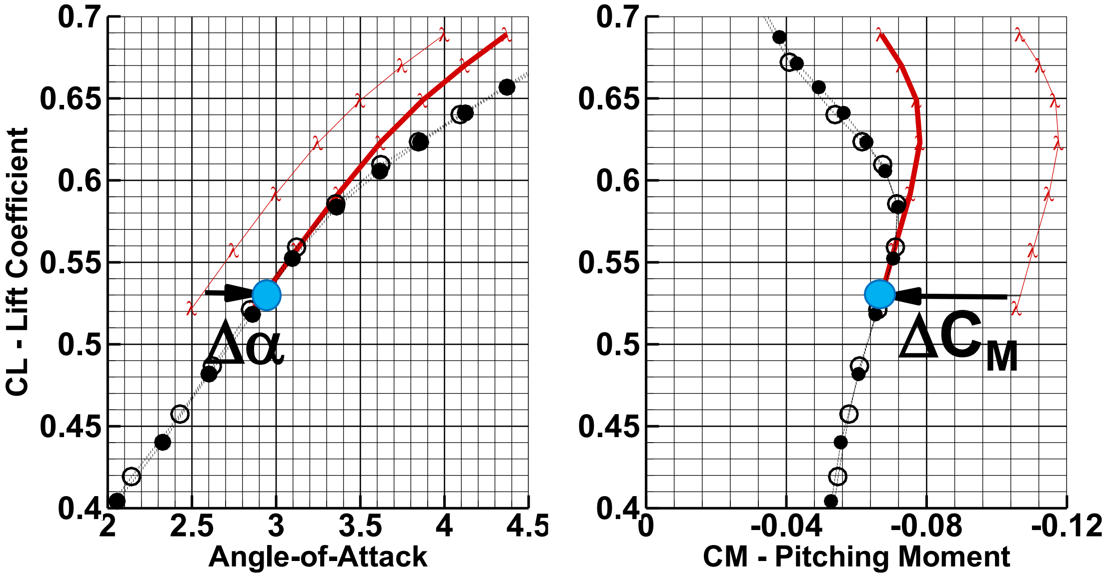
Excessive "Aft-Loading" results in higher lift and more negative pitching moment (common in all solutions)



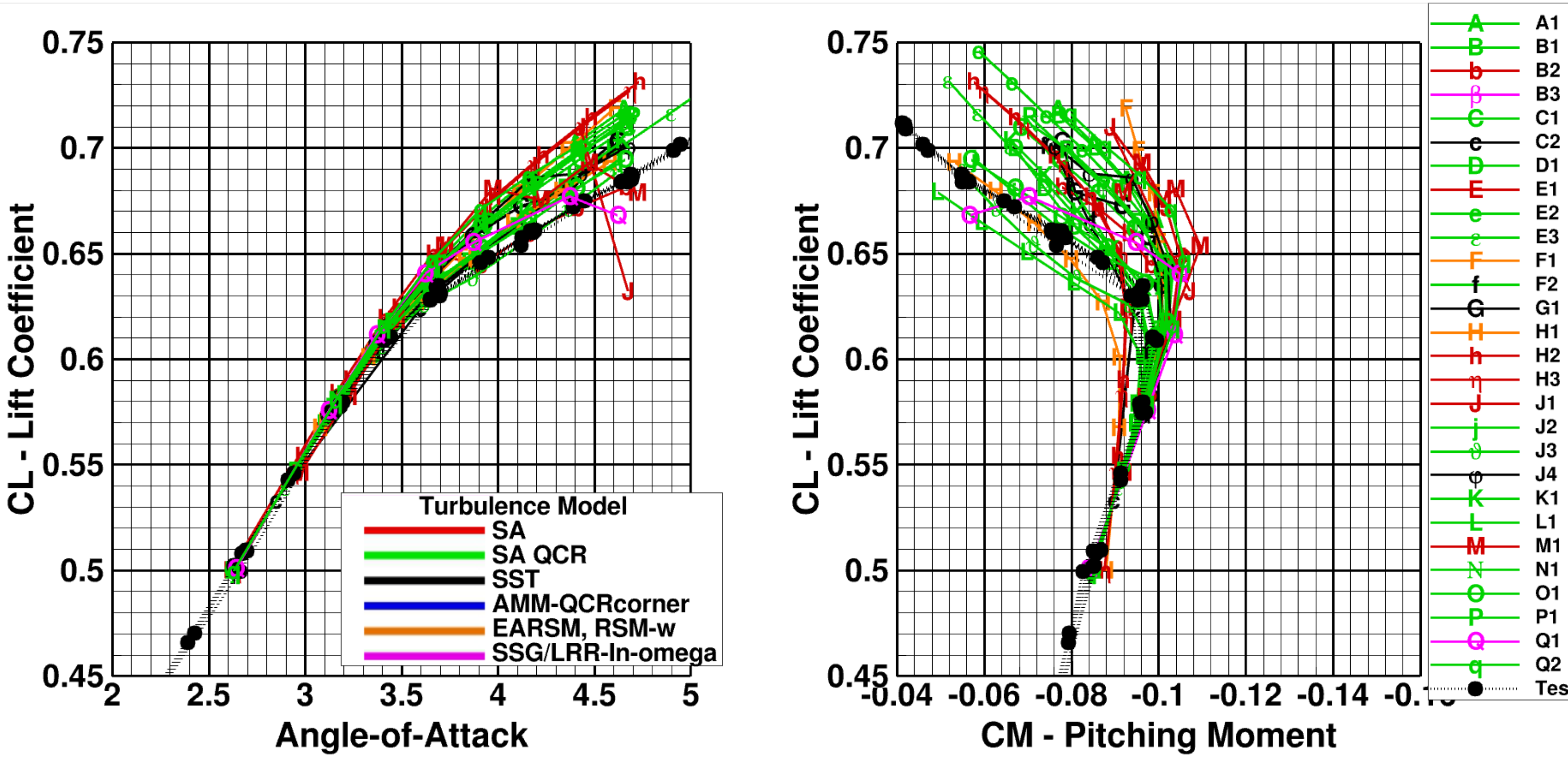
- Mounting system correction is too small to account for difference
- Paper by Curtin, M.M, Bogue, D.R., Om D., Rivers, S.M.B., Pendergraft, O.C., and Wahls, R. A., "Investigation of Transonic Reynolds Number Scaling on a Twin-Engine Transport (Invited)," AIAA-2002-0420, January 2002. suggested that excessive CFD "aft-loading" goes away with increasing Reynolds number

Collapsing CFD to a Common Value of α and C_M

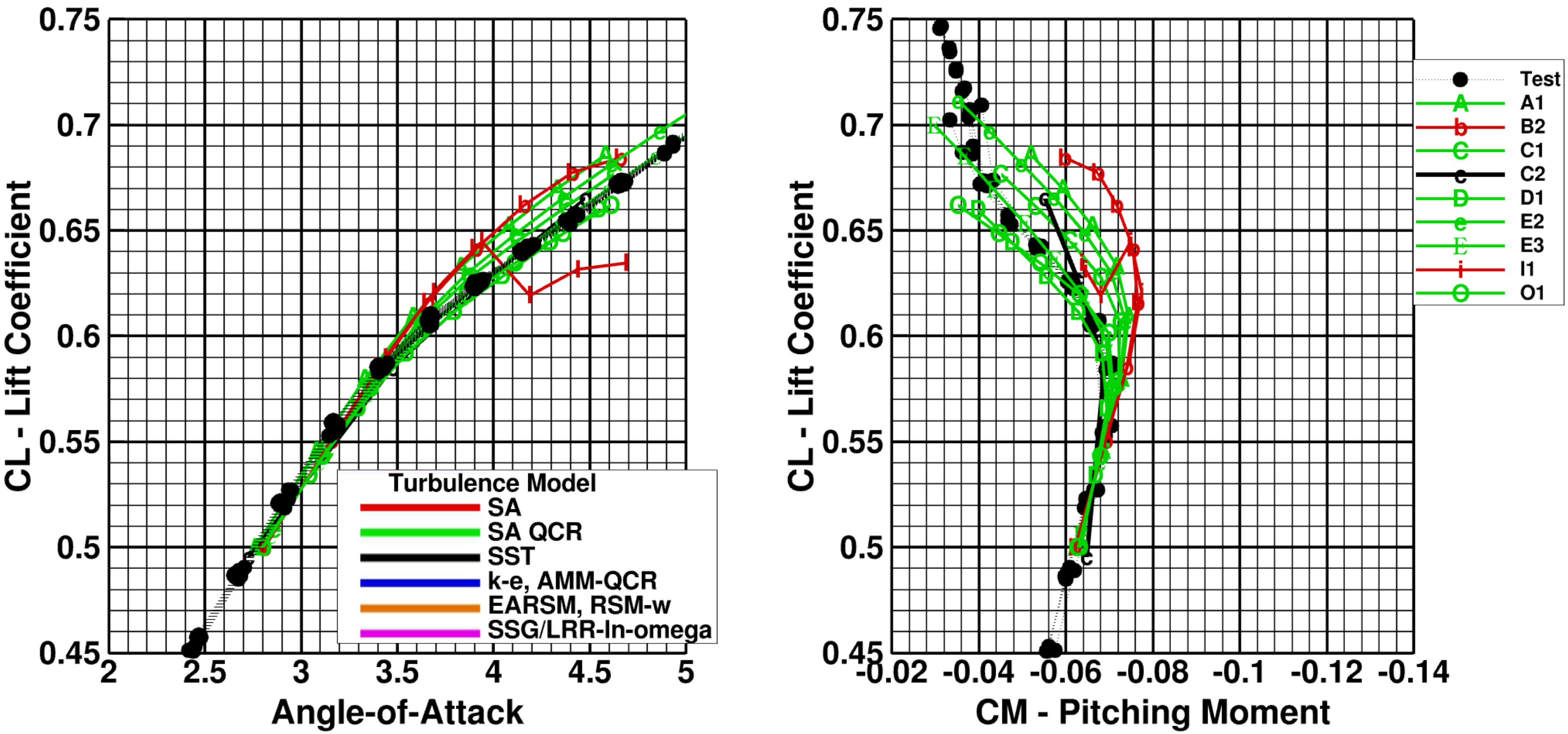
- CFD and WT are better at predicting increments than absolutes.
- Collapse CFD results to pass through a common point by adding a Δ angle-of-attack ($\Delta\alpha$) and Δ pitching moment (ΔC_M) to each solution.
- Clear view of C_L and C_M variation with α variation



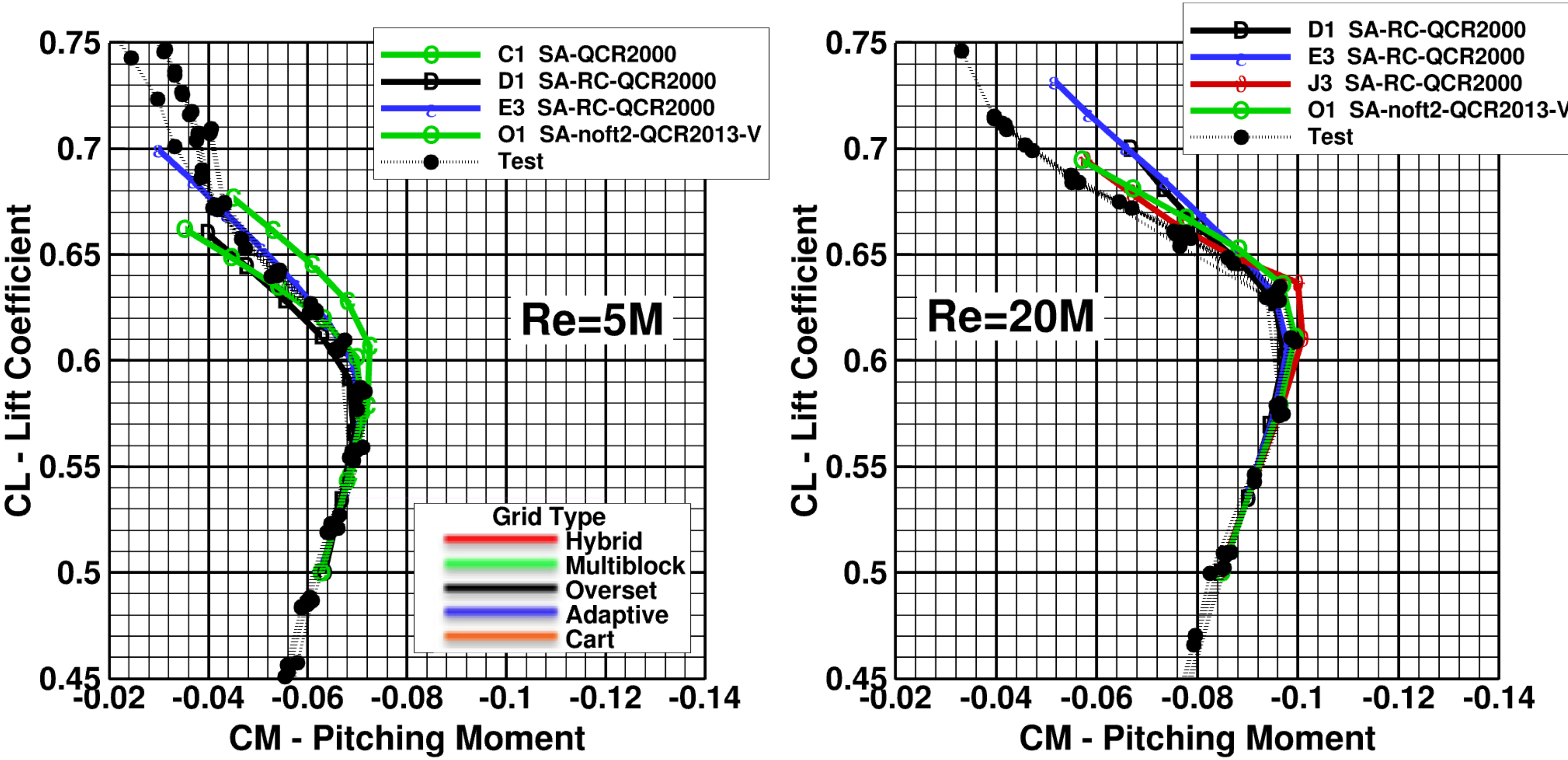
Case 2: Lift and Pitching Moment
Mach = 0.85, Re=20M
CFD Shifted to Match Test at CL=0.53

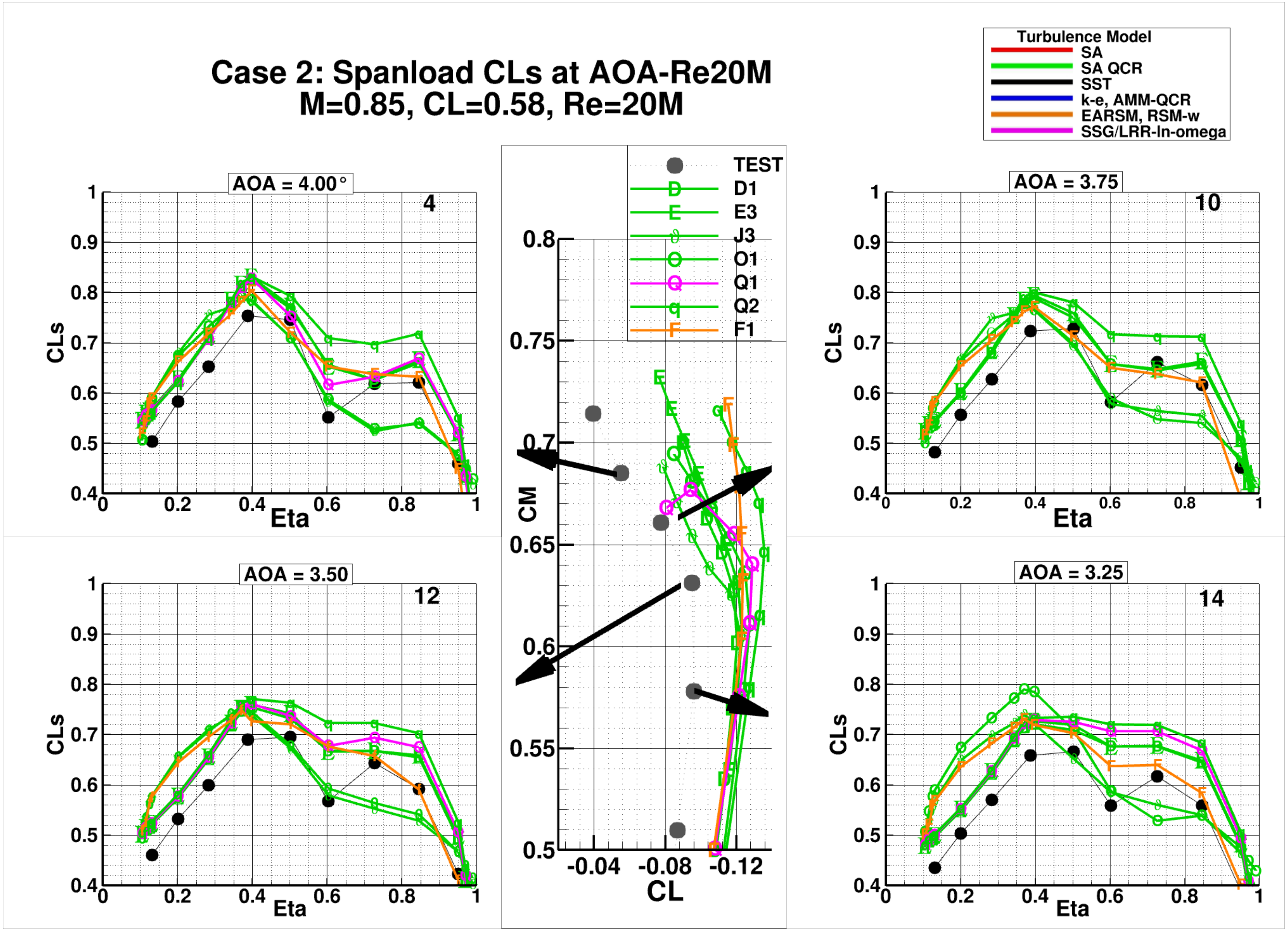


Case 2: Lift and Pitching Moment
Mach = 0.85, Re=5M
CFD Shifted to Match Test CL=0.53



Case 2: Pitching Moment
Mach = 0.85, Re=5M, Re=20M
Minus Solutions that do not Match Experimental Trends




Case 2: Spanload CLs at AOA-Re20M
M=0.85, CL=0.58, Re=20M
Turbulence Model
SA
SA QCR
SST
k-e, AMM-QCR
EARSM, RSM-w
SSG/LRR-ln-omega
AOA = 4.00°
4
AOA = 3.75
10
AOA = 3.50
12
AOA = 3.25
14
CLs
Eta
TEST
D1
E3
J3
O1
Q1
Q2
F1
CM
CL

Case 2 - Observations

- High angles of attack characterized by shock induced separation which significantly influences pitching moments.
- No clear break-outs with grid type
- Solutions that best matched pitching moment trends used SA-QCR turbulence model (but many outliers)
- Pitching moment trend for all solutions
  - Tighter moment up to CL=0.58
  - Significant force and moment spread at $\alpha=4.25°$ $\Delta CL=0.05$, $\Delta CM=0.043$
- Excessive aft-loading on outboard wing sections contributes to too negative section pitching moments and excessive section lift.

Outline:

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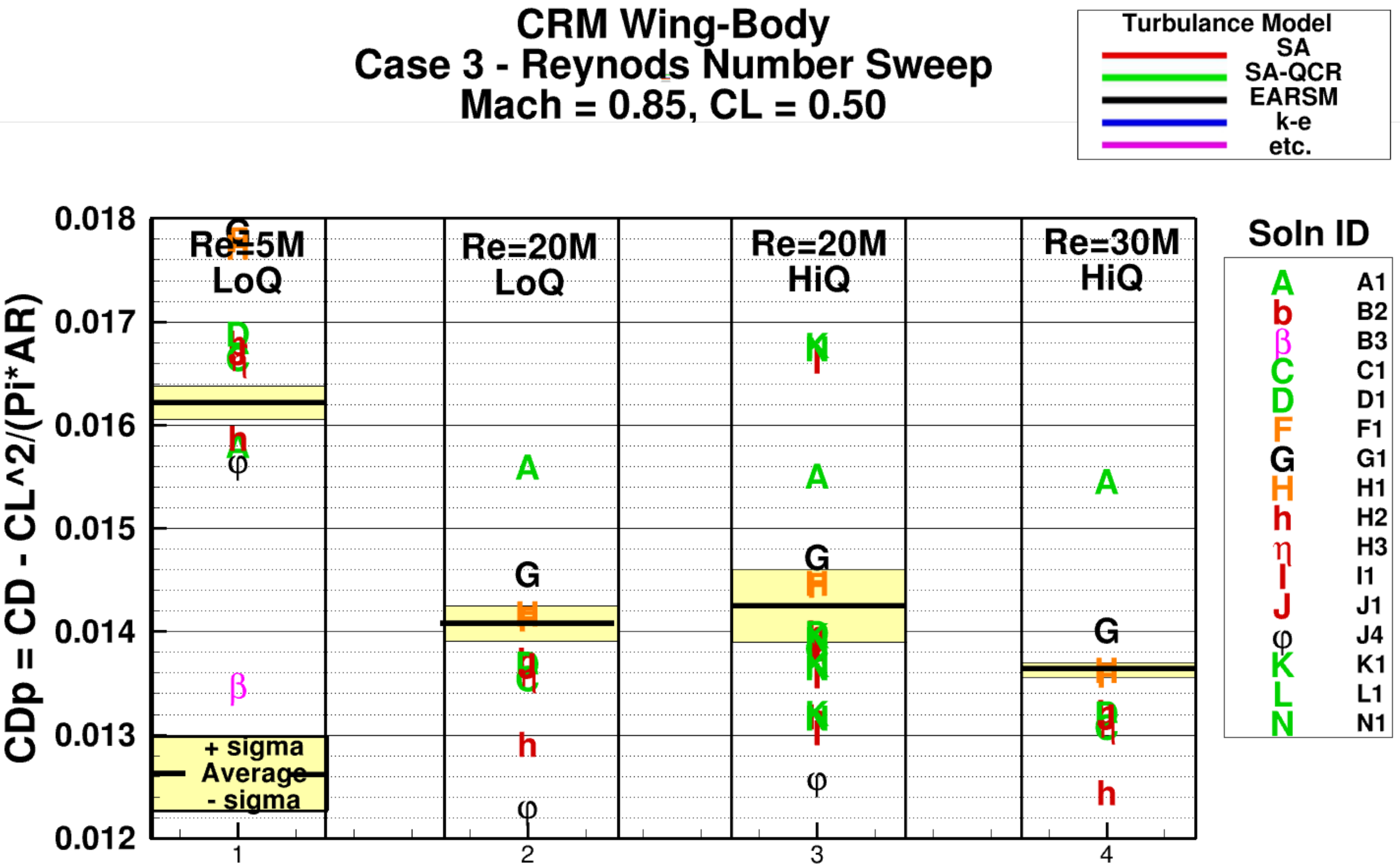
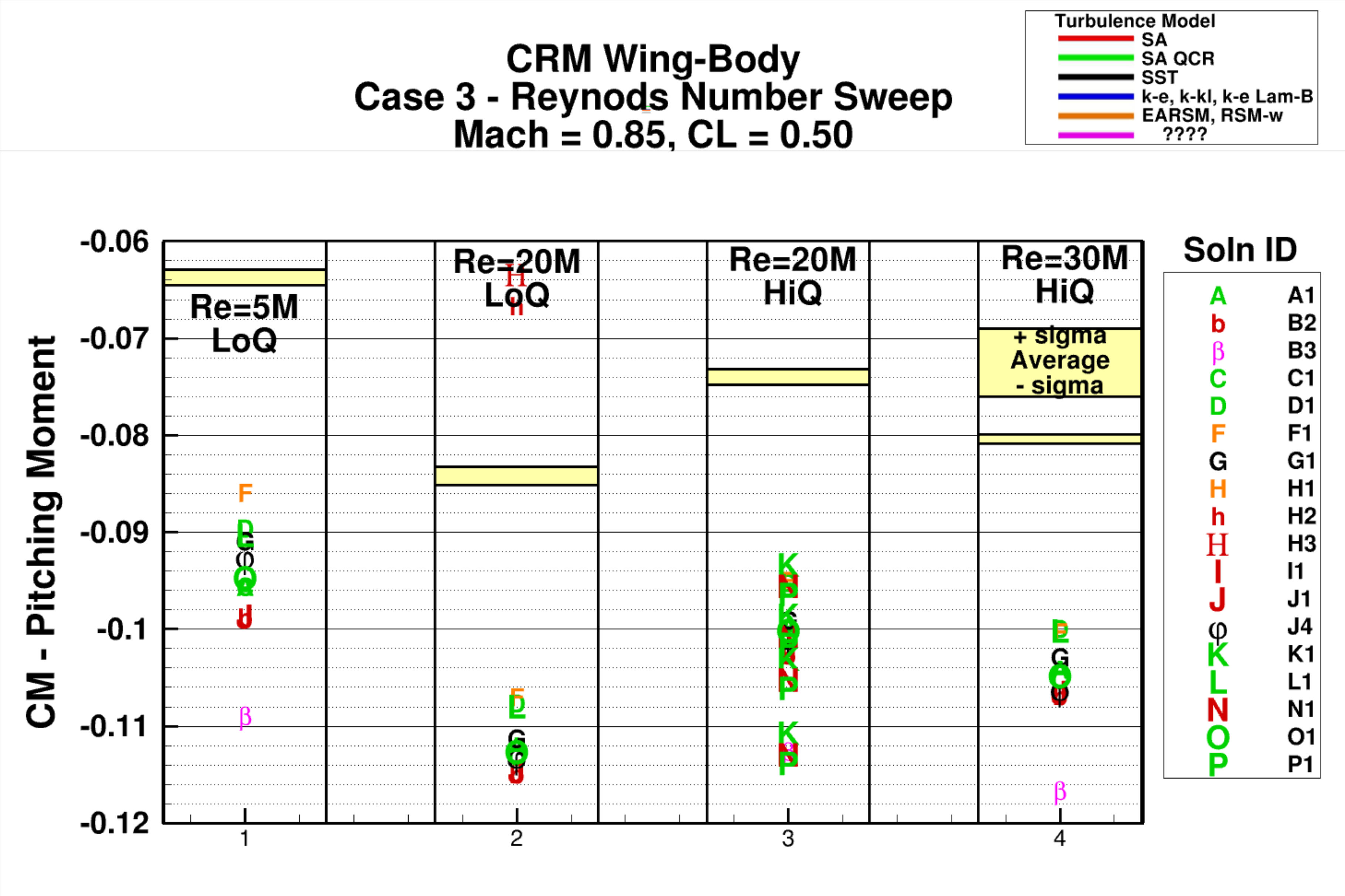
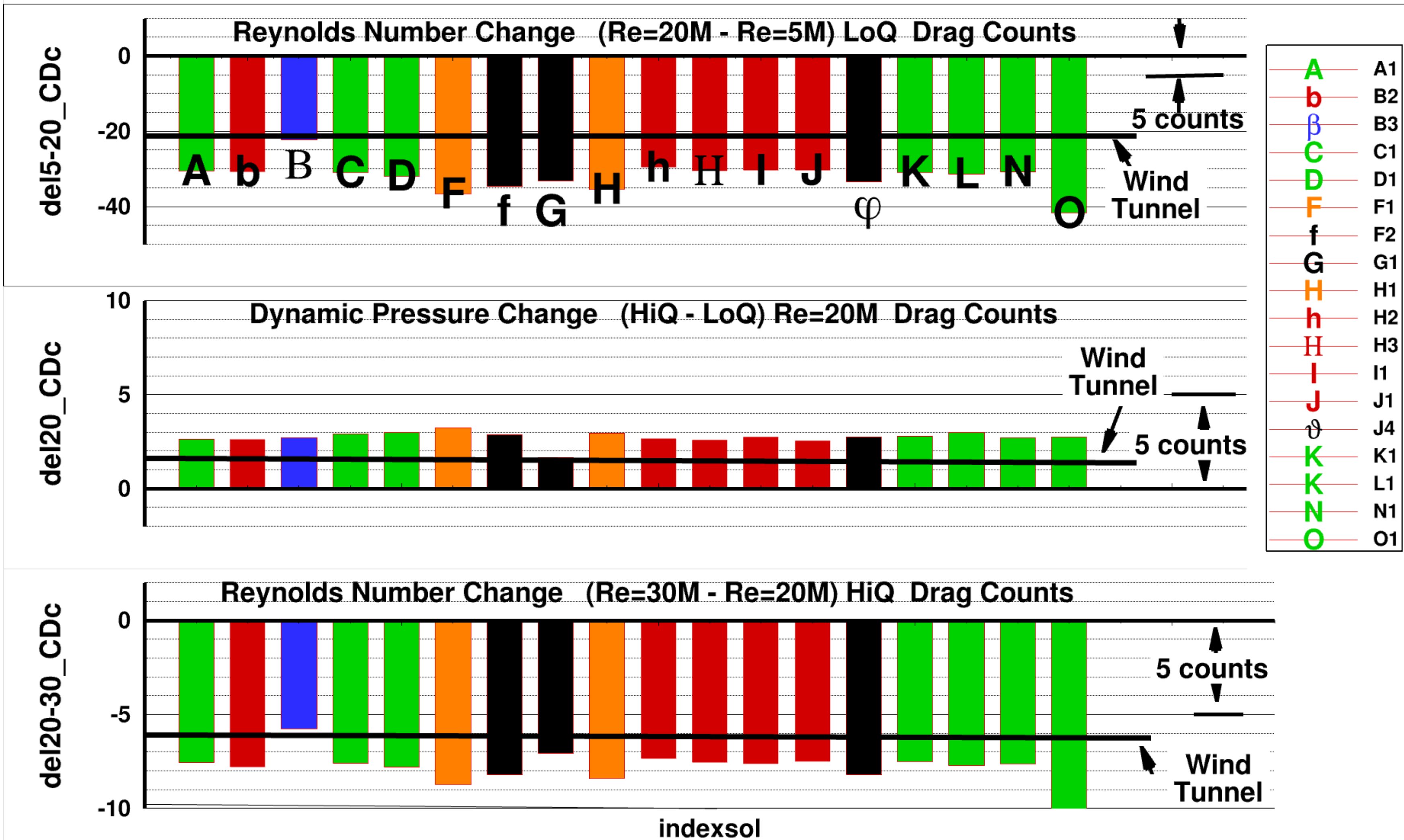
CRM Wing-Body Reynolds Number Sweep At Constant CL (Required): Flow conditions are: M = 0.85, CL = 0.50, medium grids;

- Re = 5M, LoQ – R5 grid using 2.50-deg LoQ AE CRM geometry, Reference temperature = 100° F (Same LoQ R5 medium grid solution from Case 2b)
- Re=20M, LoQ – R30 grid using 2.50-deg LoQ AE CRM geometry, Reference temperature = -250° F (Same LoQ R30 medium grid solution from Case 2a)
- Re=20M, HiQ – R30 grid using 2.50-deg HiQ AE CRM geometry and R30grid, Reference temperature = -182° F
- Re=30M, HiQ – R30 grid using 2.50-deg HiQ AE CRM geometry and R30grid, Reference temperature = -250° F


CRM Wing-Body
Case 3 - Reynods Number Sweep
Mach = 0.85, CL = 0.50
Turbulance Model
SA
SA-QCR
EARSM
k-e
etc.
Soln ID
A A1
b B2
β B3
C C1
D D1
F F1
G G1
H H1
h H2
η H3
I I1
J J1
φ J4
K K1
L L1
N N1
Re=5M LoQ
Re=20M LoQ
Re=20M HiQ
Re=30M HiQ
+ sigma
Average
- sigma
CDp = CD - CL^2/(Pi*AR)
0.018
0.017
0.016
0.015
0.014
0.013
0.012
1
2
3
4


CRM Wing-Body
Case 3 - Reynods Number Sweep
Mach = 0.85, CL = 0.50
Turbulence Model
SA
SA QCR
SST
k-e, k-kl, k-e Lam-B
EARSM, RSM-w
????
CM - Pitching Moment
Re=5M
LoQ
Re=20M
LoQ
Re=20M
HiQ
Re=30M
HiQ
+ sigma
Average
- sigma
-0.06
-0.07
-0.08
-0.09
-0.1
-0.11
-0.12
1
2
3
4
Soln ID
A A1
b B2
β B3
C C1
D D1
F F1
G G1
H H1
h H2
H H3
I I1
J J1
φ J4
K K1
L L1
N N1
O O1
P P1

Case 3: CRM Wing-Body
Reynolds Number Sweep At Constant CL



Case 3 - Observations

- Drag trends with changes in Reynolds number and dynamic pressure are correctly predicted

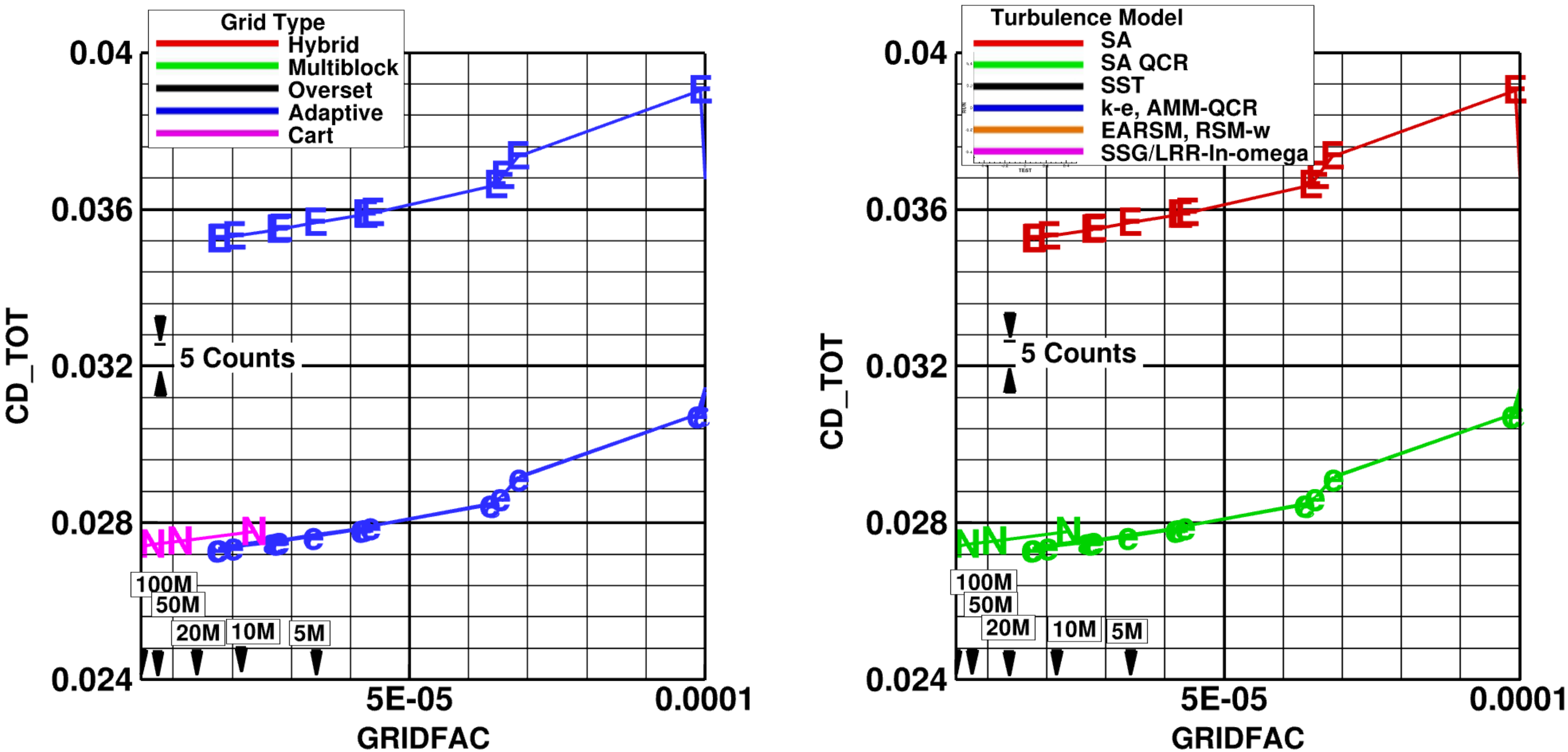
Outline:

- Participant Data
- Case 1: Grid Convergence Study
- Case 2: Angle of Attack Sweep
- Case 3: Reynolds Number Sweep
- Case 4: Grid Adaptation
- Case 5: Beyond RANS
- Case 6: Coupled Aero-Structural Simulation
- Observations/Issues

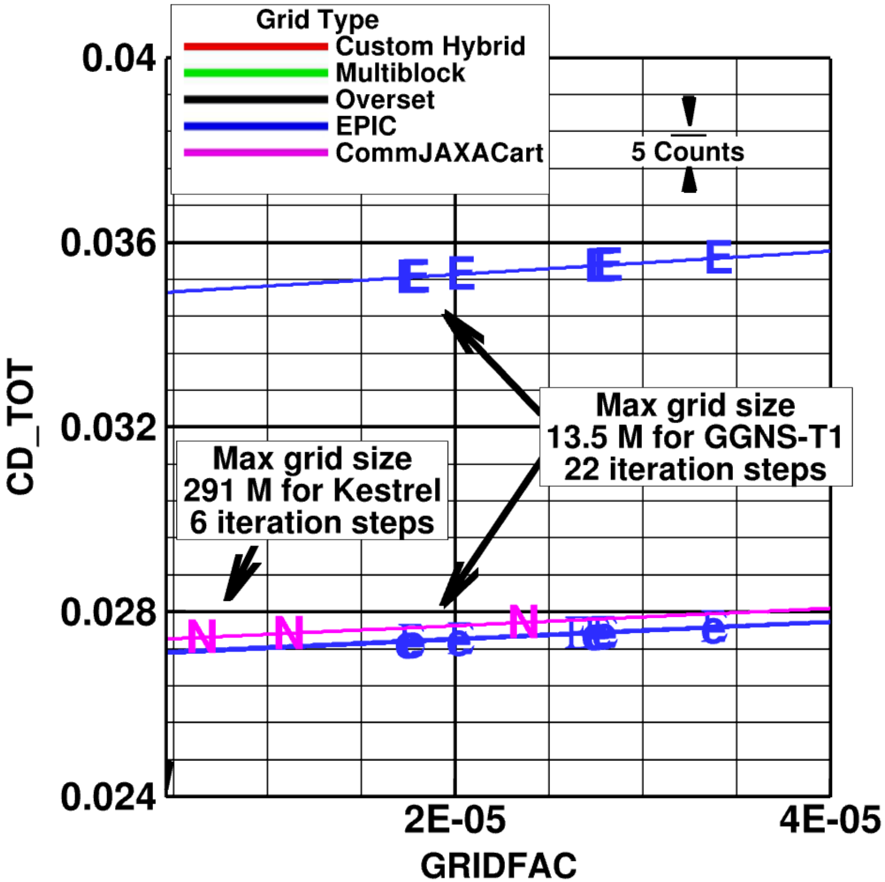
Case 4: CRM WB Grid Adaptation:

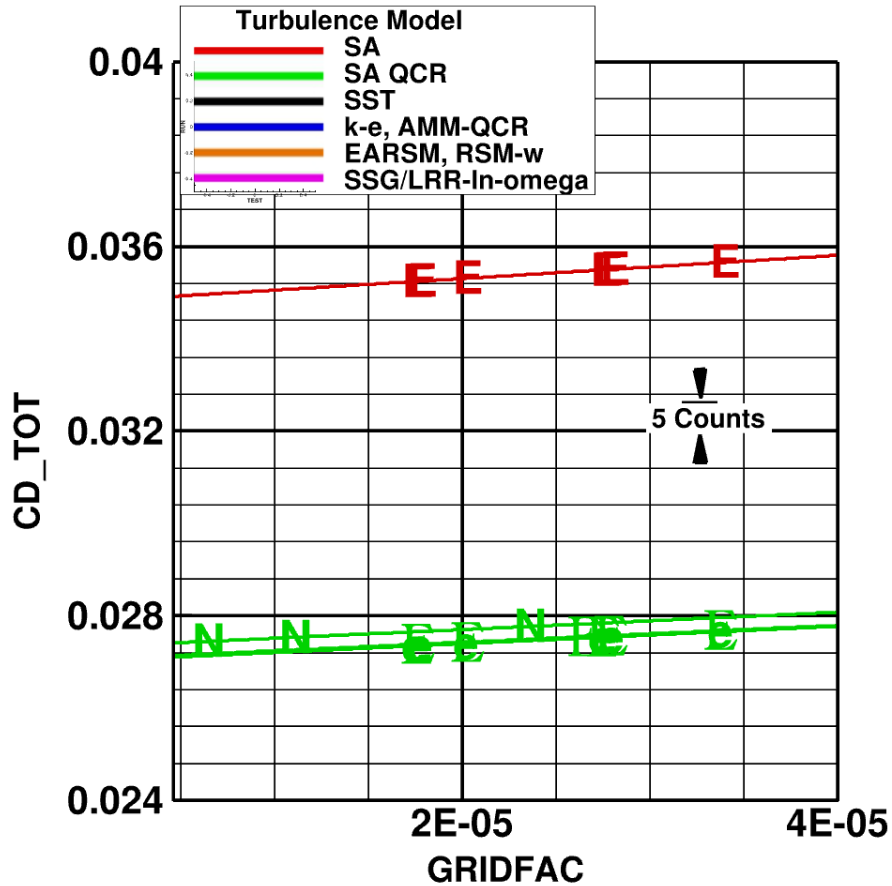
- NASA Common Research Model, Wing-Body
- Mach=0.85, C_L=0.500±0.001
- Chord Reynolds Number: 20x10^6, 5x10^6 Optional
- Solution Adapted Grid
- Angle of Attack sweep – (preferred priority):
- CL = 0.58 3.00-deg LoQ AE CRM geometry
  - ☐ $\alpha = 4.00°$ 4.00-deg LoQ AE CRM geometry
  - ☐ $\alpha = 3.50°$ 3.50-deg LoQ AE CRM geometry
  - ☐ $\alpha = 4.25°$ 4.25-deg LoQ AE CRM geometry
  - ☐ $\alpha = 3.25°$ 3.25-deg LoQ AE CRM geometry
  - ☐ $\alpha = 3.75°$ 3.75-deg LoQ AE CRM geometry

Case 4 CD_T (Total) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 20M



Case 4 CD_T (Total) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 20M





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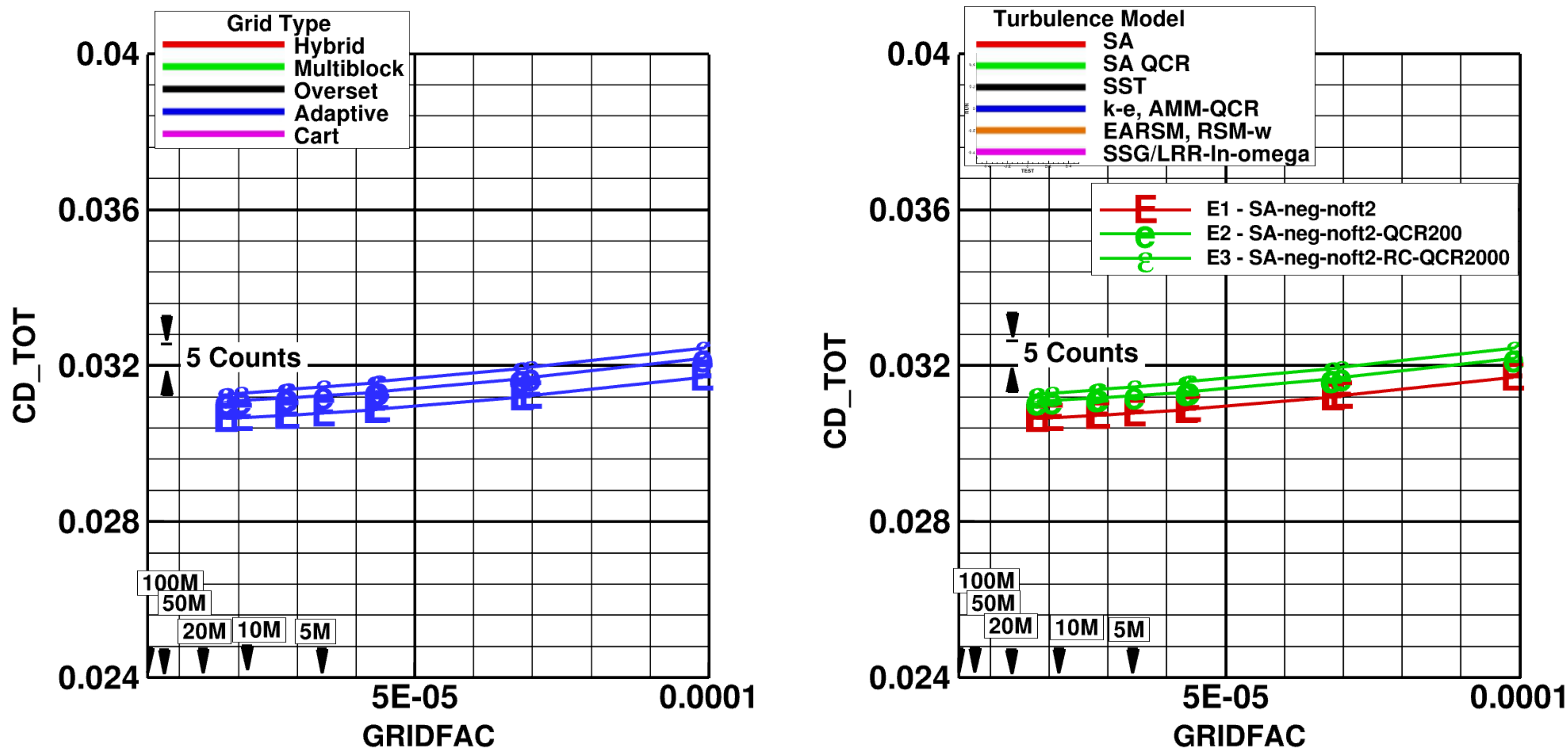
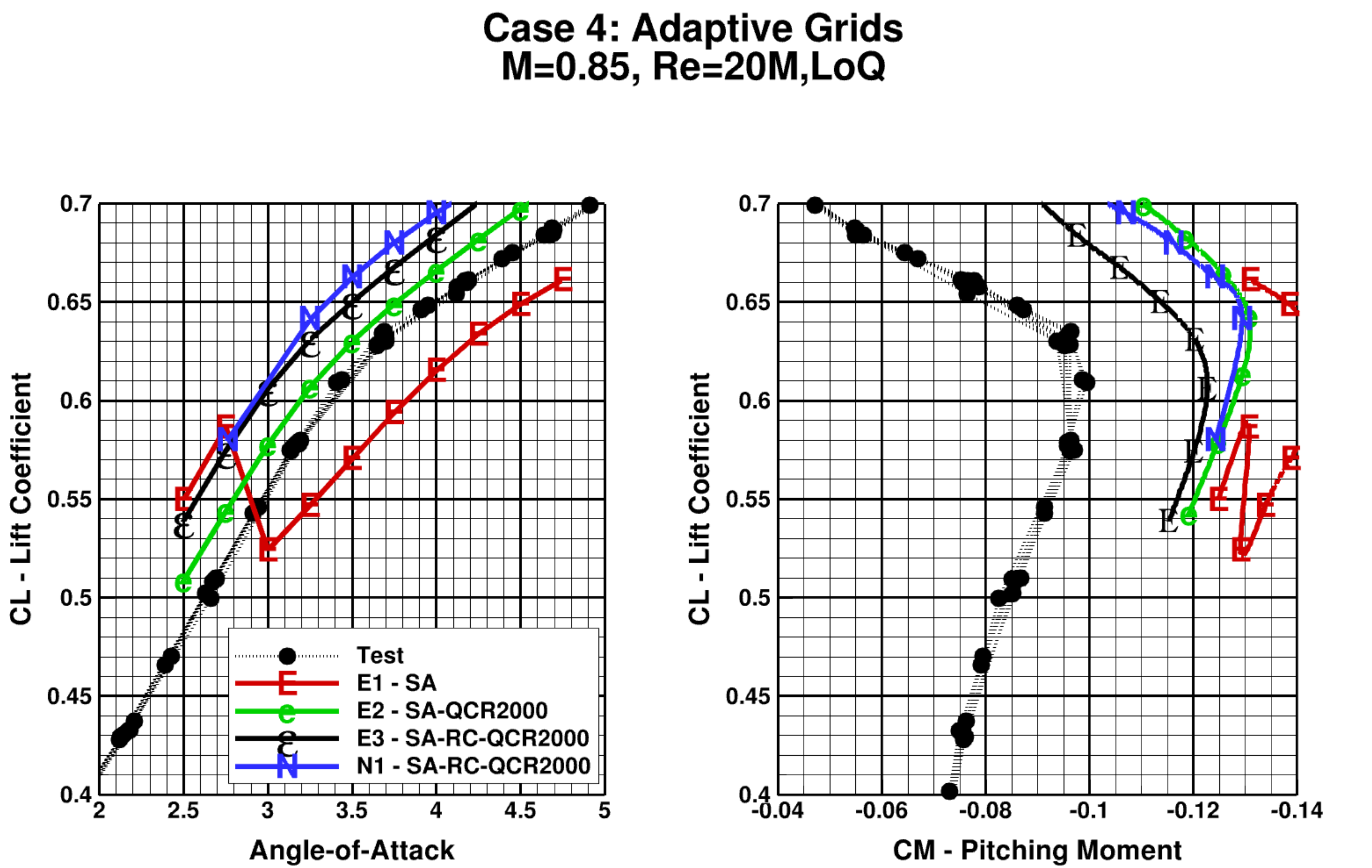
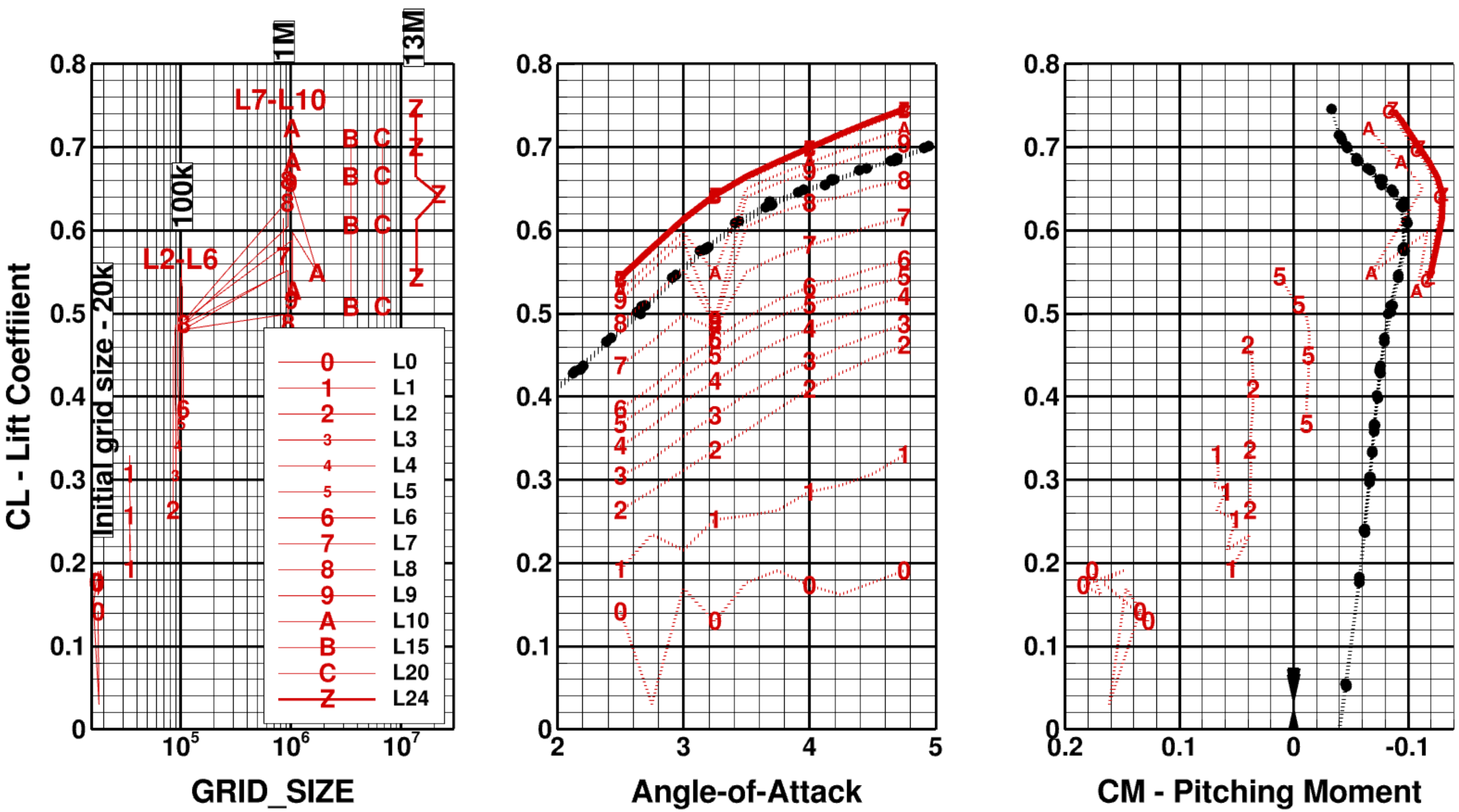
Case 4 CD_T (Total) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 5M

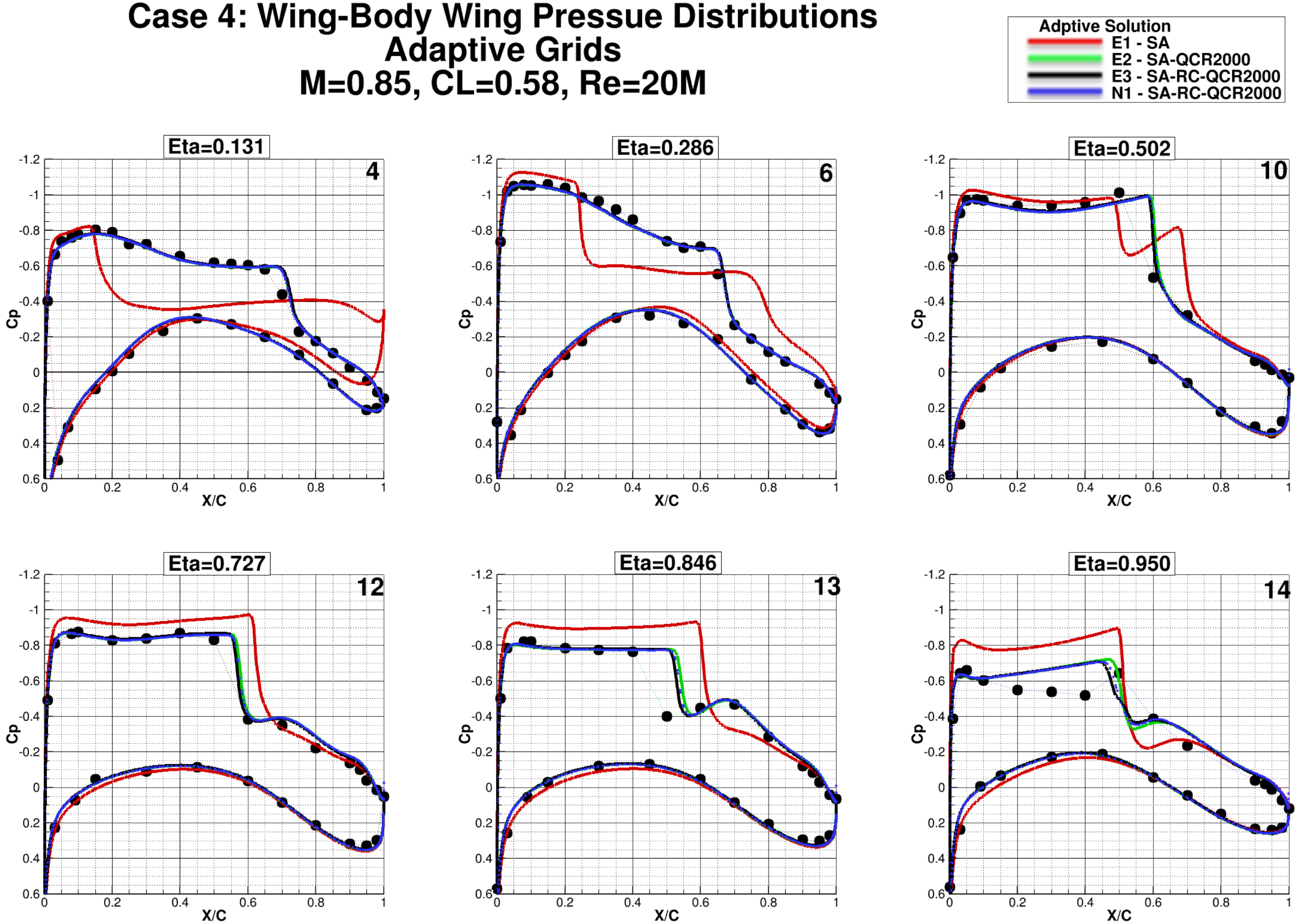



Case 4: Adaptive Grids
M=0.85, Re=20M,LoQ
CL - Lift Coefficient
Angle-of-Attack
Test
E1 - SA
E2 - SA-QCR2000
E3 - SA-RC-QCR2000
N1 - SA-RC-QCR2000
CM - Pitching Moment
0.7
0.65
0.6
0.55
0.5
0.45
0.4
2
2.5
3
3.5
4
4.5
5
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14

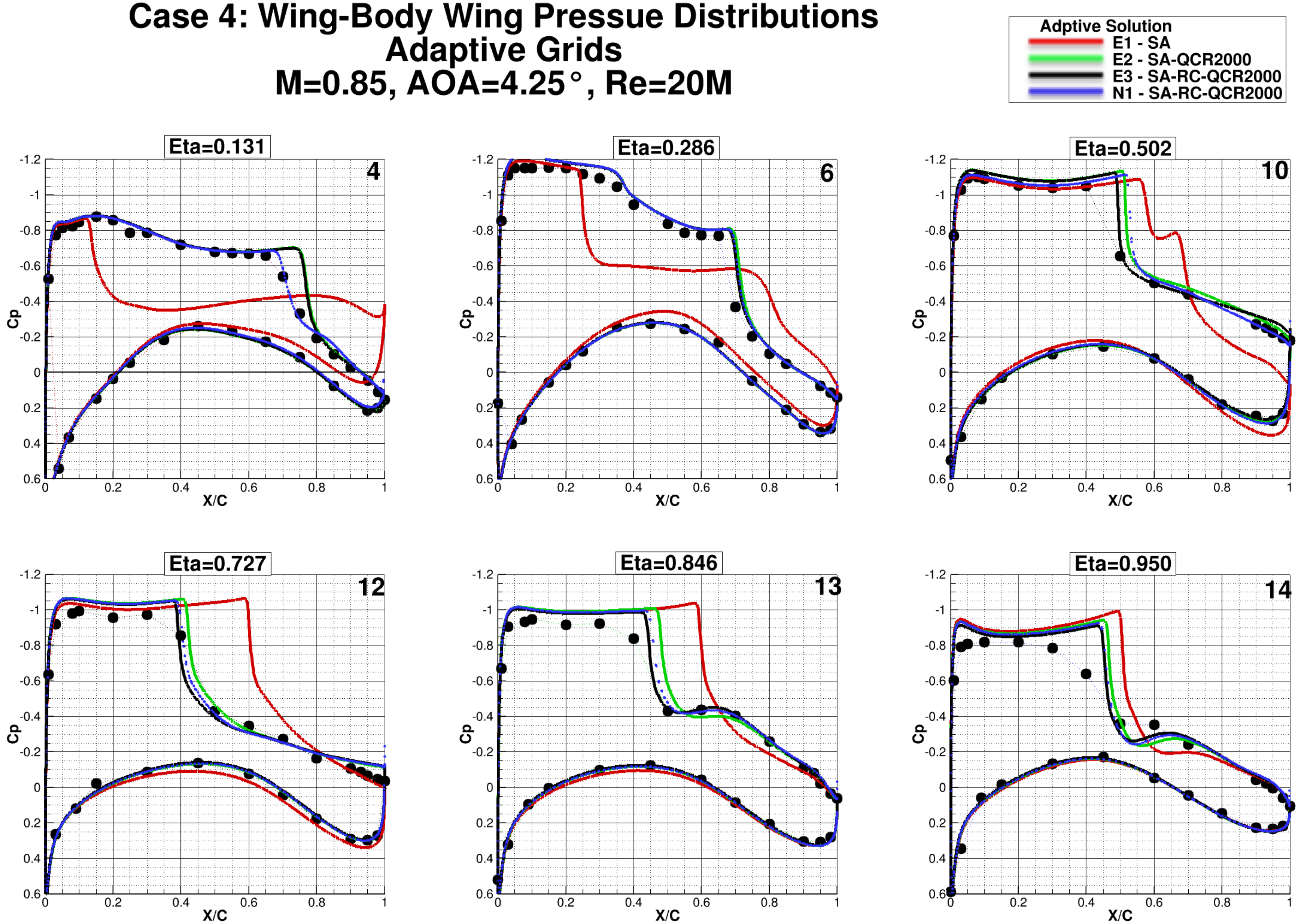
Case 4: Adaptive Grids
GGNS_T1/EPIC Adaptive Grid Process
24 Levels



Case 4: Wing-Body Wing Pressue Distributions
Adaptive Grids
M=0.85, CL=0.58, Re=20M



Case 4: Wing-Body Wing Pressue Distributions
Adaptive Grids
M=0.85, AOA=4.25°, Re=20M



Case 4 - Observations

- Little benefit is seen for adaptive grid solutions compared to fixed grid solutions for this simple wing-body geometry.
- Decades have been spent developing and validating gridding guidelines for these “simple” geometries and expected flow features.
- The benefit of adaptive grid solutions is to be seen for geometries/flow features for which there is little prior experience.

Outline:

- Participant Data
- Case 1: Grid Convergence Study
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- Observations/Issues

Case 5: Beyond RANS [Optional]:

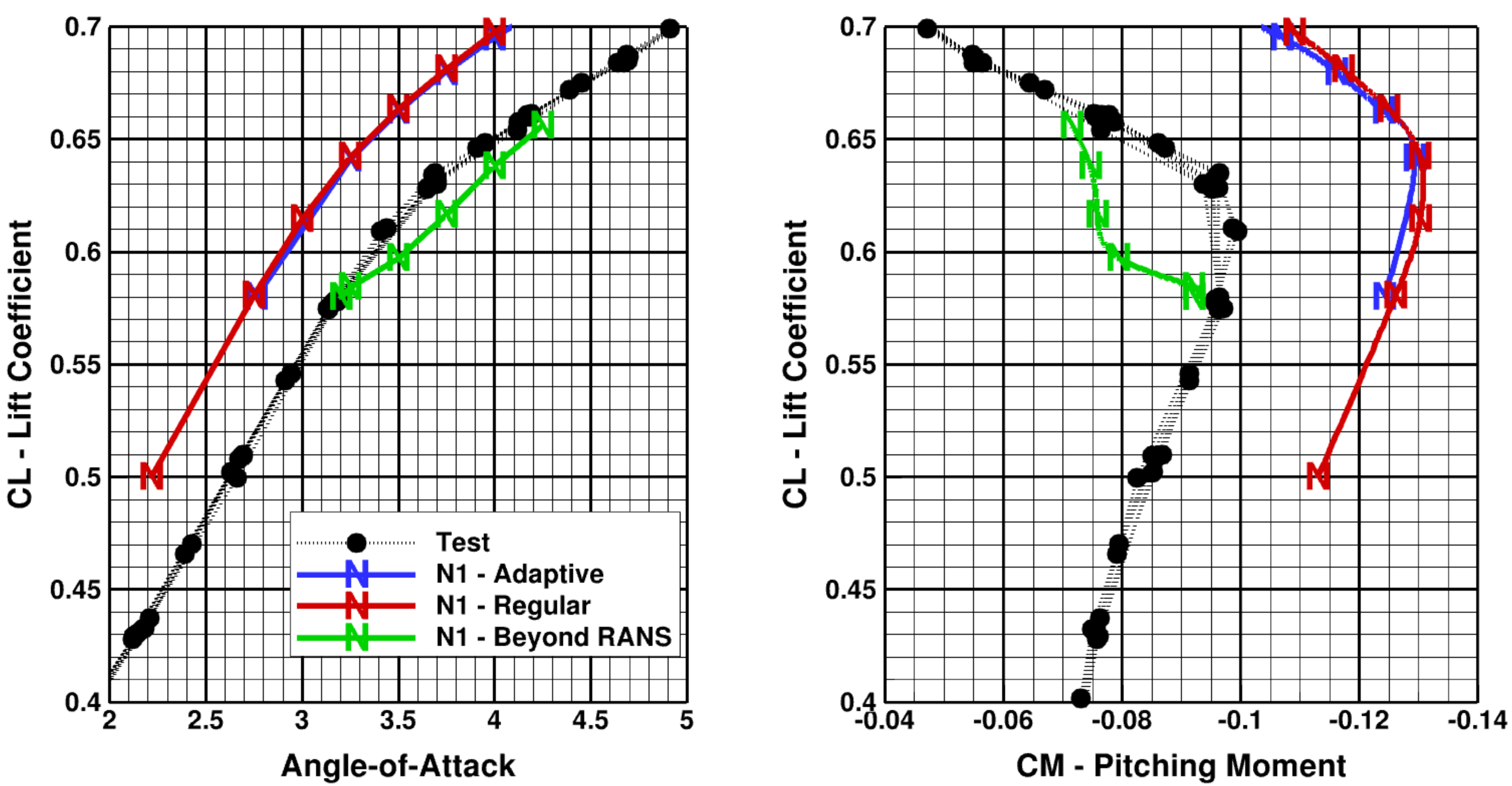
Solution technologies beyond steady RANS such as URANS, DDES, WMLES, Lattice Boltzmann, etc. Flow conditions are: M = 0.85; Re = 20 million; Reference temperature = -250°F. Single solution at CL = 0.58 or alpha sweep. Baseline grids not provided

Angle of Attack sweep – (preferred priority):

CL = 0.58	3.00-deg LoQ AE CRM geometry
α = 4.00°	4.00-deg LoQ AE CRM geometry
α = 3.50°	3.50-deg LoQ AE CRM geometry
α = 4.25°	4.25-deg LoQ AE CRM geometry
α = 3.25°	3.25-deg LoQ AE CRM geometry
α = 3.75°	3.75-deg LoQ AE CRM geometry

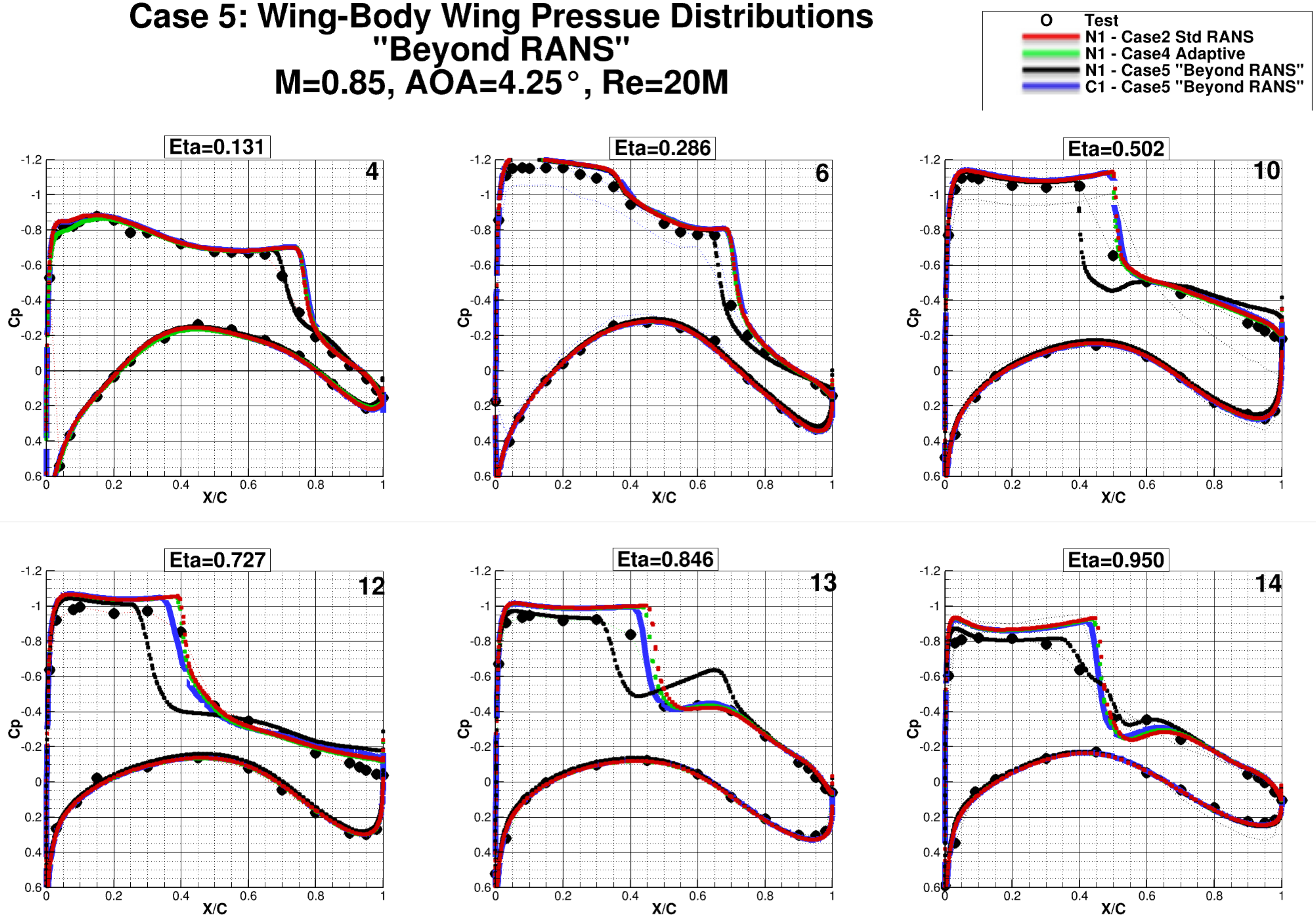
(Please order results in Angle-of-Attack monotonic order)

Case 5 "Beyond RANS"
M=0.85, Re=20M,LoQ



Case 5: Wing-Body Wing Pressue Distributions "Beyond RANS"

M=0.85, AOA=4.25°, Re=20M



Case 5 - Observations

- **Difficult to make any meaningful observations from limited number of solutions and time available to examine results.**

Outline:

- Participant Data
- Case 1: Grid Convergence Study
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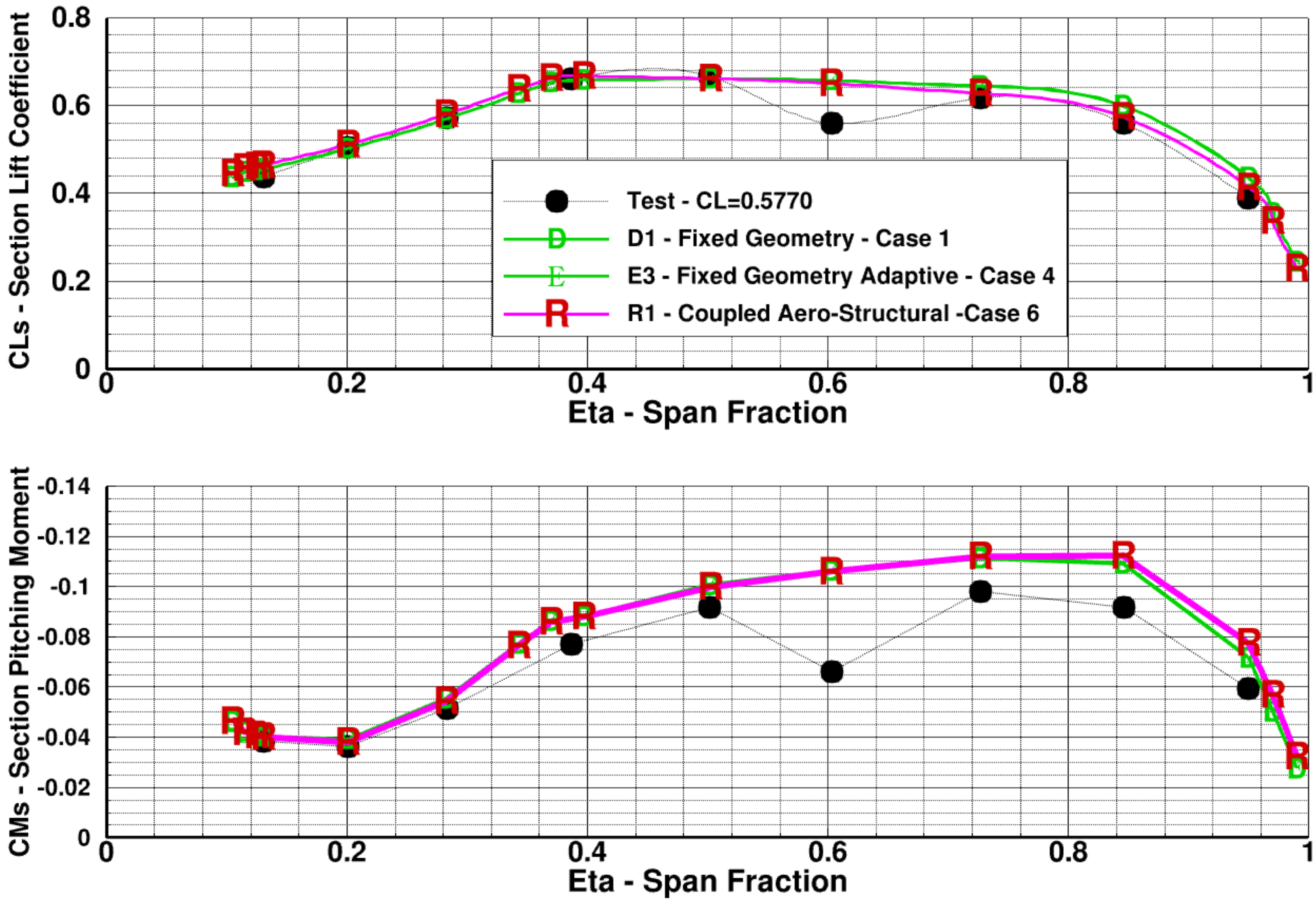
- Observations/Issues

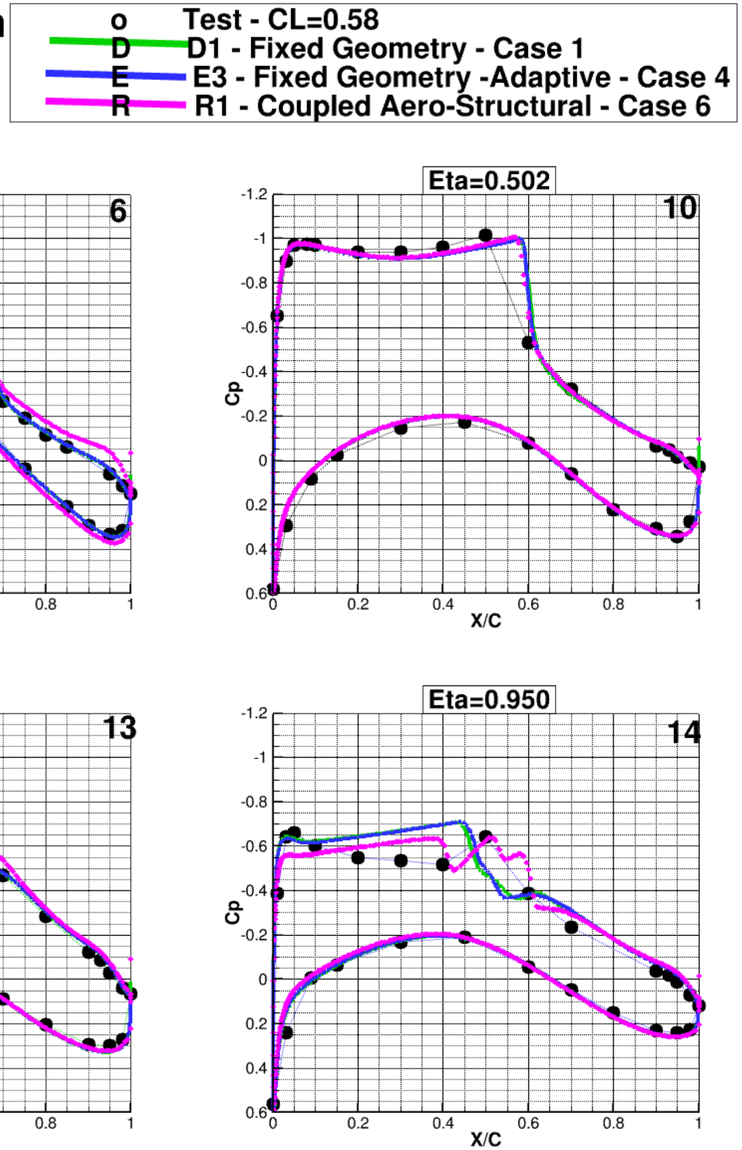
Case 6: CRM WB Coupled Aero-Structural Simulation :

- NASA Common Research Model, Wing-Body
- Mach=0.85, C_L=0.500±0.001
- Chord Reynolds Number: 20×10^{6}, 5×10^{6} Optional
- Fixed lift condition for the CRM Wing-Body coupled with computational structural analysis
- Structural FEM from the CRM Website
- Angle of Attack sweep – (preferred priority):
- CL = 0.58 3.00-deg LoQ AE CRM geometry
  - a = 4.00° 4.00-deg LoQ AE CRM geometry
  - a = 3.50° 3.50-deg LoQ AE CRM geometry
  - a = 4.25° 4.25-deg LoQ AE CRM geometry
  - a = 3.25° 3.25-deg LoQ AE CRM geometry
  - a = 3.75° 3.75-deg LoQ AE CRM geometry

Case 6: Coupled Aero-Structural Simulation
Section Lift and Pitching Moment
Mach=0.85, CL=0.58, Re=20M



Case 6: Coupled Aero-Structural Simulation Wing-Body Wing Pressue Distributions M=0.85, CL=0.58, Re=20M



Case 6 - Observations

- Difficult to make any meaningful observations from limited number of solutions and time available to examine results.

Outline:

- Participant Data
- Case 1: Grid Convergence Study
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- Observations/Issues

General Observations and Comments:

- Very successful workshop. Thank You!
  - 30 data submittals, many with parametric variations in grid type and/or turbulence model
- Still more variation than desired
  - Some improvement from DPW6: We are getting better
- Drag comparisons to wind tunnel generally favorable but too much variation of pitching moment at higher angles of attack – we need to better understand the interaction of grid, solver, turbulence model
- A new CFD study of the CRM wind tunnel mounting system effects is needed, and should include the effects on the CRM Wing-Body, and Wing-Body-Tail configurations.

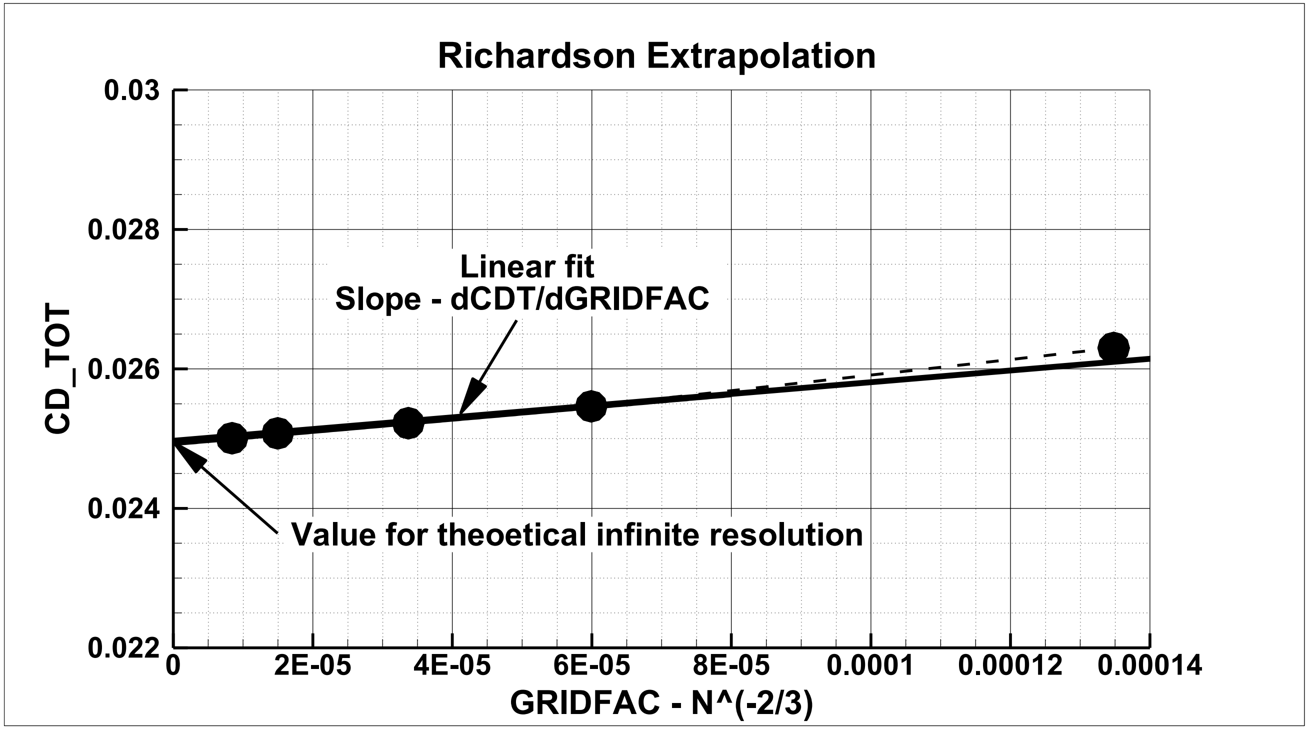
- **Further detailed experimental measurements that adequately capture the flow separation and unsteadiness on these types of configurations at "off-design" conditions are needed. Hard to make CFD progress without adequate experimental data for guidance and validation.**
- **These solution sets and experimental data represent a gold mine of information to further the knowledge of CFD and aerodynamics – GREAT PROJECTS FOR MASTERS STDENTS.**

For detailed analyses of DPW4, 5, and 6 featuring the NASA CRM - Tinoco, Edward N., "An Evaluation and Recommendations for Further CFD Research Based on the NASA Common Research Model (CRM) Analysis from the AIAA Drag Prediction Workshop (DPW) Series," NASA/CR-2019-220284

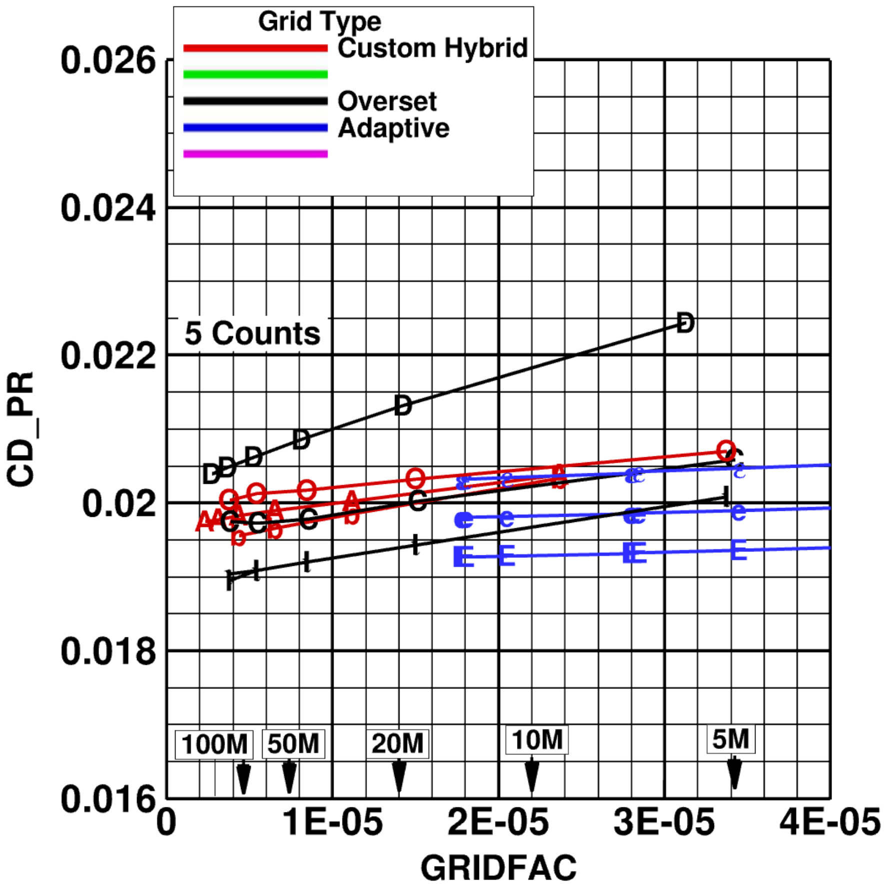
Grid Convergence?

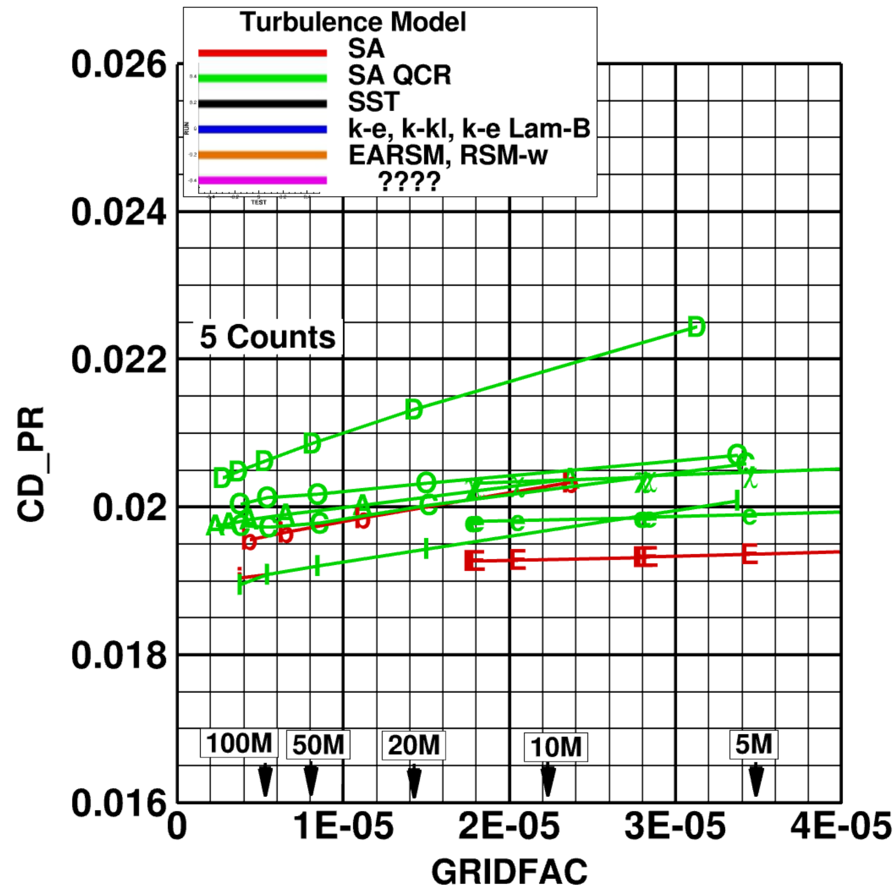
Richardson Extrapolation:

- Standard 2nd order least squares fit
- For 2nd order codes, should be linear vs. Grid_Factor = $N^{-2/3}$
- Y-intercept estimates theoretical infinite resolution (continuum) result



Case 1: CD_PR (Pressure Drag) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 5M





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Case 1: CD_SF Skin Friction) Grid Convergence
Mach = 0.85, CL = 0.58
Re = 5M