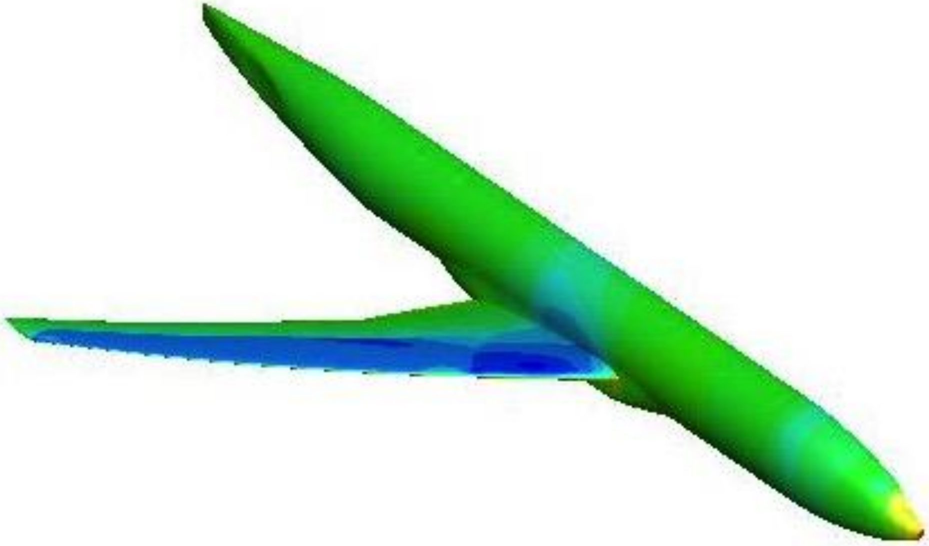
"Drag Predictions at and beyond Cruise for the Common Research Model by an International Collaborative Community"



Edward N. Tinoco

The Boeing Company, Retired

and

Stefan Keye

DLR

This presentation is a summary of the 7th CFD Drag Prediction Workshop held in June 2022 in conjunction with AVIATION 2022

Objectives of the Drag Prediction Workshop series:

- 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
- To provide an impartial international forum for evaluating the effectiveness of CFD Navier Stokes solvers
- To identify areas needing additional research and development

Principles

- Use Public Domain Subject Geometries
- Maintain a public-domain accessible database of geometries, grids, and results

Drag Prediction Workshop History

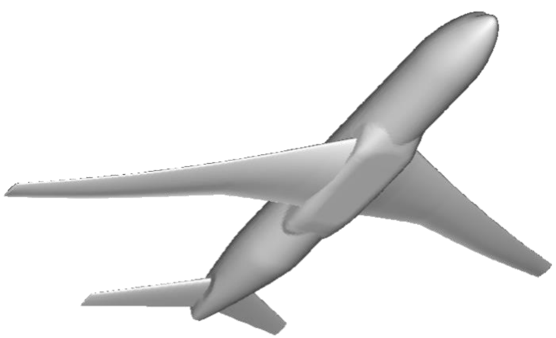
DPW1	2001	DLR F4 Wing-Body
DPW2	2003	DLR F6 Wing-Body & Wing-Body-Nacelle
DPW3	2006	DLR F6 Wing-Body +/- FX2B Fairing
DPW4	2009	NASA Common Research Model (CRM) Wing-Body & Wing-Body-Tail
DPW5	2012	NASA CRM Wing-Body
DPW6	2016	NASA CRM Wing-Body & Wing-Body-Nacelle
DPW7	2022	NASA CRM Wing-Body

Outline:

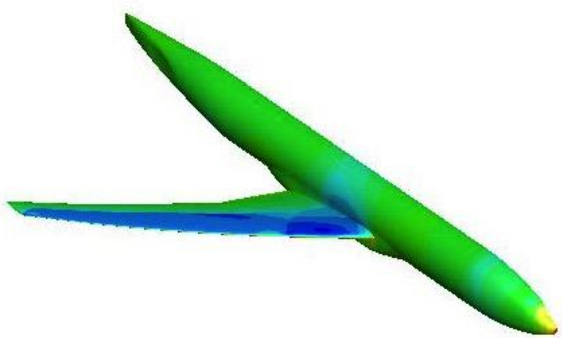
- Configuration and Participants
- Case 1: Grid Convergence Study
- Case 2: Angle of Attack Sweep
- Case 3: Reynolds Number Sweep
- Case 4: Grid Adaptation (Optional)
- Case 5: Beyond RANS (Optional)
- Case 6: Coupled Aero-Structural Simulation by Stefan Keye (Optional)
- Observations/Issues

NASA Common Research Model (CRM)

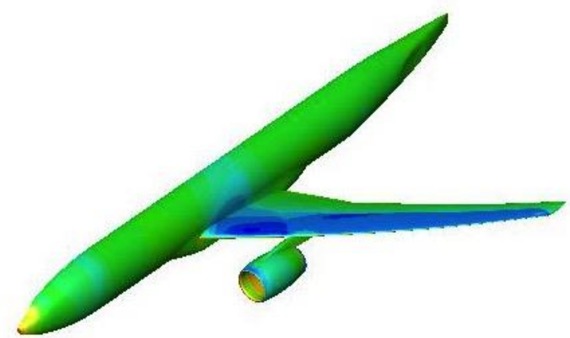
- Designed to be representative of a modern jet transport configuration
- Built to be tested in cryogenic wind tunnels (NTF & ETW)
- Available geometries and grids include wing measured aeroelastic twist and deflection for a range of angles of attack at Mach=0.85 at two different dynamic pressures
- In addition to the NASA model different scale wind tunnel models have been built and tested by ONERA and JAXA



DPW4



DPW5, DPW6, DPW7



DPW6

Participant Data for DPW7:

- 18 Teams/Organizations
  - 7 N. America, 7 Europe, 4 Asia
  - 7 Government, 3 Industry, 4 Academia, 4 Commercial
- 33 Total Data Submittals
- Grid Types:
  - 20 Unstructured (12 Teams)
  - 4 Overset (3 Teams)
  - 8 Structured Multi-block (5 Teams)
  - 1 Custom Cartesian (1 Team)
- Turbulence Models:
  - 16 SA-QCR (all types), 7 SA w/o QCR, 5 SST, 2 EARSM, 1 SSG/LRR, 1 AMM-QCR, 1 RSM-ln(w)

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- Observations/Issues

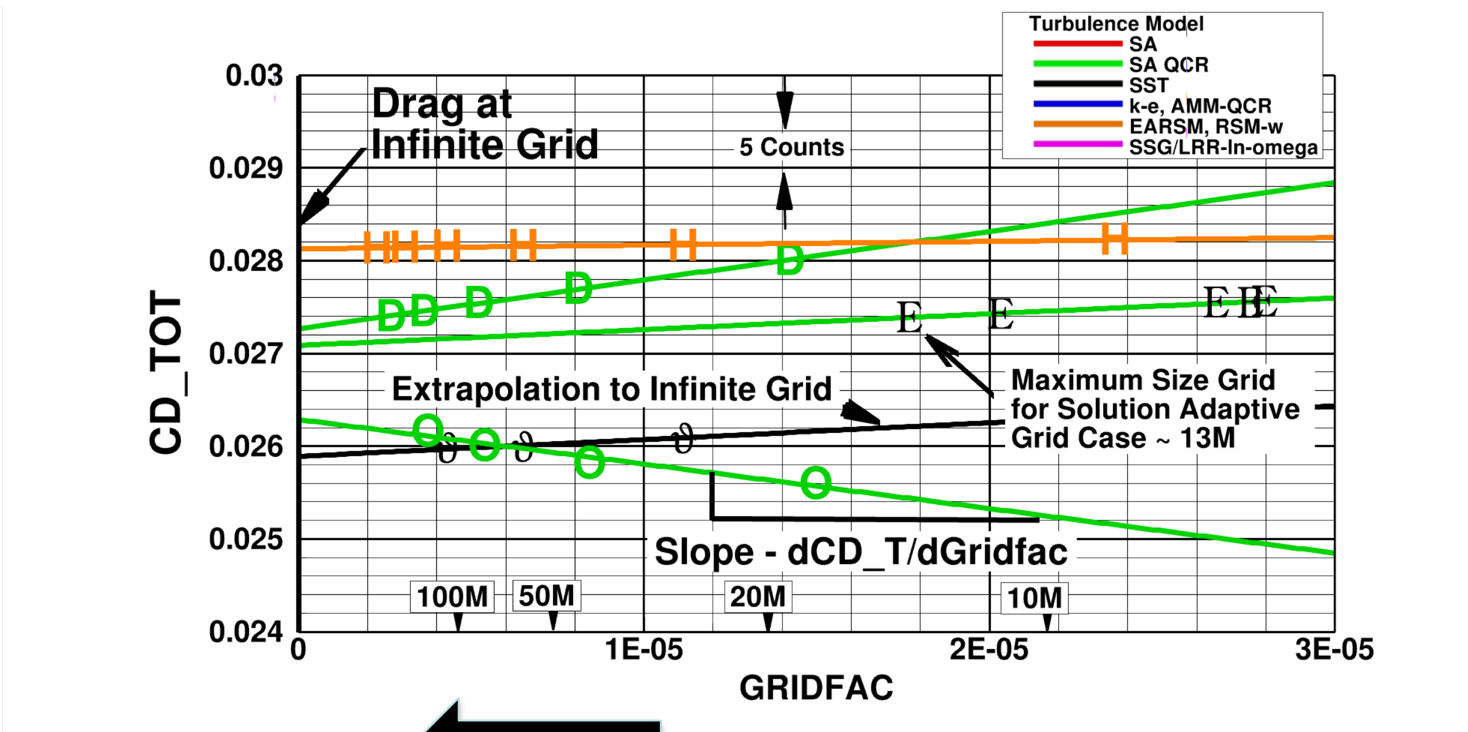
Case 1: Grid Convergence Study

- Mach=0.85, C_L=0.580±0.001 (Note that this C_L is considerably higher than the design C_L of 0.50 at the beginning of shock induced separation)
- Chord Reynolds Number: $20x10^6$, $5x10^6$ Optional
- Parametric family of grids "uniformly" refined in thee coordinate directions – grid resolution level:
  - 1) Tiny (~5M) 2) Coarse 3) Medium,
  - 4) Fine 5) Extra-Fine 6) Super-Fine (~200M+)

Grid Convergence?

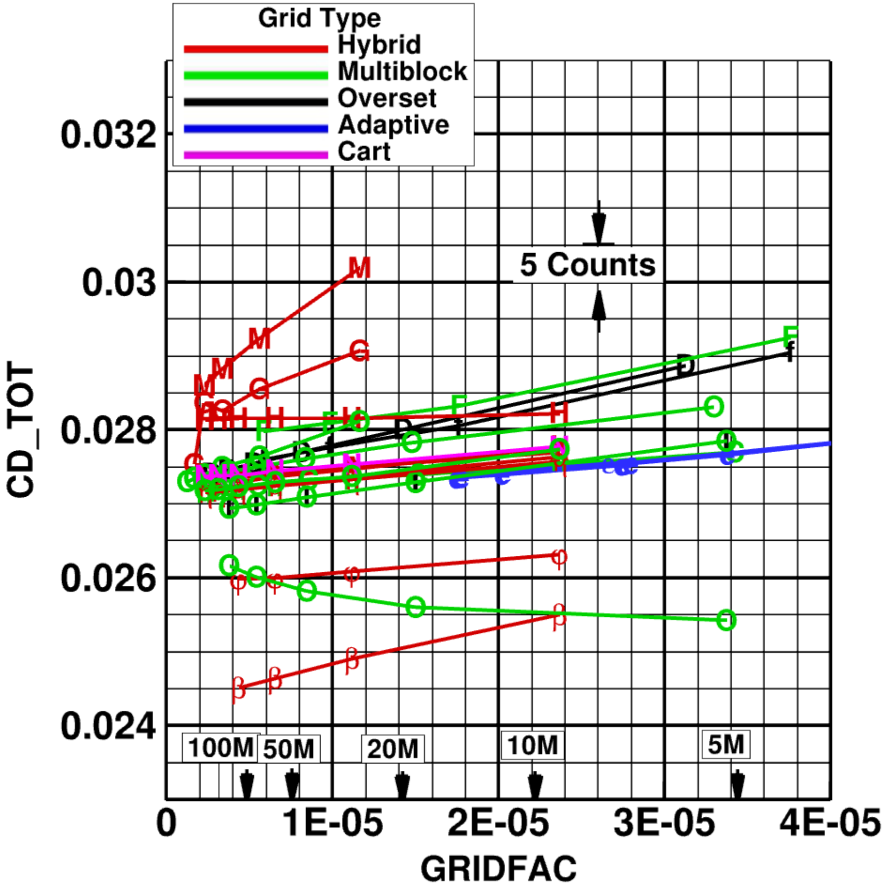
Richardson Extrapolation:

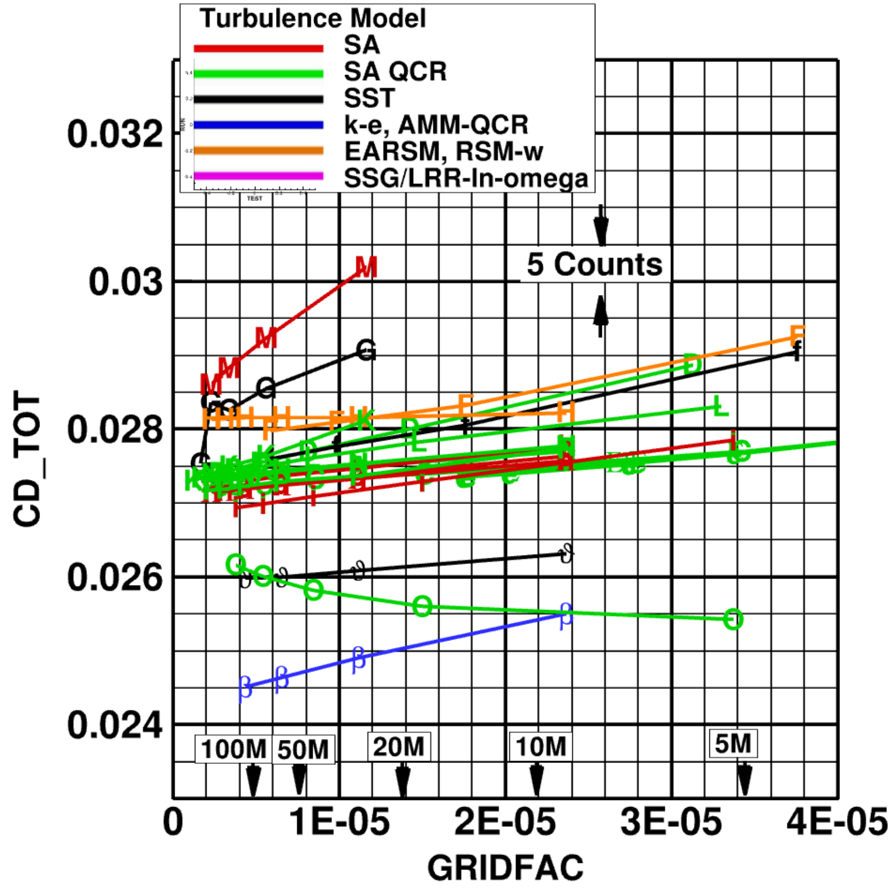
- Standard 2nd order least squares fit
- For 2nd order codes, should be linear vs. Grid_Factor = $N^{-2/3}$
- Y-intercept estimates theoretical infinite resolution (continuum) result



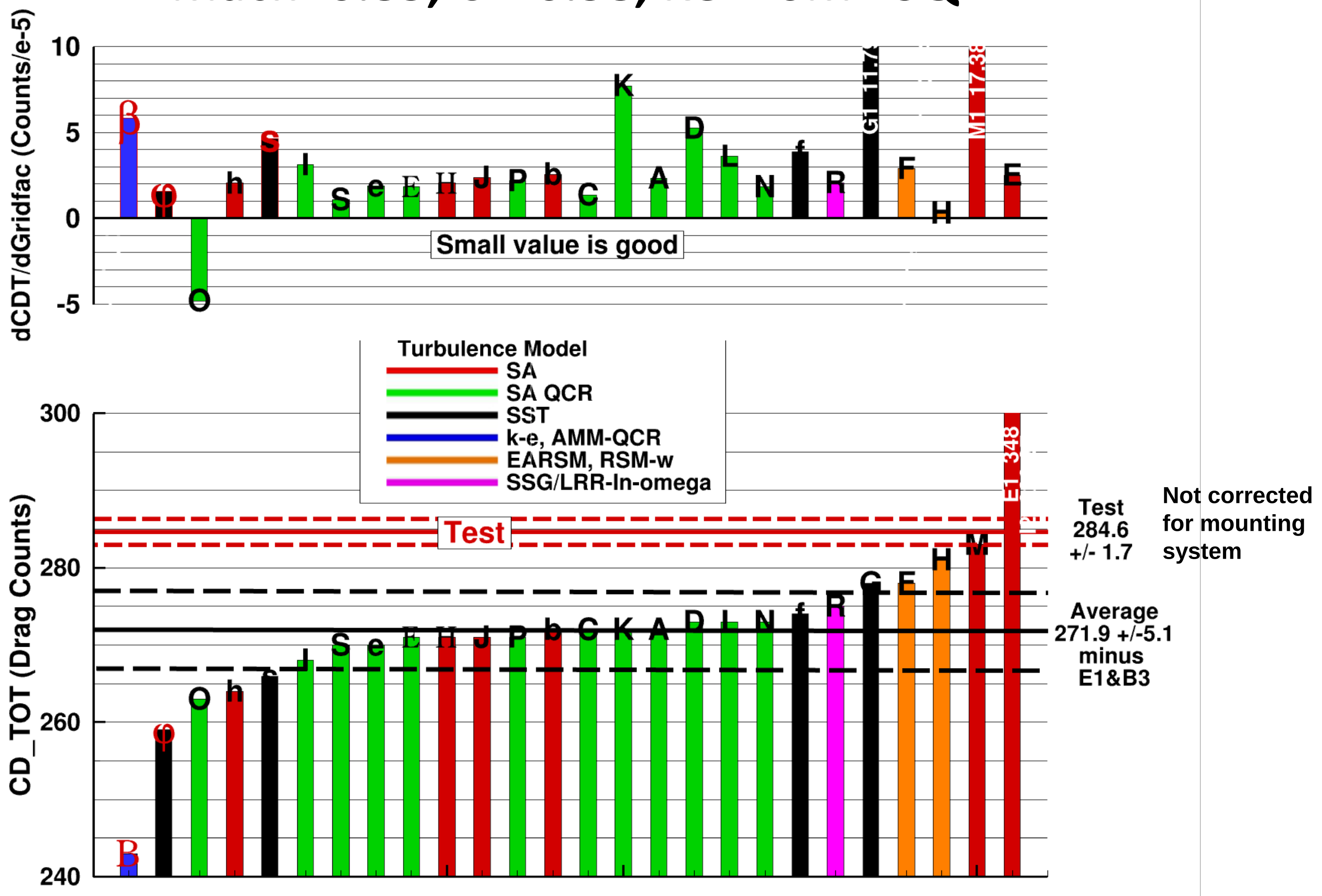
Increasing grid size

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

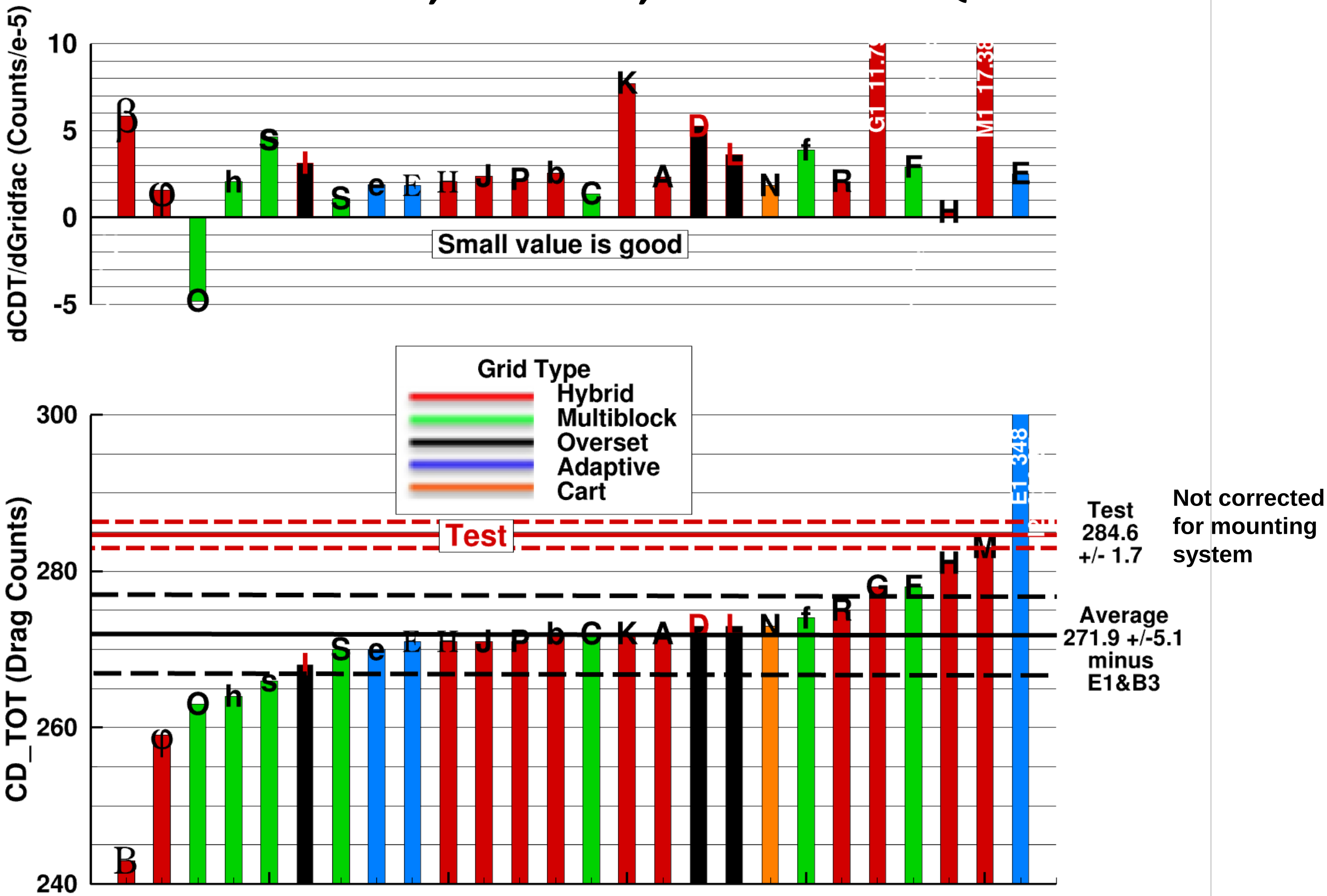




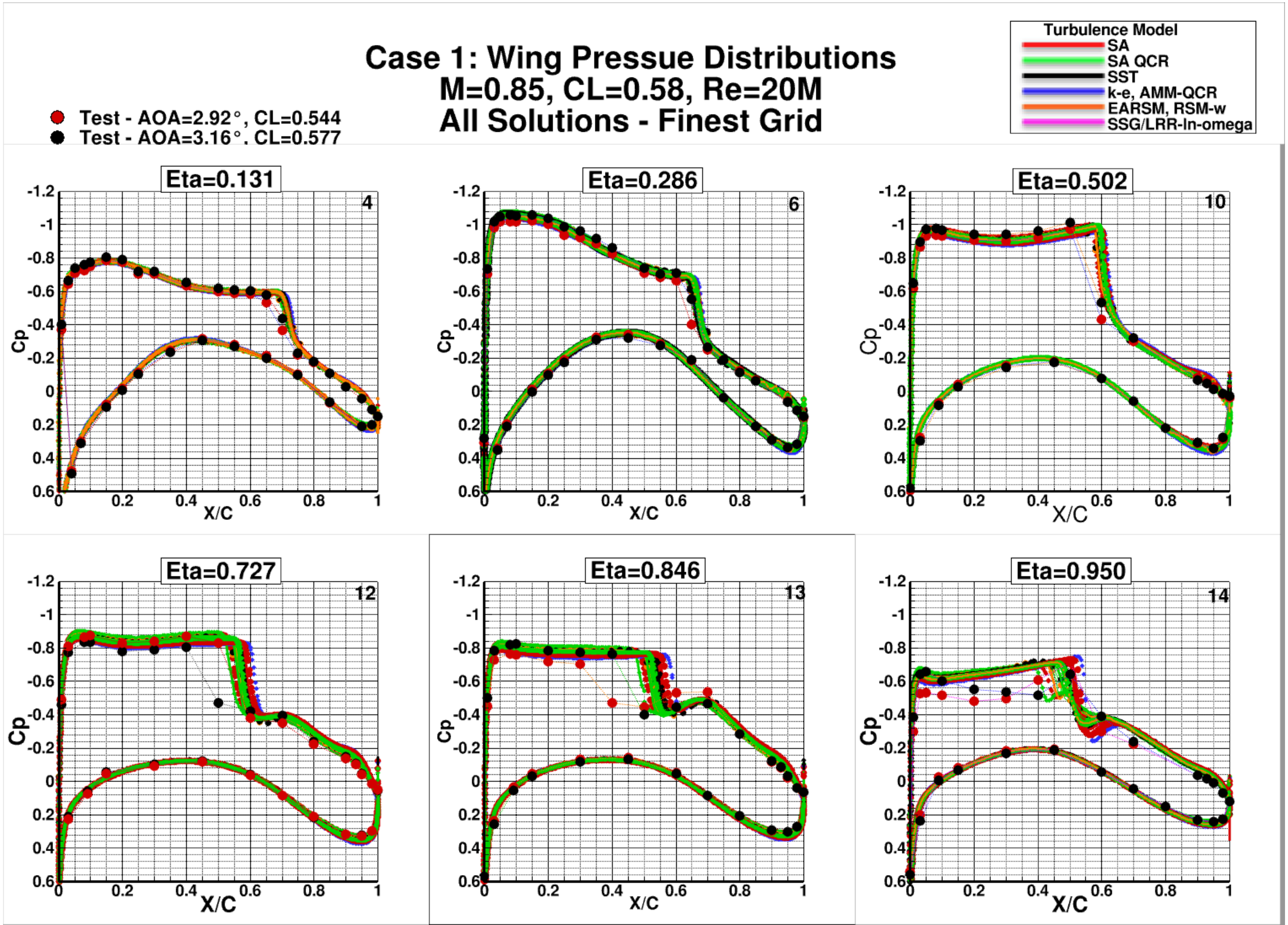
Drag Convergence Sensitivity
Mach=0.85, CL=0.58, Re=20M LoQ



Drag Convergence Sensitivity
Mach=0.85, CL=0.58, Re=20M LoQ



Drag Predictions at and beyond Cruise for the Common Research Model by an International Collaborative Community



Applied Aerodynamics Technical Committee

Drag Predictions at and beyond Cruise for the Common Research Model by an International Collaborative Community

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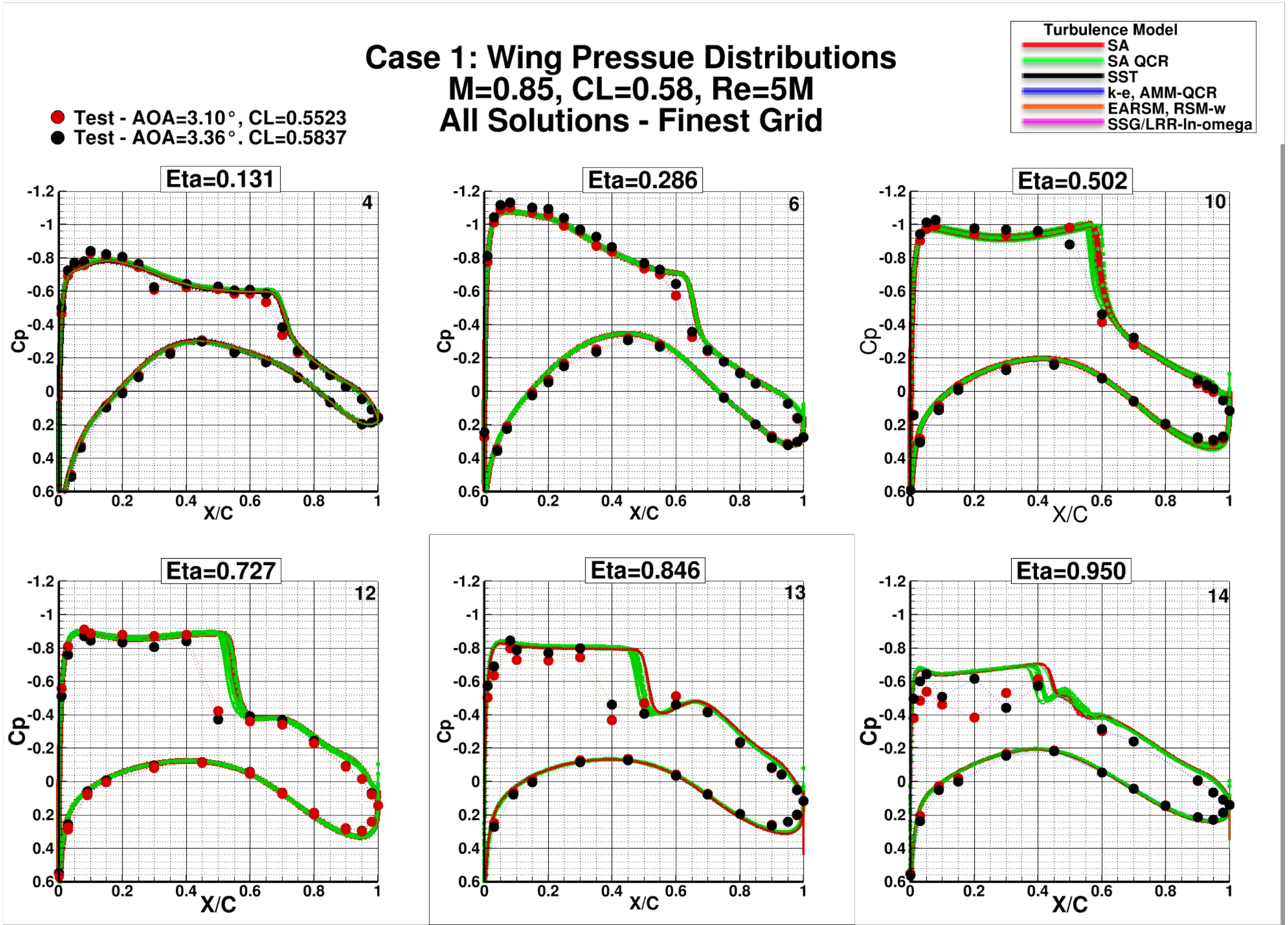

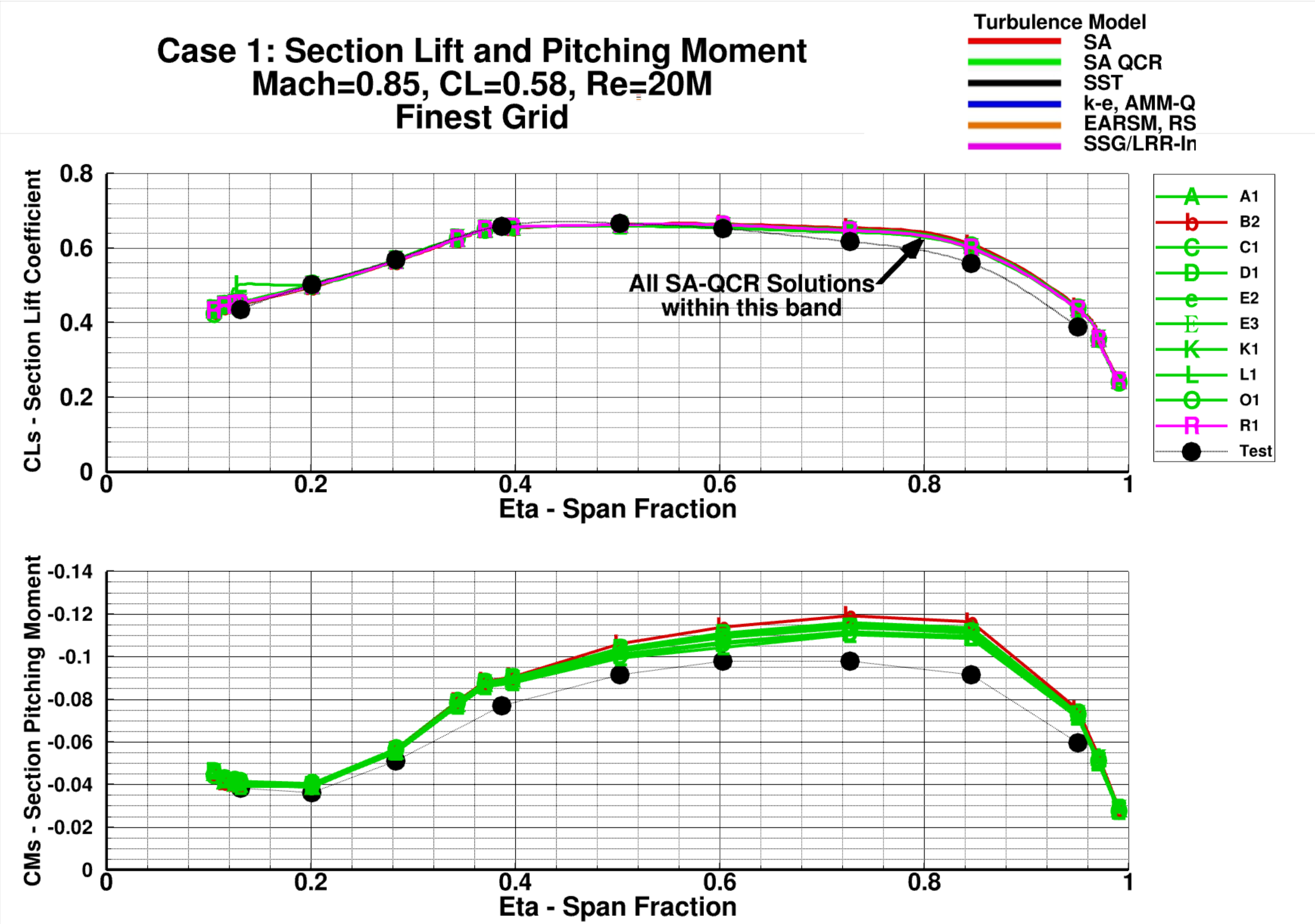
Case 1: Section Lift and Pitching Moment
Mach=0.85, CL=0.58, Re=20M
Finest Grid
Turbulence Model
SA
SA QCR
SST
k-e, AMM-Q
EARSM, RS
SSG/LRR-In
A1
B2
C1
D1
E2
E3
K1
L1
O1
R1
Test
CLs - Section Lift Coefficient
Eta - Span Fraction
All SA-QCR Solutions within this band
CMs - Section Pitching Moment
Eta - 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 (MOSTLY ATTACHED FLOW) CONDITION!**

Outline:

- Configuration and Participants
- Case 1: Grid Convergence Study
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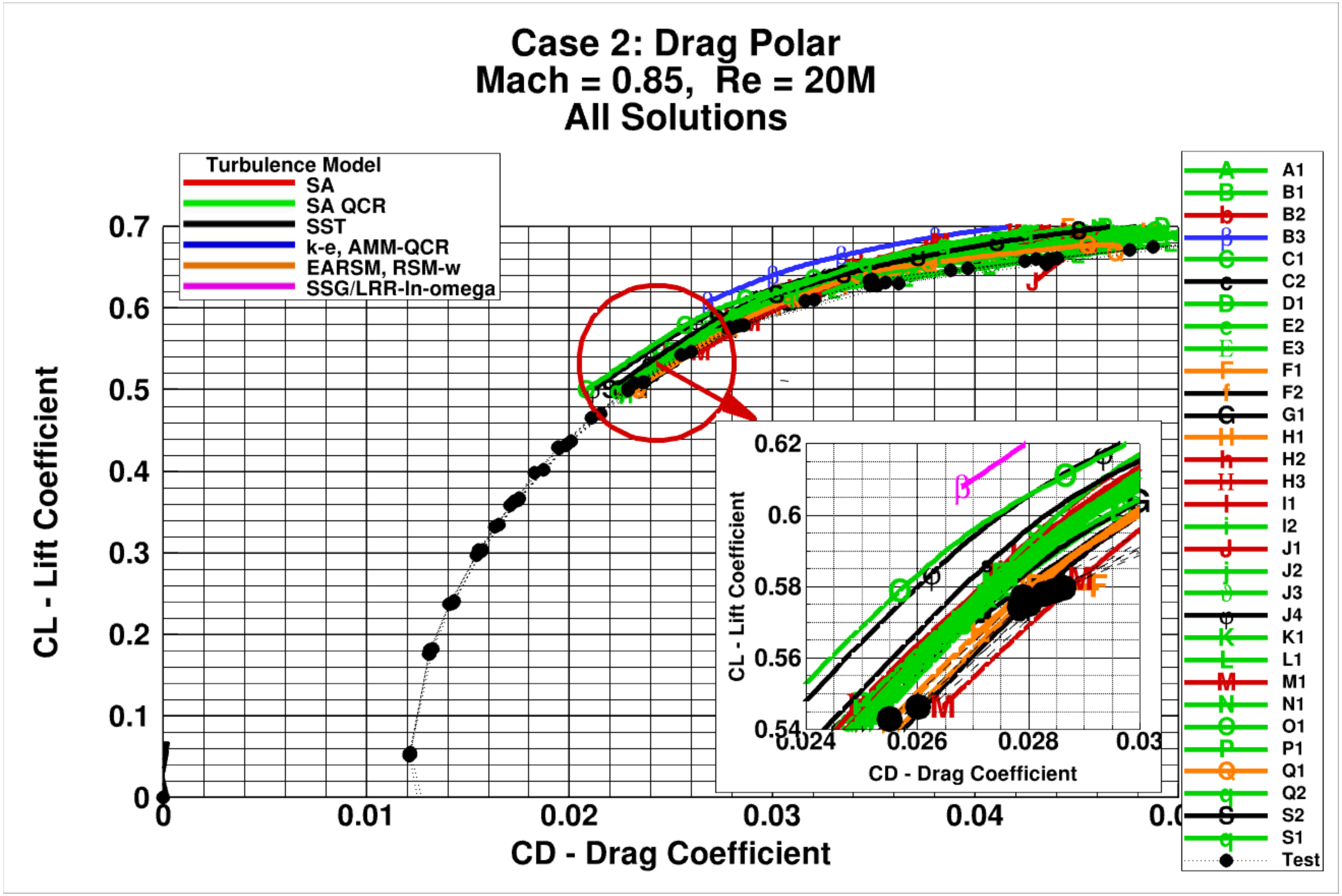
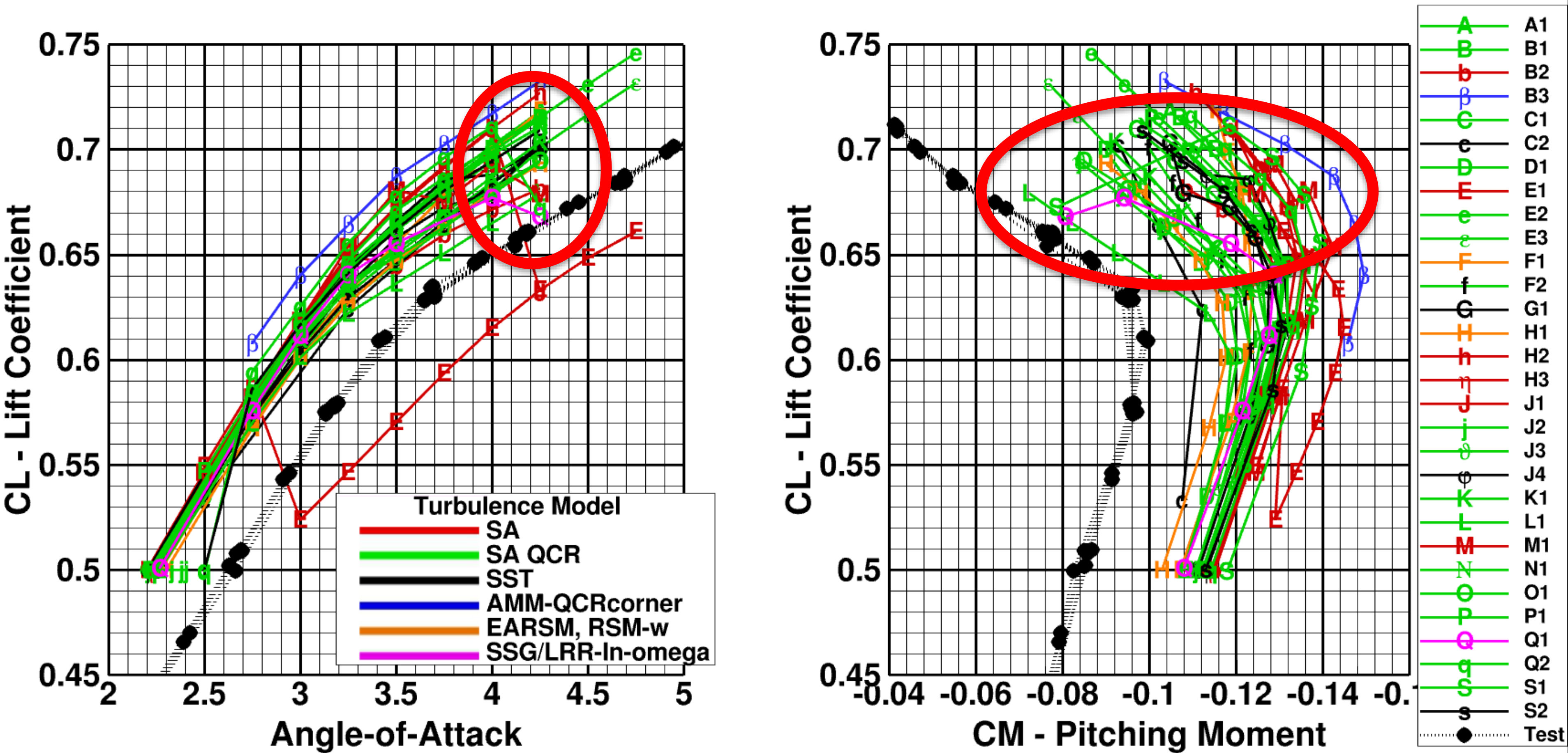
- Observations/Issues

Case 2: Angle of Attack Sweep

- **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: Drag Polar
Mach = 0.85, Re = 20M
All Solutions
Turbulence Model
SA
SA QCR
SST
k-e, AMM-QCR
EARSM, RSM-w
SSG/LRR-ln-omega
CL - Lift Coefficient
CD - Drag Coefficient
A1
B1
B2
B3
C1
C2
D1
E2
E3
F1
F2
G1
H1
H2
H3
I1
I2
J1
J2
J3
J4
K1
L1
M1
N1
O1
P1
Q1
Q2
S2
S1
Test

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



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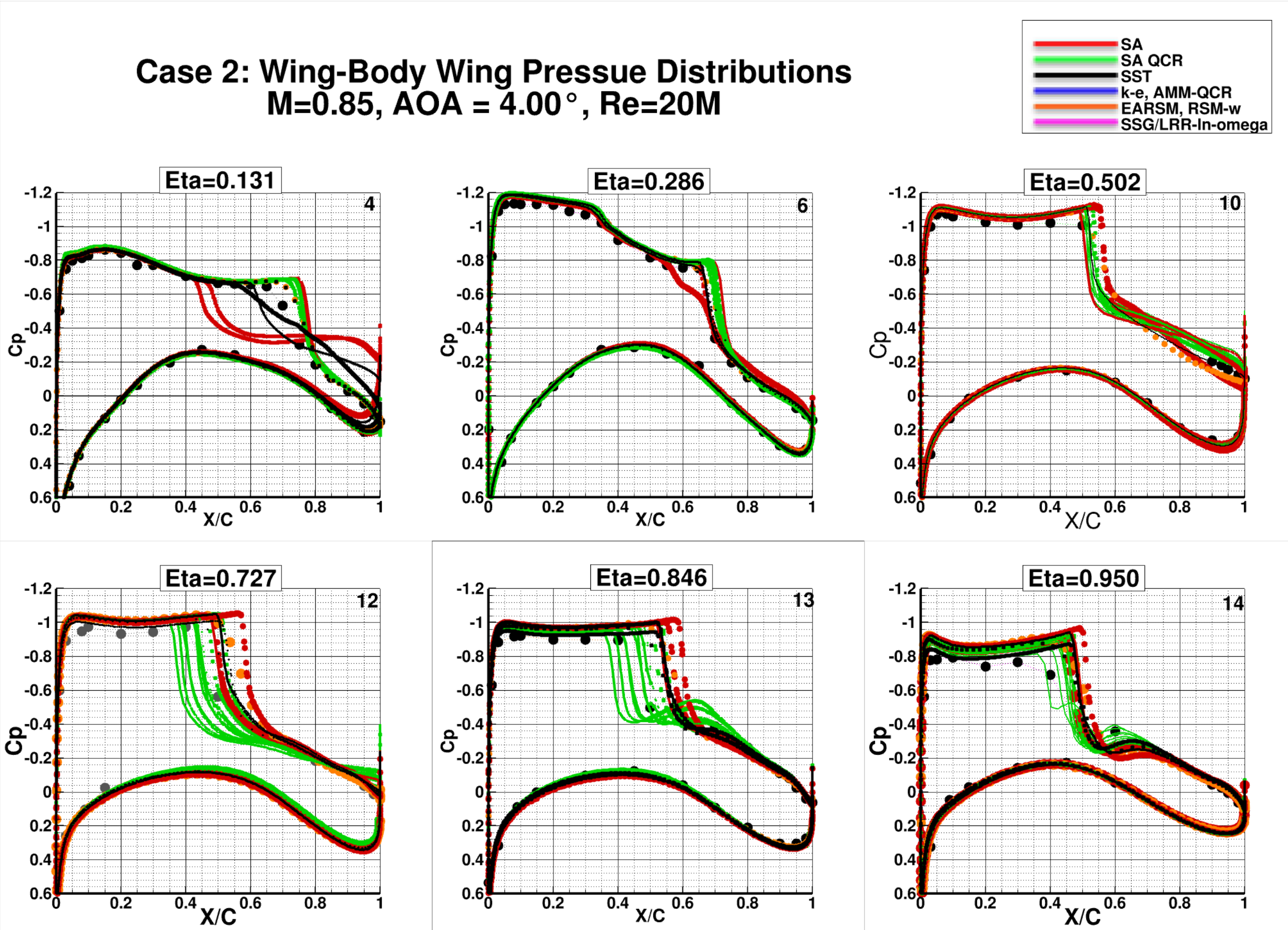
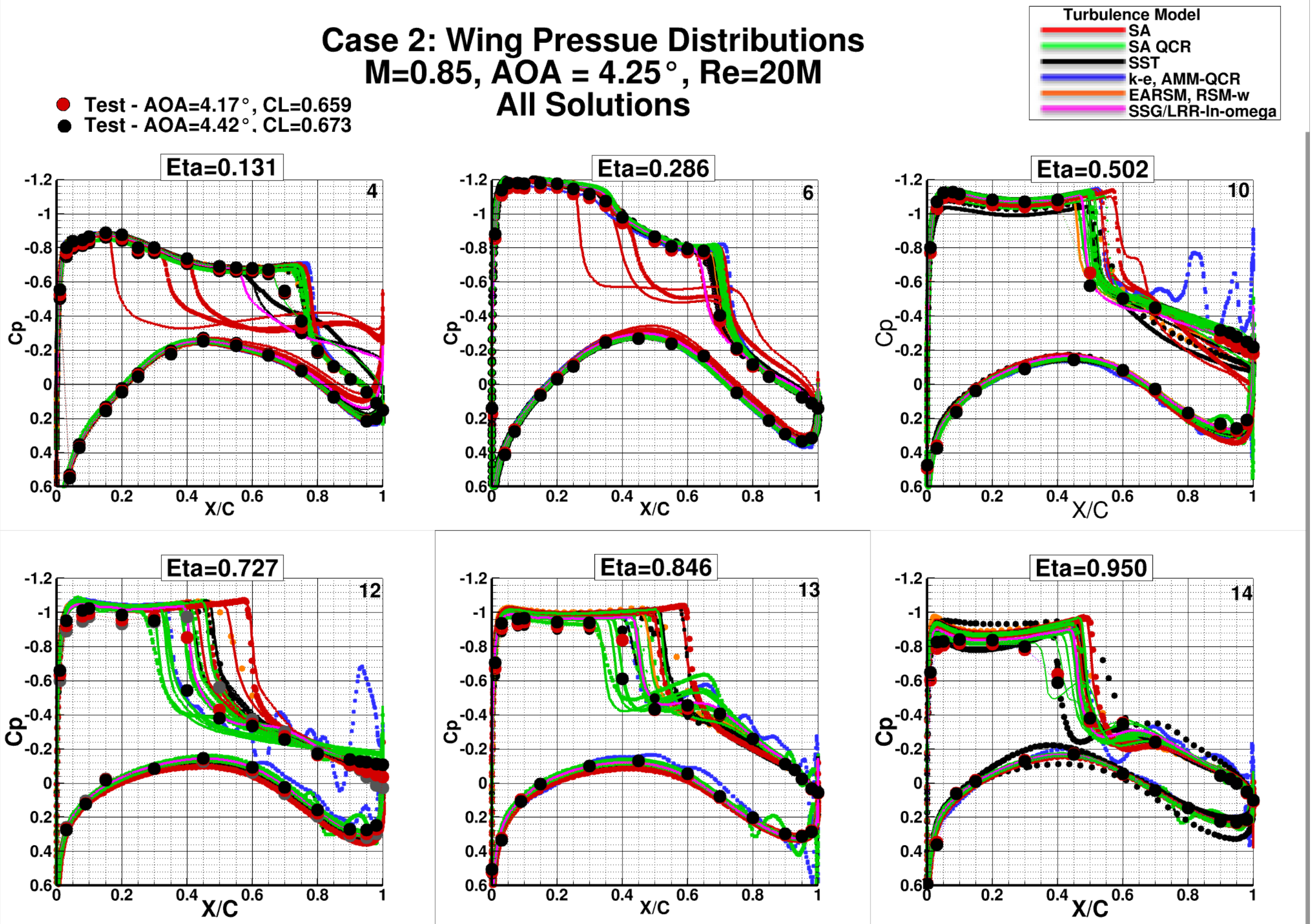
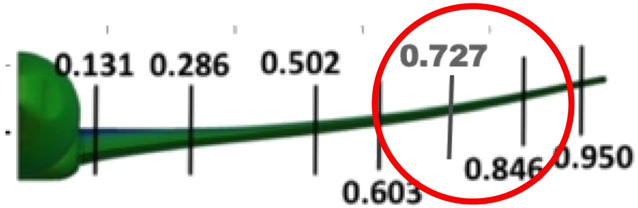


Case 2: Wing Pressue Distributions
M=0.85, AOA = 4.25°, Re=20M
All Solutions



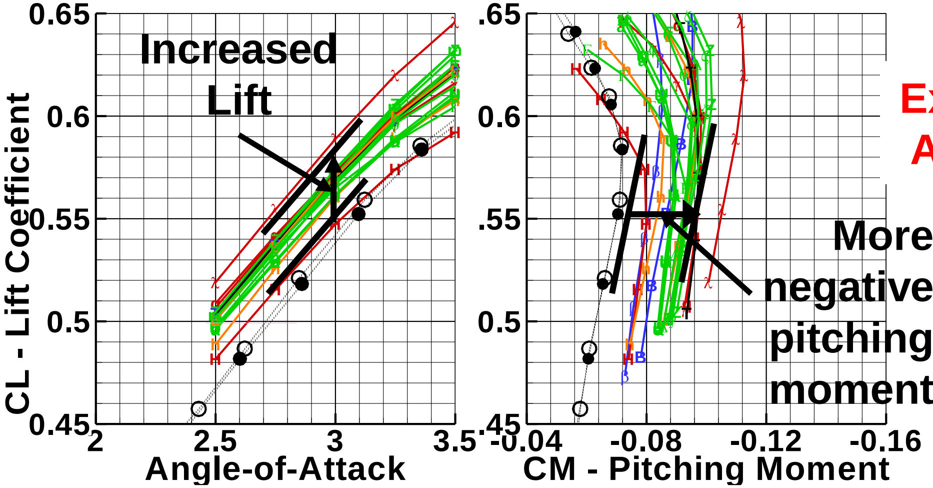
Excessive Aft-Loading

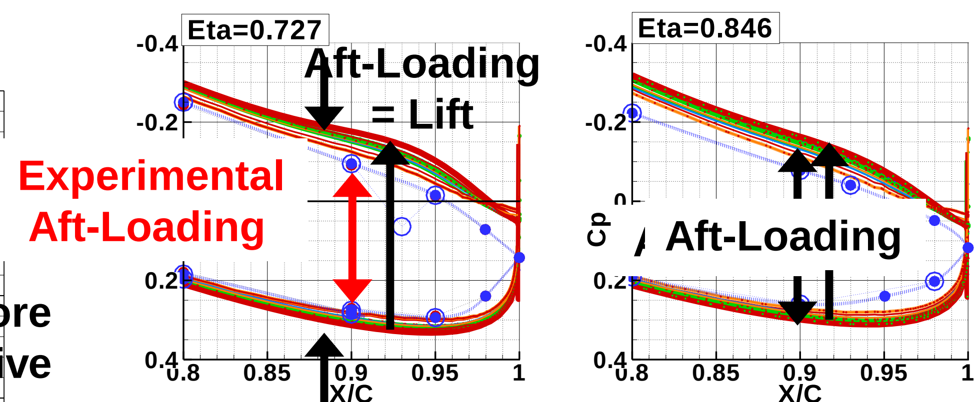
- Excessive aft-loading contributes to greater lift and more negative (nose down) pitching moment
- Little changed with increasing angle-of-attack
- NOT a geometry problem!



Trailing Edge Pressures

CFD Aft-Loading



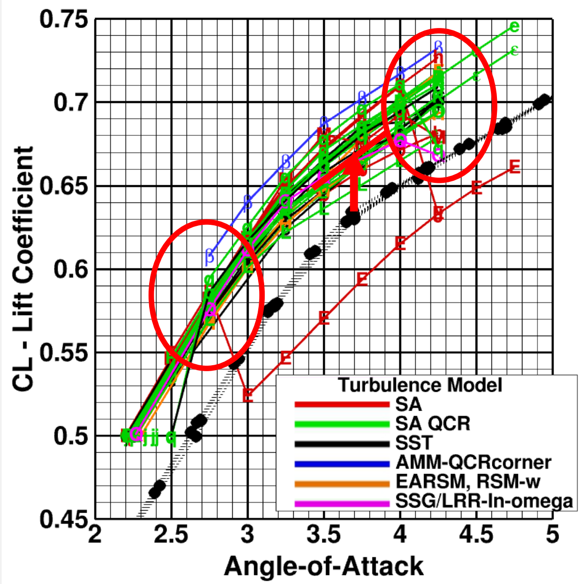


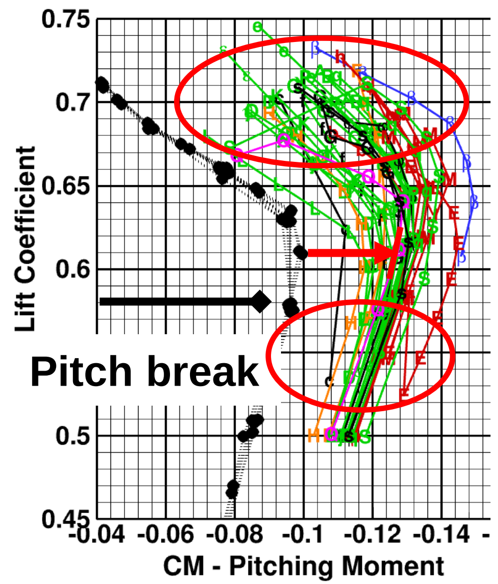
Experimental Data

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

- **Solution level: aft-loading**
- **Solution spread: shock location**
- **Accurate prediction of pitch break and subsequent pitching moment behavior important for safety!**

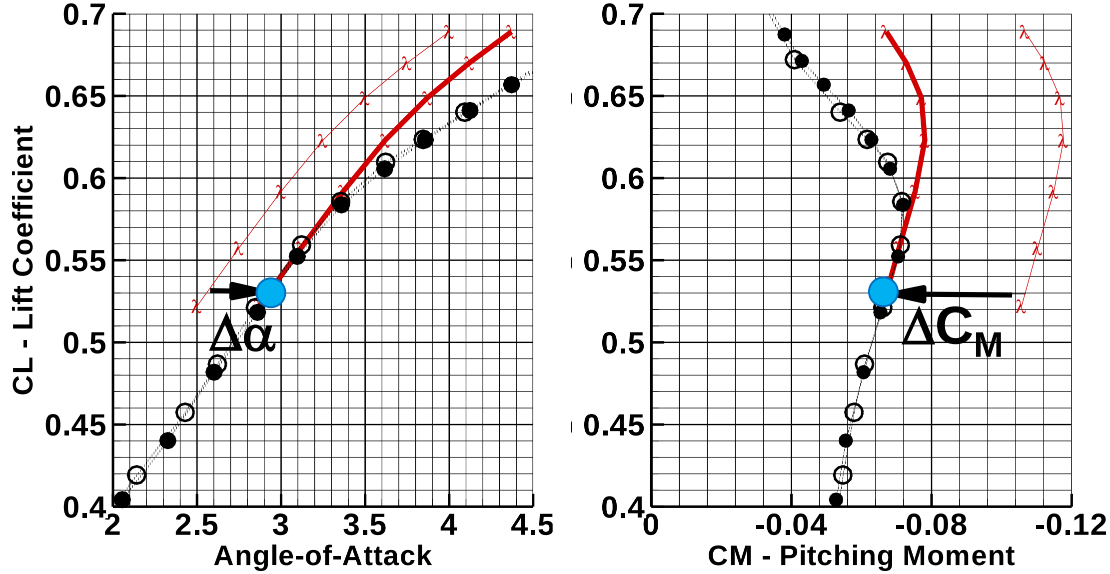
How can we make any sense of these results?





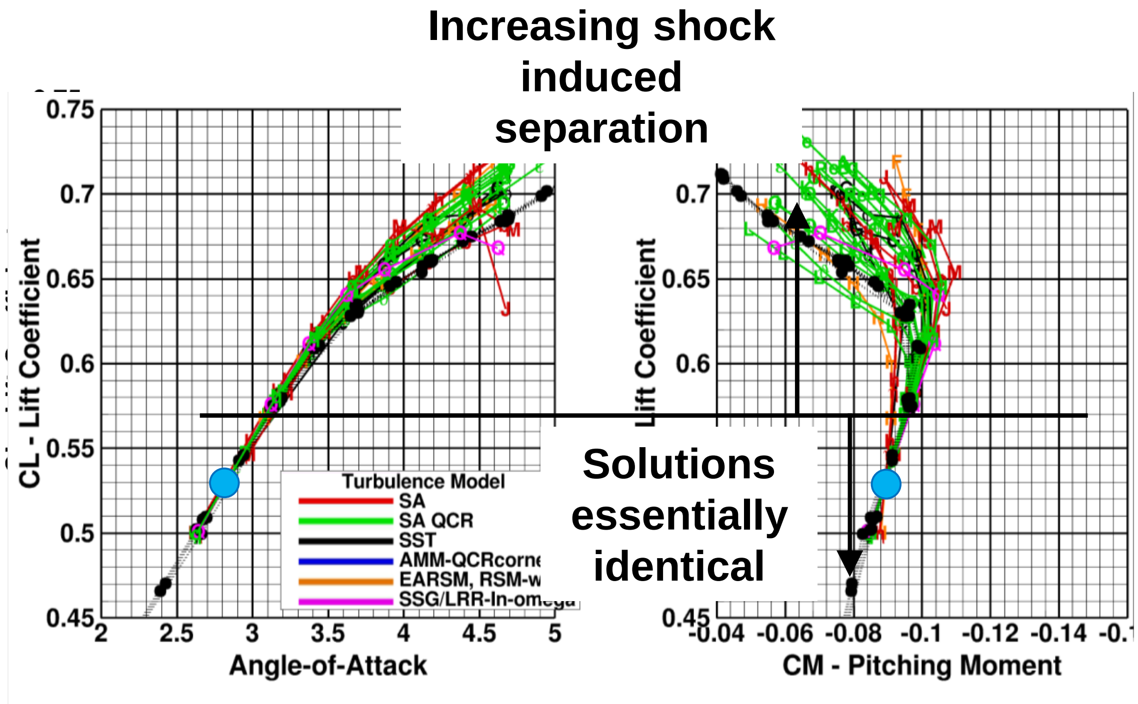
Collapsing CFD to a Common Value of α and C_M

- **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 (Δa) and Δ pitching moment (ΔC_M) to each solution.**
- **Clear view of C_L and C_M variation with a variation**

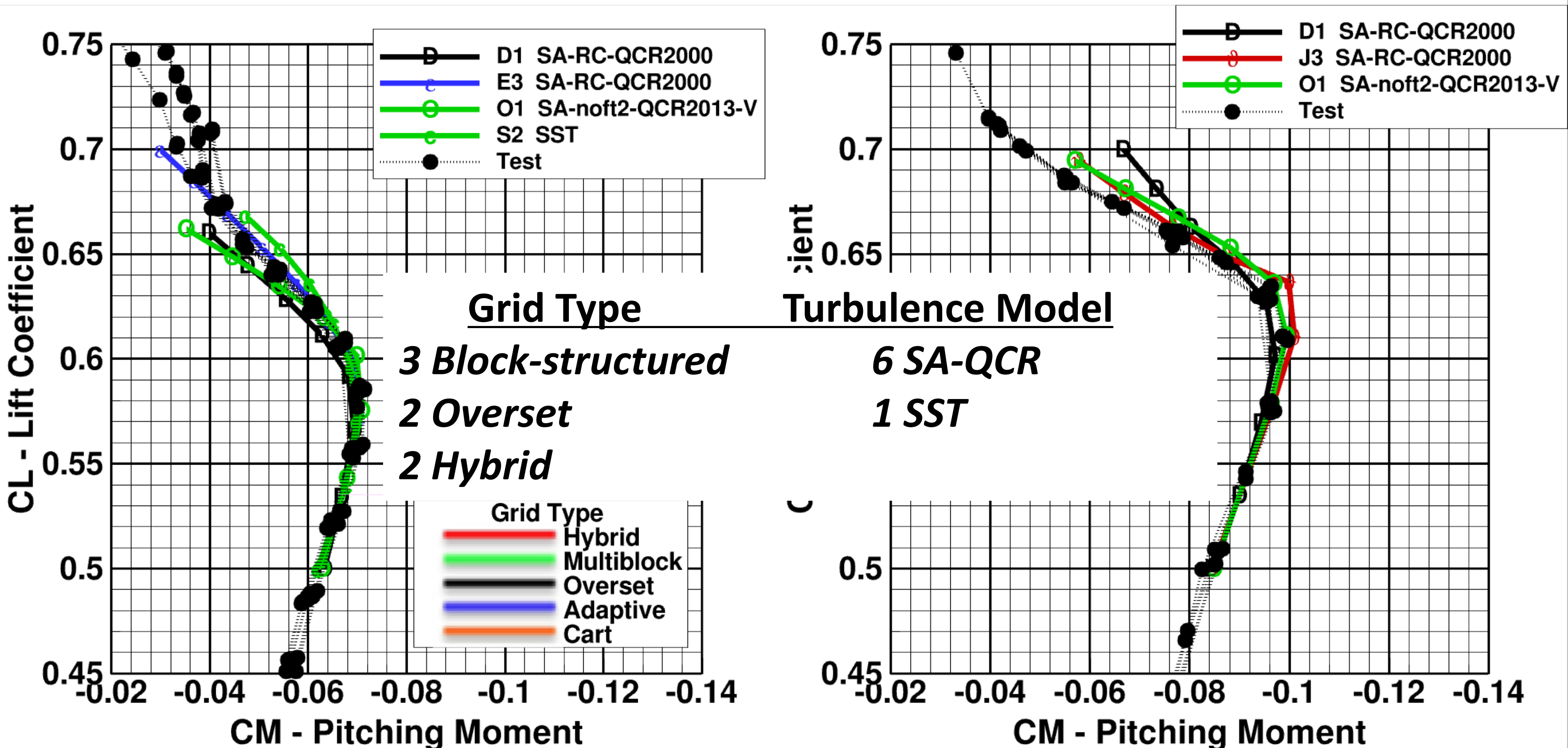


Lift and Pitching Moment Shifted to Match Experiment at $C_L = 0.53$.

- Collapsing data to a common point where the flow is still attached allows a better look at how the solutions vary with increasing angle-of-attack
- Note that up to about a C_L=0.57 all solutions are essentially identical
- Shock induced separation is increasing above C_L=0.57



Case 2: Pitching Moment
Mach = 0.85, Re=5M, Re=20M
Selected Solutions that Best Match Experimental Trends



Grid Type	Turbulence Model
3 Block-structured	*6 SA-QCR*
2 Overset	*1 SST*
2 Hybrid	

Case 2 - Observations

- High angles of attack characterized by shock induced separation which significantly influences pitching moments.
- Pitching moment trend for all solutions
  - Tighter moment up to CL=0.58
  - Significant force and moment spread at a=4.25° DCL=0.05, DCM=0.043
- Most solutions that best matched pitching moment trends used SA-QCR turbulence model and a structured grid (but many outliers)
- Excessive aft-loading on outboard wing sections contributes to too negative section pitching moments and excessive section lift.

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- Observations/Issues

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

Flow conditions are: M = 0.85, CL = 0.50 (Design cruise)
Different grid with appropriate Re spacing and aeroelastic twist and deflection for each condition

- **Re = 5M LoQ, Reference temperature = 100° F (Same LoQ R5 medium grid solution from Case 2b)**
- **Re=20M LoQ, Reference temperature = -250° F (Same LoQ R30 medium grid solution from Case 2a)**
- **Re=20M HiQ Reference temperature = -182° F**
- **Re=30M HiQ Reference temperature = -250° F**

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Drag Predictions at and beyond Cruise for the Common Research Model by an International Collaborative Community

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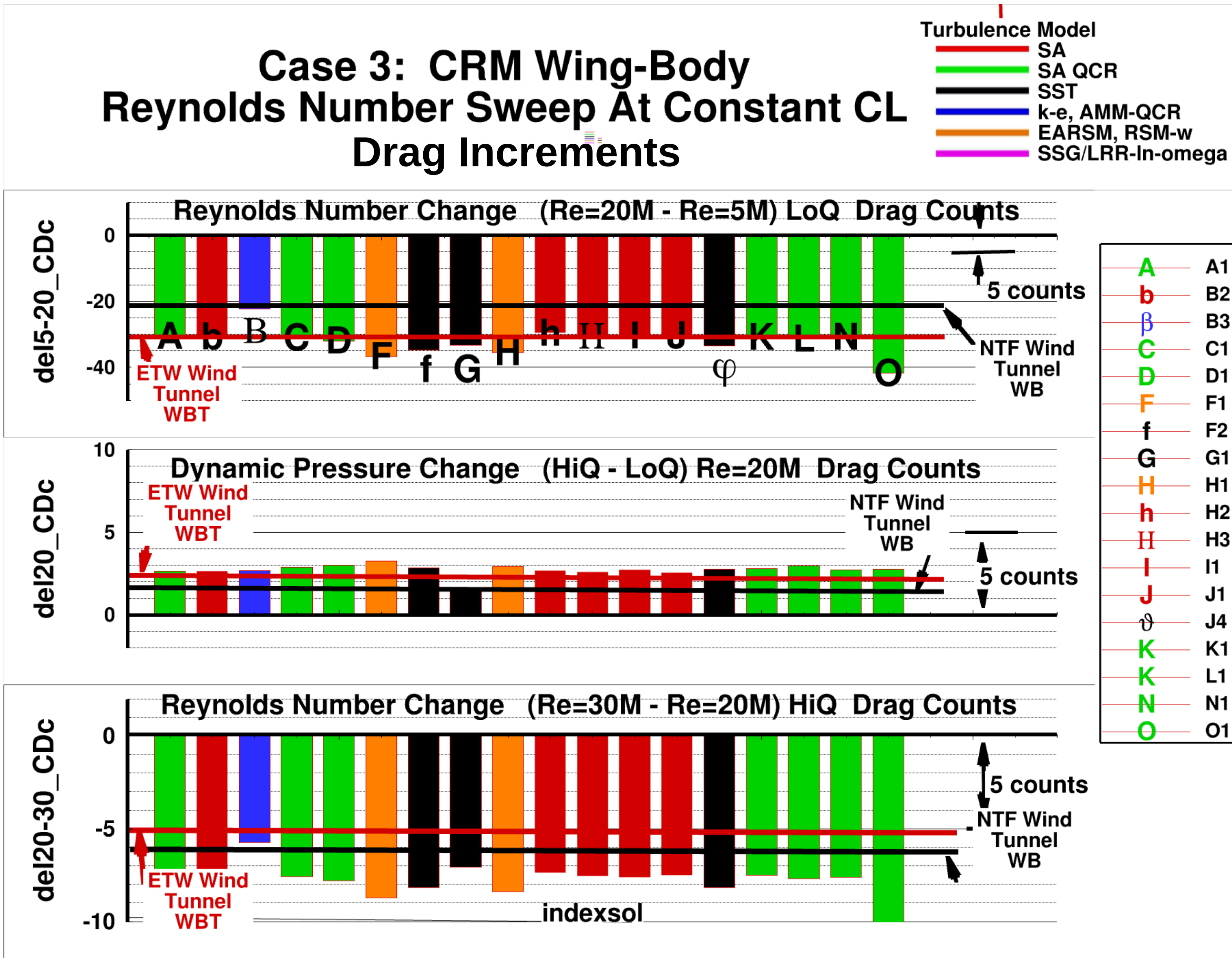
Delta Drag due to Reynolds number change 5M > 20M

Delta Drag due to dynamic pressure change 1310>1980 psf

Delta Drag due to Reynolds number change 20M > 30M



Case 3 - Observations

- **Computational drag trends with changes in Reynolds number and dynamic pressure were consistent with the test data.**
- **Little difference with choice of turbulence model**

Outline:

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- Observations/Issues

Case 4: CRM WB Grid Adaptation:

- Mach=0.85
- Chord Reynolds Number: $20x10^{6,}$ $5x10^{6}$ Optional
- Angle of Attack sweep – (preferred priority):
  - CL = 0.58
  - □ 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
- Solution Adapted Grids instead of specified fixed grids

Drag Predictions at and beyond Cruise for the Common Research Model by an International Collaborative Community

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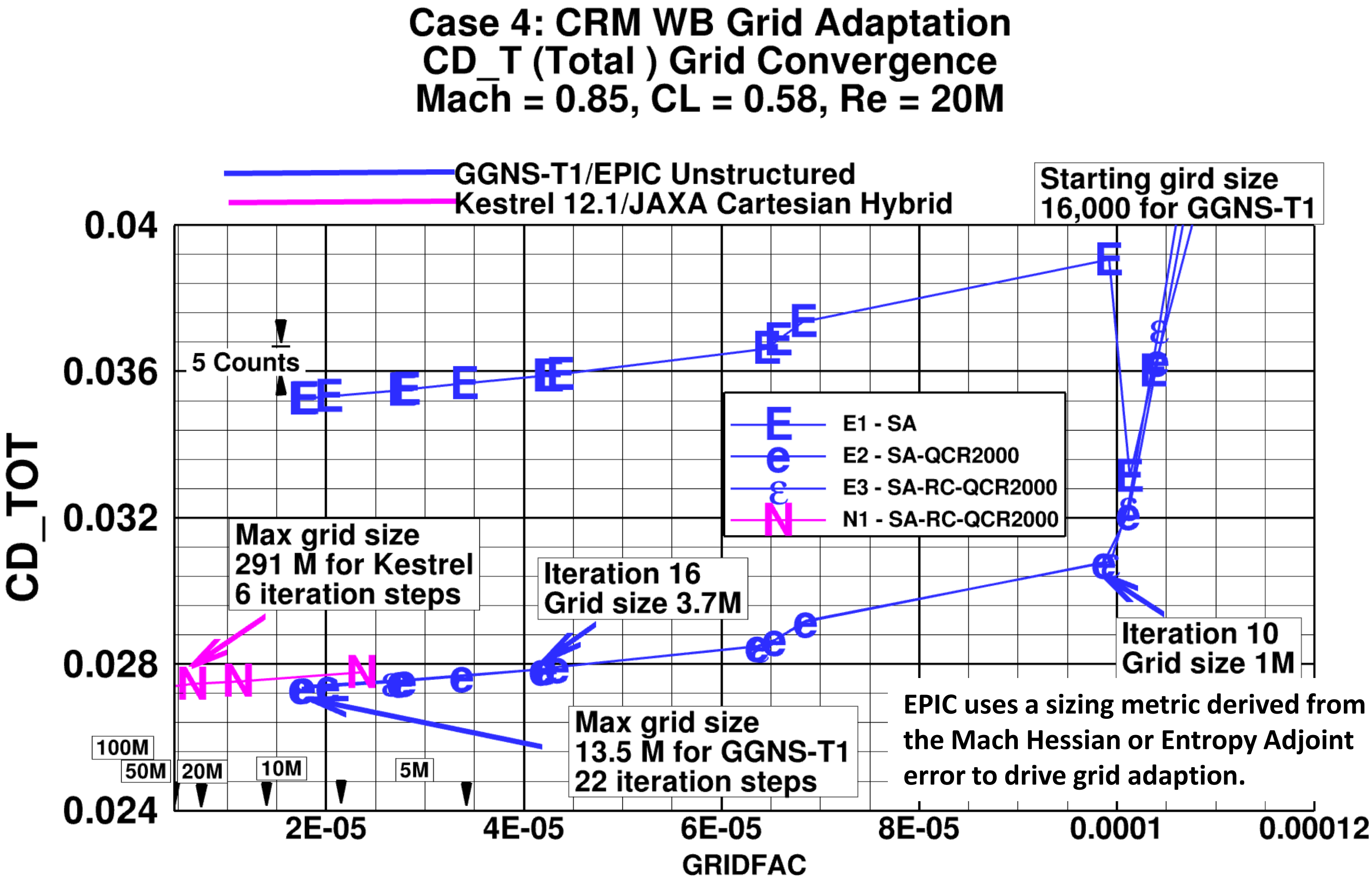
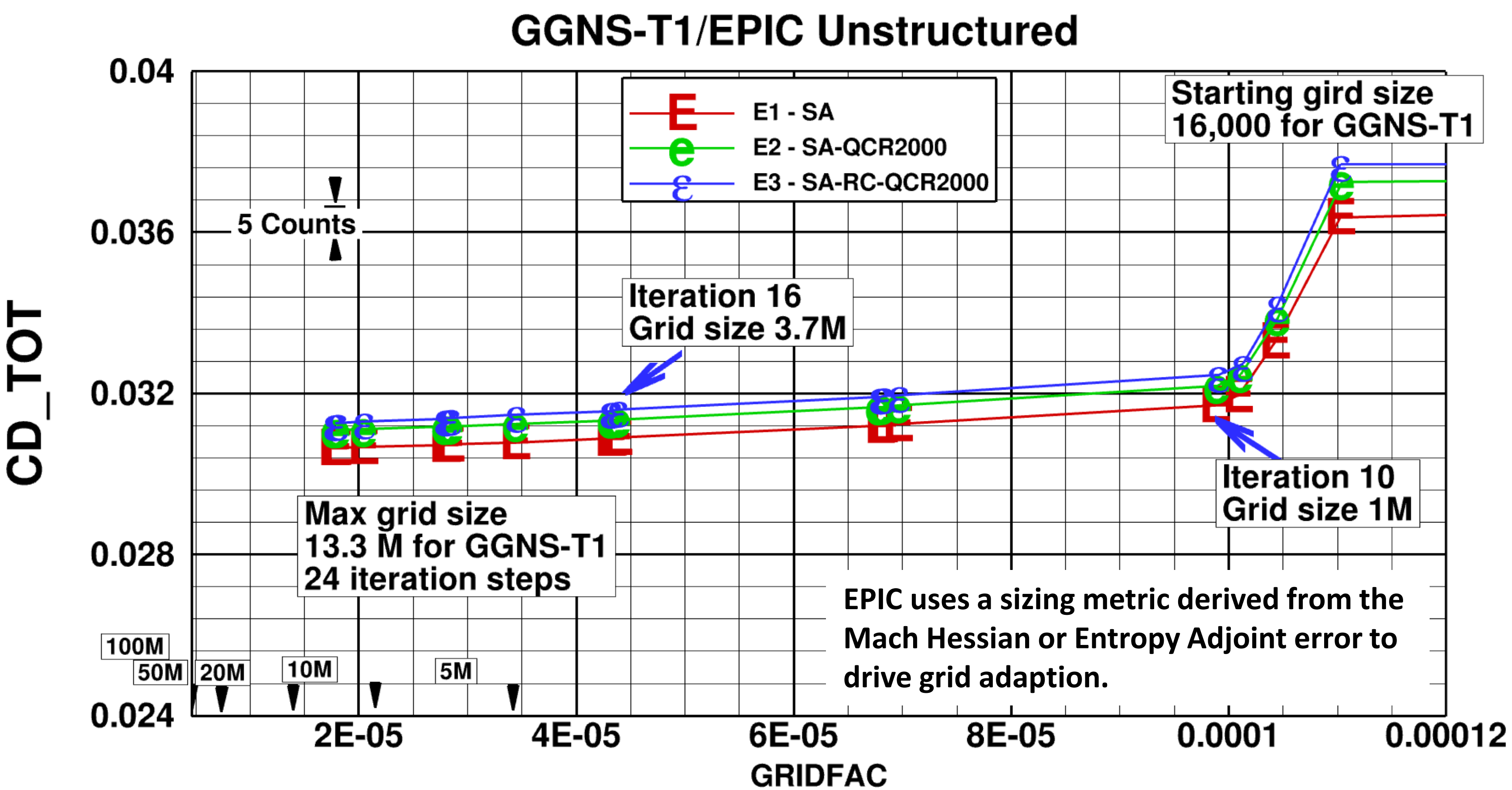


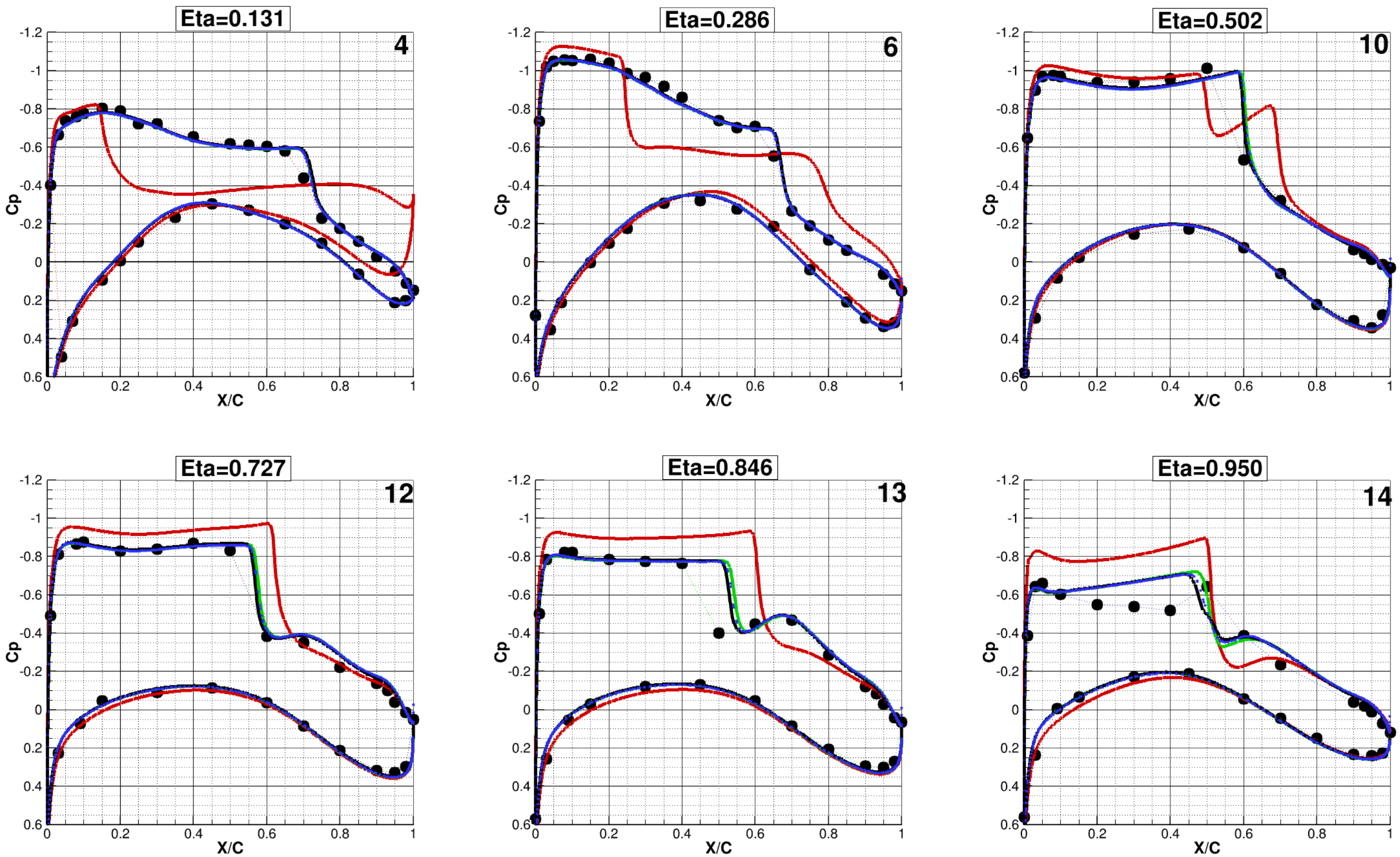
EPIC uses a sizing metric derived from the Mach Hessian or Entropy Adjoint error to drive grid adaption.

Drag Predictions at and beyond Cruise for the Common Research Model by an International Collaborative Community

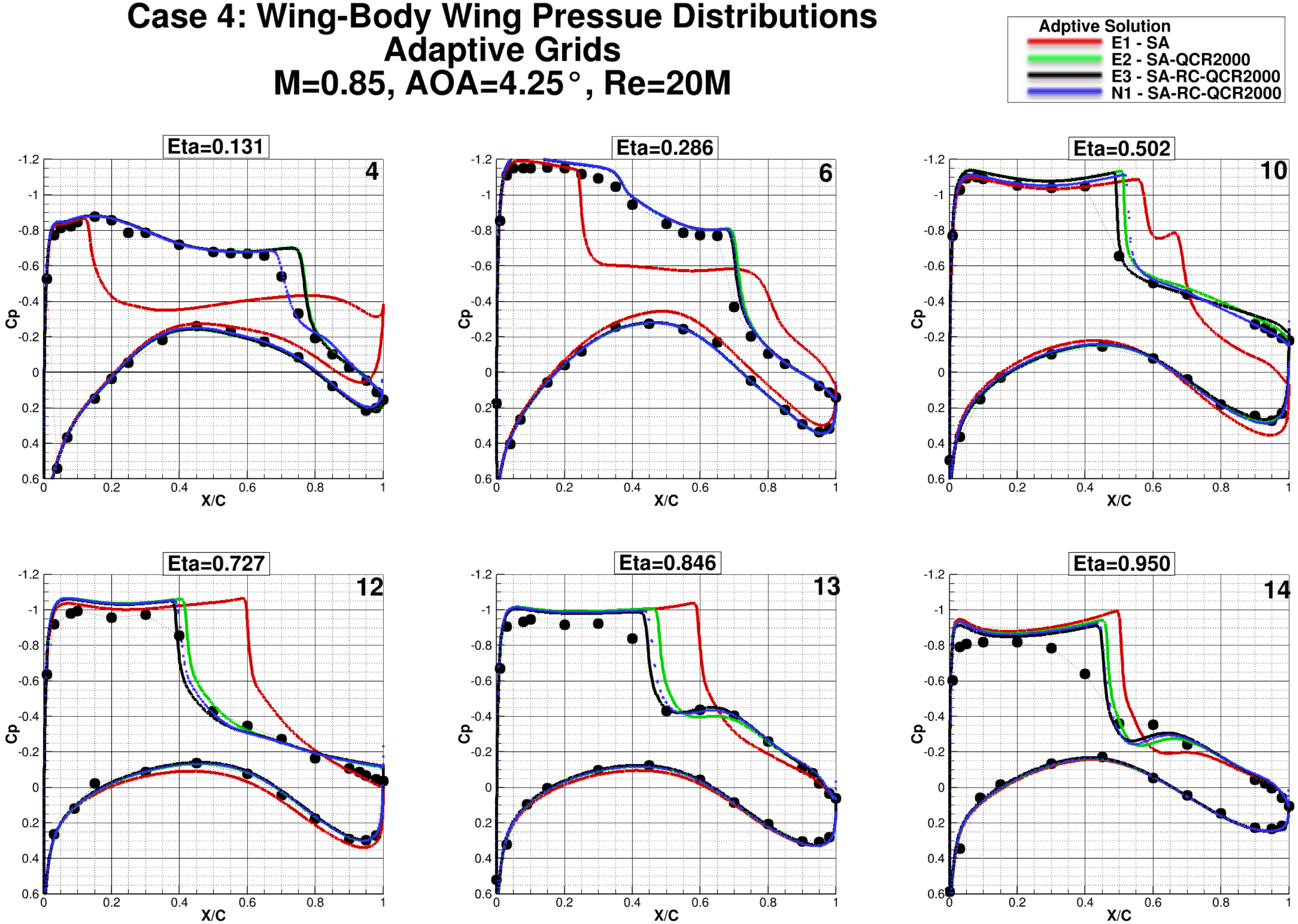
Case 4: CRM WB Grid Adaptation
CD_T (Total) Grid Convergence
Mach = 0.85, CL = 0.58, Re = 5M



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.**

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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

Only one solution submitted. Insufficient information submitted to draw any meaningful conclusions

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- Observations/Issues

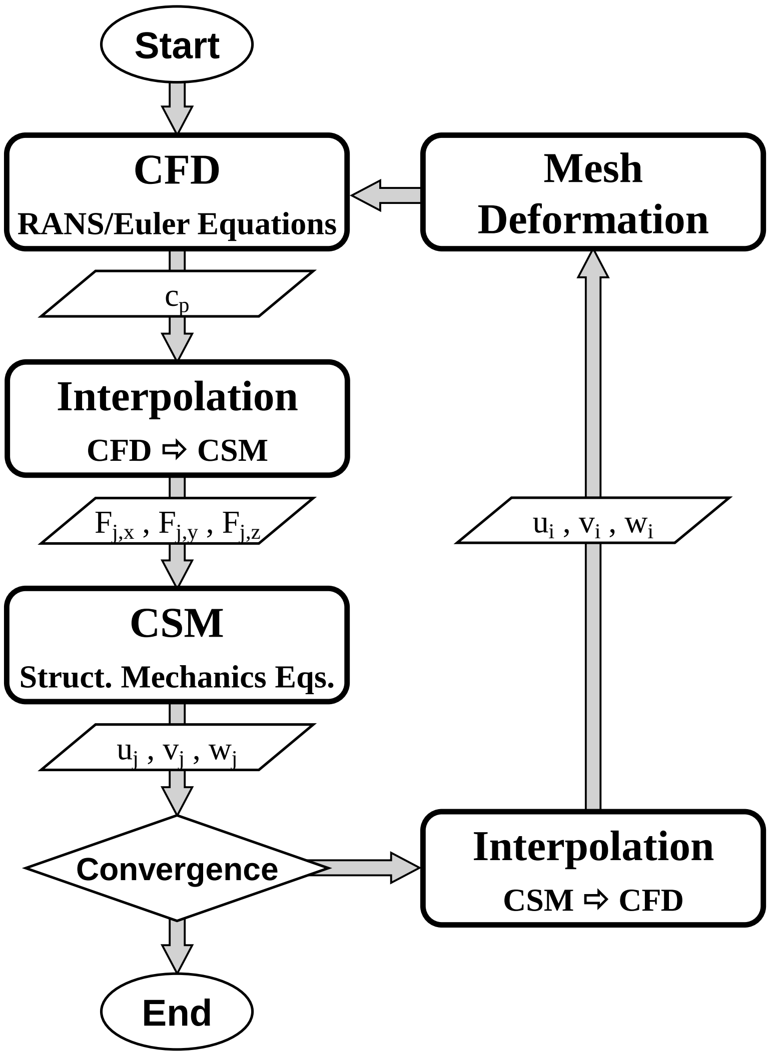
Case 6: CRM WB Coupled Aero-Structural Simulation: (Optional)

- Mach=0.85, C_L=0.580±0.001
- Chord Reynolds Number: 20x10^6, 5x10^6 Optional
- Fixed lift condition and/or Alpha Sweep for the CRM Wing-Body coupled with computational structural analysis
- Structural FEM from the CRM Website
- 'Medium' Grid Level, NoQ CRM geometry (Jig Shape)

- Solutions requested for:
  a) Target Lift Coefficient: C_L = 0.580, and/or
  b) Angle of Attack sweep: α = [3.25°, 3.50°, ..., 4.25°]

Common Approach to static Aero-Elastic Simulations:

- **Direct coupling of CFD simulation and structural analysis methods to determine the static aero-elastic equilibrium state.**
- **Simultaneous interaction between outer fluid flow and flexible aircraft structure simulated through:**
  1. alternating computation of solutions of the RANS equations and the structural mechanics equations,
  2. repeated interpolation of aerodynamic loads and structural deformations.
- **Start from initial RANS CFD solution,**



Case 6 Coupled Aero-Structural Simulation

CASE 6 PARTICIPANTS		
Organization	Metacomp Technologies Inc., USA	German Aerospace Center (DLR)
ID	K1	R1
CFD Code	CFD++ 20.1	TAU 2020.1.0
Turbulence Model	SARC-QCR	RSM-$ln(\omega)$
Grid Type	Common Hybrid (JAXA)	Common Hybrid (DLR)
CSM Code	ICSM++	NASTRAN 2019.0
Coupling Method	direct	direct
Force Interpolation	nearest neighbor	nearest neighbor
Mesh Deformation	RBF	RBF

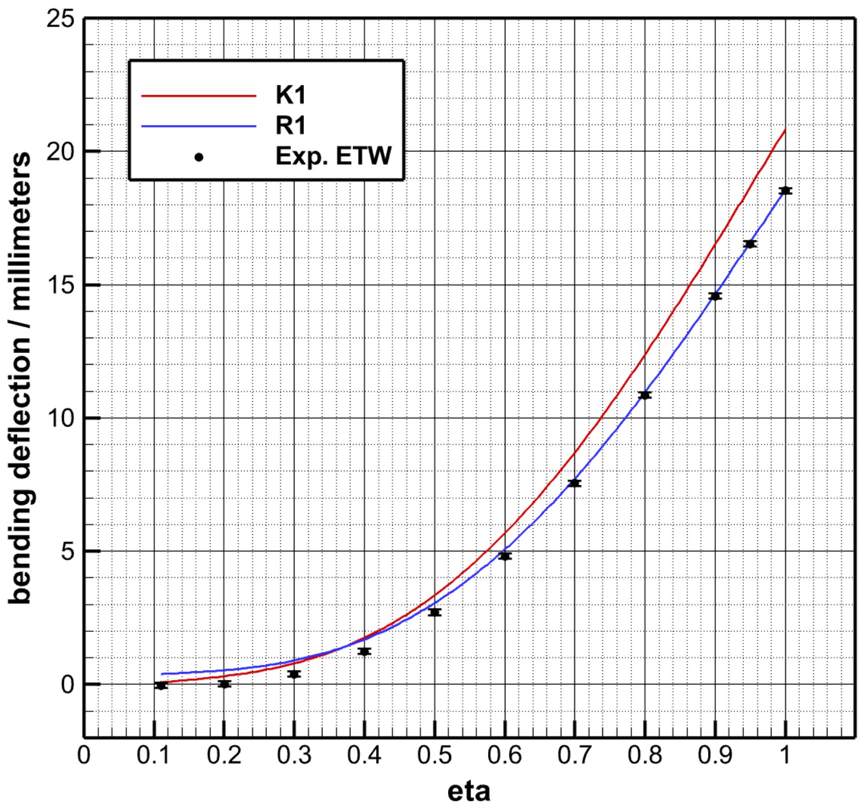
Case 6 Coupled Aero-Structural Simulation

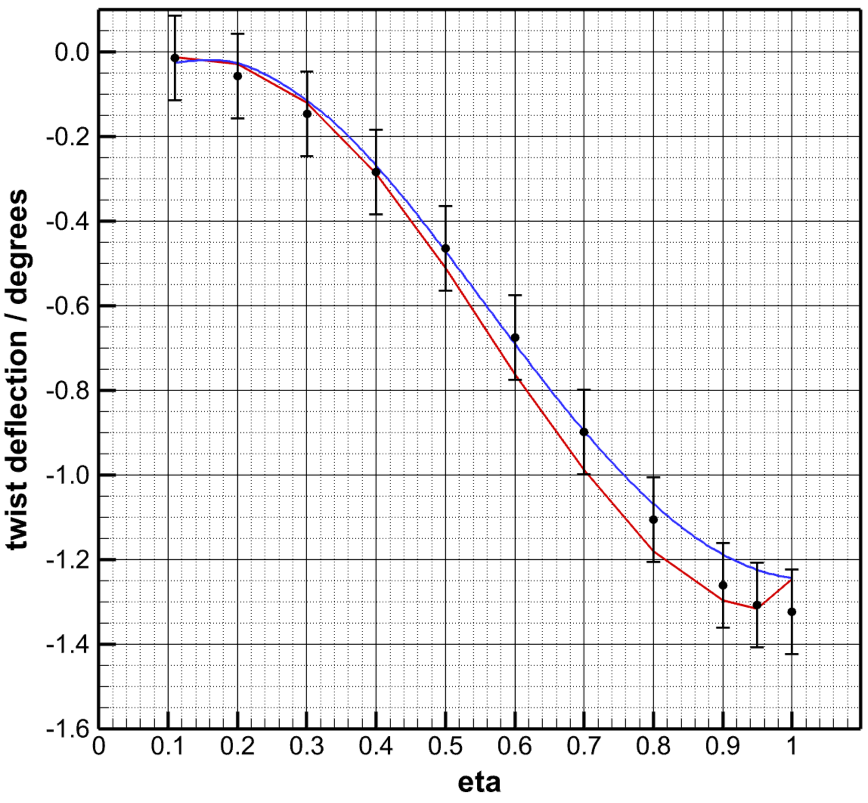
CASE 6 PARTICIPANTS		
Organization	Metacomp Technologies Inc., USA	German Aerospace Center (DLR)
ID		
CFD Cod		
Turbulen		
Grid Typ		R)
CSM Coc		)
Coupling Method	direct	direct
Force Interpolation	nearest neighbor	nearest neighbor
Mesh Deformation	RBF	RBF

Data submitted for Case 6:

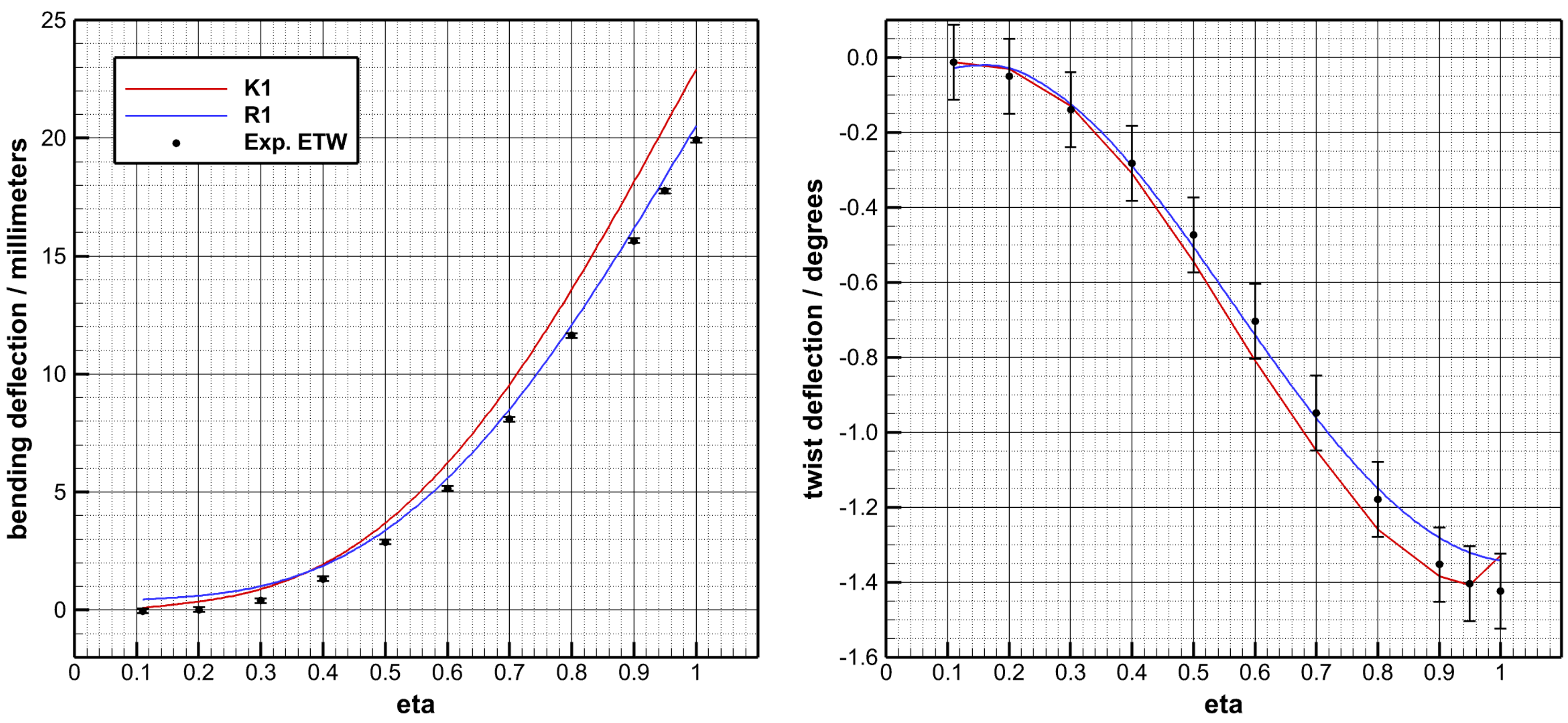
- **Wing bending and twist deformations.**
- **Sectional lift and moment distributions.**
- **Static pressure distributions.**

Case 6: Coupled Aero-Structural Simulation
Wing Bending & Twist Deformation
M=0.85, CL=0.58, Re=20M

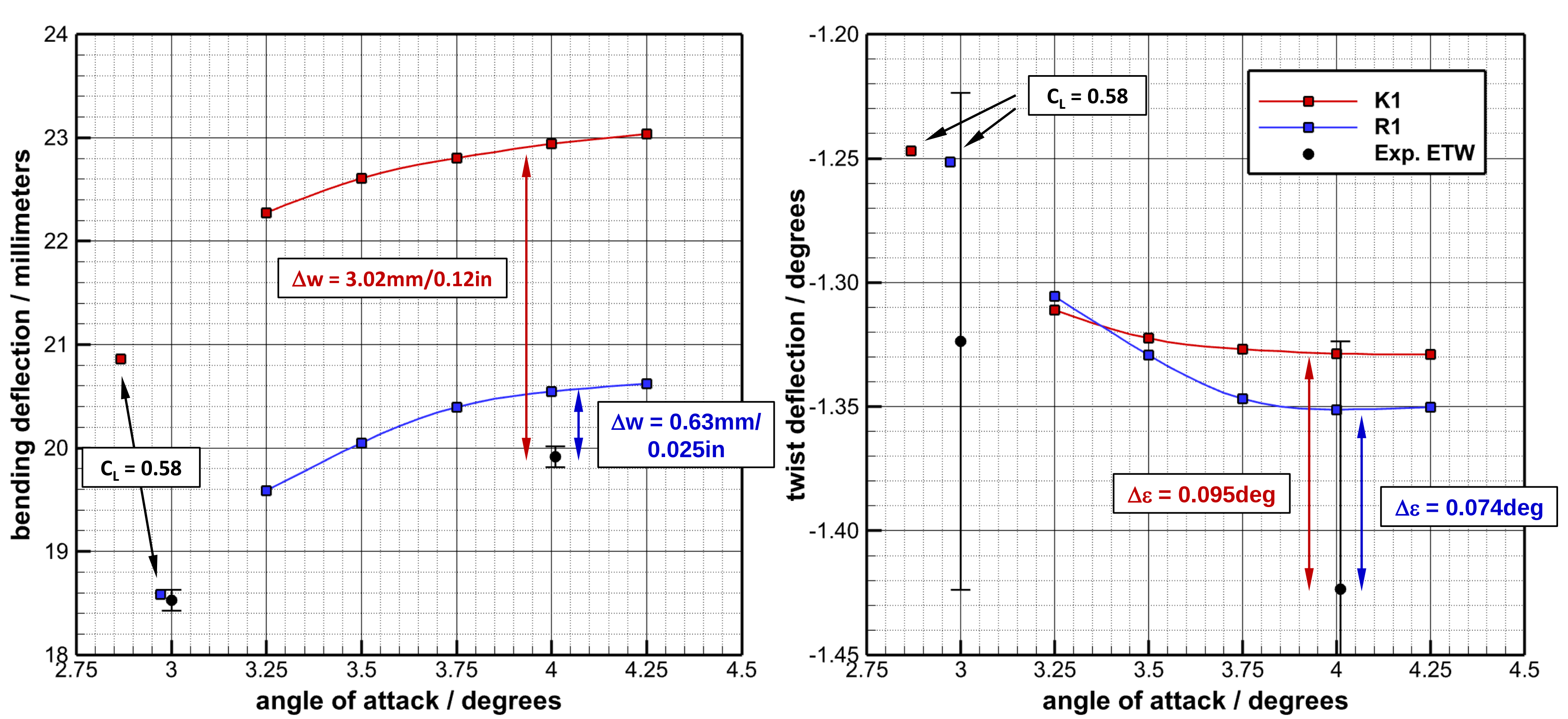




Case 6: Coupled Aero-Structural Simulation
Wing Bending & Twist Deformation
M=0.85, AOA=4.00°, Re=20M

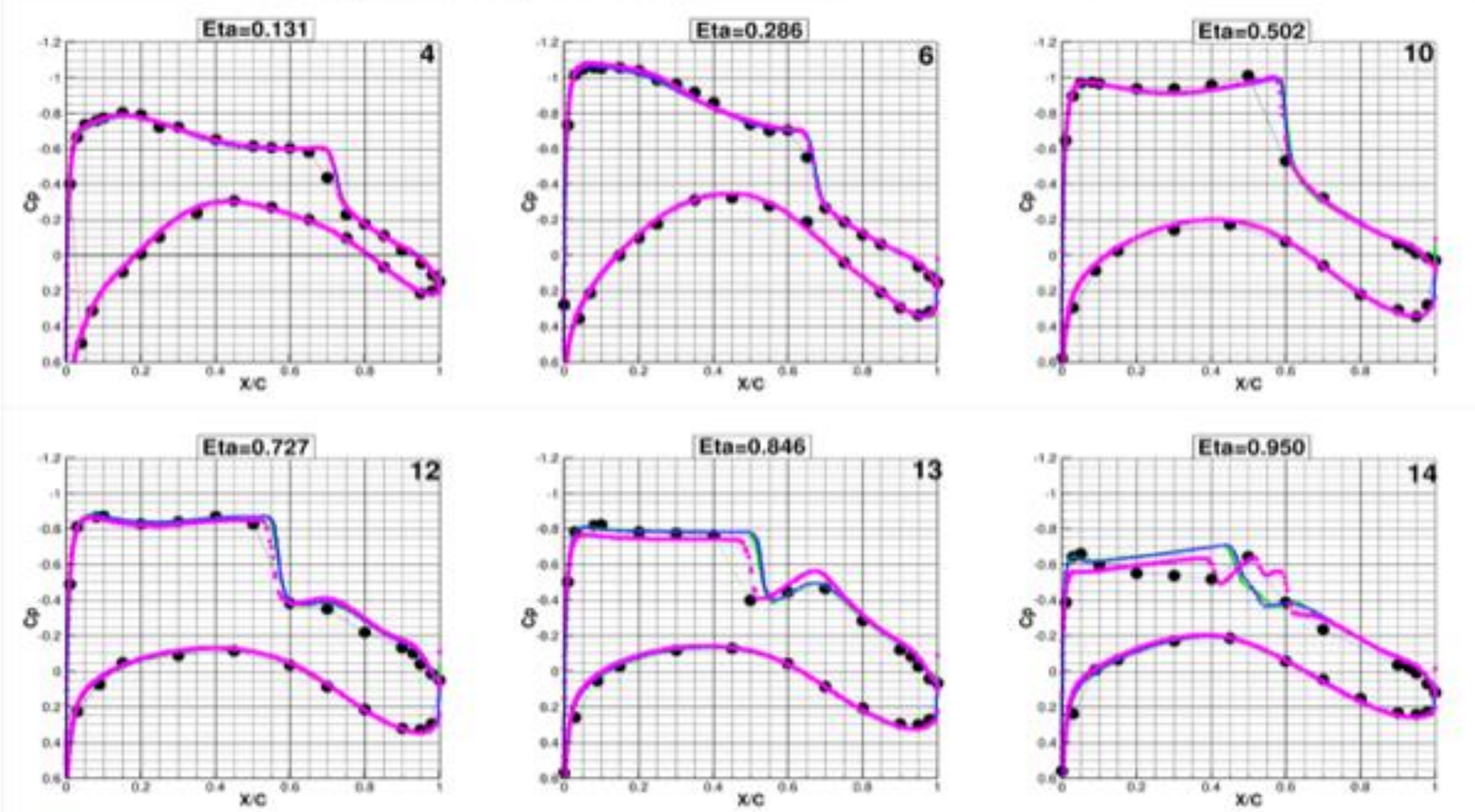


Case 6: Coupled Aero-Structural Simulation
Wing Tip Bending & Twist Deformation
M=0.85, Re=20M

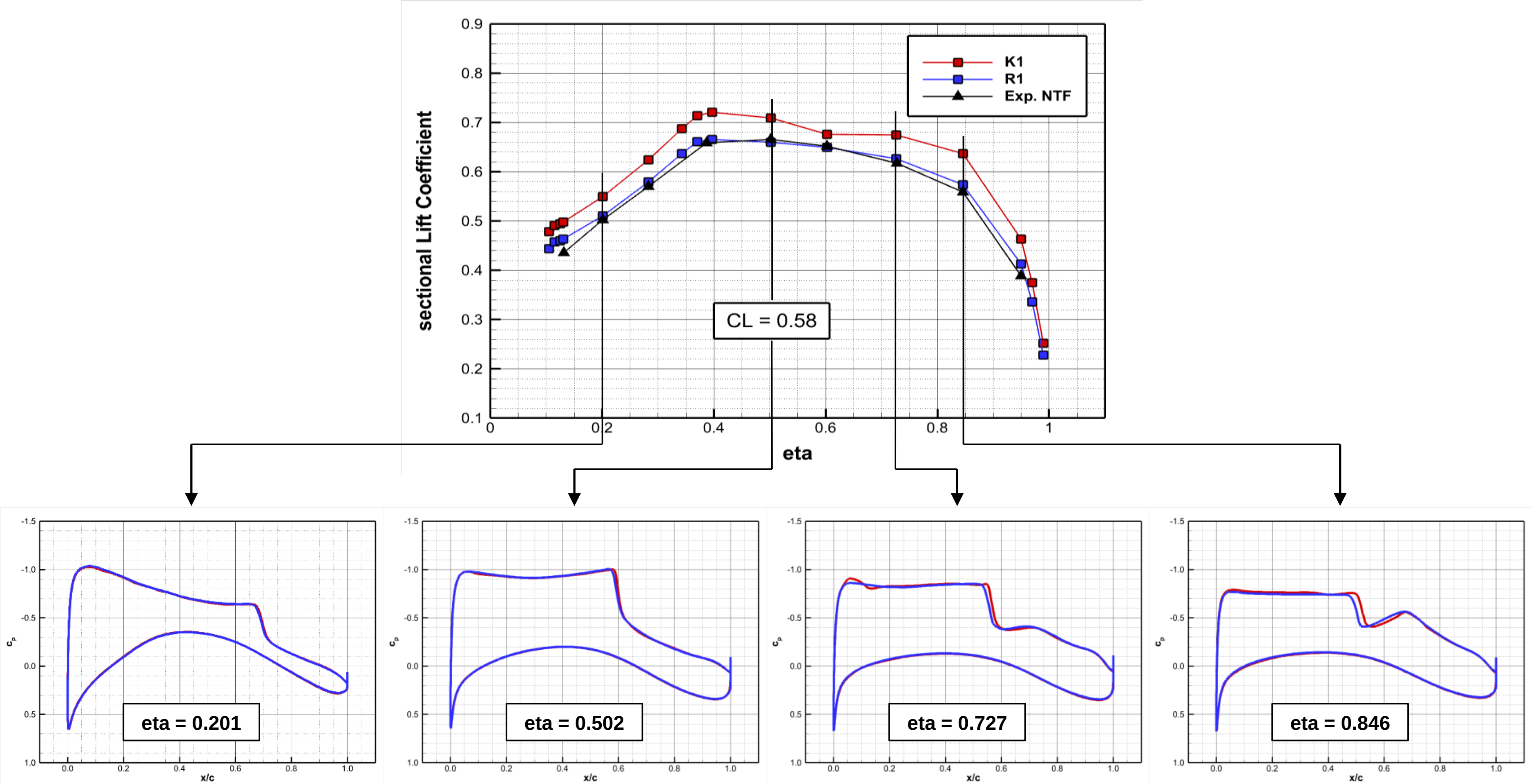


Case 6: Coupled Aero-Structural Simulation Wing Pressure Distributions M= 0.85, CL=0.58, Re=20M

- ● Exp. NTF
- D1 – Fixed Geometry – Case 1
- E3 – Fixed Geometry – Adaptive – Case 4
- R1 – Coupled Aero-Structural – Case 6



Case 6: Coupled Aero-Structural Simulation
Lift Distribution vs. Span & static Pressure Distributions
M= 0.85, CL=0.58, Re=20M



Case 6 - Observations

- **Difficult to make any meaningful observations from limited number of solutions available.**
- **Participants data show some differences in wing bending deformation, but good agreement for twist.**
- **Very good agreement of static pressure distributions over entire wing and for all angles-of-attack.**
- **Small differences in spanwise lift distribution.**

Outline:

- Configuration and Participants
- Case 1: Grid Convergence Study
- Case 2: Angle of Attack Sweep
- Case 3: Reynolds Number Sweep
- Case 4: Grid Adaptation (Optional)
- Case 5: Beyond RANS (Optional)
- Case 6: Coupled Aero-Structural Simulation by Stefan Keye (Optional)
- Observations/Issues

General Observations and Comments:

- Drag comparisons 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.
- We need to better understand the issue of the excessive aft loading
- A few solutions matched the test data at the high angles of attack very well – but WHY? (Steady RANS vs Unsteady WT test).
- 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.

General Observations and Comments:

- **These solution sets and experimental data represent a gold mine of information to further the knowledge of CFD and aerodynamics – GREAT PROJECTS FOR MASTERS STUDENTS.**

Where do we go from here?

1 or 2 paper sessions planned for AIAA Aviation 2023 in June

8th Drag Prediction Workshop ??????

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

Thank You for Your Interest

Questions?