# Retrospective: DPW through the years with focus on CRM and Test Case 2b

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# Outline

– Introduction
– Brief Overview of DPW1, DPW2, and DPW3
– Introduction of the NASA High Speed Common Research Model
– Brief Introduction to DPW4, DPW5, Aeroelastics, DPW6,and DPW7
– Grid Convergence Results
– Angle-of-Attack Sweeps
– Other Results
– Issues
– General Observations and Comments

# CFD Drag Prediction Workshop

## Objectives

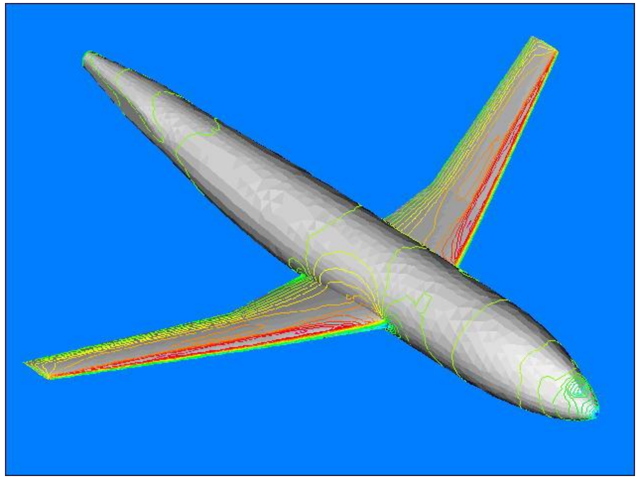
- To assess state-of-the-art CFD methods as practical aerodynamic tools for prediction of forces & moments on industry-relevant geometries, with a focus on drag
- To provide an impartial international forum for evaluating the effectiveness of CFD NS solvers
- To identify areas needing additional research and development

## Principles

- Use public-domain subject geometries and test data
- Maintain a public-domain accessible database of geometries, grids, and results

# 1st CFD Drag Prediction Workshop – 2001 (Anaheim)

## DLR-4F Wind Tunnel Model



**Required:**

- **Case 1:** $M_\infty$ =0.75, $C_L$= 0.500 ± 0.005
- **Case 2:** $M_\infty$ =0.75, $\alpha$= -3°, -2°, -1°, 0°, 1°, 2°

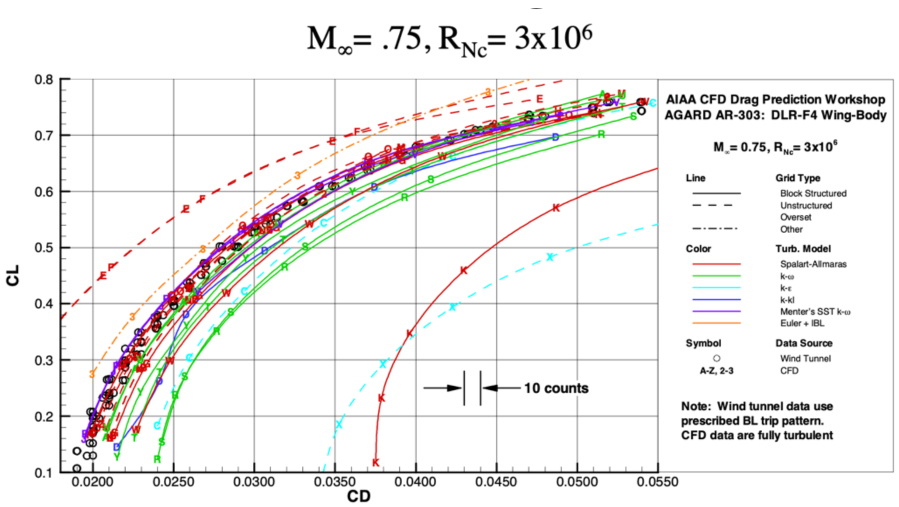
**Optional:**

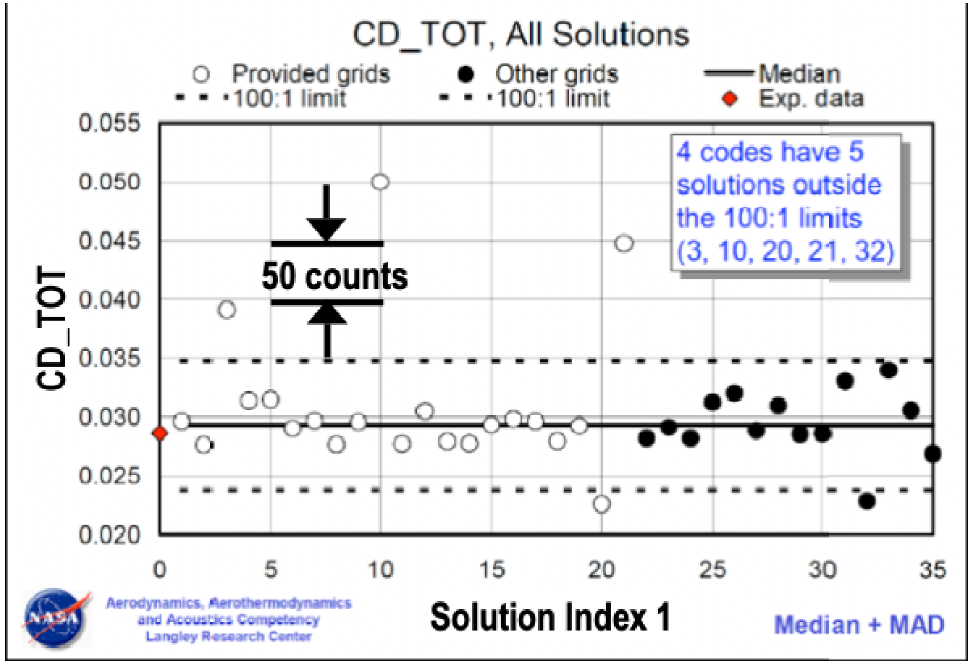
- **Cases 3:** $M_\infty$ sweep, $C_L$= .500
- **Cases 4:** $M_\infty$ sweep, $C_L$= .400, .600

**Standard Grids Supplied, Custom Grids Encouraged**

- **18 Participants**
- **28 Submittals**
- **14 Codes**
- **Grids Types**
  - **8 Block Structured**
  - **2 Overset**
  - **7 Unstructured**
  - **1 Cartesian**
- **Turbulence Models**
  - **14 Spalart-Allmaras (all variations)**
  - **10 k-omega**
  - **2 Realizable k- epsilon**
  - **Other**

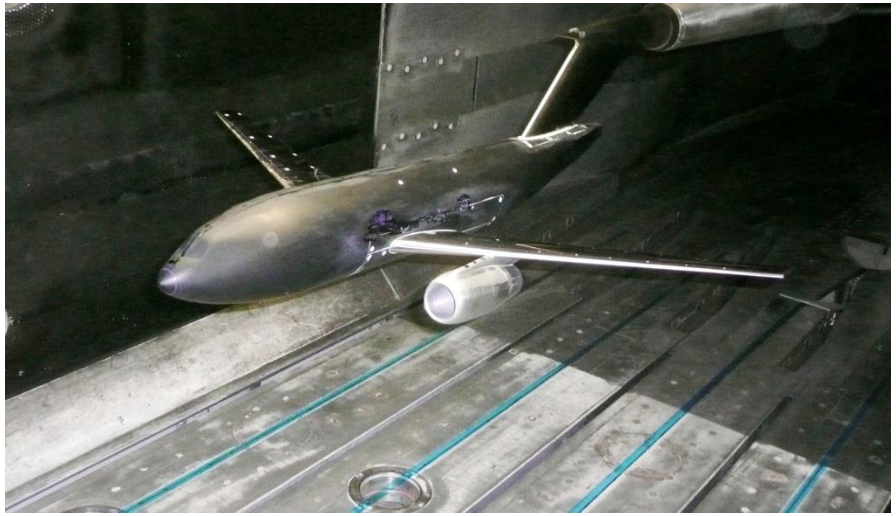
# 1st CFD Drag Prediction Workshop – 2001 (Anaheim)




- 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 a
  - CFD $C_M$ generally more nose-down

## DLR-6F Wind Tunnel Model



**Required: Both Wing-Body and Wing-Body-Strut Nacelle**

- **Case 1:** $M_\infty$ =0.75, $C_L$= 0.500 ± 0.005
- **Case 2:** $M_\infty$ =0.75, $\alpha$= -3°, -2°, -1°, 0°, 1°, 2°

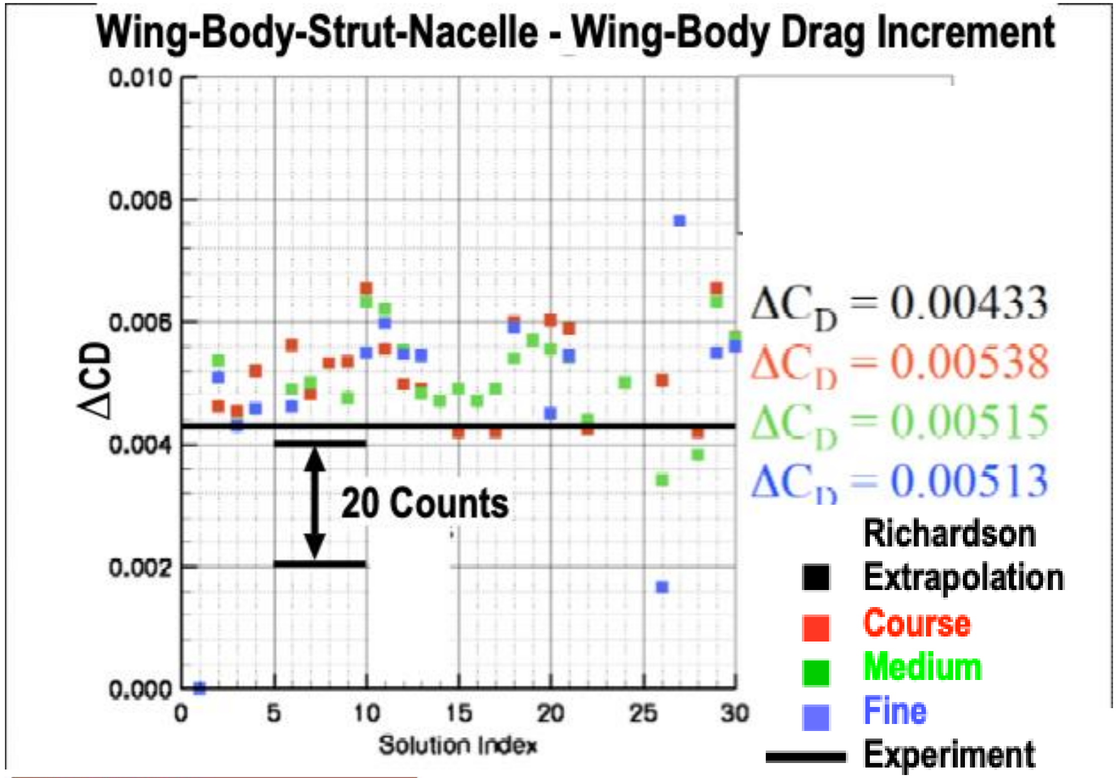
**Optional:**

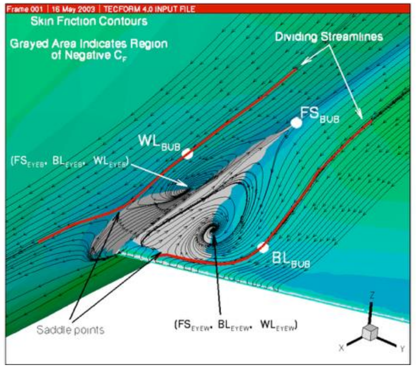
- **Cases 3:** Tripped vs. Tully Turbulent
- **Cases 4:** $M_\infty$ sweep, $C_L$= .500

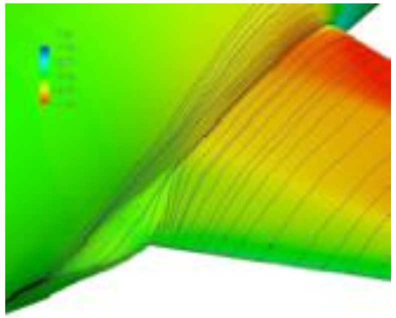
**Standard Grids Supplied, Custom Grids Encouraged**

- **22 Participants**
- **30 Submittals**
- **20 Codes**
- **Grids Types**
  - **14 Block Structured**
  - **5 Overset**
  - **11 Unstructured**
- **Turbulence Models**
  - **16 Spalart-Allmaras (all variations)**
  - **5 Menter SST**
  - **3 k-omega**
  - **1 Realizable k- epsilon**
  - **1 k-Wilcox**

# 2nd CFD Drag Prediction Workshop – 2003 (Orlando)



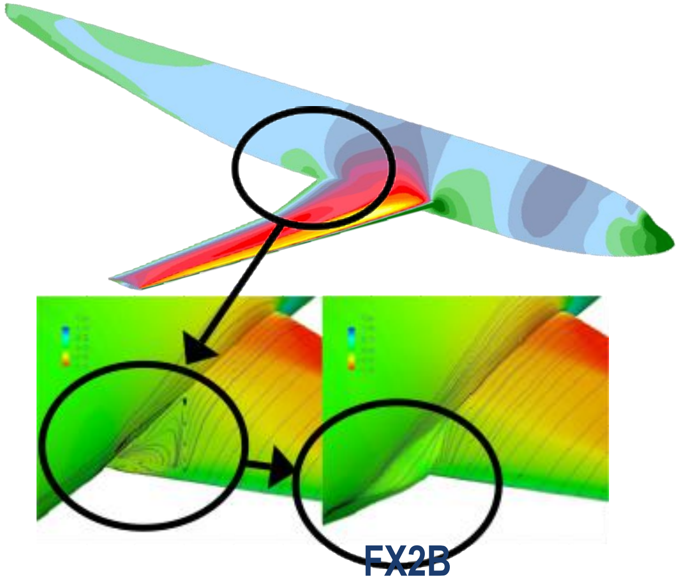



- Results in general vary similar to DPW-I
- Grid convergence study envisioned, but provided grids proved insufficient (Richardson extrapolation issue)
- Compared to DPW-I, large reduction in overall spread, but dispersion of the core essentially unchanged
- Configuration Increment (pylon/nacelle) much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

Large side-of-body separation led to design of a fairing for DPW3 drag increment test case

# 3rd CFD Drag Prediction Workshop – 2006 (San Francisco)

## DLR-6F Wind Tunnel Model




Fairing Designed to Elimate Side-of-Body Separation

**Configuration 1 - DLR-F6 Wing-Body with and without FX2B fairing**

- Grid Convergence $M_\infty$ =0.75, $C_L$= 0.500
- Alpha Sweep $M_\infty$ =0.75, a= -3° to 1.5°

## Simple Wings

Same wings featured in DPW8

**Configuration 2 - Wing Alone Comparison**

DPW-W1 - baseline

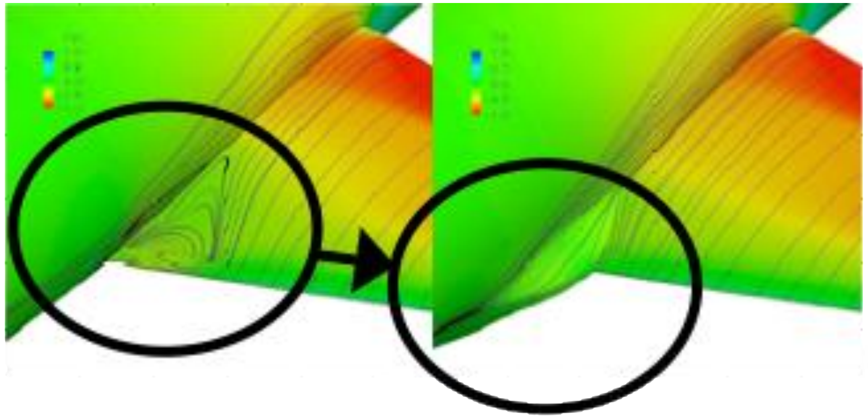
DPW-W2 - simple optimization

- Grid convergence study at Mach=0.76, alpha=0.5
- Drag polar at Mach=0.76, alpha= -1 to 3°

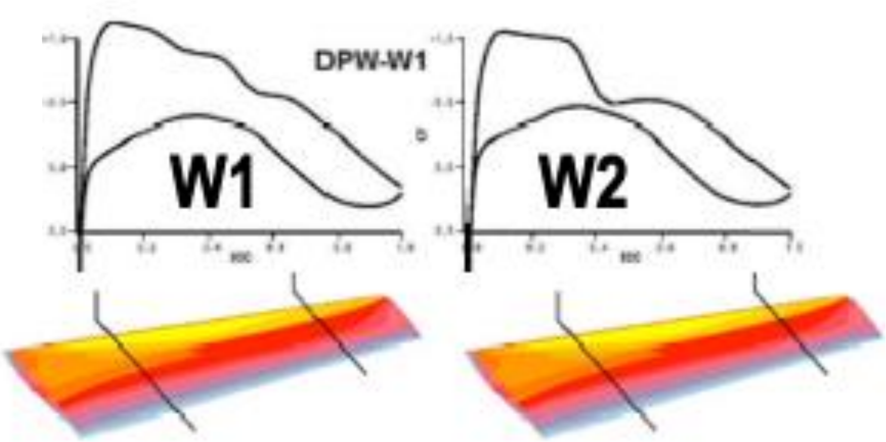
### Standard Grids Supplied, Custom Grids Encouraged

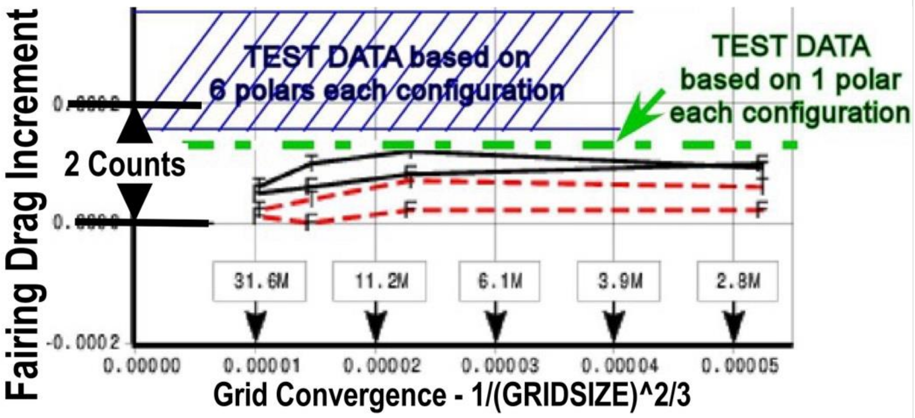
- 15 Participants
- 30 Submittals
- 18 Codes
- Grids Types
  - 11 Block Structured
  - 4 Overset
  - 11 Unstructured

- Turbulence Models
  - 12 Spalart-Allmaras
    - (all variations)
  - 8 Menter SST
  - 3 EASM
  - 2 k-omega
  - 2 k-epsilon



FX2B Fairing Designed to Elimate Side-of-Body Separation





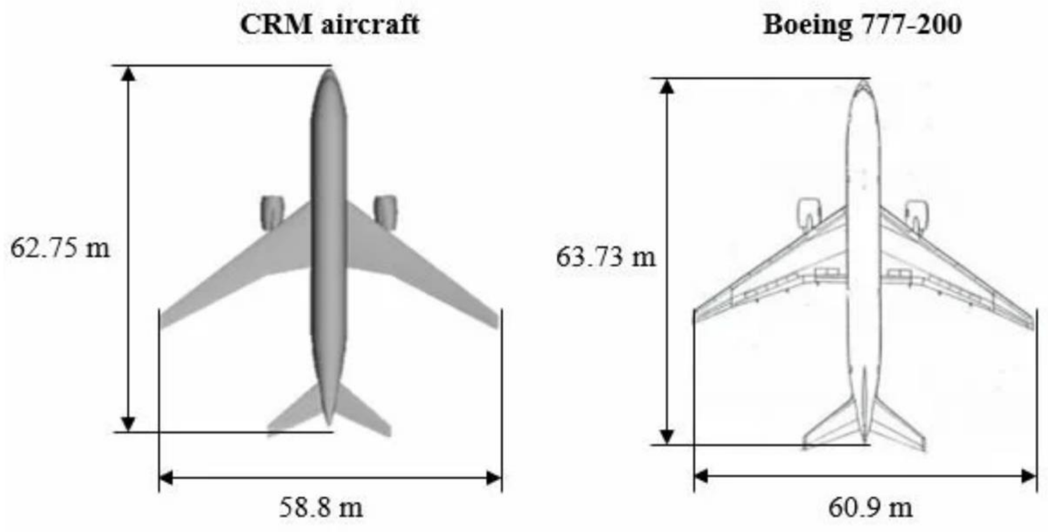
- Inboard separation bubble continues to be a major source of difficulty
- No major trends based on grid type or turbulence model
- Grid convergence characteristics suggest difficulty in generating consistent sets of grids
- Some sets had obvious problems with convergence, matching CL

Good news

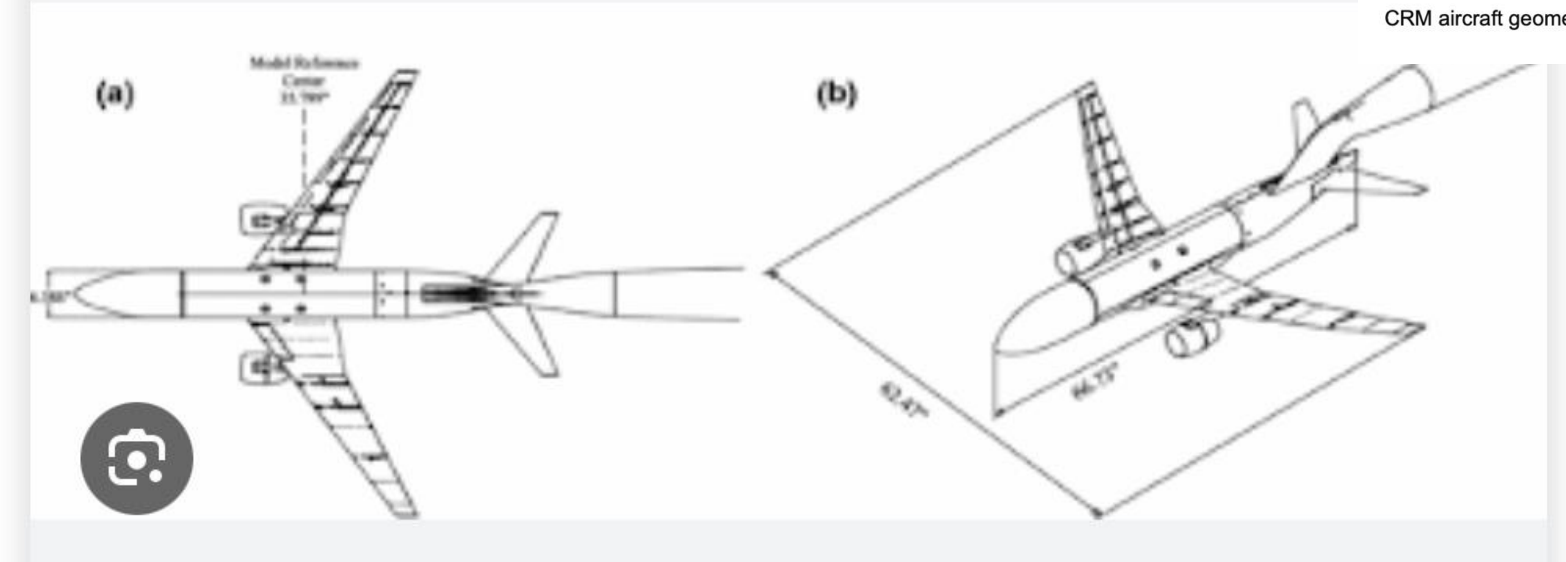
- Just about all solution sets showed the fairing to reduce drag

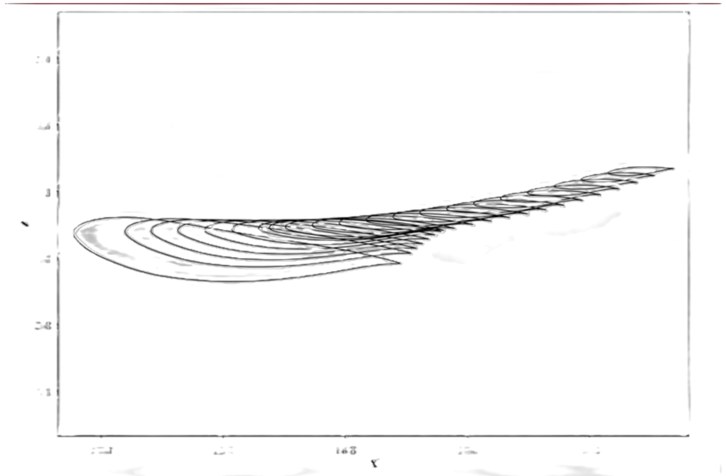
# NASA High Speed Common Research Model (CRM)

- **Developed in response to a need for a generic but relevant high speed transport geometry that could be used by anyone without any restrictions.**
- **Geometry and wind tunnel test data are available at**
  https://commonresearchmodel.larc.nasa.gov




CRM aircraft geometry compared with a traditional Part 25 transport category aircraft (Boeing 777-200) [2].



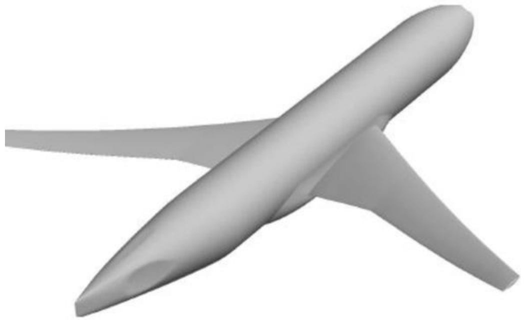



# NASA High Speed Common Research Model (CRM)

- **Built to be tested in cryogenic wind tunnels (NTF & ETW)**
- **Different scale wind tunnel models have also been built and tested by ONERA and JAXA**

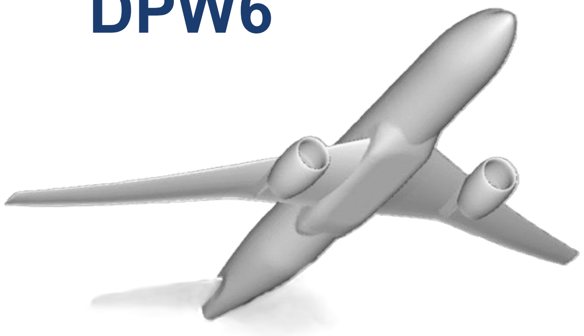

**Subject in**

**DPW4, DPW5, DPW6, DPW7, DPW8**



**DPW4**

**DPW6**

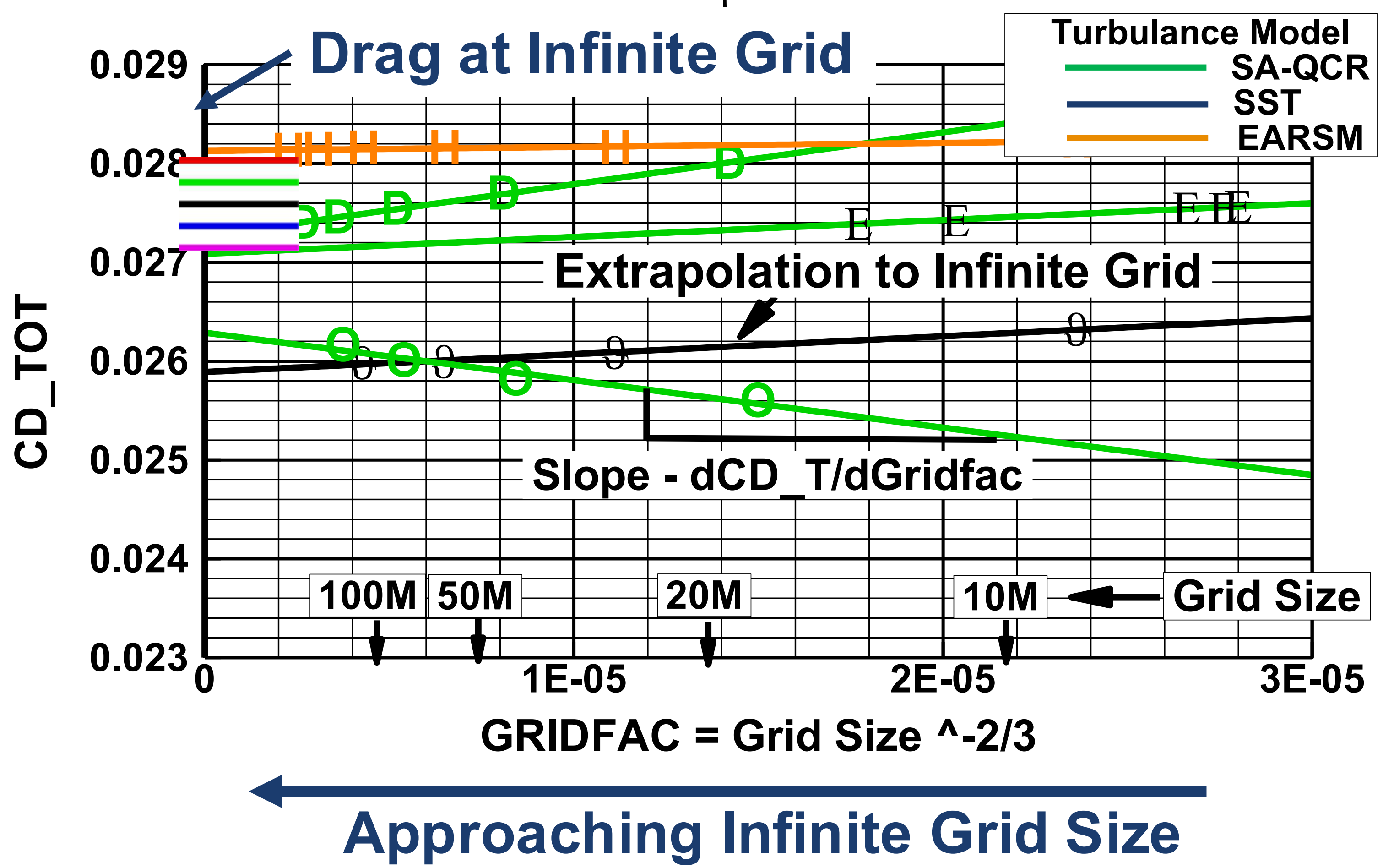


**For more detail on previous CRM DPWs: Tinoco, NASA CR Summary Report (CR-2019-220284)**

# Grid Convergence Studies

## Richardson Extrapolation

- Solutions are obtained on a parametric family of three-dimensional meshes that have been “uniformly” refined in all three coordinate directions.
- Plot function vs 1/(grid size$^{2/3}$) for family of grid sizes
- For 2$^{nd}$ order codes, should be linear vs. Grid_Factor = $N^{-2/3}$
- 0-intercept estimates theoretical infinite resolution (continuum) result

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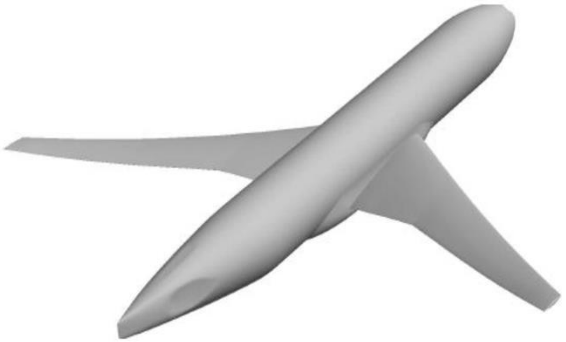
# 4th CFD Drag Prediction Workshop – 2009 (San Antonio)

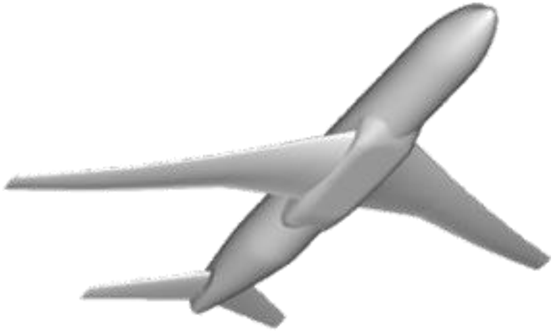
AIAA

## NASA High Speed Common Research Model (CRM)

### CRM WingBody



### CRM WingBodyTail



- **Case 1a:** Grid Convergence $M_\infty$ =0.85, $C_L$= 0.500 ± 0.005 Tail=0°
- **Case 1b:** Downwash Study $M_\infty$ =0.85, $\alpha$= 0° to 4°, Tail=-2°, 0°, 2, off

**Optional:**

- **Cases 2:** $M_\infty$ sweep, 0.70 to 0,87. $C_L$= .400, .450, .500 Tail=0°
- **Cases 3:** Reynolds number study M=0.85. Re=5M & 20M

**Standard Grids Supplied, Custom Grids Encouraged**

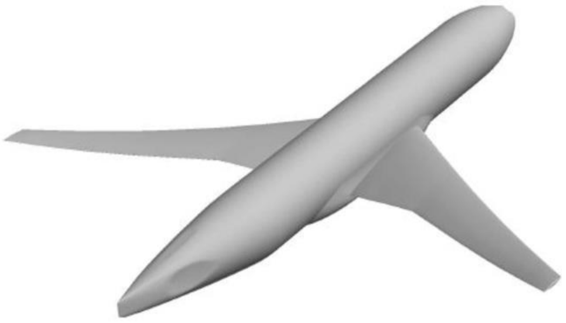
## 18 Participants, 28 Data Submittals from 17 organizations

- **Grid types: 17 Unstructured, 11 Structured**
- **Turbulence Models**
  - **18 Spalart-Allmaras (all variations)**
  - **7 Menter SST k-omega**
  - **1 EARSM (Explicit Algebraic Reynolds Stress Model)**
  - **1 SSG/LLR-omega (Reynolds Stress Model)**
  - **1 Realizable k- epsilon**

# 5th CFD Drag Prediction Workshop – 2012 (New Orleans)

## NASA High Speed Common Research Model (CRM)

### CRM WingBody



- **Case 1: Grid Convergence** $M_\infty$ =0.85, $C_L$= 0.500 ± 0.001, Re=5M
- **Case 2: Angle-of-Attack Sweep** $M_\infty$ =0.85, $\alpha$= 2.5° to 4°, Re=5M
- **Cases 3: Turbulence Model Verification**
  - 2D Zero Pressure Gradient Flat Plate: M = 0.20; $RE_L = 5x10^6$; $T_{ref}$ = 540° R
  - 2D Bump-in-channel: M = 0.20; $RE_L = 3x10^6$; $T_{ref}$ = 540° R
  - 2D NACA 0012 Airfoil: M = 0.15; $RE_C = 6x10^6$; $T_{ref}$ = 540° R

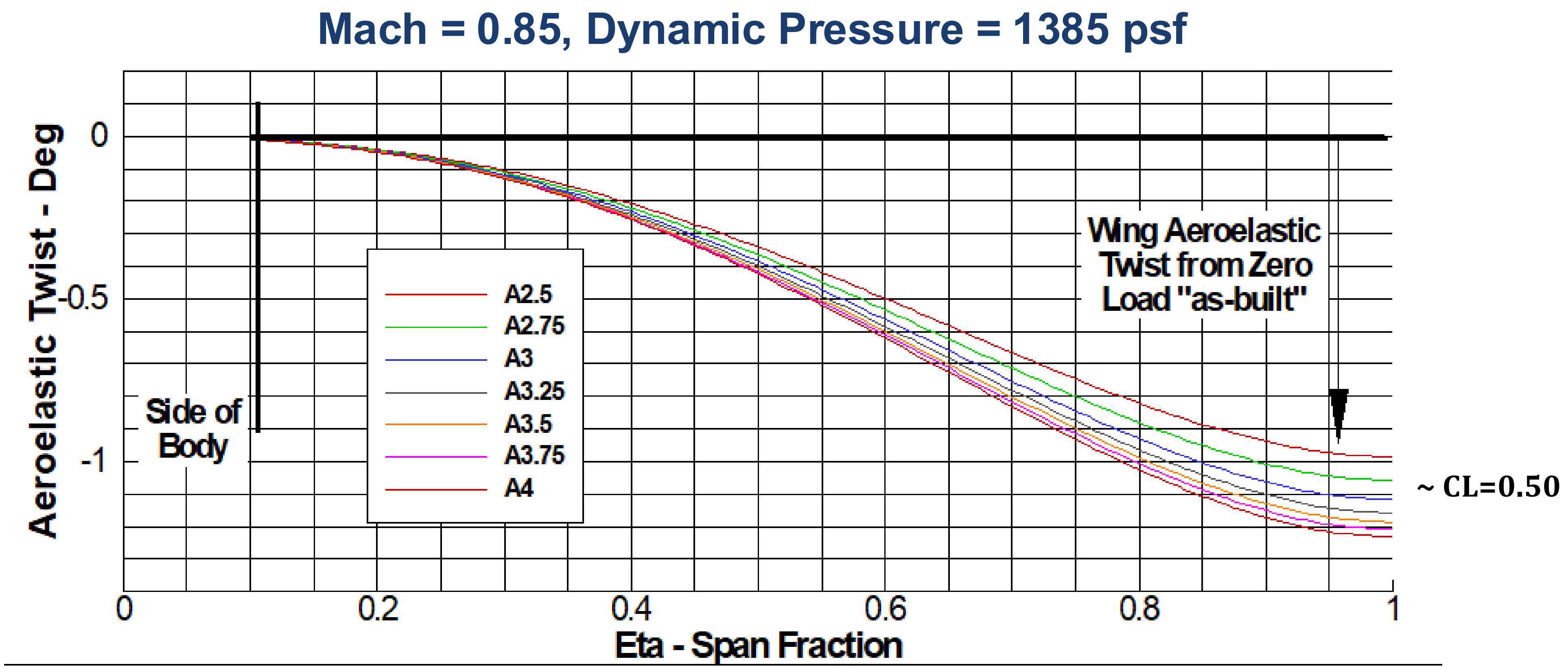
**Standard Grids Supplied, Custom Grids Encouraged**

## 27 Participants, 57 Data Submittals from 22 organizations

- **Grid types: 25 Unstructured, 12 Structured**
- **Turbulence Models**
  - – 38 Spalart-Allmaras (all variations)
  - – 13 Menter SST k-omega
  - –1 EARSM (Explicit Algebraic Reynolds Stress Model)
  - –1 Lag-RSTSA
  - –4 Goldberg $R_T$

# Static Aeroelastics at Transonic Speeds

## Static Aeroelastic Wing Twist Distribution Derived from Wind Tunnel Measurements




**Model geometry and grids defined for each angle of attack**

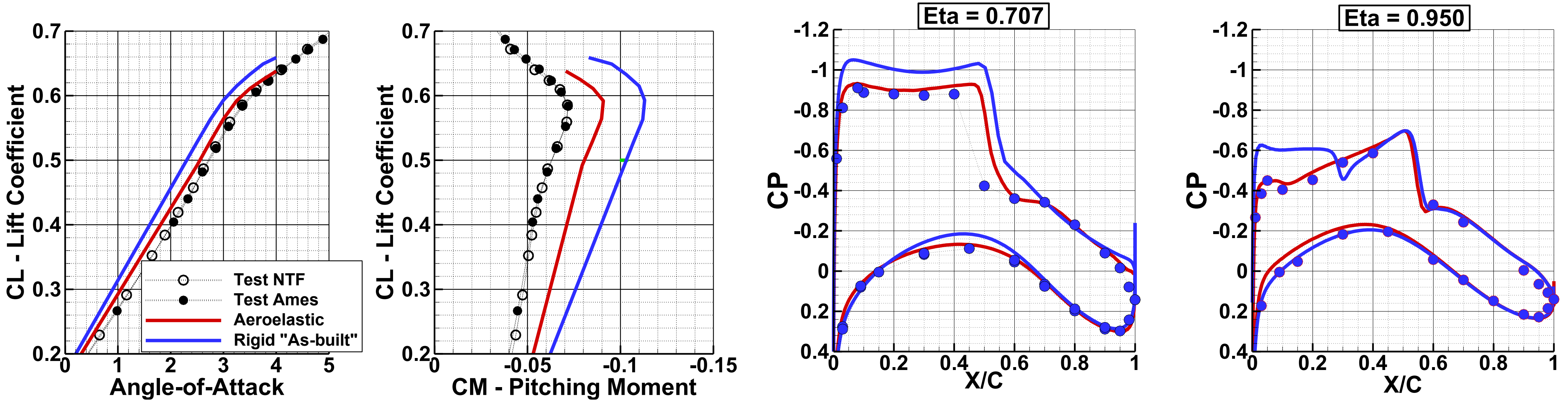
# Importance of Aeroelastics at Transonic Speeds

AIAA

- Wind Tunnel model aeroelastic deformation is significant

Static Aeroelastic (based on WT test measurements)

Rigid “As-Built”



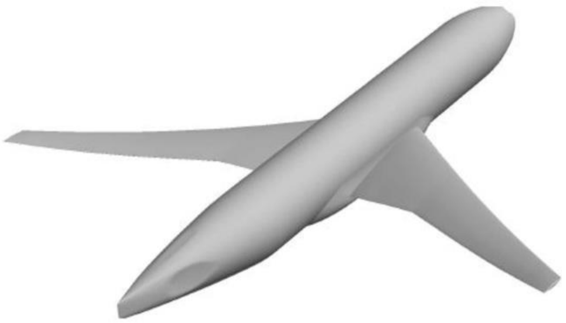

- Available geometries and grids include:
  - Wing measured aeroelastic twist and deflection
  - Range of angles-of-attack and dynamic pressures

https://dpw.larc.nasa.gov

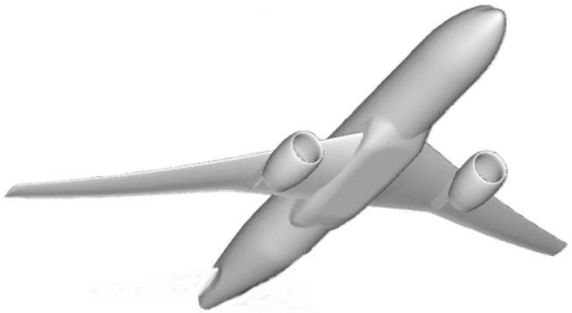
# 6th CFD Drag Prediction Workshop – 2016 (Washington, D.C.)

## NASA High Speed Common Research Model (CRM)

CRM WingBody



CRM WingBody PylonNacelle



- <u>Case 1: </u>**Turbulence Model Verification**
  2D NACA 0012 Airfoil: $M = 0.15$; $RE_C = 6x10^6$; $T_{ref} = 540°$ R
- **<u>Case 2:</u> Grid Convergence / Nacelle-Pylon Drag Increment**
  $M_\infty = 0.85$, $C_L = 0.500 \pm 0.001$, Re=5M
- **<u>Case 3:</u> Angle-of-Attack Sweep** $M_\infty = 0.85$, $\alpha = 2.5°$ to 4°, Re=5M
- **Case 4: CRM WB Grid Adaptation [Optional]**
- **Case 5: CRM WB Coupled Aero-Structural Simulation [Optional]**

**Standard Grids Supplied, Custom Grids Encouraged**

**27 Participants, 55 Data Submittals from 25 organizations**

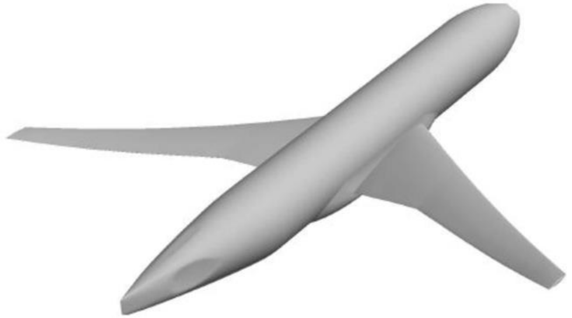
- **Grid types: 26 Unstructured, 11 Structured, 7 Cartesian**
- **Turbulence Models**
  - **28 Spalart-Allmaras (all variations)**
  - **3 Menter SST k-omega**
  - **1 EARSM (Explicit Algebraic Reynolds Stress Model)**
  - **1 RSM-w**
  - **5 k-e**

# 7th CFD Drag Prediction Workshop – 2022(Chicago)

AIAA

## NASA High Speed Common Research Model (CRM)

### CRM WingBody



Mach – 0.85, Re=5M, Re=20M

- Case 1: Grid Convergence Study
- Case 2: Angle-of-Attack Sweep
- Case 3: Reynolds Number Sweep

Low Q, Re=5M, Re=20M: Hi Q, Re=20M, Re=30M: (Optional)

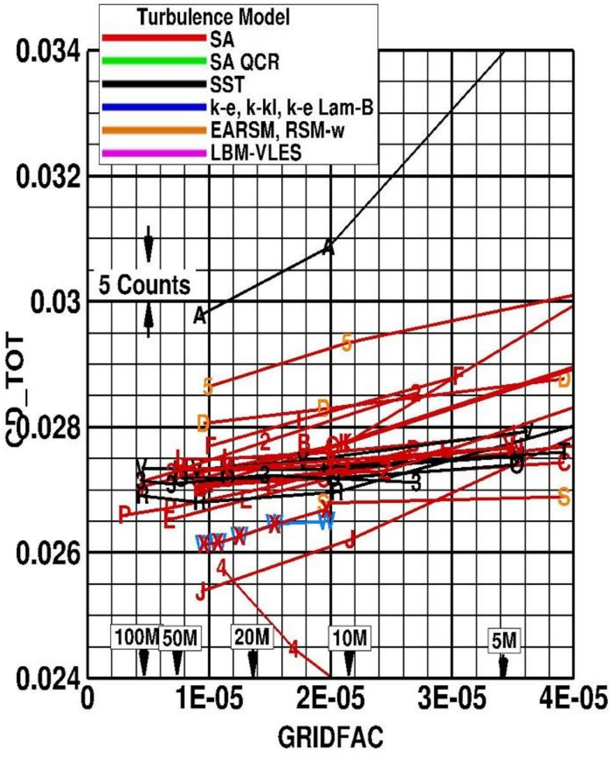
- Case 4: Grid Adaptation
- Case 5: Beyond RANS)- Insufficient input
- Case 6: Coupled Aero-Structural Simulation

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

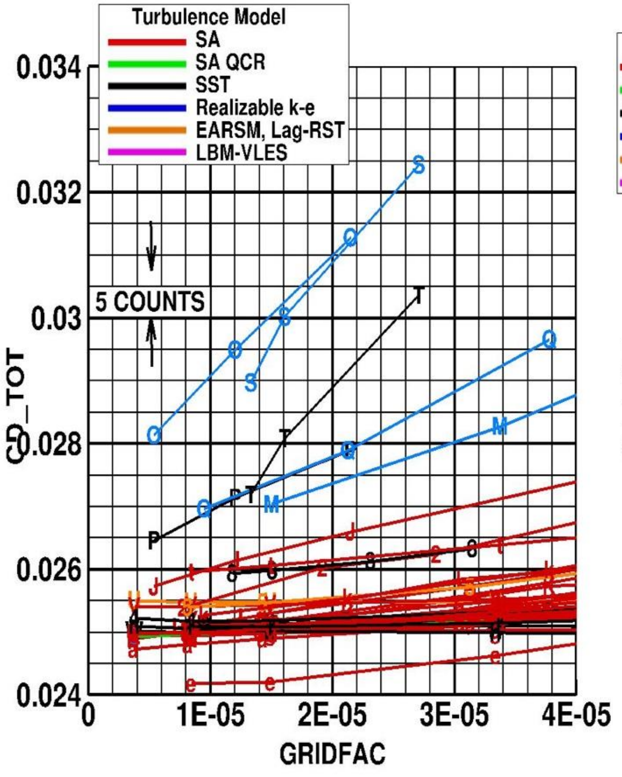
  1 SSG/LRR, 1 AMM-QCR, 1 RSM-ln(w)

# GRID Convergence – Turbulence Model

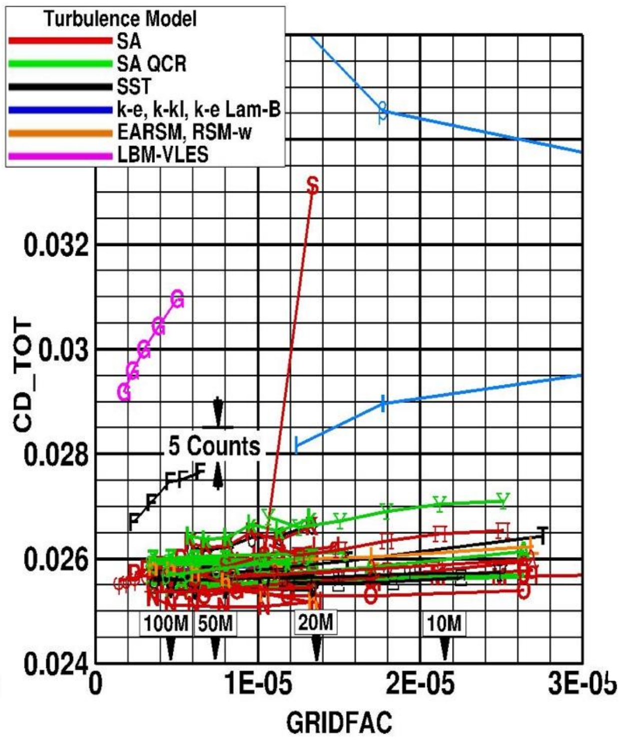
**DPW4**
**Wing-Body-Tail**
**Re=5M**
**2009**



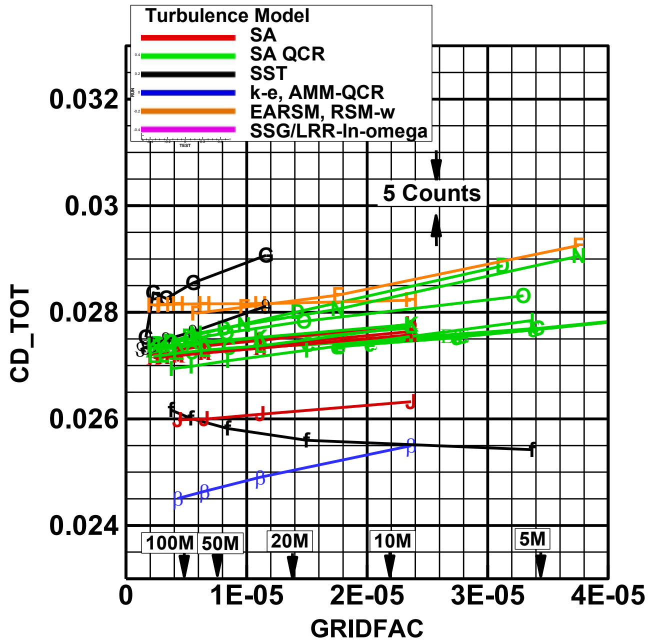

**DPW5**
**Wing-Body**
**Re=5M**
**2012**



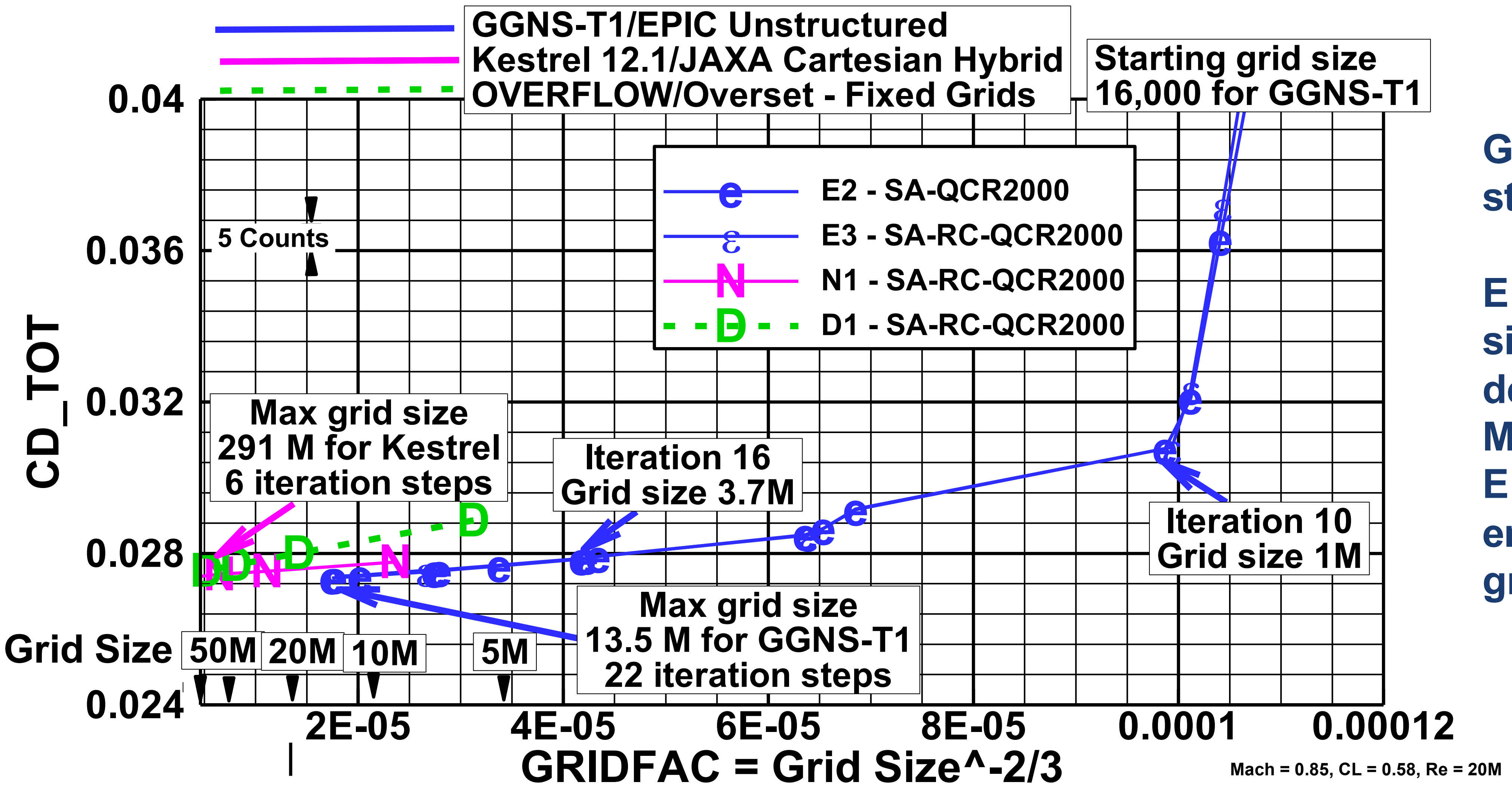

**DPW6**
**Wing-Body**
**Re=5M**
**2016**




**DPW7**
**Wing-Body**
**Re=20M**
**2022**



# Grid Convergence - Adaptive Solutions

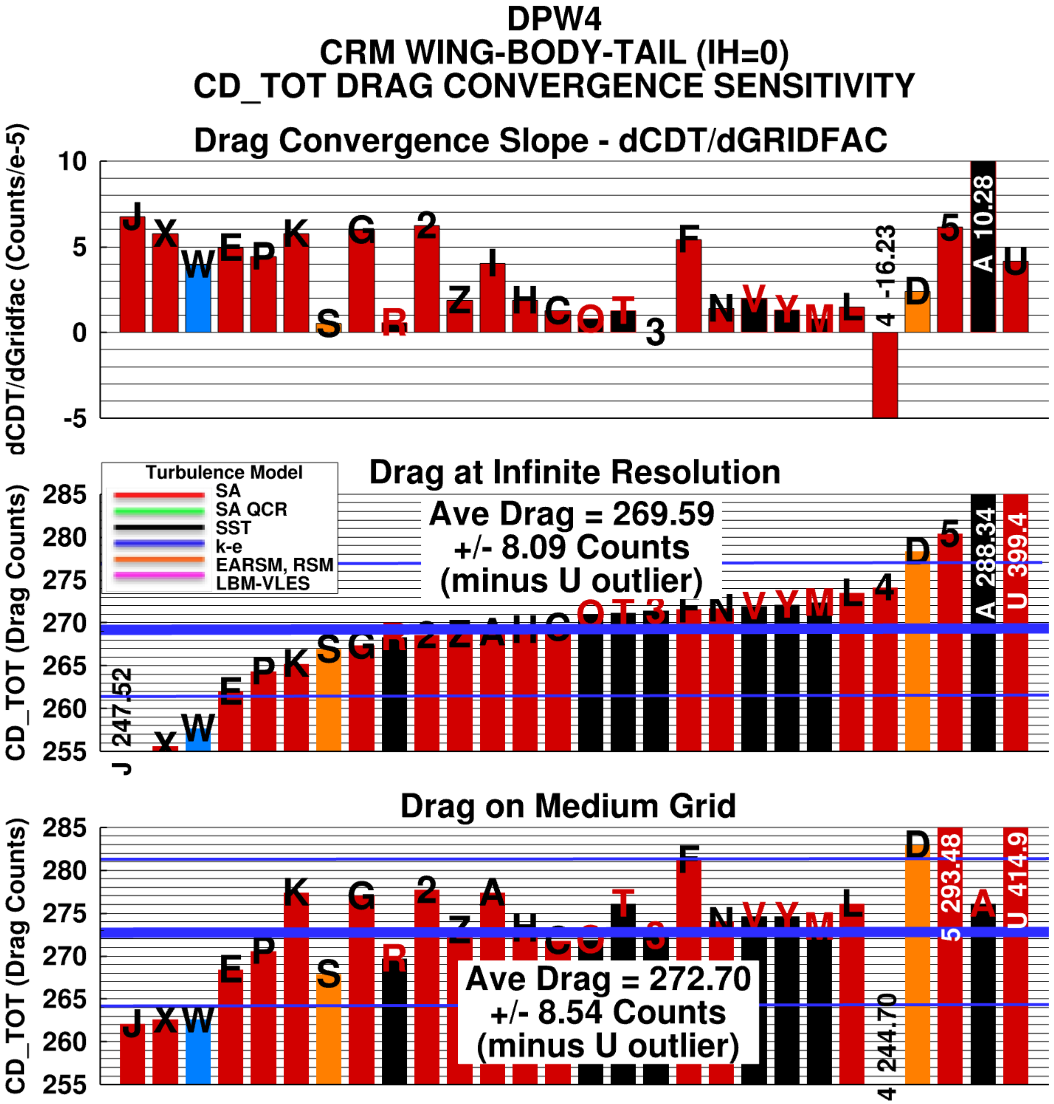


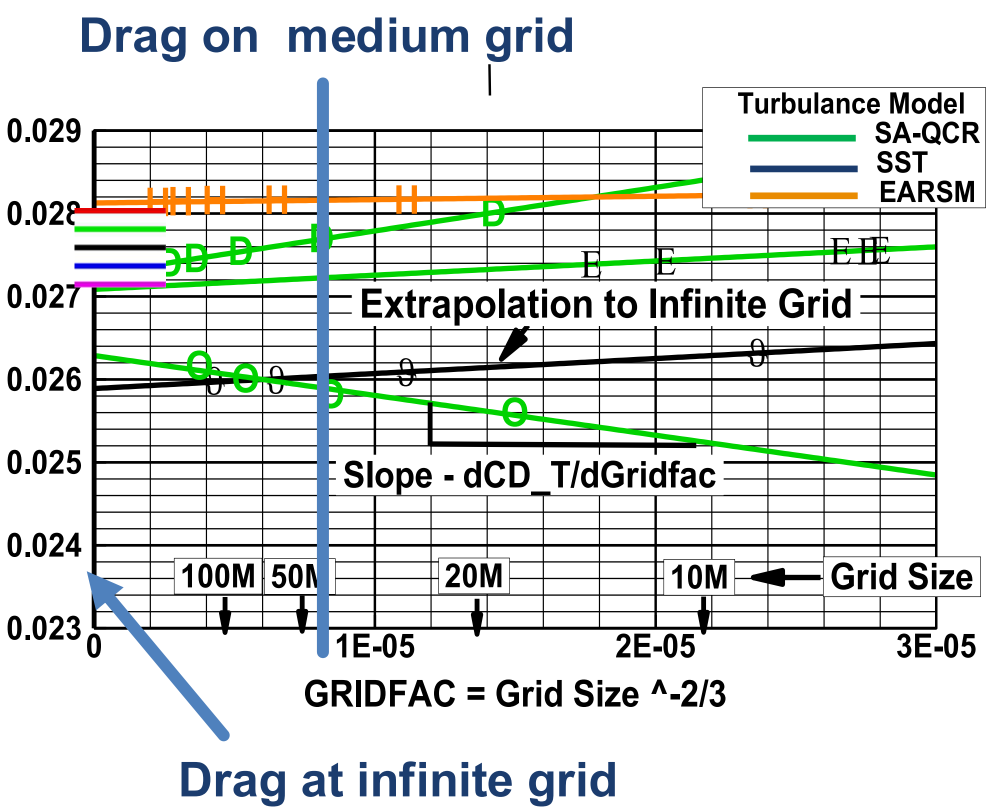

**GGNS uses a strong solver**

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

20 **AIAA 2022-1245 Session: Adaptive Meshing, Error Estimation, and Uncertainty Quantification II**

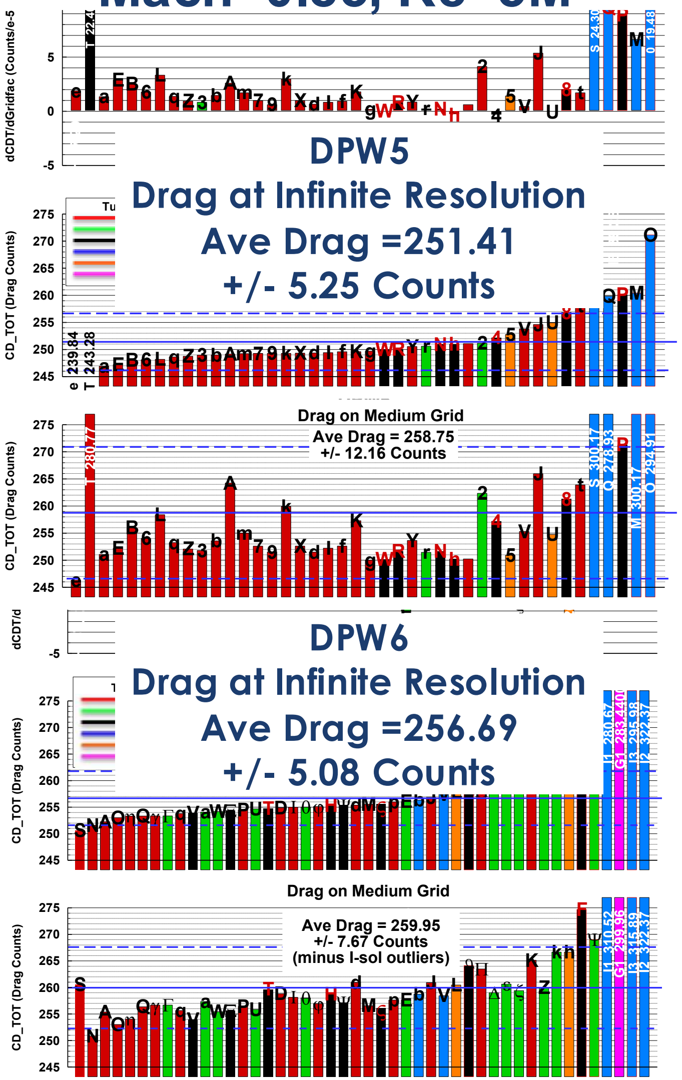
# Total Drag and Drag Sensitivity Convergence



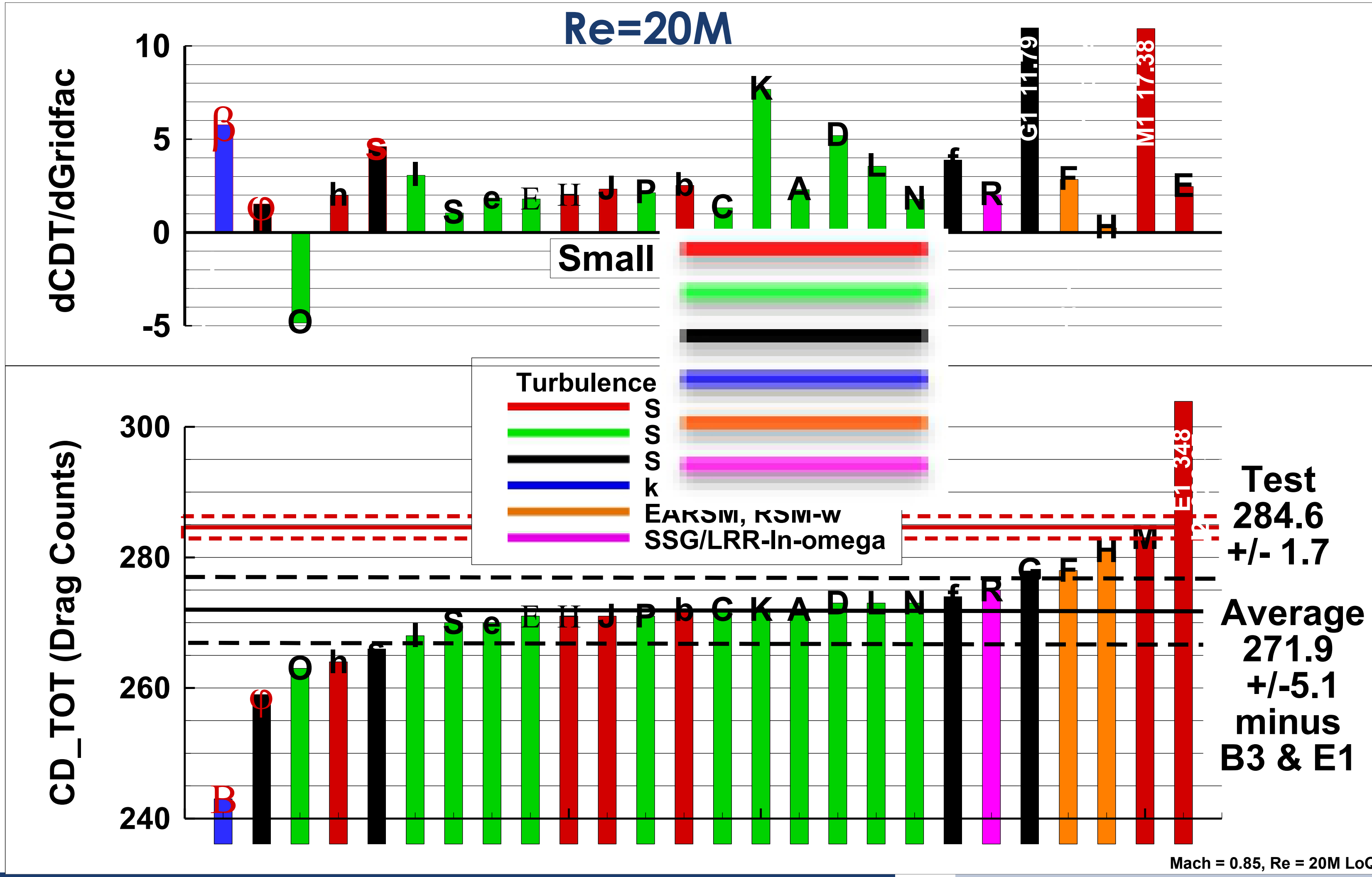



# Total Drag and Drag Sensitivity Convergence

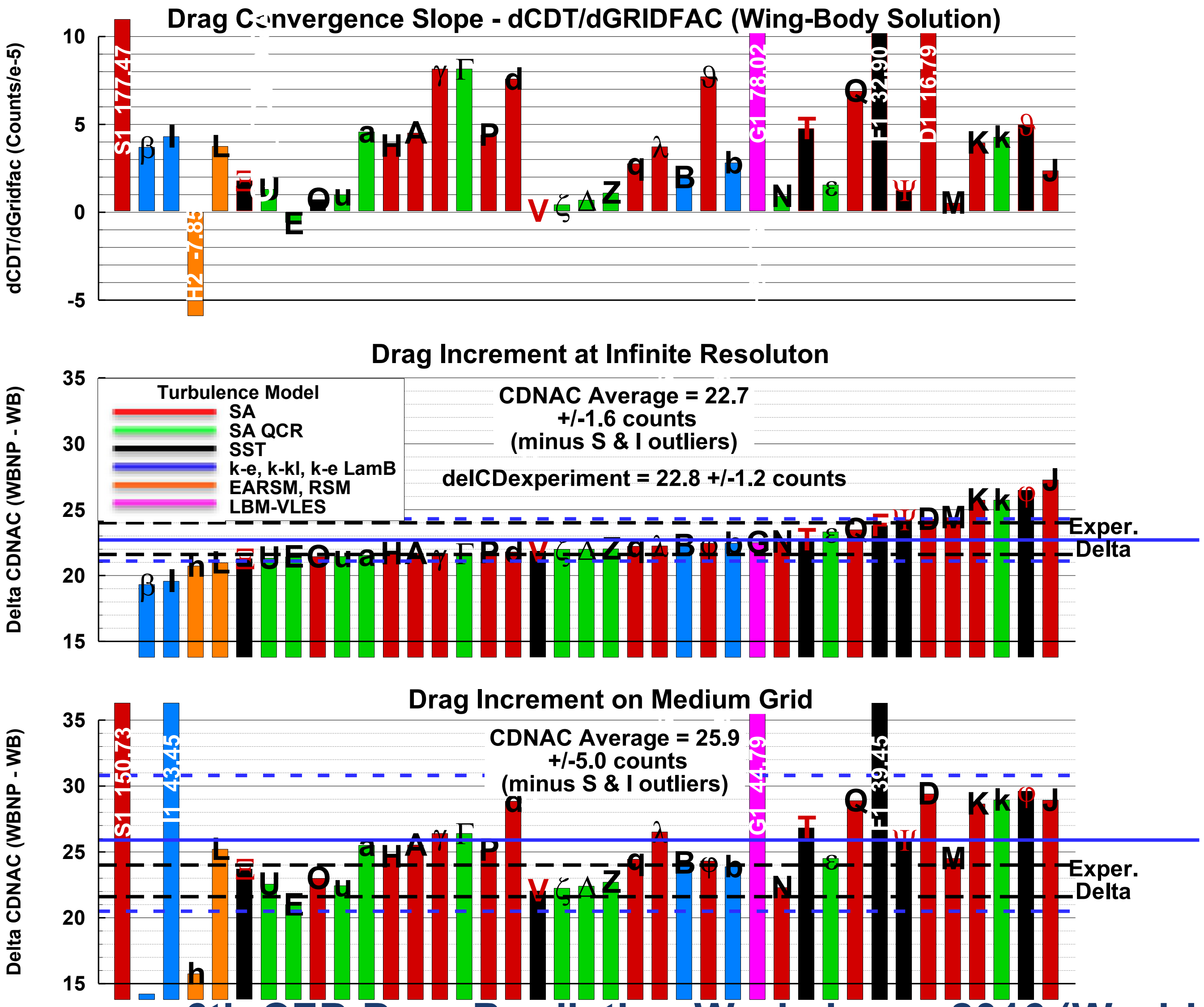
Mach=0.85, Re=5M



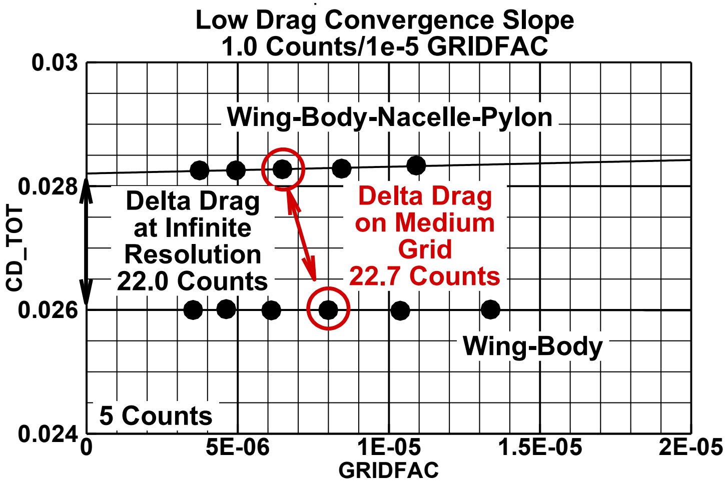

DPW7
Mach=0.85,
Re=20M

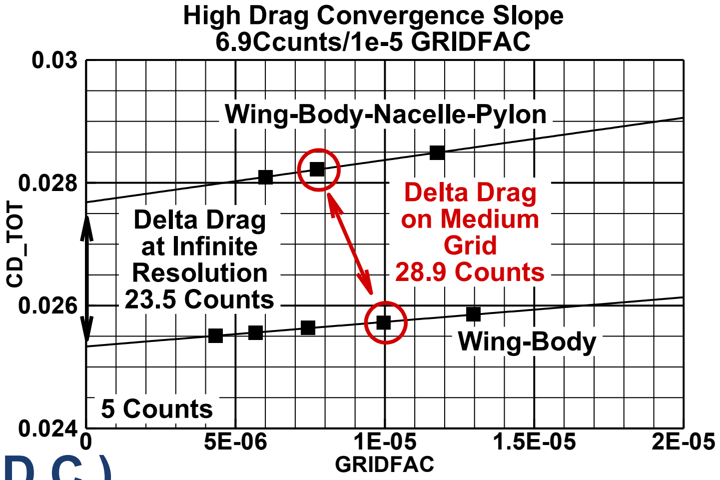


# Nacelle-Pylon Drag Increment



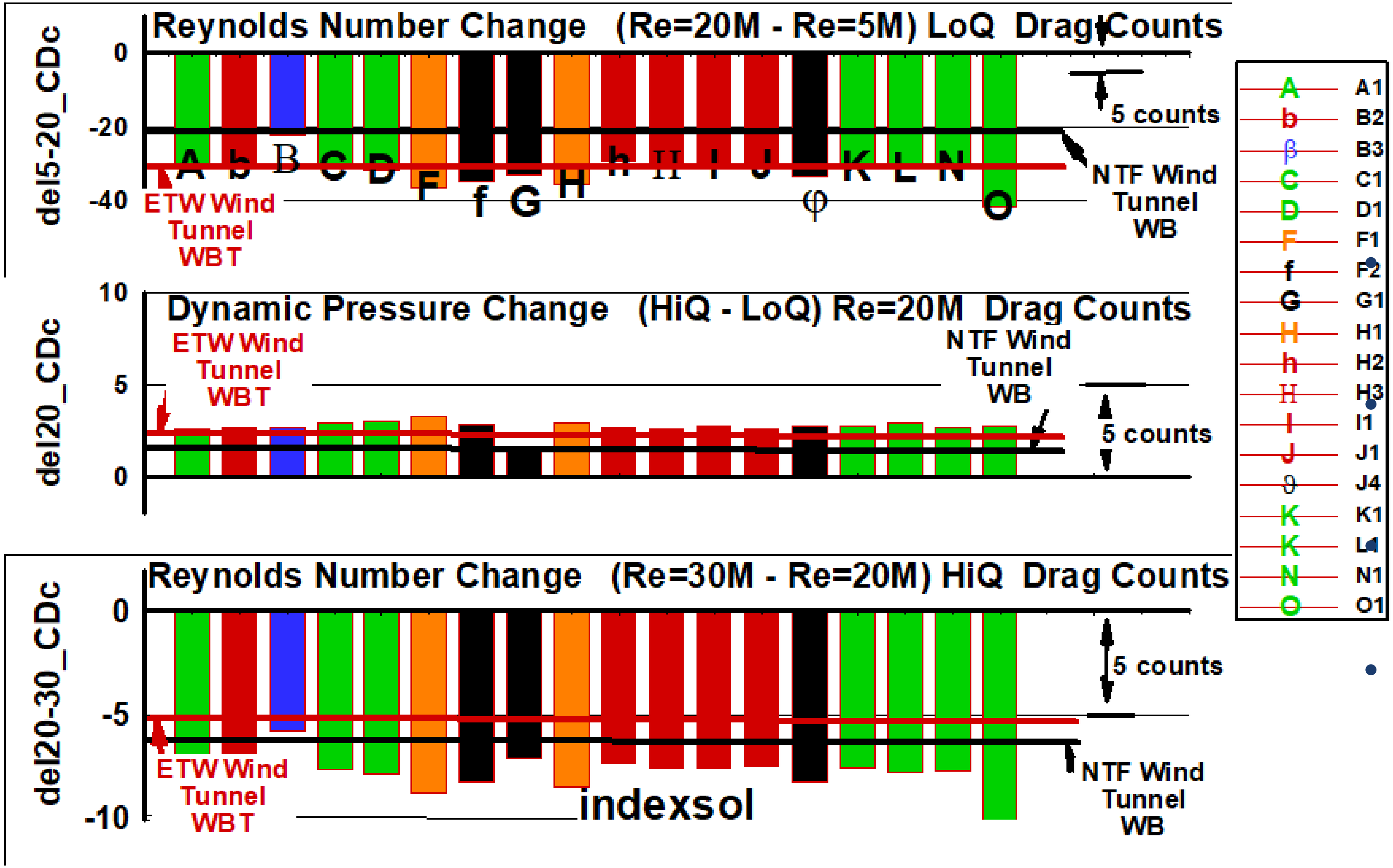

## Potential Impact of Drag Convergence Slope on Drag Increment




6th CFD Drag Prediction Workshop – 2016 (Washington, D.C.)

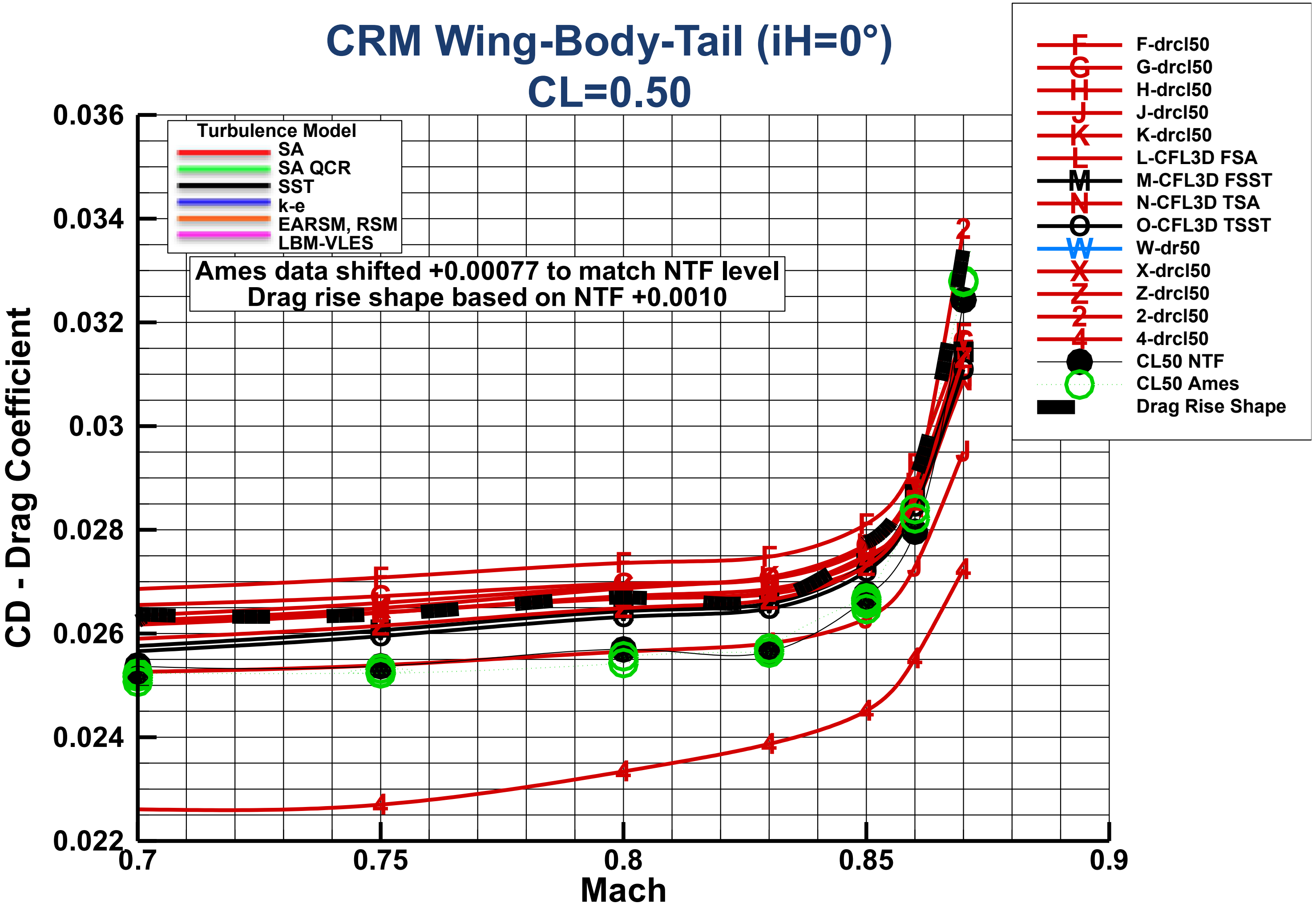
# Reynolds Number Sweep at Constant CL




Re = 5M to Re = 30M
M = 0.85, CL = 0.50 (Cruise)

- Re = 5M, LoQ – R5 grid using 2.50-deg LoQ AE CRM
- Re=20M, LoQ – R30 grid using 2.50-deg LoQ AE CRM
- Re=20M, HiQ – R30 grid using <u>2.50-deg HiQ AE CRM</u>
- Re=30M, HiQ – R30 grid using <u>2.50-deg HiQ AE CRM</u>

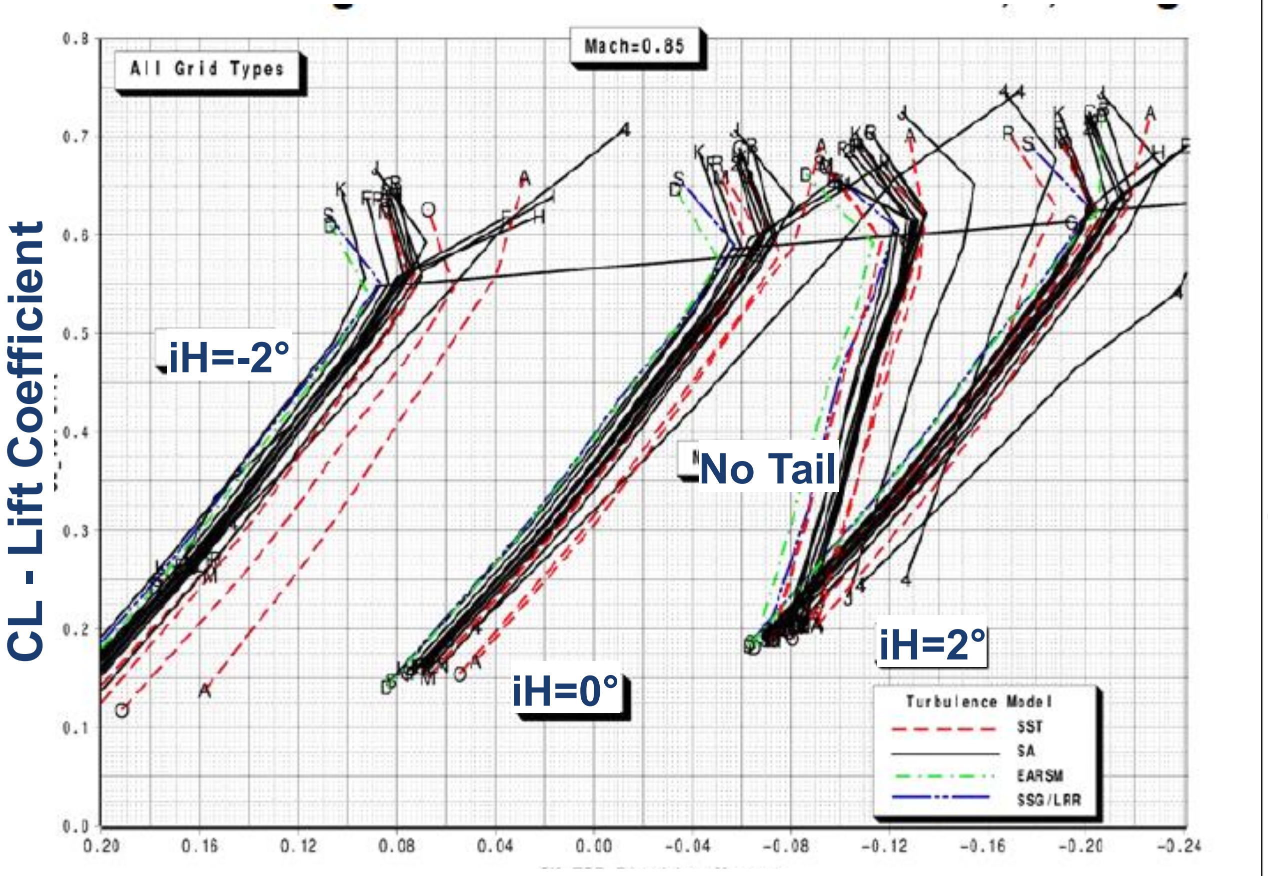
# Drag Rise

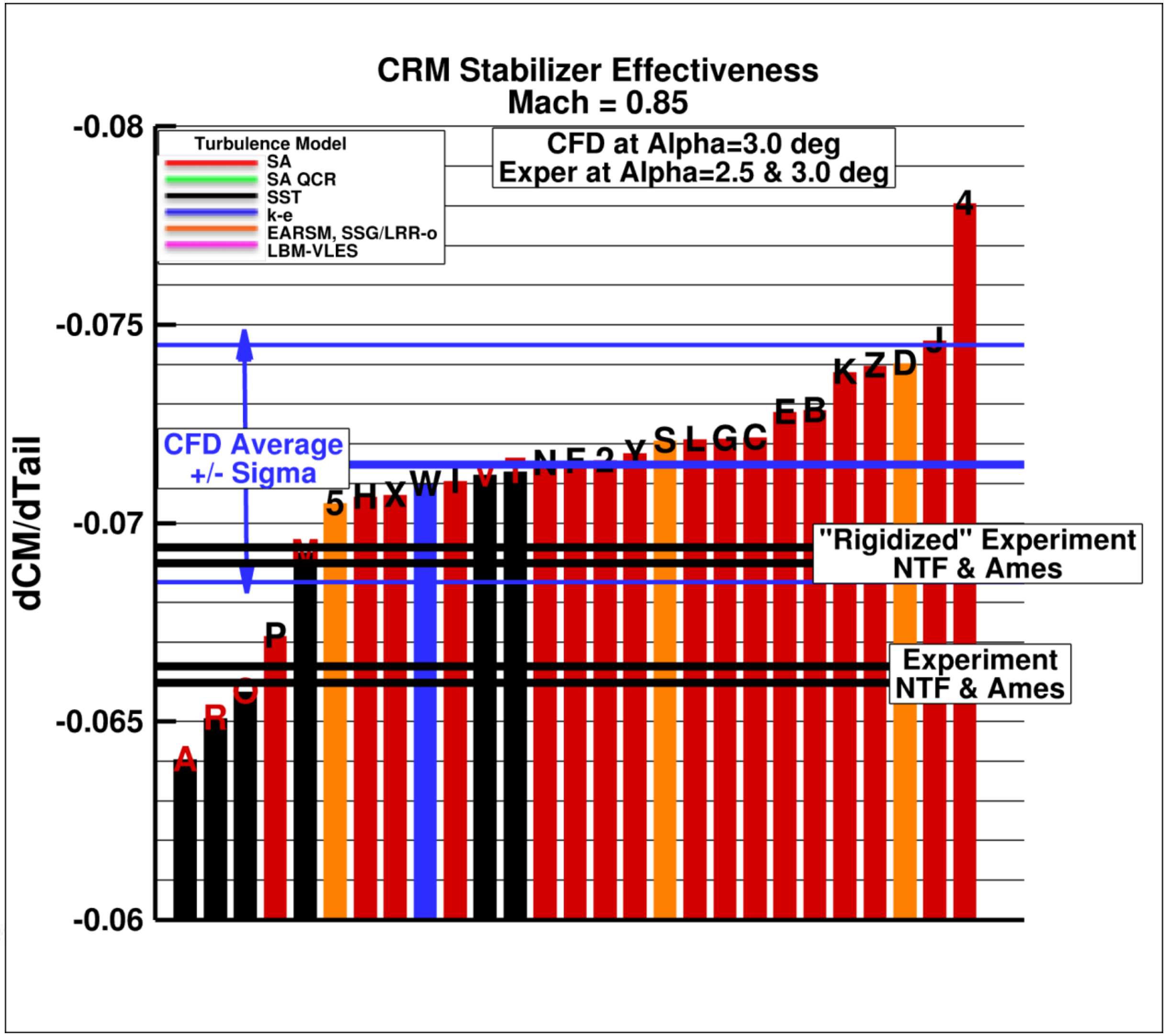



## 4th CFD Drag Prediction Workshop – 2009 (San Antonio)

# CRM Stabilizer Effectiveness

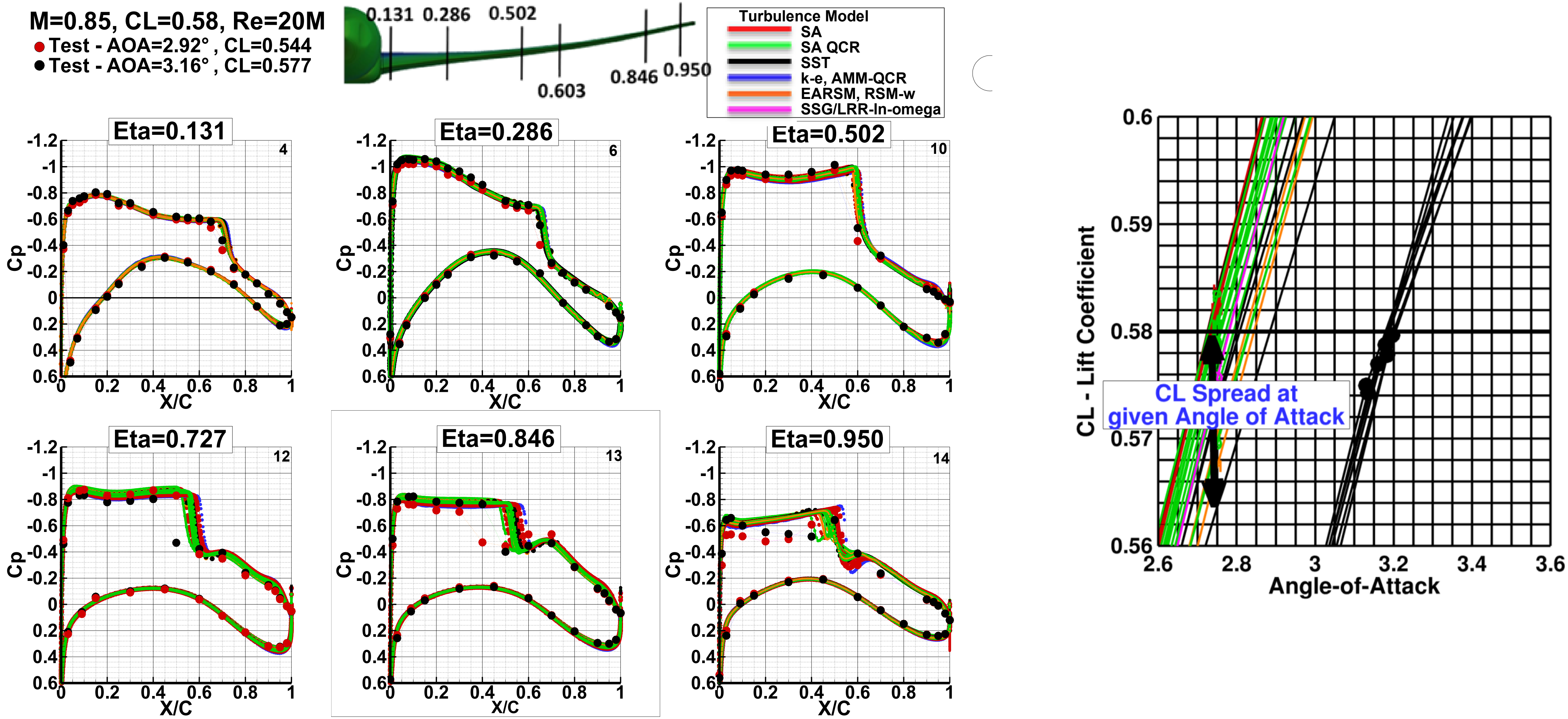
Mach=0.85, Re=5M



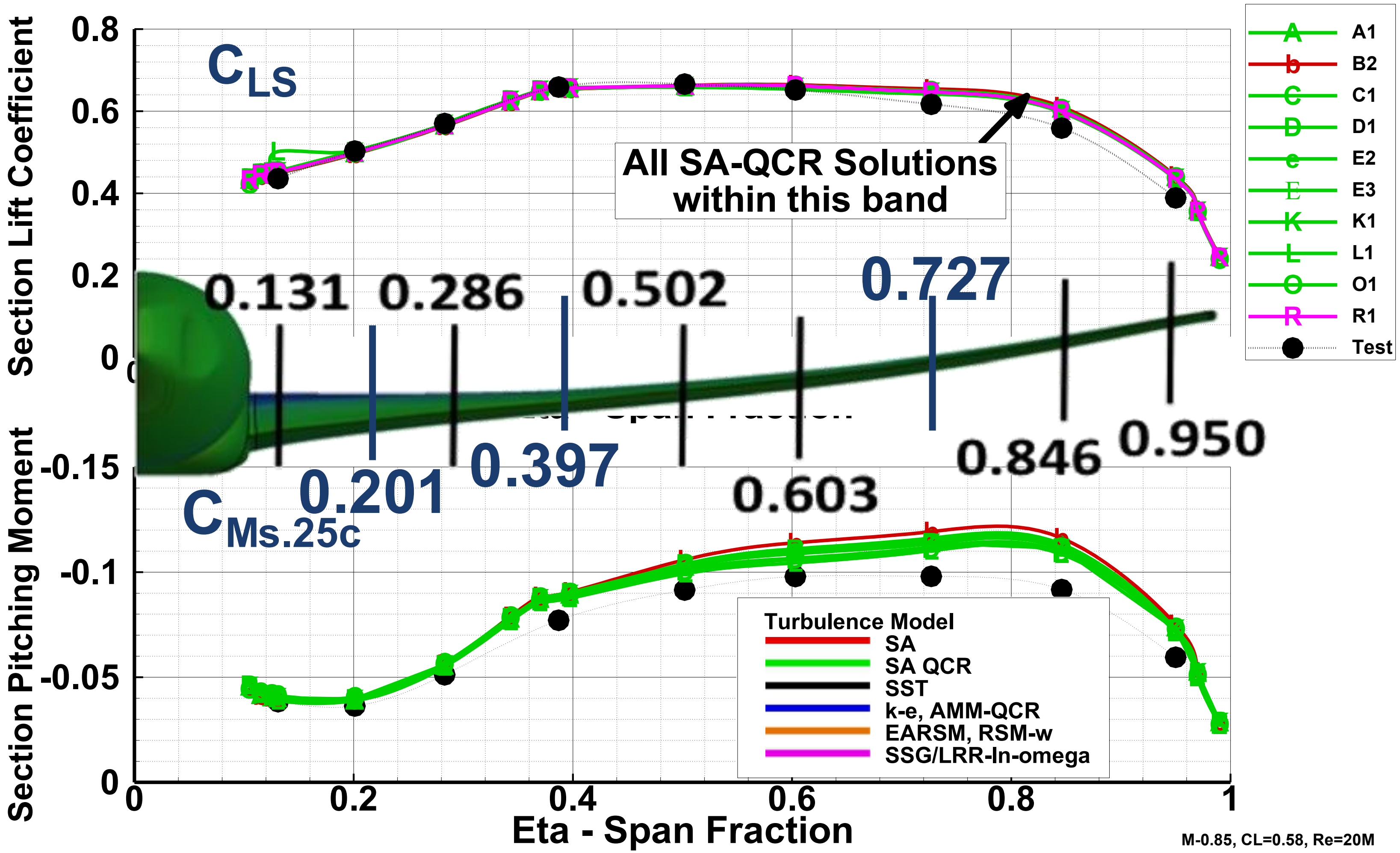

4th CFD Drag Prediction Workshop – 2009 (San Antonio)

# Wing Pressure Distributions – All Solutions



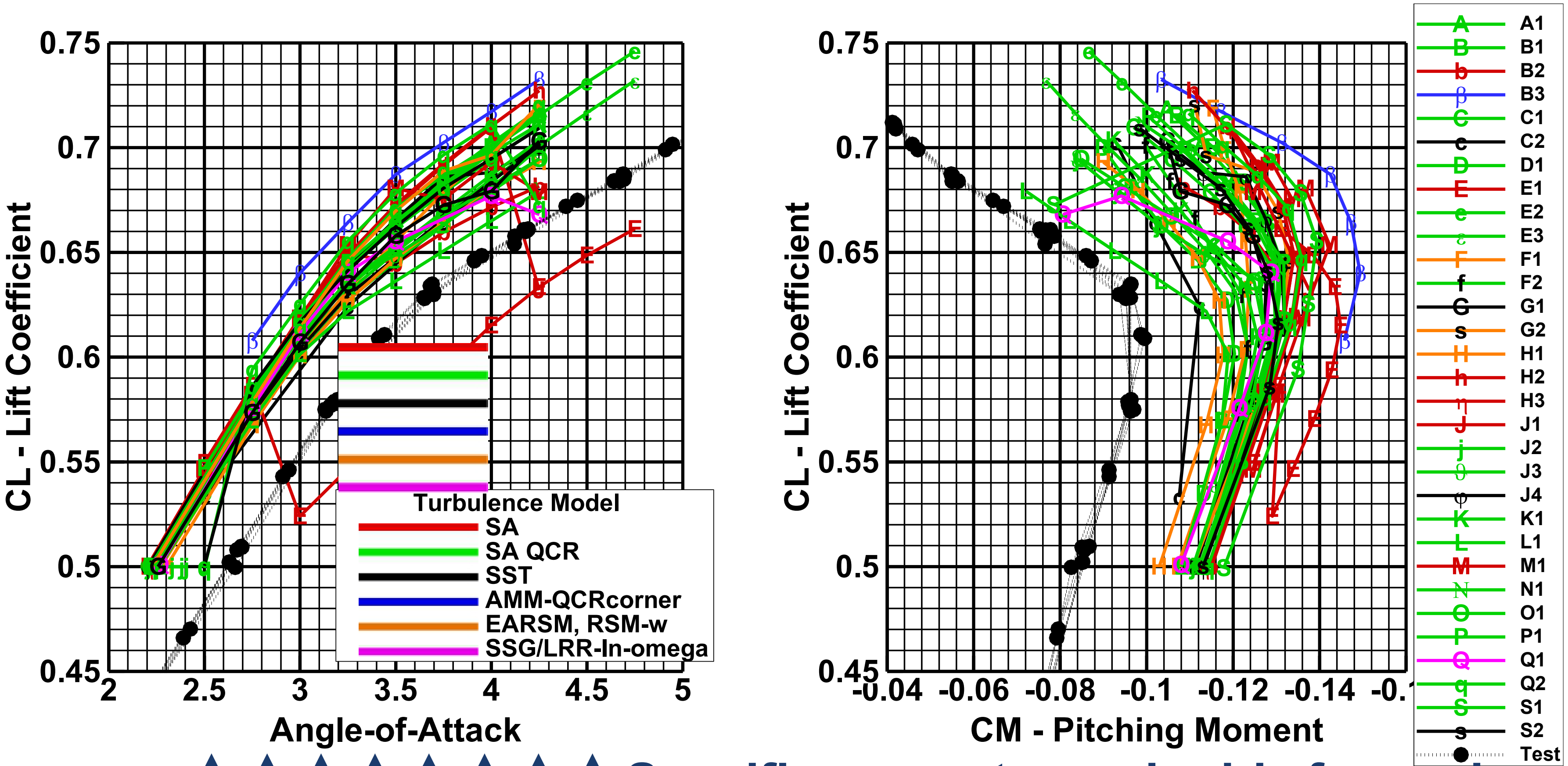
# Wing Section Lift and Moment

## Mach = 0.85, CL = 0.58, Re = 20M



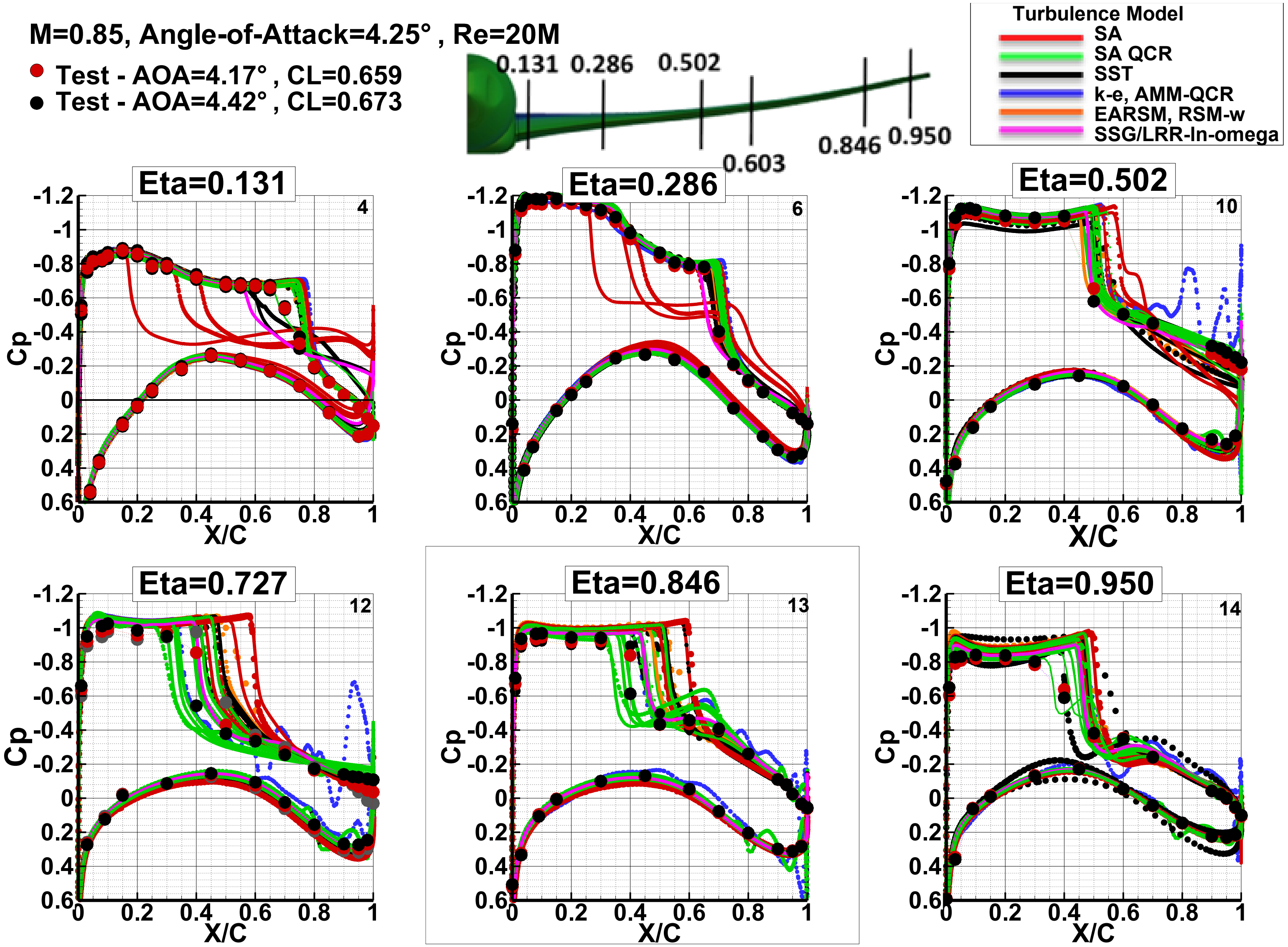
# Lift and pitching moment for all solutions

## Mach = 0.85, Re = 20M

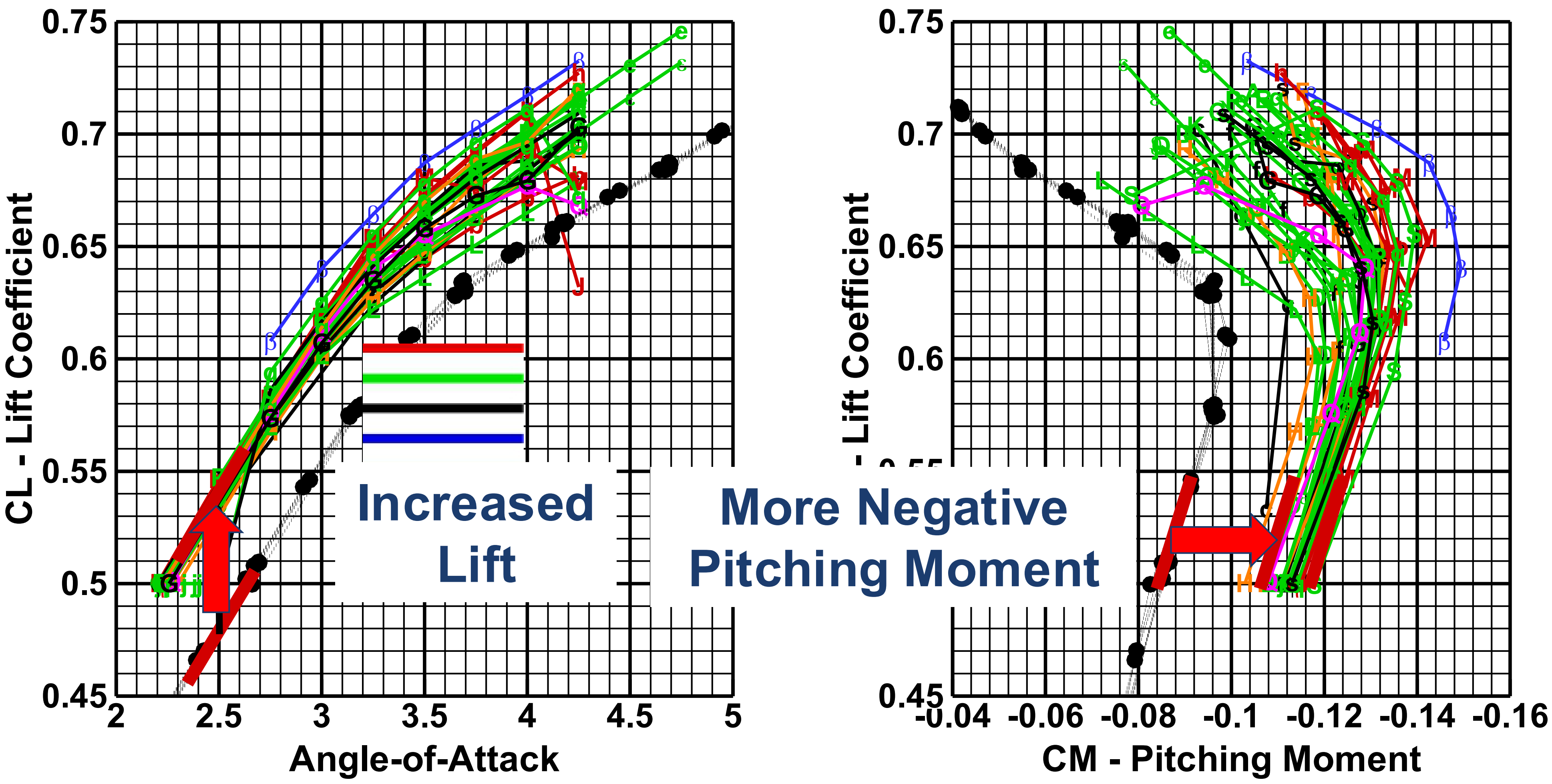



**Specific geometry and grids for each $\alpha$**

# Wing Pressure Distributions – 4.25° angle-of-attack



# Issues: Solution Offset

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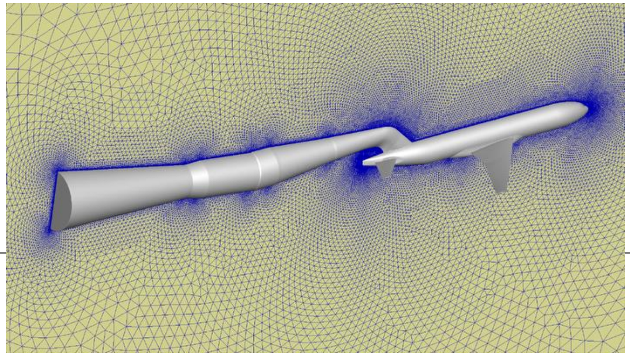
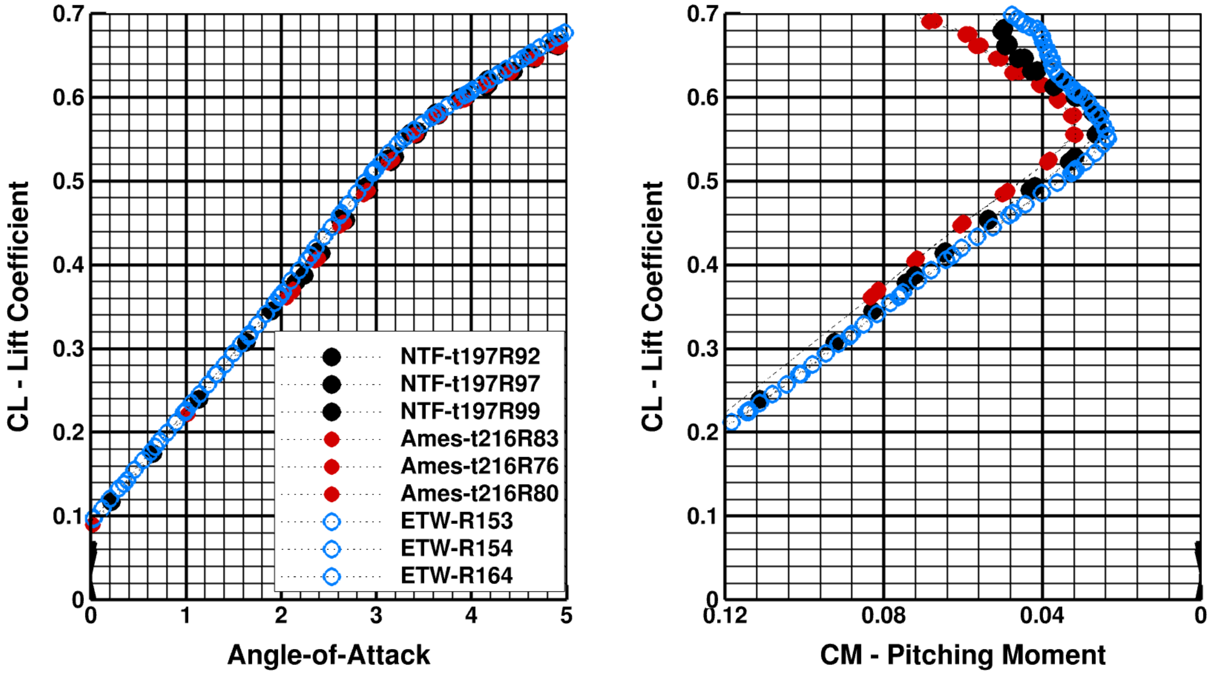
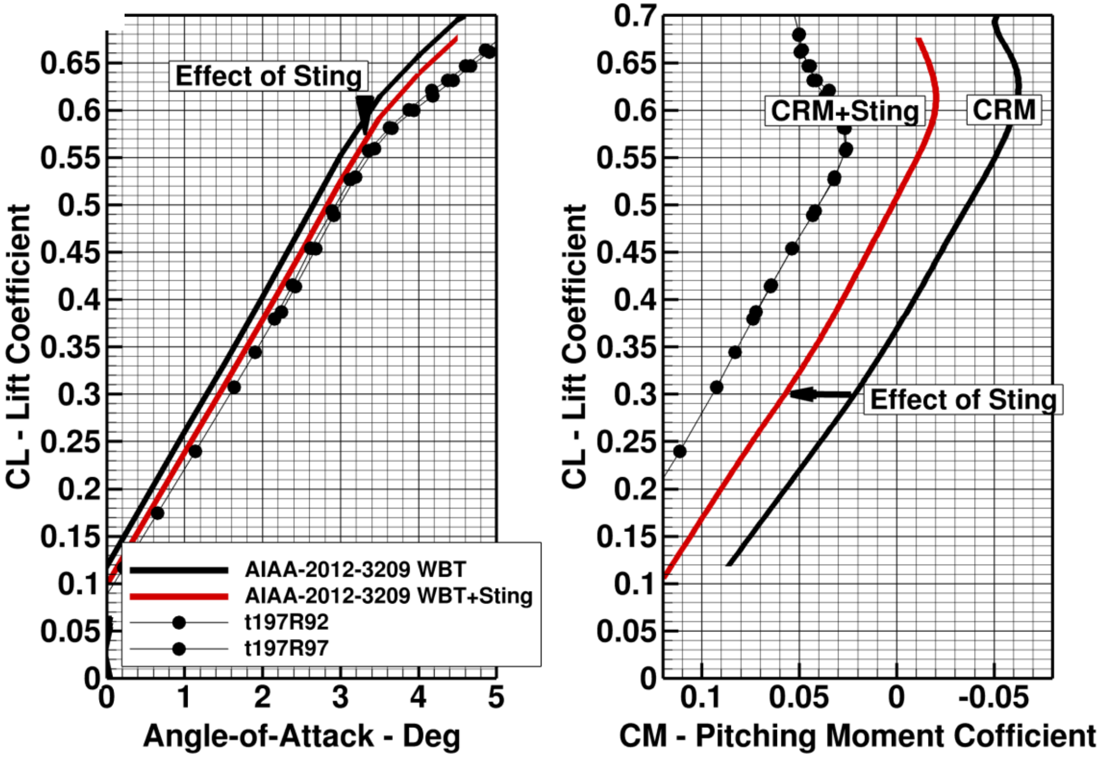
# Issue: Solution Offset – Wind Tunnel Environment

- Wind tunnel results from NTF, Ames, and ETW in close agreement
- Different wall system in each tunnel
- Same mounting system used in each tunnel
- Initial CFD reported in AIAA-2012-3209
- Now subject of Working Group #4: Test Environment

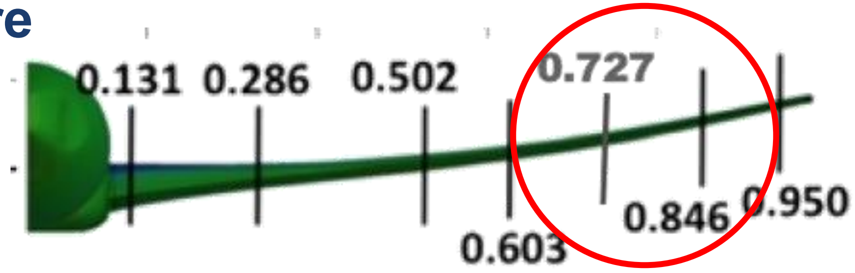


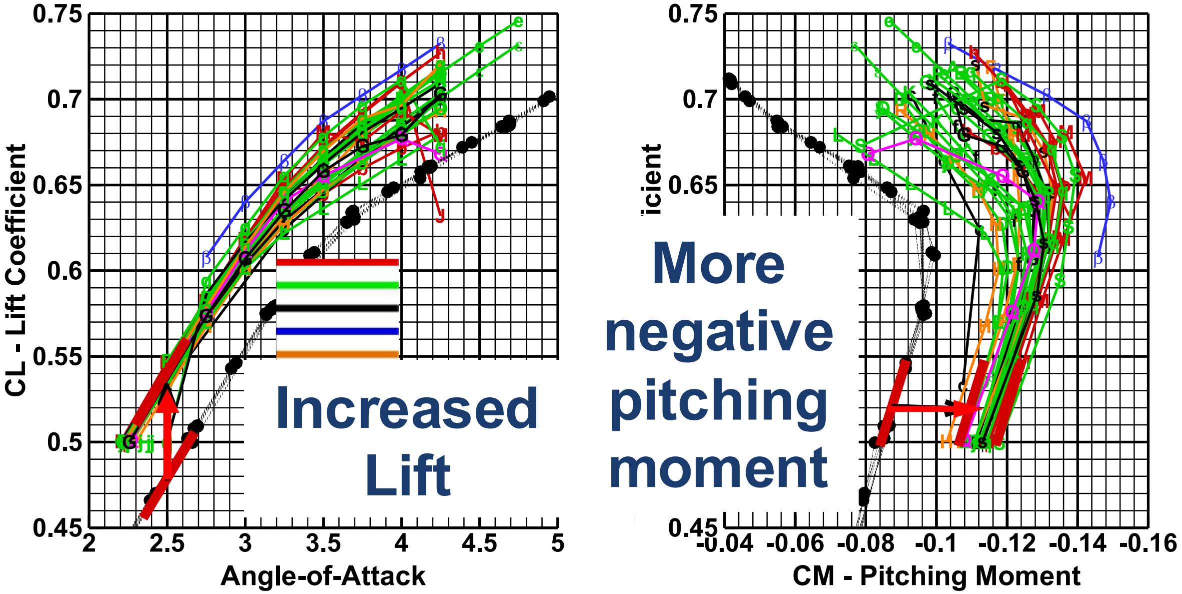


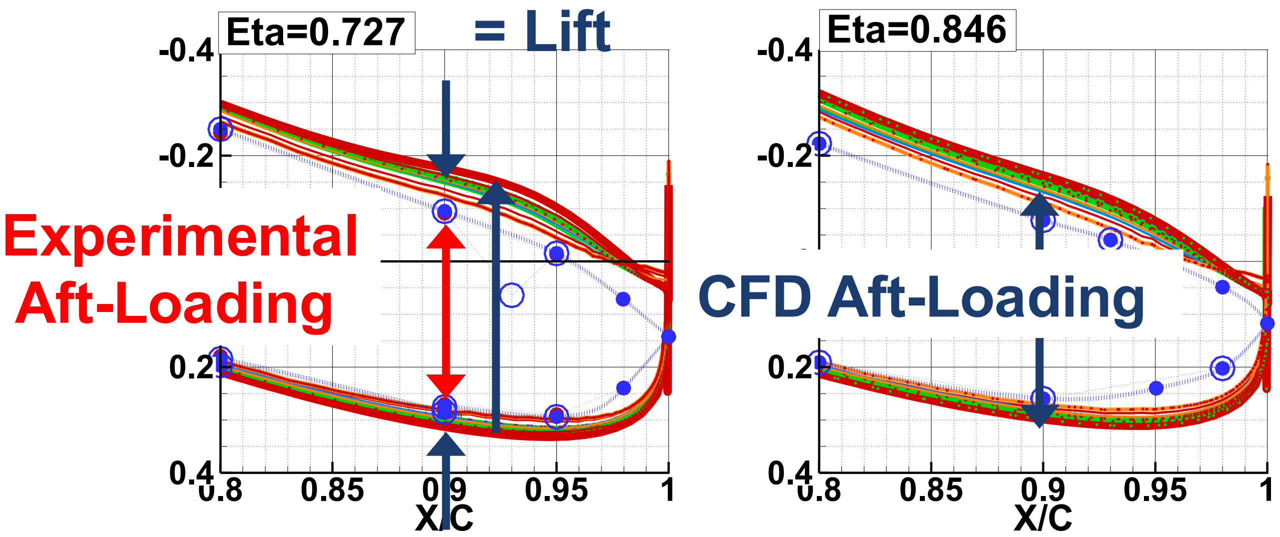



# Issue: Solution Offset - Excessive CFD Aft-Loading?

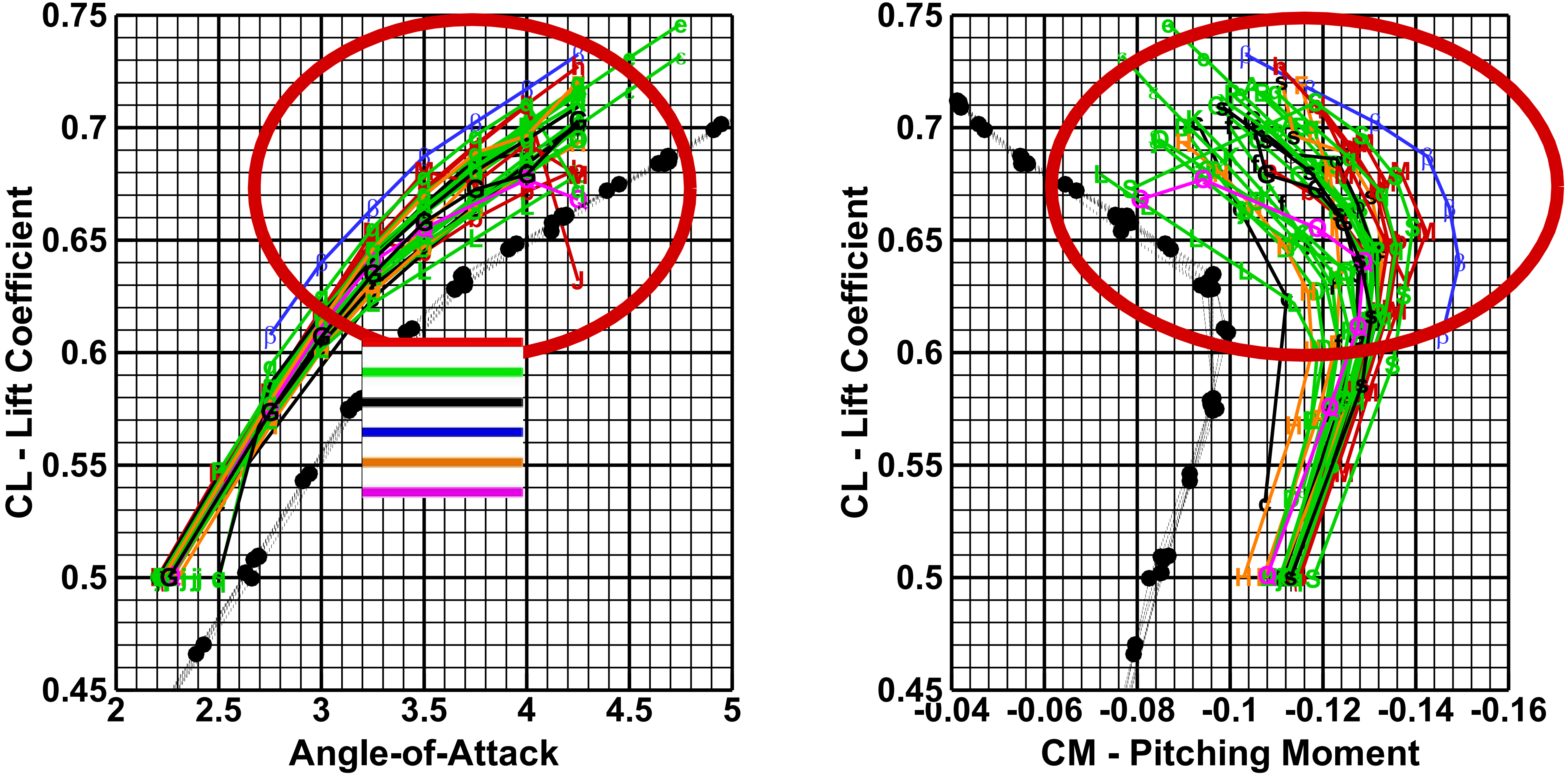
- Excessive aft-loading contributes to greater lift and more negative (nose down) pitching moment
- NOT a geometry problem!
- Seen on other models w/significant aft TE camber - AIAA-2002-0420
- BUT! Appears to account for only a fraction of the off-set
- Wind tunnel mounting system + aft loading??



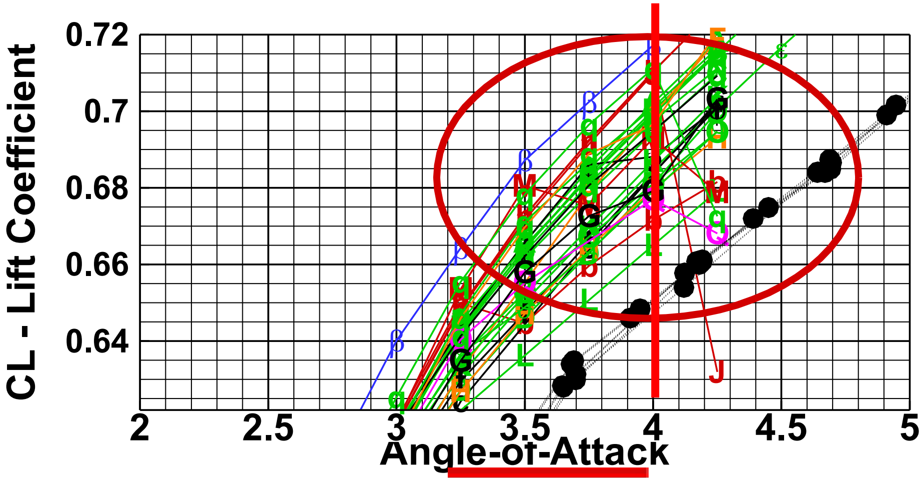



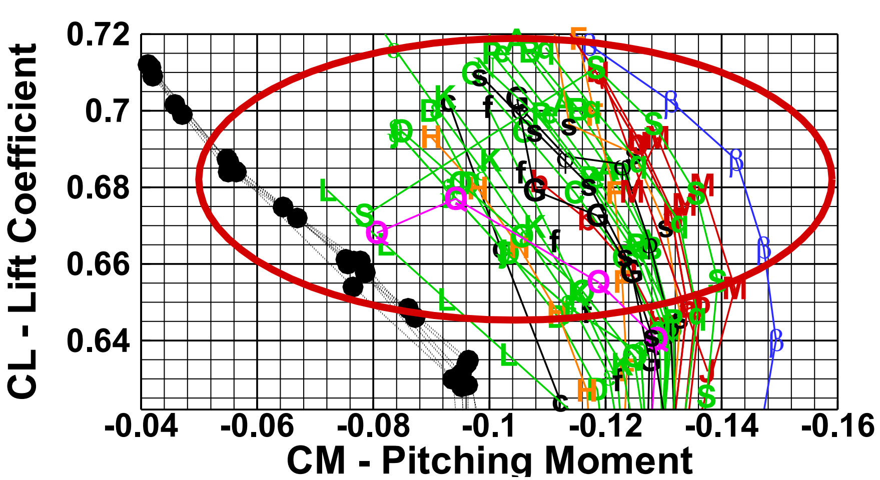



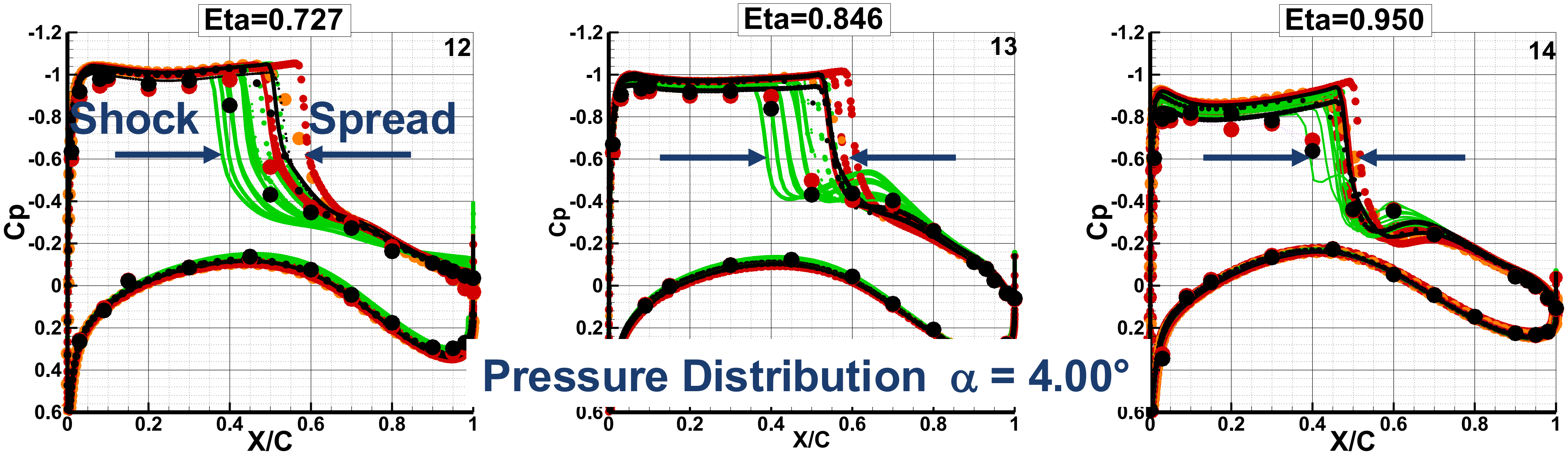
# Issues: Excessive Solution Spread



# Solution Spread – Predicted Shock Location



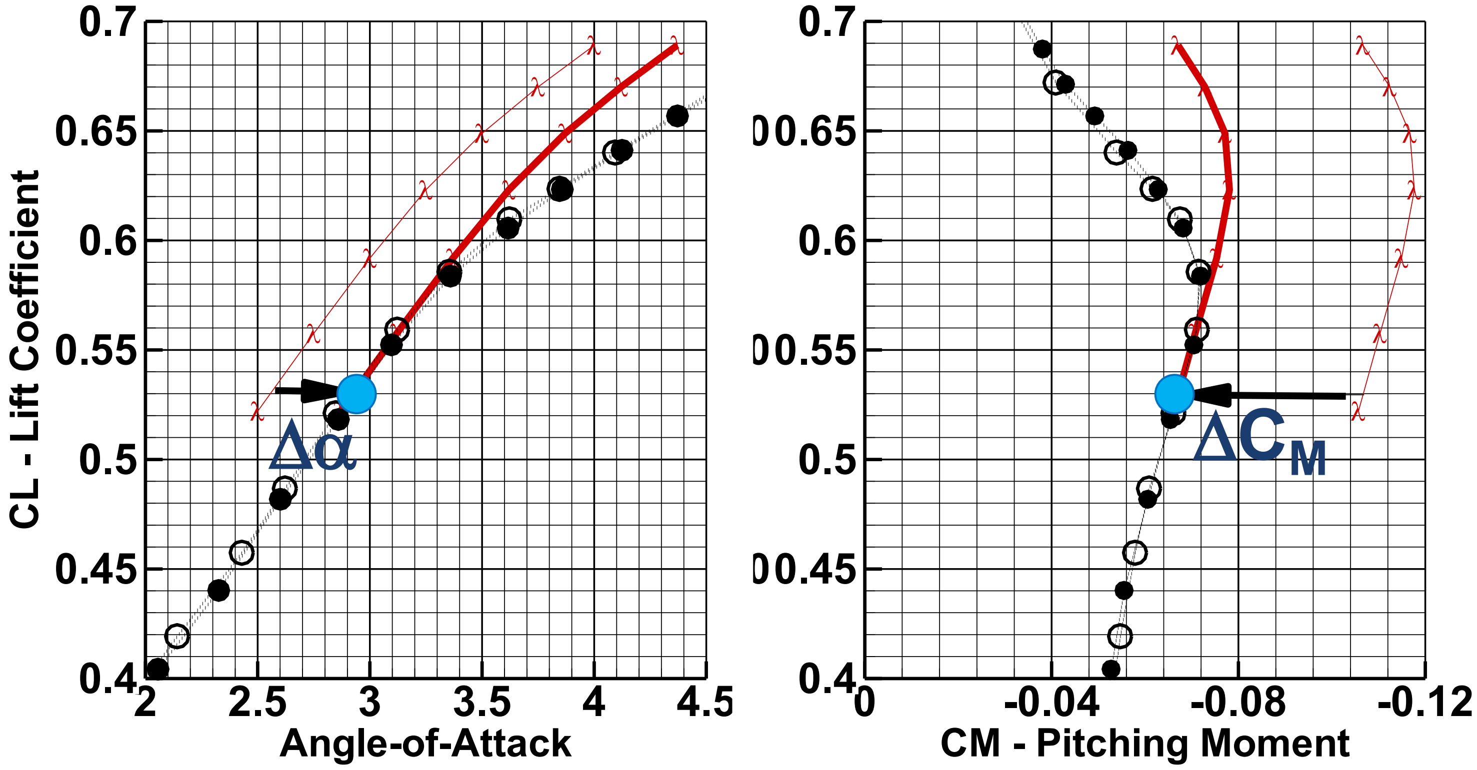




Pressure Distribution $\alpha$ = 4.00°

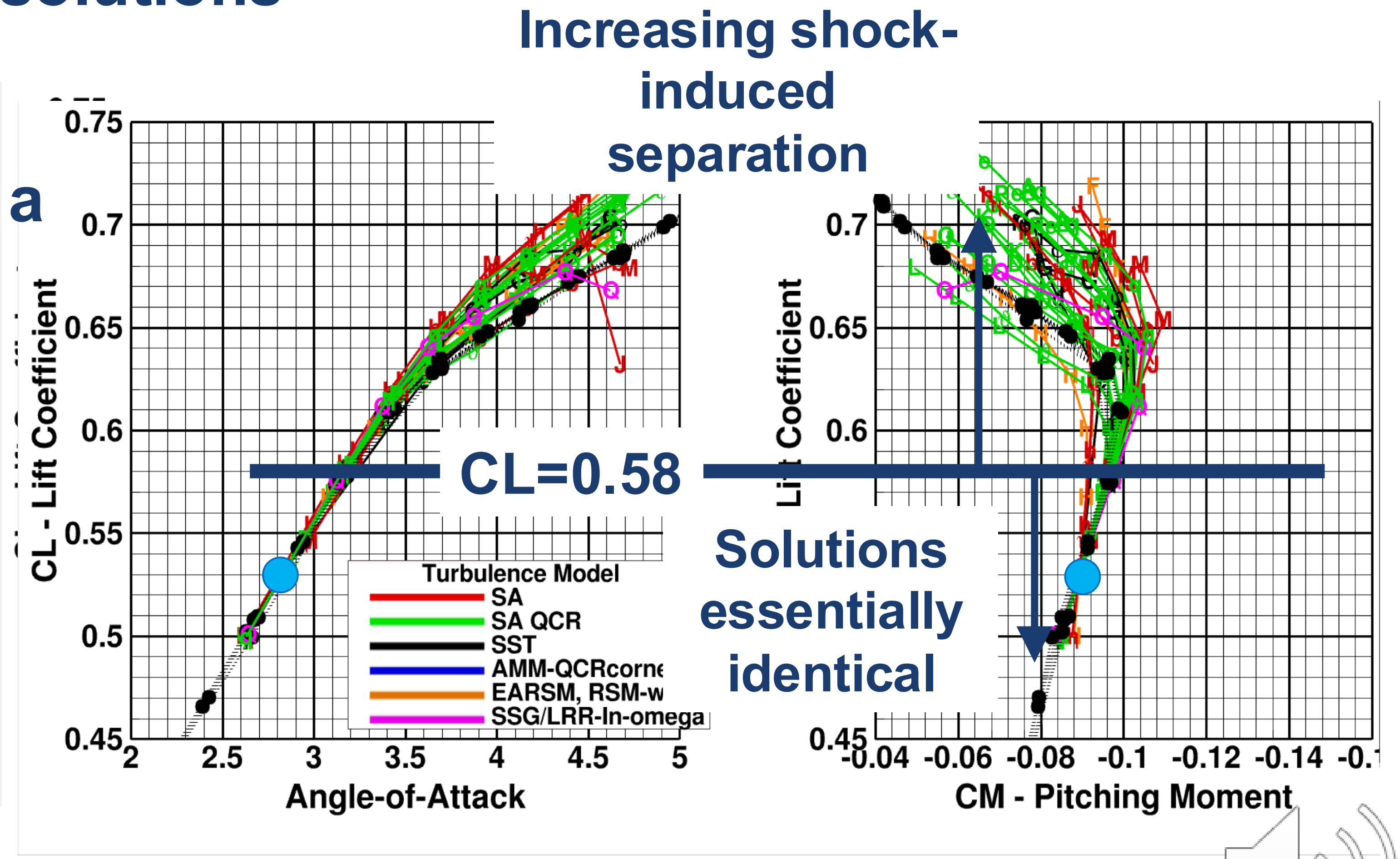
# Collapsing CFD to a Common Value of a and $C_M$

- **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 ($\Delta C_M$) 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.

- **Starting with the original solutions**
- **Collapse the data to a common point by adding a $\Delta\alpha$ and $\Delta$ CM to each solution**
- **Allows a better look at how the solutions vary with increasing angle-of-attack**



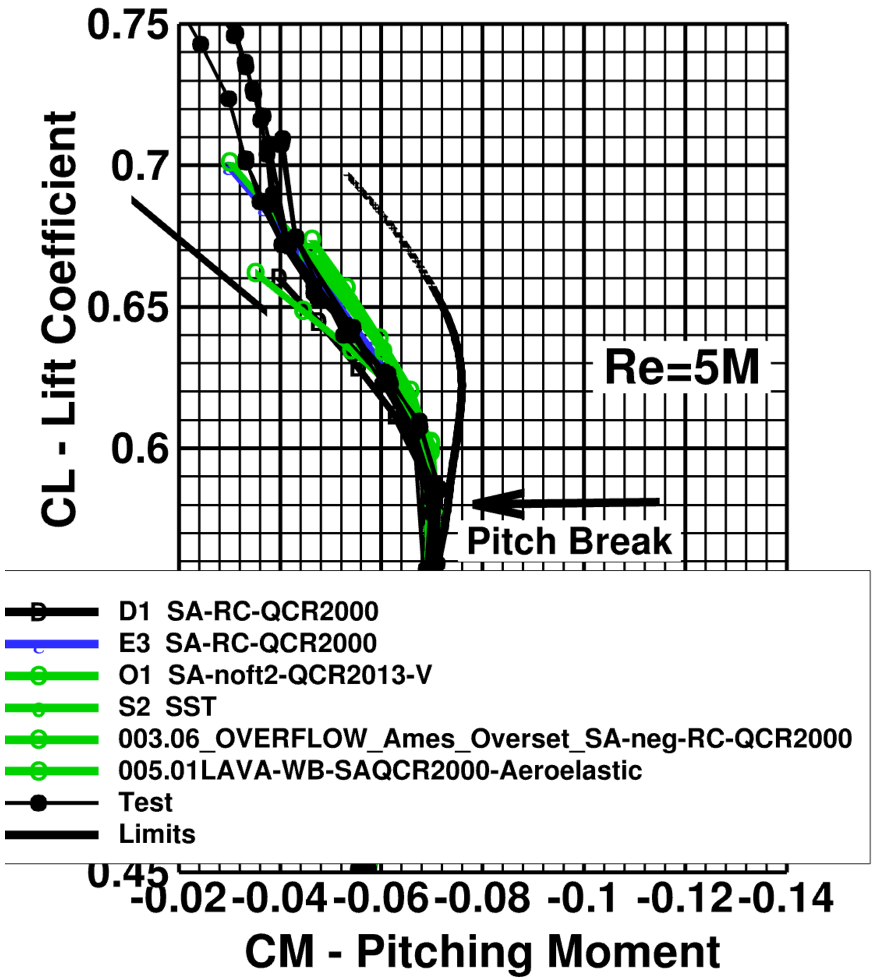
## Best Matches

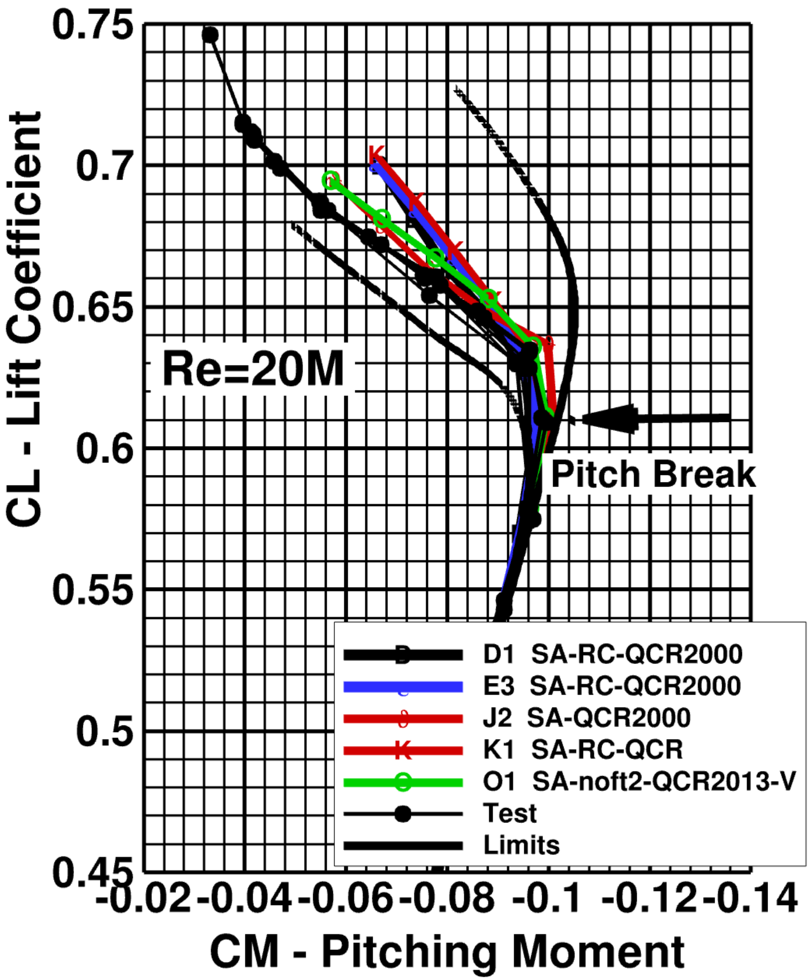
- 6 out of 23 @ Re = 5M

Includes DPW8

- 5 out of 31 @ Re = 20M

- 3 Solvers best matched both 5M & 20M data

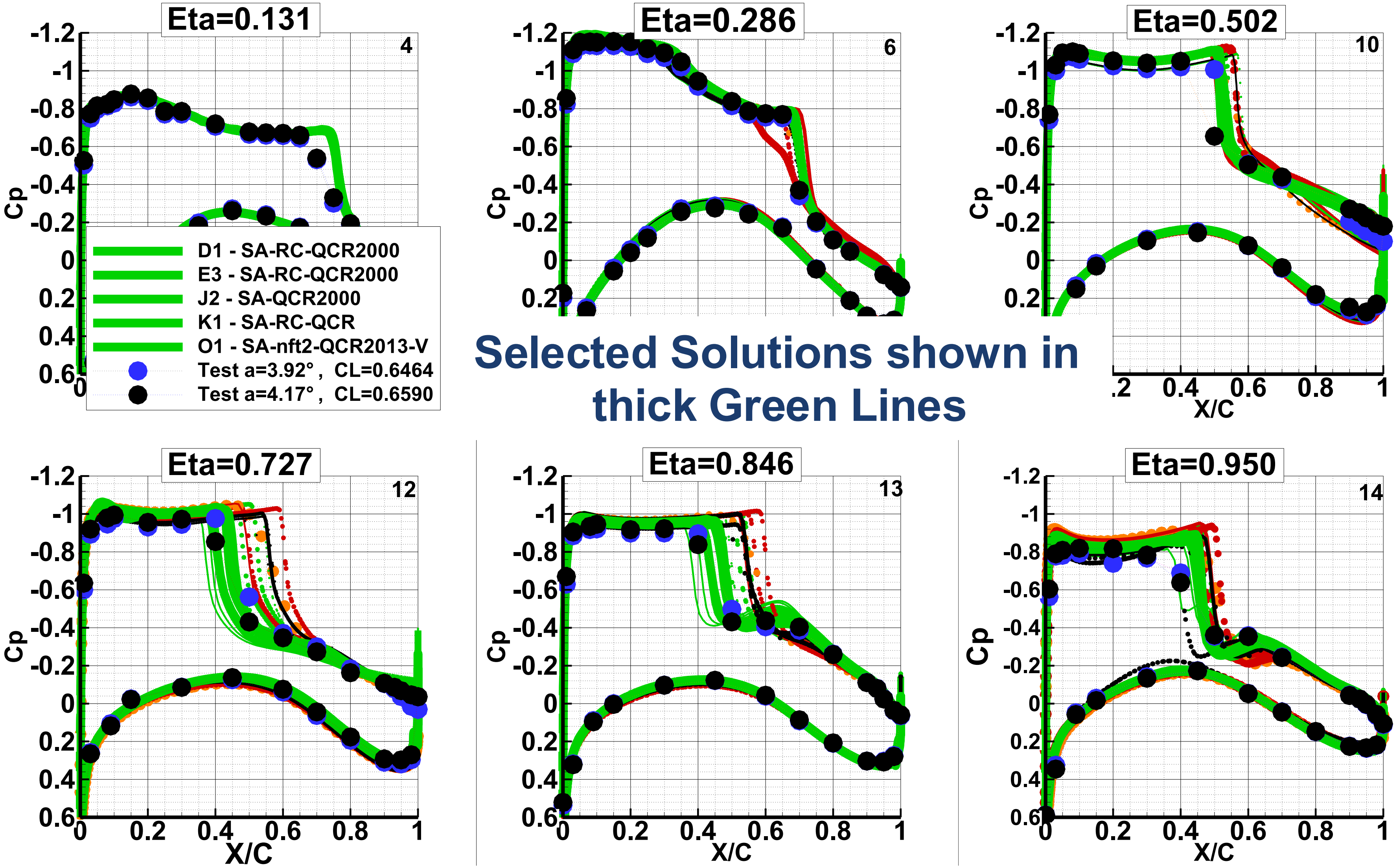



Mach = 0.85, Re=5M, Re=20M-Selected Solutions

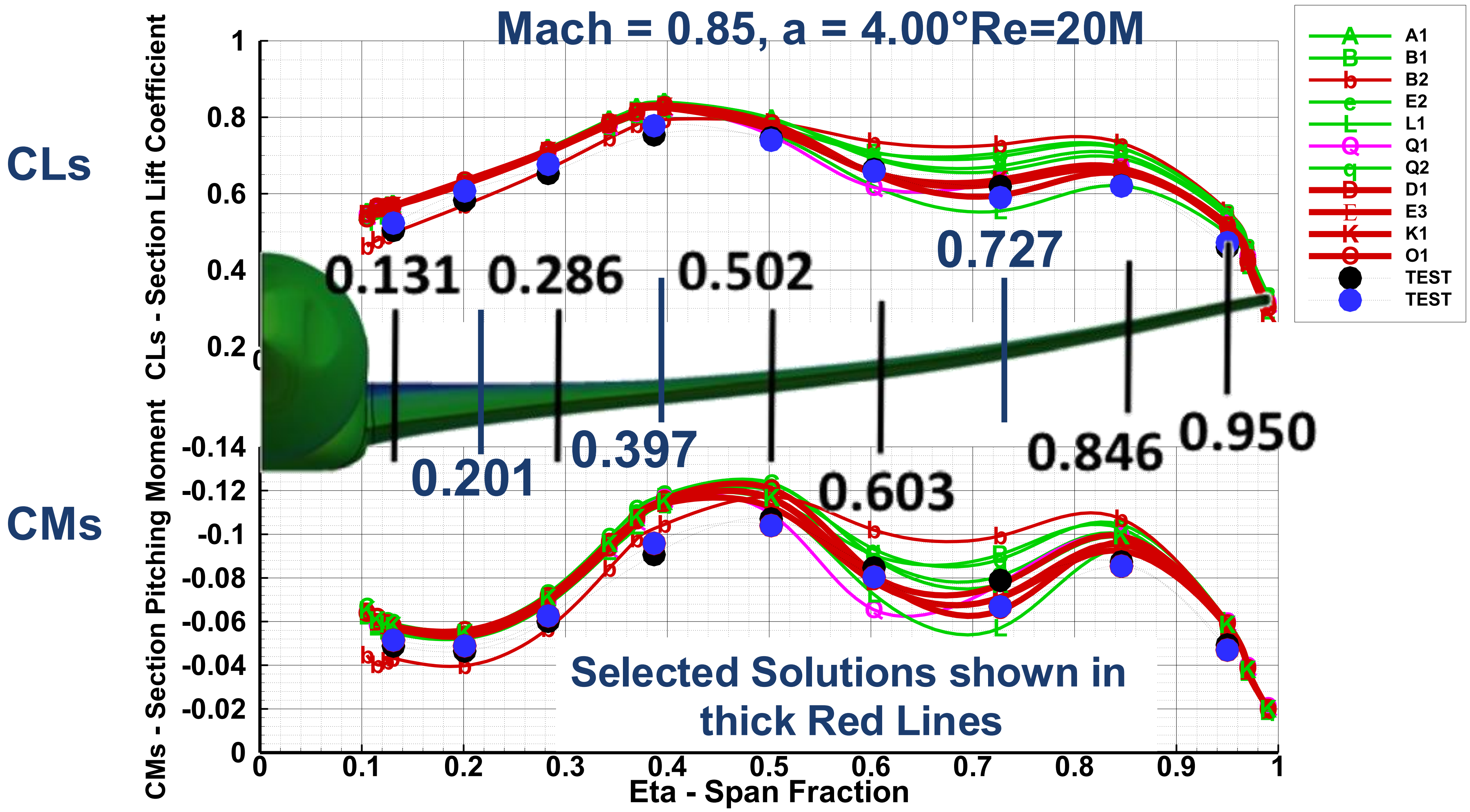
- All but one used some variation of SA-QCR turbulence model

# Wing Pressure Distributions – 4.0° angle-of-attack




**Selected Solutions shown in thick Green Lines**

# Wing Section Lift and Moment Distribution



# General Observations and Comments:

- Attached flow – Drag:  Consistent results – Good.
- Too much variation of Lift and Pitching moment at higher angles of attack – Shock-induced separation: We need to better understand the interaction of grid, solver, turbulence model.
- 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!).
- MUST advance the state-of-the-art on solution adaptive grid solvers. Bigger grids are not the answer. Having them in the right place is.
- Need further detailed experimental measurements that adequately capture the flow separation and unsteadiness – Could uPSP help?.

# General Observations and Comments:

- **DPW-8/AePW-4: Working Groups are focusing on many of these issues. Must continue!**
  - **Working Group #1: Source of Scatter Working Group**
  - **Working Group #2: Static Aeroelastic Deformation Working Group (with AePW)**
  - **Working Group #3: Buffet Working Group (with AePW)**
  - **Working Group #4: Wind Tunnel Test Environment Working Group**
- **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?

### DPW-9 ??

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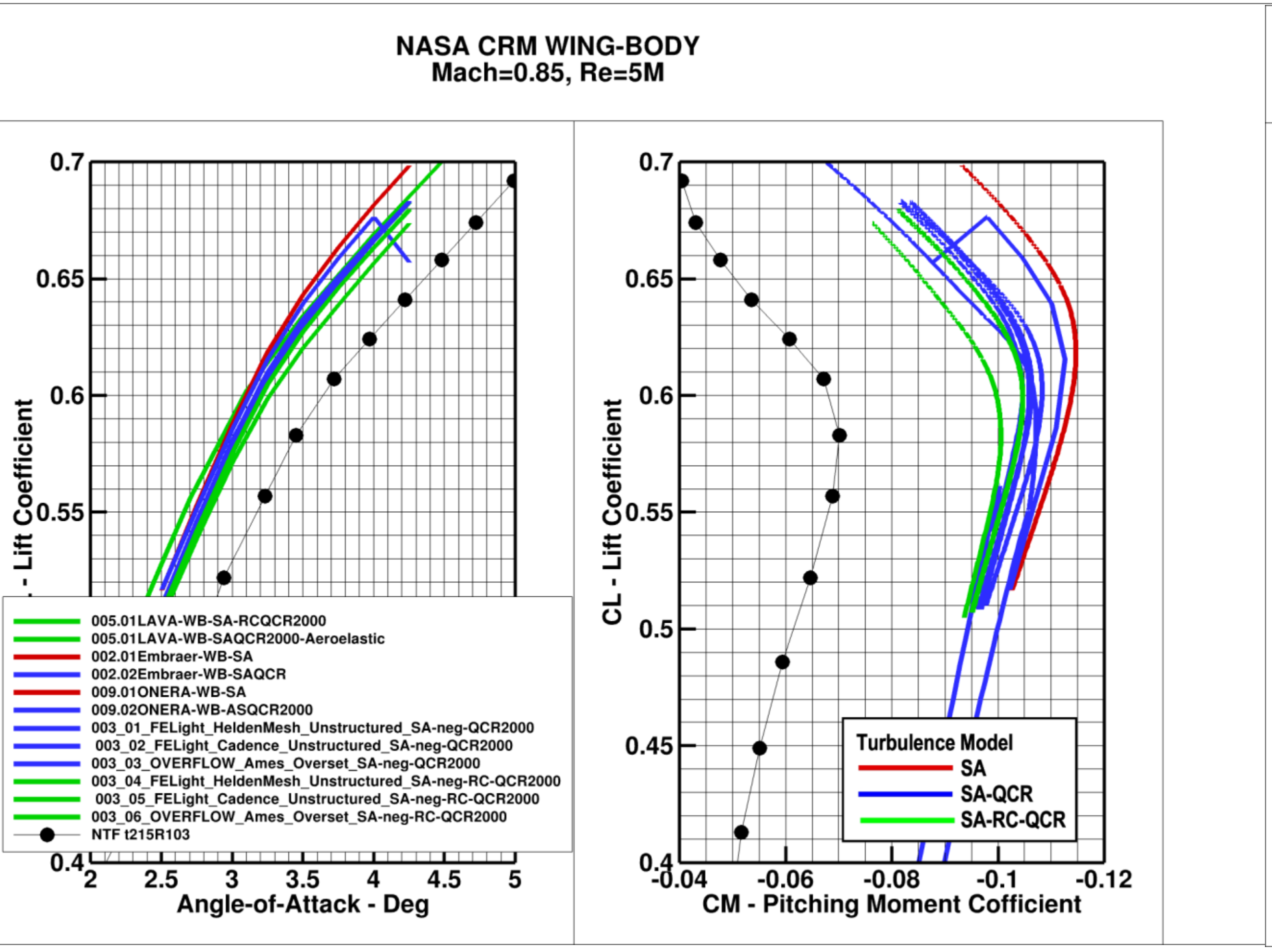
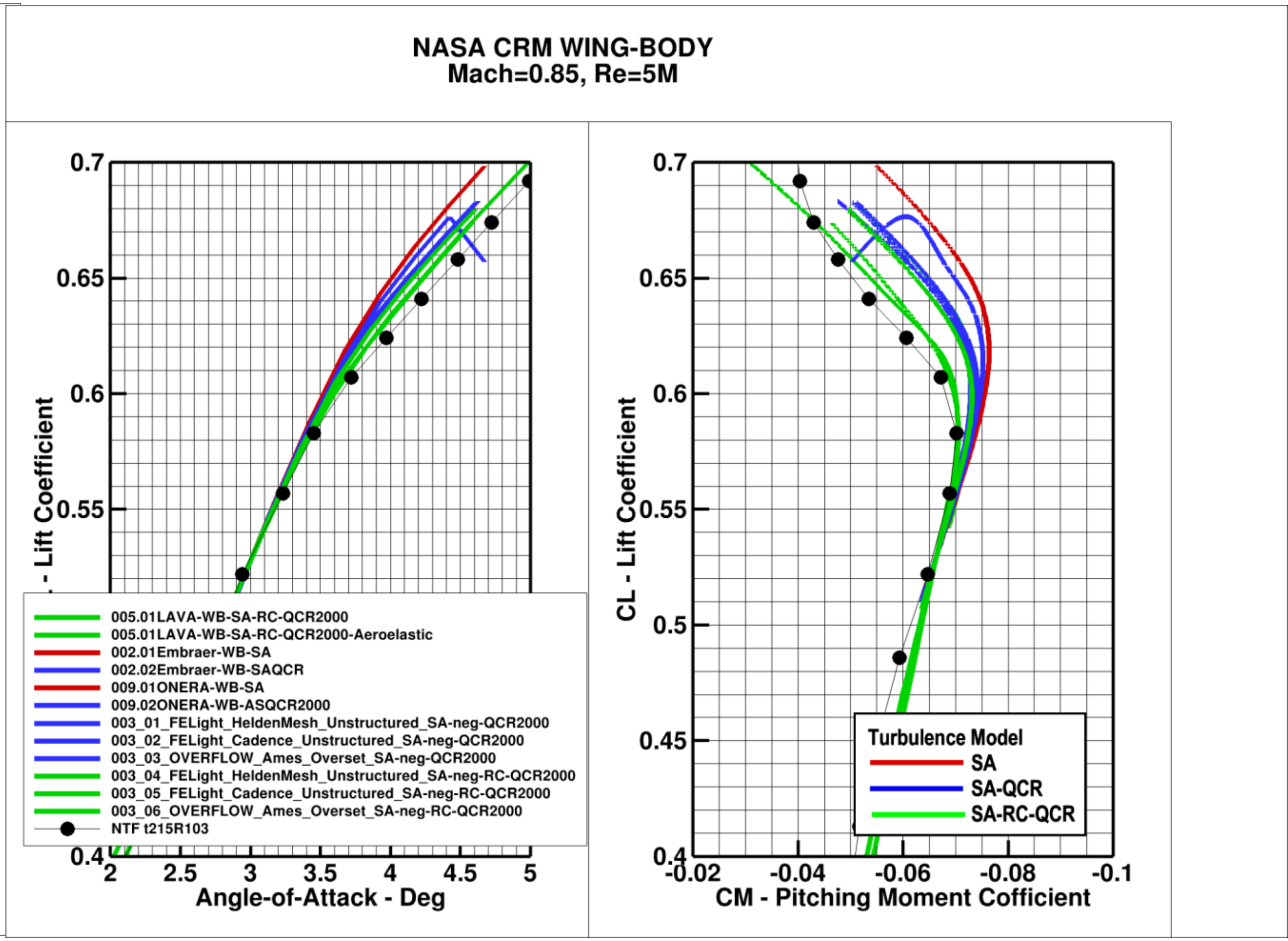
# Lift and pitching moment for all solutions – DPW8

## Mach = 0.85, Re = 5M

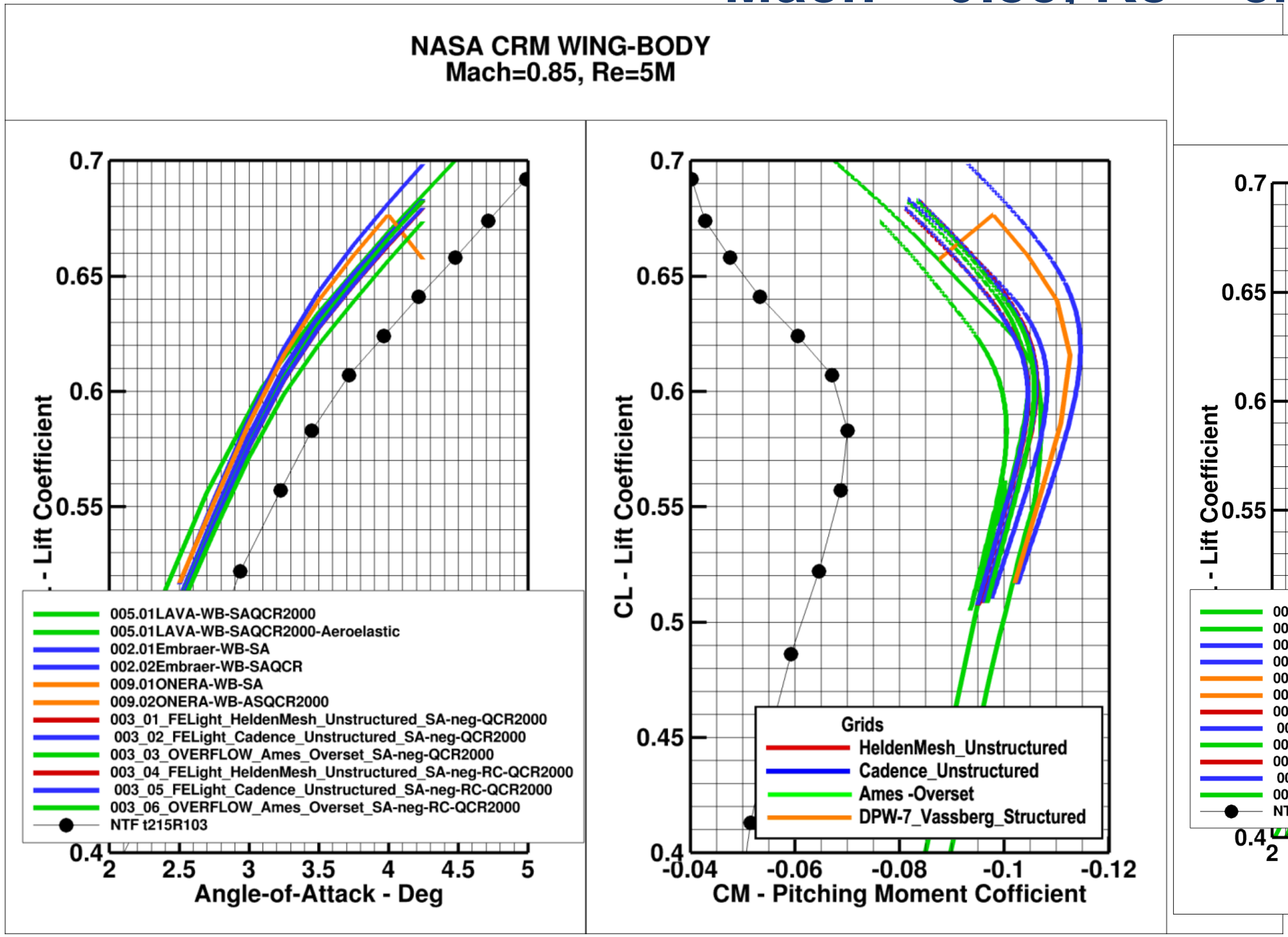


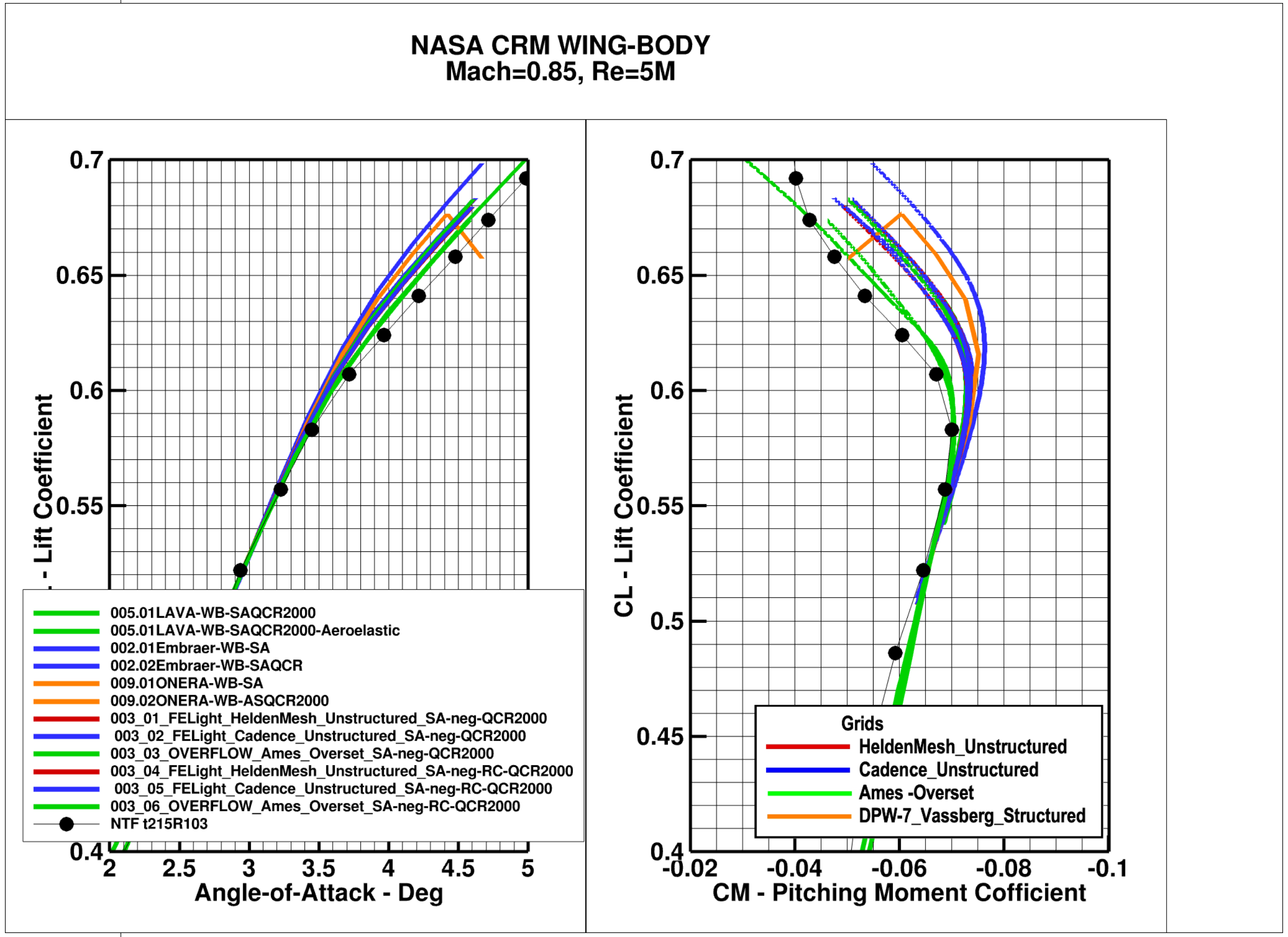




↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ **Specific geometry and grids for each α**

# Lift and pitching moment for all solutions – DPW8

## Mach = 0.85, Re = 5M

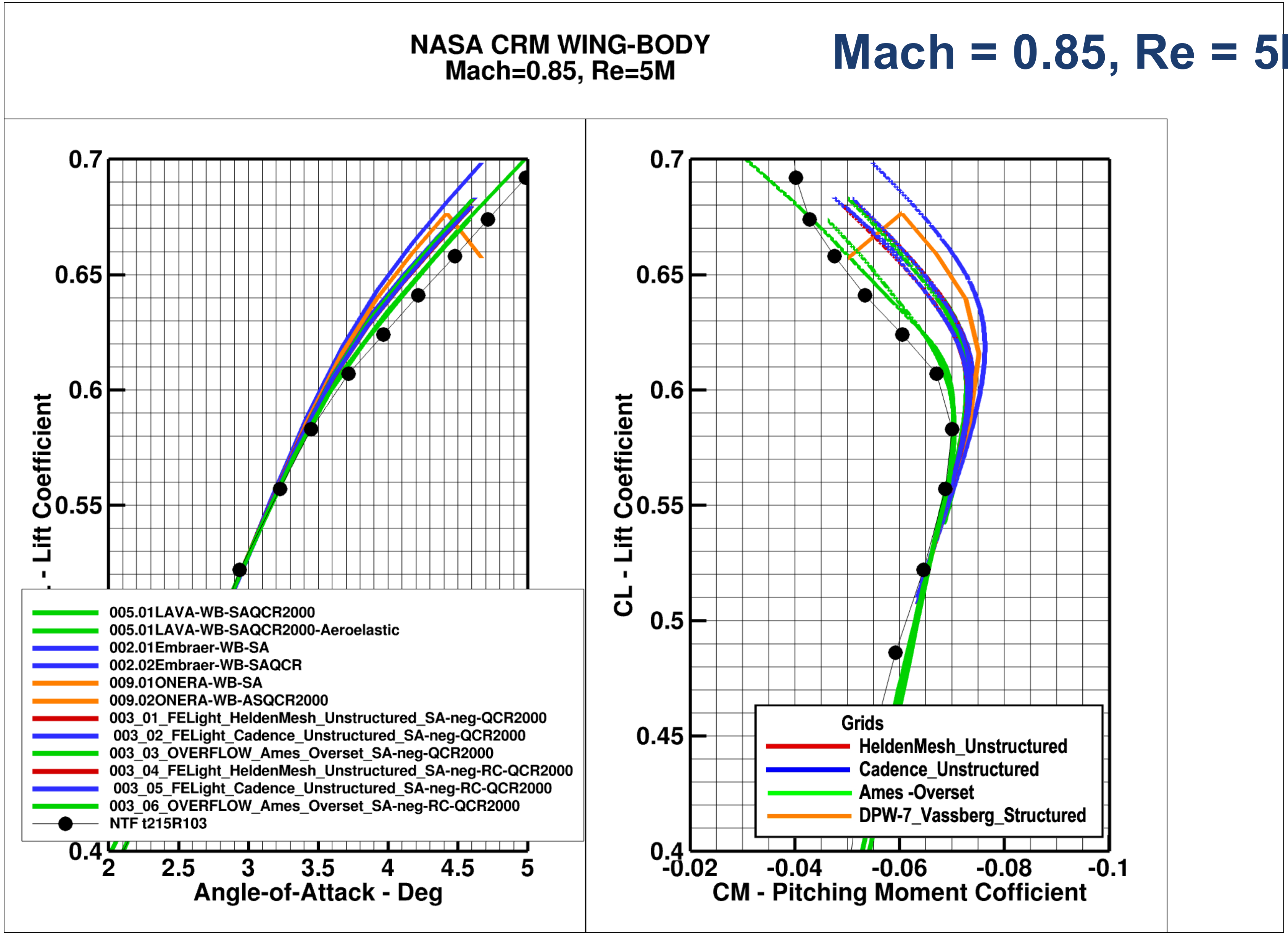


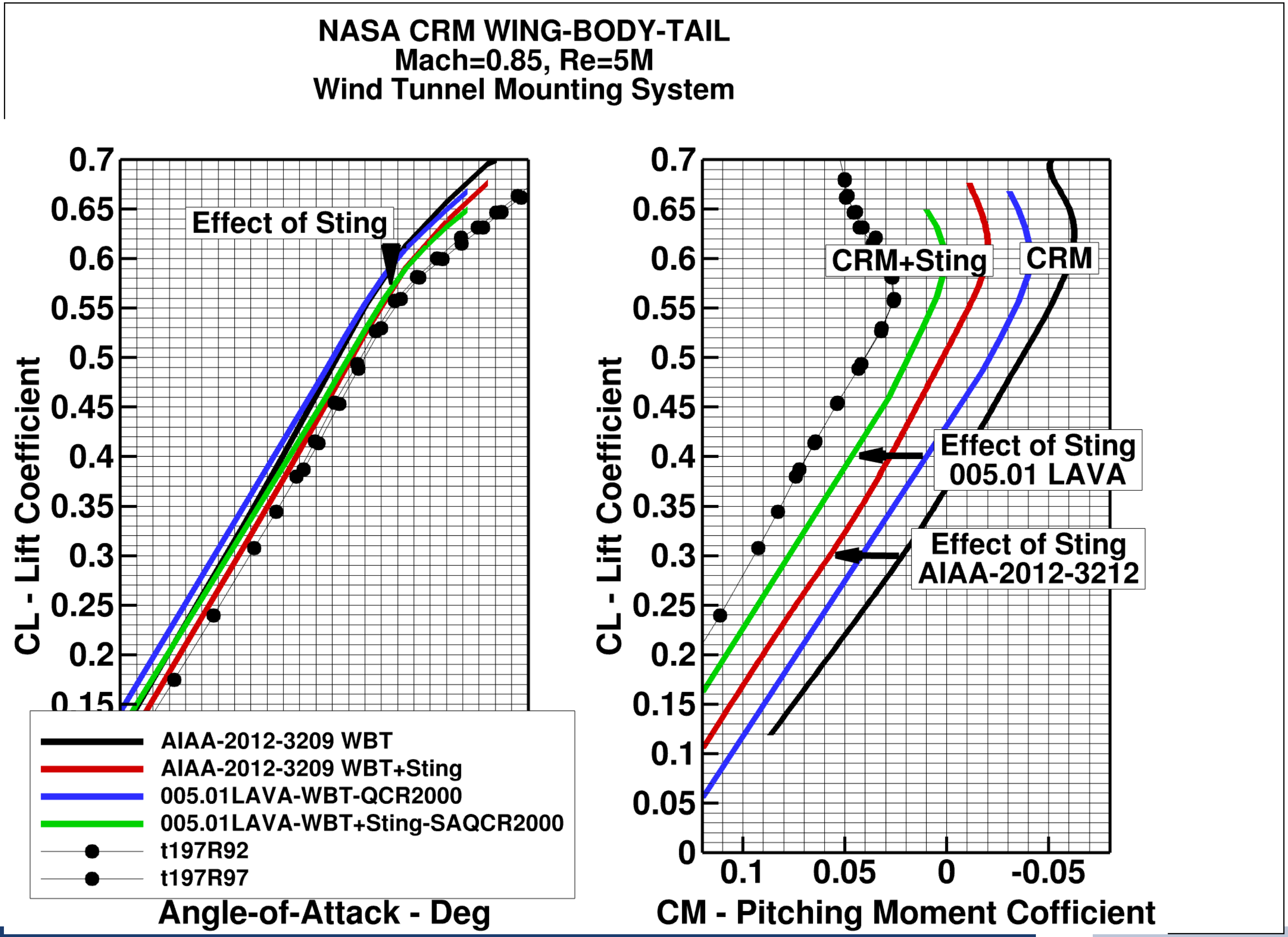




↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑ Specific geometry and grids for each $\alpha$

# Lift and pitching moment for all solutions

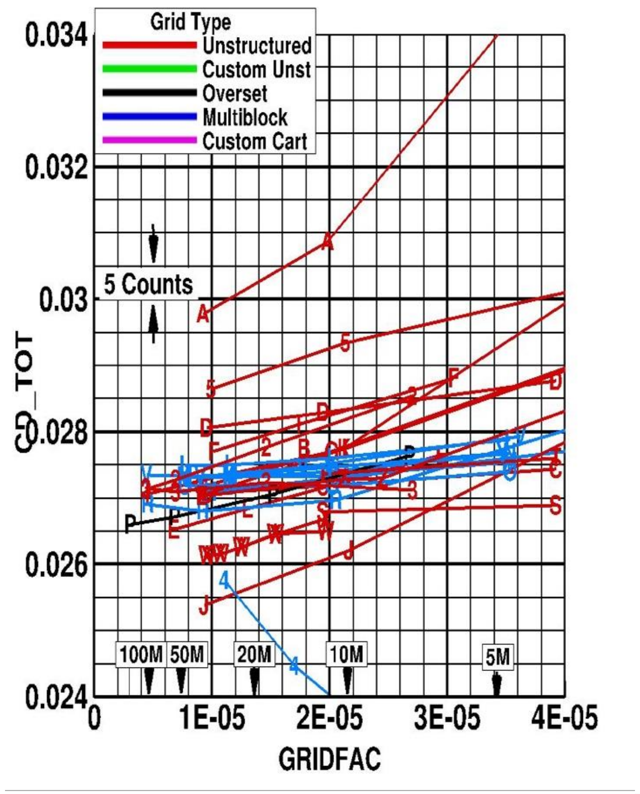
Mach = 0.85, Re = 5M

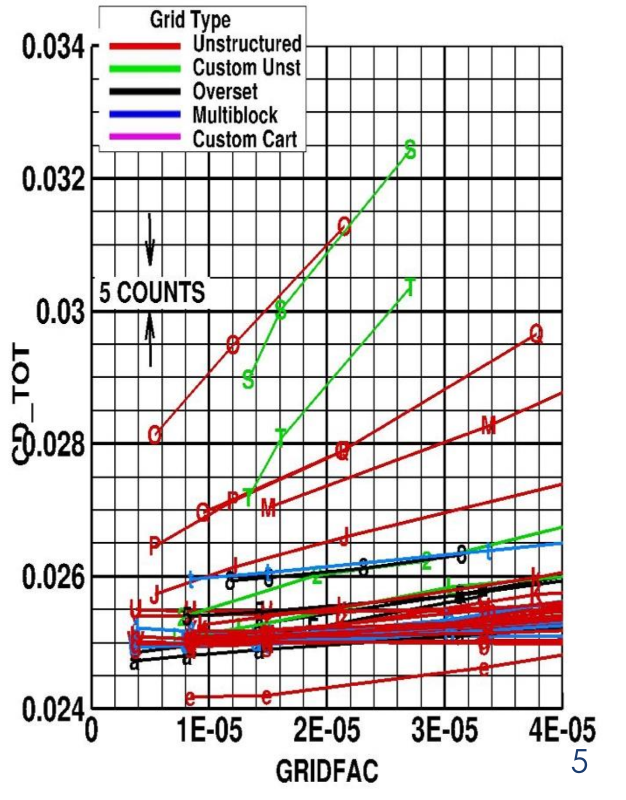


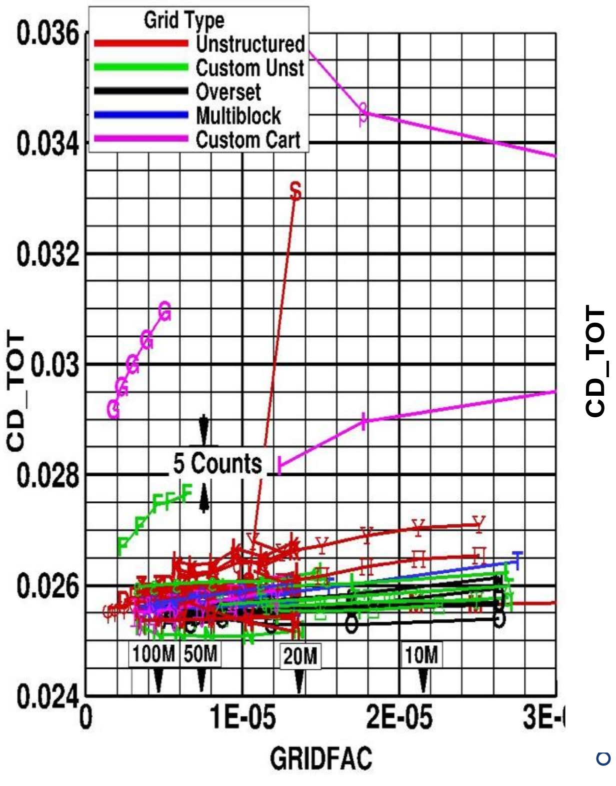

NASA CRM WING-BODY-TAIL
Mach=0.85, Re=5M
Wind Tunnel Mounting System
Effect of Sting
CL - Lift Coefficient
Angle-of-Attack - Deg
CRM+Sting
CRM
Effect of Sting
005.01 LAVA
Effect of Sting
AIAA-2012-3212
CM - Pitching Moment Cofficient
AIAA-2012-3209 WBT
AIAA-2012-3209 WBT+Sting
005.01LAVA-WBT-QCR2000
005.01LAVA-WBT+Sting-SAQCR2000
t197R92
t197R97

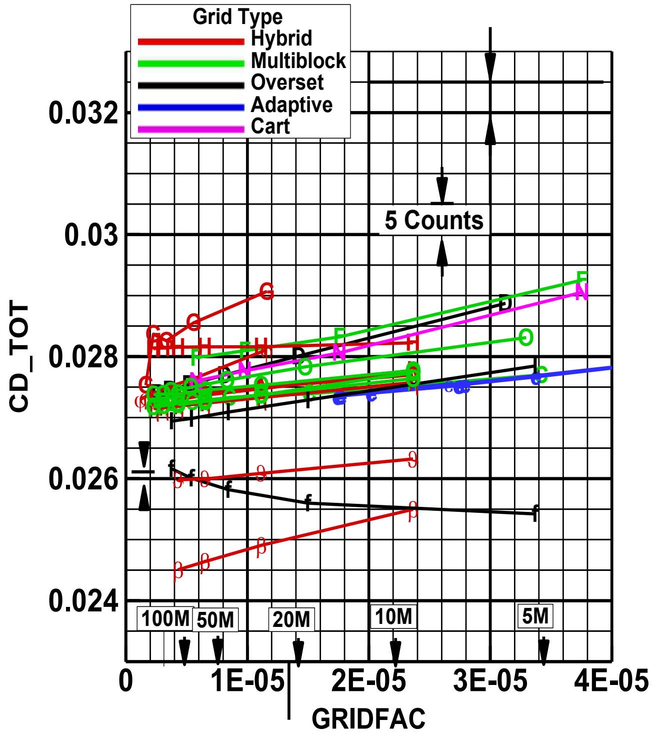
# GRID Convergence – Grid Type

| DPW4 | DPW5 | DPW6 | DPW7 |
| --- | --- | --- | --- |
| Wing-Body-Tail | Wing-Body | Wing-Body | Wing-Body |
| Re=5M | Re=5M | Re=5M | Re=20M |
| 2009 | 2012 | 2016 | 2022 |



# Drag Polar for all solutions