OVERFLOW & GGNS-T1 Analysis of the NASA CRM WB configuration for DPW-VII

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Joshua Krakos	Boeing Research & Technology

Outline

- **Flow Solvers and Grid Summary**
  - OVERFLOW (NASA)
  - GGNS-T1 (Boeing)
- **Convergence History**
- **Cases Analyzed**
  - OVERFLOW
  - GGNS-T1
- **Results**
  - Case 1: CRM Wing-Body Grid Convergence Study
  - Case 2: CRM Wing-Body Alpha Sweep
  - Case 3: CRM Wing-Body Reynolds Number Sweep At Constant CL
  - Case 4: CRM Wing-Body Alpha Sweep with Grid Adaptation
- **Conclusions**

OVERFLOW: Solver, Grid and Computing Platform

OVERFLOW version 2.3e

- **Same setup as used for past workshops for consistency**
  - 2nd order central differencing
    - Central / Beam-Warming scalar pentadiagonal scheme (IRHS=0, ILHS=2)
  - SA turbulence model (SA-neg-noft2) with:
    - RC: rotation/curvature corrections
    - QCR: nonlinear stress model via QCR
  - fully turbulent boundary layer, free stream initial conditions
  - full N-S, exact wall distance calculation
- **Common Overset Grid**
  - Provided by Committee
- **Utilized Ivy Bridge nodes with 2 ten-core processor per node**

case	grid	points (M)	cores	sec/it	sec/it/grid	iterations	wall clock
T	Tiny	5.72 M	40	0.94	16.550e-8	20000	5.1 hrs
C	Coarse	18.62 M	40	1.95	10.450e-8	20000	10.5 hrs
M	Medium	43.32 M	120	1.60	3.703e-8	25000	10.9 hrs
F	Fine	83.66 M	220	2.10	2.511e-8	25000	14.3 hrs
X	Extra Fine	143.47 M	300	2.28	1.599e-8	30000	18.8 hrs
U	Ultra Fine	226.59 M	460	2.79	1.240e-8	35000	26.9 hrs

GGNS-T1: Solver, Grid and Computing Platform

GGNS-T1

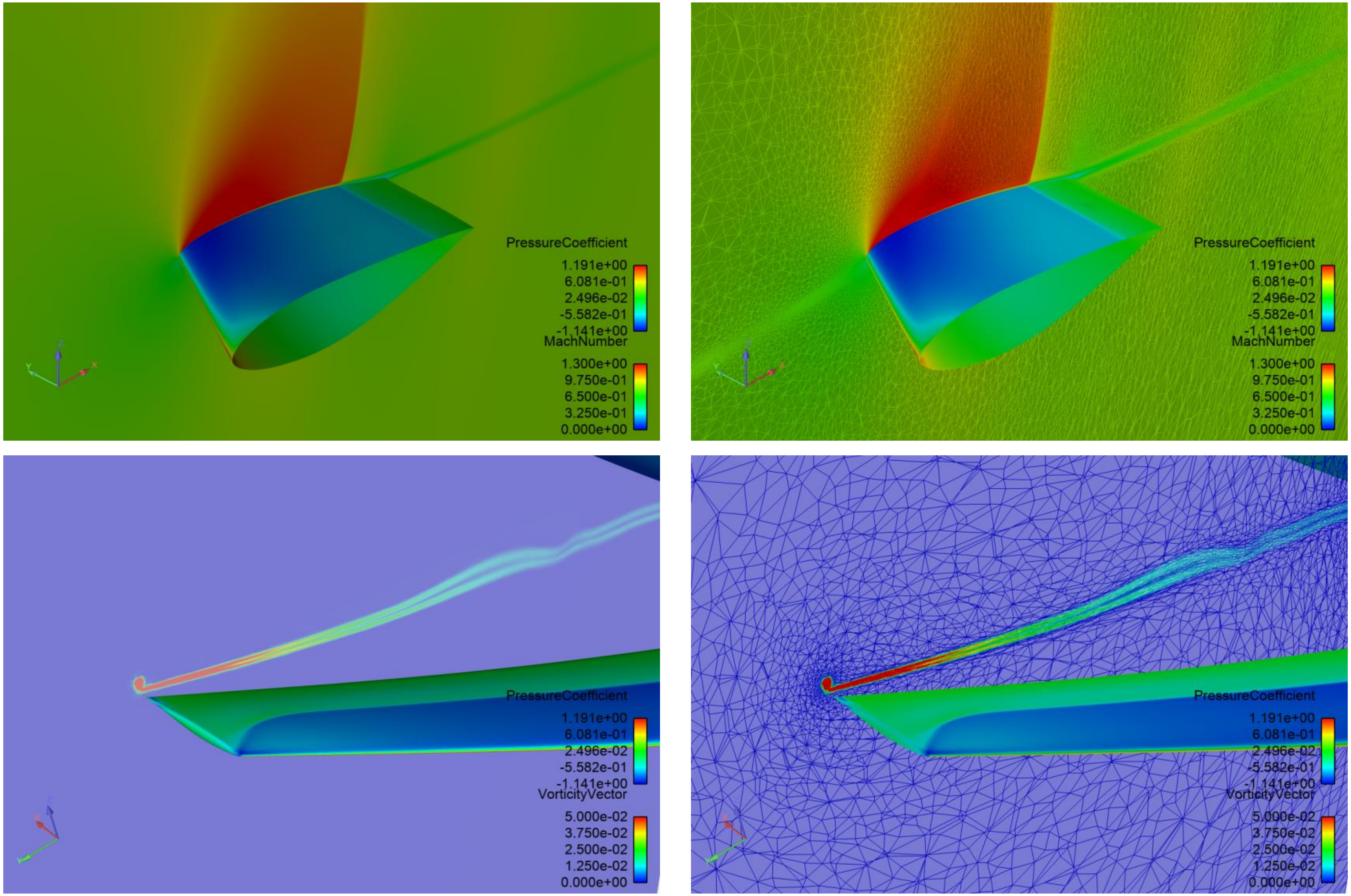
- **Discretization**
  - SU/PG(1)
    - Tetrahedral cells
    - piecewise-linear, globally continuous finite elements
    - Residual-based stabilization
  - Shock capturing/artificial dissipation by (Glasby et.al.[1])
- **Solver**
  - RANS, steady-state (SA, SA-QCR2000, SARC-QCR2000 fully turbulent)
  - Fully coupled turbulence equations
  - Exact Jacobians (except SARC) with operator overloading
  - Pseudo-transient continuation to steady-state
  - Newton's method
  - Parallel MPI implementation based on PETSc [2]
  - 12 orders for the dual-volume weighted discrete residuals
  - 10 orders for the adjoint linear system residual
- **Adaptation : EPIC [3]**
  - Goal oriented (GO) "$\varepsilon_1 + \varepsilon_2$, multi-component" from [4]
- **400 cores x 24 hours for 24 solver/adaptation cycles**
  - Includes primal and adjoint solves and grid adaptation times

EPIC Adapted Grids

Drag Adjoint Adaption

case	grid	points (M)
-	L0 – L13	0 –> 1.8 M
-	L14 – L16	~3.6 M
-	L17	~5.0 M
-	L18 - L20	~6.8 M
-	L21	~10.9 M
-	L22 – L24	~13.5 M

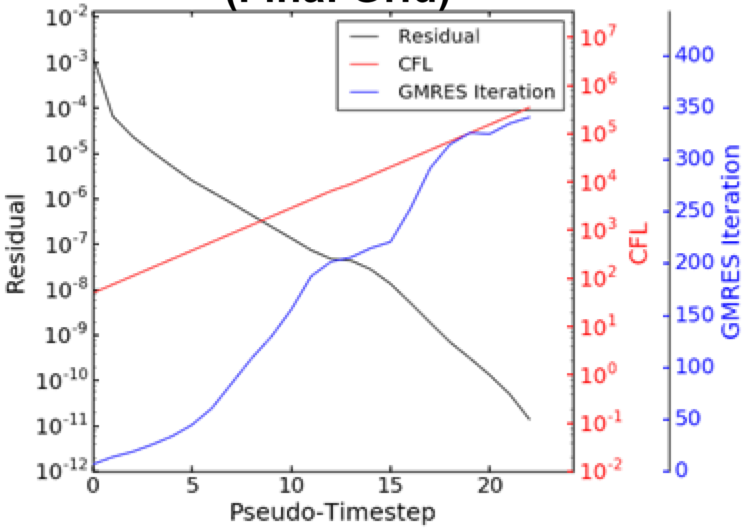
GGNS-T1/EPIC Grid Visualization



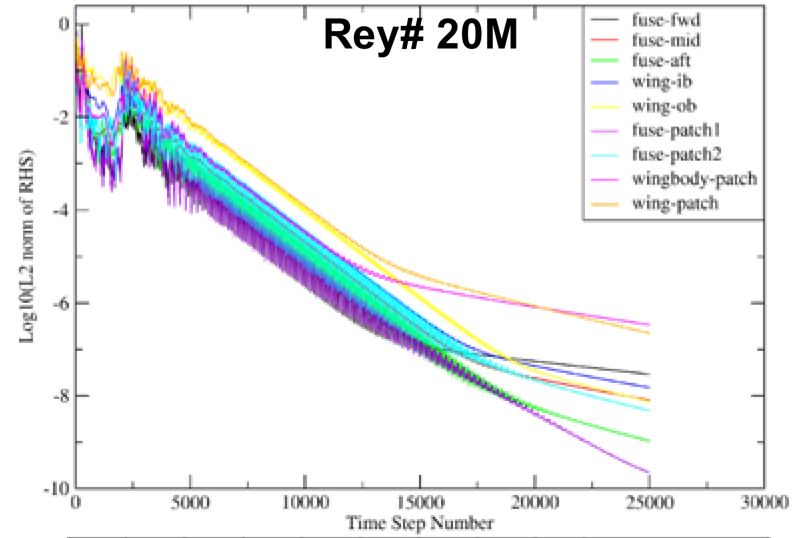
Convergence History: Residuals

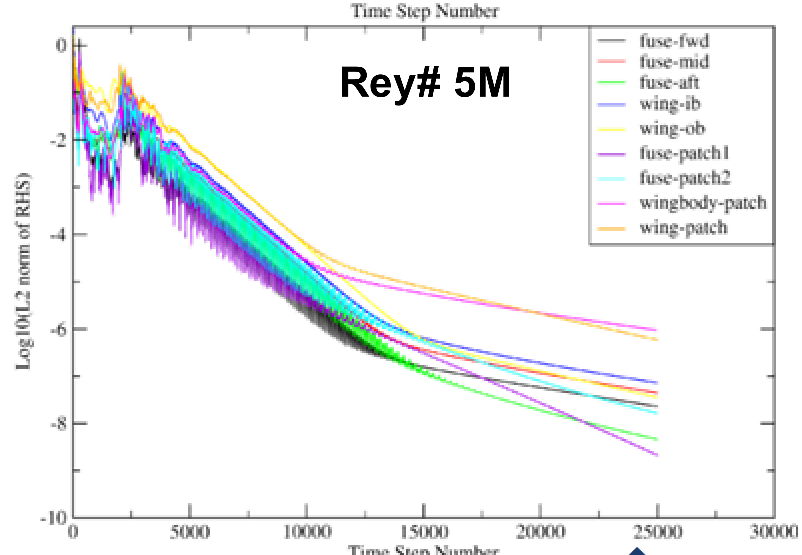
- **Residuals for Mach 0.85, CL = 0.58**
  - Medium Grid

GGNS-T1 (Final Grid)



OVERFLOW





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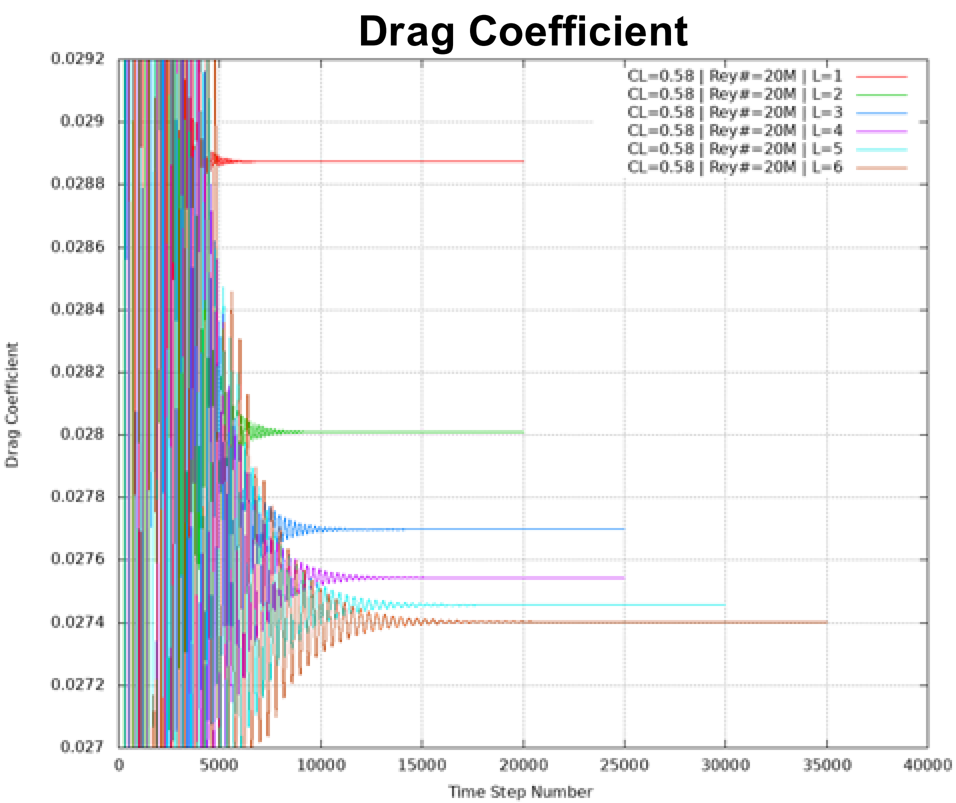
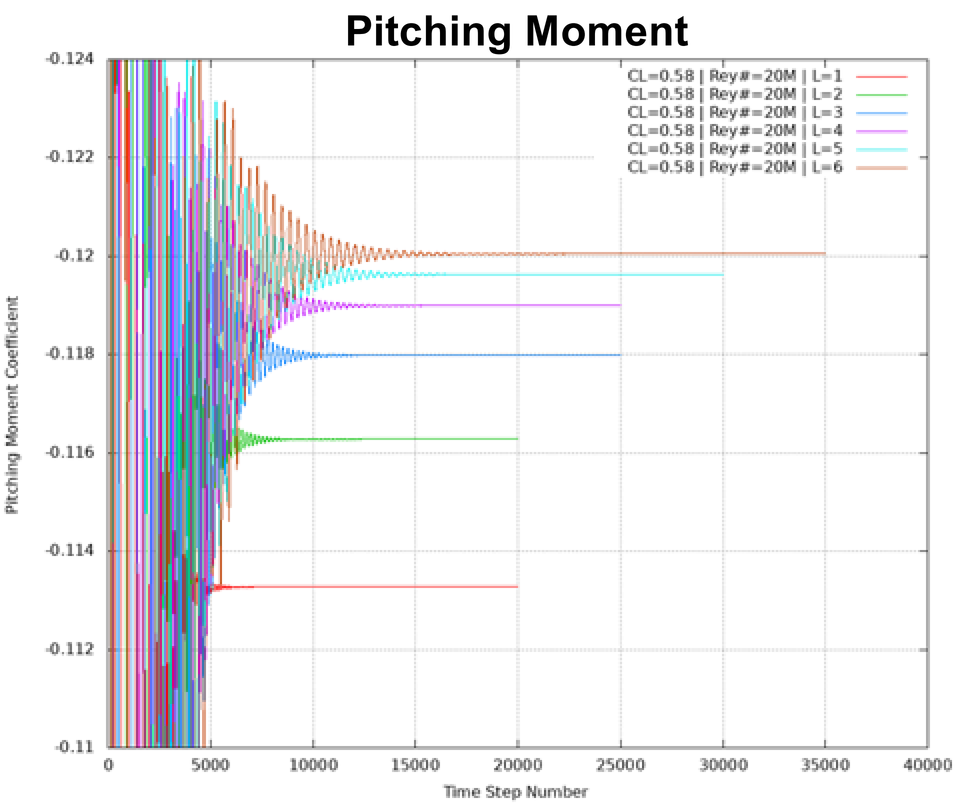
Convergence History: Force/Moment

- **Forces/Moments for Mach=0.85, CL=0.58**





Cases Analyzed

Case 1: Grid Convergence Study (CL=0.58)	OVERFLOW	GGNS-T1
Case 1a: Rey# 20M	X	X
Case 1b: Rey# 5M	X	X

Case 2: Alpha Sweep (Fixed Grid)	OVERFLOW	GGNS-T1
Case 2a: Rey# 20M	X	X
Case 2b: Rey# 5M	X	X

Case 3: Reynolds Number / Q Sweep	OVERFLOW	GGNS-T1
Case 3: CL=0.50	X	X

Case 4: Alpha Sweep (Grid Adaptive)	OVERFLOW	GGNS-T1
Case 4a: Rey# 20M		X
Case 4b: Rey# 5M		X

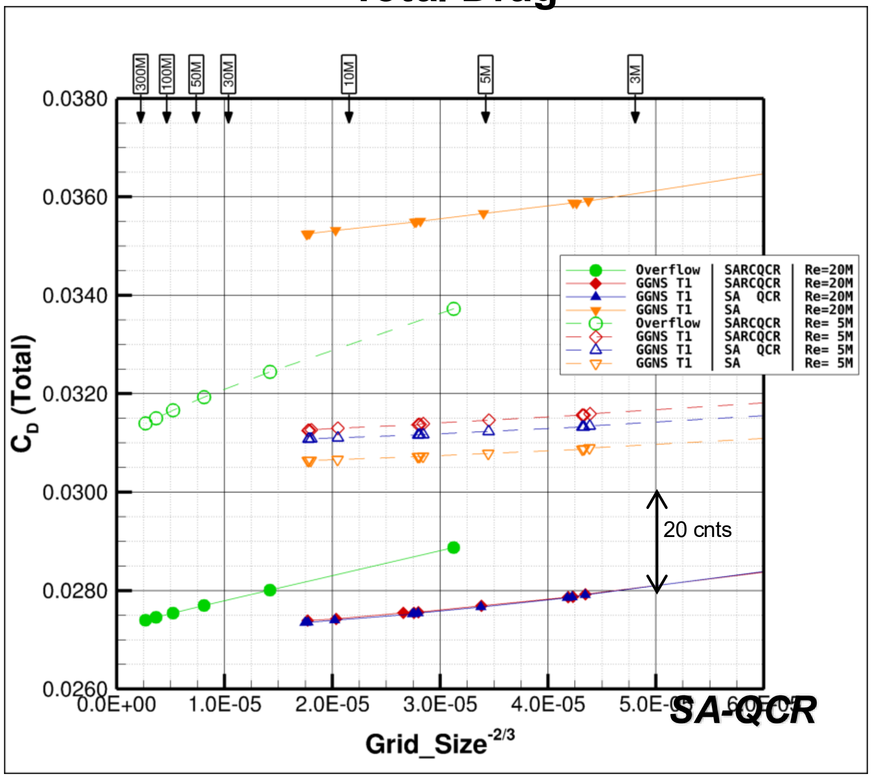
Case 1

CRM Wing-Body Grid Convergence Study

Case 1: CRM Wing-Body Grid Convergence Study

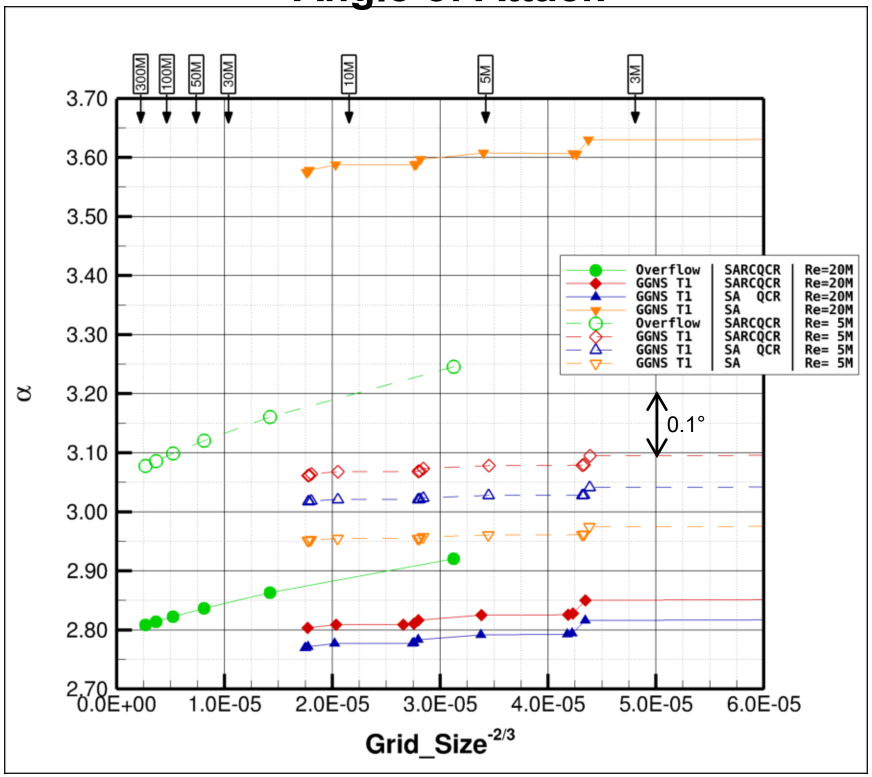
- **Case 1a: Mach=0.85, CL=0.58, Rey# 20M**
  - Closed Symbols
- **Case 1b: Mach=0.85, CL=0.58, Rey# 5M**
  - Open Symbols

Total Drag



← Increasing Grid Size

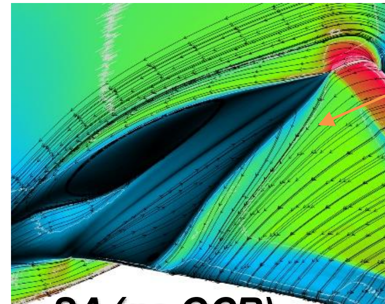
Angle of Attack



← Increasing Grid Size

Case 1: CRM Wing-Body Grid Convergence Study

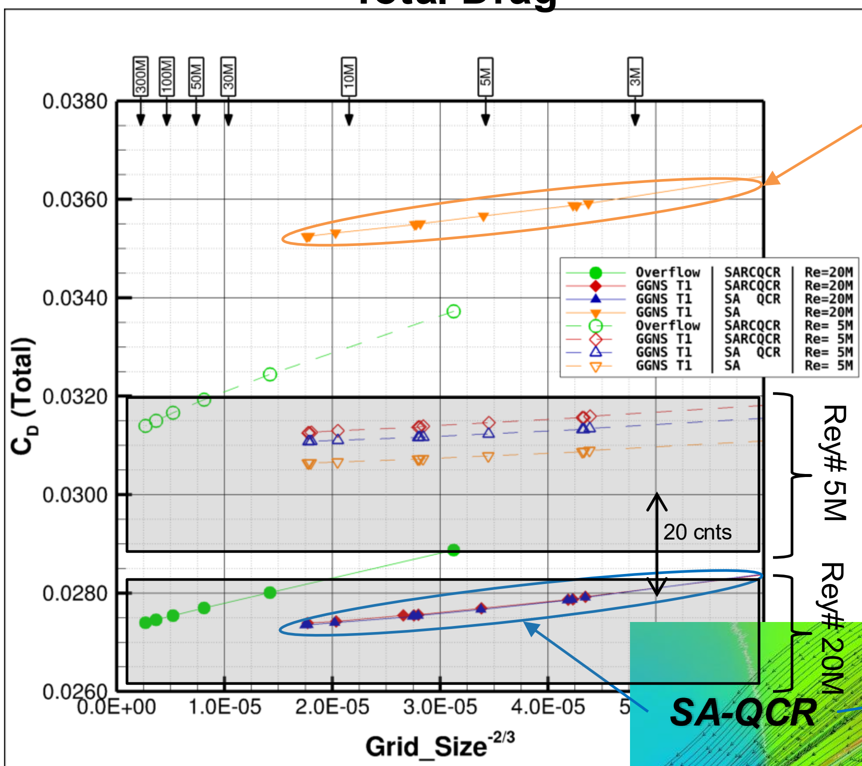
- **Case 1a: Mach=0.85, CL=0.58, Rey# 20M**
  - Closed Symbols
- **Case 1b: Mach=0.85, CL=0.58, Rey# 5M**
  - Open Symbols



SA (no QCR)

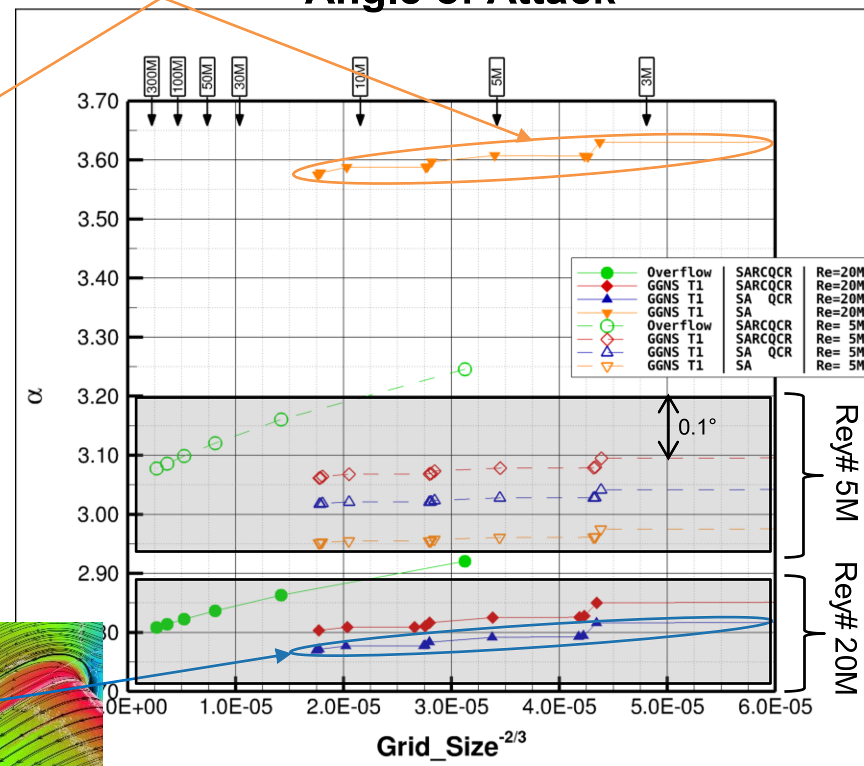
spurious side-of-body juncture separation!

Total Drag

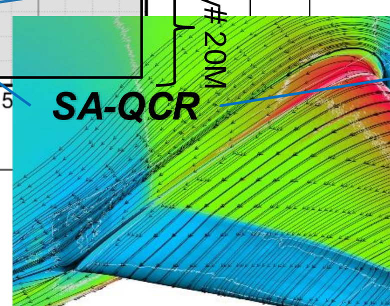


← Increasing Grid Size

Angle of Attack



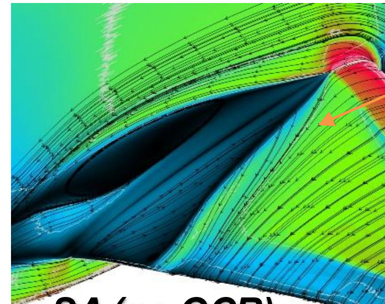
← Increasing Grid Size



SA-QCR

Case 1: CRM Wing-Body Grid Convergence Study

- **Case 1a: Mach=0.85, CL=0.58, Rey# 20M**
  - Closed Symbols
- **Case 1b: Mach=0.85, CL=0.58, Rey# 5M**
  - Open Symbols

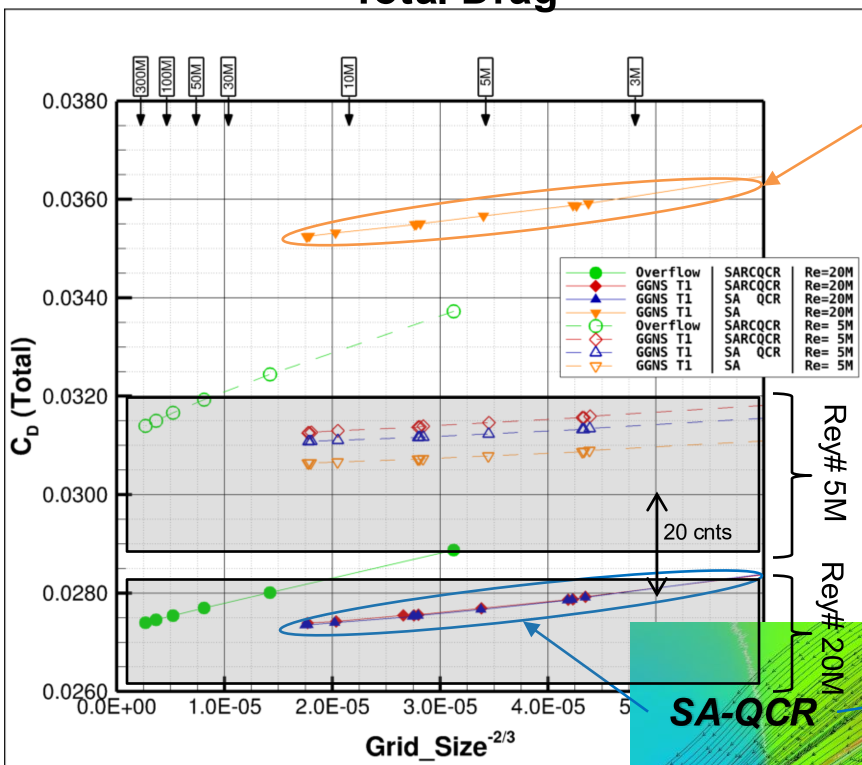


SA (no QCR)

spurious side-of-body juncture separation!

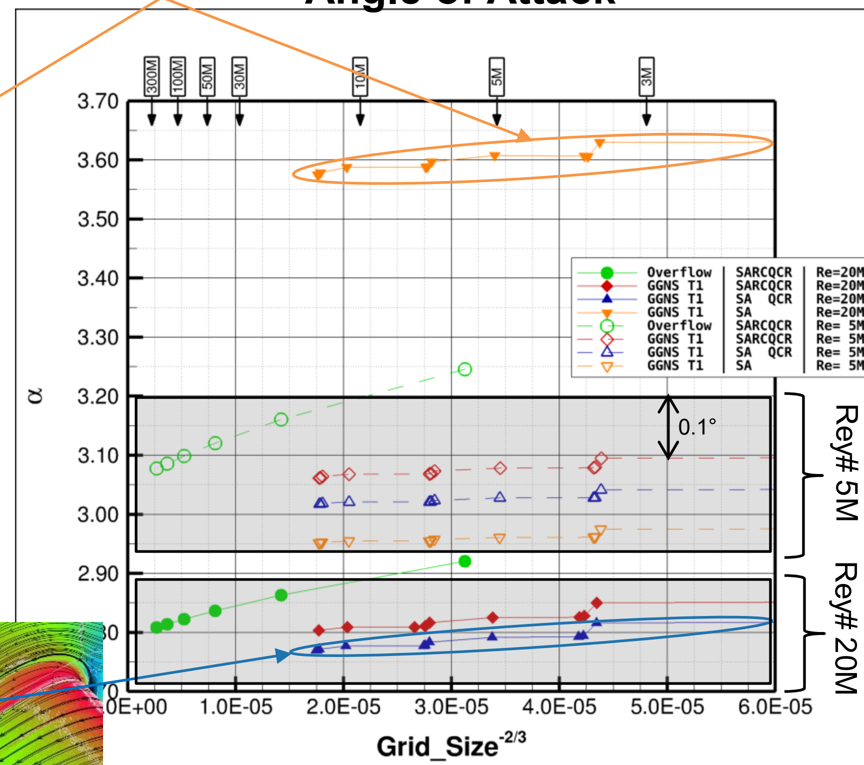
SA (no QCR) will be ignored on remainder of Case 1 charts

Total Drag

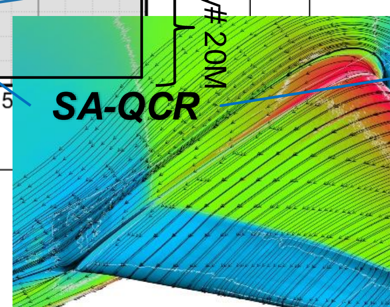


← Increasing Grid Size

Angle of Attack



← Increasing Grid Size

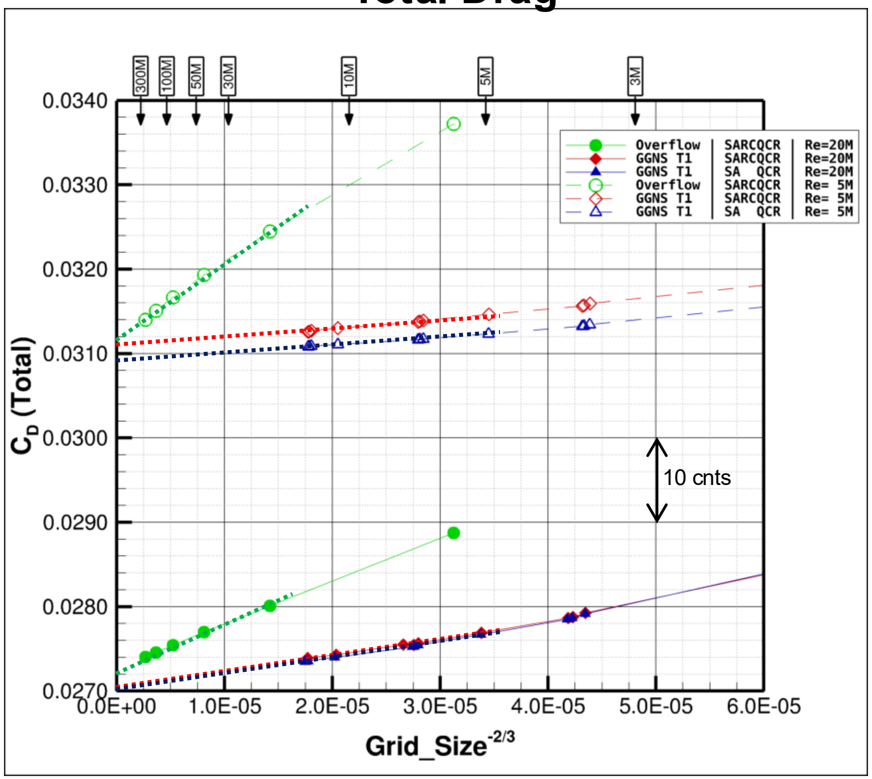


SA-QCR

Case 1: CRM Wing-Body Grid Convergence Study

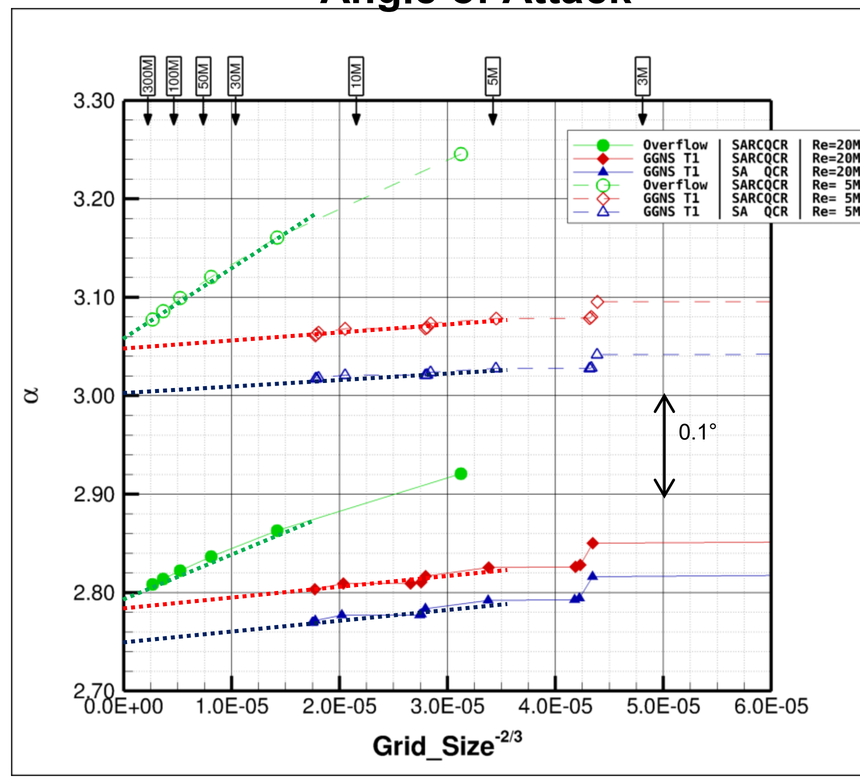
- **Case 1a: Mach=0.85, CL=0.58, Rey# 20M**
  - Closed Symbols
- **Case 1b: Mach=0.85, CL=0.58, Rey# 5M**
  - Open Symbols

Total Drag



← Increasing Grid Size

Angle of Attack

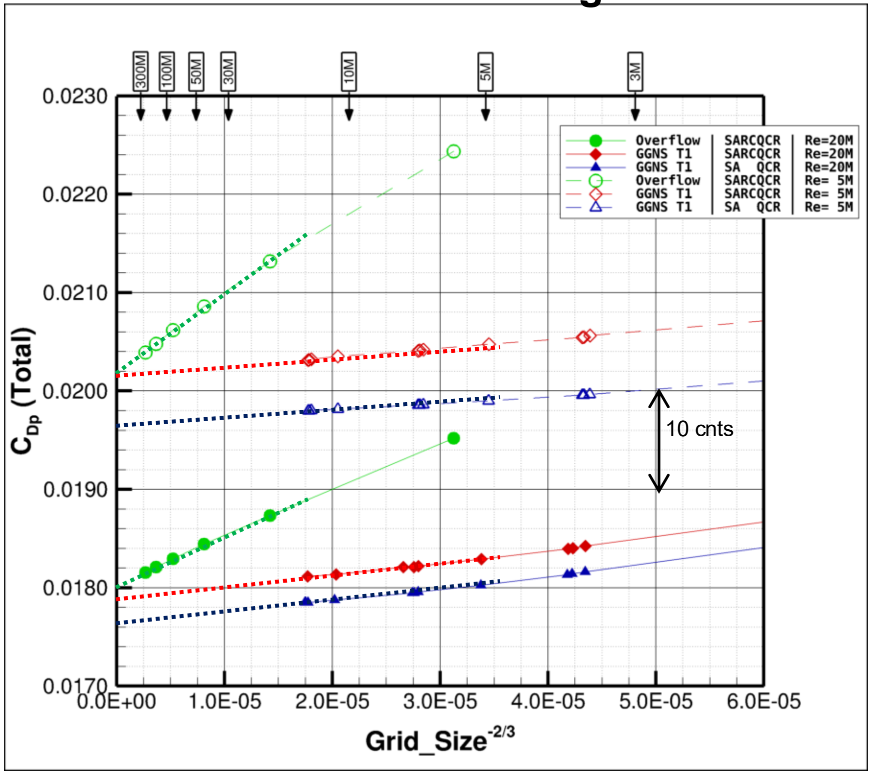


← Increasing Grid Size

Case 1: CRM Wing-Body Grid Convergence Study

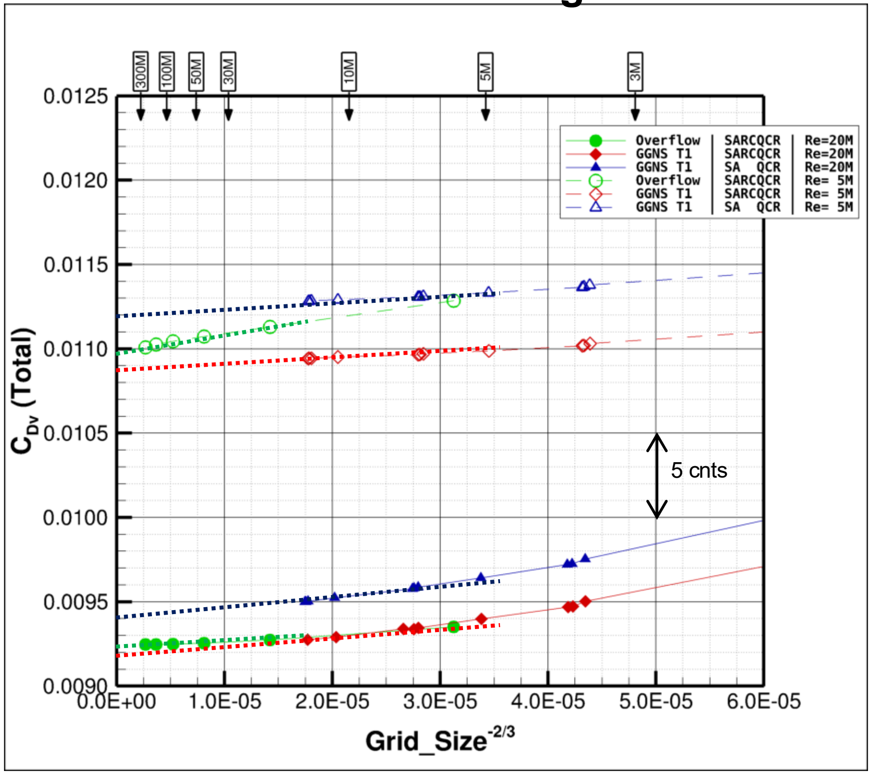
- **Case 1a: Mach=0.85, CL=0.58, Rey# 20M**
  - Closed Symbols
- **Case 1b: Mach=0.85, CL=0.58, Rey# 5M**
  - Open Symbols

Pressure Drag



← Increasing Grid Size

Viscous Drag

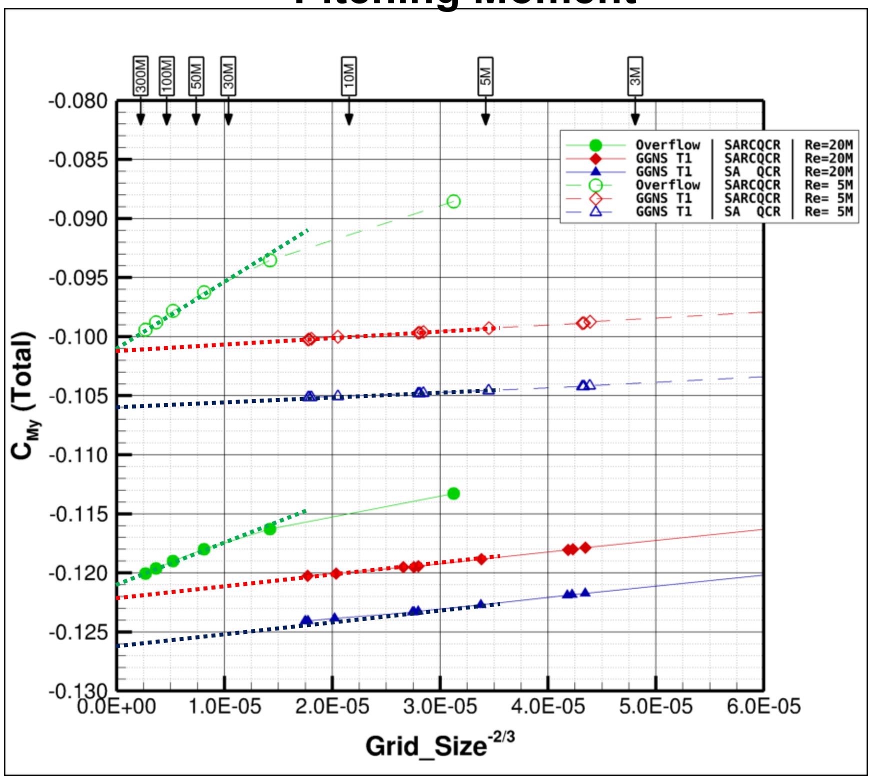


← Increasing Grid Size

Case 1: CRM Wing-Body Grid Convergence Study

- **Case 1a: Mach=0.85, CL=0.58, Rey# 20M**
  - Closed Symbols
- **Case 1b: Mach=0.85, CL=0.58, Rey# 5M**
  - Open Symbols

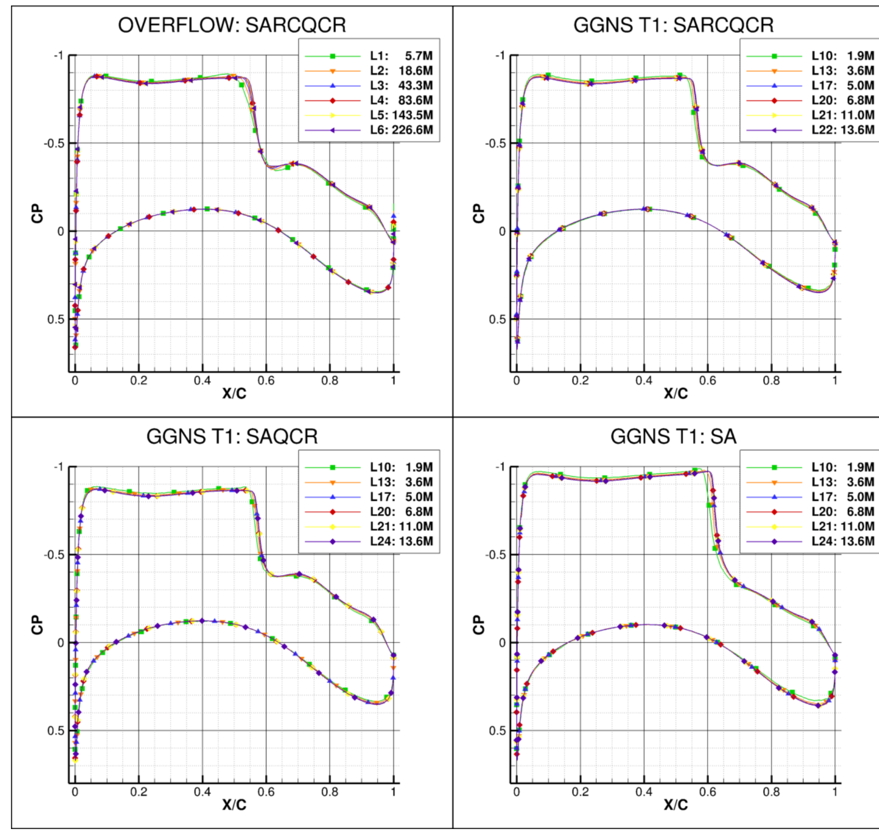
Pitching Moment



← Increasing Grid Size

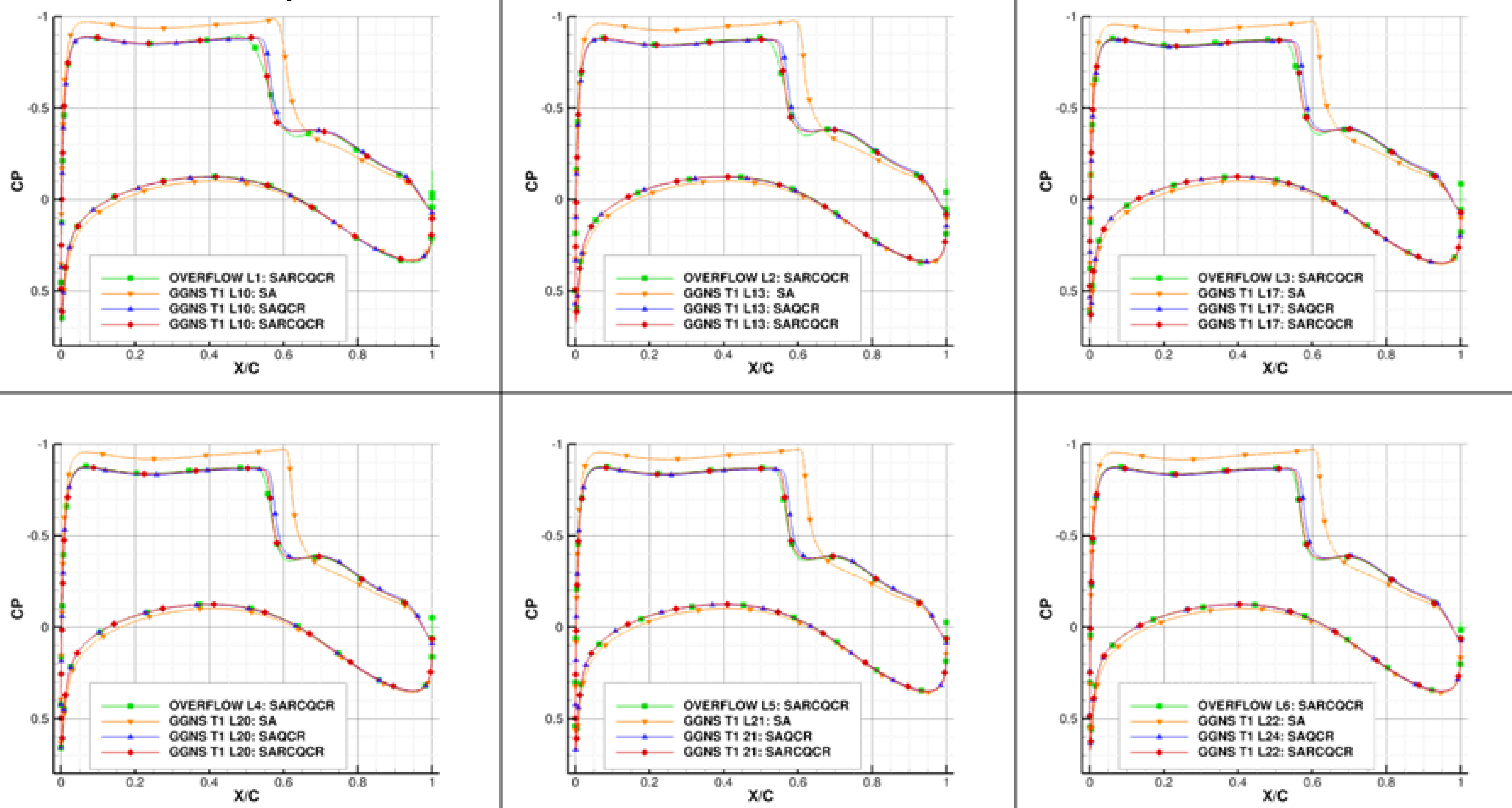
Pressure Comparison (CL=0.58, Rey# 20M)

Section 12 – Eta = 0.7268



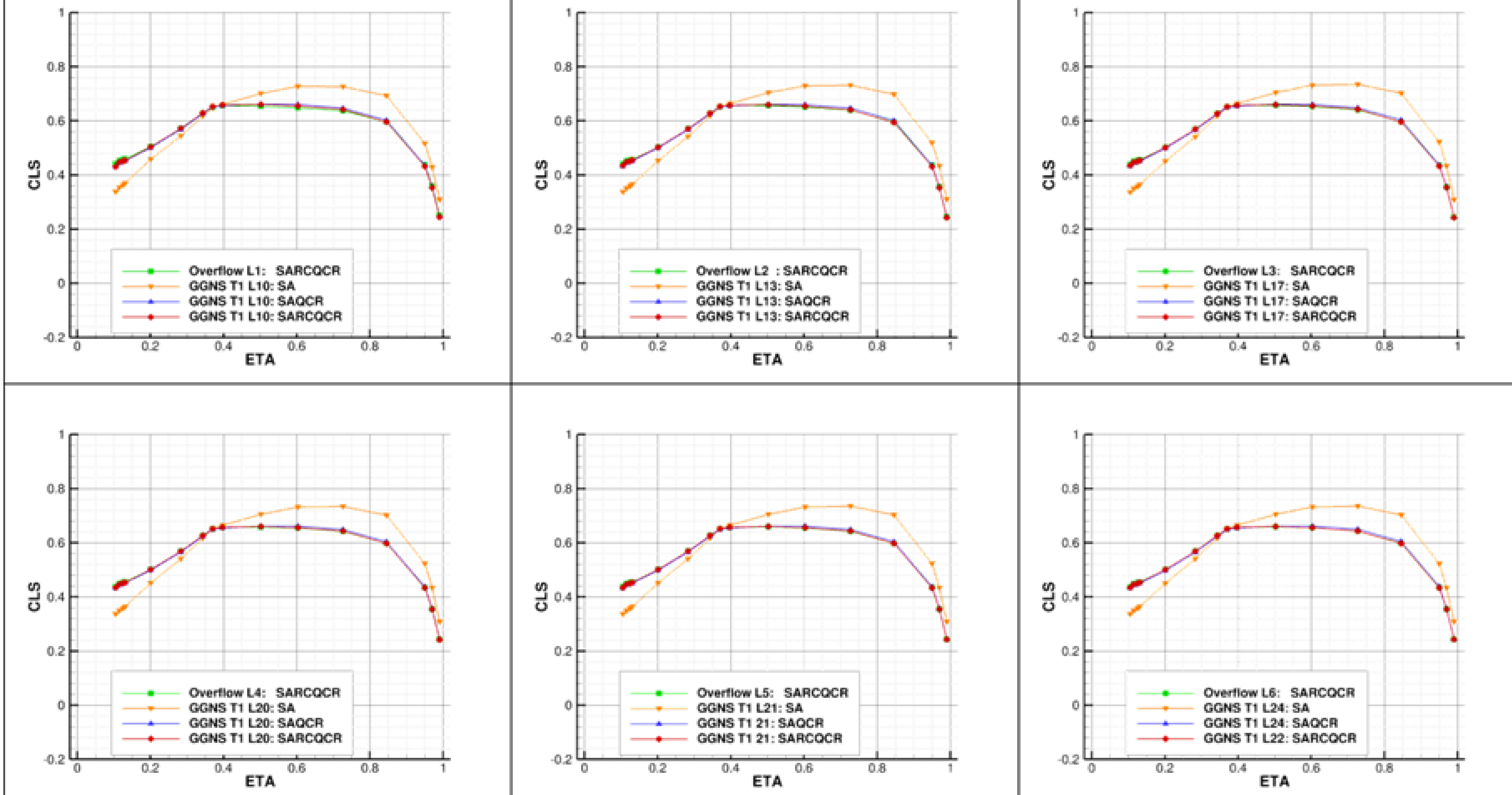
Case 1: CRM Wing-Body Grid Convergence Study

- **Pressure comparison: Section 12 – Eta = 0.7268**
  - CL=0.58, Rey# 20M



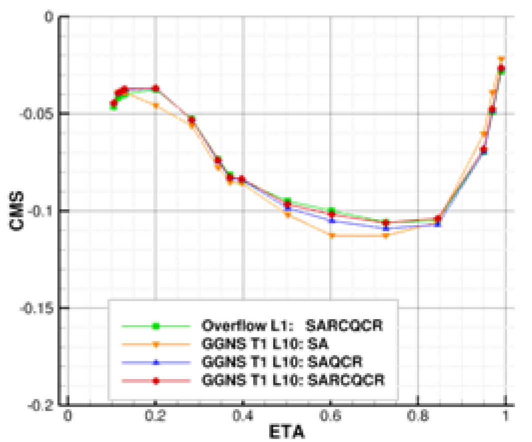
Case 1: CRM Wing-Body Grid Convergence Study

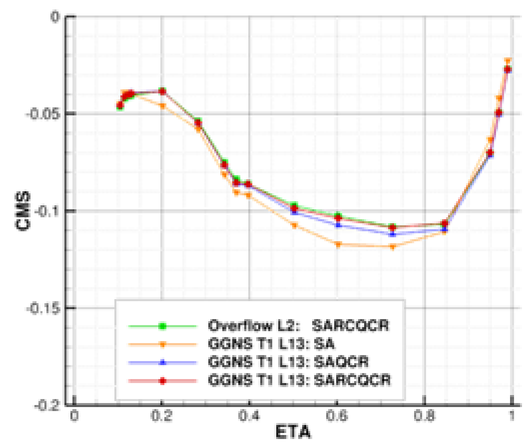
- **Spanload comparison**
  - CL=0.58, Rey# 20M

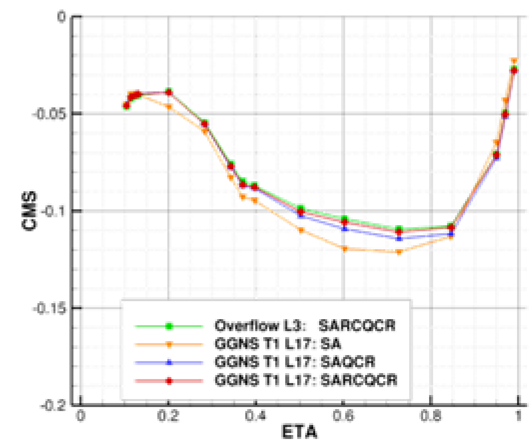


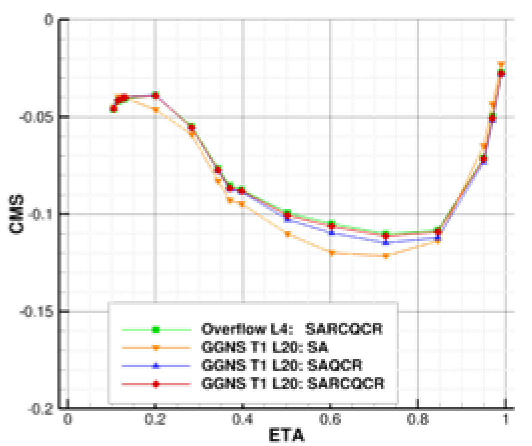
Case 1: CRM Wing-Body Grid Convergence Study

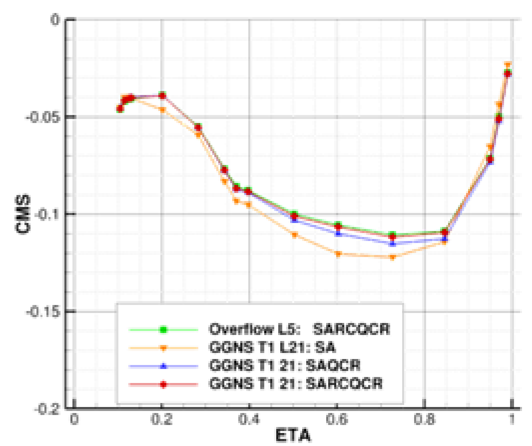
- **Sectional Moment comparison**
  - CL=0.58, Rey# 20M

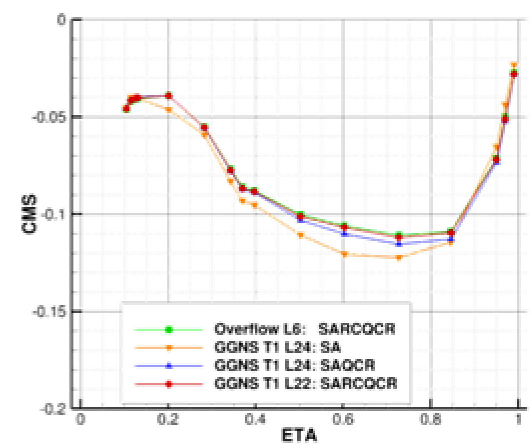












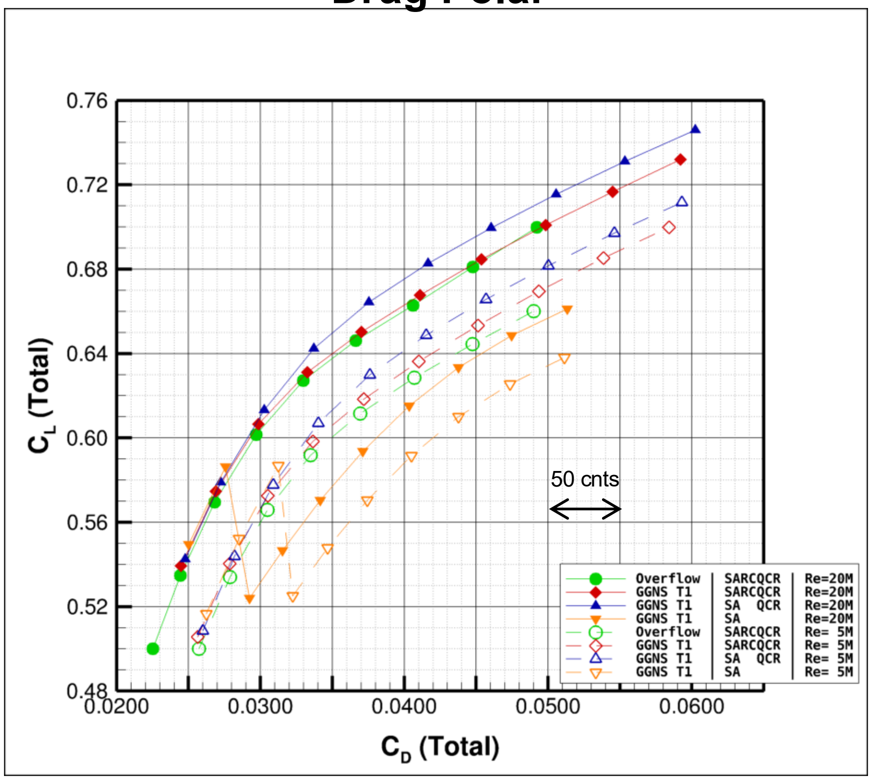
Case 2

CRM Wing-Body Alpha Sweep

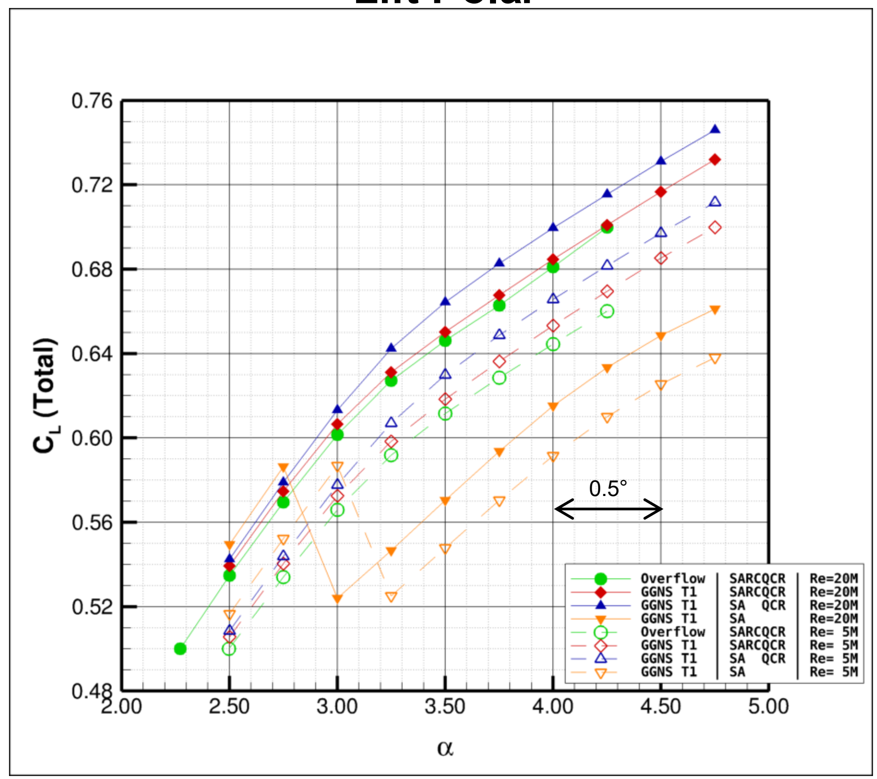
CRM Wing-Body Alpha Sweep

- **Case 2a: Mach=0.85, Rey# 20M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Closed Symbols
- **Case 2b: Mach=0.85, Rey# 5M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Open Symbols

Drag Polar



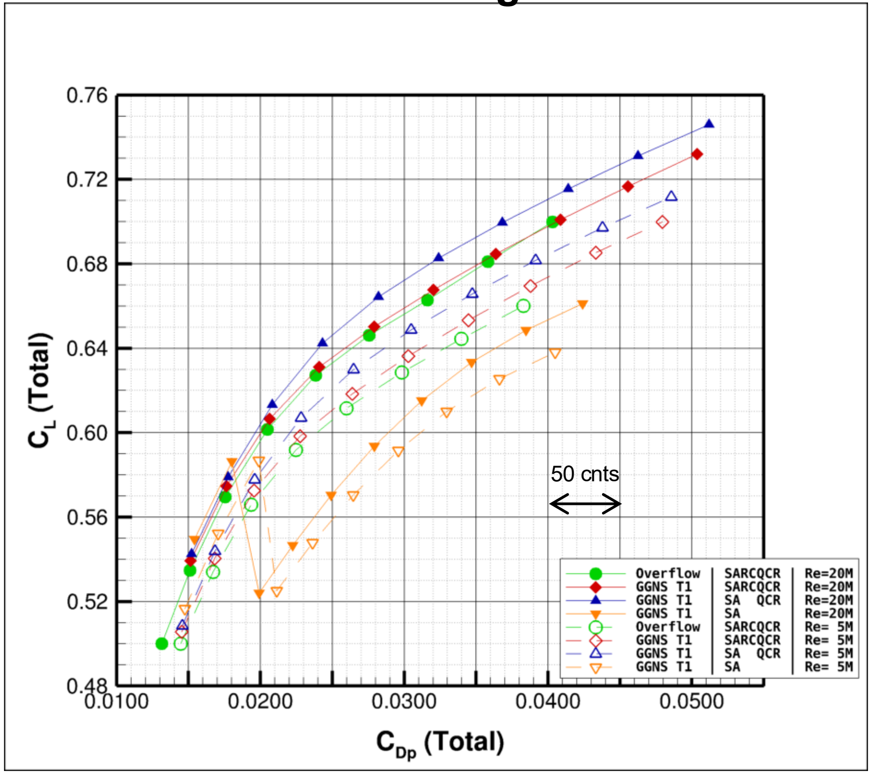
Lift Polar



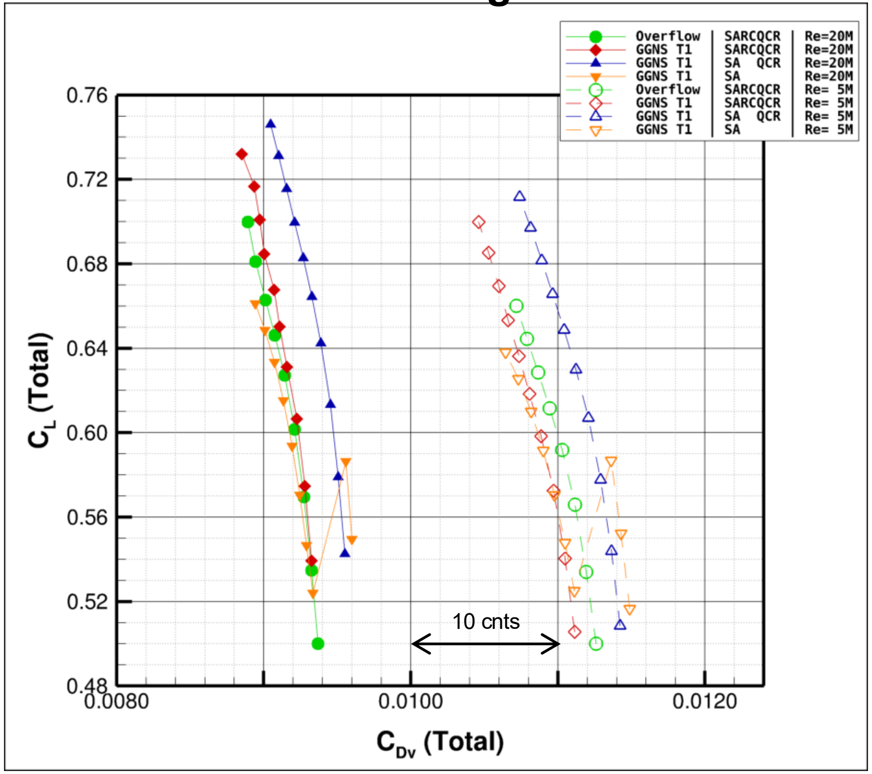
Case 2: CRM Wing-Body Alpha Sweep

- **Case 2a: Mach=0.85, Rey# 20M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Closed Symbols
- **Case 2b: Mach=0.85, Rey# 5M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Open Symbols

Pressure Drag Polar



Viscous Drag Polar



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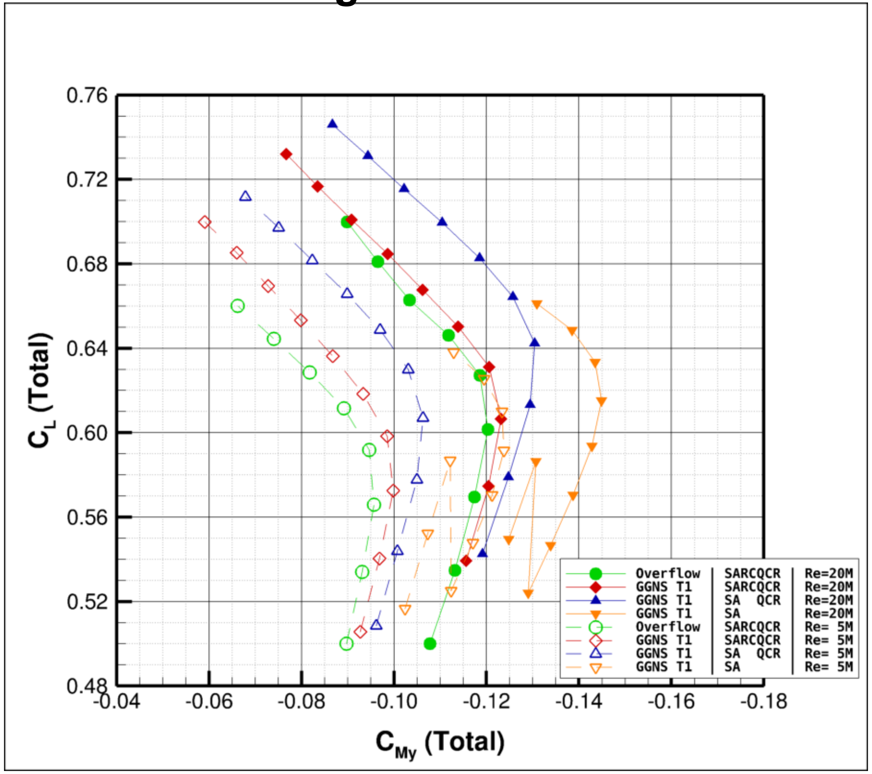
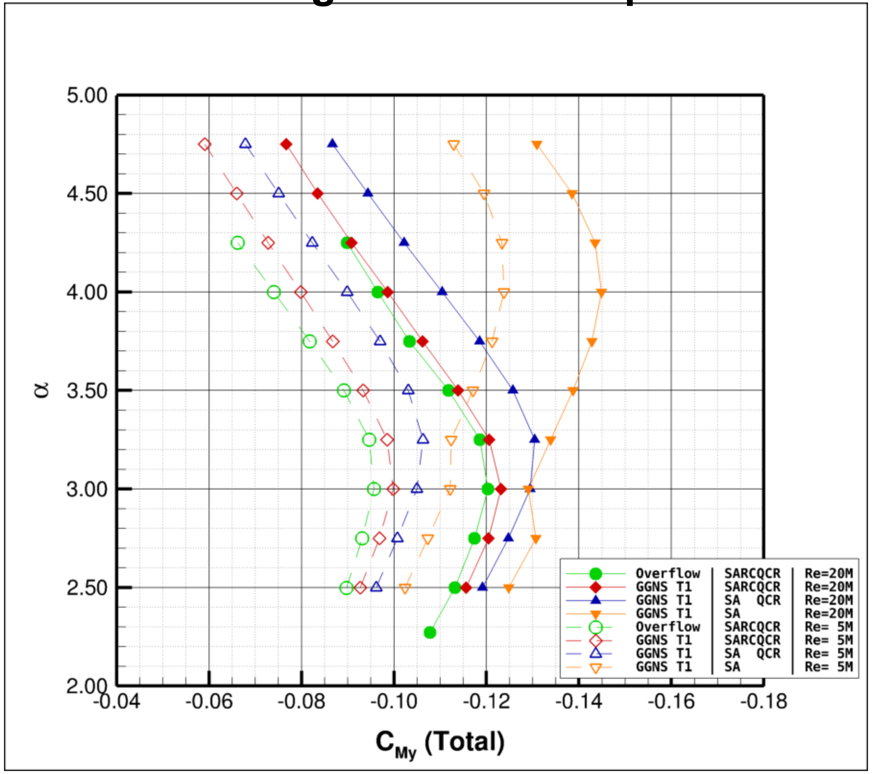
Case 2: CRM Wing-Body Alpha Sweep

- **Case 2a: Mach=0.85, Rey# 20M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Closed Symbols
- **Case 2b: Mach=0.85, Rey# 5M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Open Symbols

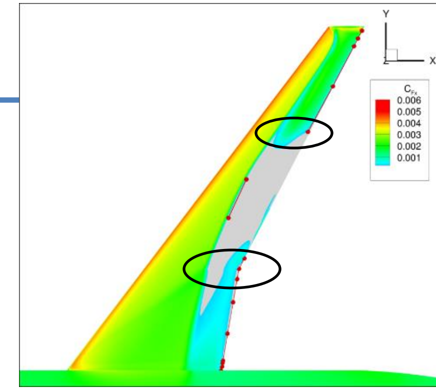
Pitching Moment vs. CL



Pitching Moment vs Alpha

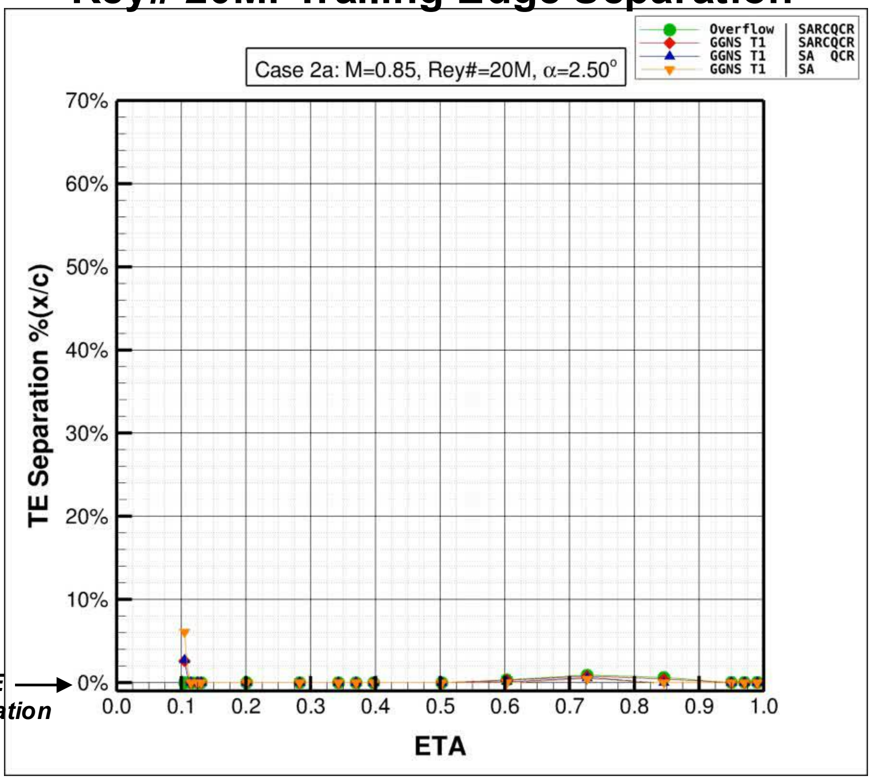


Case 2: CRM Wing-Body Alpha Sweep



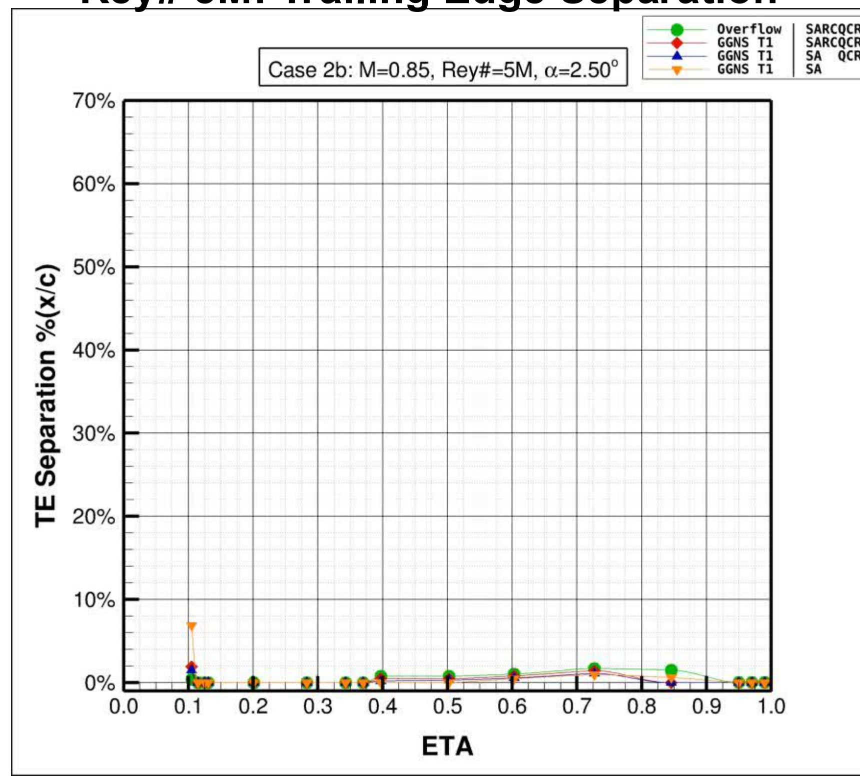
- **Case 2a: Mach=0.85, Rey# 20M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Closed Symbols
- **Case 2b: Mach=0.85, Rey# 5M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Open Symbols

Rey# 20M: Trailing Edge Separation



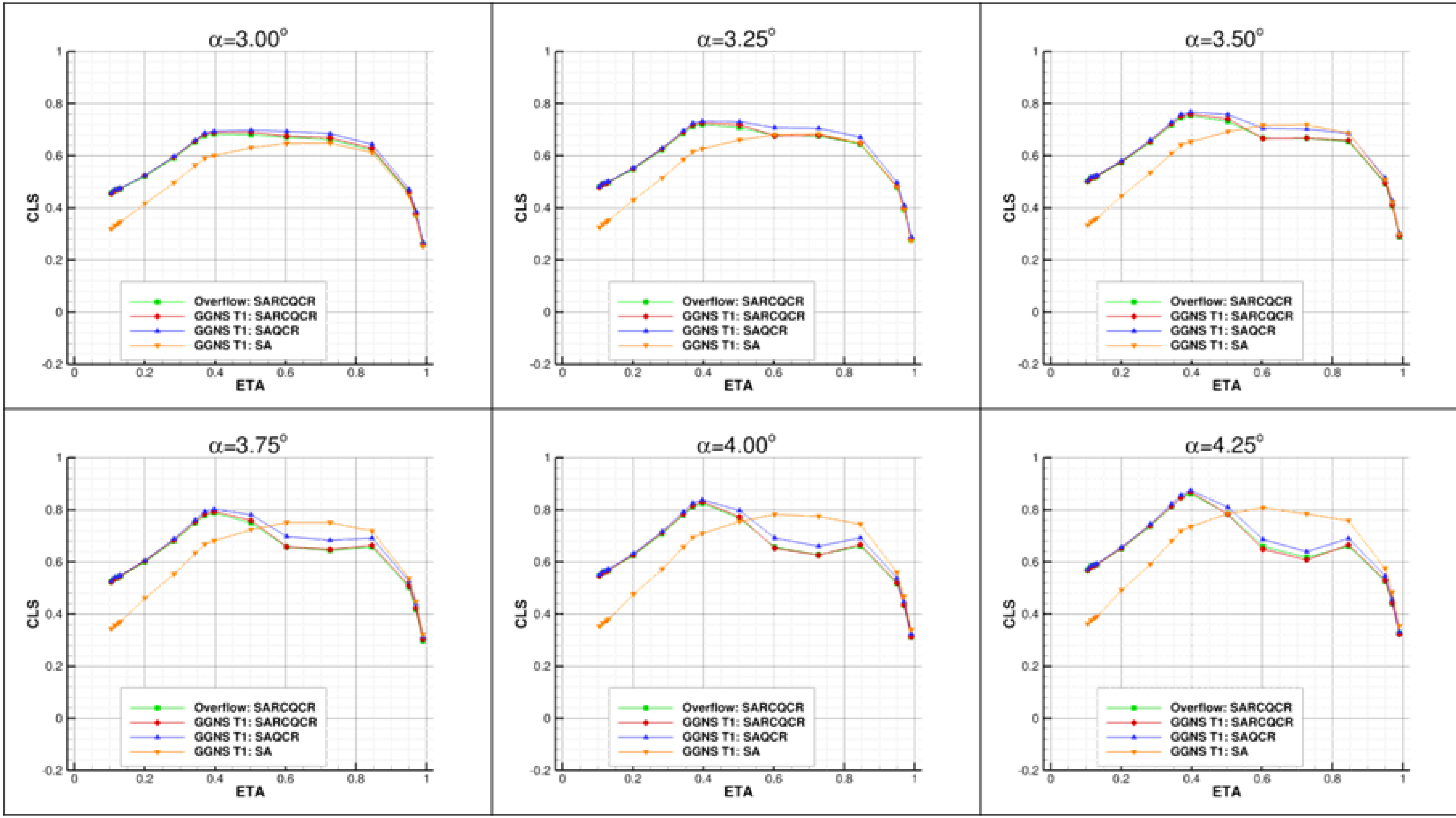
No TE Separation

Rey# 5M: Trailing Edge Separation



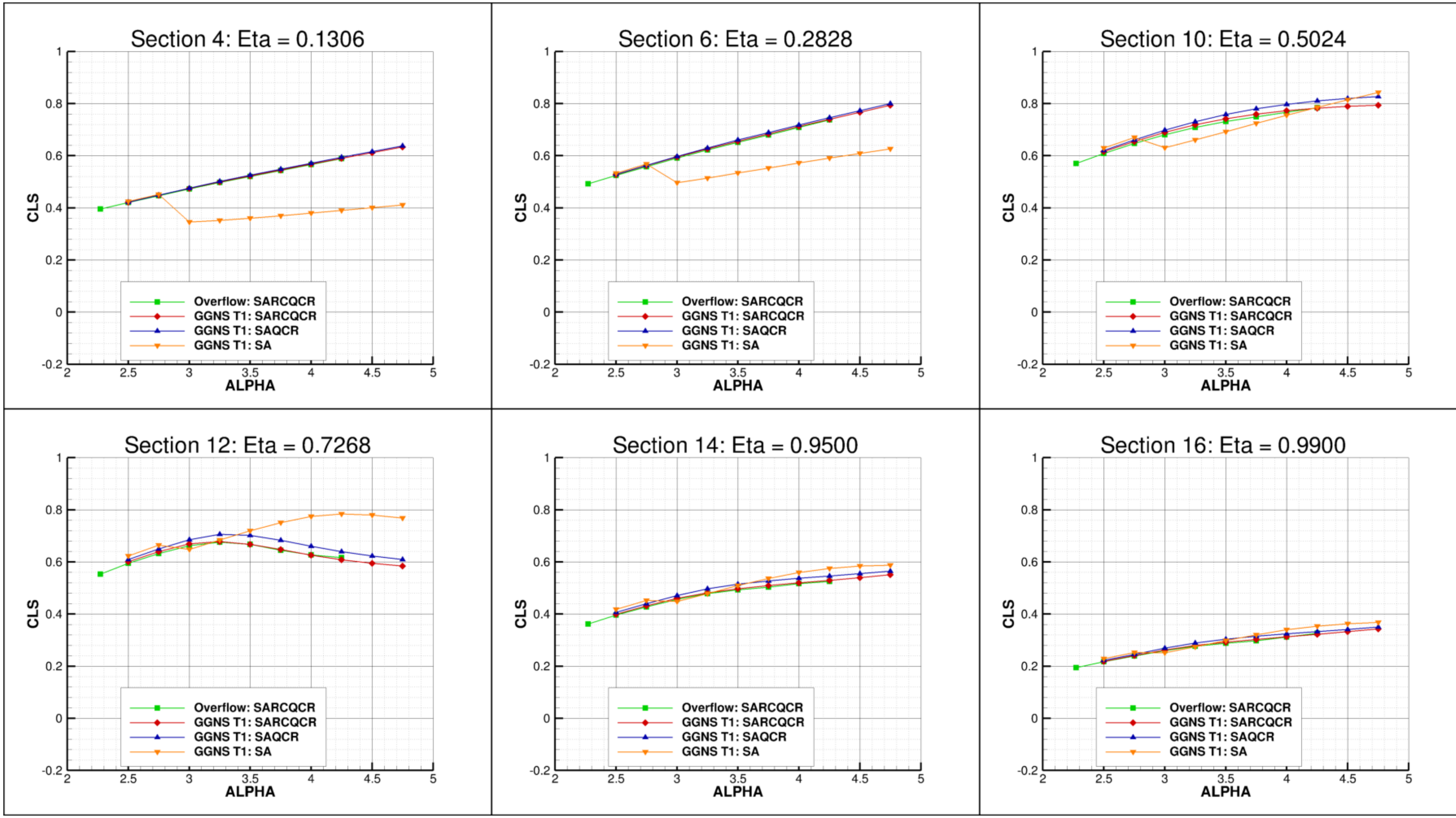
Case 2: CRM Wing-Body Alpha Sweep

- **Spanload comparison**



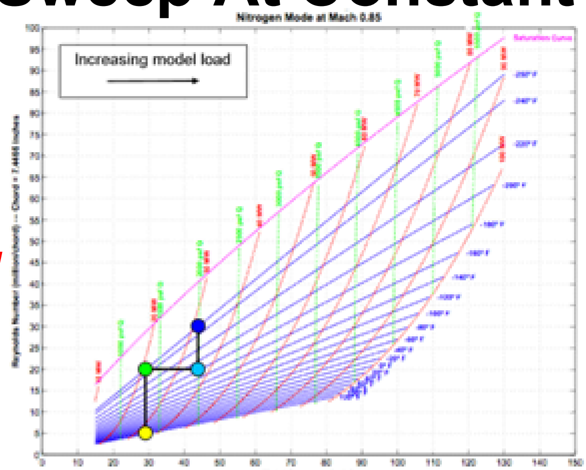
Case 2: CRM Wing-Body Alpha Sweep

- **Spanload comparison**



Case 3

Wing-Body Reynolds Number Sweep At Constant CL



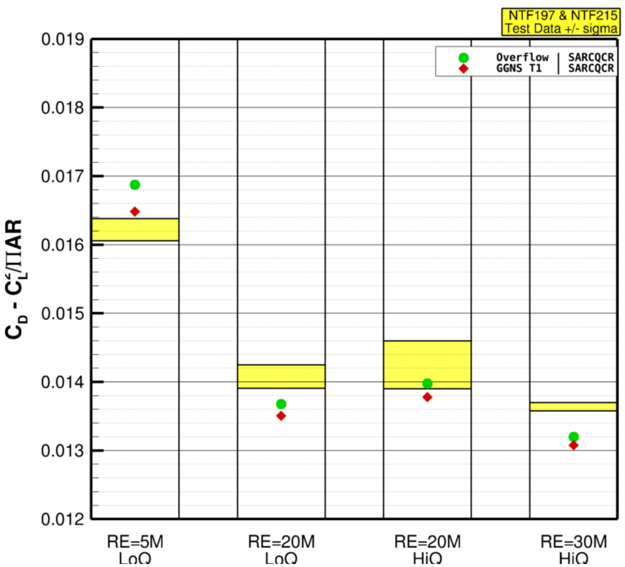
1. CL=0.50, Mach=0.85, LoQ, Rey# 5M
2. CL=0.50, Mach=0.85, LoQ, ***Rey# 20M***
3. CL=0.50, Mach=0.85, ***HiQ***, Rey# 20M
4. CL=0.50, Mach=0.85, HiQ, ***Rey# 30M***

AIAA-2008-6919, Vassberg, et al.
"Development of a Common Research Model for Applied CFD Validation Studies"

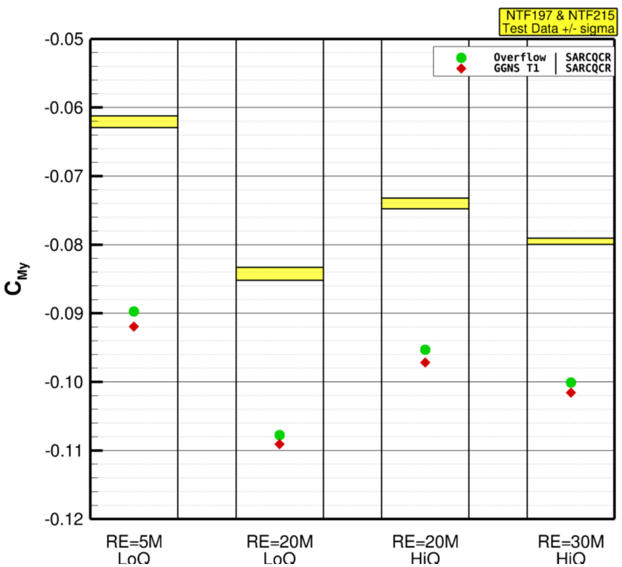
Case 3: Wing-Body Reynolds # Sweep At Constant CL=0.50

- **Case 3:**
  1. CL=0.50, Mach=0.85, LoQ, Rey# 5M
  2. CL=0.50, Mach=0.85, LoQ, ***Rey# 20M***
  3. CL=0.50, Mach=0.85, ***HiQ***, Rey# 20M
  4. CL=0.50, Mach=0.85, HiQ, ***Rey# 30M***

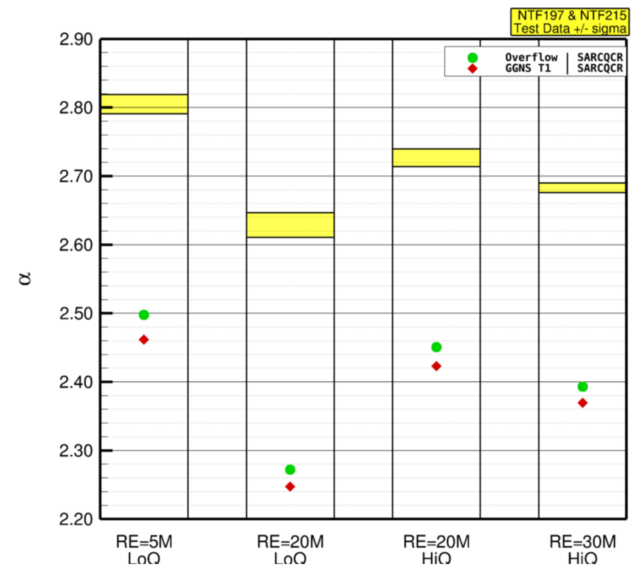
CDideal



Pitching Moment



Angle of Attack



NTF197 & NTF215
Test Data +/- sigma

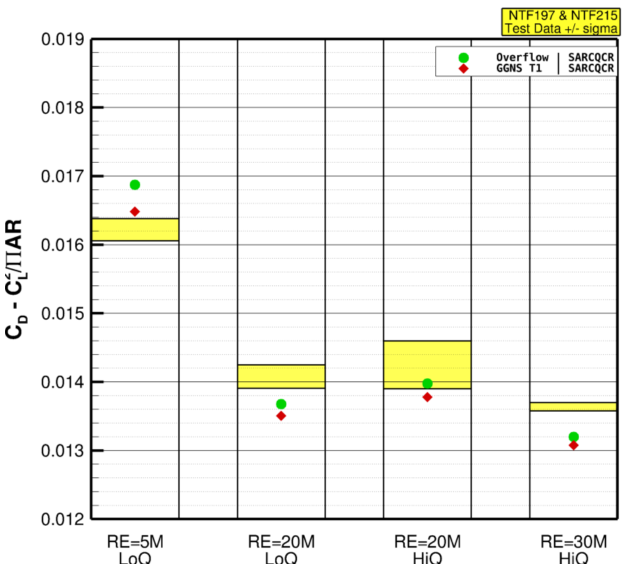
AIAA 2012-0707, M. Rivers and C. Hunter "Support System Effects on the NASA Common Research Model"
AIAA 2012-3209, M. Rivers, C. Hunter, and R. Campbell "Further Investigation of the Support System Effects and Wing Twist on the NASA Common Research Model"

Adding the model support system to the CFD model changes wing, tail and aft body pressures and increases CM by ~0.03 and α by ~0.2° at CL = 0.50 for the Wing-Body-Tail configuration

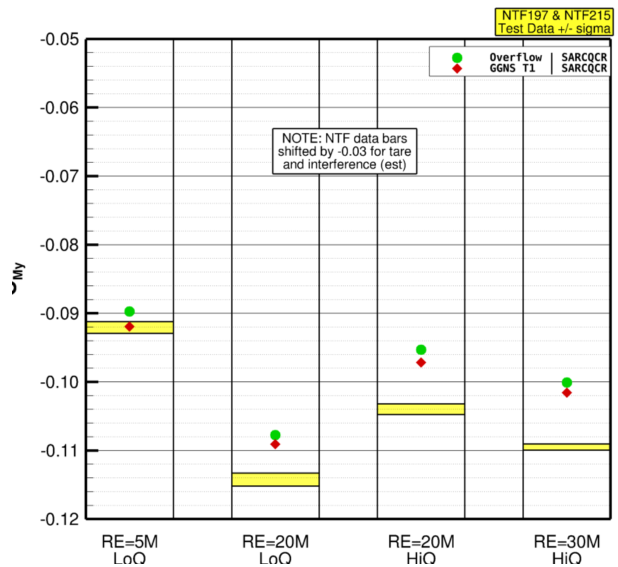
Case 3: Wing-Body Reynolds # Sweep At Constant CL=0.50

- **Case 3:**
  1. CL=0.50, Mach=0.85, LoQ, Rey# 5M
  2. CL=0.50, Mach=0.85, LoQ, ***Rey# 20M***
  3. CL=0.50, Mach=0.85, ***HiQ***, Rey# 20M
  4. CL=0.50, Mach=0.85, HiQ, ***Rey# 30M***

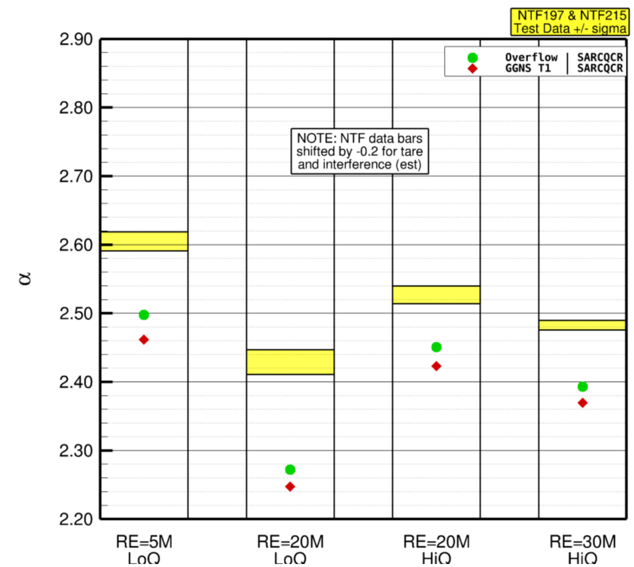
CDideal



Pitching Moment



Angle of Attack



NTF197 & NTF215
Test Data +/- sigma

AIAA 2012-0707, M. Rivers and C. Hunter "Support System Effects on the NASA Common Research Model"
AIAA 2012-3209, M. Rivers, C. Hunter, and R. Campbell "Further Investigation of the Support System Effects and Wing Twist on the NASA Common Research Model"

Adding the model support system to the CFD model changes wing, tail and aft body pressures and increases CM by ~0.03 and α by ~0.2° at CL = 0.50 for the Wing-Body-Tail configuration

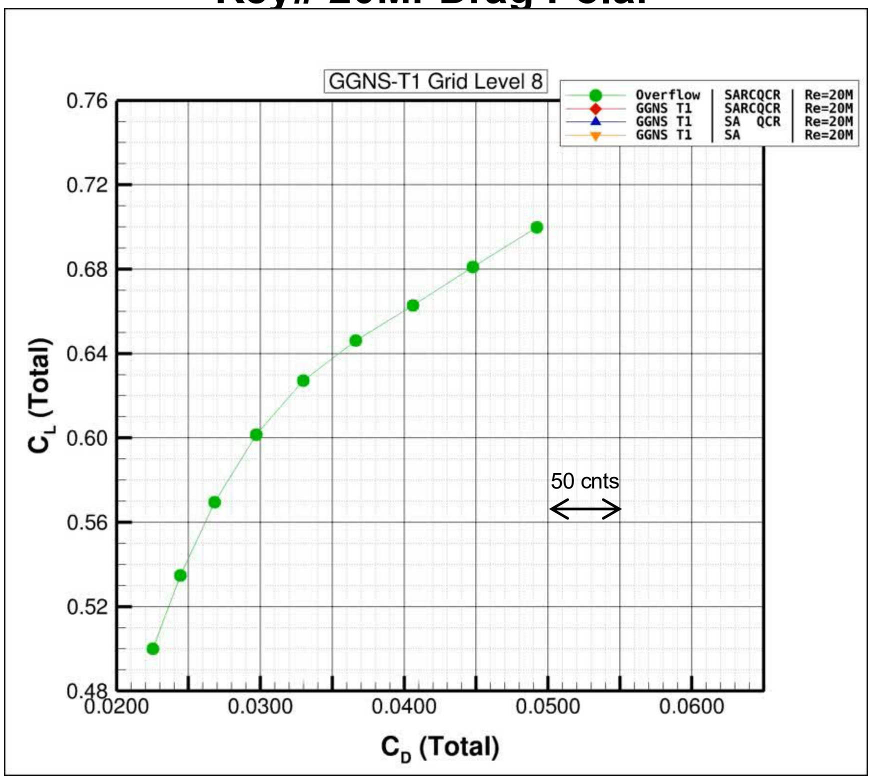
Case 4

CRM Wing-Body Alpha Sweep with Grid Adaptation

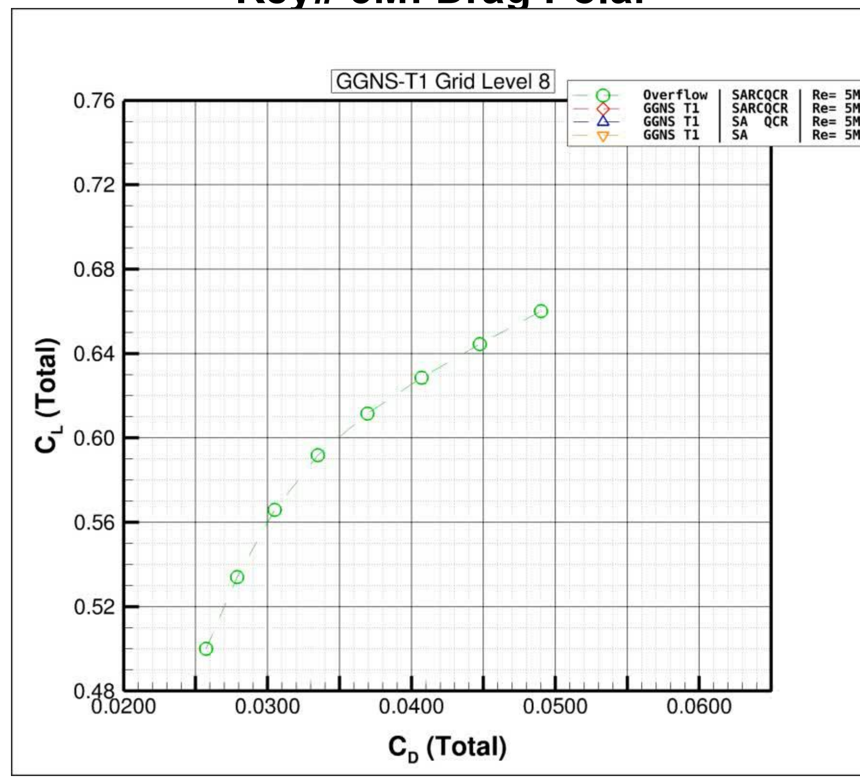
Case 4: CRM Wing-Body Alpha Sweep with Grid Adaptation

- **Case 4a: Mach=0.85, Rey# 20M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Closed Symbols
- **Case 4b: Mach=0.85, Rey# 5M, Alpha=[2.75° - 4.25° by 0.25°]**
  - Open Symbols

Rey# 20M: Drag Polar



Rey# 5M: Drag Polar



Conclusions

- **Solver Comparison**
  - The agreement between very different grid and solver strategies is very impressive
- **Turbulence Model**
  - SA without QCR results in non-physical side-of-body separation
    - Consistent with previous DPW results
  - RC terms have an impact on forces/moments
    - Reduced lift and more positive pitching moment at constant alpha
- **Grid Adaption**
  - GGNS-T1 with EPIC adaption based on the drag adjoint achieves results for Lift, Drag, and Pitching Moment comparable to OVERFLOW on the L6-UltraFine grid with an order of magnitude smaller grid!
    - Overflow L6: 226.6M
    - GGNS-T1 L24: ~13M
  - Alternative grid adaption based on flow features and/or the lift adjoint based metrics converge to the same result as the those shown here based on the drag adjoint.

References

- [1] K R Holst, R S Glasby, J T Erwin, D L Stefanski, J G Coder, High-Order Shock Capturing Techniques using HPCMP CREATE-AV Kestrel, AIAA Scitech 2019 Forum, 2019
- [2] https://petsc.org
- [3] Todd Michal and Joshua Krakos, Anisotropic Mesh Adaptation Through Edge Primitive Operations, AIAA Paper 2012--159
- [4] Dmitry S. Kamenetskiy, Joshua A. Krakos, Todd Michal, Francesco Clerici, Frédéric Alauzet, Adrien Loseille, Michael A. Park, Stephen L. Wood, Aravind Balan, Marshall C. Galbraith, Anisotropic Goal-Based Mesh Adaptation Metric Clarification and Development, AIAA paper 2022-1245