DPW-6 Results Using FUN3D

With Focus on k-kL-MEAH2015 Turbulence Model

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Overview

- Brief description of FUN3D and the k-kL-MEAH2015 turbulence model
- NACA 0012 Verification Case
- WB and WBNP configurations
  - Grid study (C_L=0.5)
- WB Case
  - C_L, C_D and C_m variations with angle of attack
- Results related to:
  - Effect of using limiter
  - Turbulence Models: k-kL-MEAH2015, SA, and SST

FUN3D

- Node-based finite-volume solver for mixed element grids
- Blended upwind (Roe) and UMUSCL with κ=0.5
- Tested both with no limiter and with hminmod limiter (stencil-based min-mod limiter from Barth augmented with a heuristic pressure limiter)
- Full Navier-Stokes terms
- Most turbulence models solved loosely-coupled to mean flow equations
- Adjoint-based adaptation and design-optimization capability (not used for this study)
- http://fun3d.larc.nasa.gov

k-kL-MEAH2015 Turbulence Model

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho U_j k}{\partial x_j}=\left[P_k+\frac{\partial}{\partial x_j}\left(\mu_l+\sigma_k \mu_t \frac{\partial k}{\partial x_j}\right)-2\mu_l \frac{k}{d^2}\right]-C_k \rho \frac{k^{2.5}}{(kL)}$$

$$\frac{\partial \rho (kL)}{\partial t}+\frac{\partial \rho U_j (kL)}{\partial x_j}=\left[C_{(kL)1}\frac{(kL)}{k}P_k+\frac{\partial}{\partial x_j}\left(\mu_l+\sigma_{(kL)}\mu_t \frac{\partial (kL)}{\partial x_j}\right)-6\mu_l \frac{(kL)}{d^2}f_{kL}\right]-C_{(kL)2}\rho k^{1.5}$$

$$\mu_t = C_\mu^{1/4}\frac{\rho(kL)}{k^{1/2}}$$

This term based on the SAS formulation of Menter and Egorov; however, in Hamid's formulation the model functions as steady RANS as grid is refined

wall Boundary Conditions:

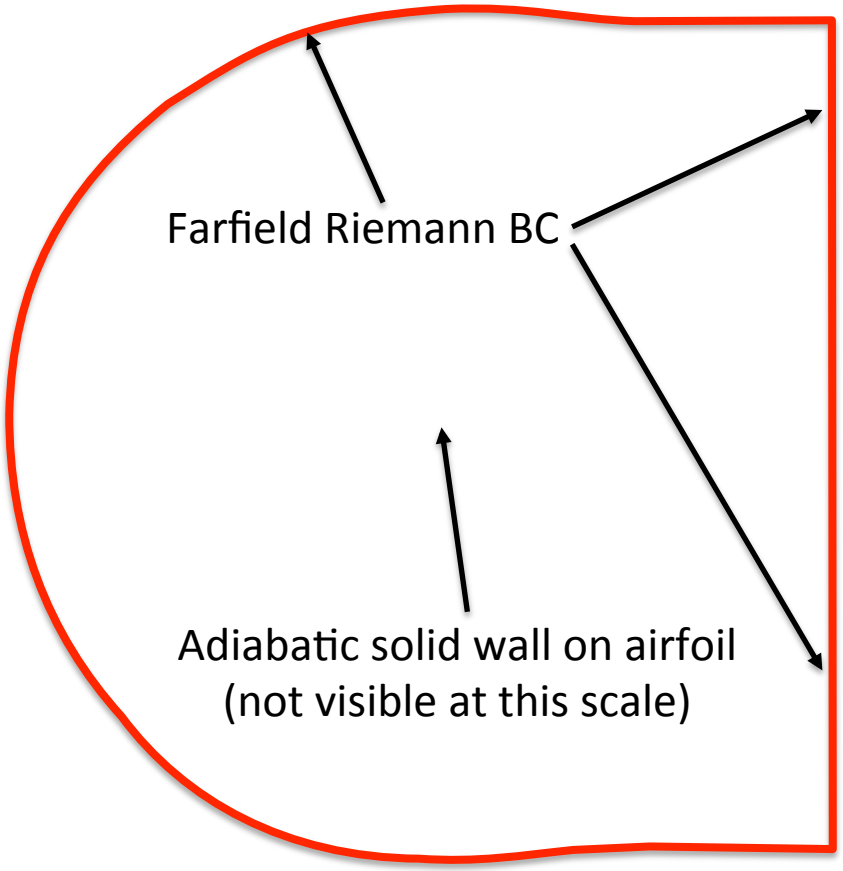
$$k_w = 0.0$$

$$(kL)_w = 0.0$$

See NASA/TM-2015-218968 Nov 2015 or AIAA-2016-3941 (w/o correction terms)

Case 1
NACA 0012 Grid Study

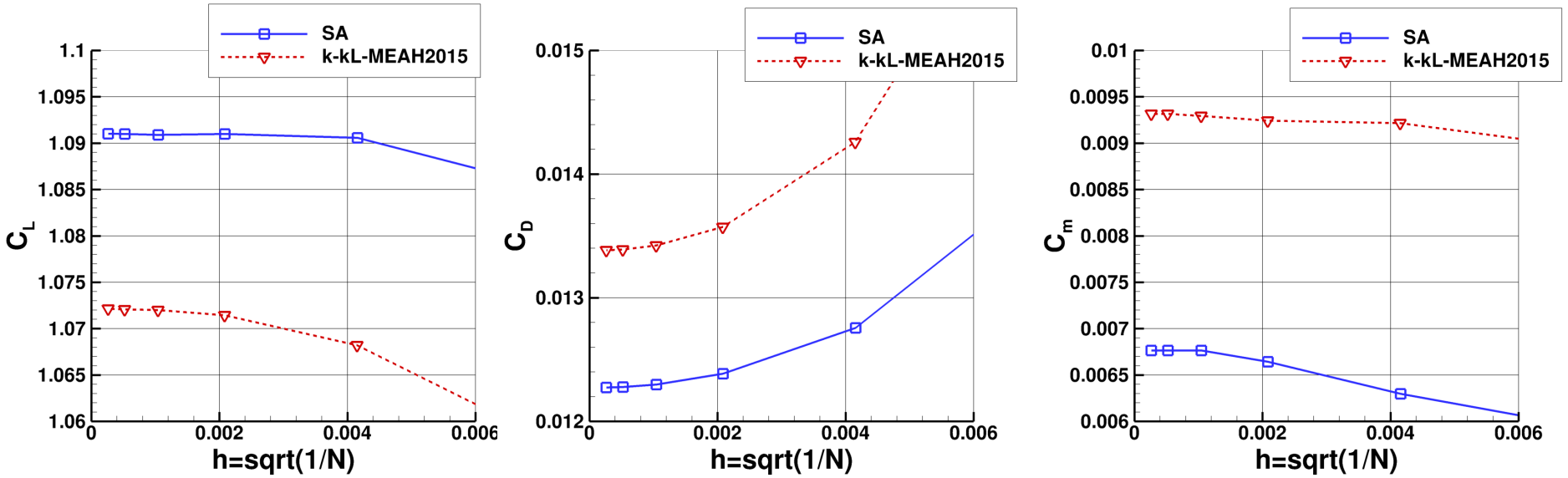
NACA 0012
M=0.15, Re=6.0x10^6, α=10 deg



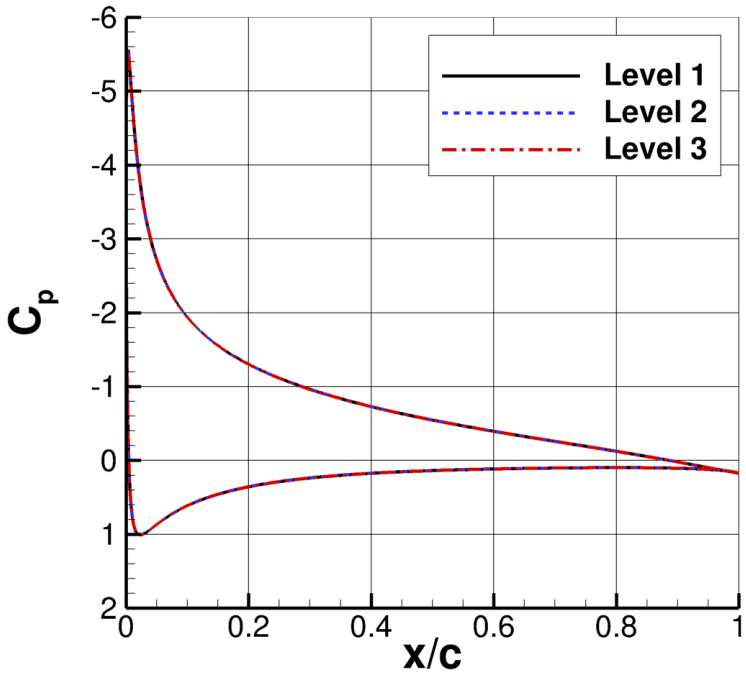
Level	Nodes
6	14,625
5	57,921
4	230,529
3	919,809
2	3,674,625
1	14,689,281

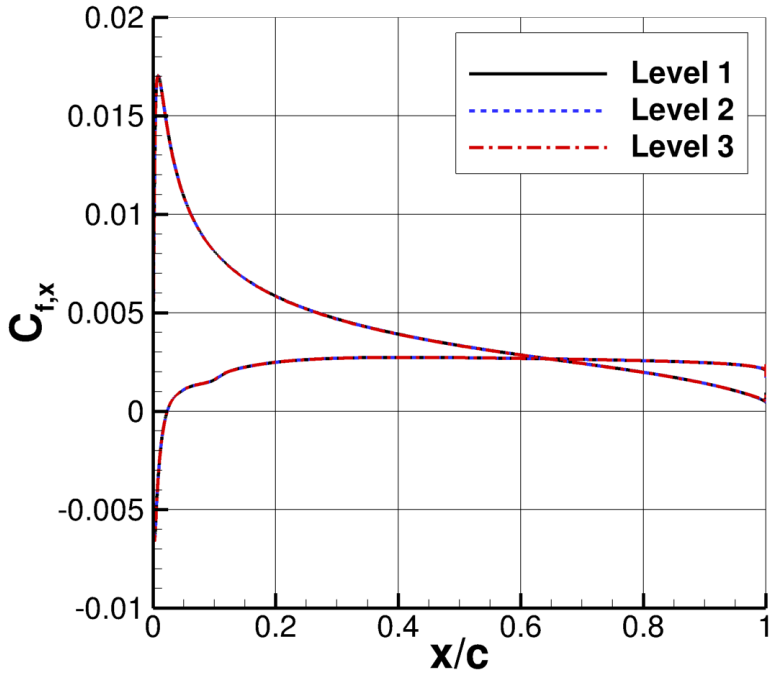
NACA 0012
M=0.15, Re=6.0x10^6, α=10 deg

Comparison of k-kL-MEAH2015 results with SA results from FUN3D



NACA 0012, k-kL-MEAH2015
M=0.15, Re=6.0x10^6, α=10 deg

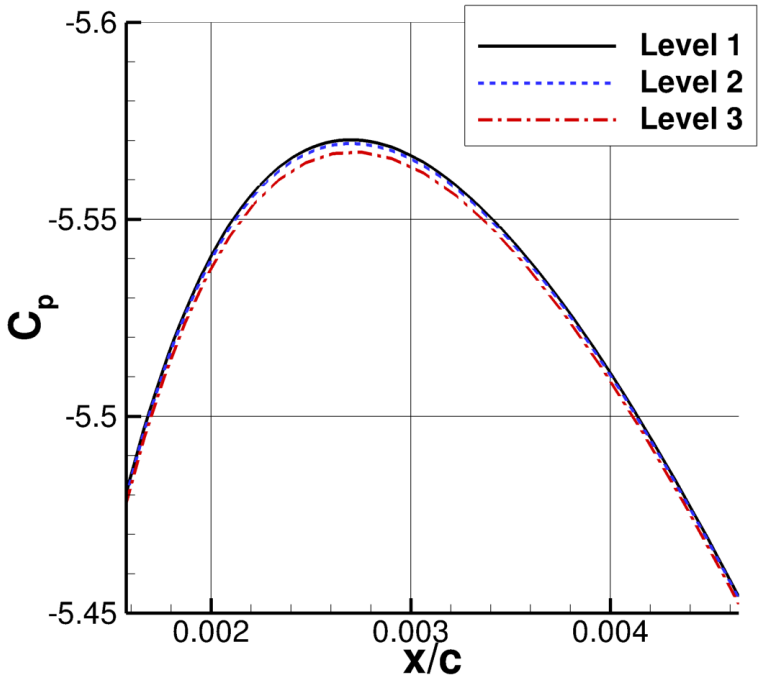


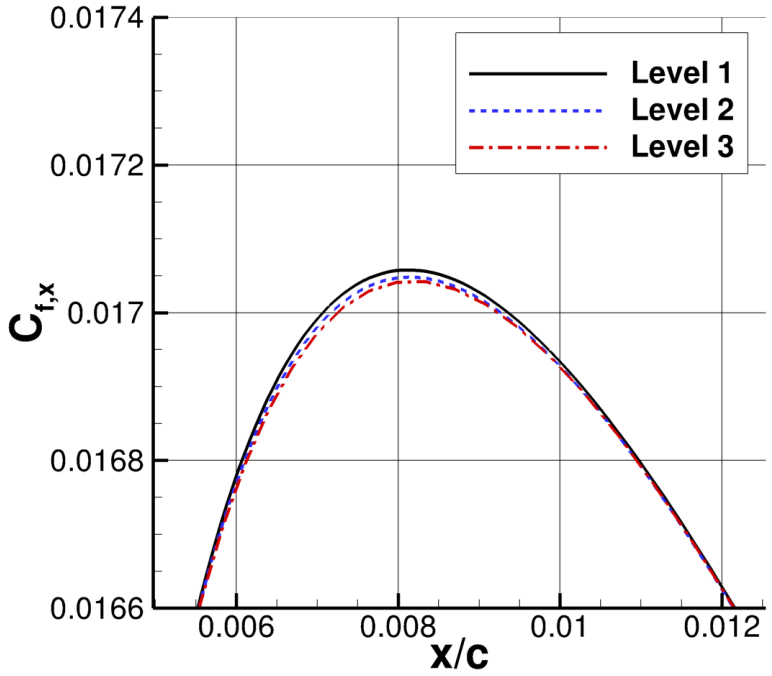


Three finest grid results are practically indistinguishable

Level 1 is finest grid

NACA 0012, k-kL-MEAH2015
M=0.15, Re=6.0x10^6, α=10 deg

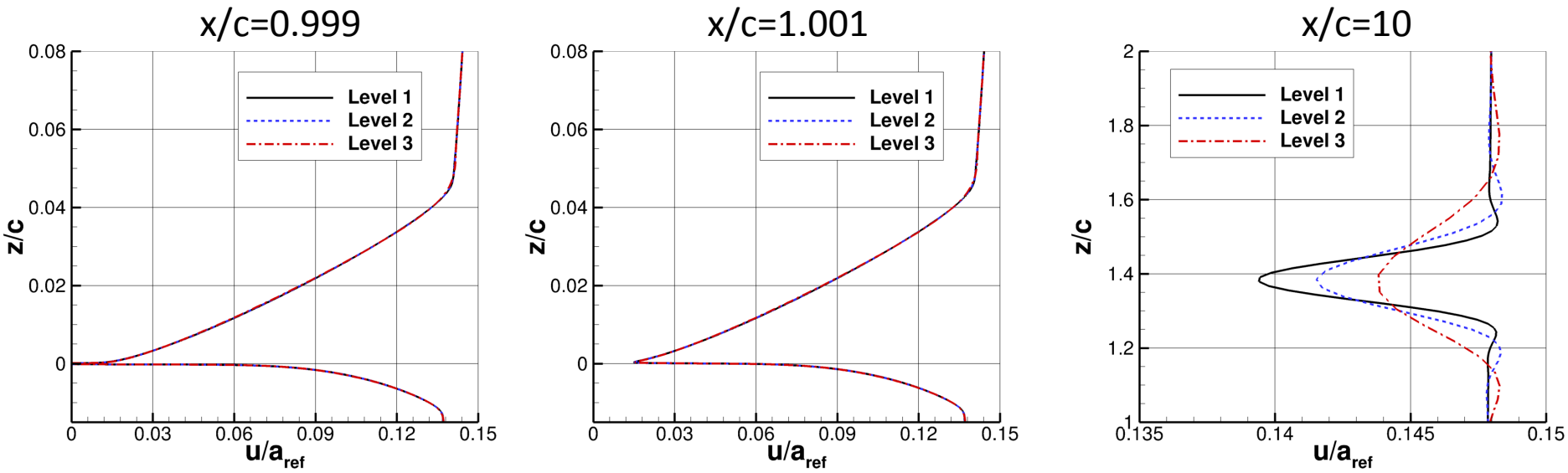




… except when zoomed in

Level 1 is finest grid

NACA 0012, k-kL-MEAH2015
M=0.15, Re=6.0x10^6, α=10 deg

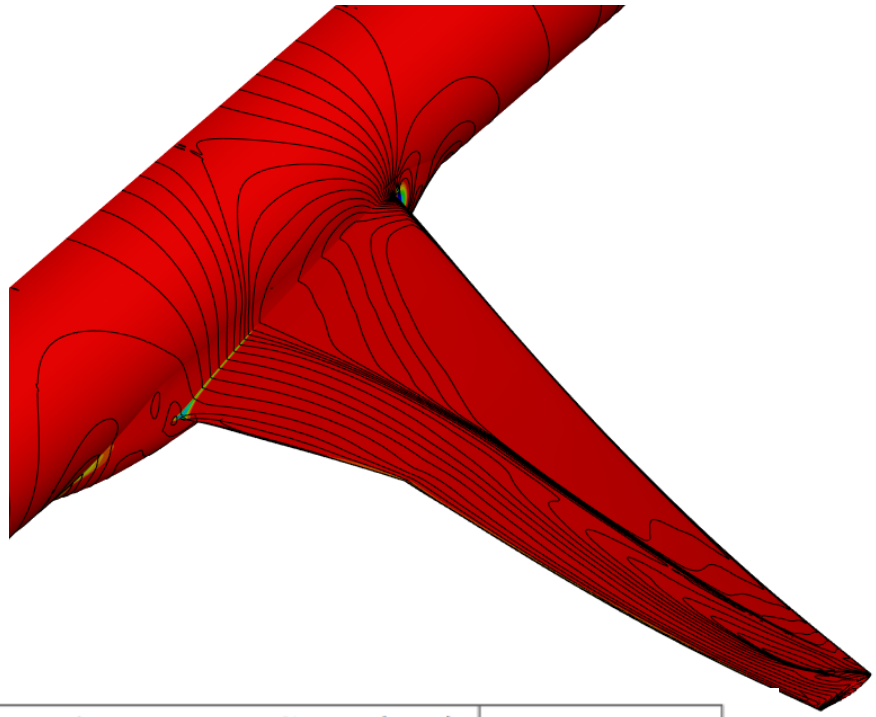


Effect of grid is minimal near body, but significant in the wake at x/c=10 (similar to SA results on TMR website)

Level 1 is finest grid

WB/WBNP CRM Configurations
Case 2, M=0.85, Re=5.0x10^6

C_L=0.5000±0.0001 Grid Study 400-3000 CPUs



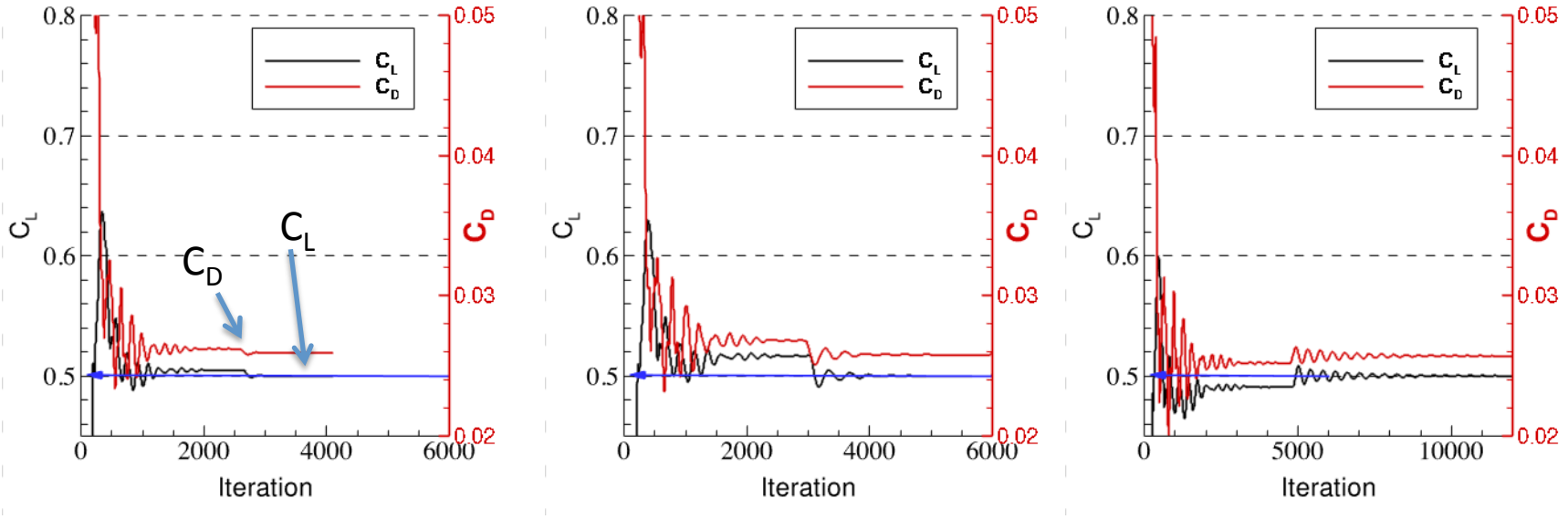
Mean Aerodynamic Chord (c_{ref})	275.80 inch
Wing Reference Area/2	297,360 inch^2
Wing Span/2	1,159.75 inch
X Moment Center	1,325.9 inch
Z Moment Center	177.95 inch
Aspect Ratio(AR)	9.0

Level	WB Nodes	WBNP Nodes
Tiny	20,472,098	27,774,771
Course	29,916,005	40,816,155
Medium	44,249,828	60,686,493
Fine	66,228,067	91,140,011
X-Fine	100,781,934	138,477,189
U-Fine	151,316,926	208,732,968

Used: Unstr. NASA GeoLab Rev 0, mixed elements

WB CRM Configuration

C_L=0.5000±0.0001 Grid Study 400-2000 CPUs



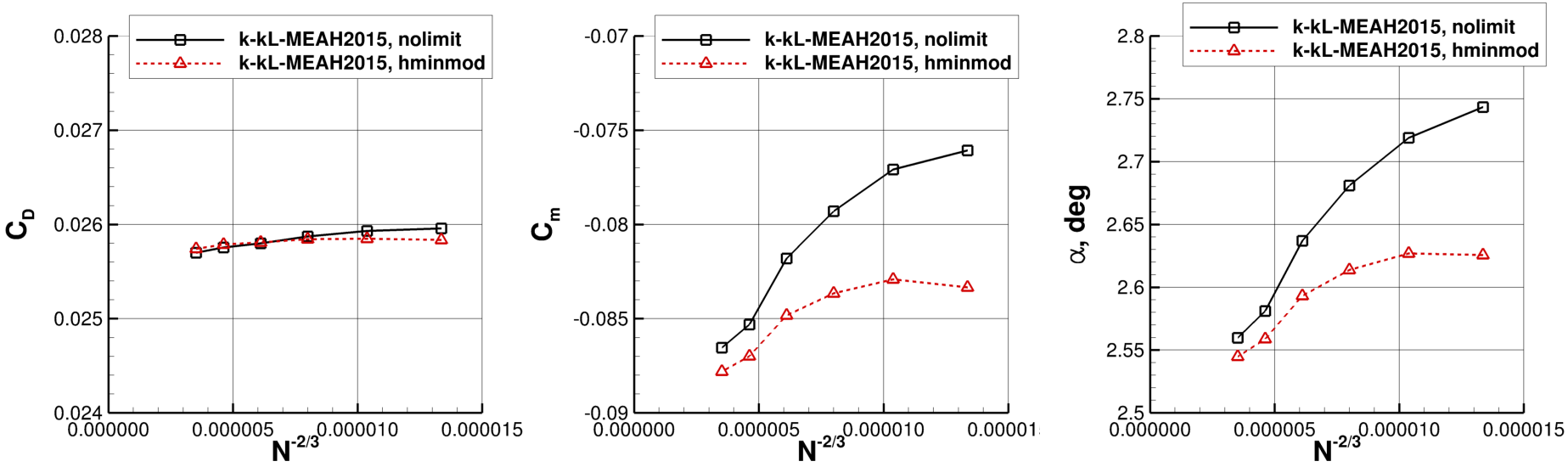
Coarse Fine Ufine

Fixed C_L runs start from α=2.75 deg result at different grid level, then turn on automated C_L driver

WB CRM Configuration

C_L=0.5000±0.0001 Grid Study 400-2000 CPUs

Limiter effect on results



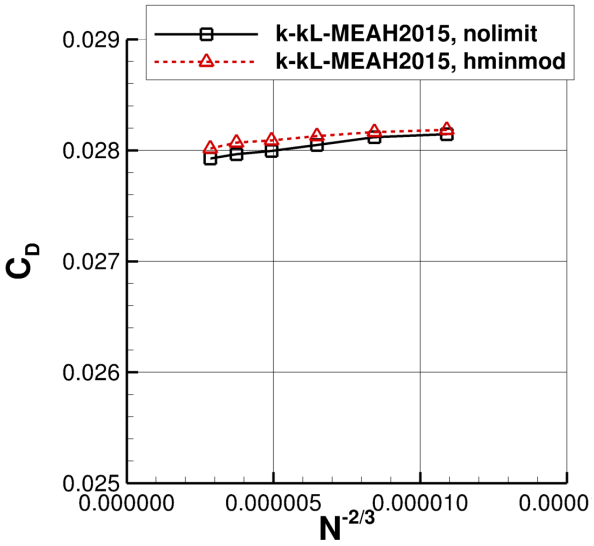
The variations of results with grid refinement are smaller when using hminmod limiter

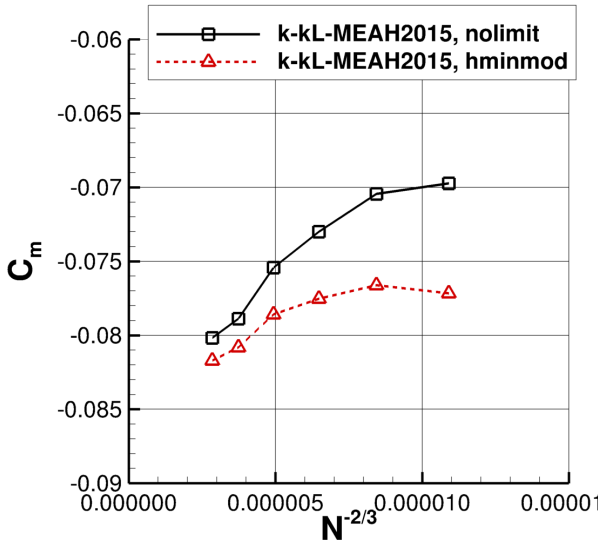
Differences between no-limiter vs. limiter generally decrease as grid refined

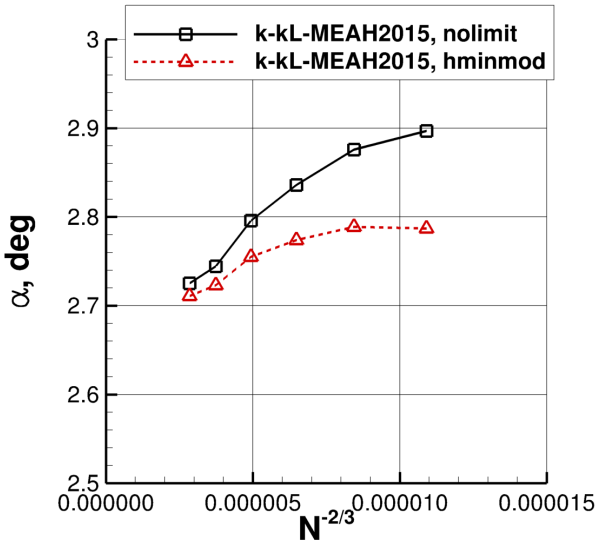
WBNP CRM Configuration

C_L=0.5000±0.0001 Grid Study 600-3000 CPUs

Limiter effect on results







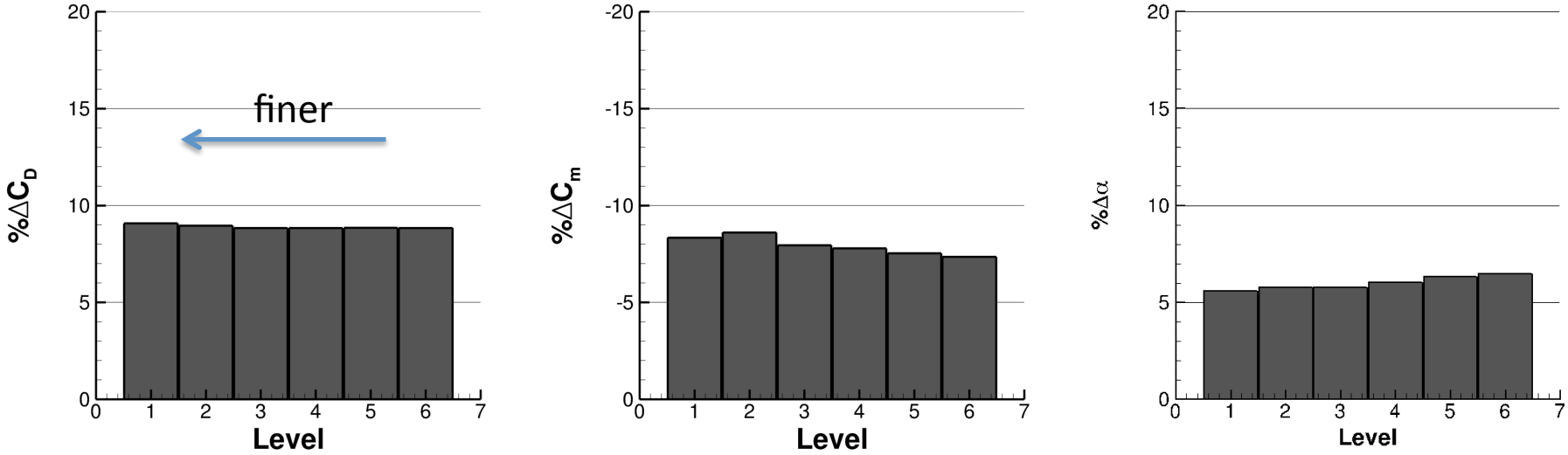
The variations of results with grid refinement are smaller when using hminmod limiter

Differences between no-limiter vs. limiter generally decrease as grid refined

Nacelle/Pylon Effect

C_L=0.5000±0.0001 Grid Study 600-3000 CPUs

Using no limiter

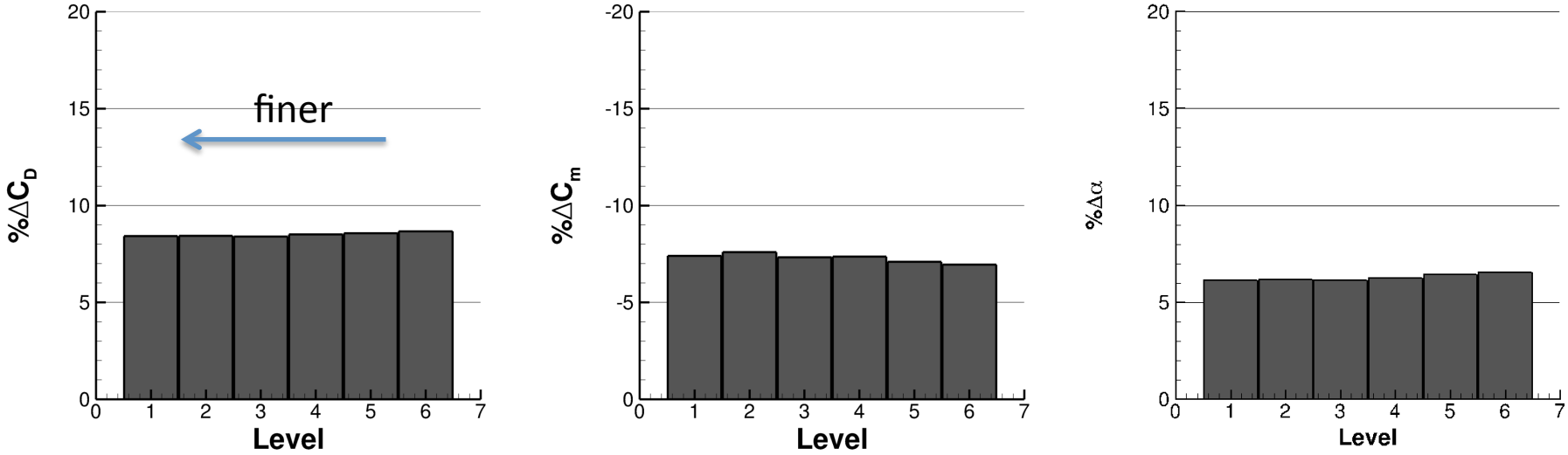


- 8.4 to 8.6 % change in drag
- -7.3 to -8.3 % change in moment
- 5.6 to 6.5% change in α

Nacelle/Pylon Effect

C_L=0.5000±0.0001 Grid Study 600-3000 CPUs

Using hminmod limiter



- 8.85 to 9.04 % change in drag
- -6.95 to -7.6% change in moment
- 6.14 to 6.54 % change in α

Case 3

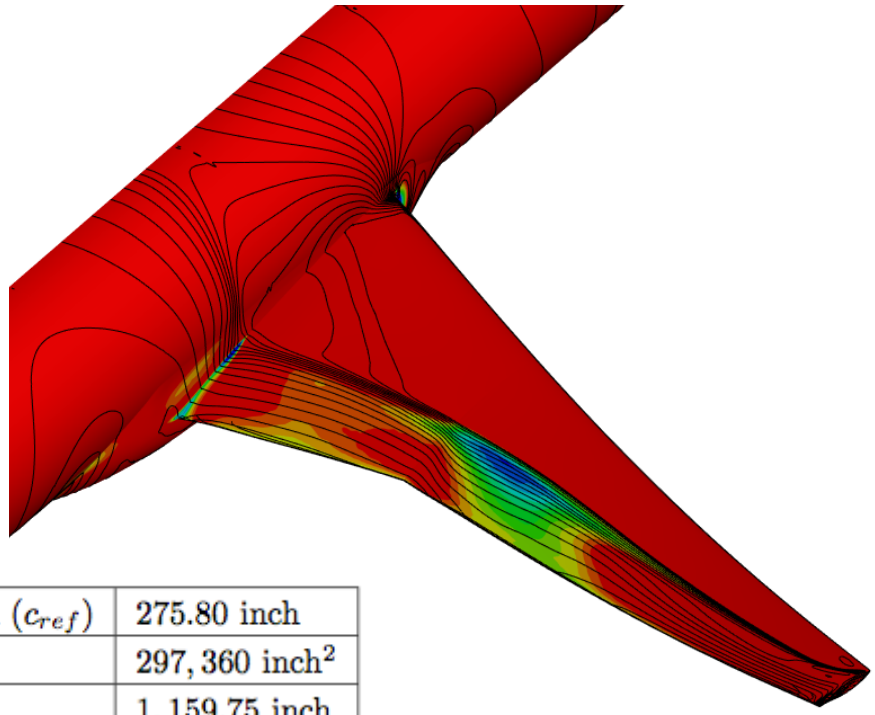
Wing Body CRM Configuration

Medium Grid M=0.85, $Re=5.0x10^6$

α = 2.50, 2.75, 3.00, 3.25, 3.50, 3.75 and 4.00 deg

Wing Body CRM Configuration
Case 3, 800 CPUs, M=0.85, Re=5.0x10^6

α=2.50,2.75,3.00,3.25,3.50,3.75 and 4.00 deg



Mean Aerodynamic Chord (c_{ref})	275.80 inch
Wing Reference Area/2	297,360 inch^2
Wing Span/2	1,159.75 inch
X Moment Center	1,325.9 inch
Z Moment Center	177.95 inch
Aspect Ratio(AR)	9.0

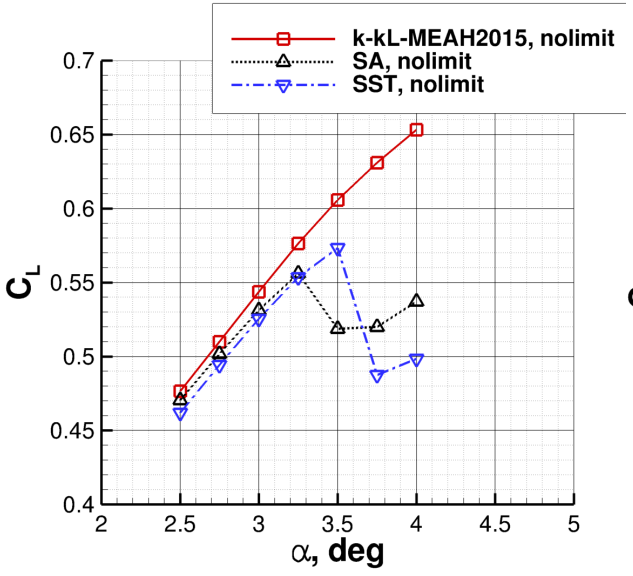
α, deg	Nodes
2.50	44,254,225
2.75	44,249,828
3.00	44,174,034
3.25	44,180,700
3.50	44,2426,17
3.75	44,217,067
4.00	44,238,097

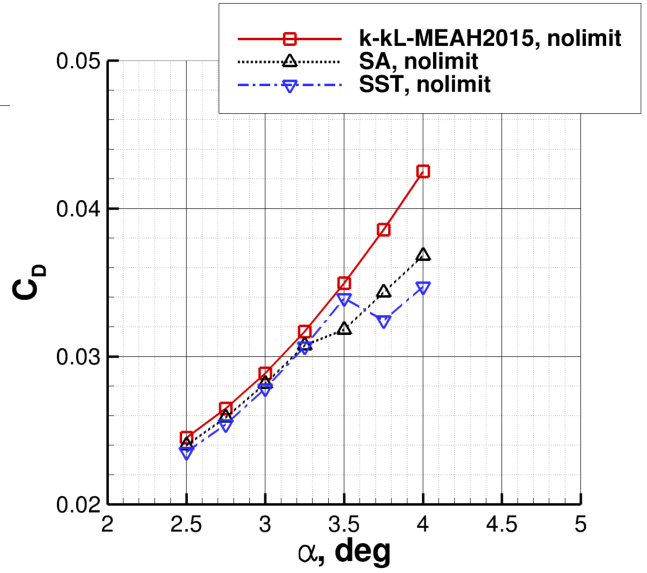
Used: Unstr. NASA GeoLab Rev 0, mixed elements

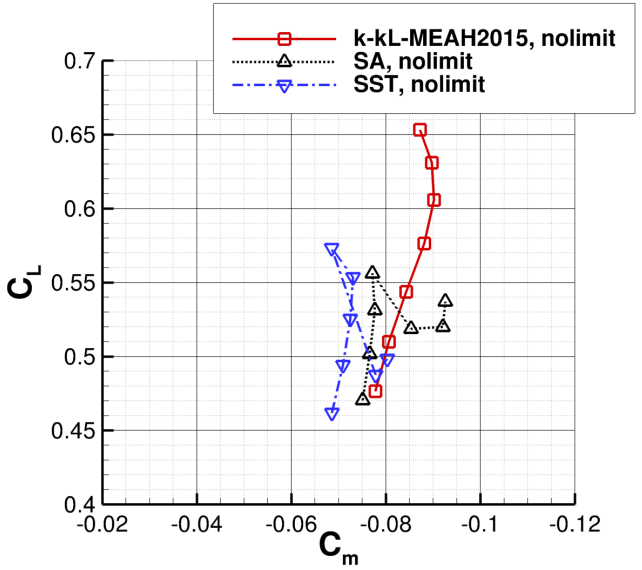
Wing Body CRM Configuration
M=0.85, Re=5.0x10^6

α=2.50,2.75,3.00,3.25,3.50,3.75 and 4.00 deg

Linear Turbulence Models Using No Limiter





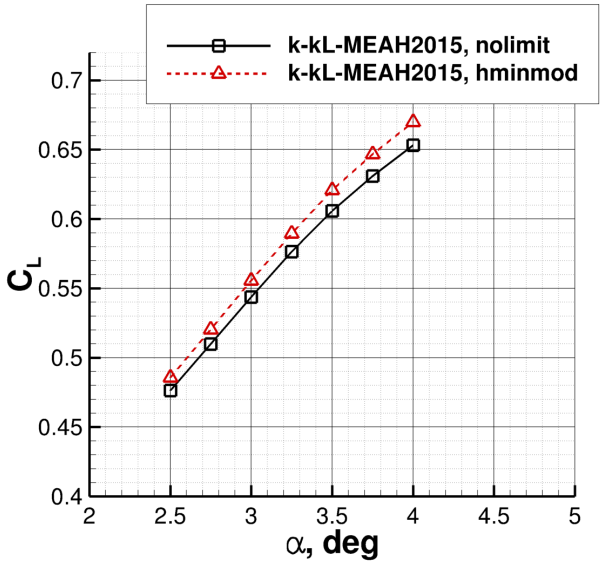


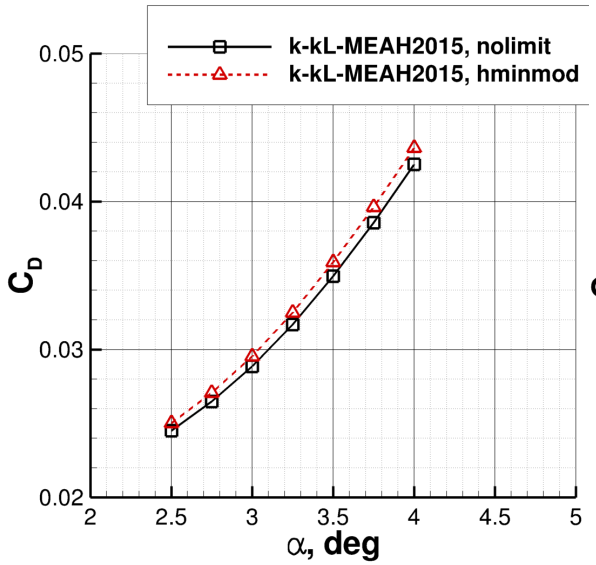
SA shows early large separation (α>3.25 deg)
k-kL-MEAH2015 shows trend similar to WT data
SST shows early large separation (α>3.50 deg)

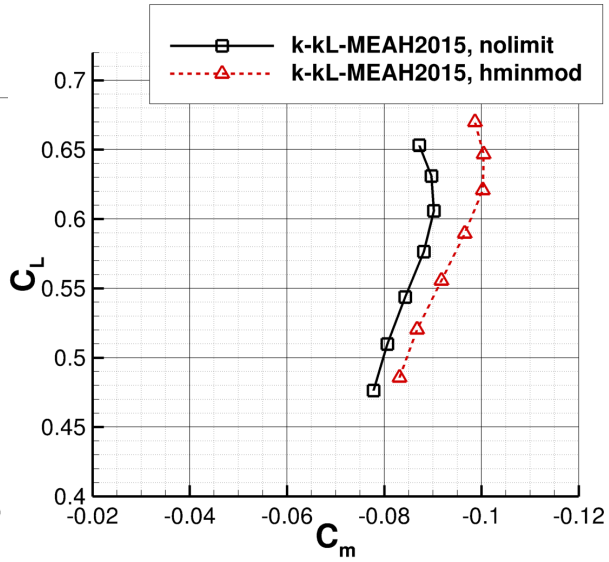
Wing Body CRM Configuration
M=0.85, Re=5.0x10^6

α=2.50,2.75,3.00,3.25,3.50,3.75 and 4.00 deg

Effect of Limiter on k-kL-MEAH2015 Results





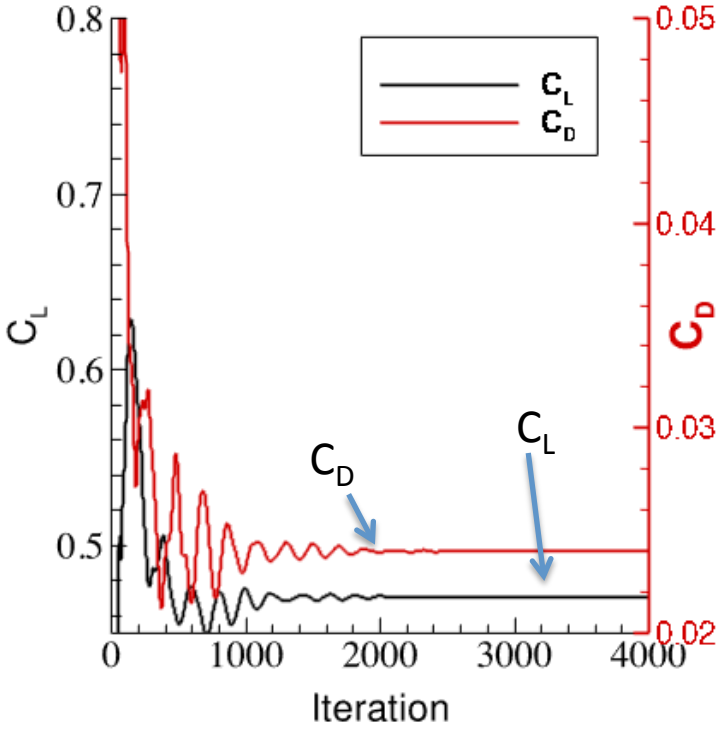


On this grid level, there are noticeable changes in the polars when running no-limiter vs. hminmod limiter

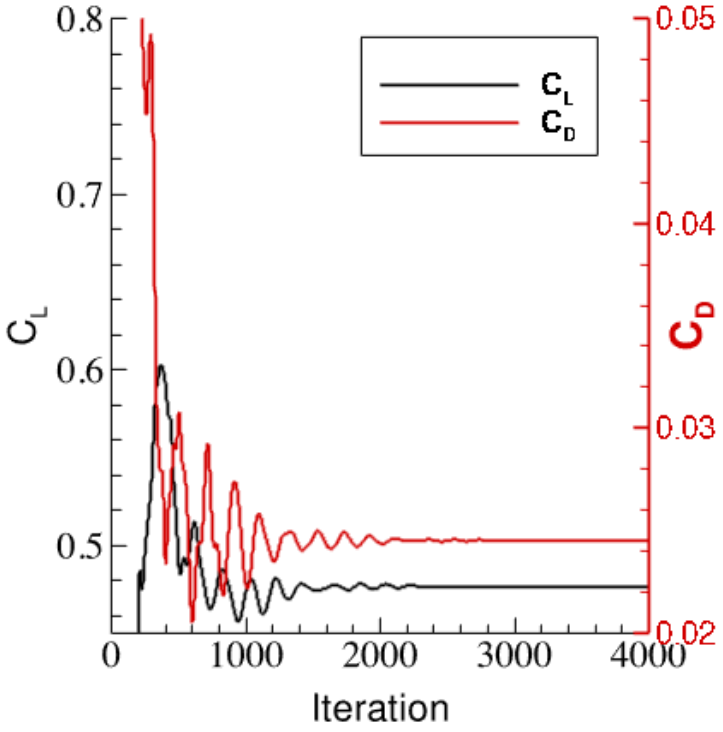
Convergence of SA and k-kL-MEAH2015

α=2.50 deg

SA



k-kL-MEAH2015



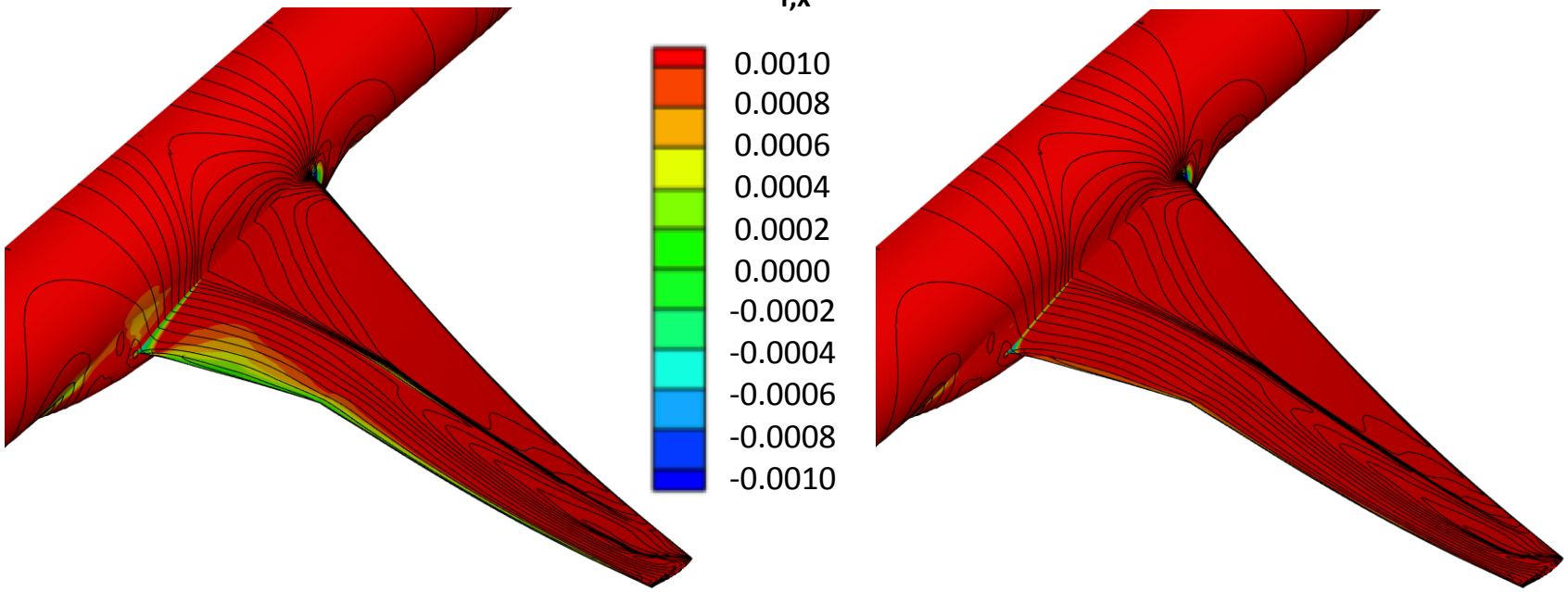
Stopping criterion: change in C_L and C_D less than 0.1% in last 1000 iterations and less than 0.05% in last 500 iterations; in all cases, residuals for all computed variables dropped by at least 4 orders

$C_{f,x}$ for SA and k-kL-MEAH2015 Results

α=2.50 deg

SA

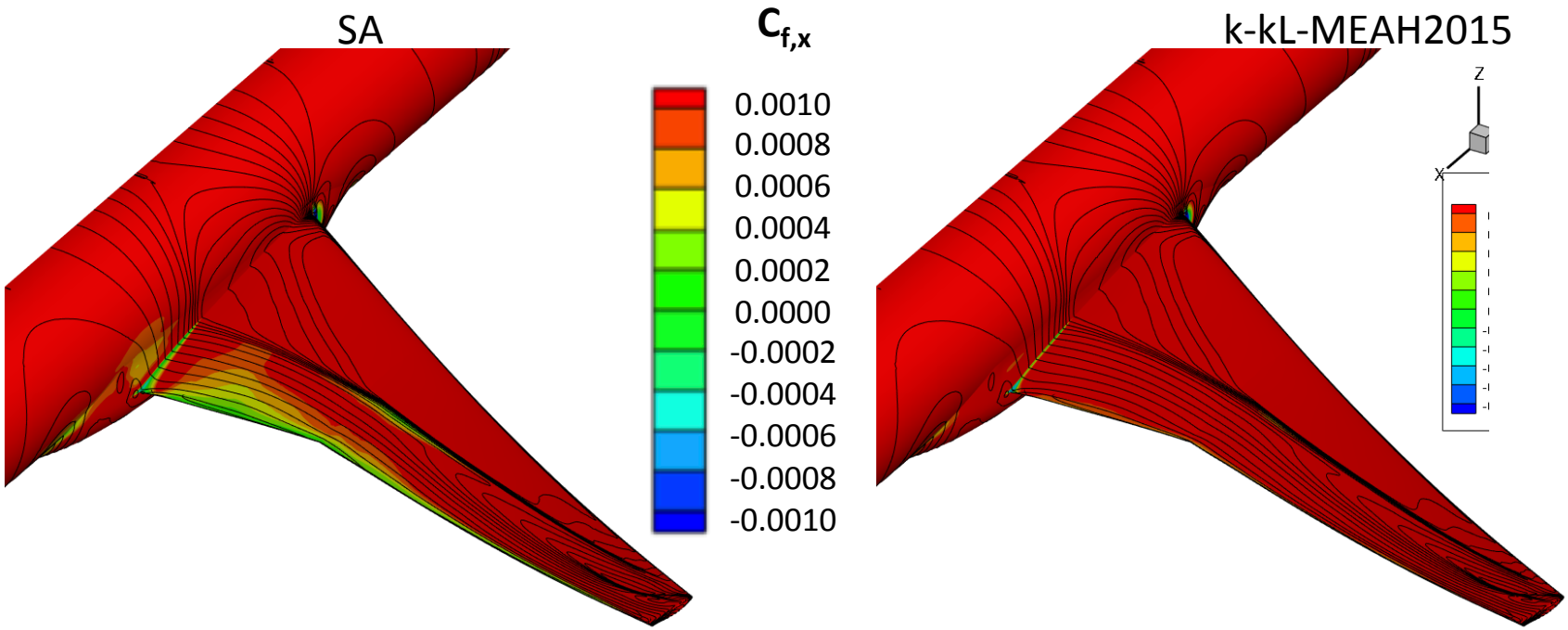
k-kL-MEAH2015



SA shows trend toward separated flow at the base of the wing;
k-kL-MEAH2015 does not

$C_{f,x}$ for SA and k-kL-MEAH2015 Results

α=2.75 deg

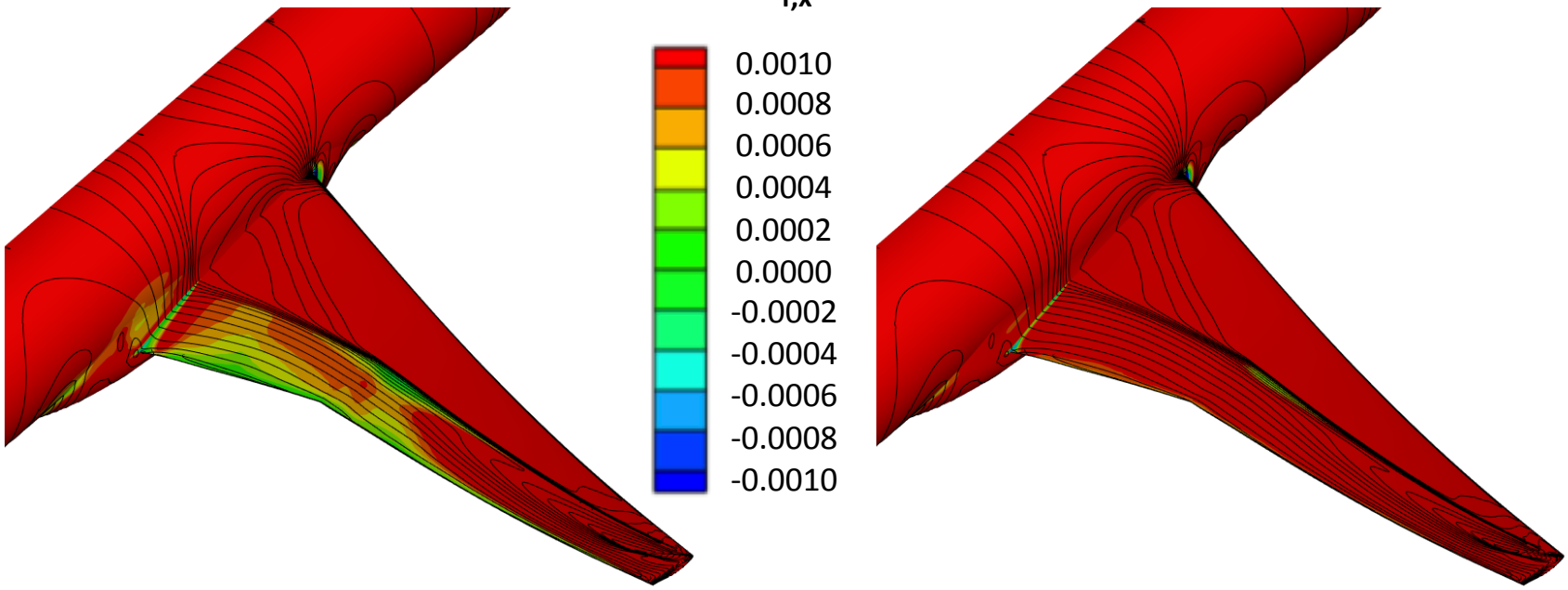


$C_{f,x}$ for SA and k-kL-MEAH2015 Results

α=3.00 deg

SA

k-kL-MEAH2015

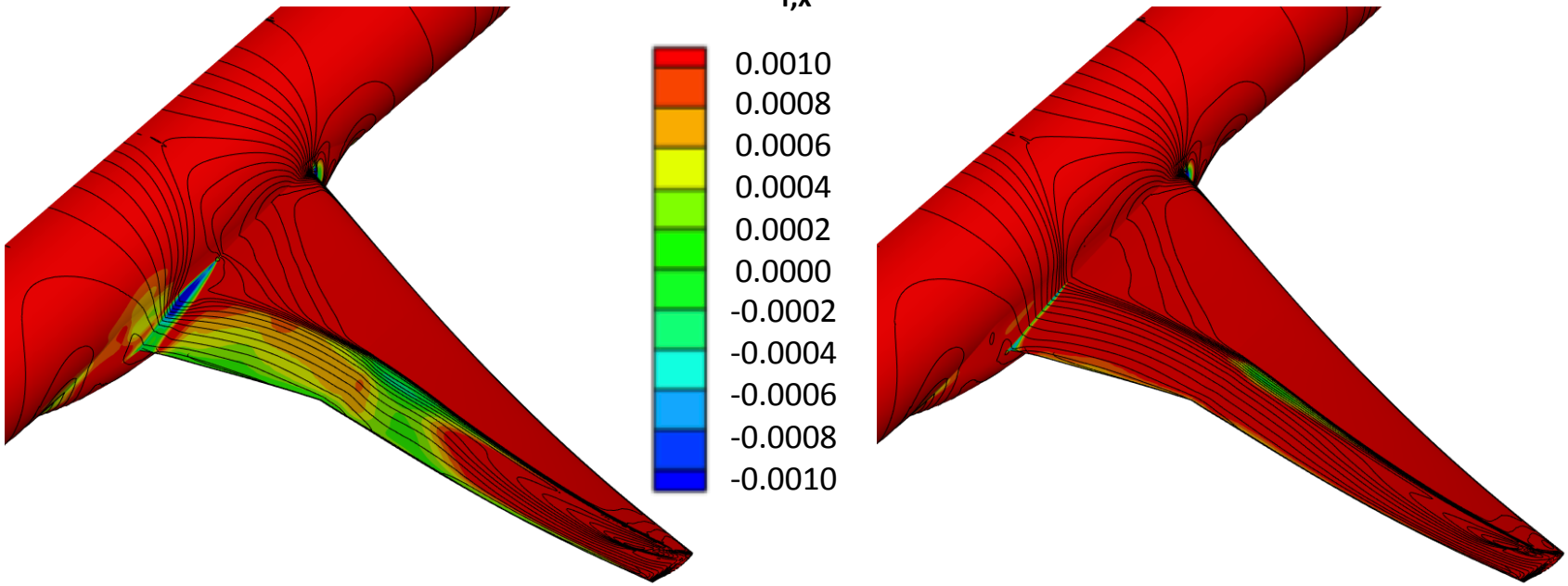


$C_{f,x}$ for SA and k-kL-MEAH2015 Results

α=3.25 deg

SA

k-kL-MEAH2015



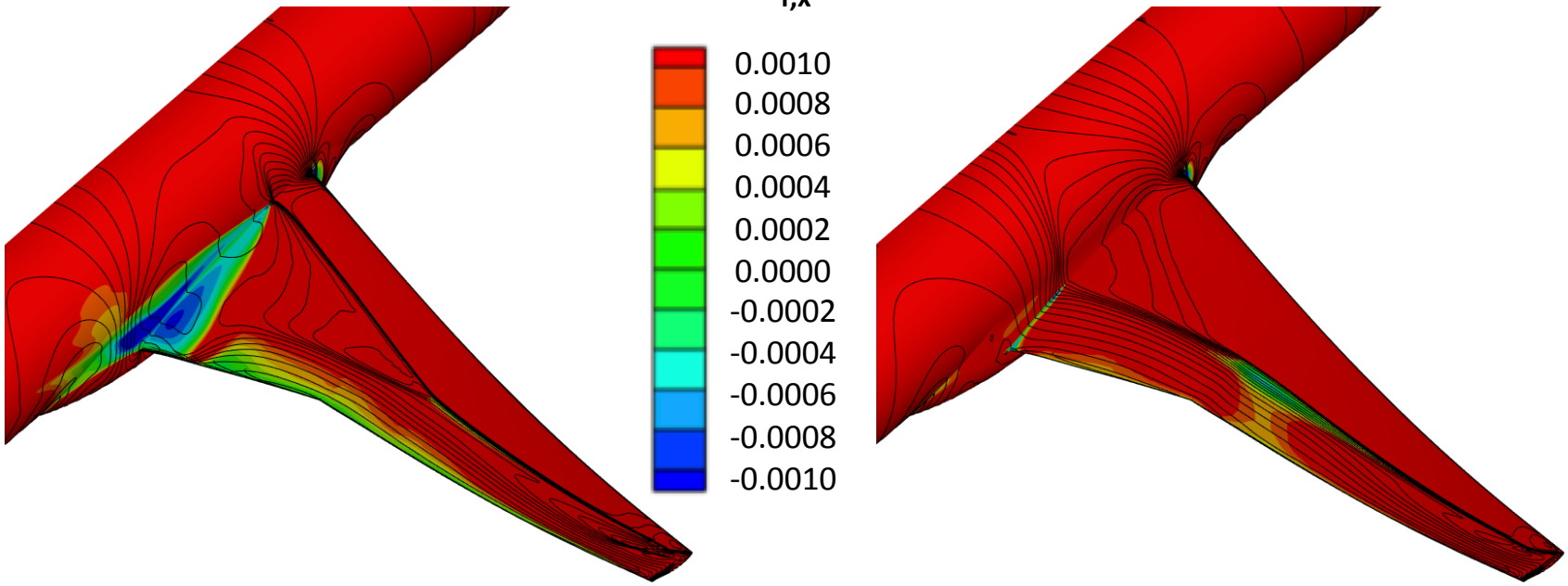
SA shows start of wing-root side-of-body (SOB) separation

$C_{f,x}$ for SA and k-kL-MEAH2015 Results

α=3.50 deg

SA

k-kL-MEAH2015



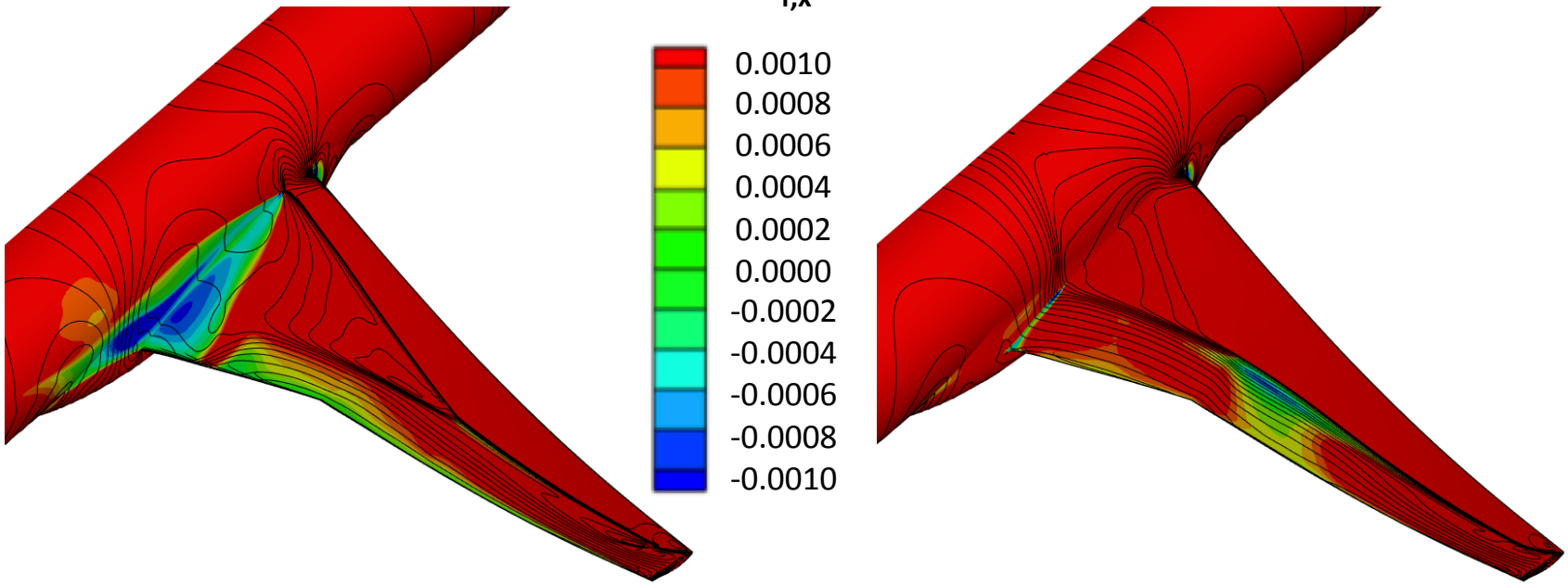
SA's wing-root SOB separation grows dramatically

$C_{f,x}$ for SA and k-kL-MEAH2015 Results

α=3.75 deg

SA

k-kL-MEAH2015

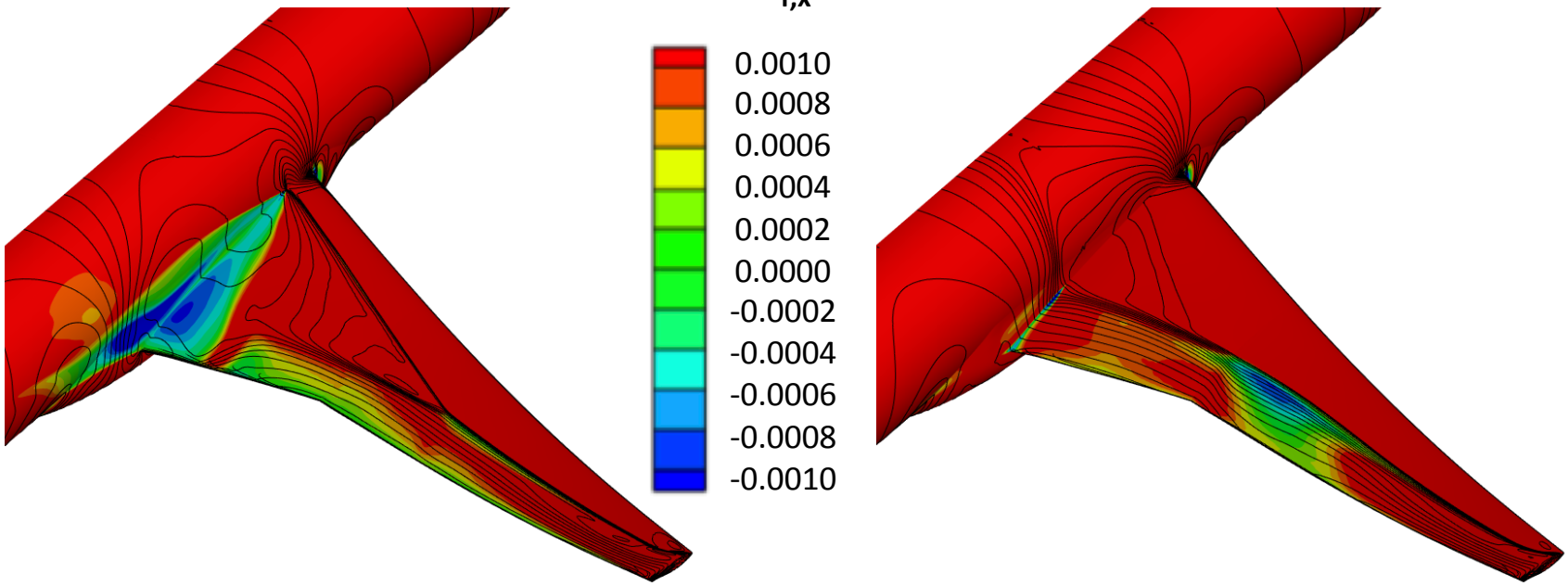


$C_{f,x}$ for SA and k-kL-MEAH2015 Results

α=4.00 deg

SA

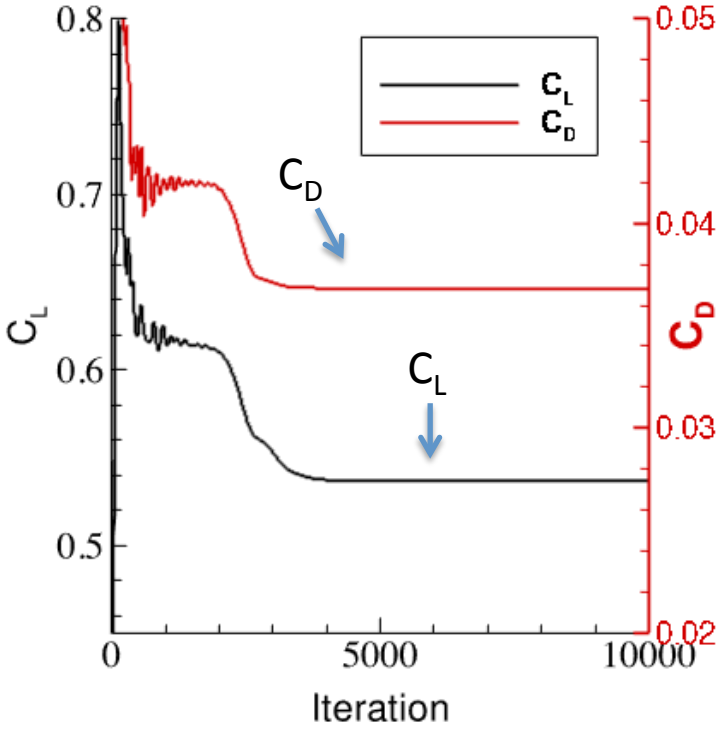
k-kL-MEAH2015



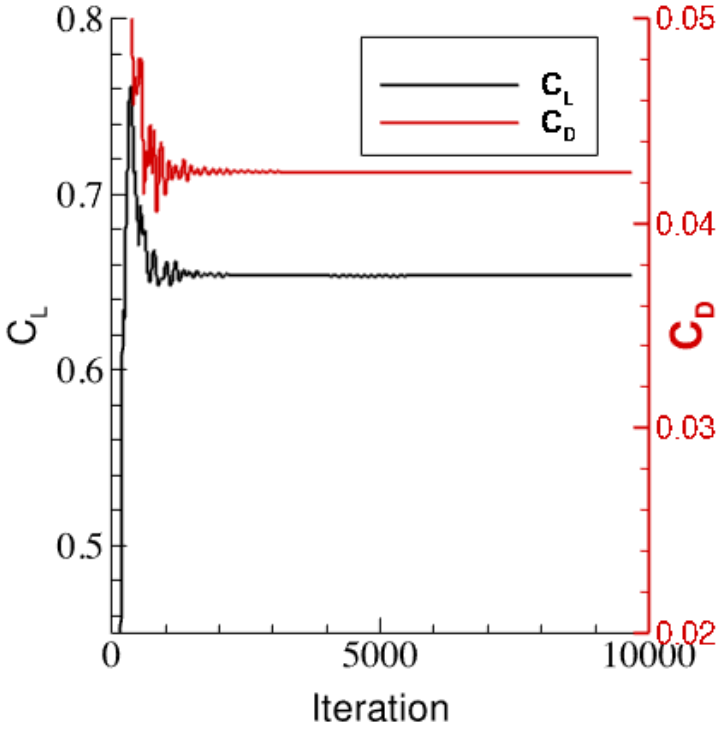
Convergence of SA and k-kL-MEAH2015

α=4.00 deg

SA



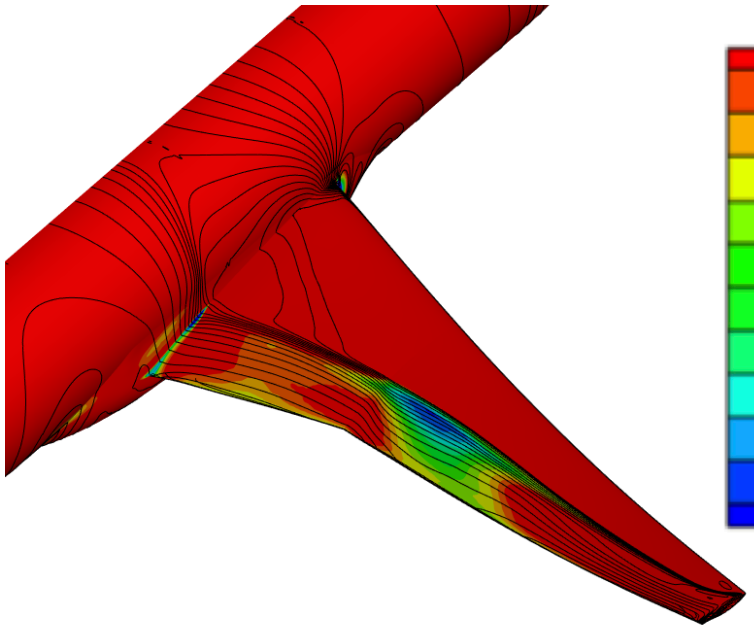
k-kL-MEAH2015



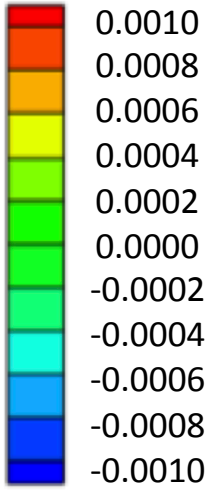
Effect of QCR on k-kL-MEAH2015

α=4.00 deg

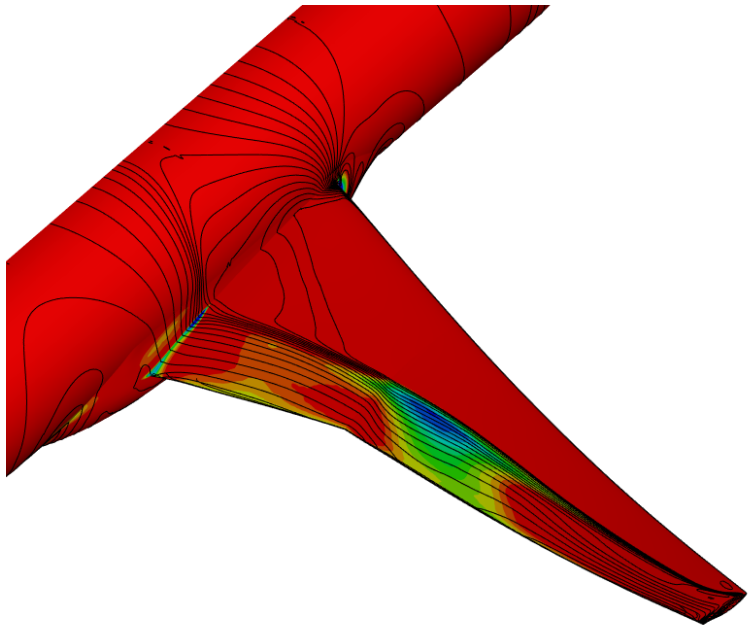
k-kL-MEAH2015



$C_{f,x}$



k-kL-MEAH2015-QCR



Linear and nonlinear k-kL-MEAH2015 predicted very similar results on the wing surface

Summary

- k-kL-MEAH2015 RANS model in FUN3D was run for DPW-6 cases
  - Model has simple zero wall BCs for both variables
  - This model was originally intended to improve separated (unsteady) results, but has turned out to be a good model for steady RANS
  - All cases in this study were fully steady
- For 0012 verification case, k-kL-MEAH2015 yielded C_L slightly lower and C_D slightly higher than SA model
- For CRM cases
  - k-kL-MEAH2015 was run both with and without a limiter: caused some differences (which generally decreased on finer grids)
  - Unlike SA and SST, the k-kL-MEAH2015 model did NOT produce large SOB separation even up to α=4.00 deg (so did not stall early)
    - Reason for this success is not known
    - Use of QCR (which can help reduce SOB separation for linear models) had little influence on k-kL-MEAH2015 at alphas tested