CFD Drag Prediction Workshop

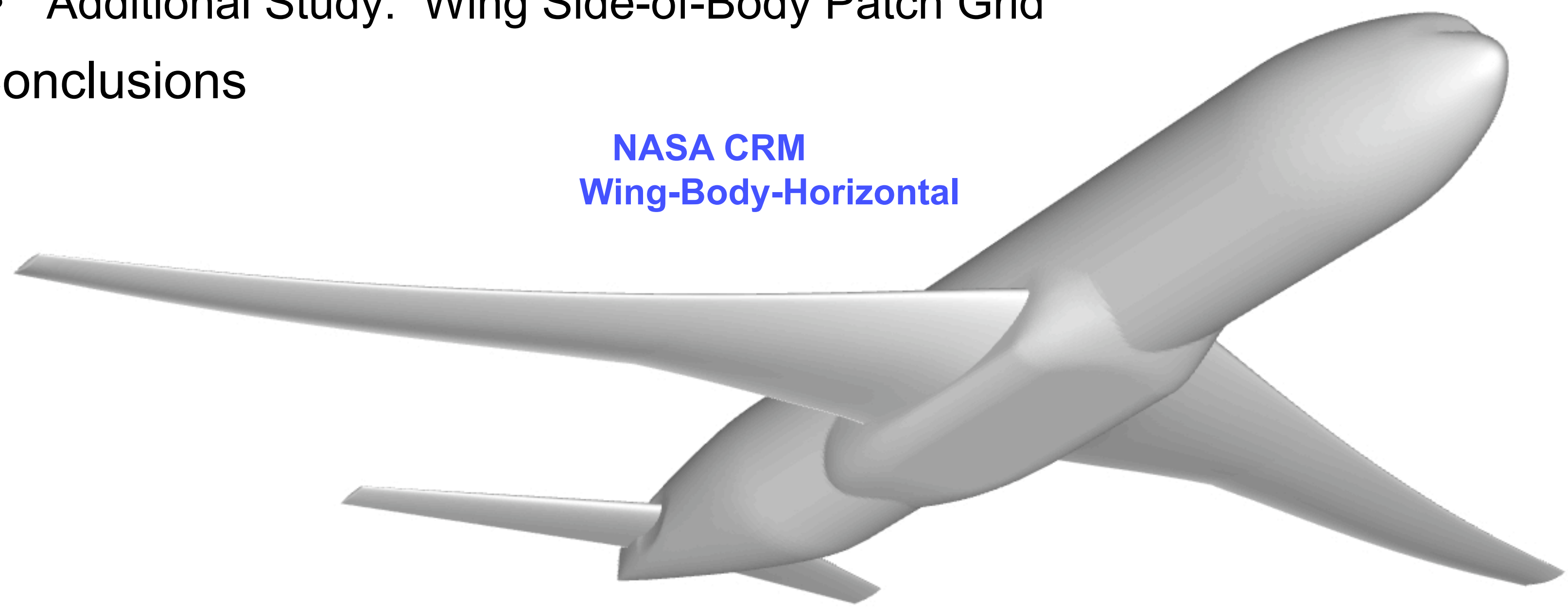
OVERFLOW Drag Prediction for the NASA Common Research Model (CRM)

Anthony J. Sclafani, John C. Vassberg, Mark A. DeHaan
The Boeing Company
Huntington Beach, California, USA

4th AIAA Drag Prediction Workshop
San Antonio, Texas
20-21 June 2009

Outline

- Flow Solver / Computing Platform
- Grid Information
- Convergence Histories and Residuals
- Results
  - Test Case 1.1: CRM Grid Convergence Study
  - Test Case 1.2: CRM Downwash Study
  - Test Case 3: Reynolds Number Study
  - Additional Study: Wing Side-of-Body Patch Grid
- Conclusions



Flow Solver / Computing Platform

OVERFLOW MPI Version 2.1t

- Analyzed multiple combinations of BB/SA, central/upwind and TLNS/FNS.
- Based primarily on what the side-of-body wing separation was doing, the following setup was used for this workshop.
  - Spalart-Allmaras turbulence model – default version "fv3"
  - central differencing
  - thin layer mode – compute viscous terms normal to wall only
- **Unless otherwise noted, OVERFLOW results are SA-Central-TL**

Parallel Processing Done on a PC Cluster

- Linux operating system
- Opteron dual core 64bit CPU nodes with 8 GB of memory each
- CRM WBH medium grid run on 16 processors (8 nodes)
  - 3.3 hours per 1000 fine grid iterations
  - Full convergence reached after 4000 fine grid iterations
  - Roughly 13 hours of wall clock time needed per case for the medium WBH grid

Grid Information

Structured Overset Grid Systems

- 11 zones for Wing-Body
- 17 zones for Wing-Body-Horizontal

Medium grid is typical for drag quality design studies

Wing-Body

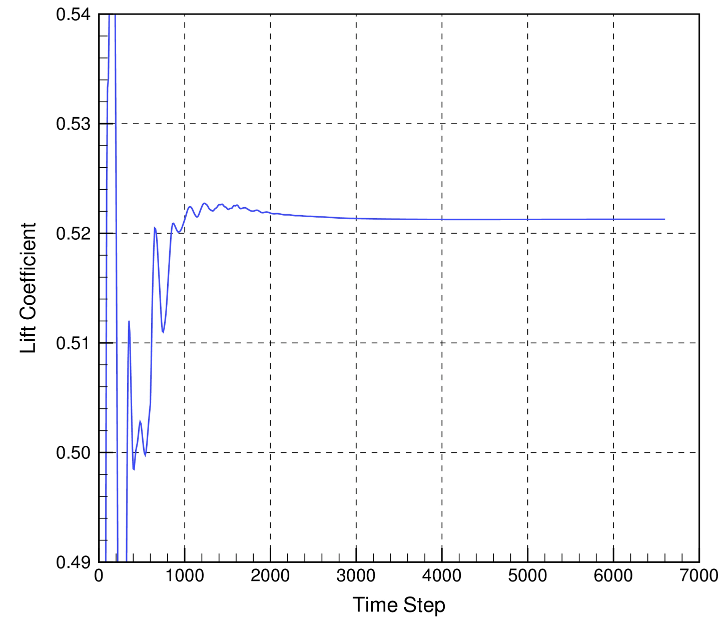
Grid	Points	$1/N^{2/3} \times 10^5$	1st Cell Size	y^+	Constant Cells	Growth Rate
Medium	12,267,995	1.88	.00079 in	.66	3	1.19

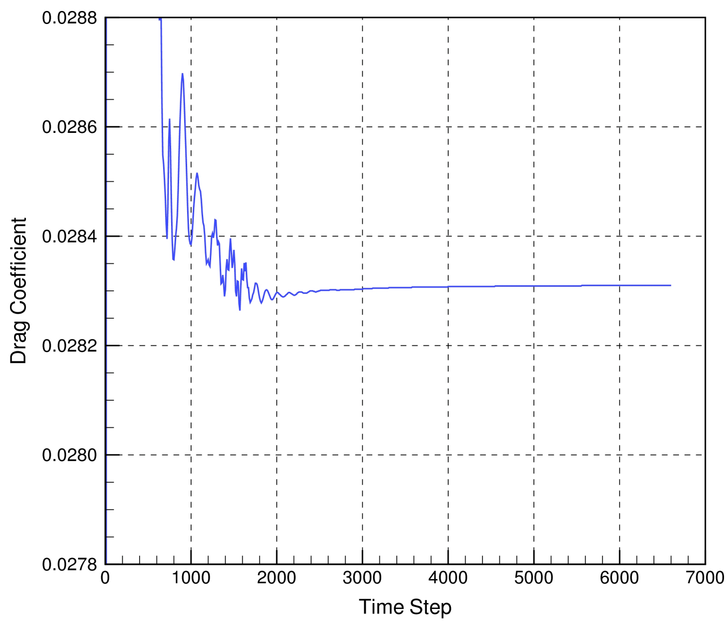
Wing-Body-Horizontal

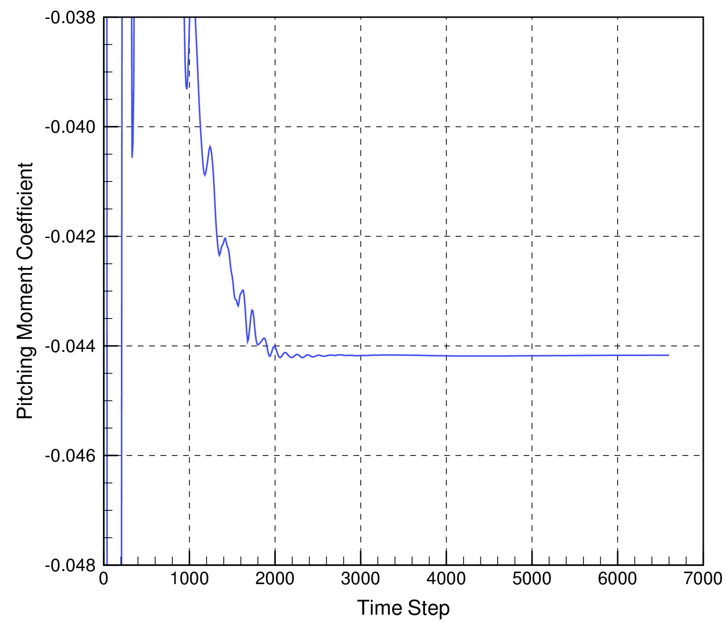
Grid	Points	$1/N^{2/3} \times 10^5$	1st Cell Size	y^+	Constant Cells	Growth Rate
Coarse	7,221,233	2.68	.00104 in	.87	2	1.26
Medium	16,932,913	1.52	.00079 in	.66	3	1.19
Fine	56,531,489	0.68	.00052 in	.44	4	1.12
Extra Fine	189,413,153	0.30	.00035 in	.29	6	1.08

OVERFLOW Convergence Histories

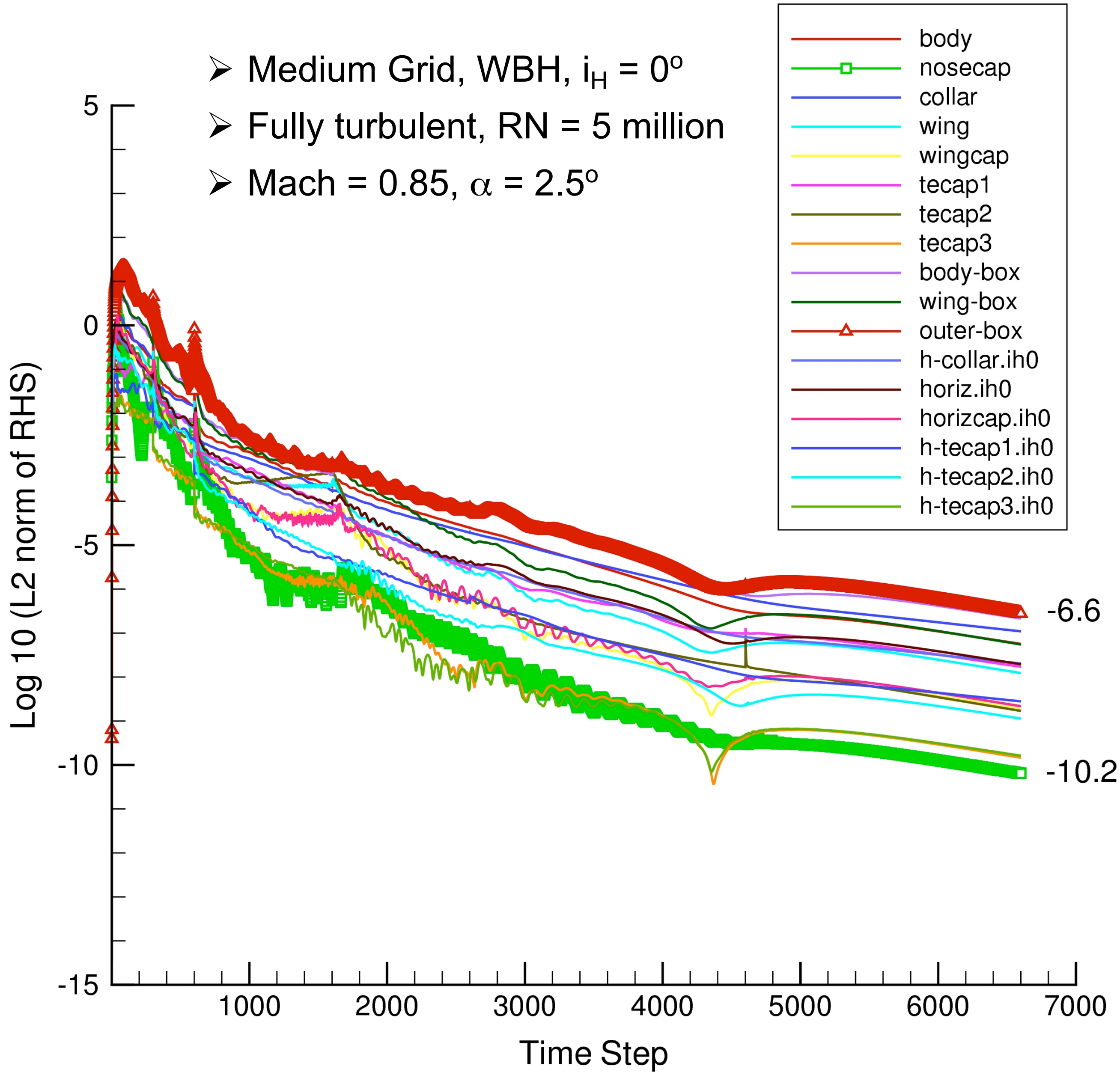
- Medium Grid, WBH, $i_H = 0^o$
- Fully turbulent, RN = 5 million
- Mach = 0.85, $\alpha = 2.5^o$
- These flat-line convergence histories are representative of the tail-off, $i_H = +2^o$ and $i_H = 0^o$ solutions.
- The $i_H = -2^o$ convergence histories exhibited a slight oscillation for some alphas (+/-.0001 in C_L).





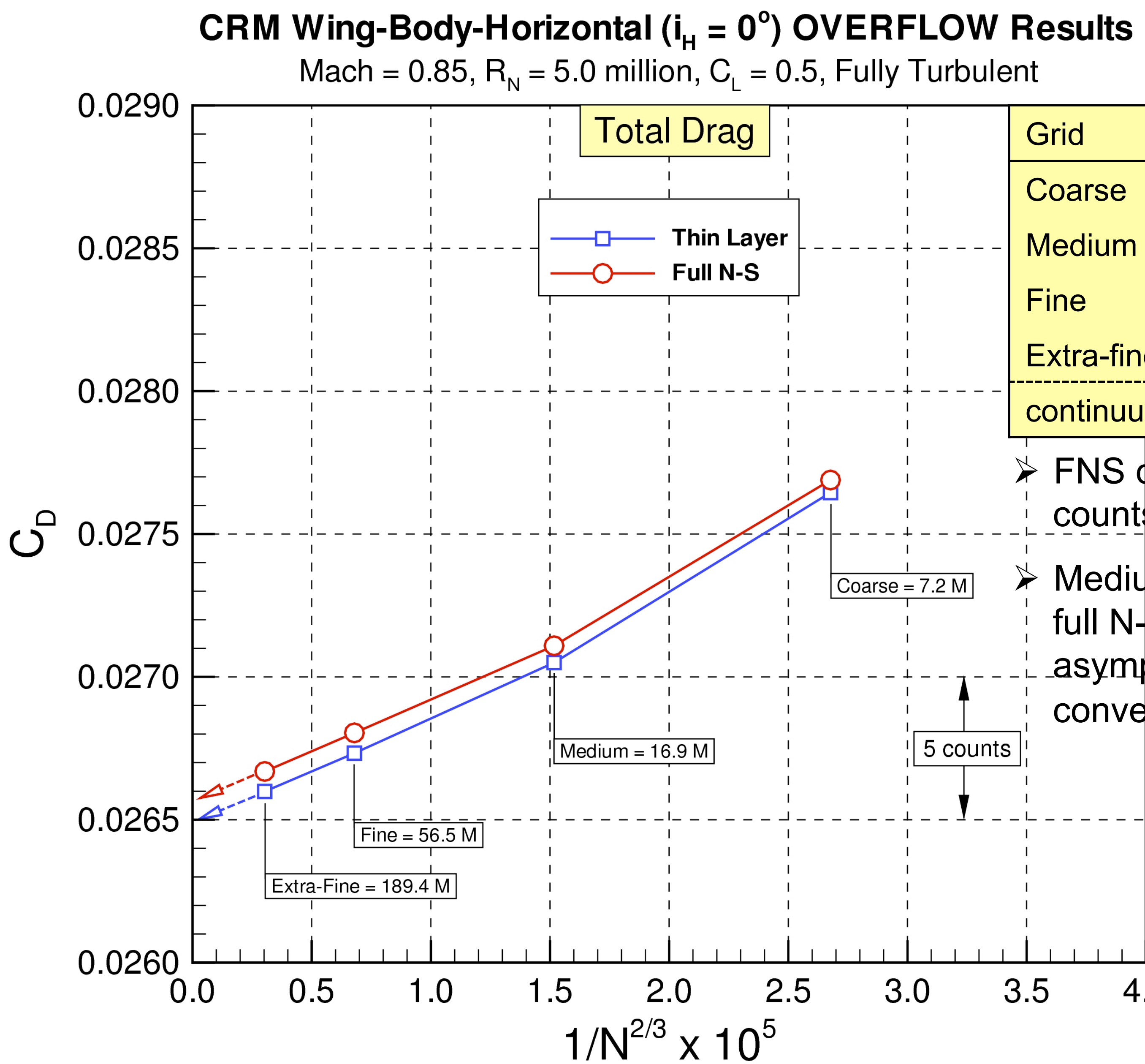


OVERFLOW Residuals



Test Case 1.1: CRM Grid Convergence Study

Test Case 1.1 – Grid Convergence Study
Total Drag



Grid	TLNS	FNS
Coarse	276.4	276.9
Medium	270.5	271.1
Fine	267.3	268.0
Extra-fine	266.0	266.7
continuum	264.9	265.6

- FNS drag level is 0.5 to 0.7 counts higher than TLNS
- Medium, fine and extra-fine full N-S results show asymptotic grid convergence

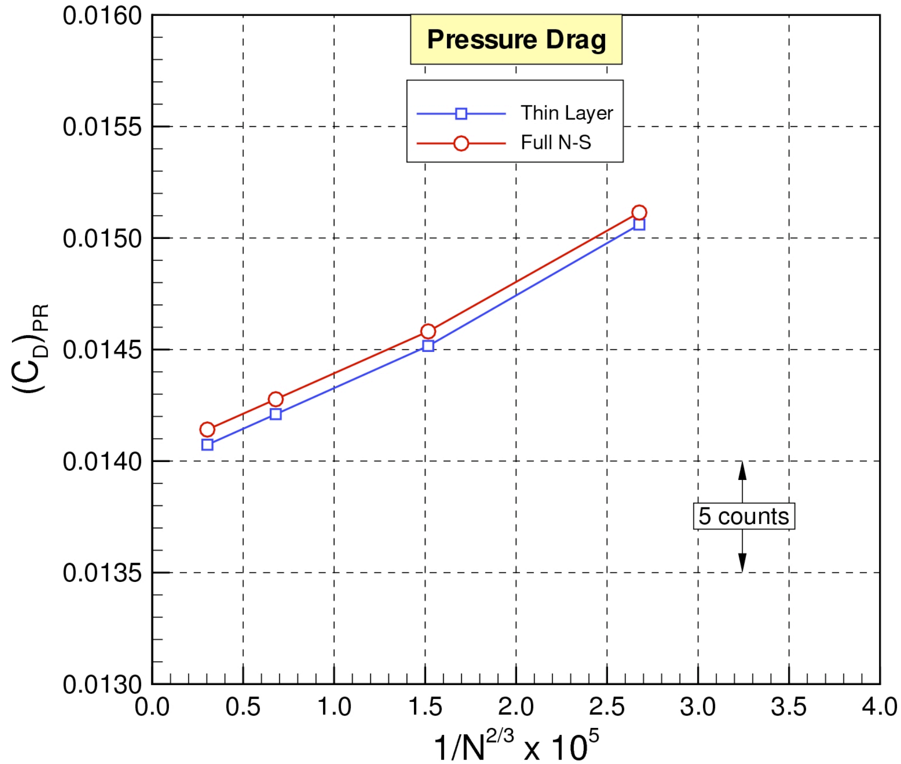
Test Case 1.1 – Grid Convergence Study

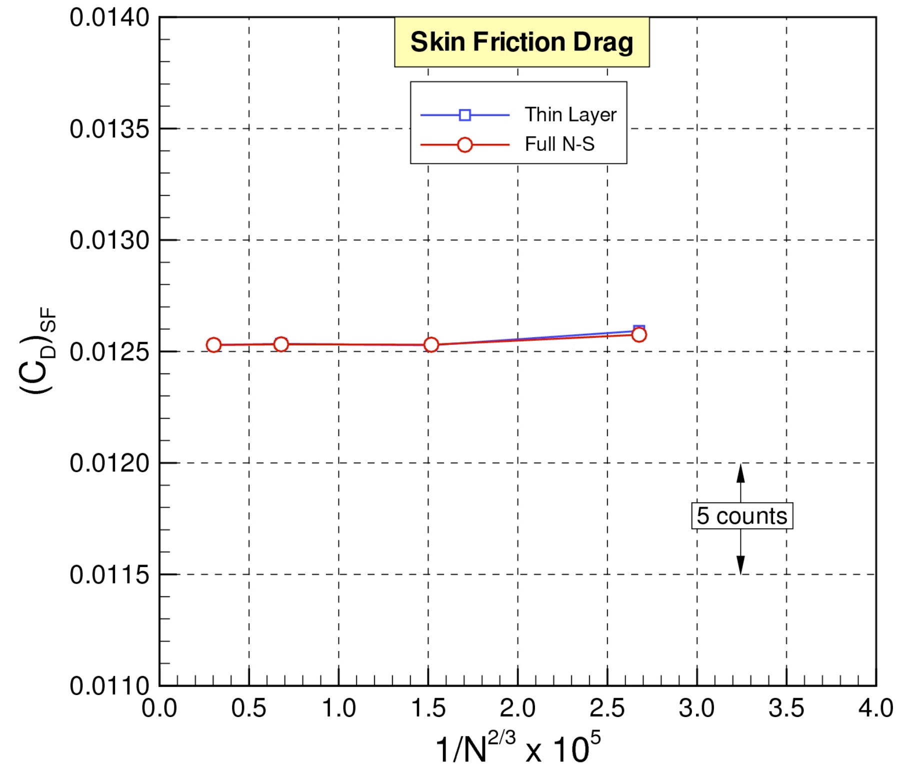
Pressure and Skin Friction Drag

CFD Drag Prediction Workshop

CRM Wing-Body-Horizontal (i_H = 0°) OVERFLOW Results

Mach = 0.85, R_N = 5.0 million, C_L = 0.5, Fully Turbulent





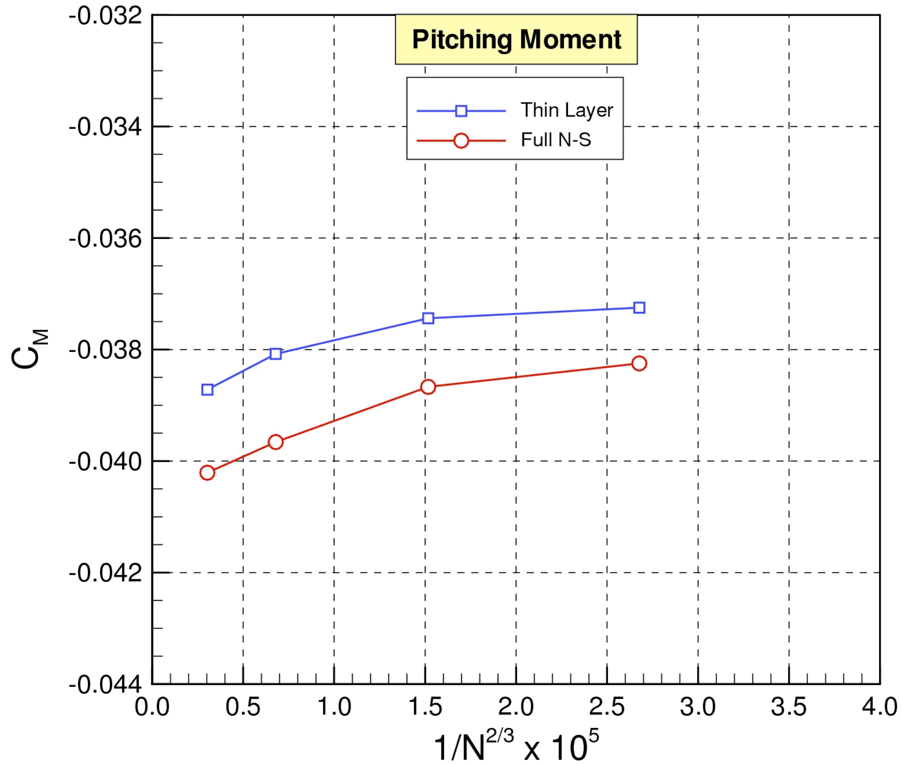
- Pressure drag trends are similar to total drag.
- Skin friction drag is relatively insensitive to grid refinement.
  - Both TLNS and FNS give about the same level of skin friction drag (125.3 counts)

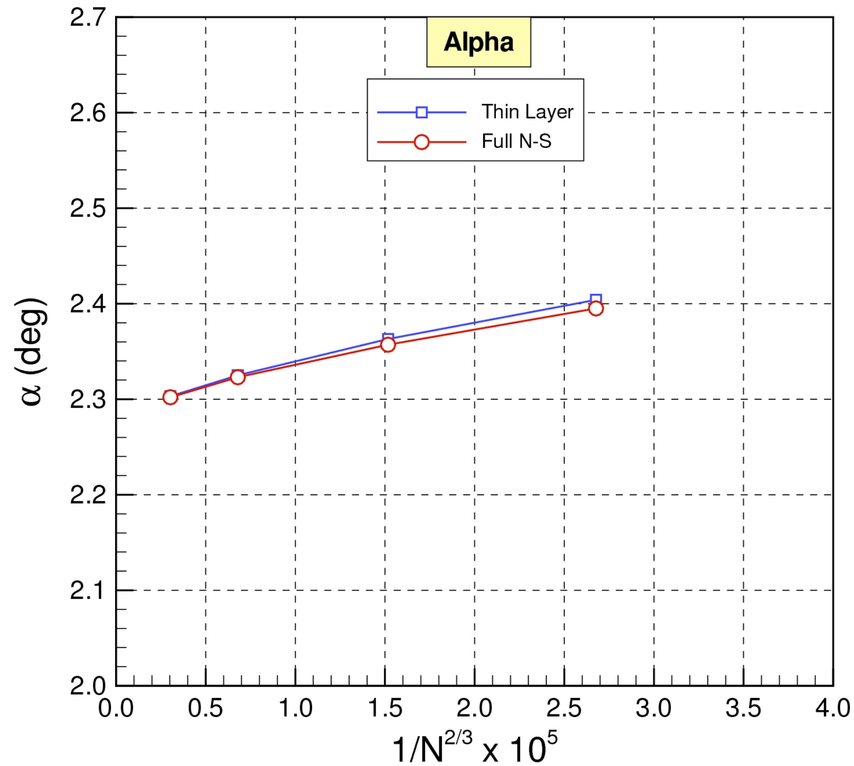
Test Case 1.1 – Grid Convergence Study

Pitching Moment and Angle-of-Attack

CRM Wing-Body-Horizontal (i_H = 0°) OVERFLOW Results

Mach = 0.85, R_N = 5.0 million, C_L = 0.5, Fully Turbulent



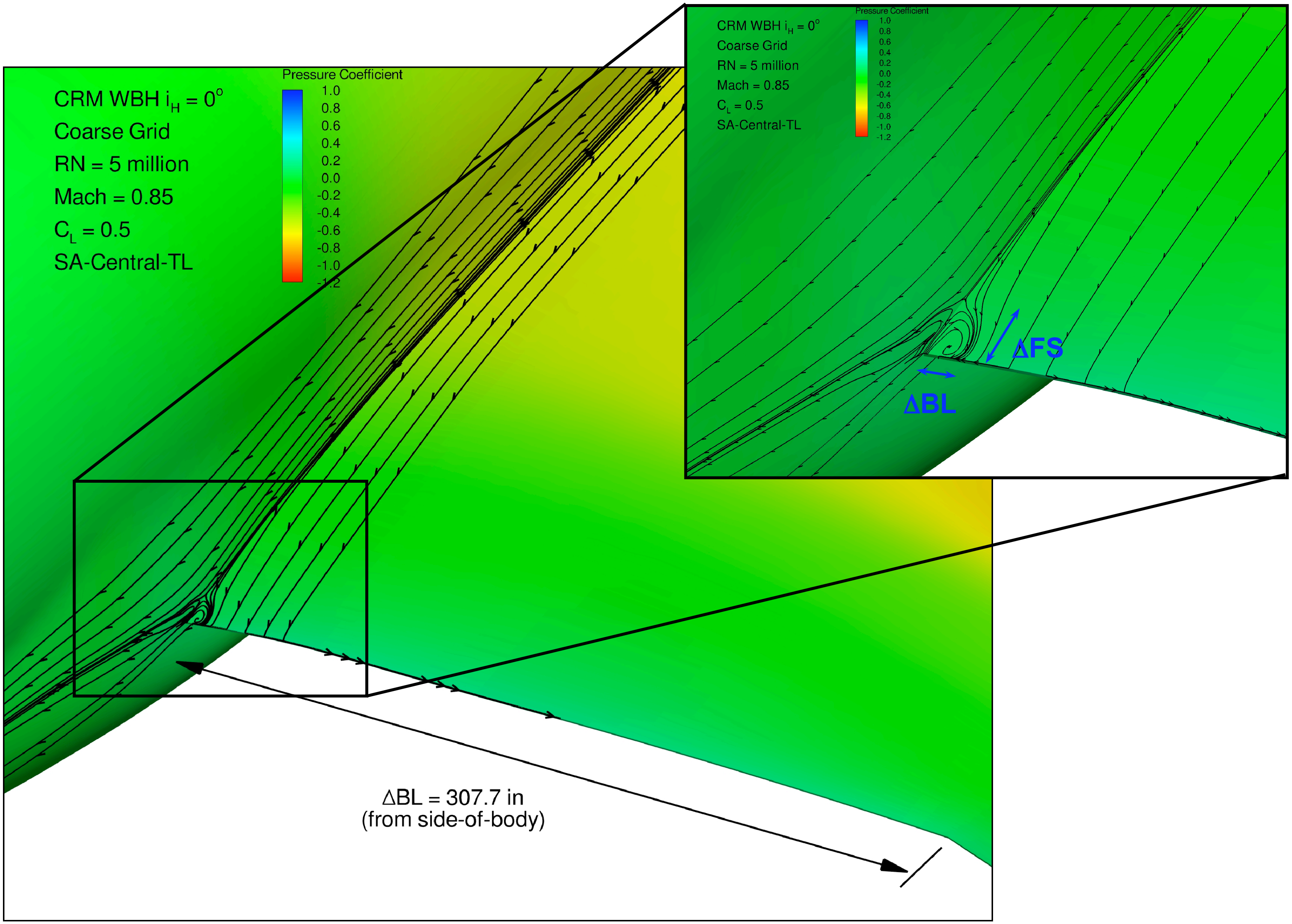


- Shift in FNS data show a more nose-down pitching moment compared to TLNS.
- Difference in angle-of-attack is reduced with grid refinement.
- As the grid is refined, the pitching moment goes more negative and the alpha drops to maintain the same level of lift.

Test Case 1.1 – Grid Convergence Study

Wing Side-of-Body Separation

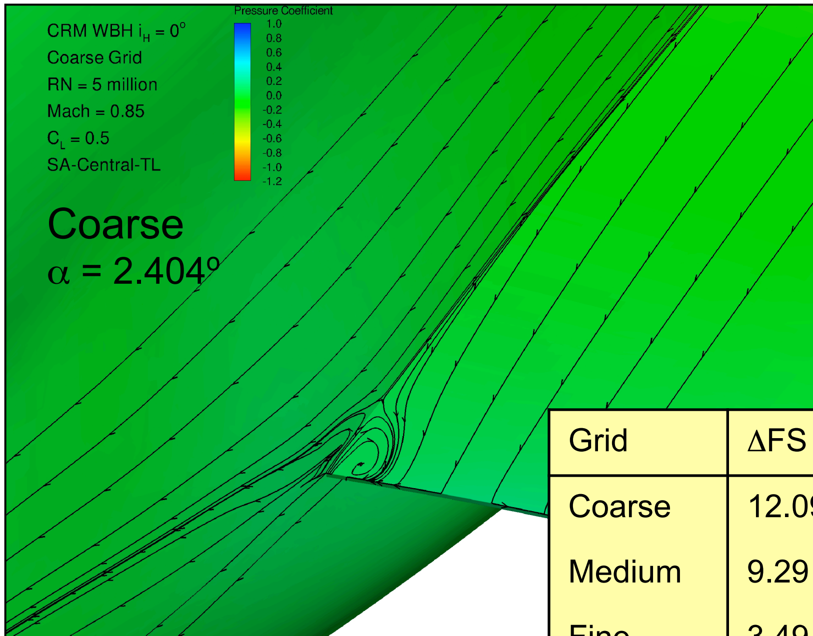
CFD Drag Prediction Workshop

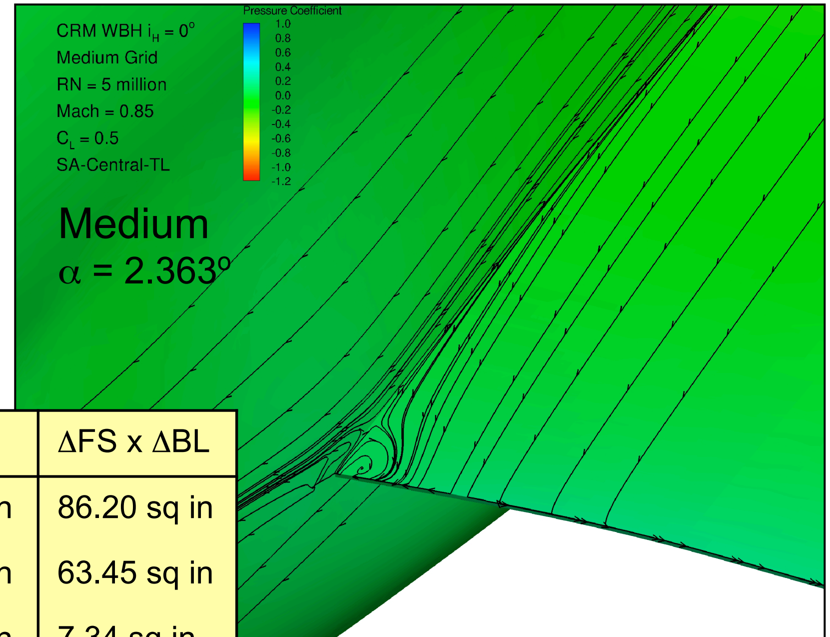


Test Case 1.1 – Grid Convergence Study

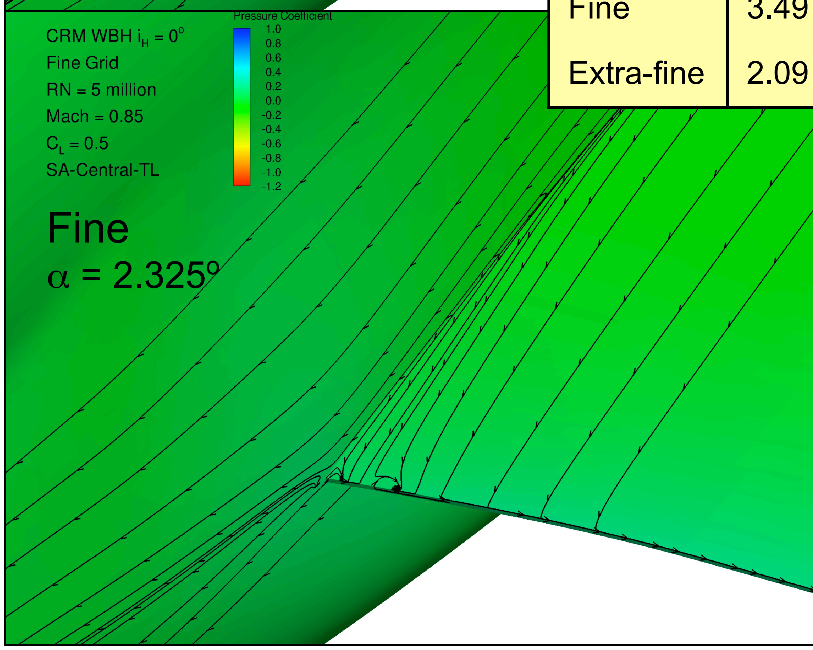
Wing Side-of-Body Separation: Grid Effect

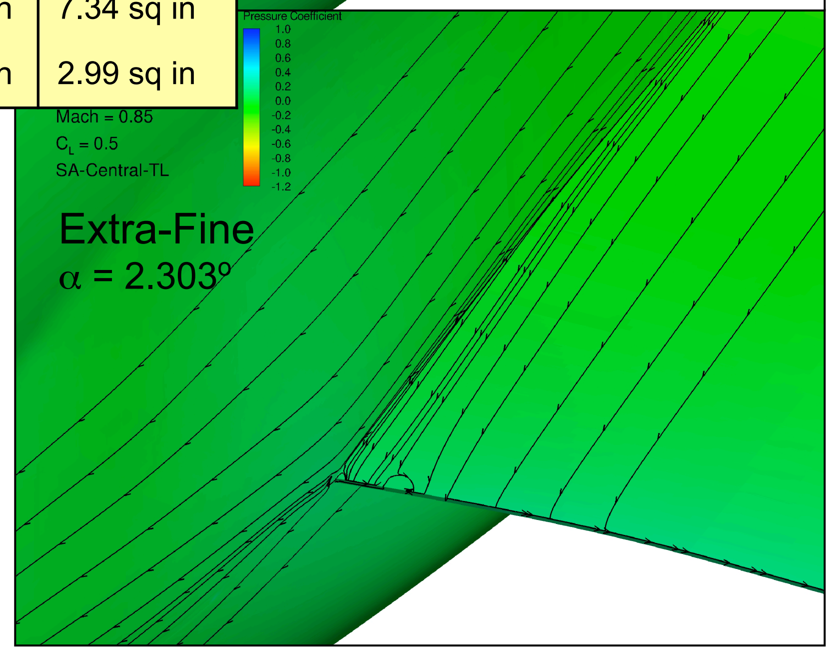
AIAA
CFD Drag Prediction Workshop





Grid	ΔFS	ΔBL	ΔFS x ΔBL
Coarse	12.09 in	7.13 in	86.20 sq in
Medium	9.29 in	6.83 in	63.45 sq in
Fine	3.49 in	2.13 in	7.34 sq in
Extra-fine	2.09 in	1.43 in	2.99 sq in

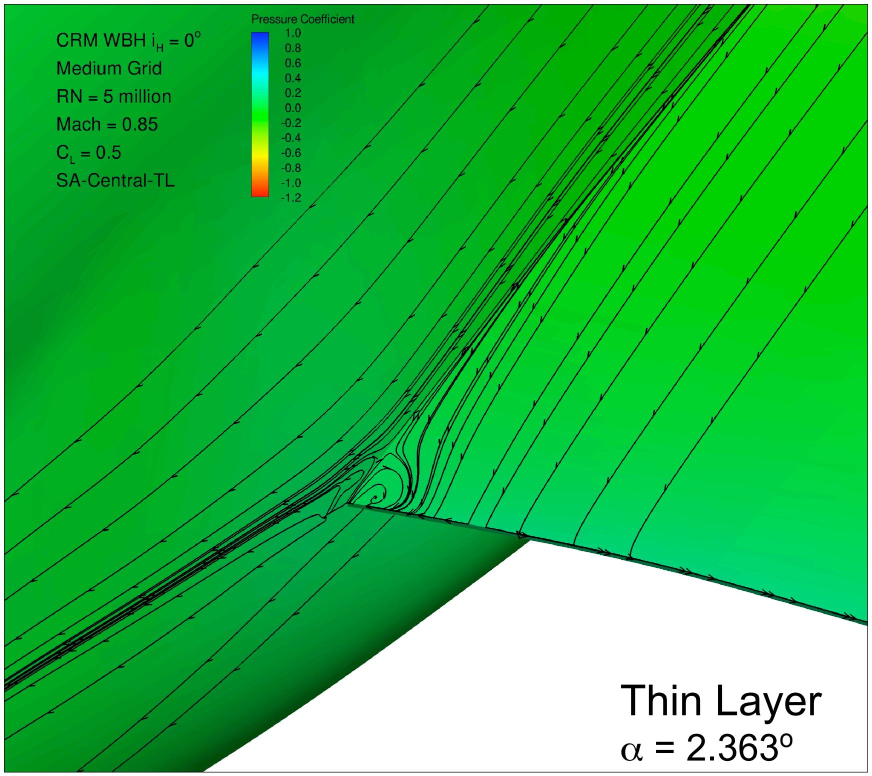


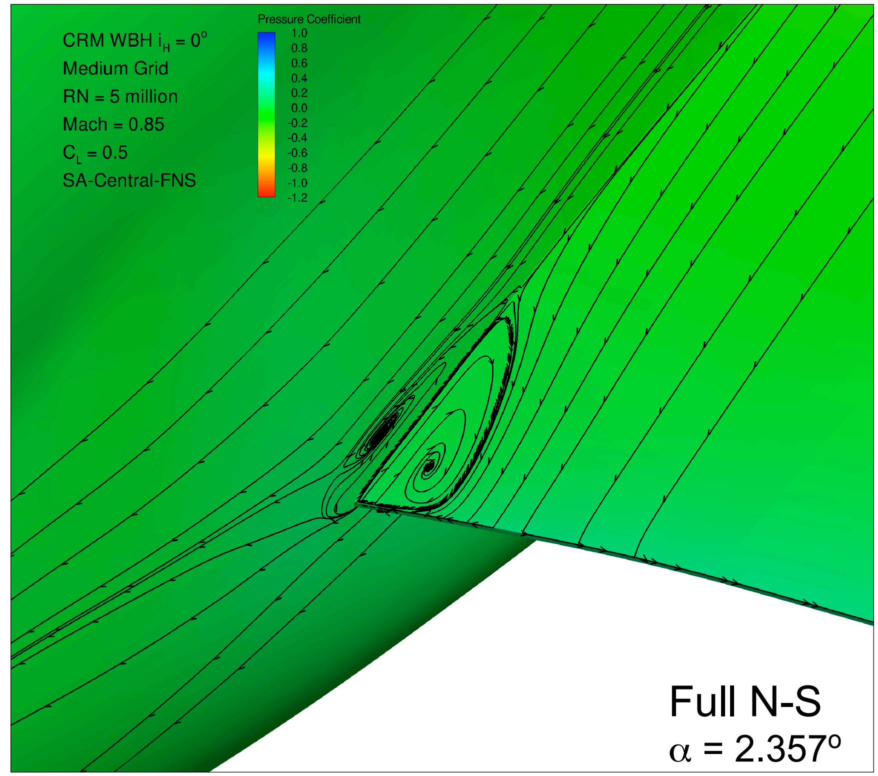


Test Case 1.1 – Grid Convergence Study

Wing Side-of-Body Separation: TLNS vs FNS

Medium Grid





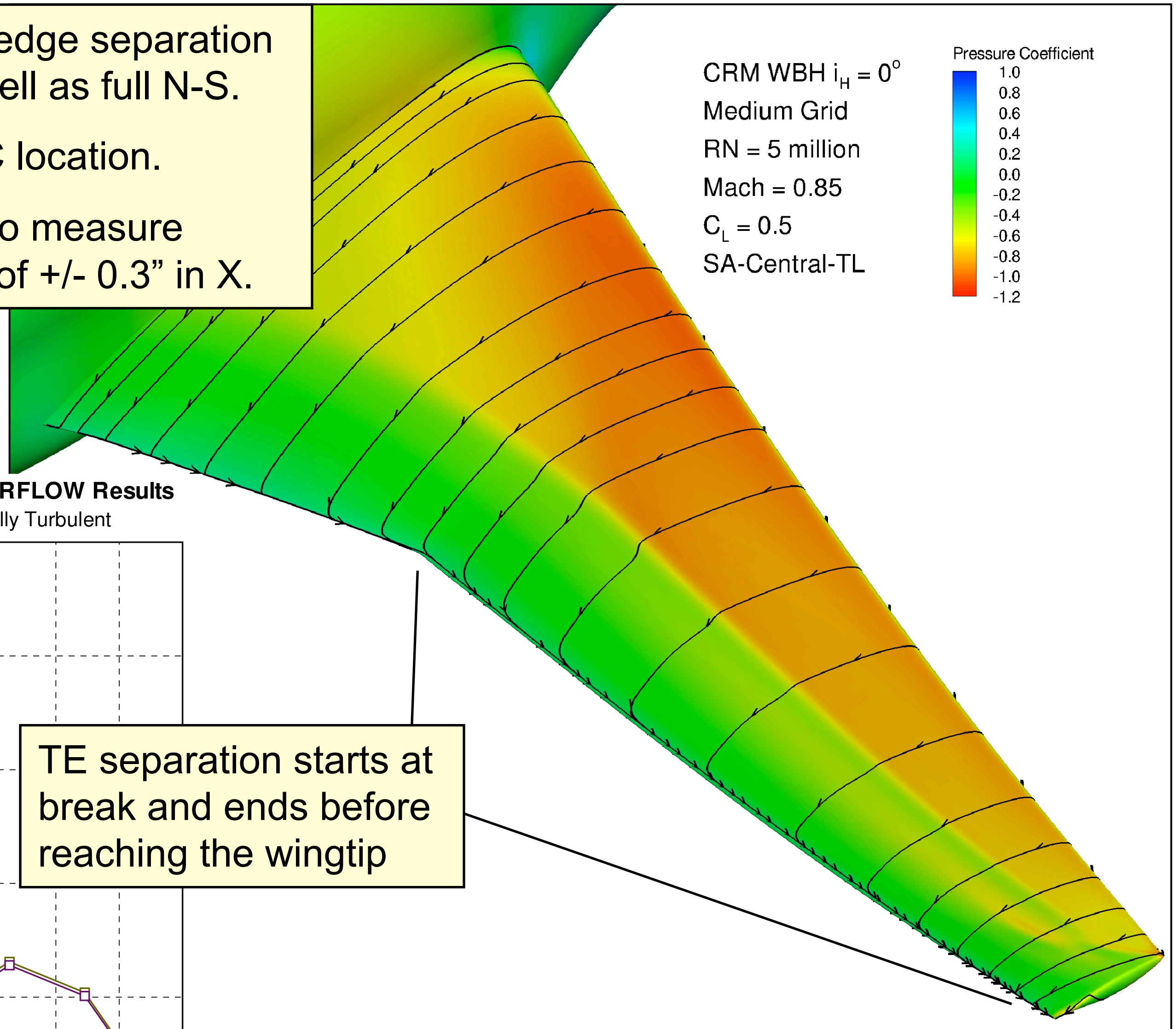
Thin Layer	Full N-S
ΔFS = 9.29 in	ΔFS = 36.33 in
ΔBL = 6.83 in	ΔBL = 11.39 in
$\Delta FS \times \Delta BL$ = 63.4 sq in	$\Delta FS \times \Delta BL$ = 413.8 sq in

Test Case 1.1 – Grid Convergence Study
Trailing-Edge Separation: Grid Effect

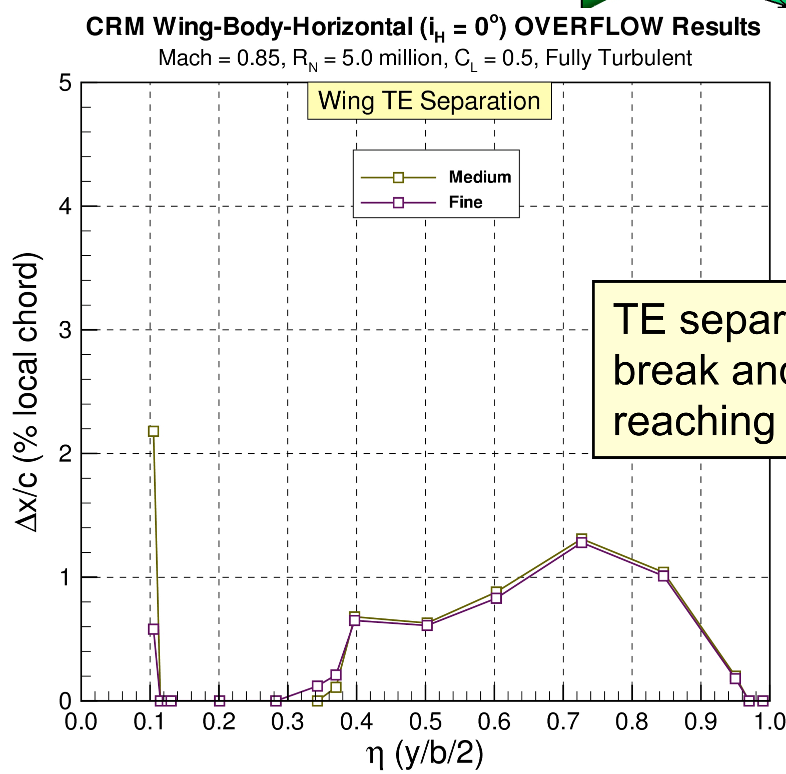
Wing upper surface trailing-edge separation exists for all grid levels as well as full N-S.

No significant change in X/C location.

- Manual approach used to measure separation has an error of +/- 0.3” in X.

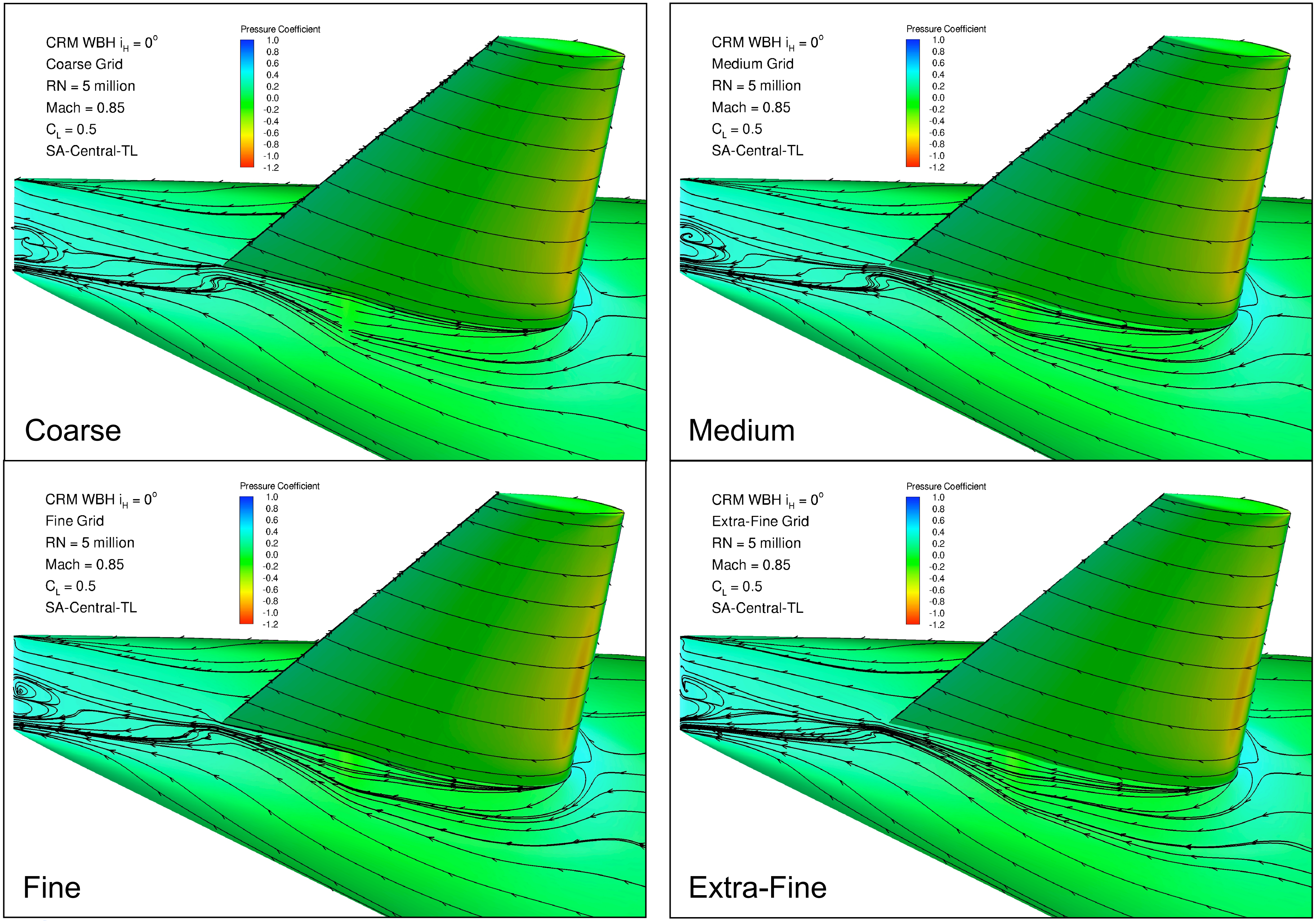


TE separation starts at break and ends before reaching the wingtip



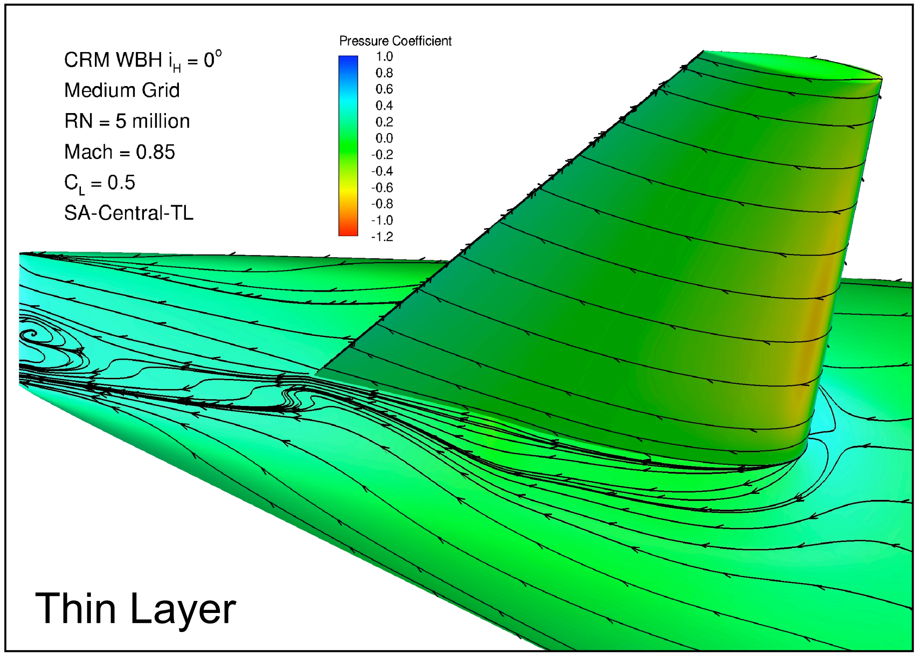
Test Case 1.1 – Grid Convergence Study
Tail Side-of-Body Separation: Grid Effect

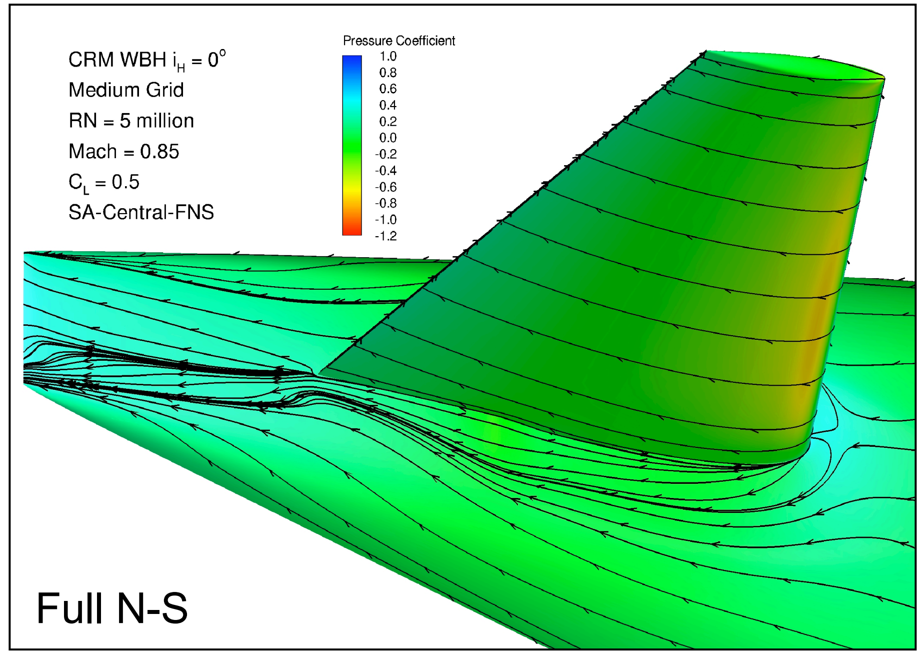
CFD Drag Prediction Workshop



Test Case 1.1 – Grid Convergence Study
Tail Side-of-Body Separation: TLNS vs FNS

Medium Grid

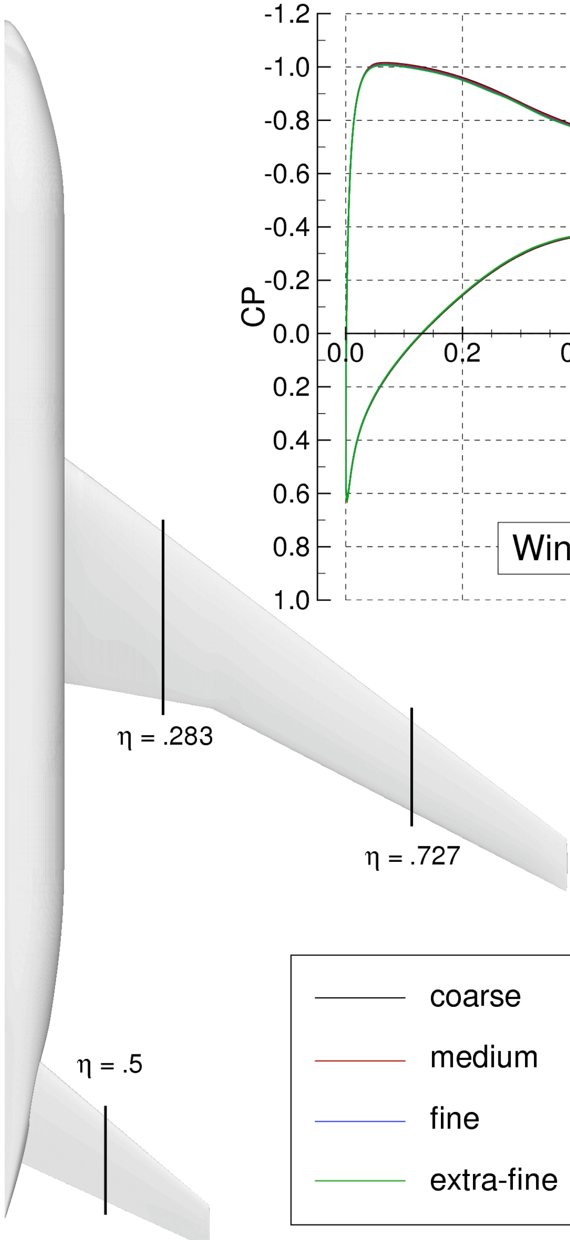


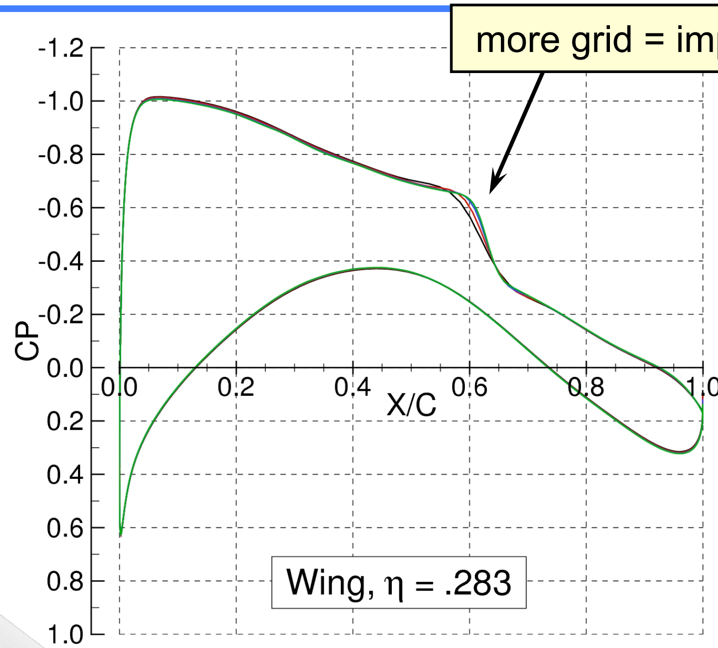


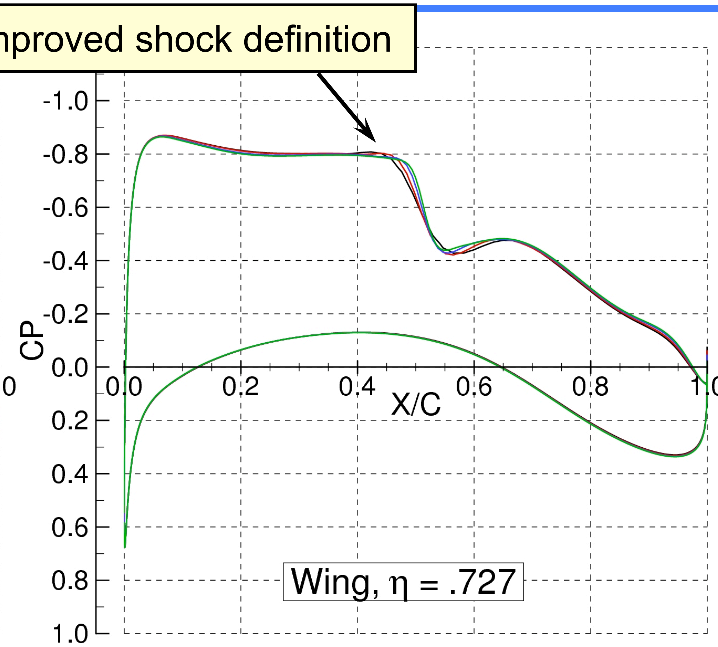
- Tailcone separation is not predicted using full N-S.
  - This TLNS-to-FNS separation trend is opposite of wing SOB separation

Test Case 1.1 – Grid Convergence Study

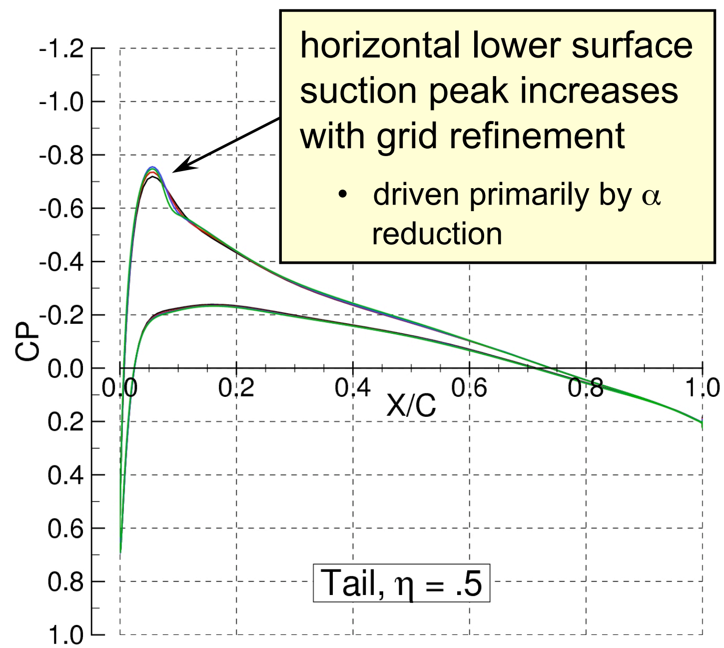
Pressure Comparisons: Grid Effect







coarse
medium
fine
extra-fine



RN = 5 million

Mach = 0.85

C_L = 0.5

i_H = 0°

SA-Central-TL

Test Case 1.1 – Grid Convergence Study

Wing Spanload Comparison: Grid Effect

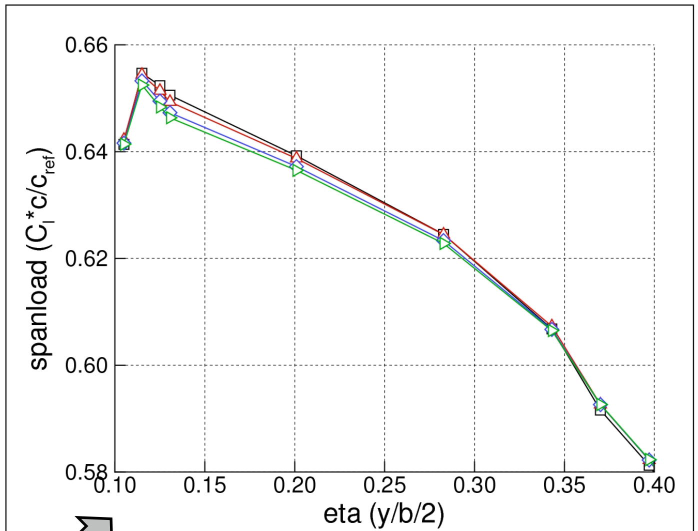
RN = 5 million

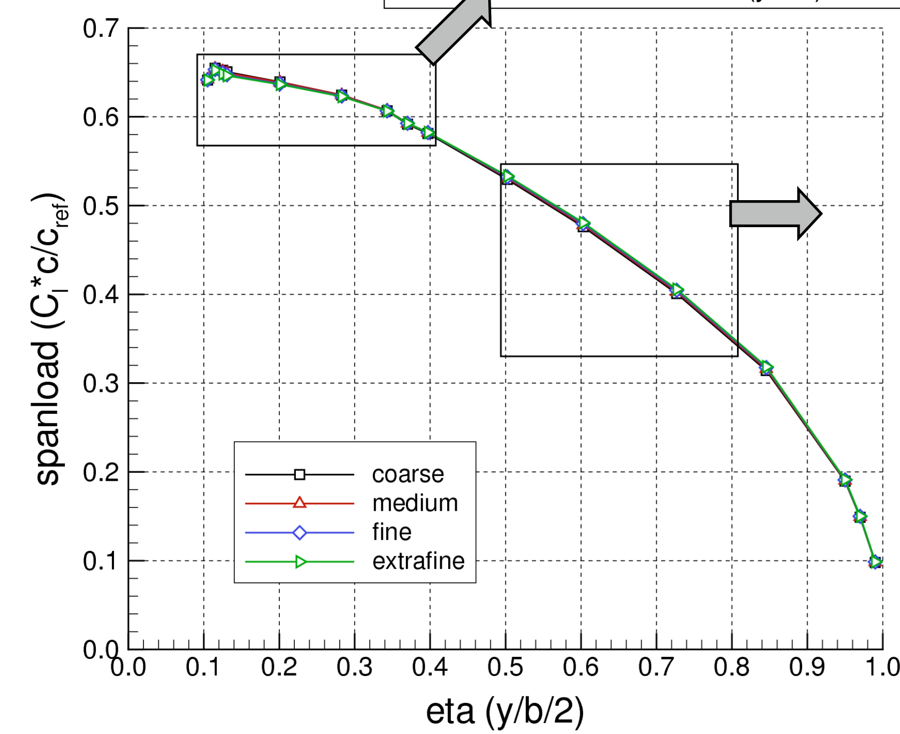
Mach = 0.85

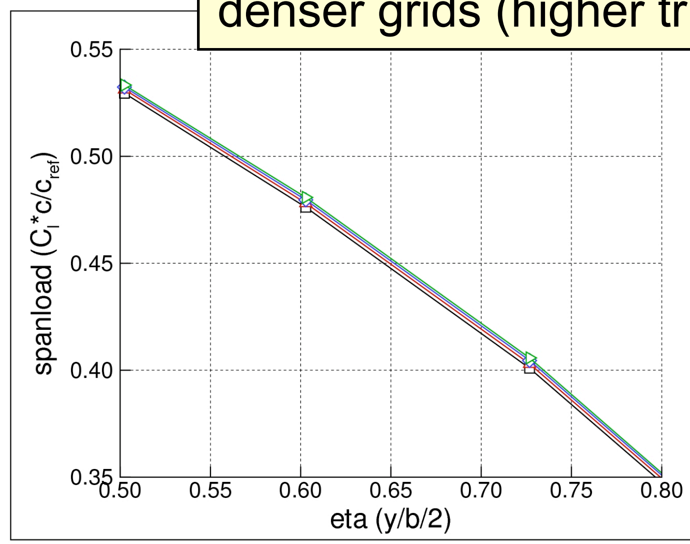
C_L = 0.5

$i_H = 0^o$

SA-Central-TL







Spanload rotates with grid refinement

- decreased loading inboard
- increased loading outboard
- driven by reduction in SOB separation and alpha reduction

Rotation results in more nose-down pitching moment for denser grids (higher trim drag)

Test Case 1.2: CRM Downwash Study

Chris Rumsey (NASA Langley) ran CFL3D on the overset grids.

Chris could not make the workshop, so some of his results will be shown here.

code	algorithm	turbulence model	viscous terms
CFL3D	upwind	SA-Ia	thin layer
OVERFLOW	central*	SA-fv3	thin layer

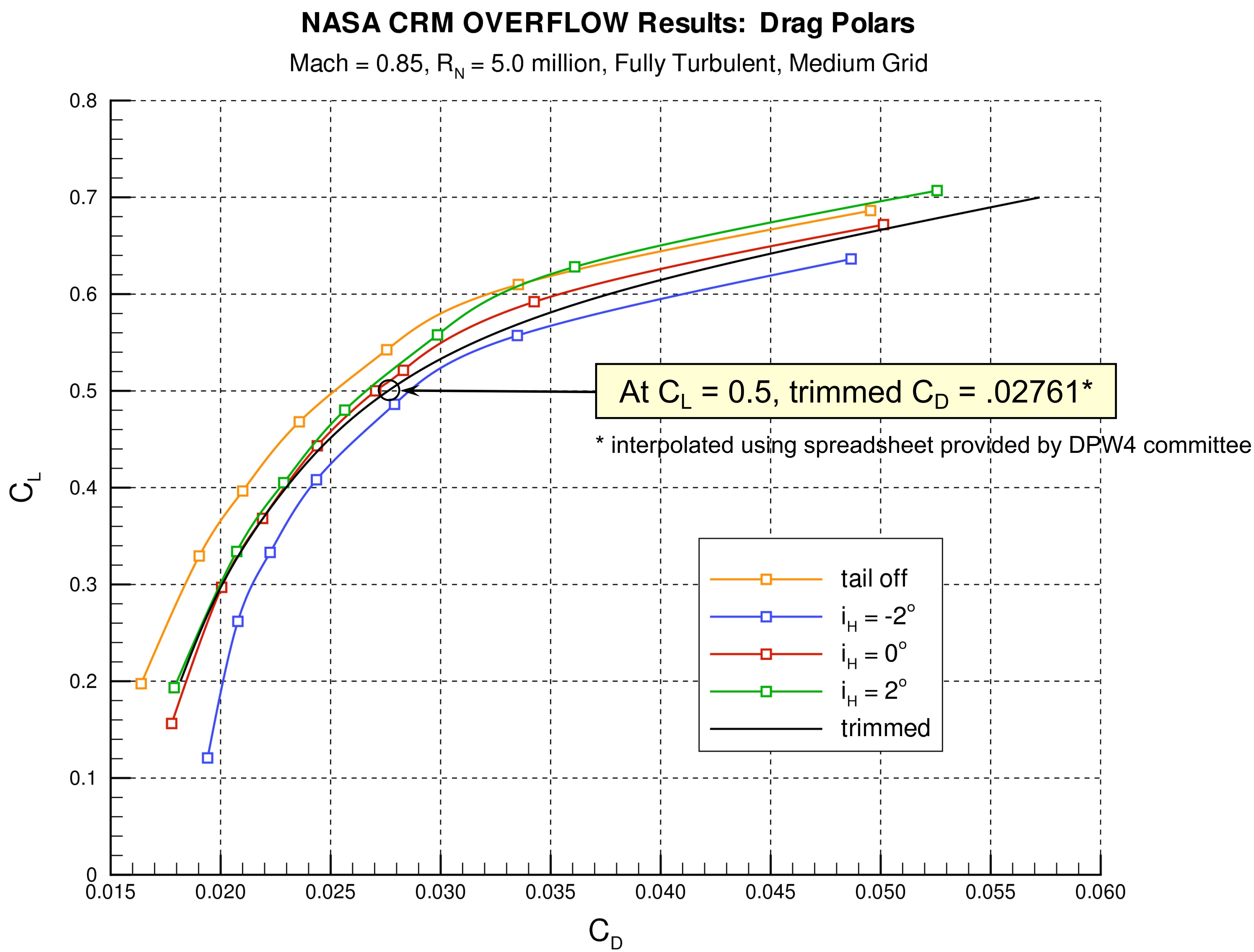
* The -2° tail setting was also analyzed in OVERFLOW using Roe upwind. The results from these additional upwind runs will be shown for comparison purposes only.

There is an issue with the CFL3D overset results shown in the next few slides. A partial explanation will be given here, but for more detailed information go to

http://cfl3d.larc.nasa.gov/Cfl3dv6/cfl3dv6.html

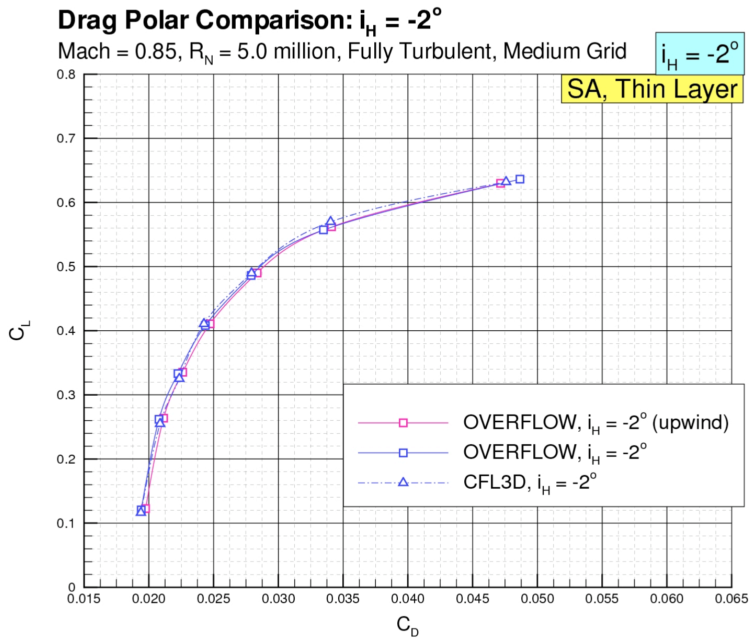
Test Case 1.2 – CRM Downwash Study

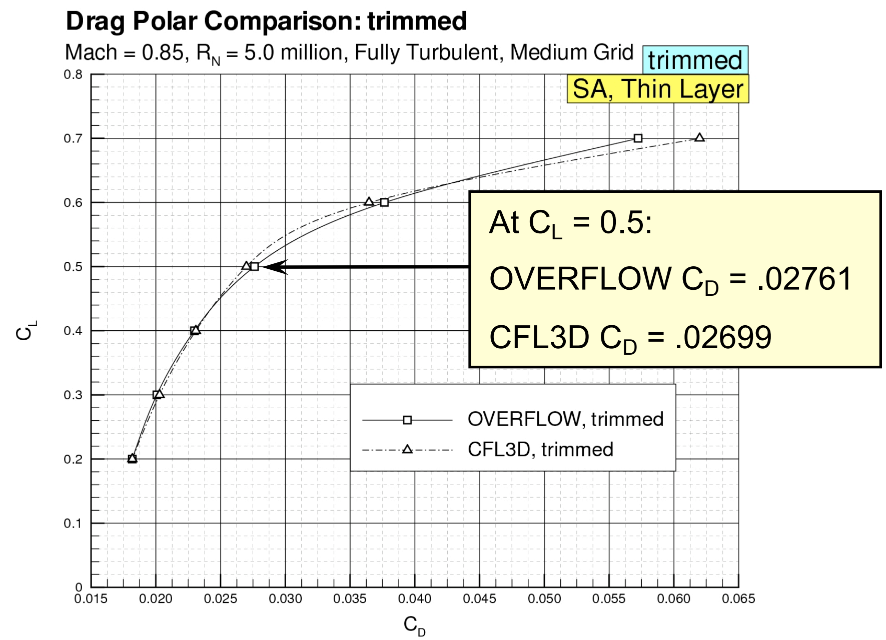
Drag Polars: OVERFLOW

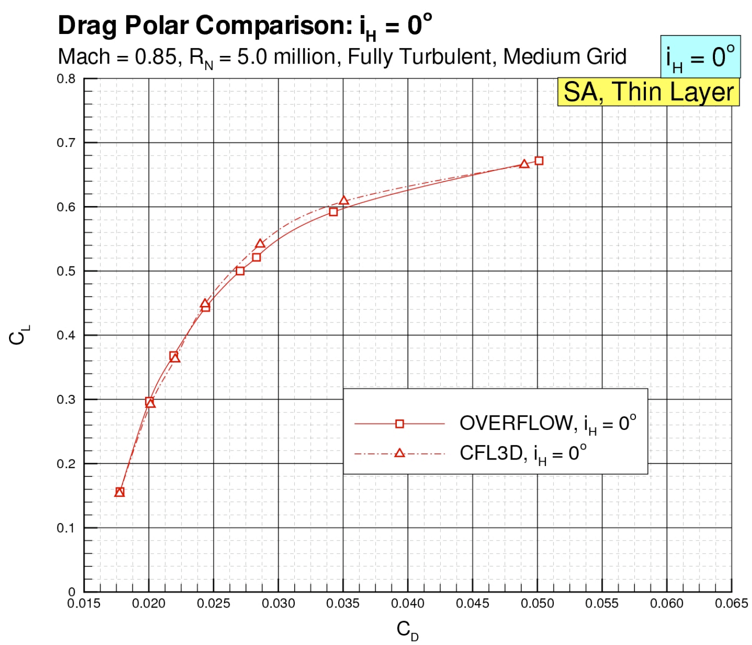


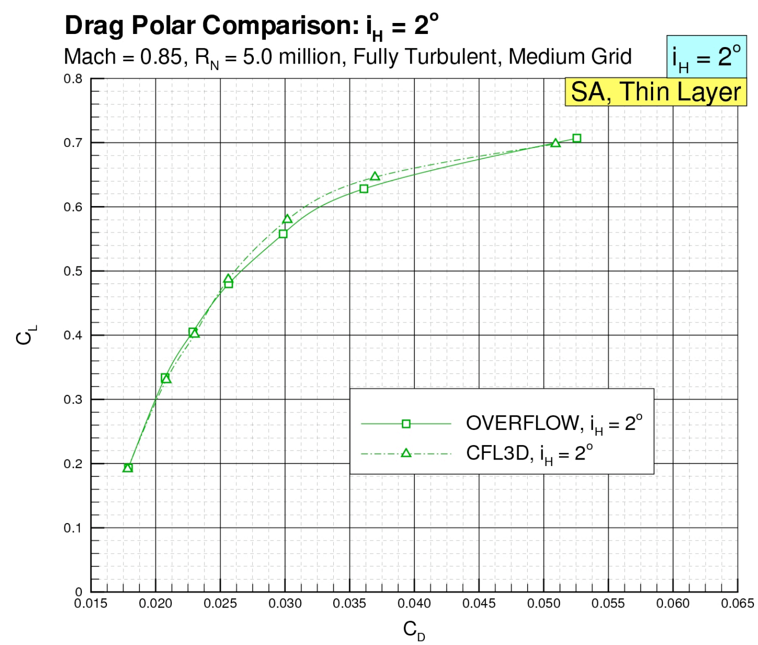
Test Case 1.2 – CRM Downwash Study

Drag Polars: OVERFLOW vs CFL3D





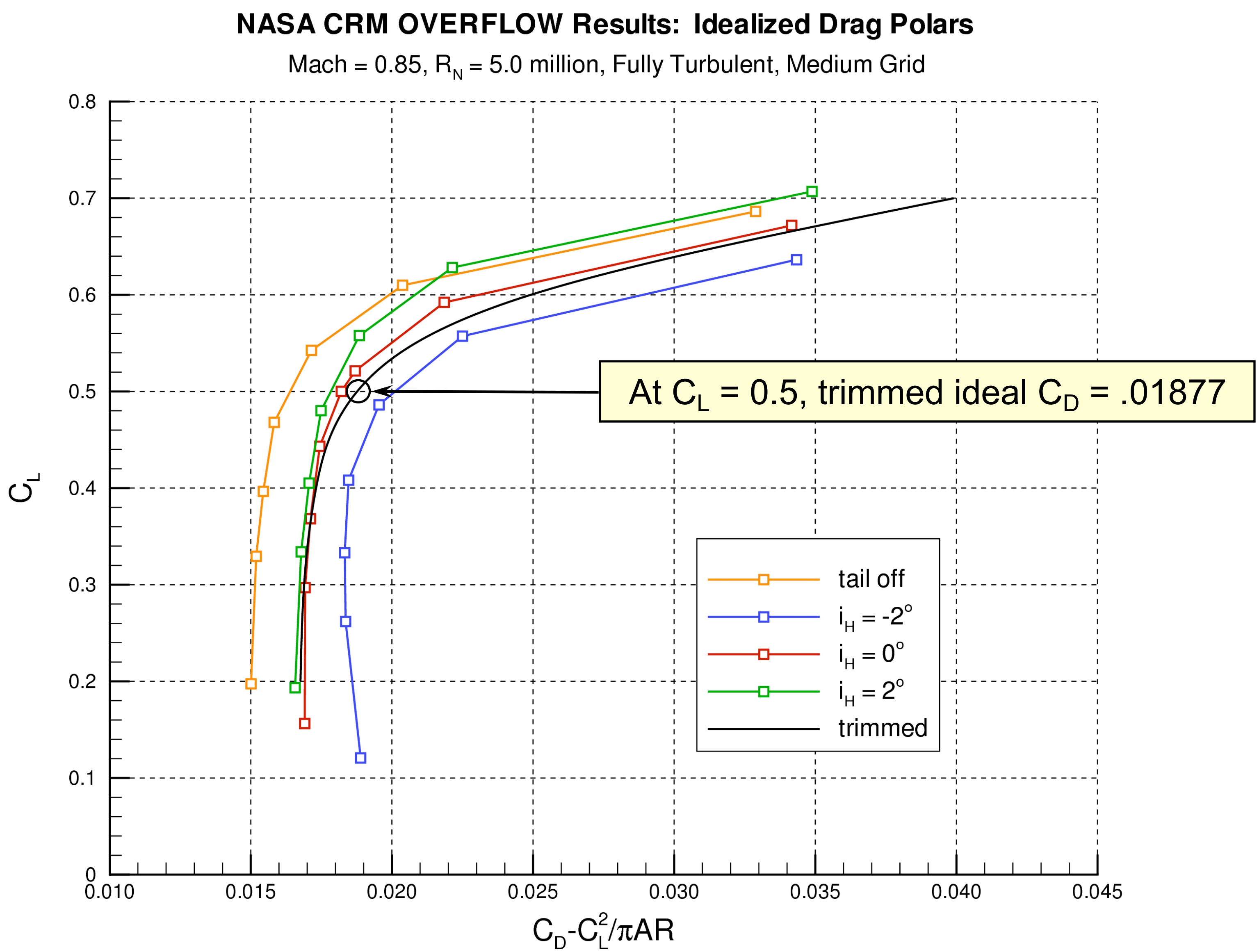




Test Case 1.2 – CRM Downwash Study

Idealized Drag Polars: OVERFLOW

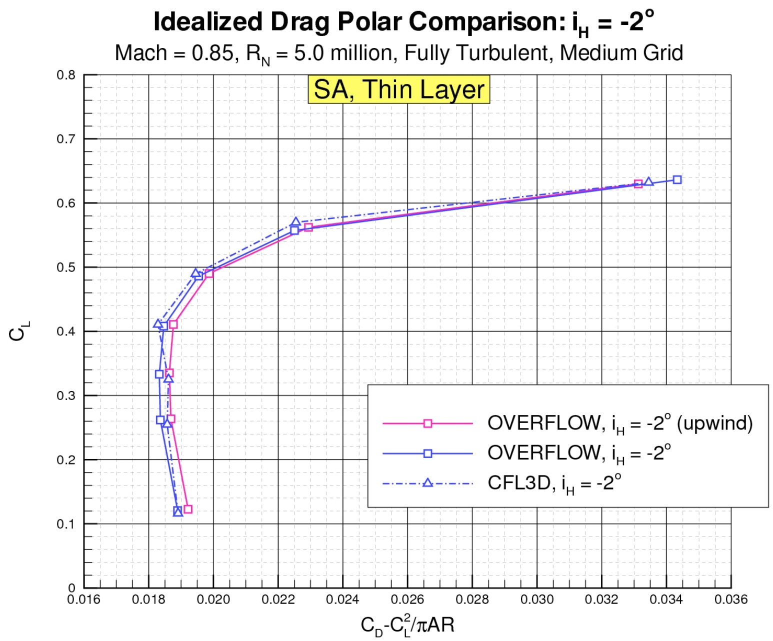
CFD Drag Prediction Workshop

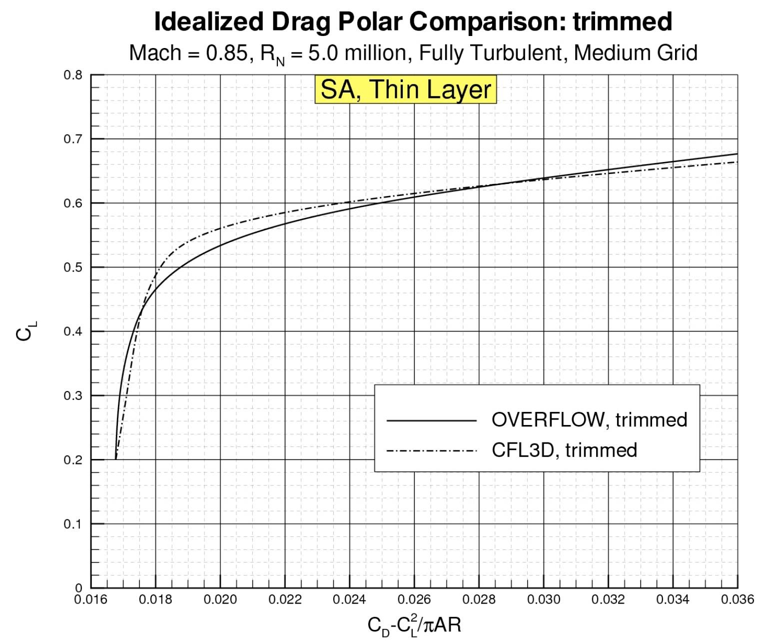


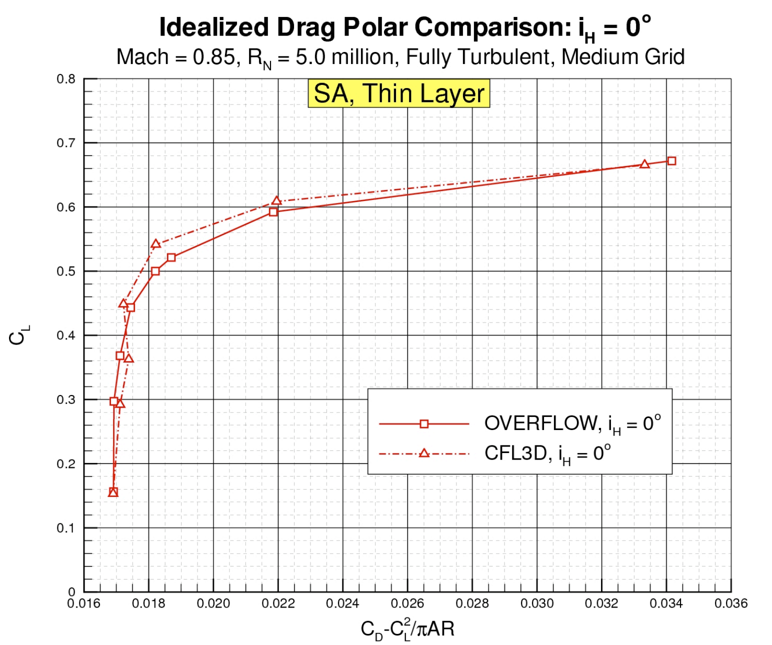
Test Case 1.2 – CRM Downwash Study

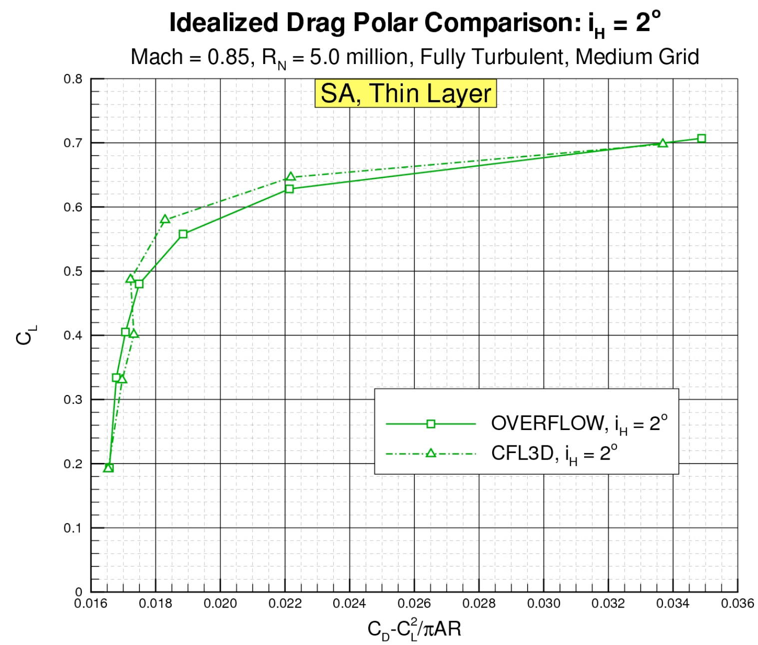
Idealized Drag Polars: OVERFLOW vs CFL3D

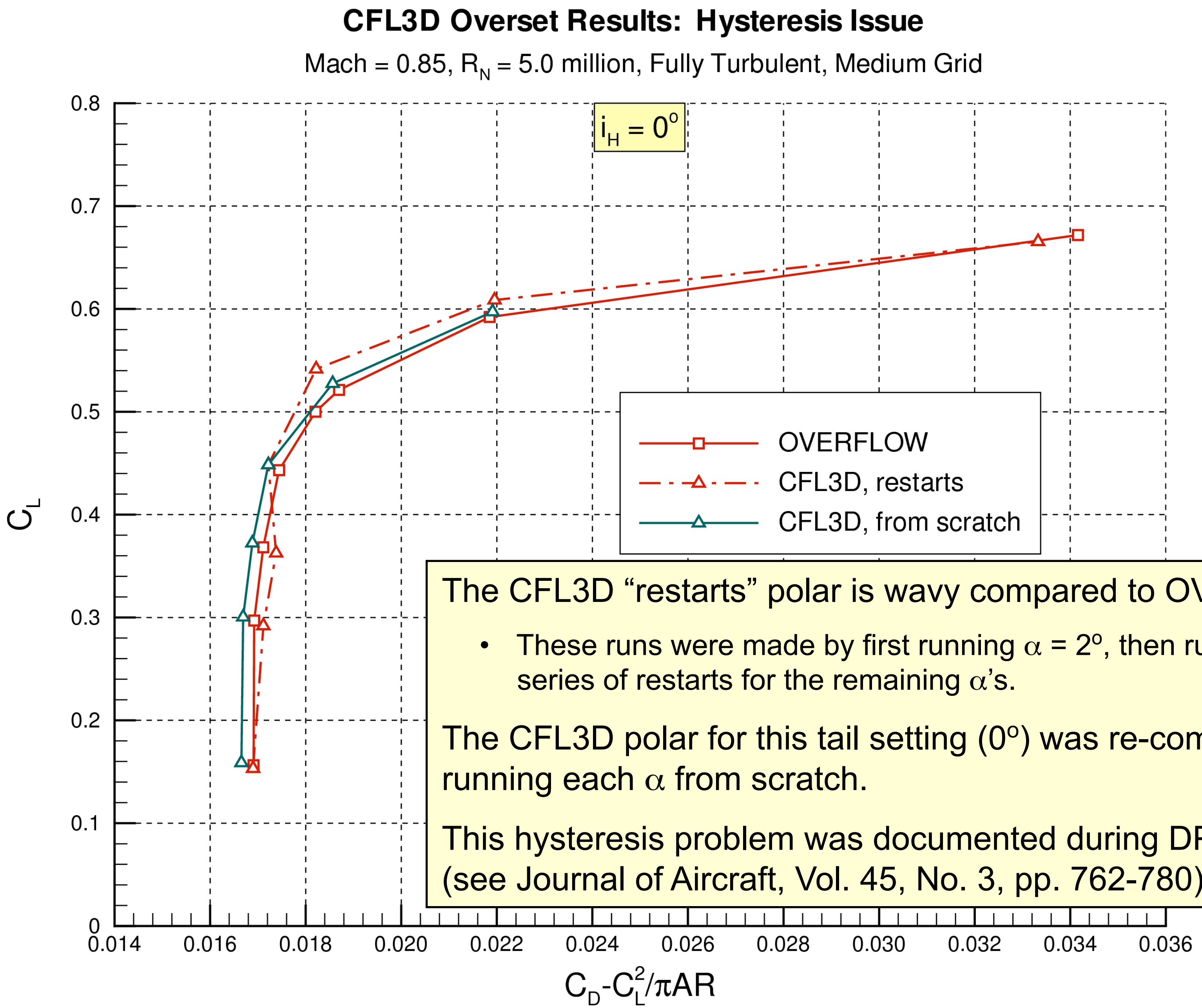
CFD Drag Prediction Workshop









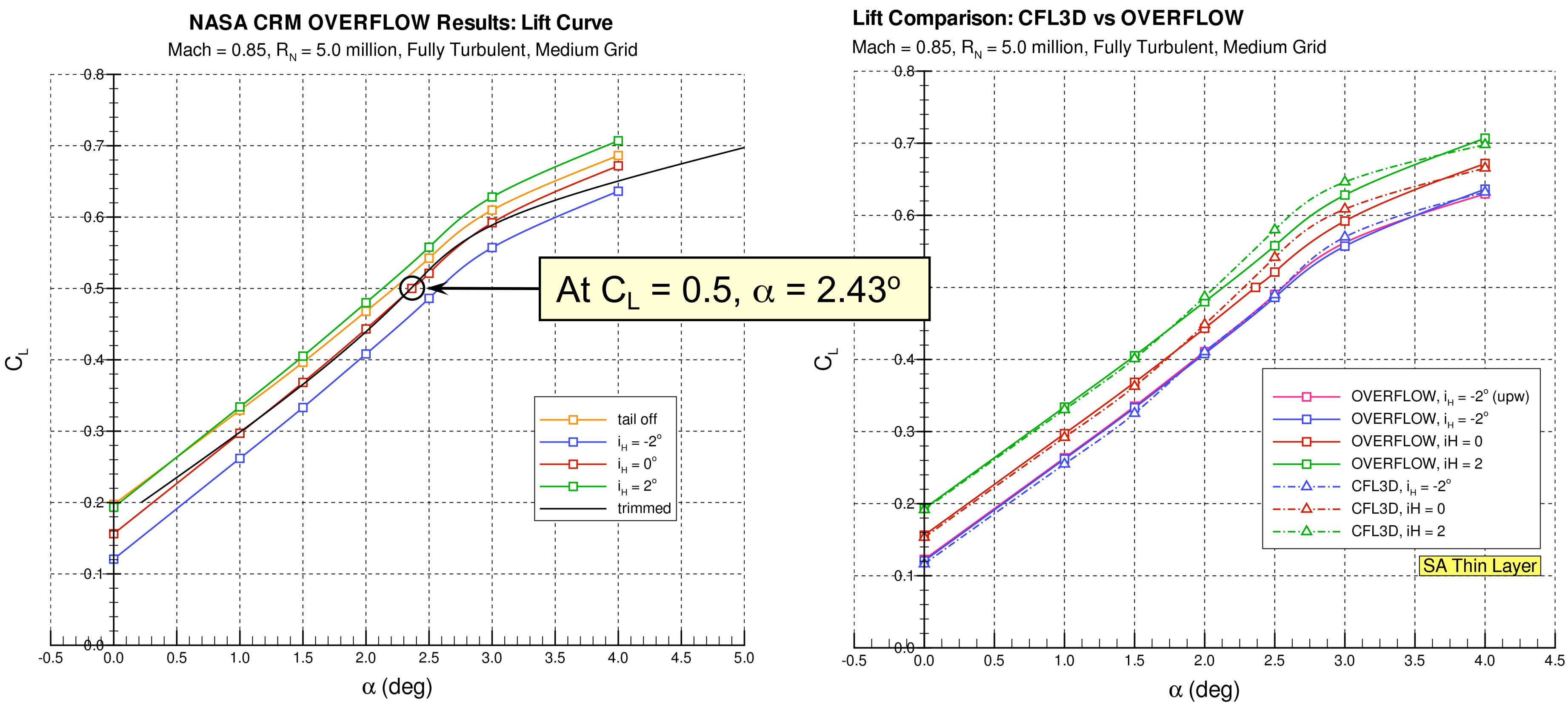


The CFL3D "restarts" polar is wavy compared to OVERFLOW

- These runs were made by first running $\alpha = 2^o$, then running a series of restarts for the remaining α's.

The CFL3D polar for this tail setting (0^o) was re-computed by running each α from scratch.

This hysteresis problem was documented during DPW-III (see Journal of Aircraft, Vol. 45, No. 3, pp. 762-780).

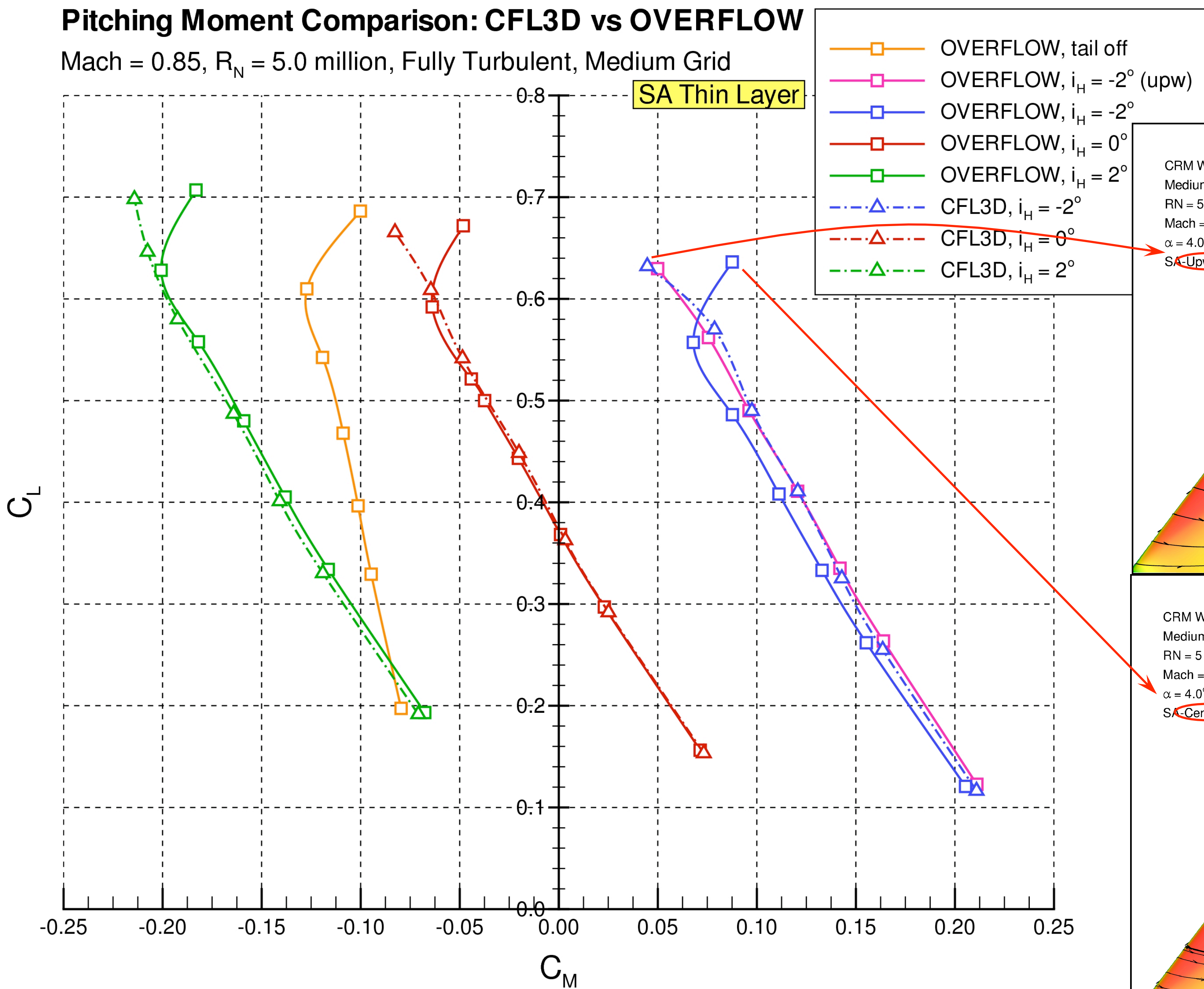


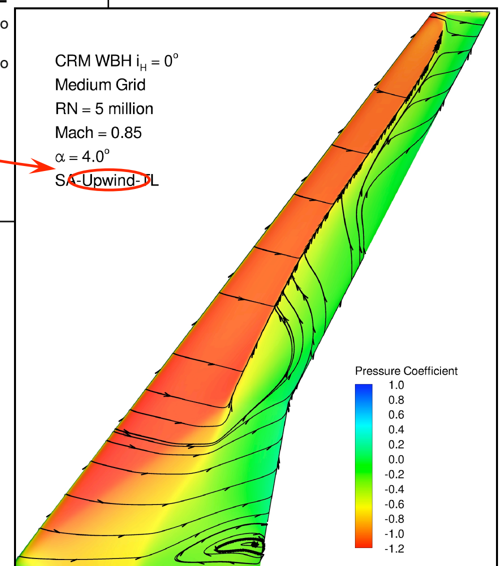
NASA CRM OVERFLOW Results: Lift Curve
Mach = 0.85, R_N = 5.0 million, Fully Turbulent, Medium Grid
C_L
α (deg)
tail off
i_H = -2°
i_H = 0°
i_H = 2°
trimmed
At C_L = 0.5, α = 2.43°
Lift Comparison: CFL3D vs OVERFLOW
Mach = 0.85, R_N = 5.0 million, Fully Turbulent, Medium Grid
C_L
α (deg)
OVERFLOW, i_H = -2° (upw)
OVERFLOW, i_H = -2°
OVERFLOW, iH = 0
OVERFLOW, iH = 2
CFL3D, i_H = -2°
CFL3D, iH = 0
CFL3D, iH = 2
SA Thin Layer

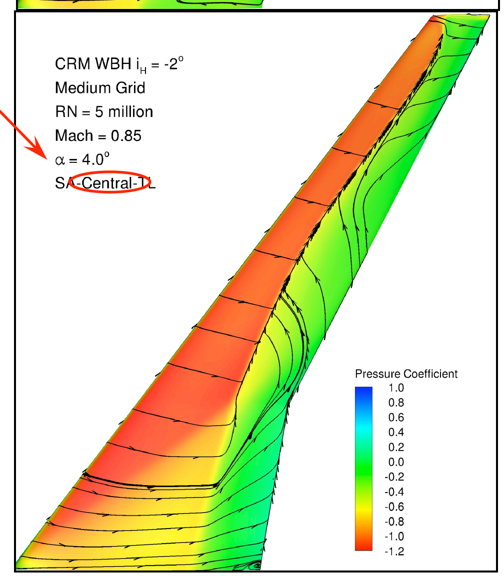
Test Case 1.2 – CRM Downwash Study

Lift vs Pitching Moment: OVERFLOW vs CFL3D

CFD Drag Prediction Workshop







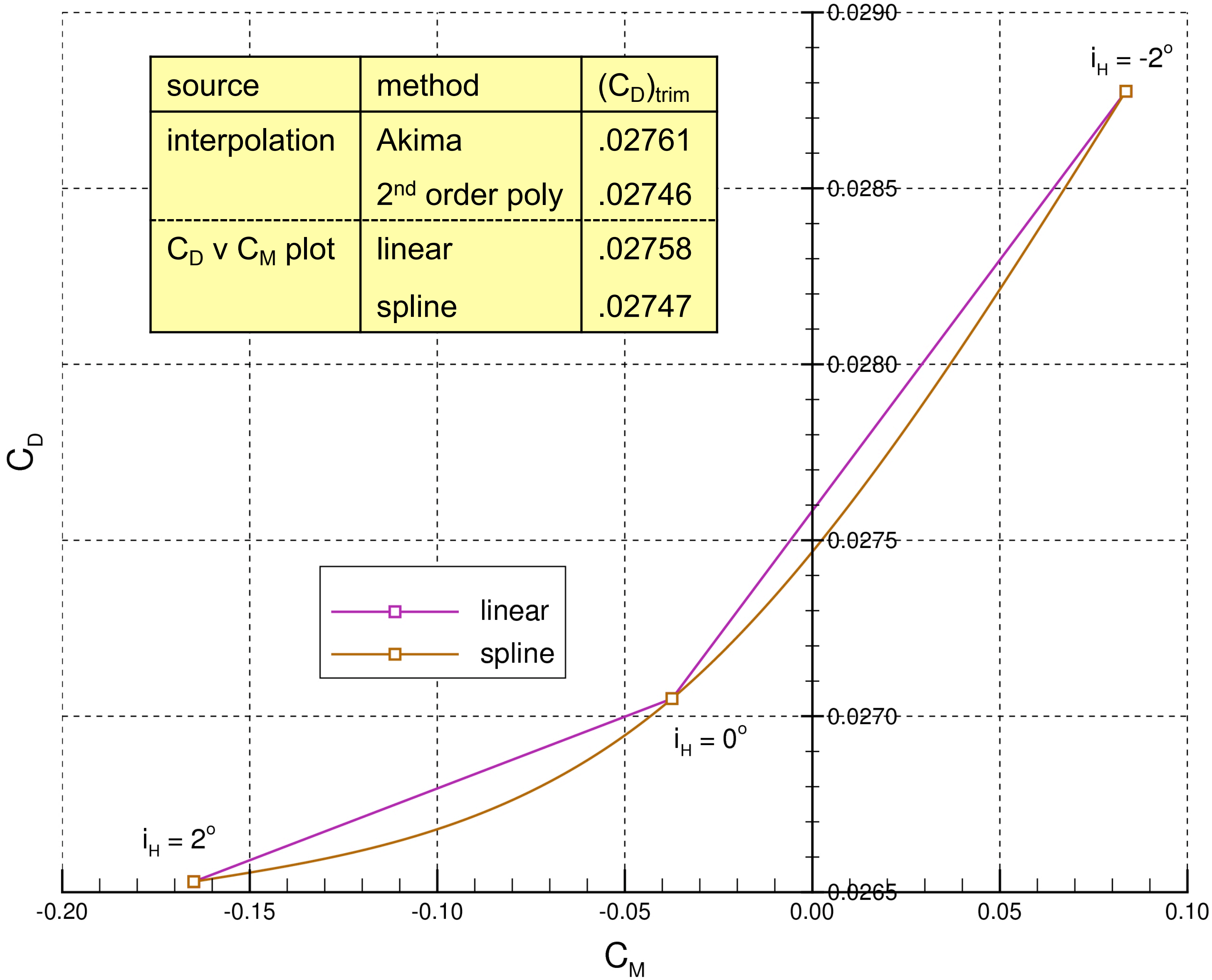
Test Case 1.2 – CRM Downwash Study

Drag vs Pitching Moment at $C_L = 0.5$

CFD Drag Prediction Workshop

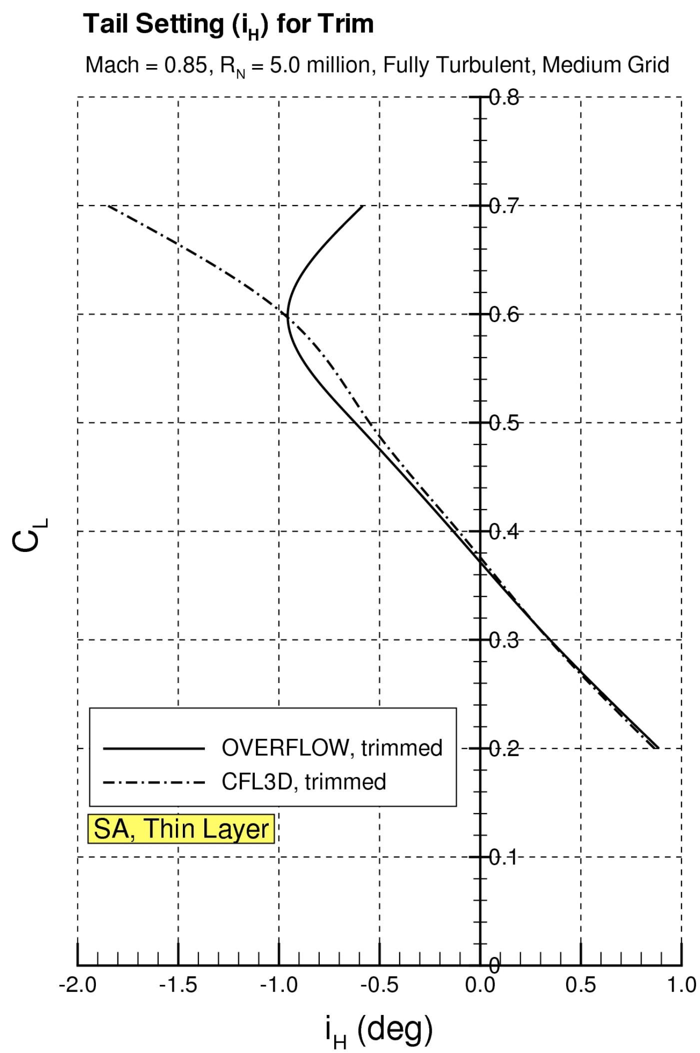
NASA CRM OVERFLOW Results: Drag vs Pitching Moment at $C_L = 0.5$

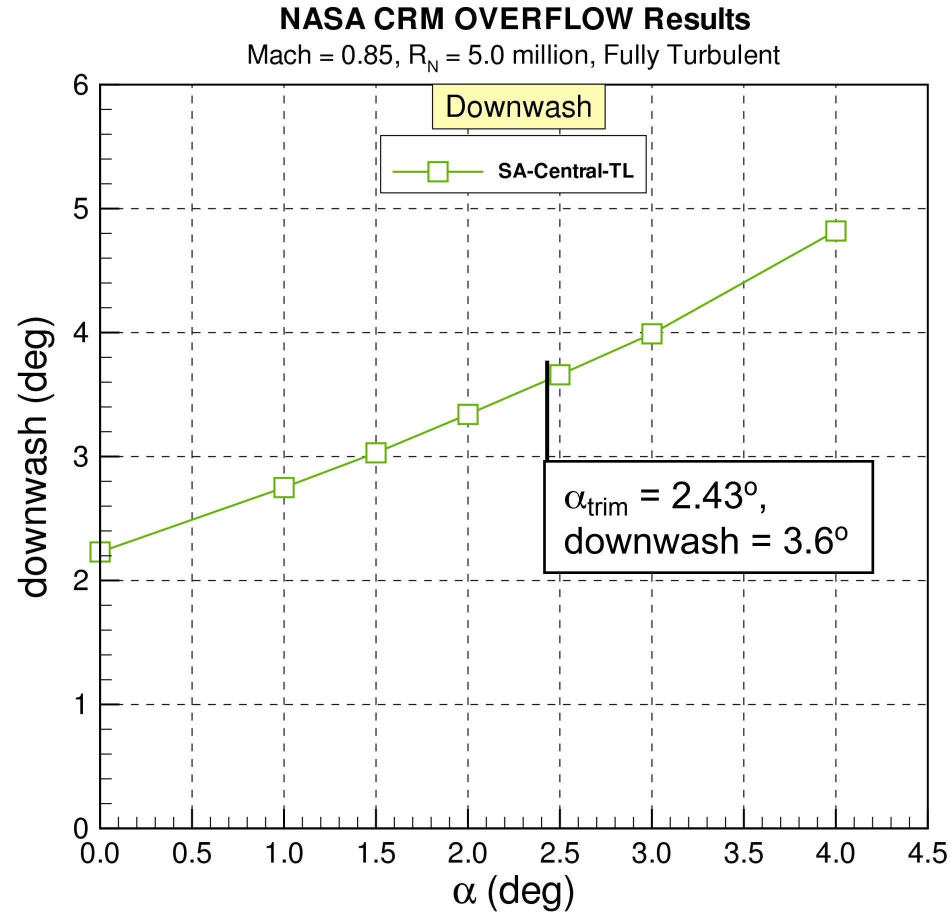
Mach = 0.85, R_N = 5.0 million, Fully Turbulent, Medium Grid



source	method	$(C_D)_{trim}$
interpolation	Akima	.02761
	2nd order poly	.02746
C_D v C_M plot	linear	.02758
	spline	.02747

Test Case 1.2 – CRM Downwash Study
Tail Setting and Downwash

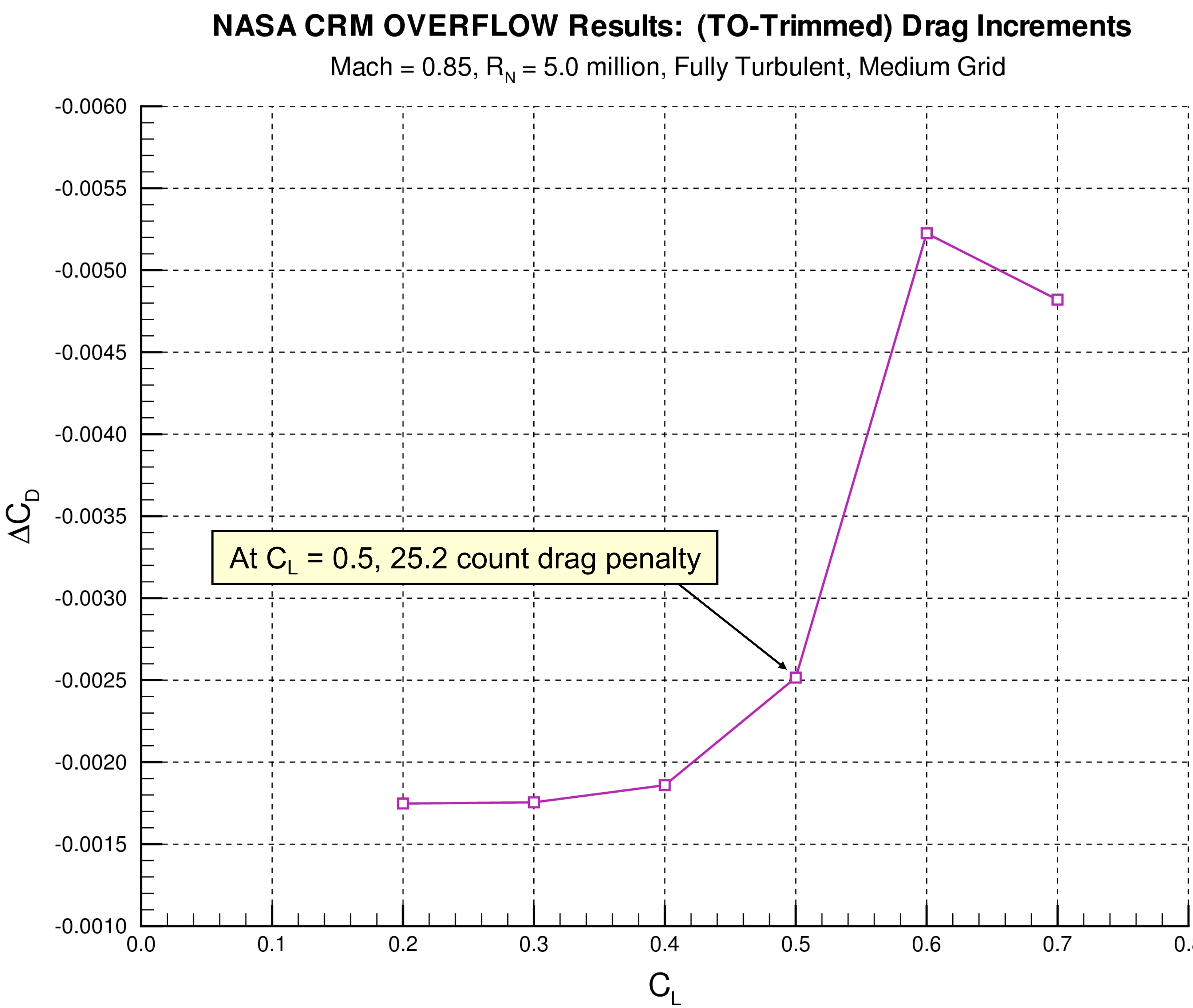




- At .50C_L, OVERFLOW trims at i_H = -0.62° and CFL3D trims at i_H = -0.55°

Test Case 1.2 – CRM Downwash Study
(TO – trimmed) Drag Increments

CFD Drag Prediction Workshop



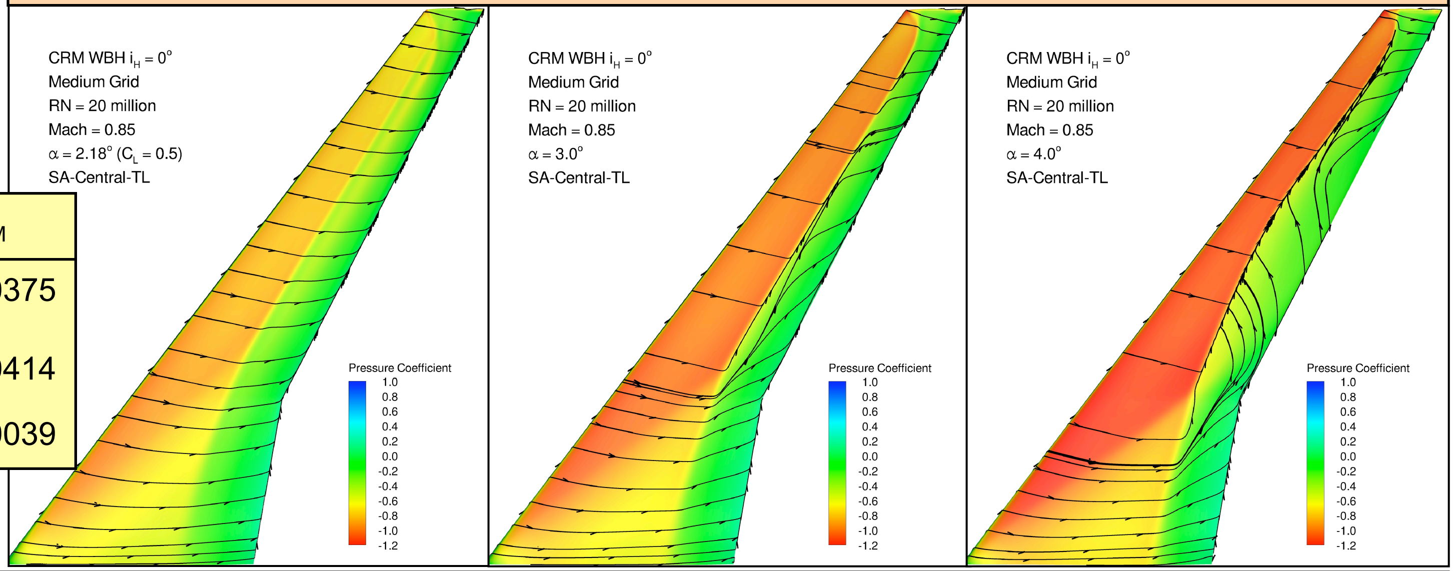
Test Case 3: Reynolds Number Study

Test Case 3 – Reynolds Number Study

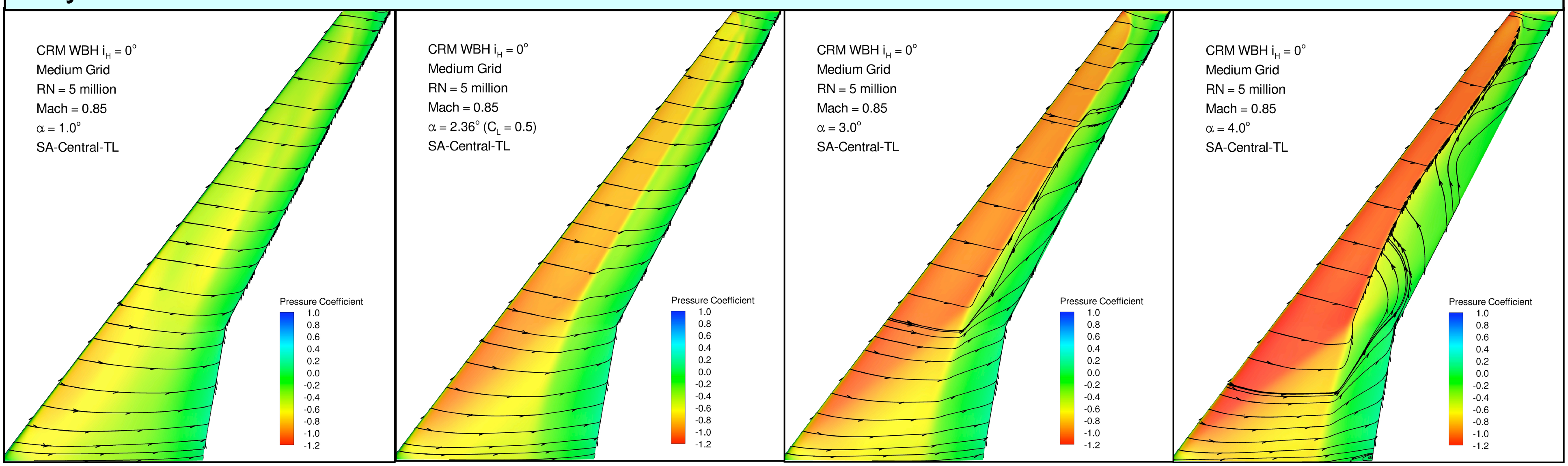
Increments and Wing Streamlines

Mach = 0.85, CL = 0.5			
RN	α	C_D	C_M
5 mil	2.364°	.02706	-.0375
20 mil	2.183°	.02404	-.0414
delta	-.181°	-.00302	-.0039

Reynolds Number = 20 million

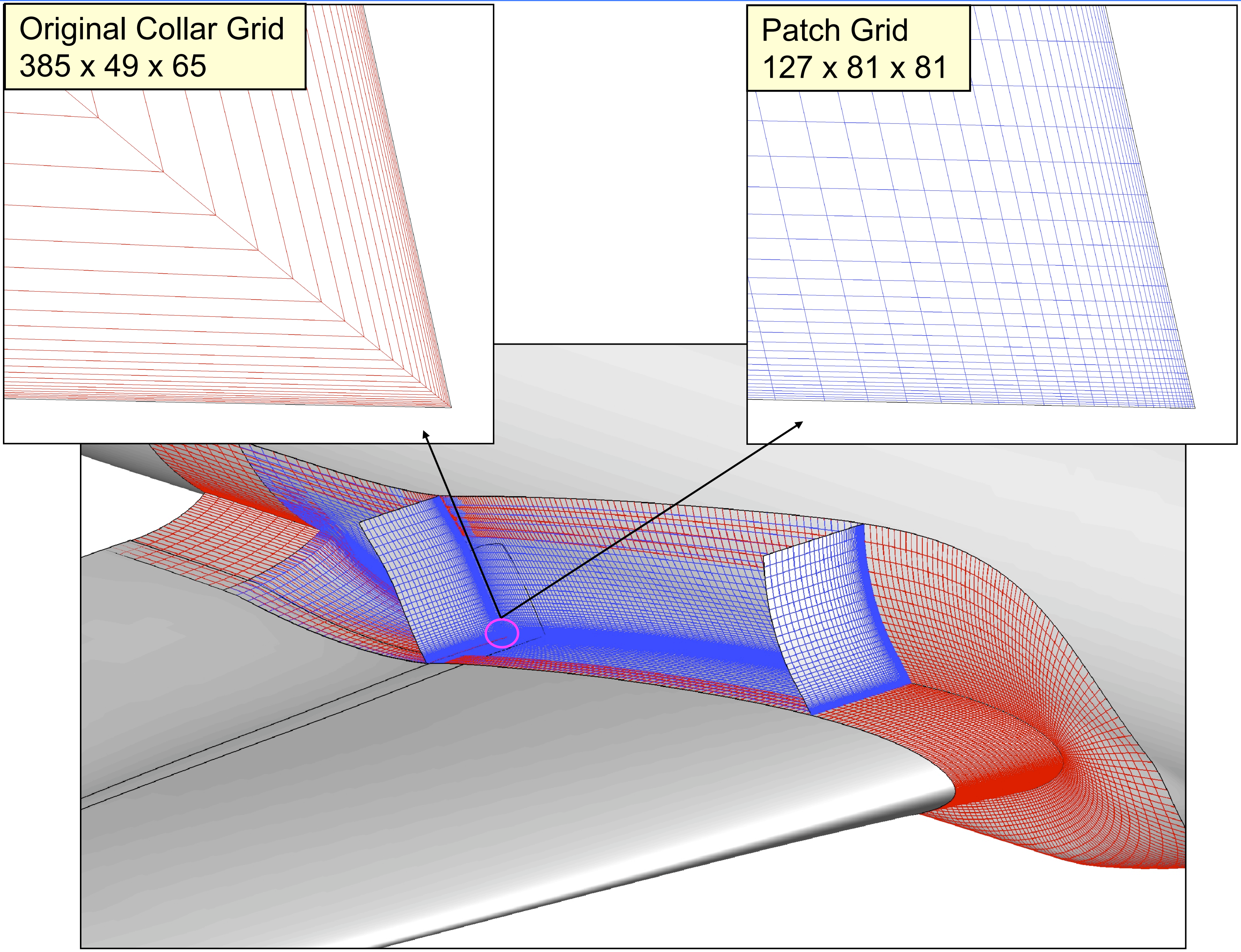


Reynolds Number = 5 million



Additional Study: Wing Side-of-Body Patch Grid

Wing Side-of-Body Patch Grid Study
Grid Comparison



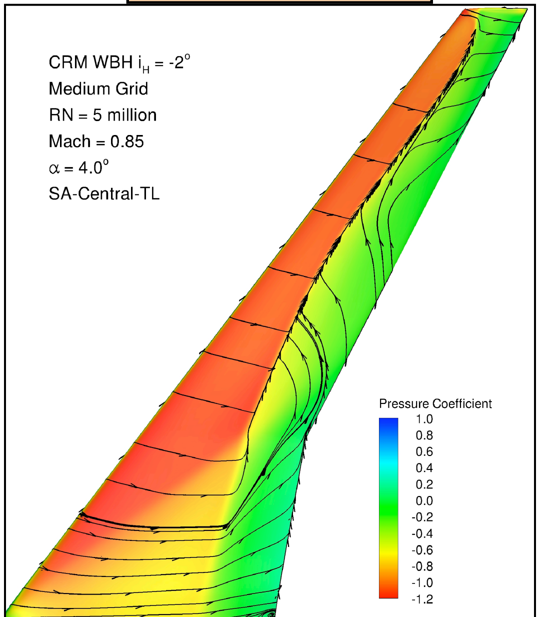
Wing Side-of-Body Patch Grid Study
Wing Streamlines – SA Central Only

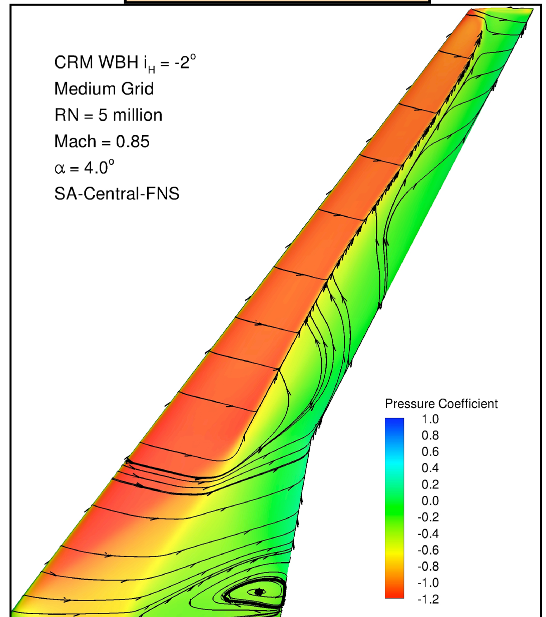
CFD Drag Prediction Workshop

Thin Layer

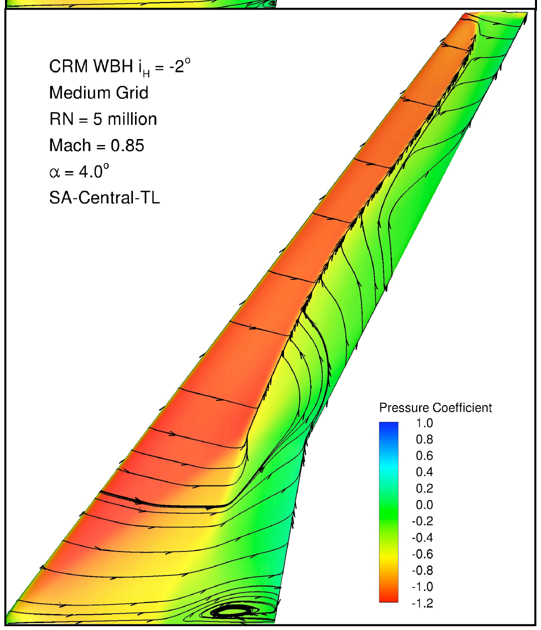
Full N-S

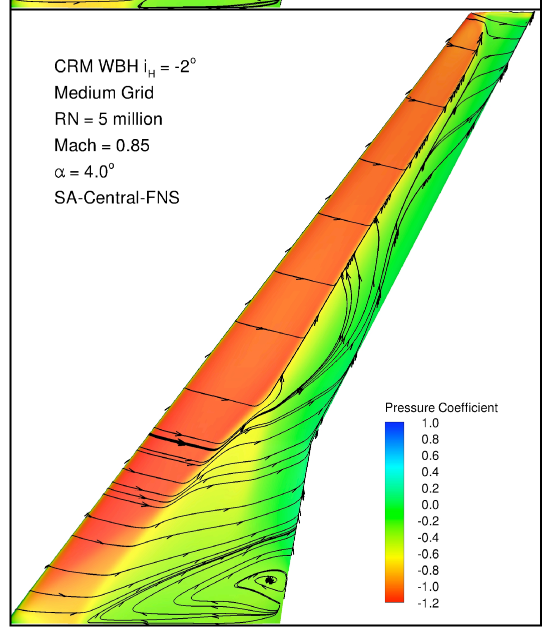
Original Grid





Patch Grid





Conclusions

Grid Convergence Study

- Coarse grid is too coarse for a grid convergence study if the goal is estimating the asymptotic trend line.
  - This has been true for both DPW-III and DPW-IV where extra-fine grid data was available
- Extra-Fine grid helps determine asymptotic grid convergence.
- Thin layer N-S wing side-of-body separation is nearly eliminated with grid refinement.
- As seen in DPW-III, full N-S produces a significantly larger side-of-body separation bubble than thin layer.

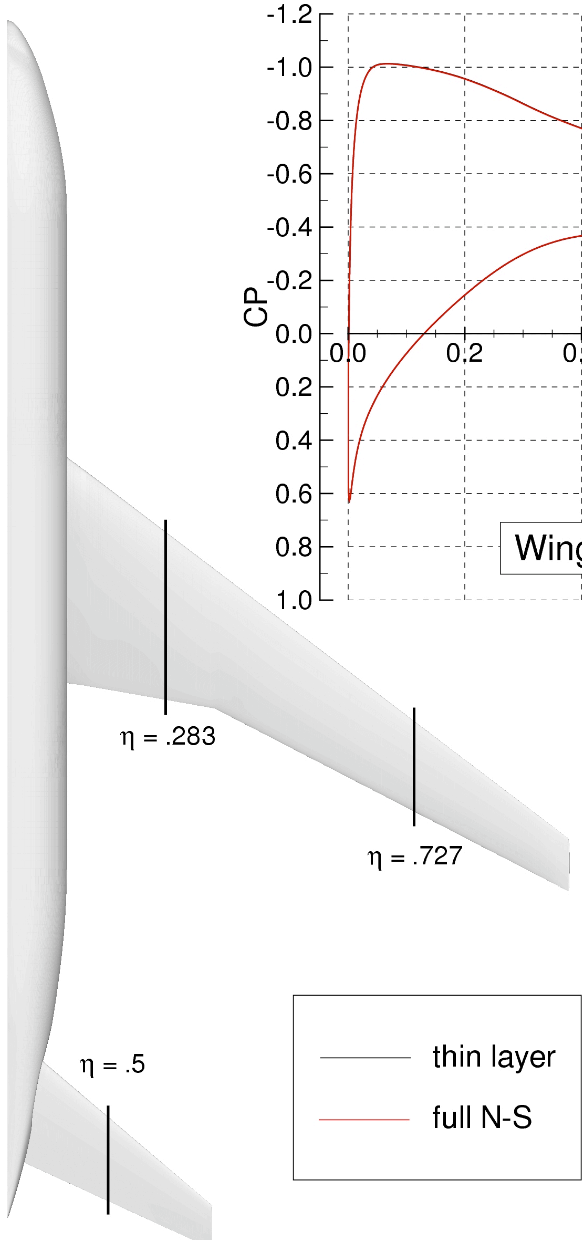
Downwash Study

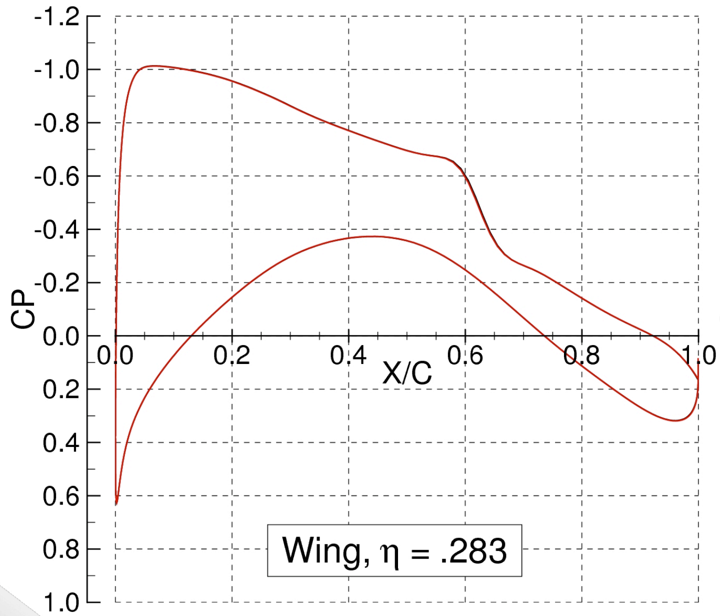
- Reasonable agreement between CFL3D and OVERFLOW.
- We are at code limitations for $\alpha = 4^o$
  - Wing side-of-body separation appears to be the stumbling block

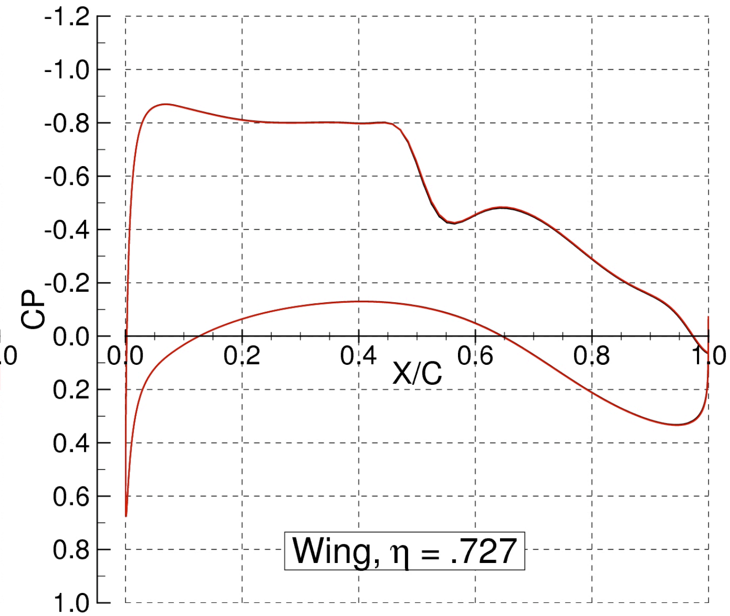
Questions?

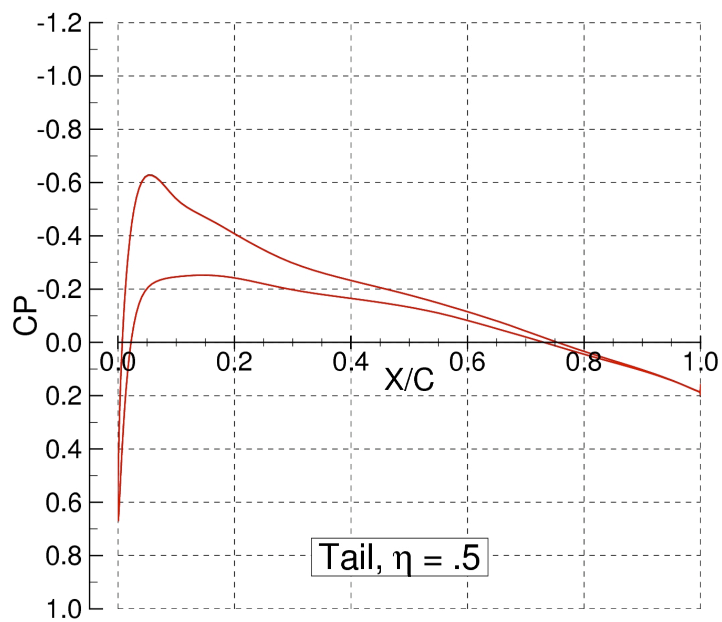
Test Case 1.1 – Grid Convergence Study

Pressure Comparisons: Thin Layer vs Full N-S









RN = 5 million

Mach = 0.85

C_L = 0.5

$i_H = 0^o$

SA-Central

Medium Grid

Test Case 1.1 – Grid Convergence Study

Wing Spanload Comparison: Thin Layer vs Full N-S

AIAA CFD Drag Prediction Workshop

RN = 5 million

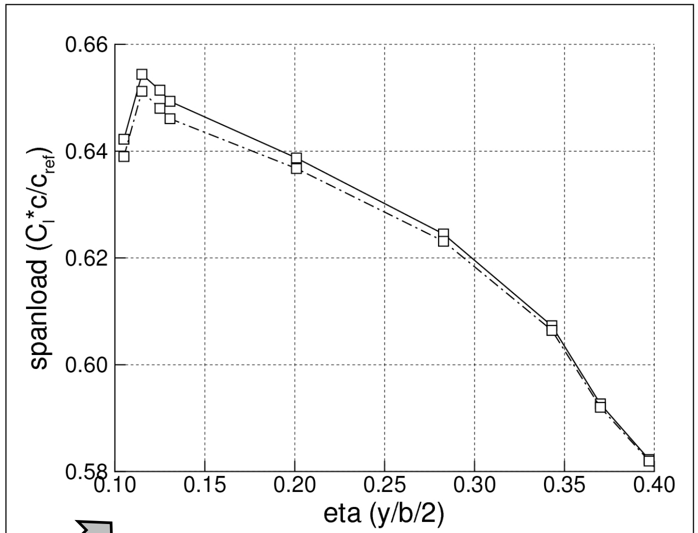
Mach = 0.85

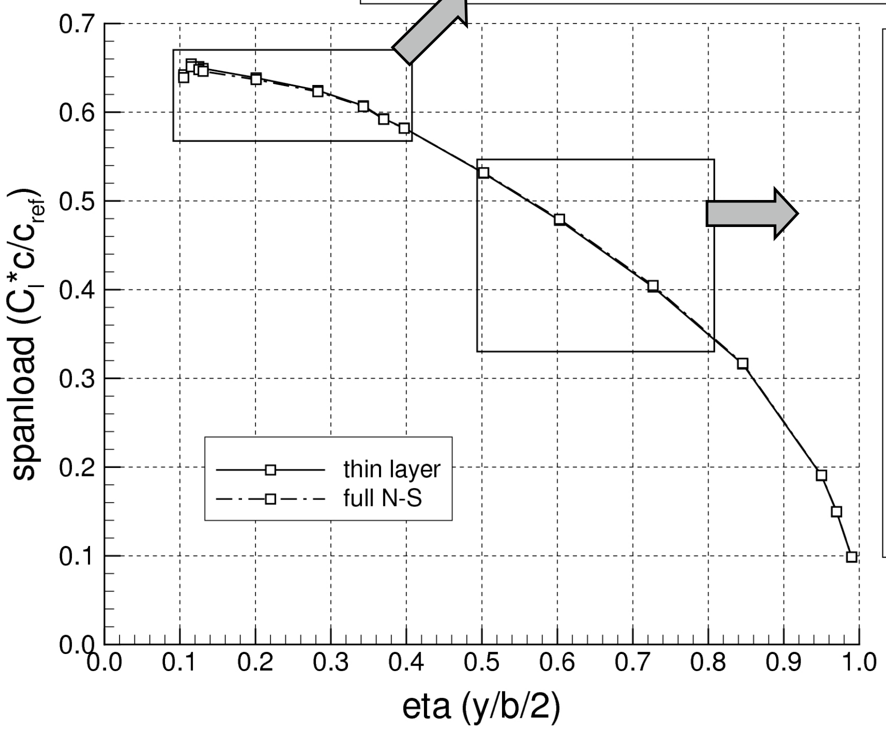
$C_L = 0.5$

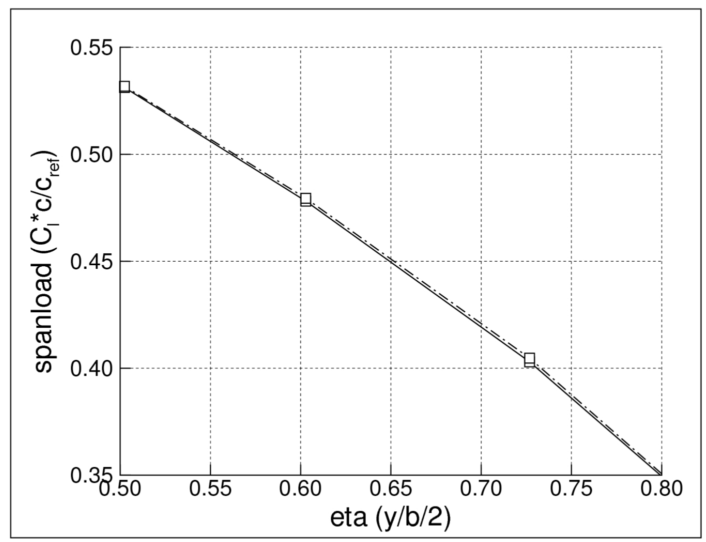
$i_H = 0^o$

SA-Central

Medium Grid







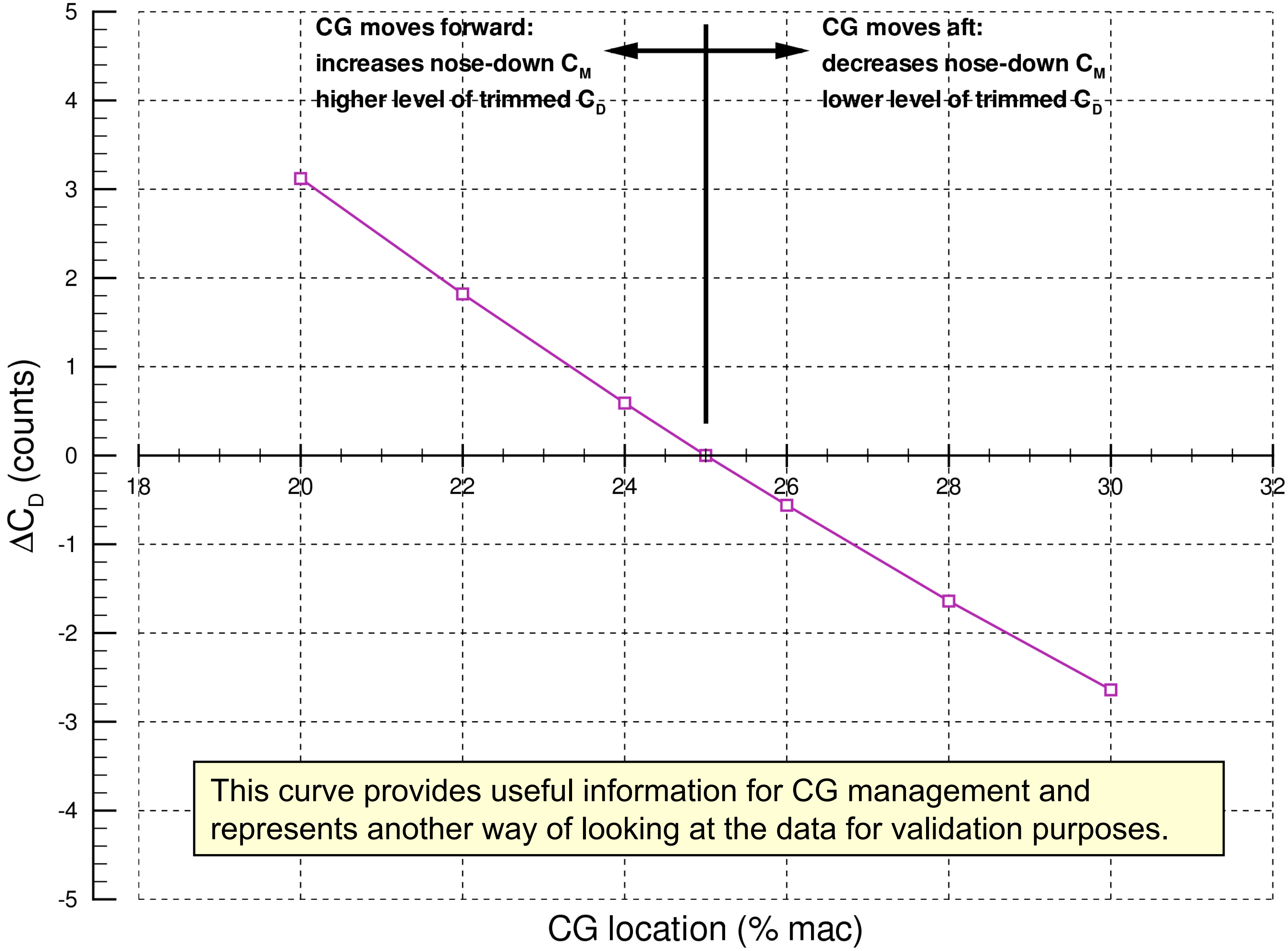
Spanload rotates with full N-S

- decreased loading inboard
- increased loading outboard
- caused by increase in SOB separation

Rotation results in more nose-down pitching moment for full N-S solution (higher trim drag)

NASA CRM OVERFLOW Results: Change in Drag with CG at C_L = 0.5

Mach = 0.85, R_N = 5.0 million, Fully Turbulent, Medium Grid



This curve provides useful information for CG management and represents another way of looking at the data for validation purposes.