



6th AIAA CFD Drag Prediction Workshop

June 16-17, 2016 in Washington, D.C. USA

Validation Study of in-house CFD tool “*Cflow*”

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16KT008948



Kawasaki
Powering your potential

Outline

■ Objectives

- to validate in-house CFD tool "*Cflow*" from viewpoints of industry application; how to set up grid, efficiency, accuracy etc.

■ Case1; Cflow Solver verification

- common grid (unstructured quad)
- SA turbulence model

■ Case2-3; Grid/Solver validation

Case 2A, 2B, 3		Turbulence model	
		<i>SA-noft2</i>	SA-noft2-QCR2000
Grid	Baseline Grid (Boeing.Babcock.Unstructured)	X	X
	<i>Original grid (Cflow.NOBLU.grid)</i>	X	X

Backgrounds and Motivation

Kawasaki originally developed

$$\text{Cflow} = \boxed{\text{Grid Generator}} + \boxed{\text{Flow Solver}}$$

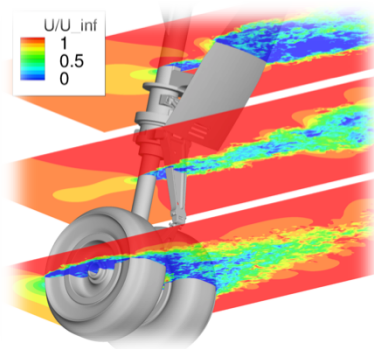
Cartesian Octree AMR
+ layered grid

highly complicated

unsteady

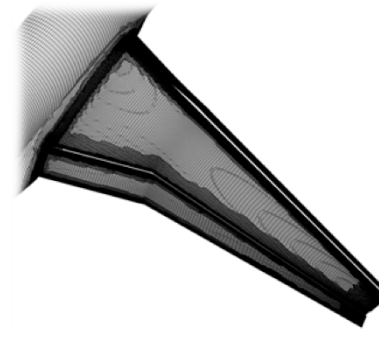
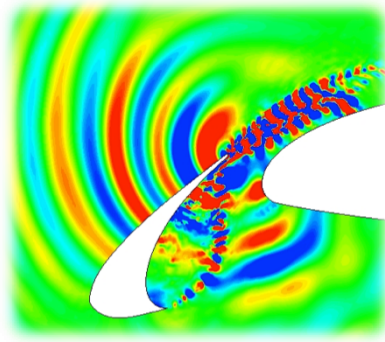
large-scale

- Participating AIAA workshop becomes a driving force for development and validation of CFD tools.



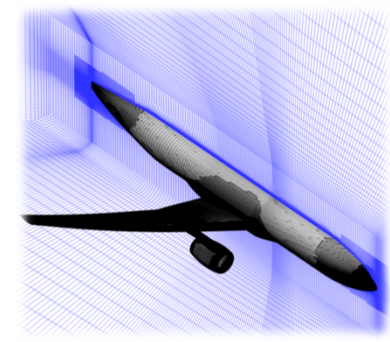
2010-2016
BANC I-IV

Aeroacoustic analysis



2013
HiLift-PW2

Aerodynamic analysis



2016
DPW6 (present)

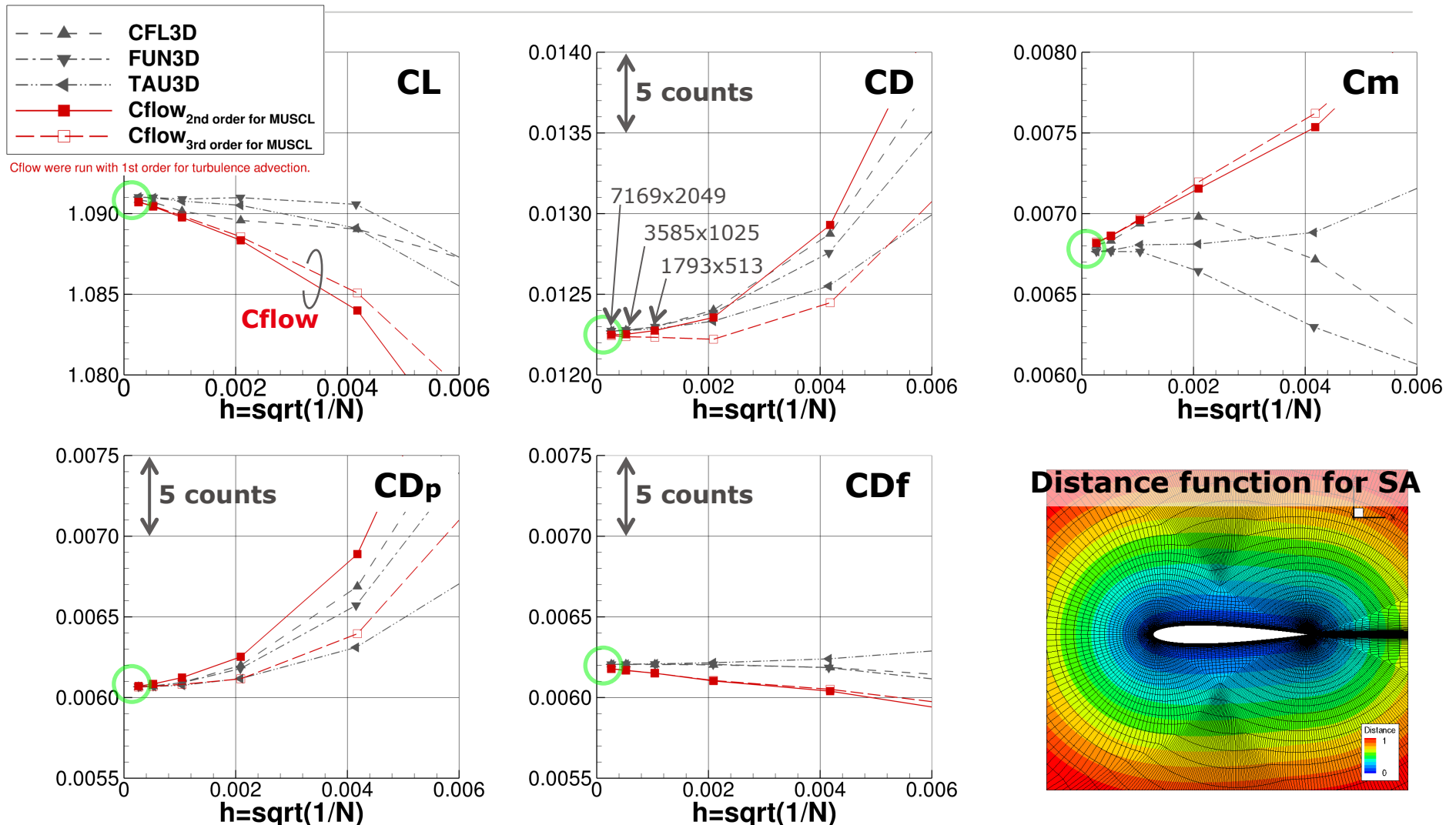
Numerical schemes of flow solver “Cflow”

Cflow = Grid Generator + **Flow Solver**

- Grid System
 - Unstructured hybrid grid (polyhedral cells)
- Governing equation
 - Compressible Navier-Stokes equations (**RANS**)
- Time integration
 - 2nd-order Matrix Free Gauss-Seidel (**MFGS**) implicit method
- Spatial discretization
 - **Cell-centered** finite volume method
 - Simple Low-dissipation AUSM scheme (**SLAU**)
 - 2nd-order accurate unstructured-MUSCL based reconstruction
- Turbulence modeling
 - Spalart-Allmaras (**SA-noft2**, SA-noft2-QCR2000)
- Parallel computation
 - MPI

Case1 : Verification Study

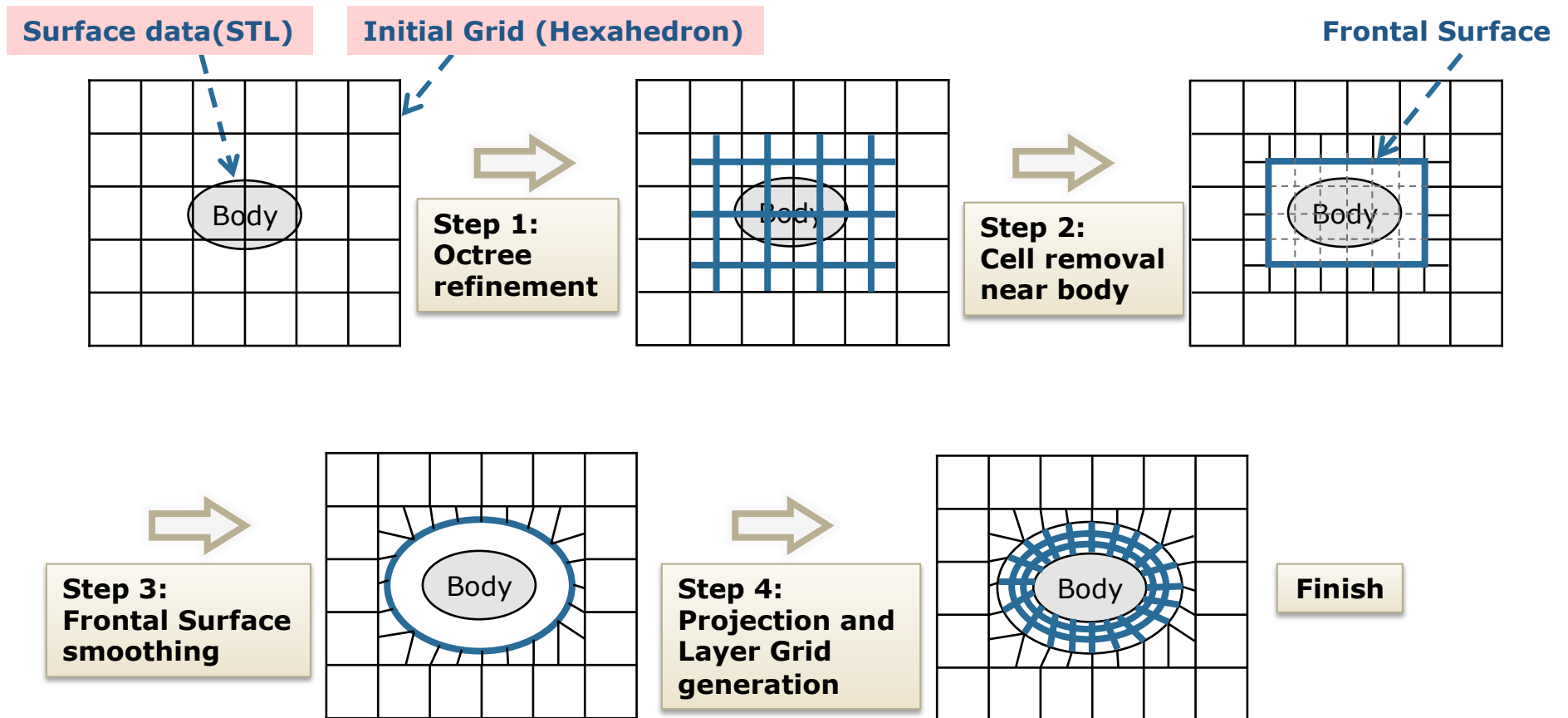
FAMILY II UNSTRUCTURED QUAD VERSIONS OF GRIDS



Cflow achieved equivalent convergence with other codes.

"Cflow" Grid Generation Procedure

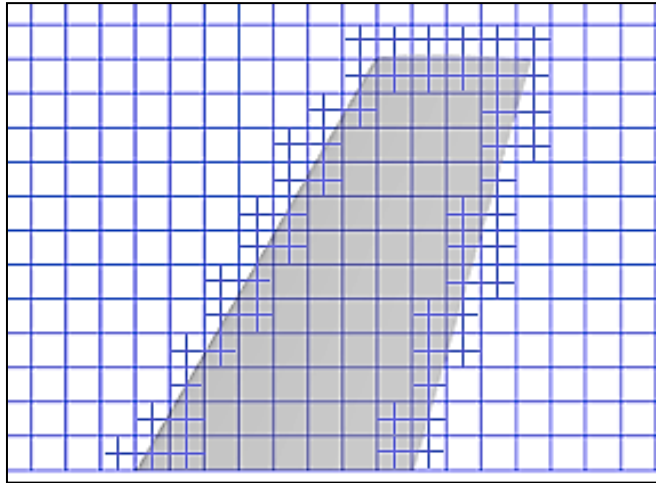
Cflow = **Grid Generator** + Flow Solver



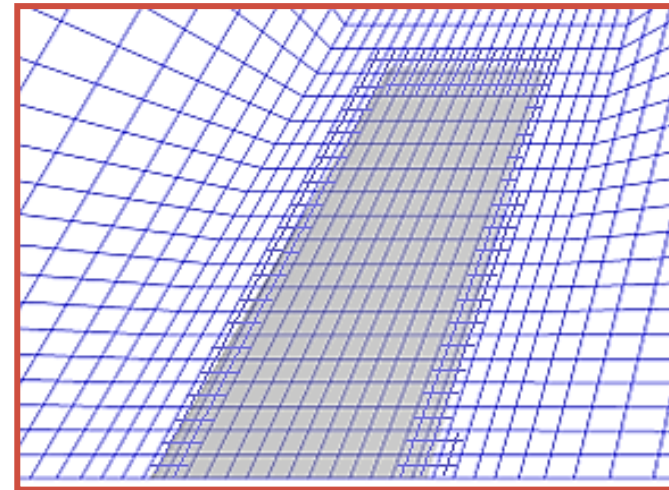
Cflow conducts automatic Cartesian based grid generation with octree Adaptive Mesh Refinement, and with Layered grid near surface for boundary layer.

Characteristics of Cflow Grid

NOBLU (Non-orthogonal Octree Boundary-fitted Layer Unstructured) Grid



Conventional Cartesian

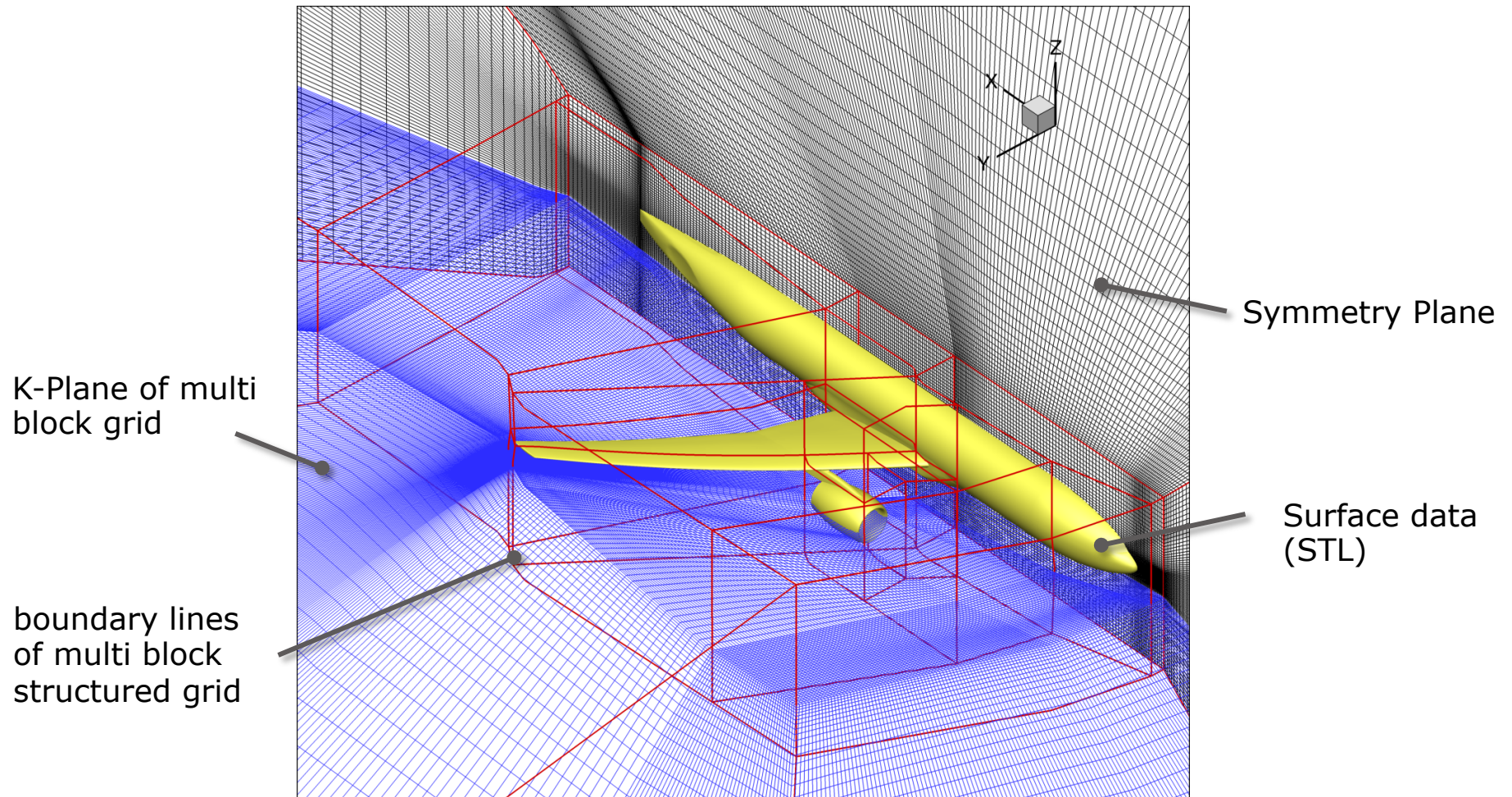


Non-Orthogonal Initial Grid

Efficient

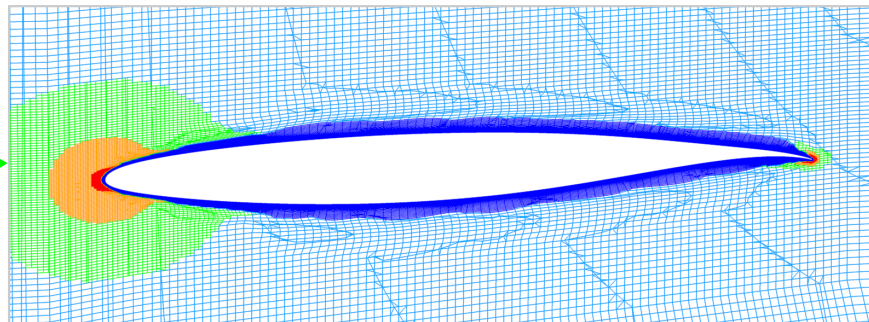
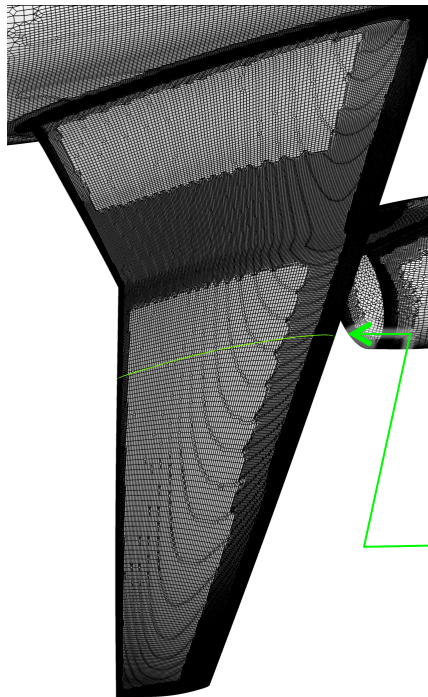
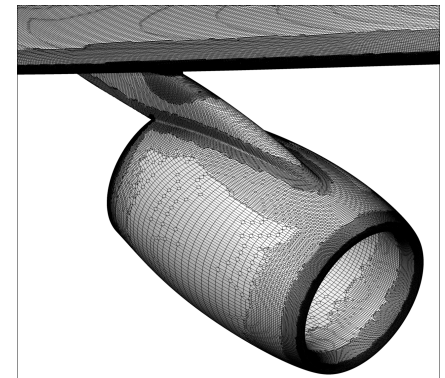
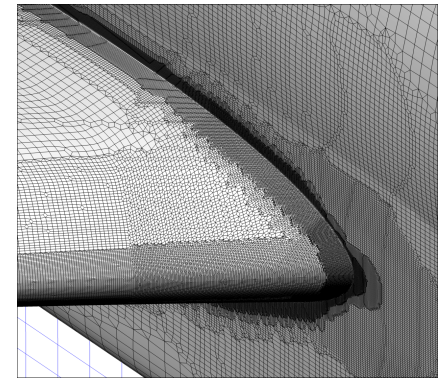
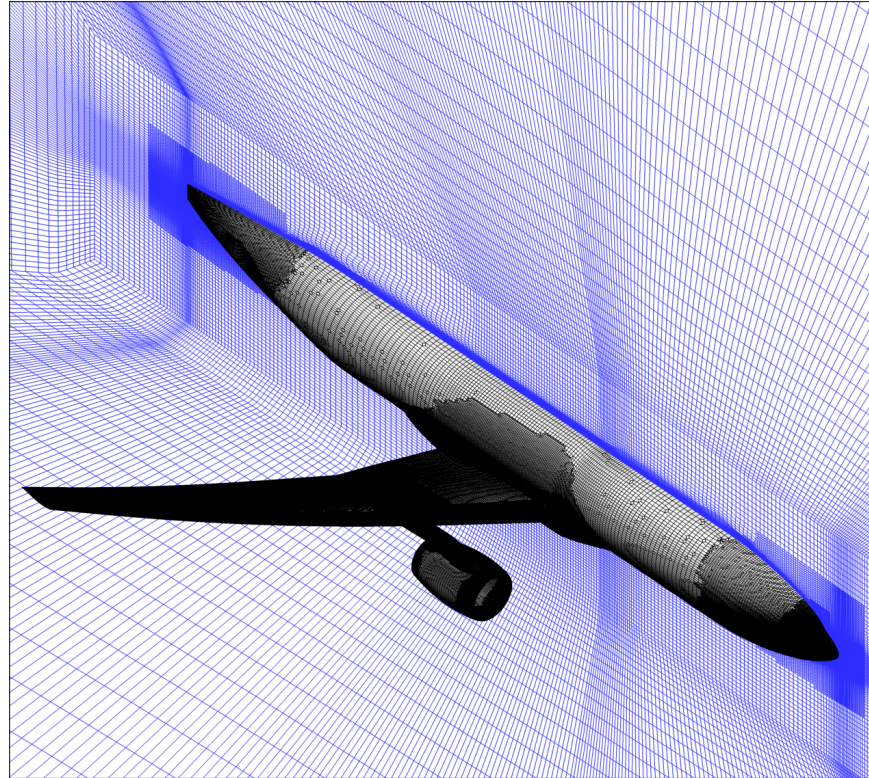
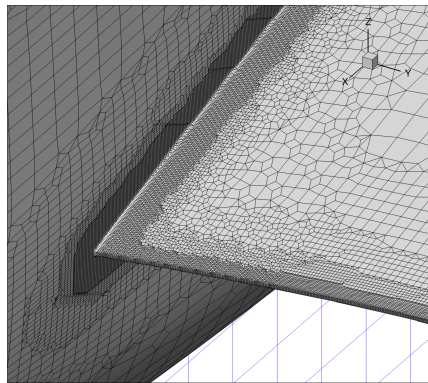
- Cflow adopts “**Non-Orthogonal Initial Grid**” to increase flexibility for high aspect ratio and sweptback configuration
- Controlling the grid spacing and aspect ratio of “Initial Grid” can achieve higher resolution around leading and trailing edge and can reduce the number of grid points.

Case2&3; CRM WB/WBNP Configuration Non-orthogonal Initial Grid Setup



One Initial grid is compatible with WB/WBNP, aeroelastic shape change.

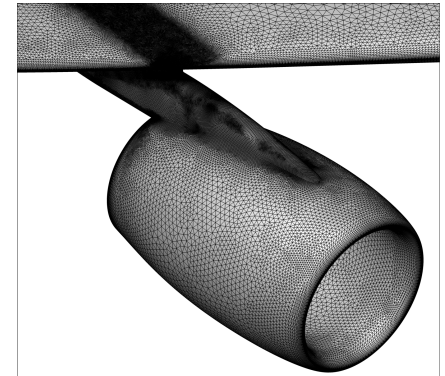
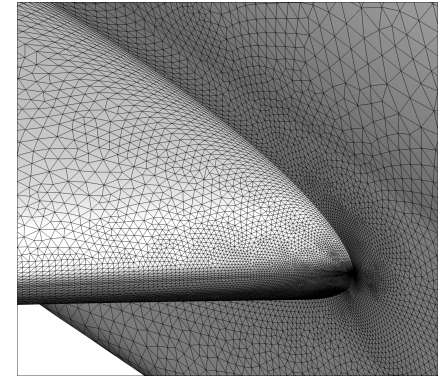
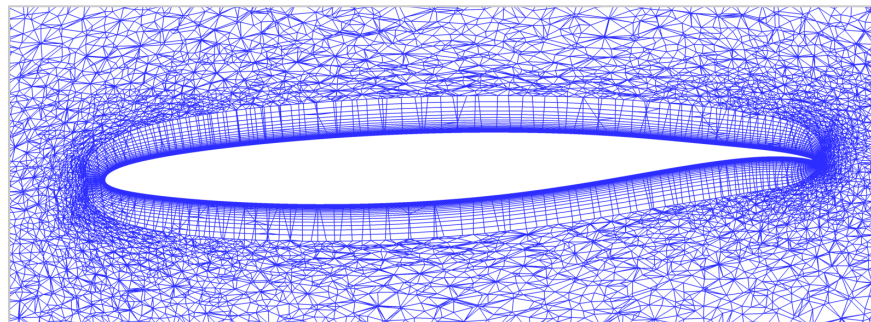
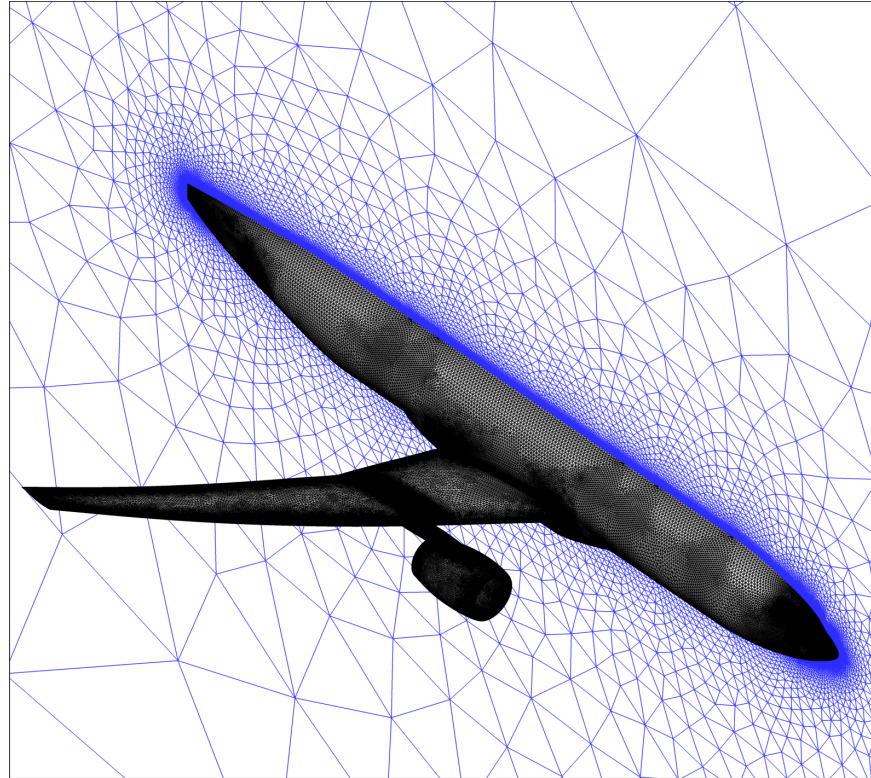
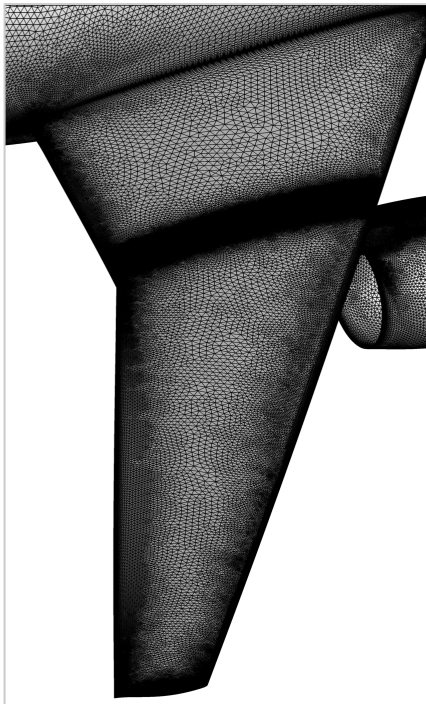
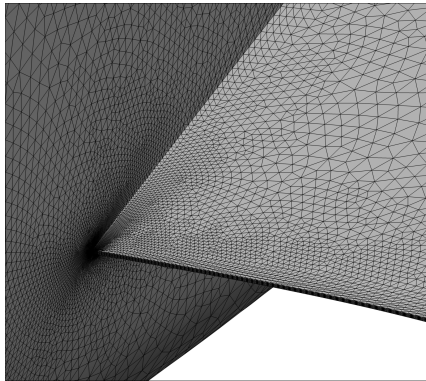
Case2&3; Cflow.NOBLU Grid



Wing Section 10 ($\eta=0.502$)

Medium Level
Surface cells 1.35M
Volume cells 68.1M
93% hexahedron
7% prism

Case2&3; Baseline Grid (Boeing.Babcock.Unstructured.CC.REV00)

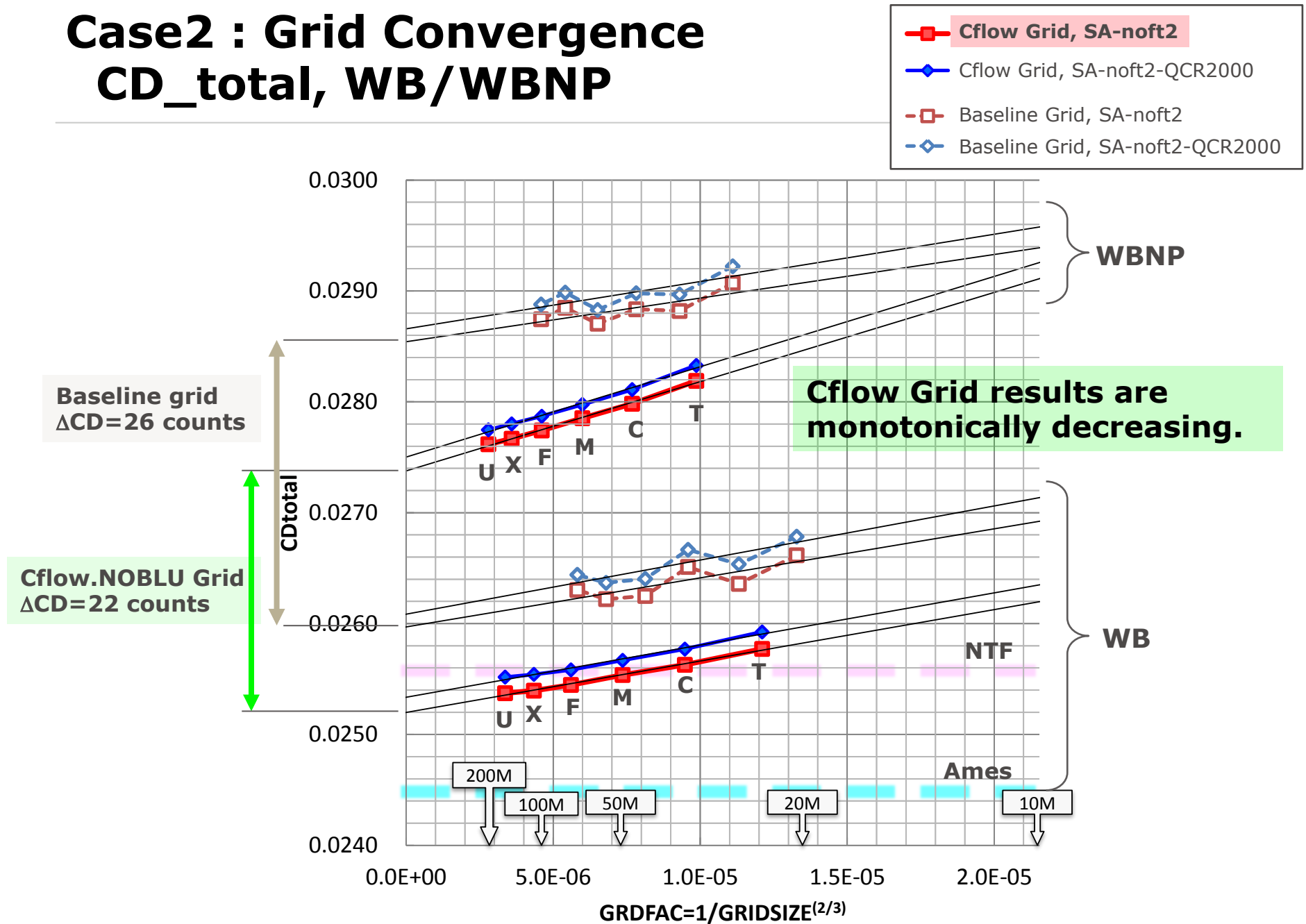


Medium Level
Surface cells 0.75M
Volume cells 45.7M
35% Tetra
65% Prism
0.1% Pyramid

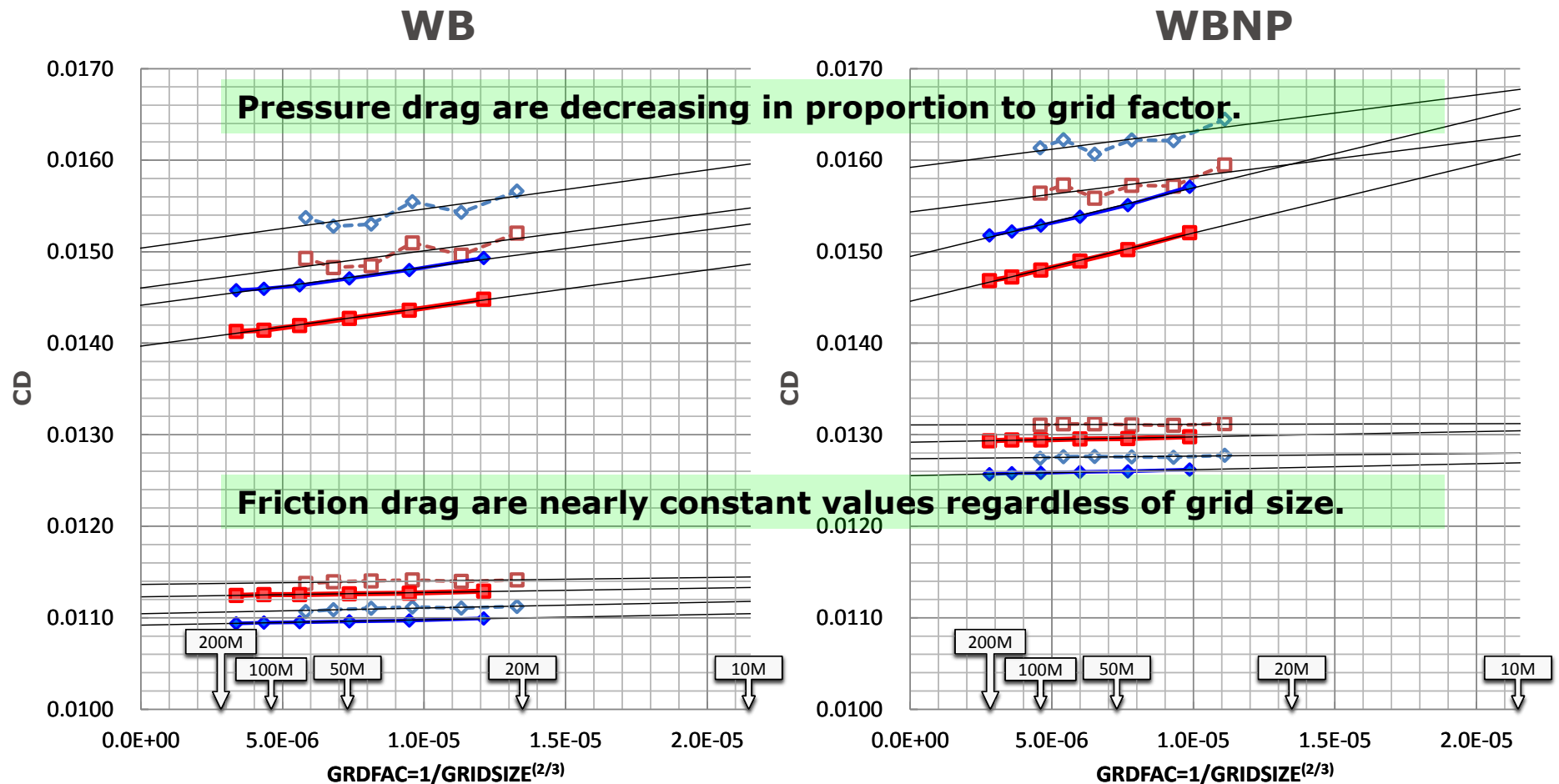
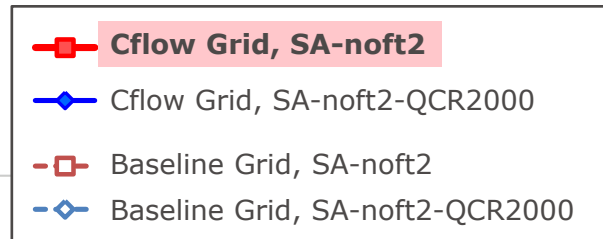
Wing Section 10 ($\eta=0.502$)

Case2 : Grid Convergence

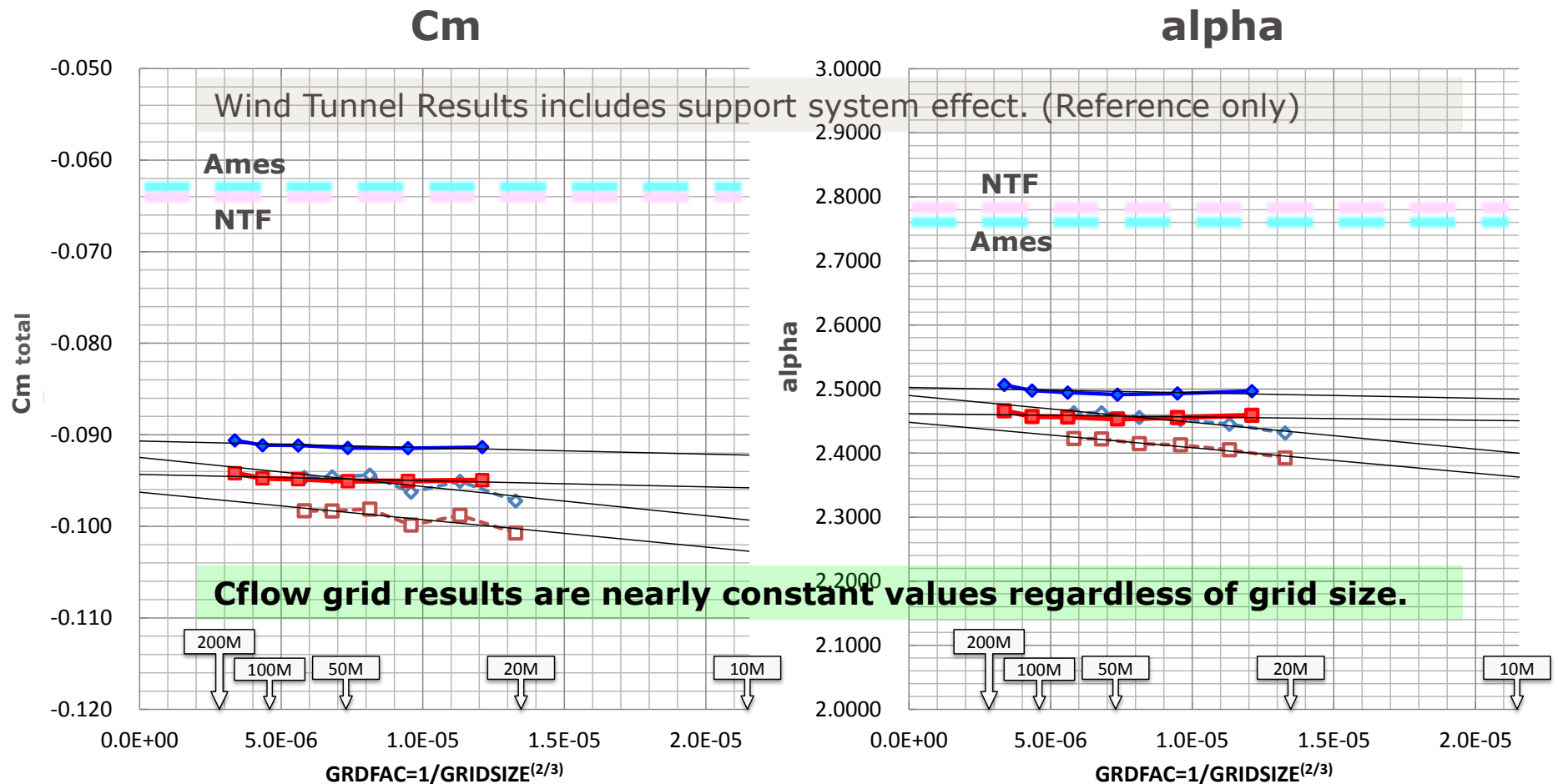
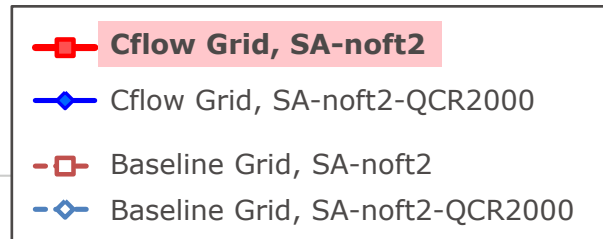
CD_total, WB/WBNP



Case2 : Grid Convergence Drag breakdown, WB/WBNP



Case2 : Grid Convergence Cm and alpha, WB



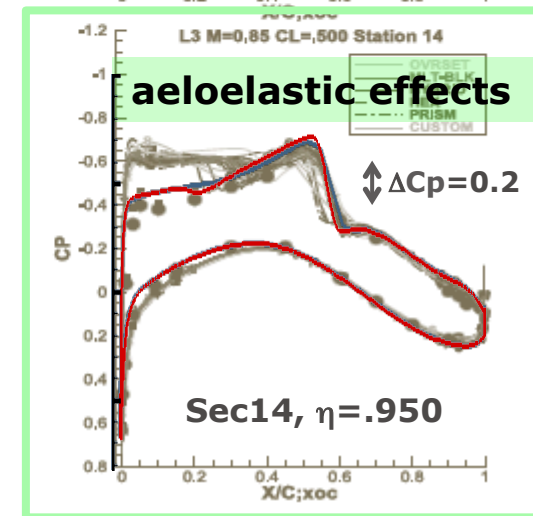
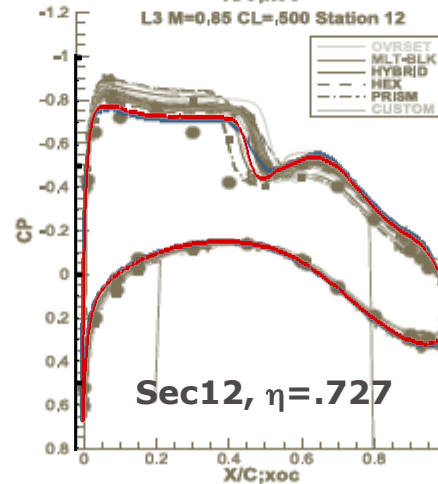
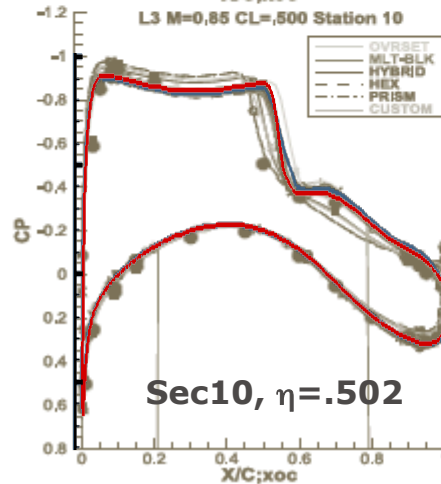
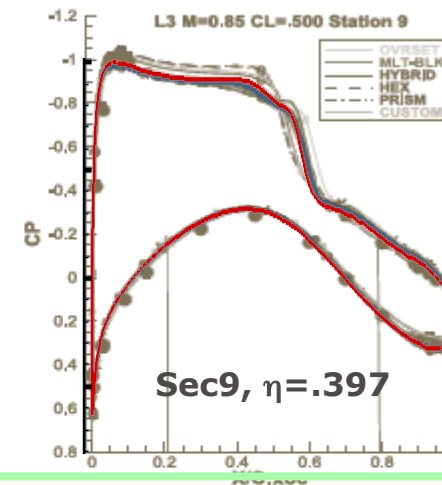
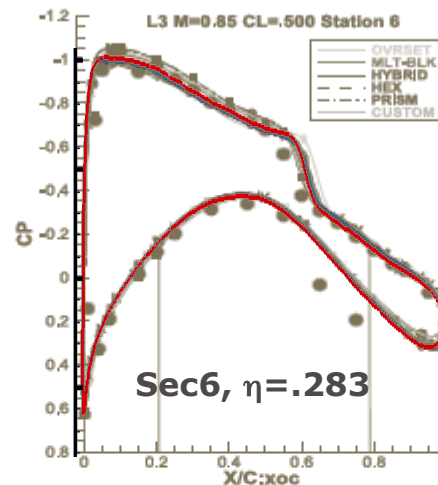
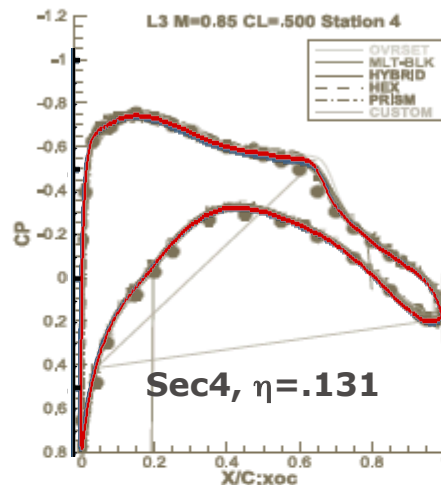
Case2 WB : spanwise Cp variation

— Cflow Grid, SA-noft2
— Baseline Grid, SA-noft2

Background gray chart is cited from
DPW5 Summary-Draft_V7_2012.pdf, p.45

Case 1: Level 3 Grid, $M=0.85$, $C_L=.50$
Spanwise Variation

NTF Test 197 Run 44:
● $\alpha=2.68^\circ$, $CL=0.485$
■ $\alpha=2.91^\circ$, $CL=0.519$

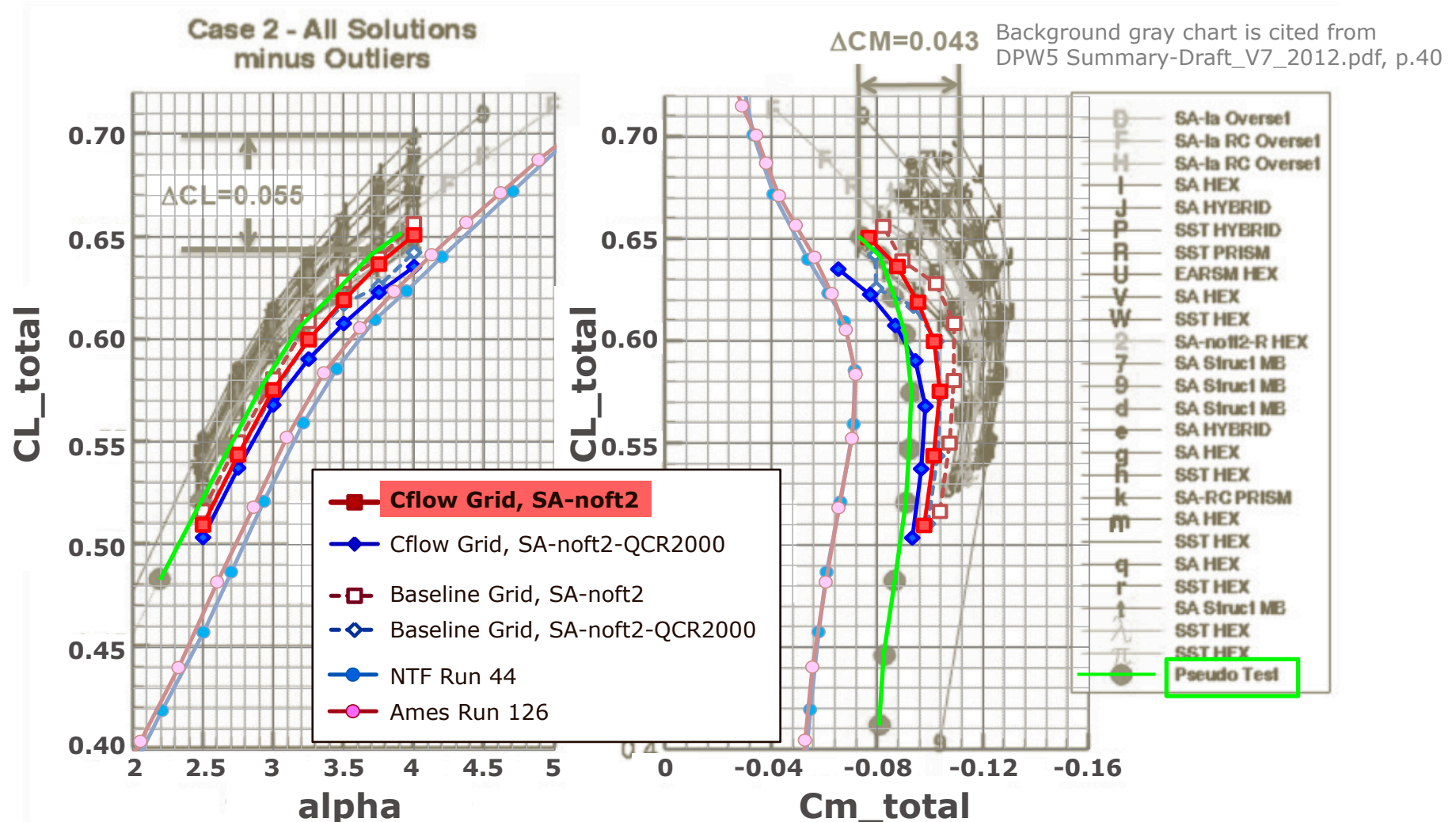


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Case3 : CRM WB Static Aero-Elastic Effect

CL-alpha, CL-Cm

DPW5 : Rigid shape
DPW6 : Aeroelastic shape



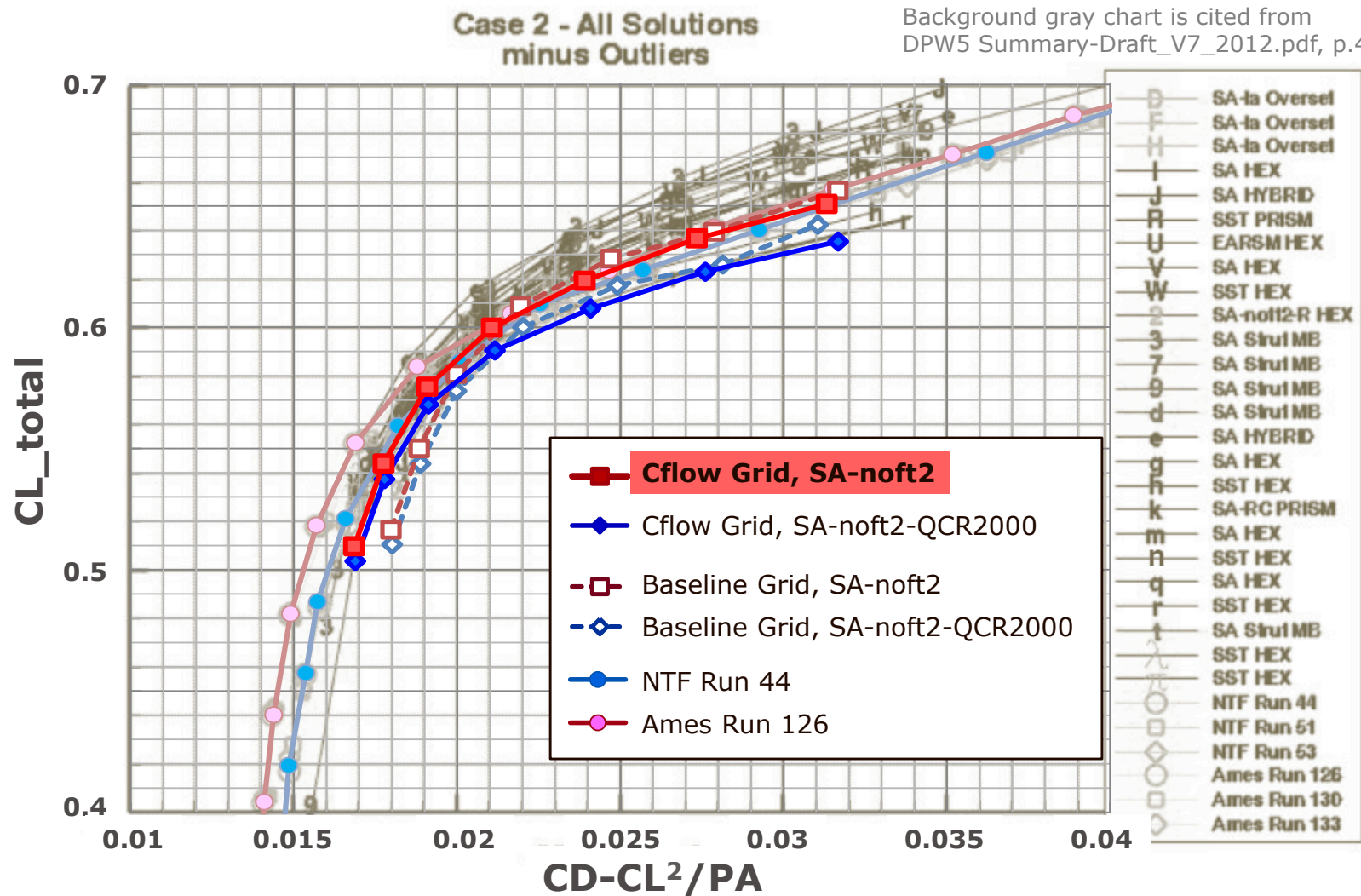
Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209

"Cflow grid, SA-noft2" corresponds to Pseudo Test data.

Case3 : CRM WB Static Aero-Elastic Effect

Drag Polar

DPW5 : Rigid shape
DPW6 : Aeroelastic shape

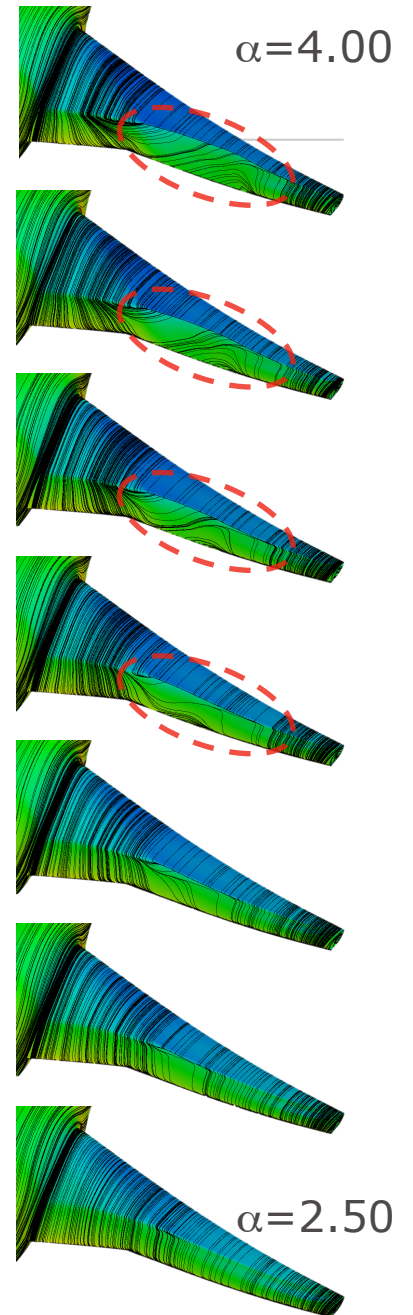
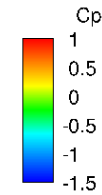
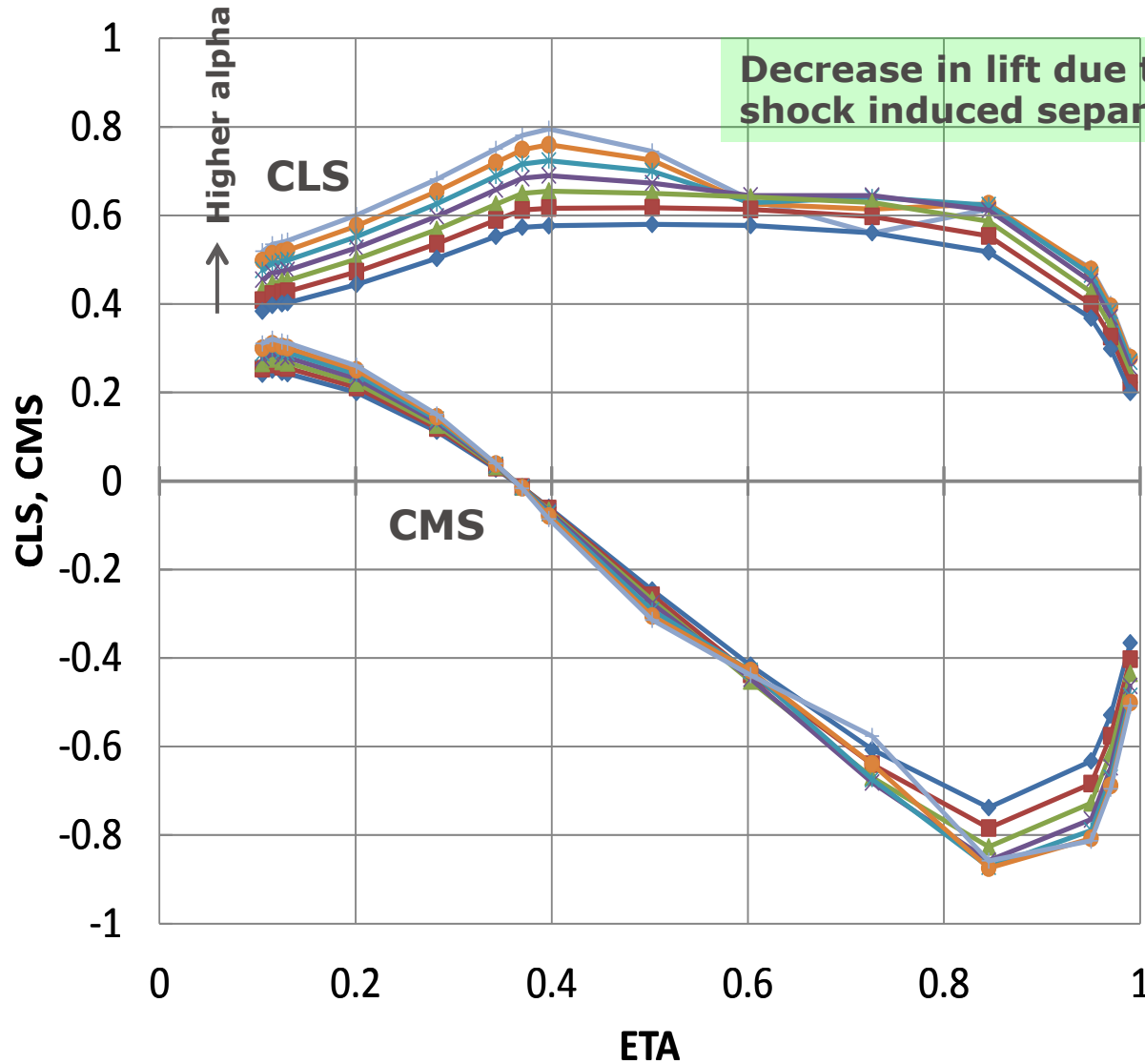


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"Cflow grid, SA-noft2" is good agreement with WT Test data.

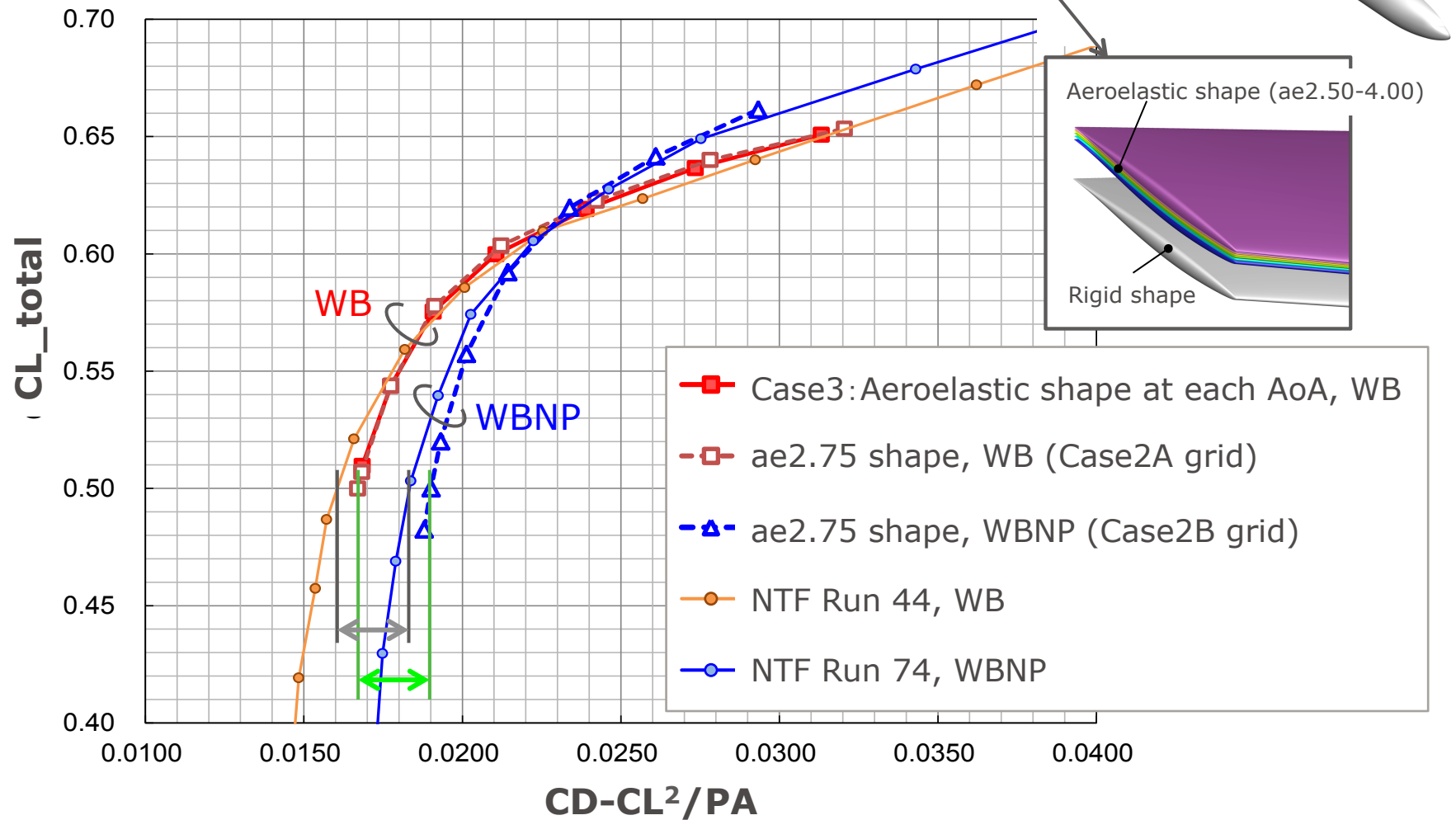
Case3 Sectional Lift & Moment

Cflow.NOBLU Grid, SA-noft2



CRM Nacelle/Pylon Drag Increment

Cflow.NOBLU Grid, SA-noft2



CFD Nacelle/Pylon drag increment is good agreement with WT Test data.

Summary

- Validation study of Kawasaki in-house CFD tool “Cflow” was conducted
 - Case1: Solver Verification
 - Cflow solver achieved equivalent convergence with other codes.
 - Case2: Grid convergence
 - Cflow original “NOBLU Grid” were applied to CRM WB/WBNP config.
 - CD_{total} and CD_p were monotonically decreasing
 - CL , CD_f , C_m , and α were nearly constant values regardless of grid size
 - Case3: Aeroelastic effect
 - Both aerodynamic characteristics and Nacelle/Pylon drag increment were good agreement with WT Test data.

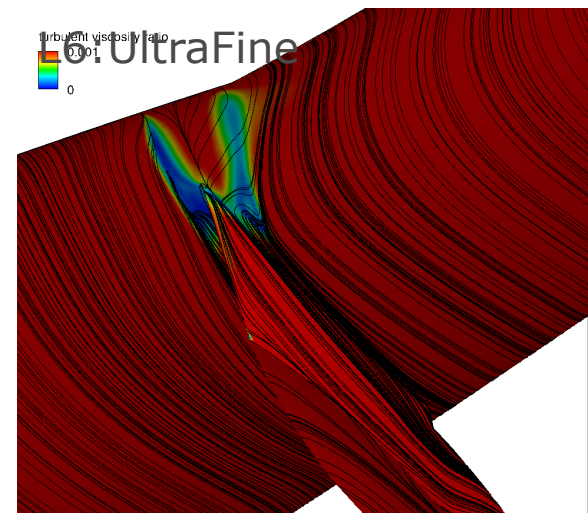
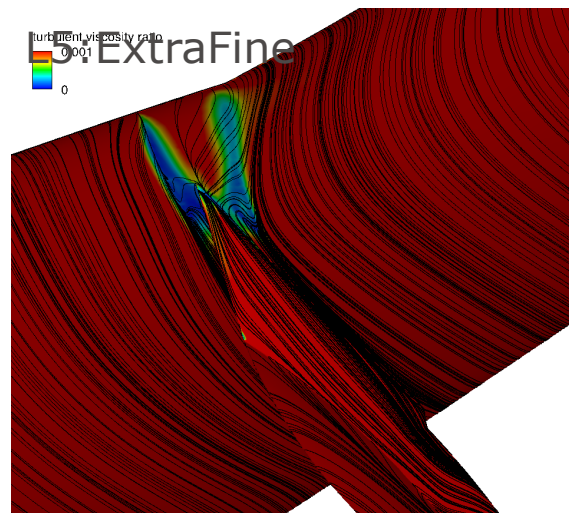
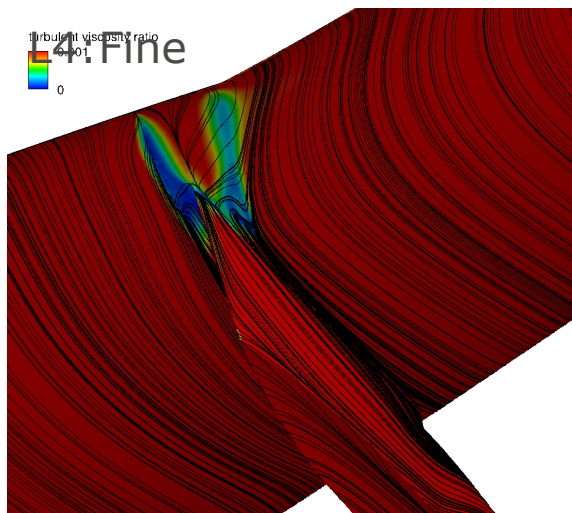
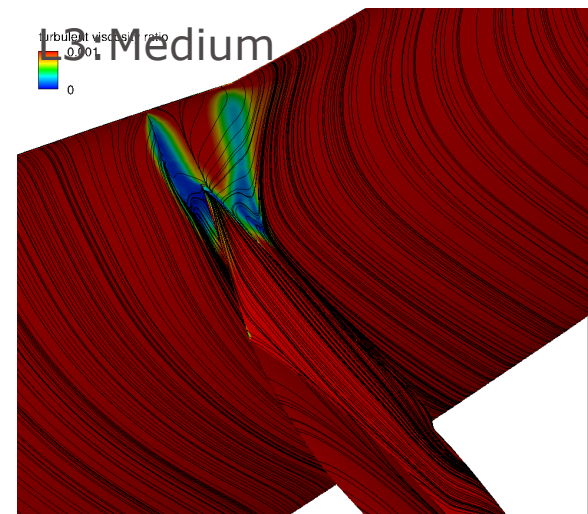
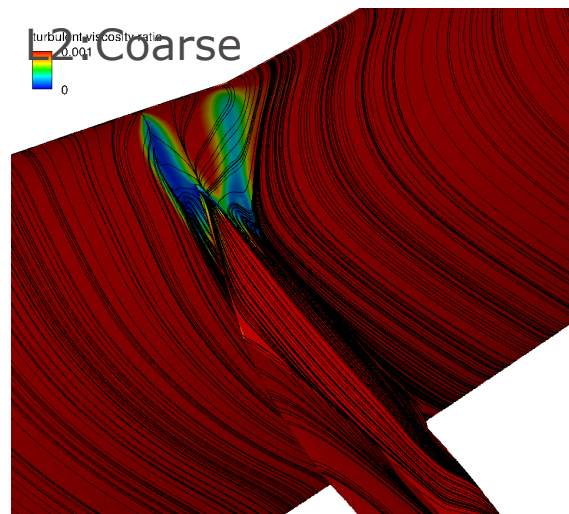
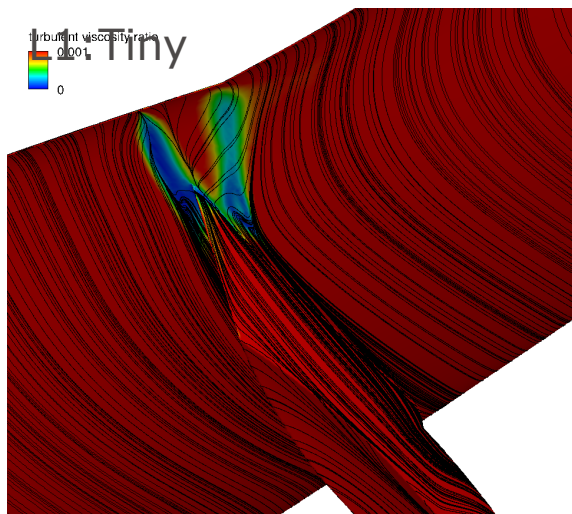
- Future Work
 - further study on turbulence model effect, baseline grid, etc.
 - enhance grid generator function of feature preservation
 - participate in HiLift-PW3

Kawasaki, working as one for the good of the planet
“Global Kawasaki”

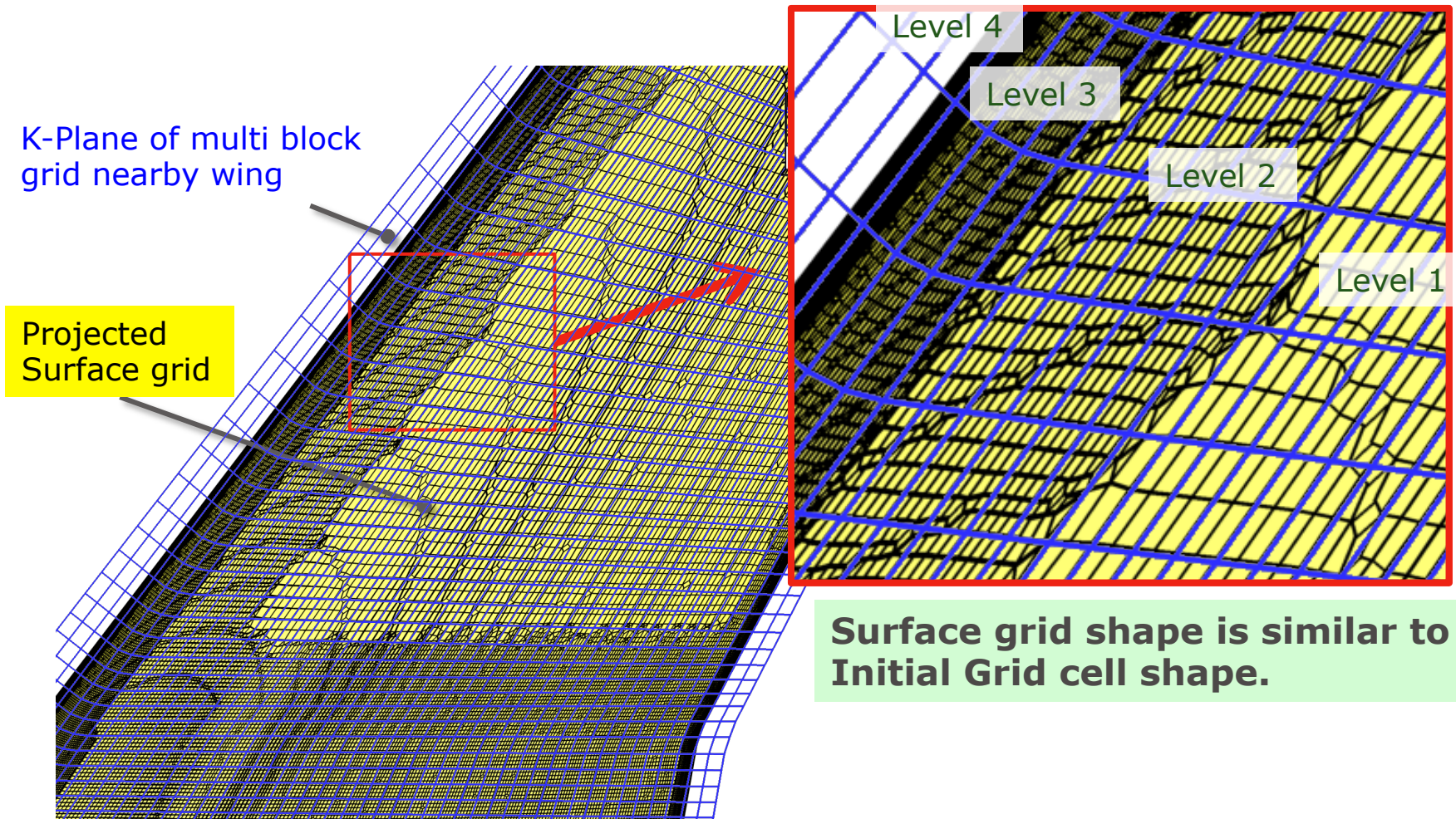
Case 2B

Cf, oilflow

WBNP, Cflow NOBLU Grid, SA-noft2

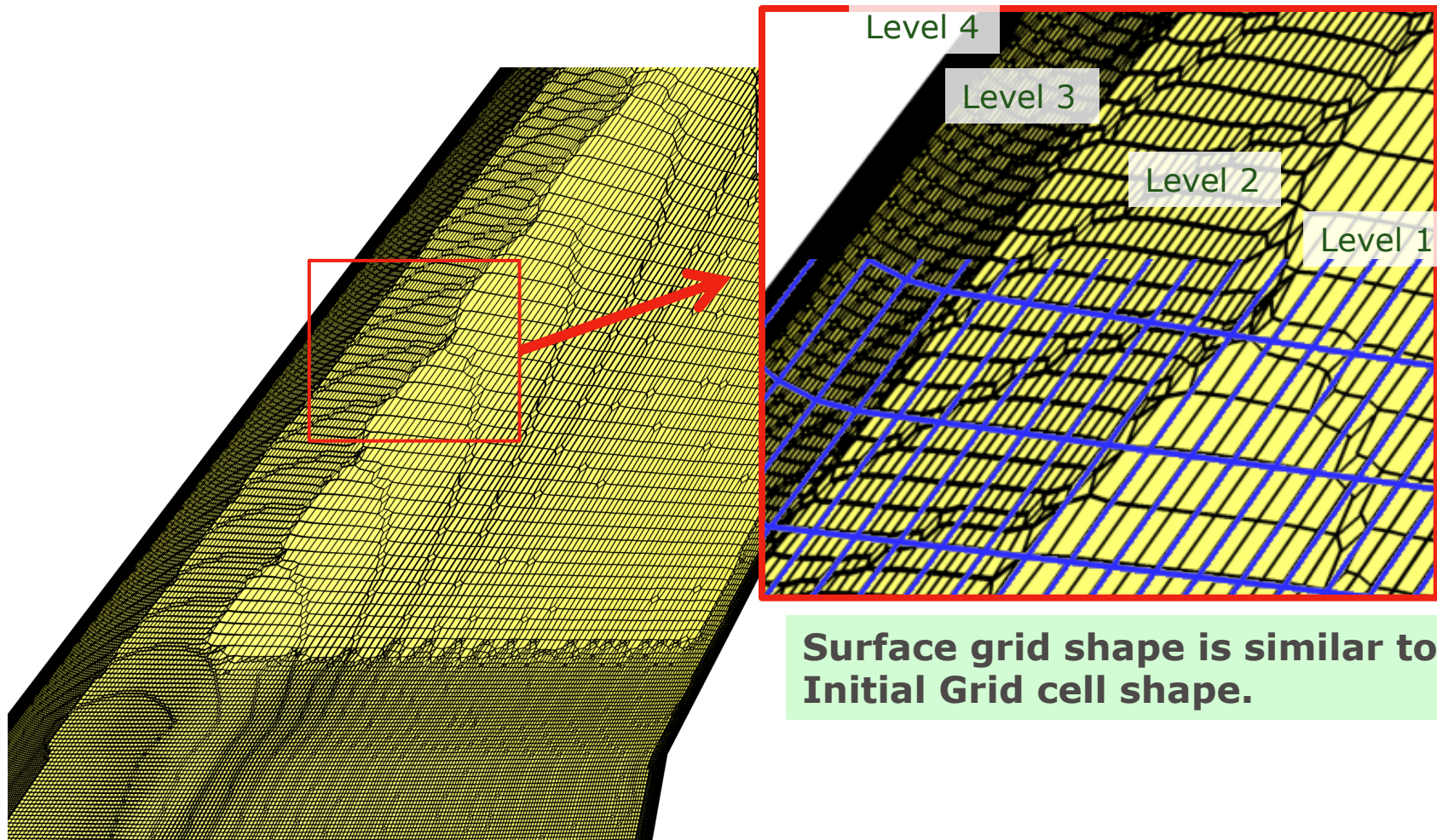


Case2&3; Cflow.NOBLU Grid



Controlling the grid spacing and aspect ratio of "Initial Grid" can achieve higher resolution around leading and trailing edge and can reduce the number of grid points.

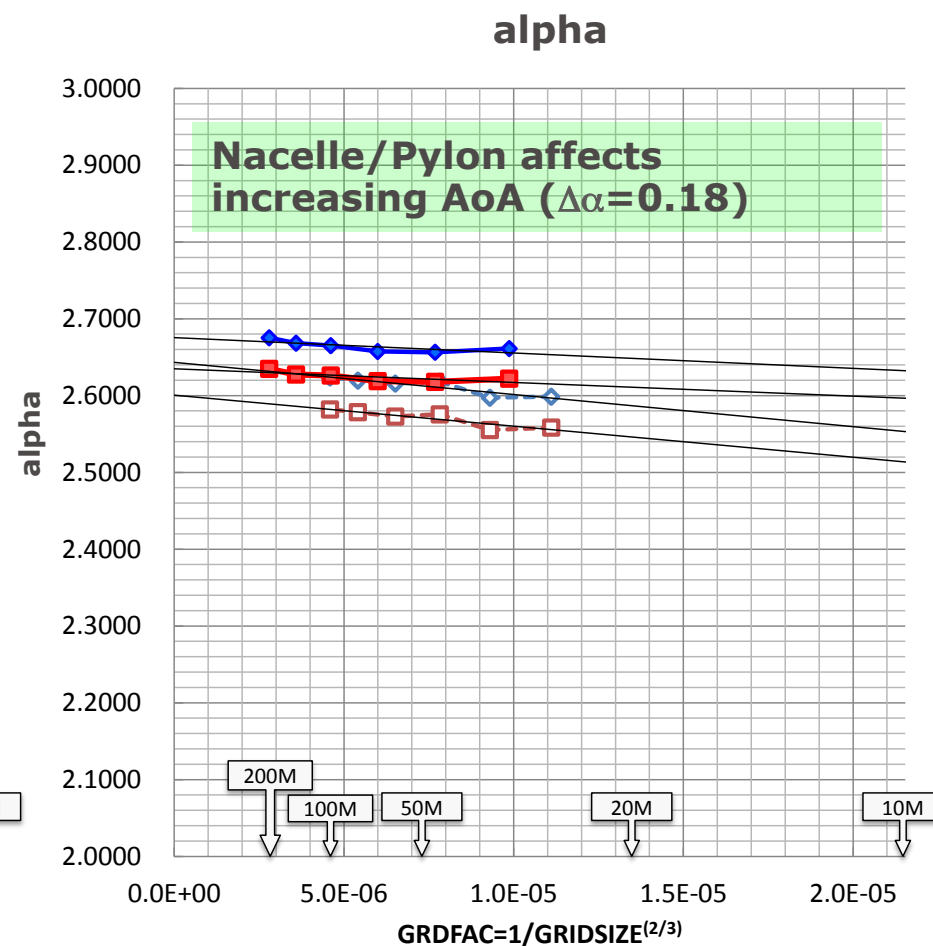
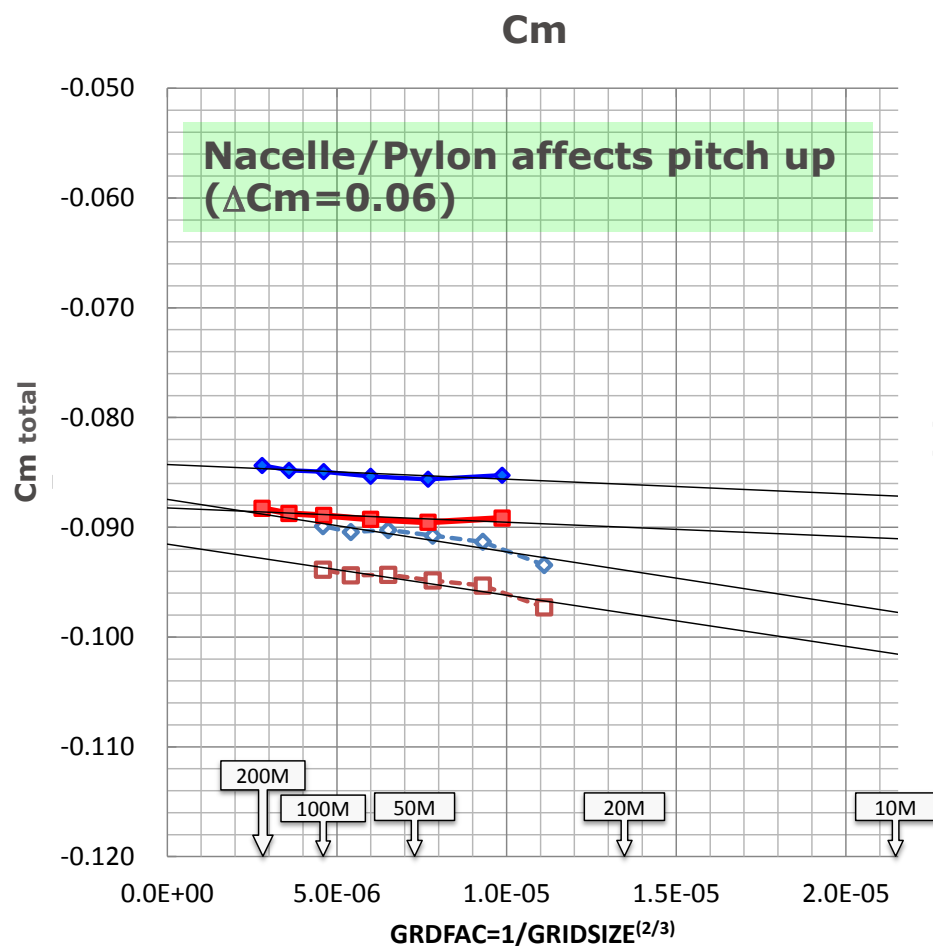
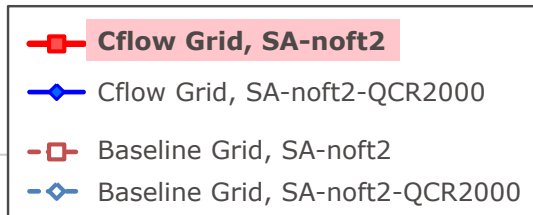
Case2&3; Cflow.NOBLU Grid



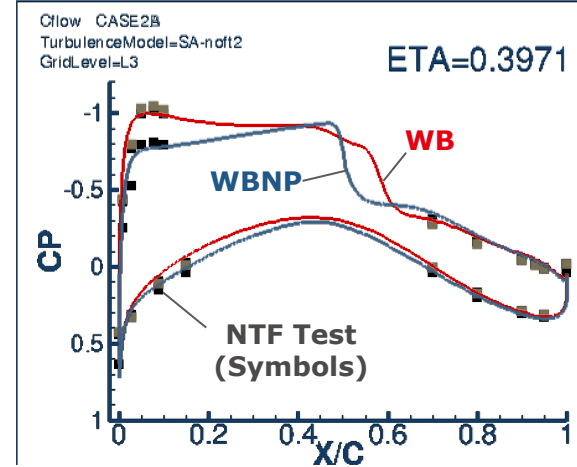
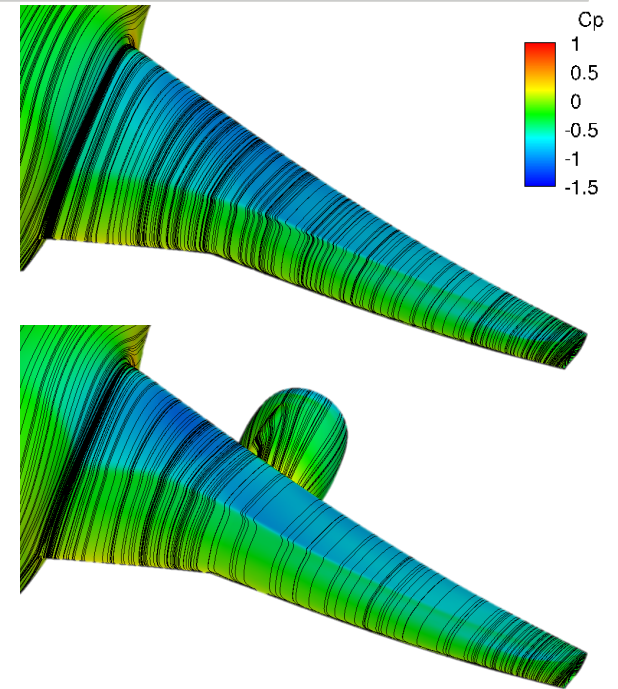
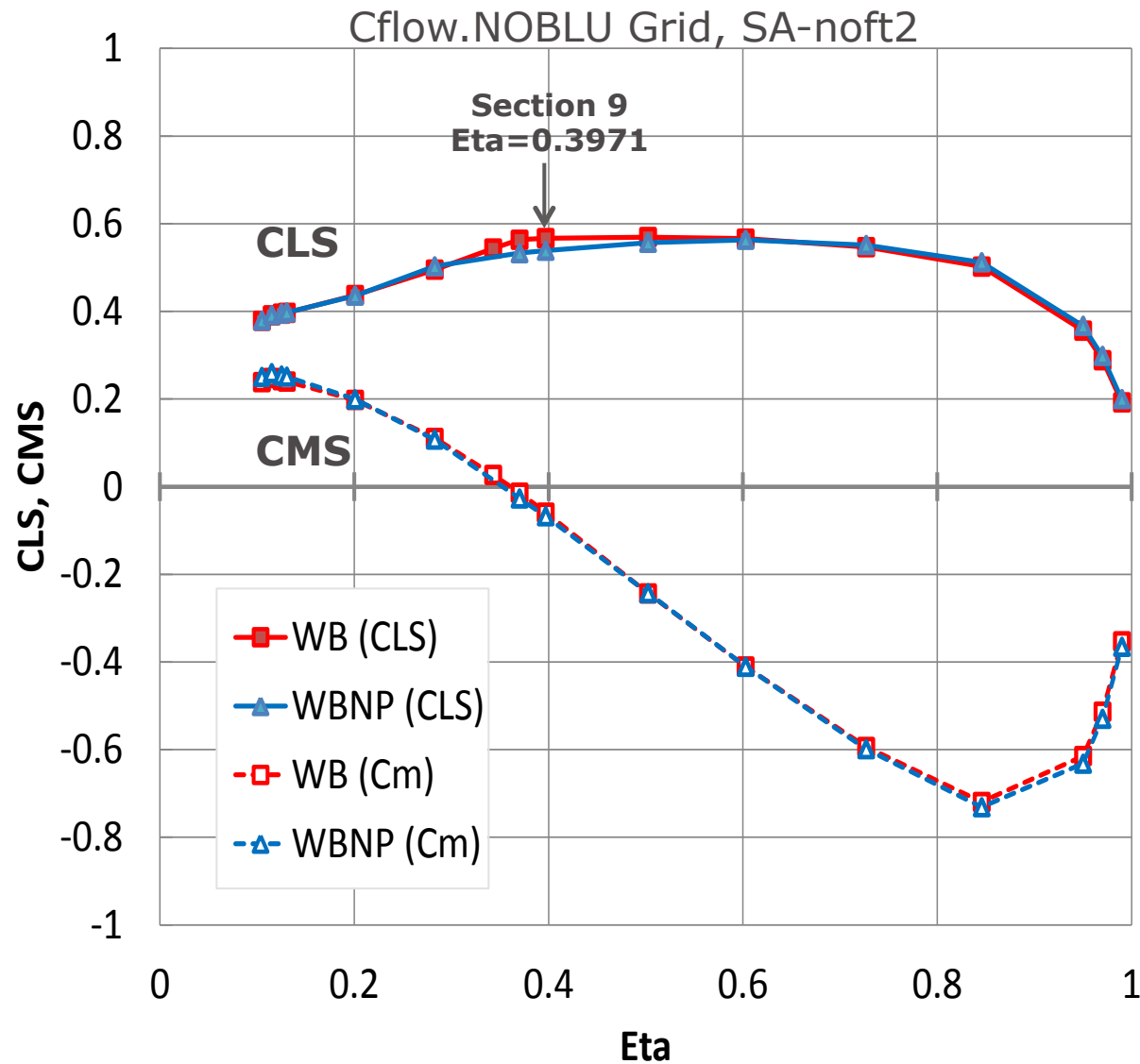
Surface grid shape is similar to Initial Grid cell shape.

Controlling the grid spacing and aspect ratio of “Initial Grid” can achieve higher resolution around leading and trailing edge and can reduce the number of grid points.

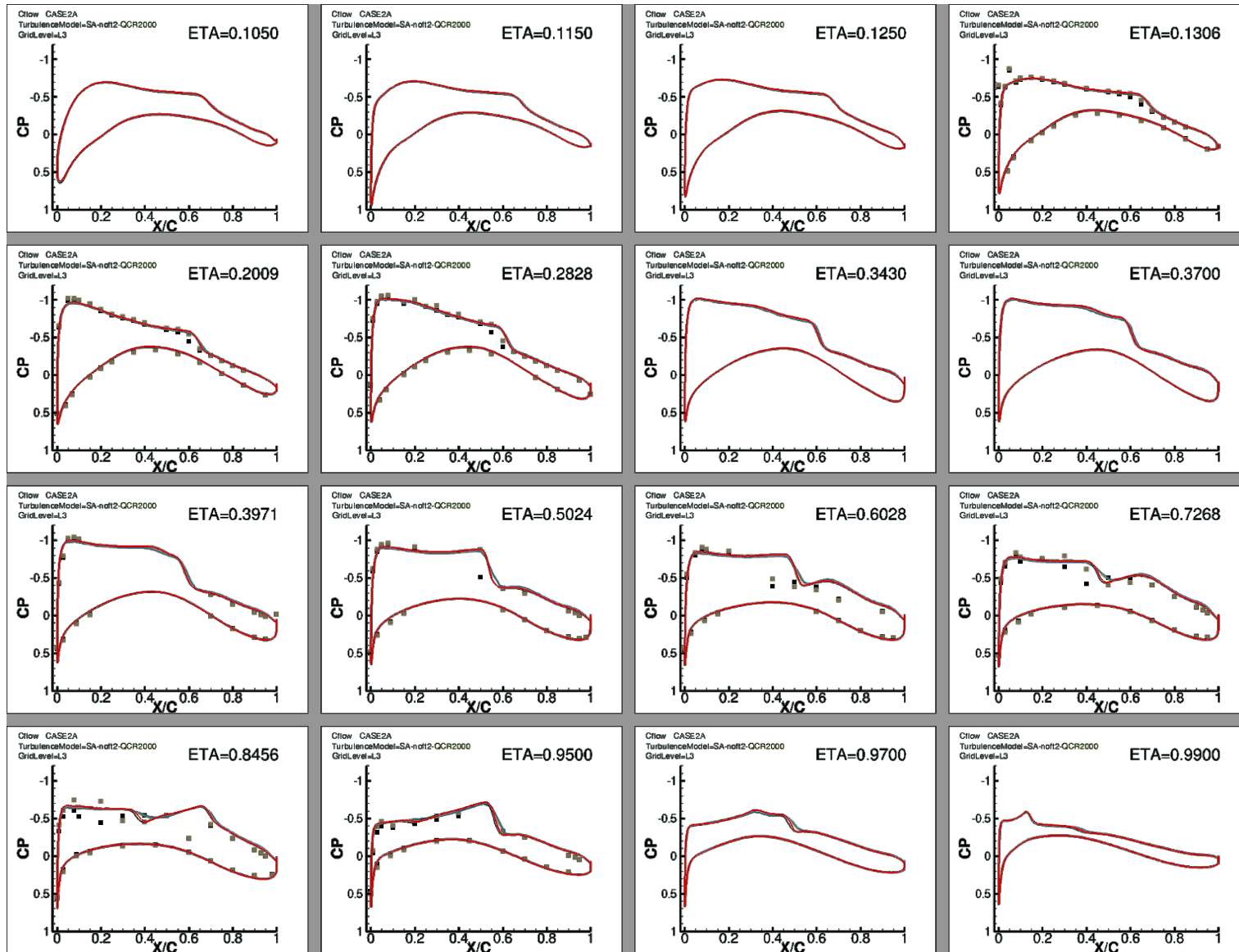
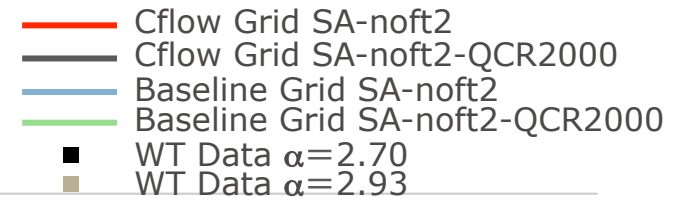
★ Case2 : Grid Convergence Cm and alpha, WBNP



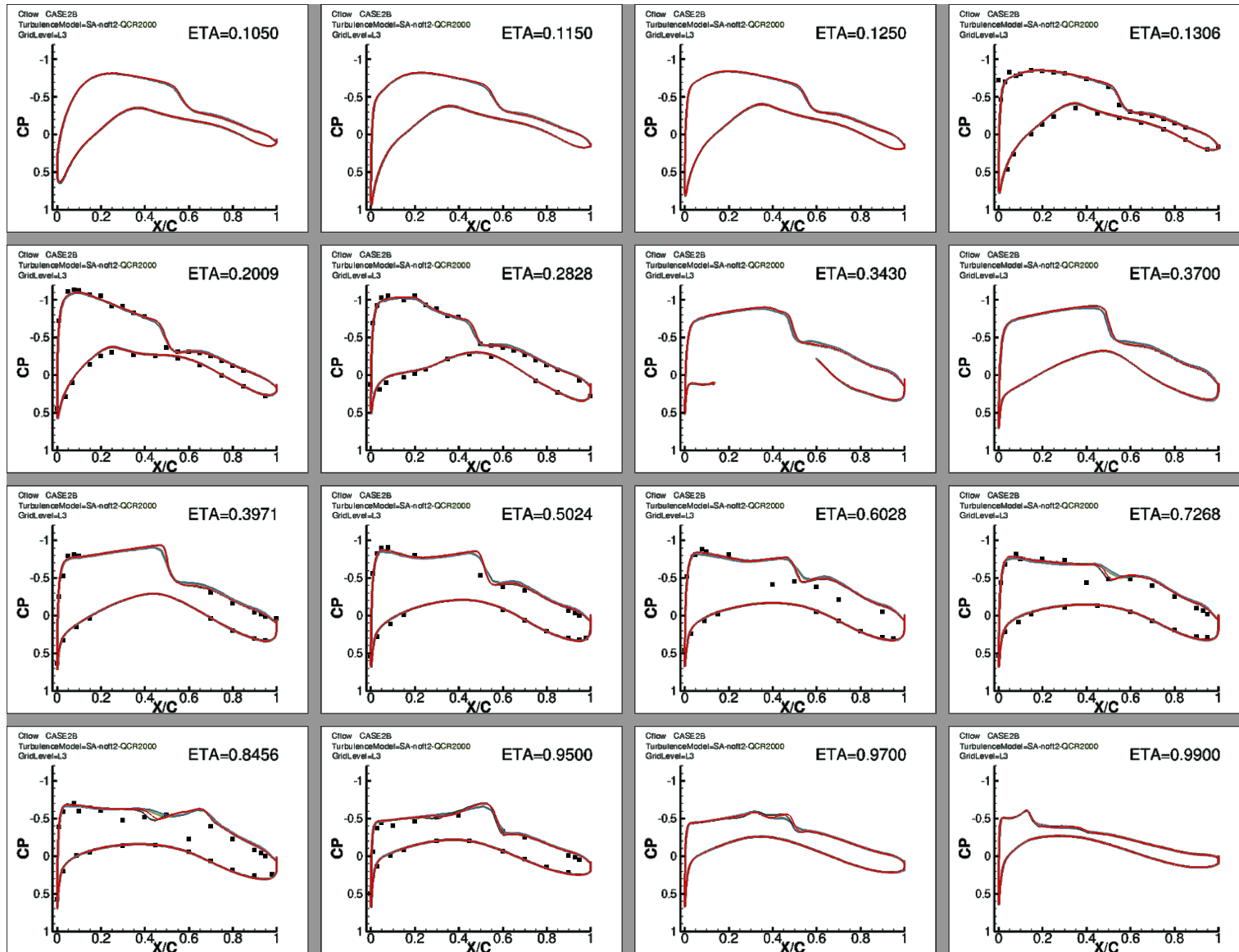
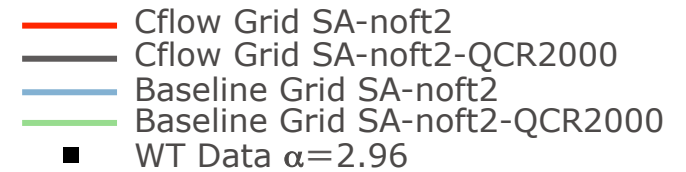
Case2 Sectional Lift & Moment WB/WBNP



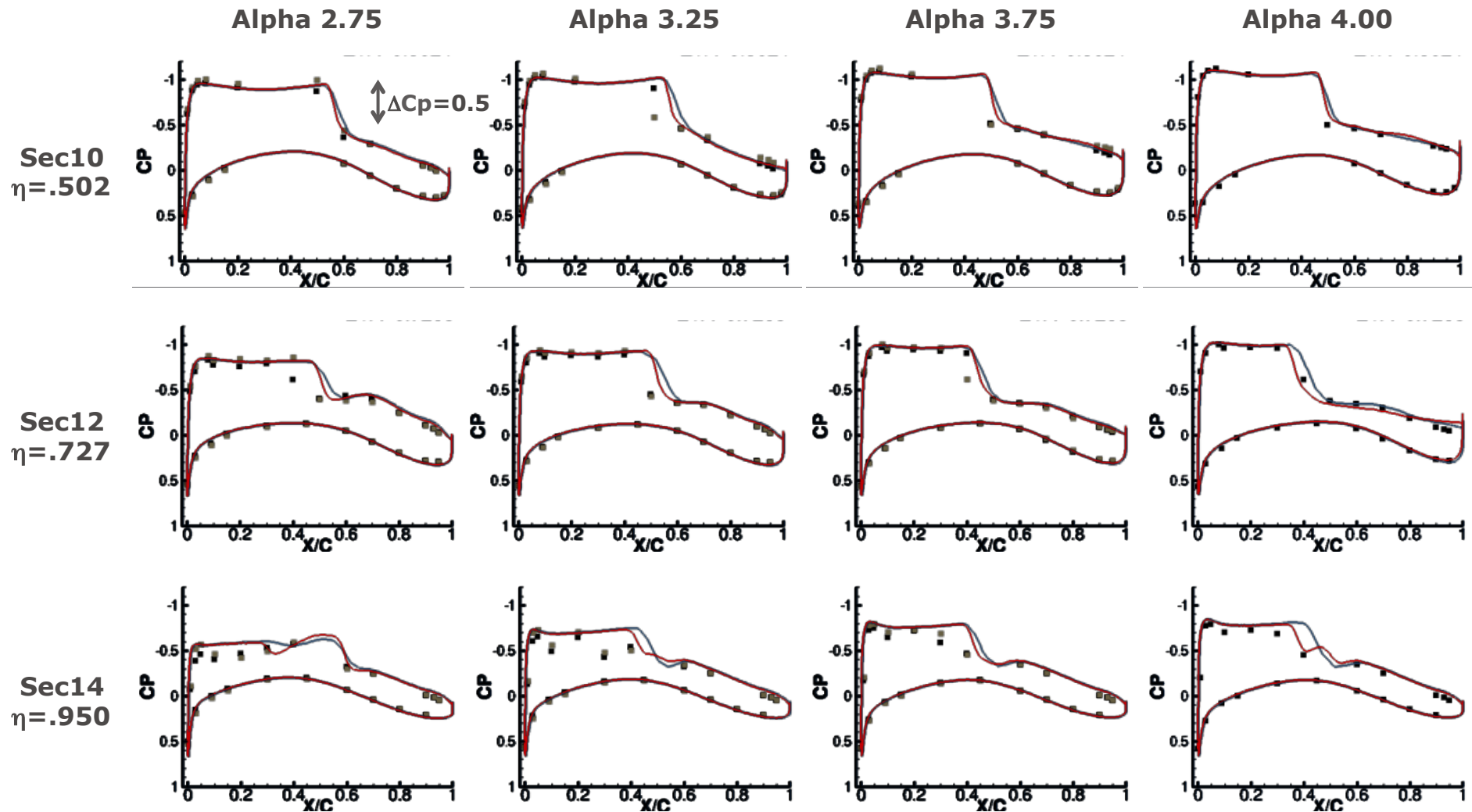
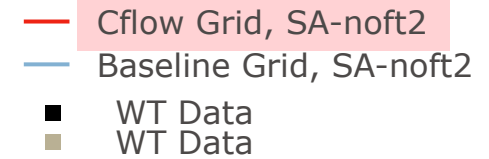
Case2A L3 Medium grid comparison



Case2B L3 Medium grid comparison



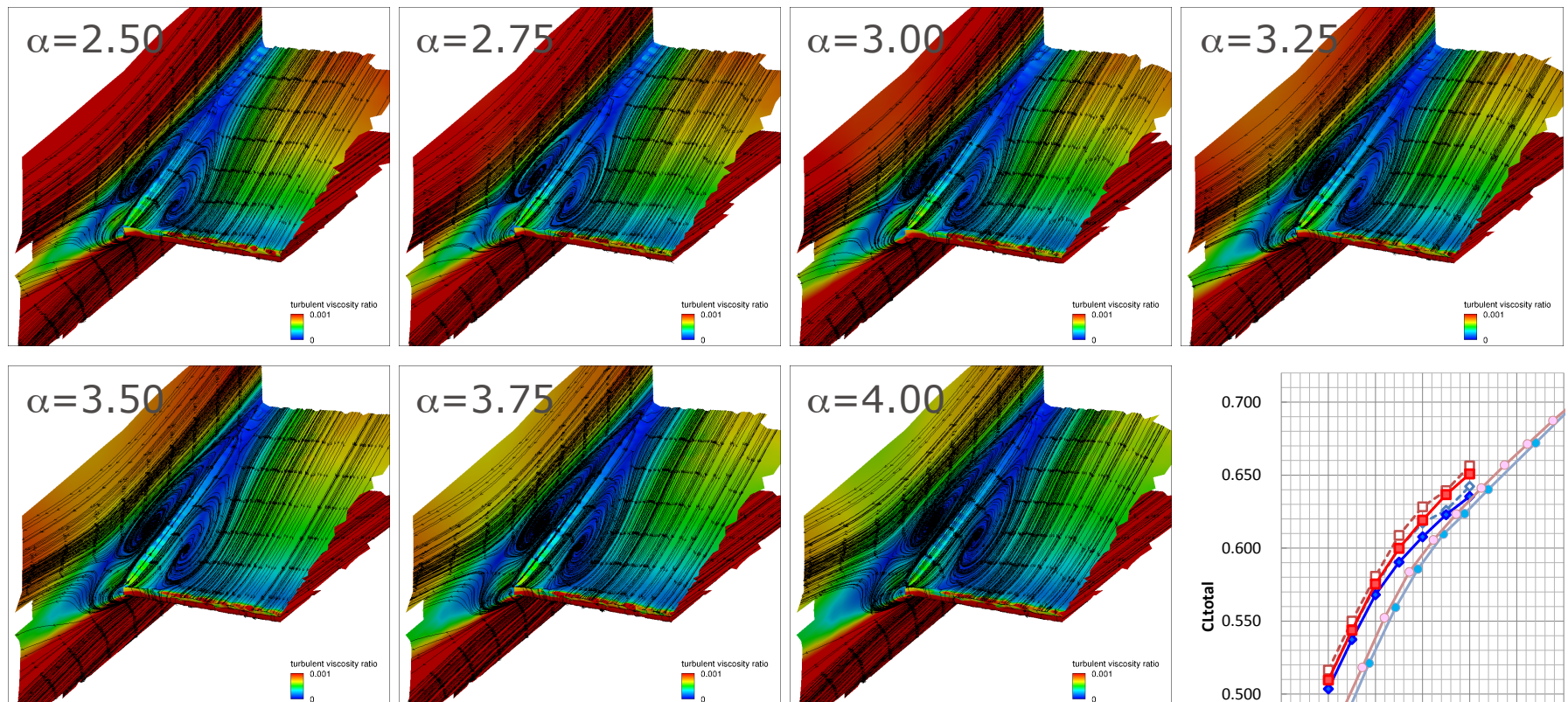
Case3 WB : Cp variation



Case 3

SOB Separation Bubble

WB, Cflow NOBLU Grid, SA-noft2



a certain size SOB separation bubble, but not massive separation