3rd AIAA CFD Drag Prediction Workshop

Computational Results by JAXA for DLR-F6 and DLR-F6 FX2B (Case 1)

Mitsuhiro MURAYAMA, Zhong LEI, and Kazuomi YAMAMOTO

Aviation Program Group (APG),

Japan Aerospace Exploration Agency (JAXA)

Kentaro TANAKA and Tohru HIRAI

Ryoyu Systems Co., Ltd.

Ryozo ITO

Daiko Denshi Tsushin, Ltd.

Hiroaki ISHIKAWA

Sanko Software Development Co., Ltd.

Objectives

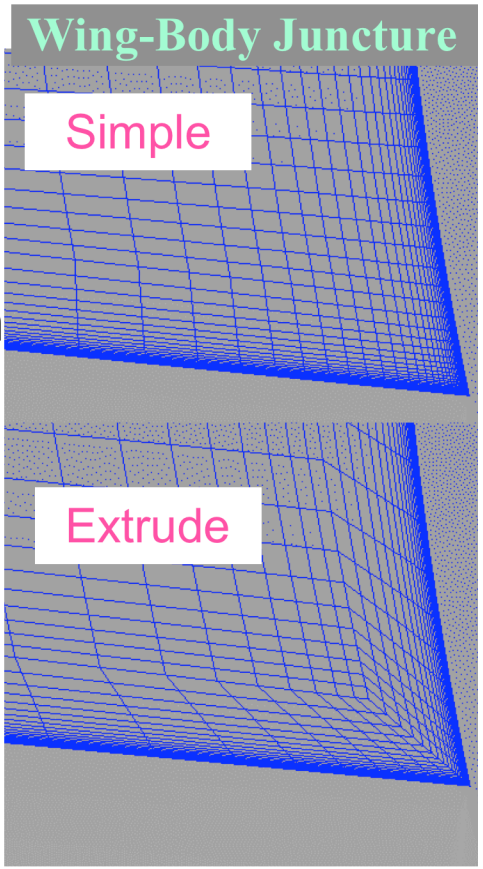
- Evaluation of CFD codes used in APG/JAXA
  - Multi-block structured mesh code, UPACS
  - Unstructured mesh code, TAS code

Focus of presentation

- Evaluation of self-made computational grids
- Grid convergence
- Comparison of upper-surface trailing-edge separation

By the structured grids for flow separation of DLR-F6

- Comparison of grid topology at wing-body junction
- Comparison of turbulence model, SA and SST



Numerical method: UPACS & TAS Code

	UPACS	TAS Code
Mesh type	Multi-block structured	Unstructured
Discretization	Cell-centered finite volume	Cell-vertex finite volume
Flux comp.	Roe 2nd order with vanAlbada's Limitter	HLLEW 2nd order with Venkatakrishnan's limitter
Time integration	MFGS	LU-SGS
Turbulence model	SA_mod, SST	SA_mod

Code

UPACS: **U**nified **P**latform for **A**erospace **C**omputational **S**imulation by JAXA

TAS Code: **T**ohoku University **A**erodynamic **S**imulation Code

Turbulence model

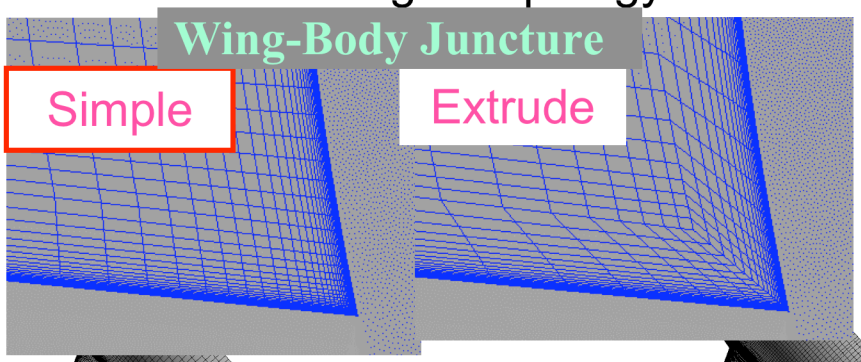
SA_mod: Spalart-Allmaras one-equation turbulence model with modifications

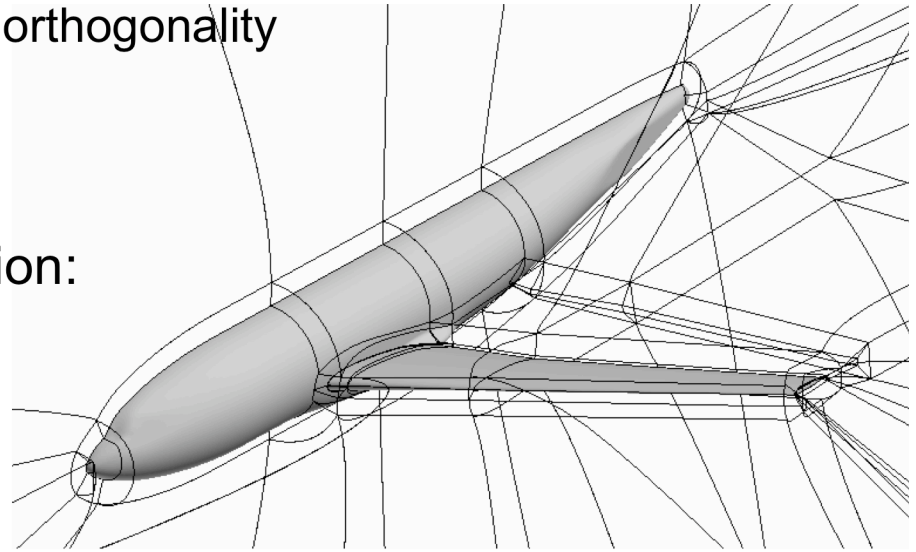
1. without trip term for transition
2. without ft2 function
3. with a modification of production term, $S = \Omega + \min(0, \hat{S} - \Omega)$

SST: Menter's shear stress transport *k-ω* two-equation model

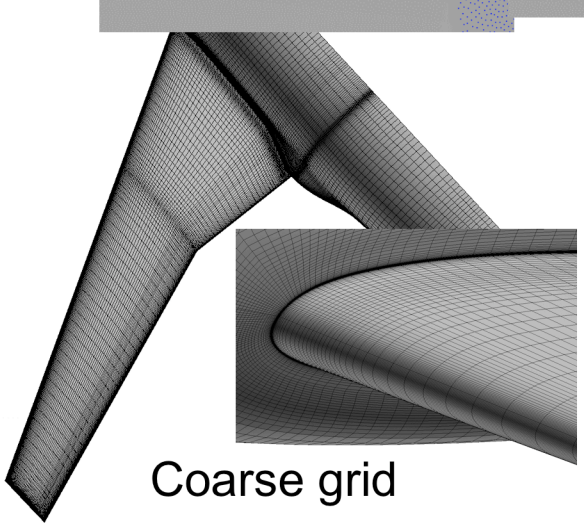
Point-matched multi-block structured grids

- Generated using a commercial software, Gridgen
  - Near the model surface:
    - O-O grid topology to guarantee good orthogonality within the boundary layer
  - Outward:
    - C-O grid topology
  - At the corner of the wing-body junction:
    - Two kinds of grid topology

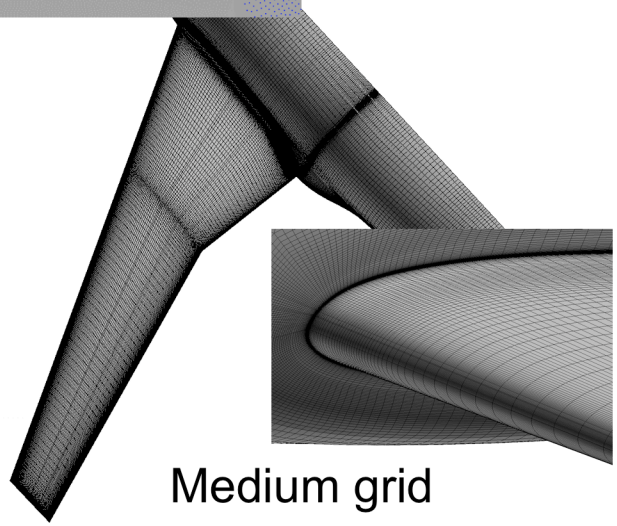




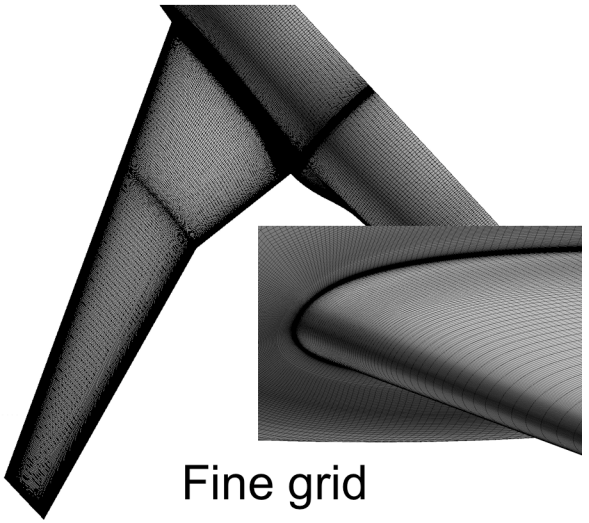
Block wire frame for DLR-F6 FX2B



Coarse grid



Medium grid



Fine grid

Mixed element unstructured grids

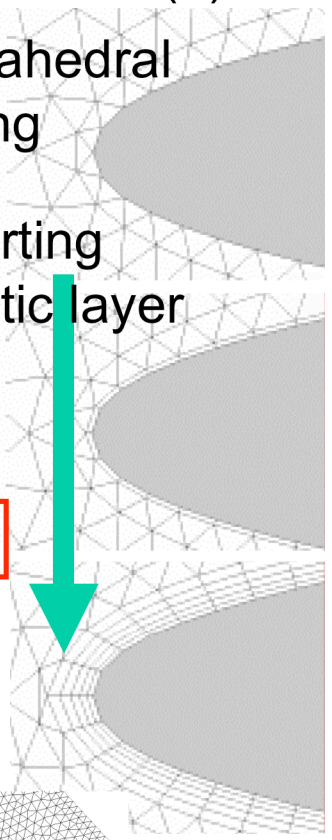
- Generated using TAS-Mesh
  - Surface grid (Triangles)
    - Direct advancing front method
    - Use of triangles that are not so stretched
  - Volume grid (Tetrahedra, Prisms, Pyramids)
    - Option of the generation method
    - (a) Delauney (tetra) → insertion of prismatic layer (prism)
    - (b) Advancing front (tetra) →insertion of prism layer (prism)
    - (c) Advancing layer (prism) →Advancing front (tetra)

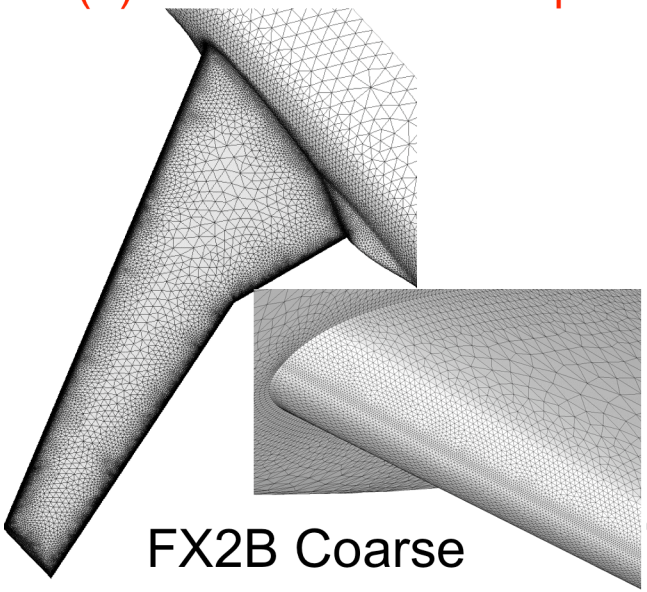
(a) is used for the computations

Procedure of (a)

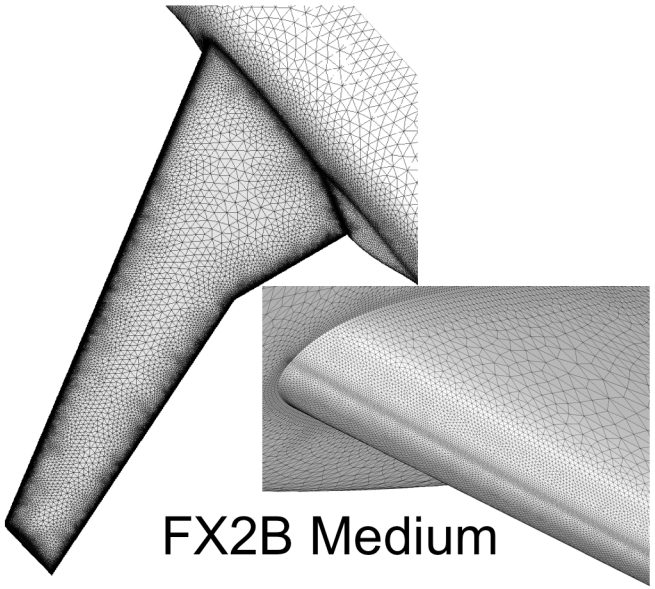
1. Tetrahedral meshing

2. Inserting prismatic layer

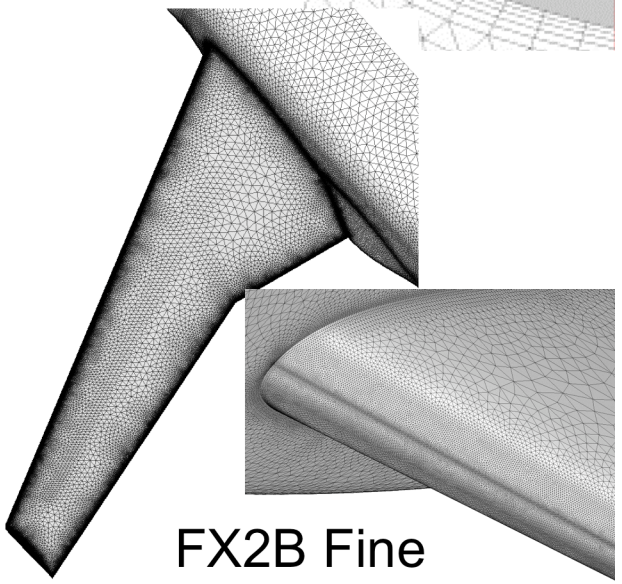




FX2B Coarse



FX2B Medium



FX2B Fine

Grid information

Structured grid (Simple)

Config.	Density	Nodes	Surf.Nodes	BL1stCellSize	GrowthRate	TE Cells
DLR-F6	Coarse	3.1M	47K	0.0006[mm]	1.29	8
	Medium	9.8M	100K	0.0004[mm]	1.17	12
	Fine	29.8M	209K	0.00027[mm]	1.12	16
DLR-F6 FX2B	Coarse	3.3M	49K	0.0006[mm]	1.29	8
	Meidum	10.0M	103K	0.0004[mm]	1.17	12
	Fine	29.8M	209K	0.00027[mm]	1.12	16

Unstructured grid

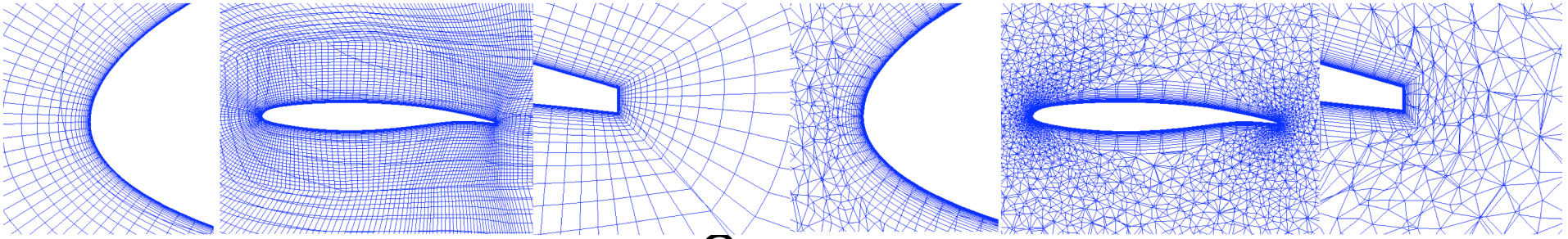
Config.	Density	Nodes	Surf.Nodes	BL1stCellSize	GrowthRate	TE Cells
DLR-F6	Coarse	5.4M	134K	0.0006[mm]	1.2	4
	Medium	9.4M	219K	0.0004[mm]	1.2	5
	Fine	17.5M	368K	0.00027[mm]	1.2	6
DLR-F6 FX2B	Coarse	5.4M	136K	0.0006[mm]	1.2	4
	Meidum	9.5M	223K	0.0004[mm]	1.2	5
	Fine	17.2M	378K	0.00027[mm]	1.2	6

Different from the grid guideline

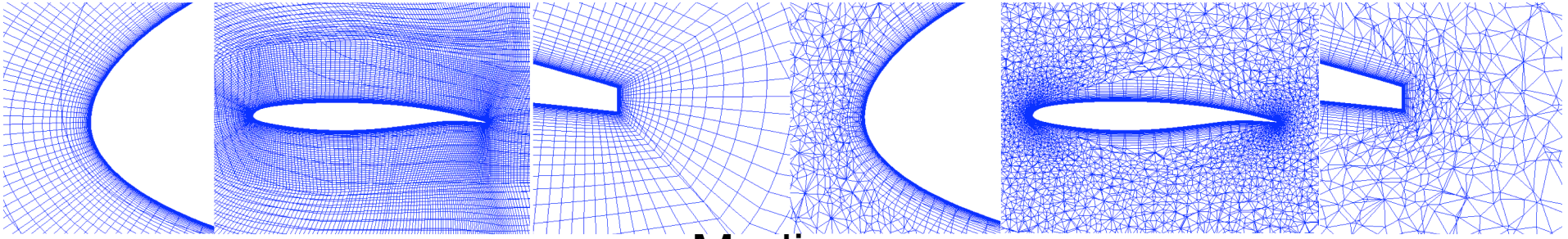
Comparison of cross-sectional view at kink location

Multi-block structured

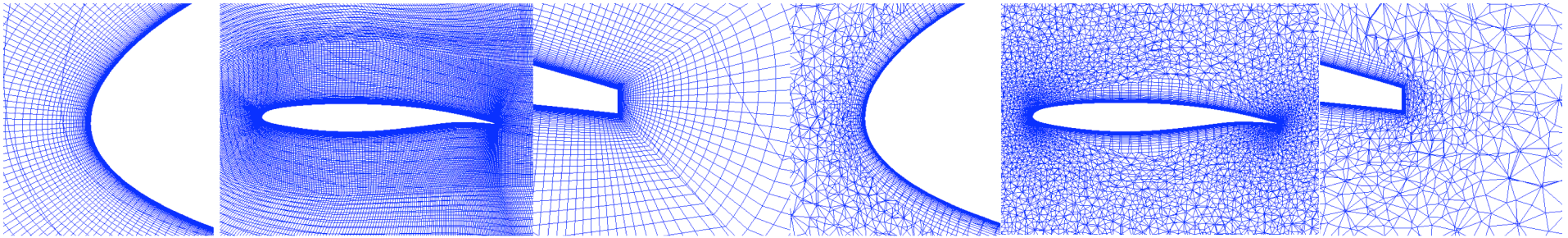
Unstructured



Coarse



Medium



Fine

Grid convergence

CD versus # of nodes, $N^{-2/3}$

at CL=0.5, M=0.75, $Re=5x10^6$, SA

CDpr:

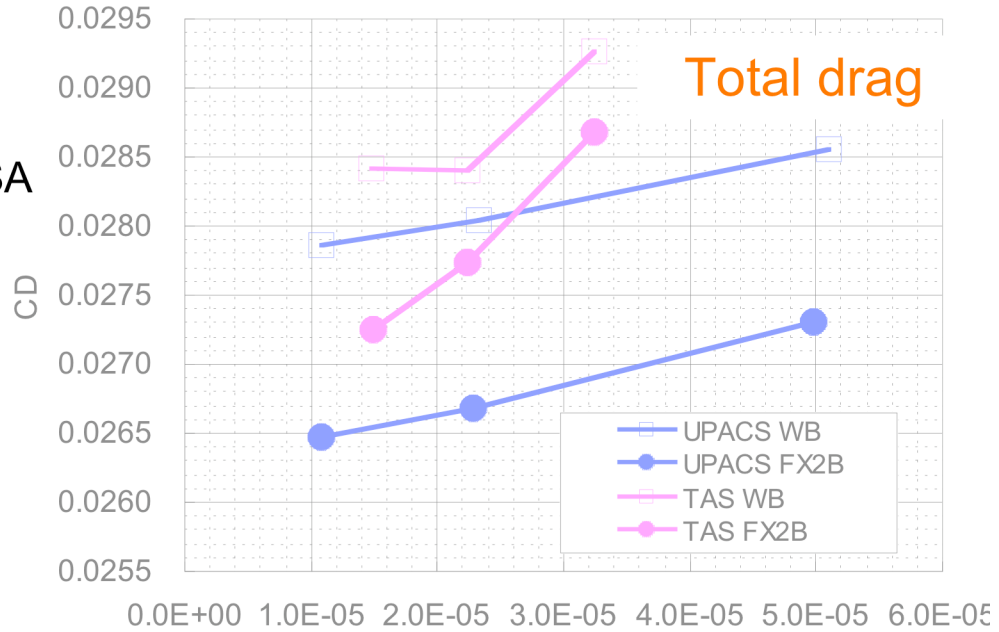
UPACS: Good convergence

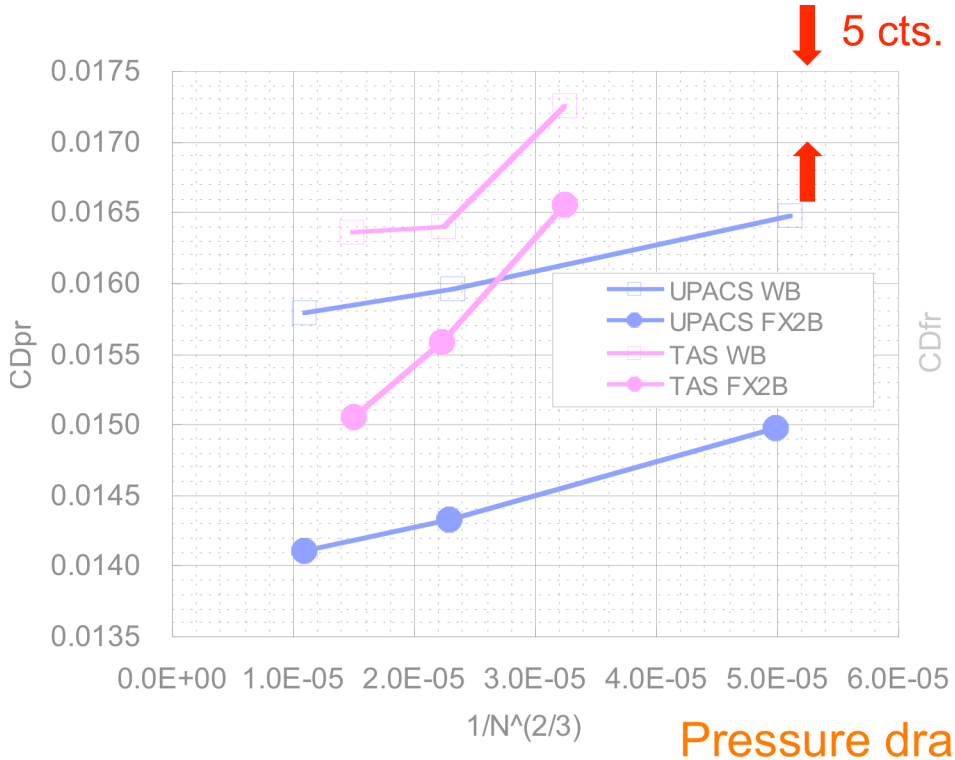
TAS: Not converged even on fine grid

Change with grid size is larger

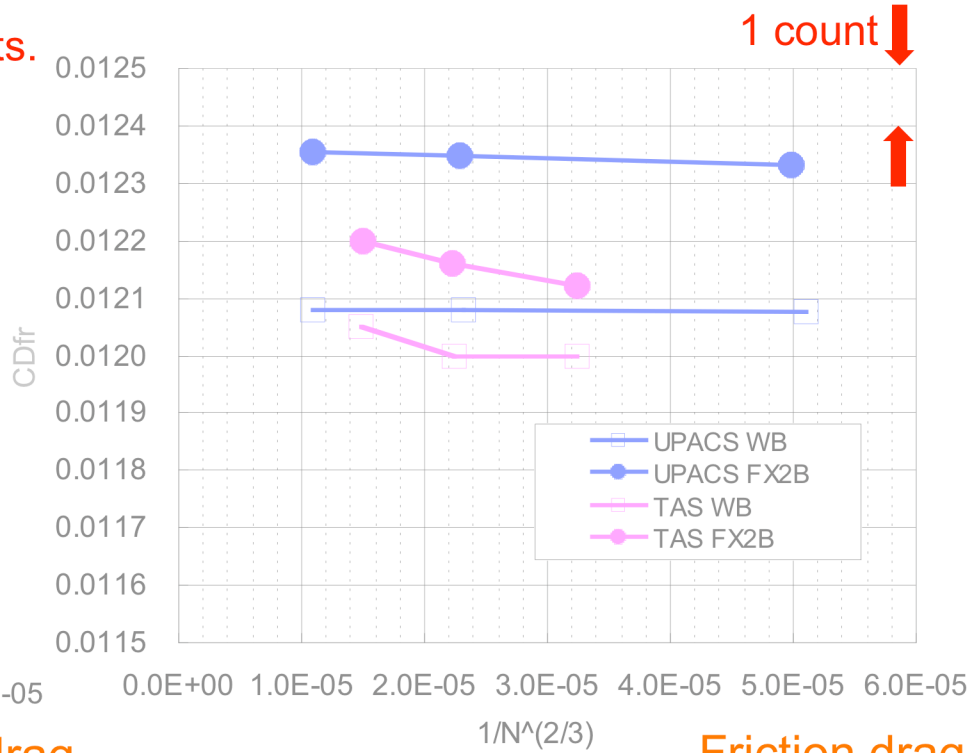
CDfr:

Change with grid size is small





Pressure drag



Friction drag

Grid convergence

CD versus # of nodes, $N^{-2/3}$

at CL=0.5, M=0.75, Re=5x10^6, SA

CDpr:

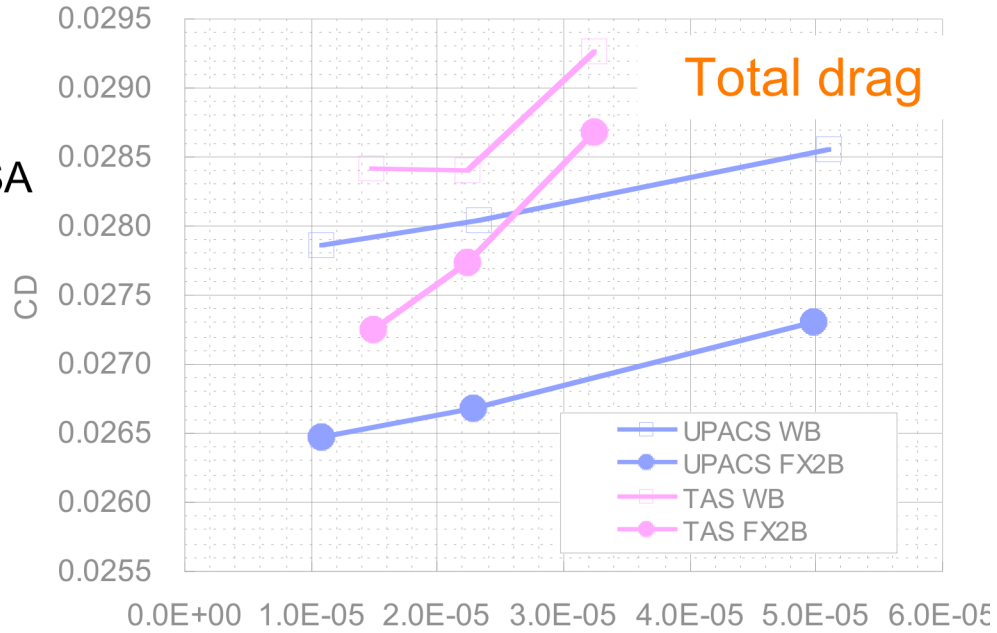
UPACS: Good convergence

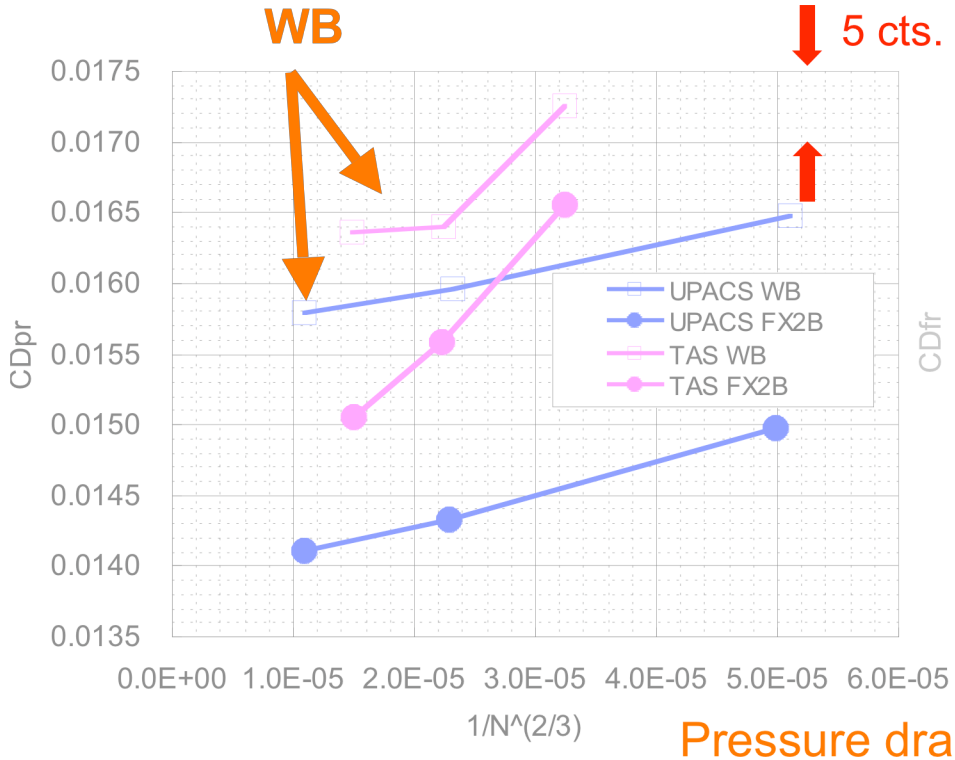
TAS: Not converged even on fine grid

Change with grid size is larger

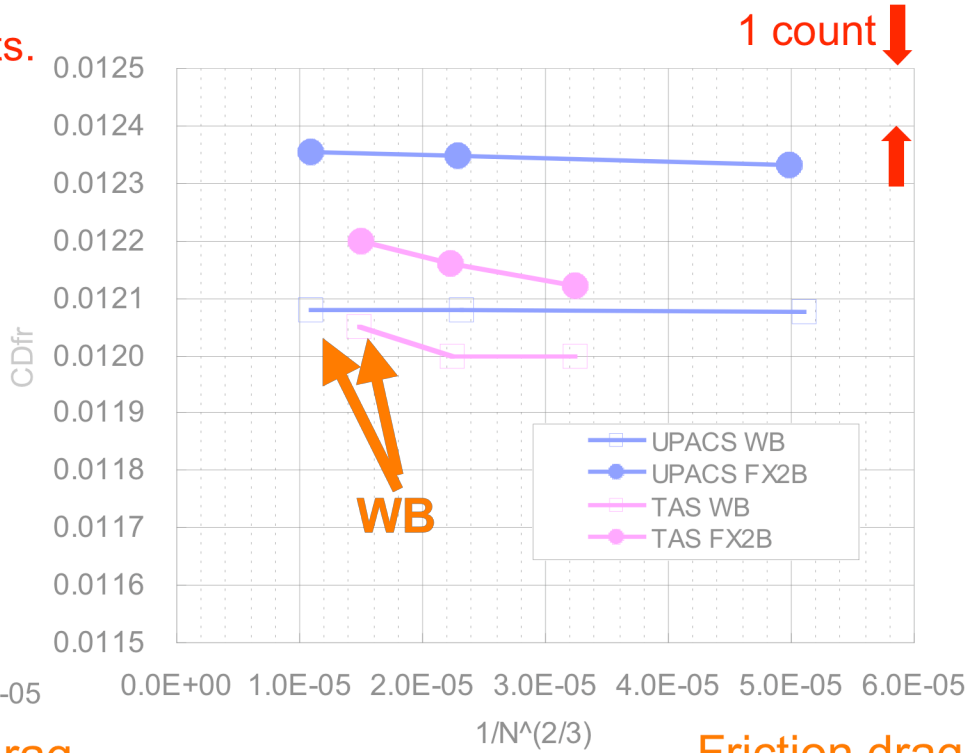
CDfr:

Change with grid size is small





Pressure drag



Friction drag

Grid convergence

CD versus # of nodes, $N^{-2/3}$

at CL=0.5, M=0.75, Re=5x10^6, SA

CDpr:

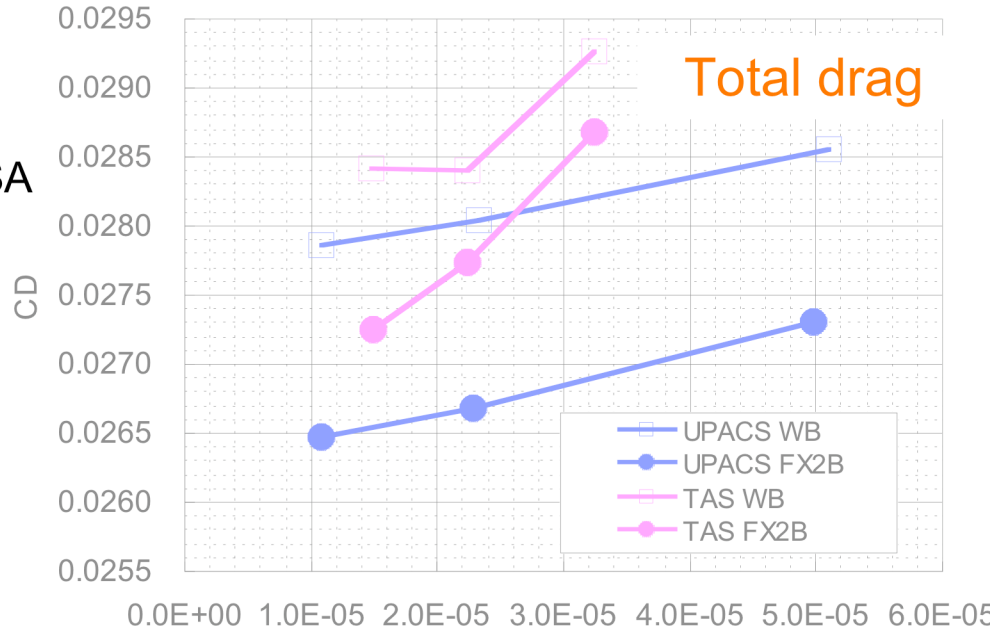
UPACS: Good convergence

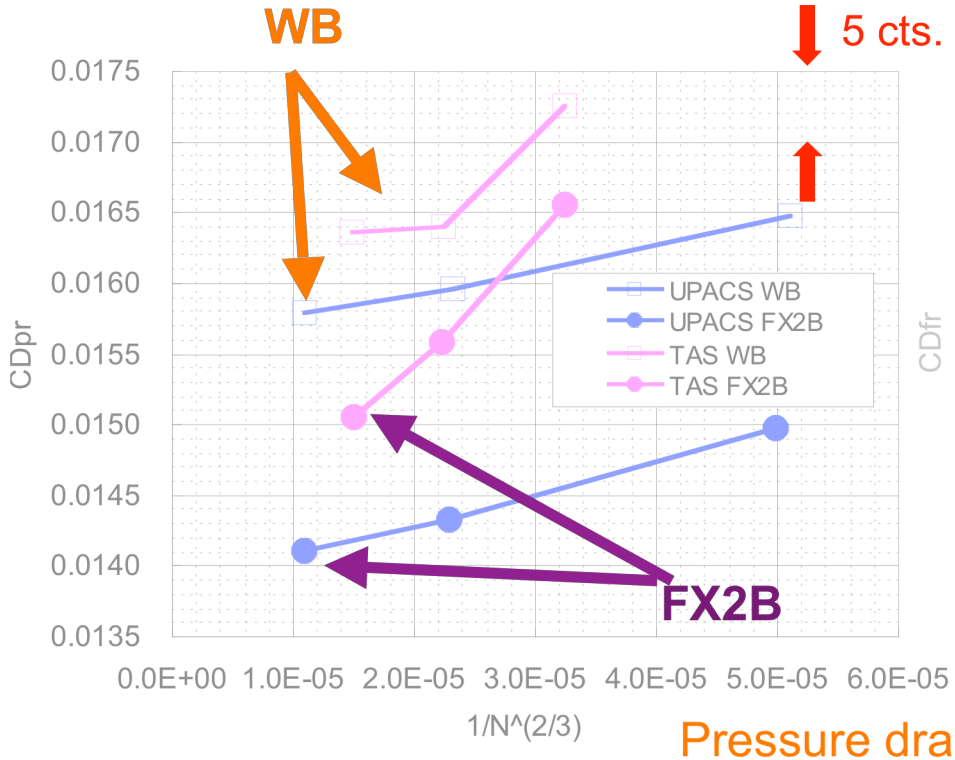
TAS: Not converged even on fine grid

Change with grid size is larger

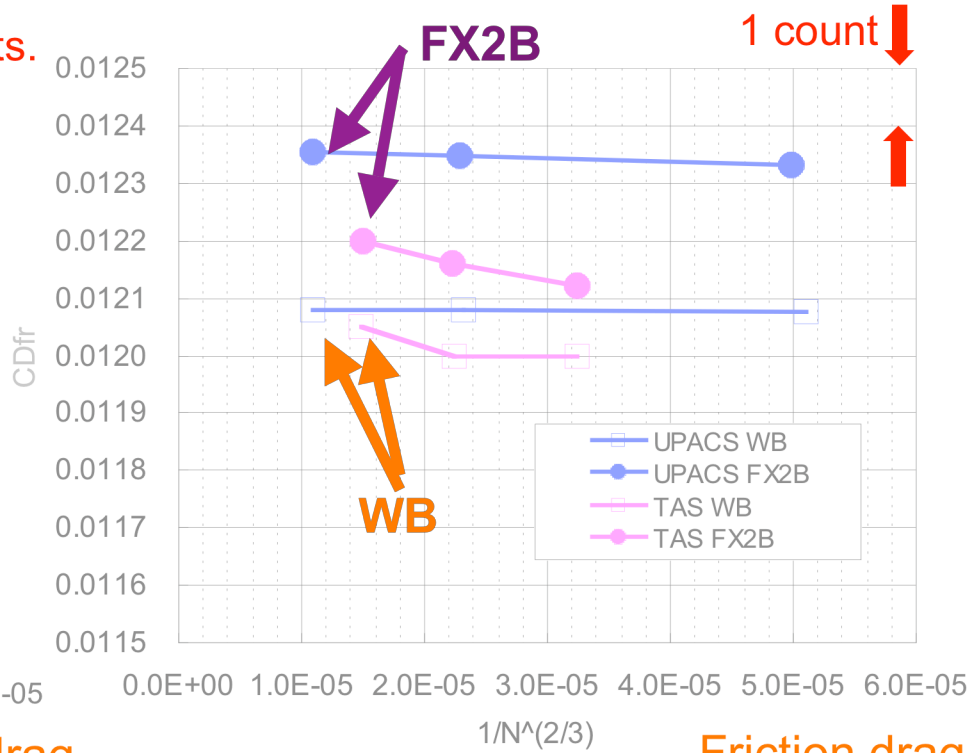
CDfr:

Change with grid size is small





Pressure drag



Friction drag

Grid convergence

CD versus # of nodes, $N^{-2/3}$

at CL=0.5, M=0.75, Re=5x10^6, SA

CDpr:

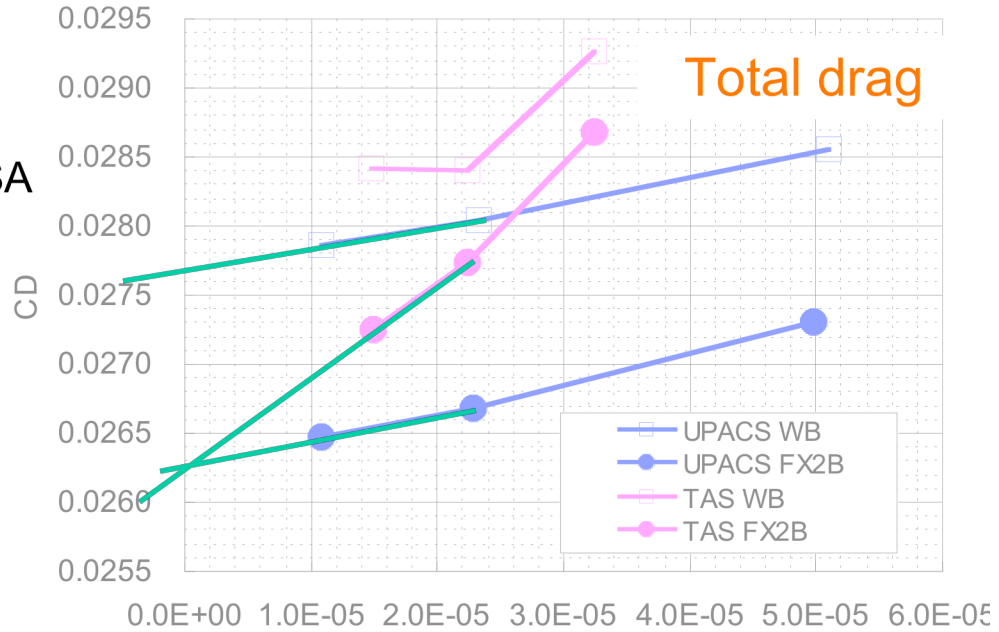
UPACS: Good convergence

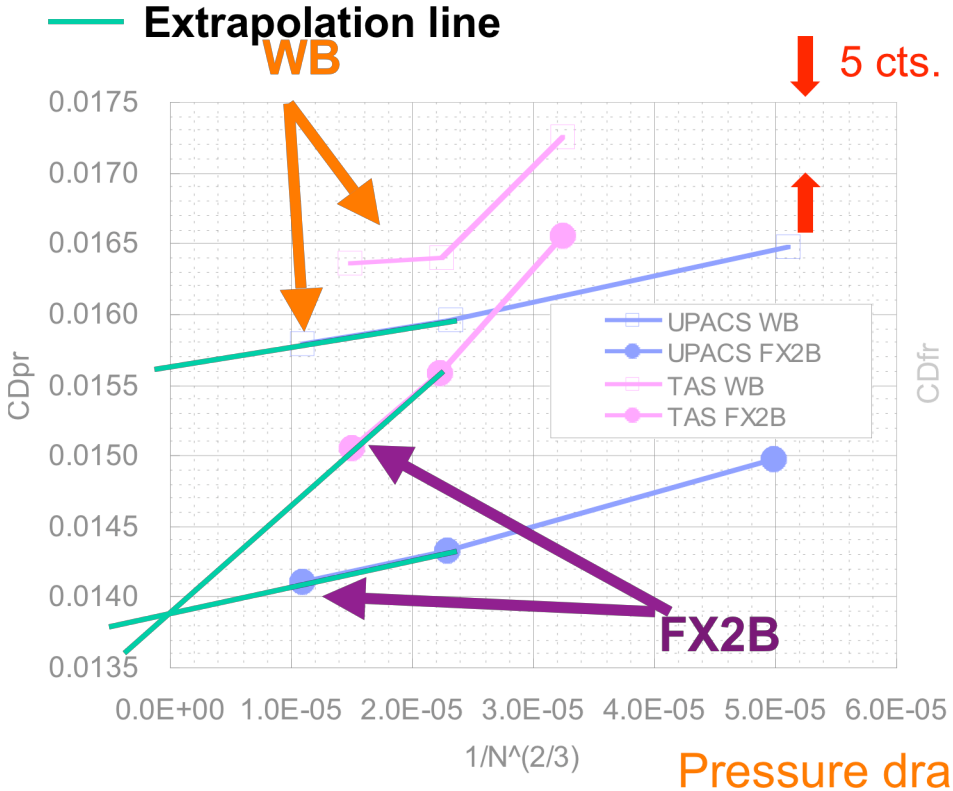
TAS: Not converged even on fine grid

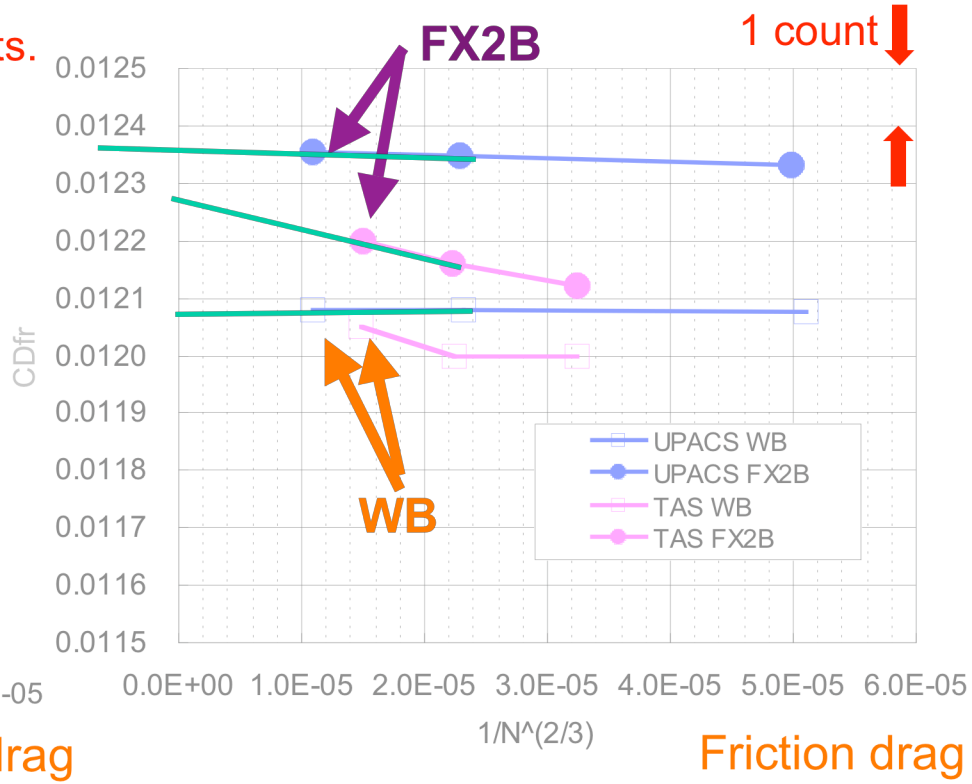
Change with grid size is larger

CDfr:

Change with grid size is small







Comparison of CL-CD on medium grids

at M=0.75, Re=5x10^6, SA

$\Delta CD_{WB-FX2B}$

UPACS:

10-14 cts.

TAS:

7 ~10 cts.

$\Delta CD_{UPACS-TAS}$

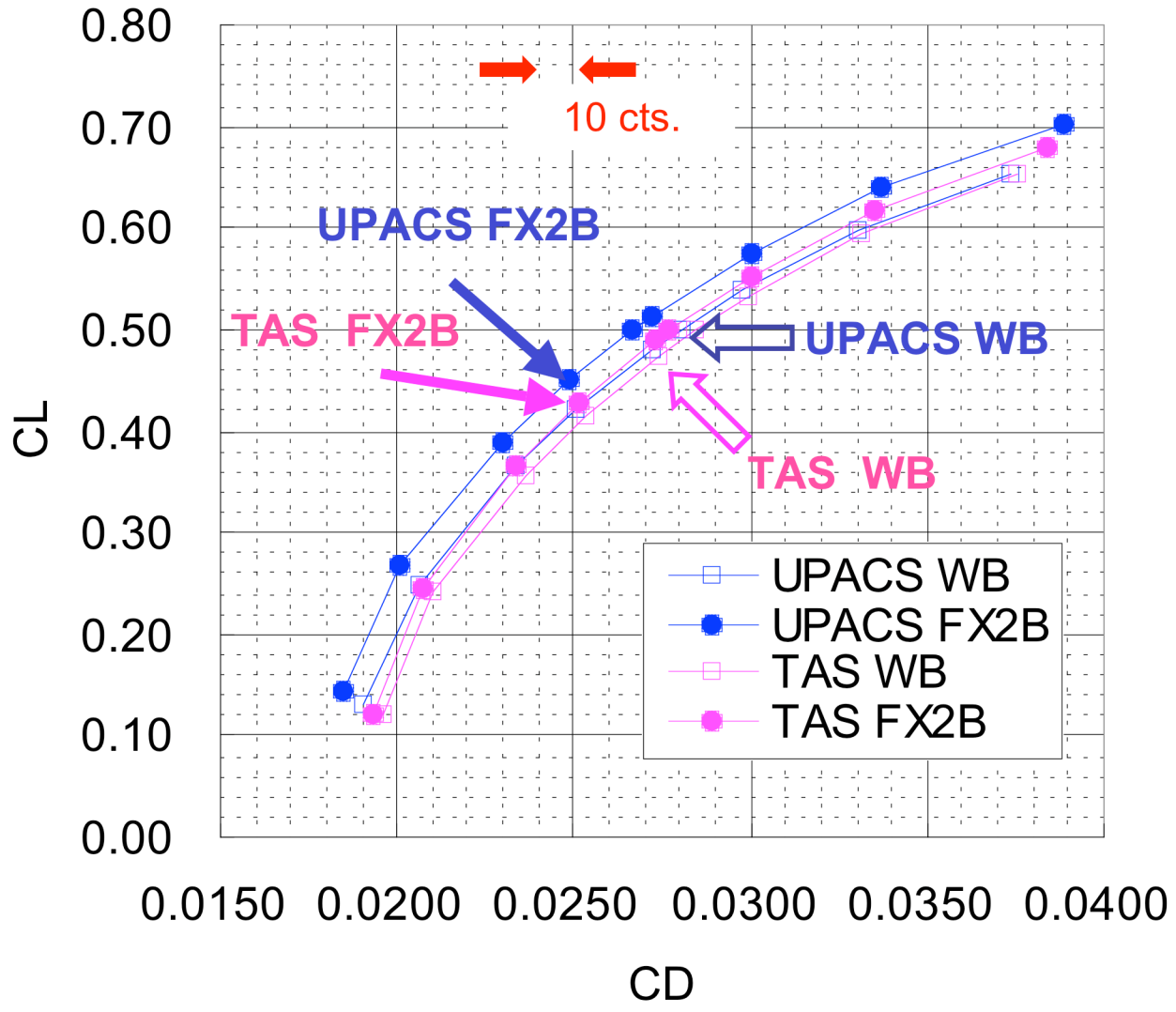
FX2B:

-10~-13 cts. shift

WB:

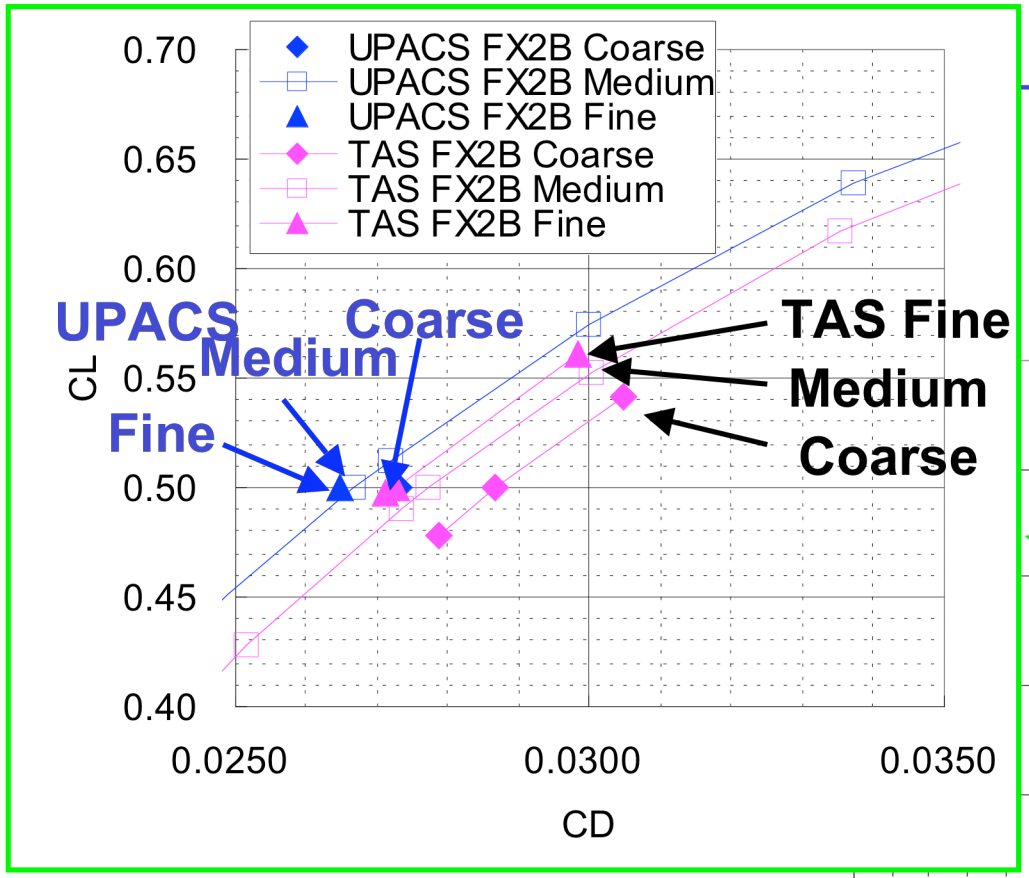
-5 cts. at lower α

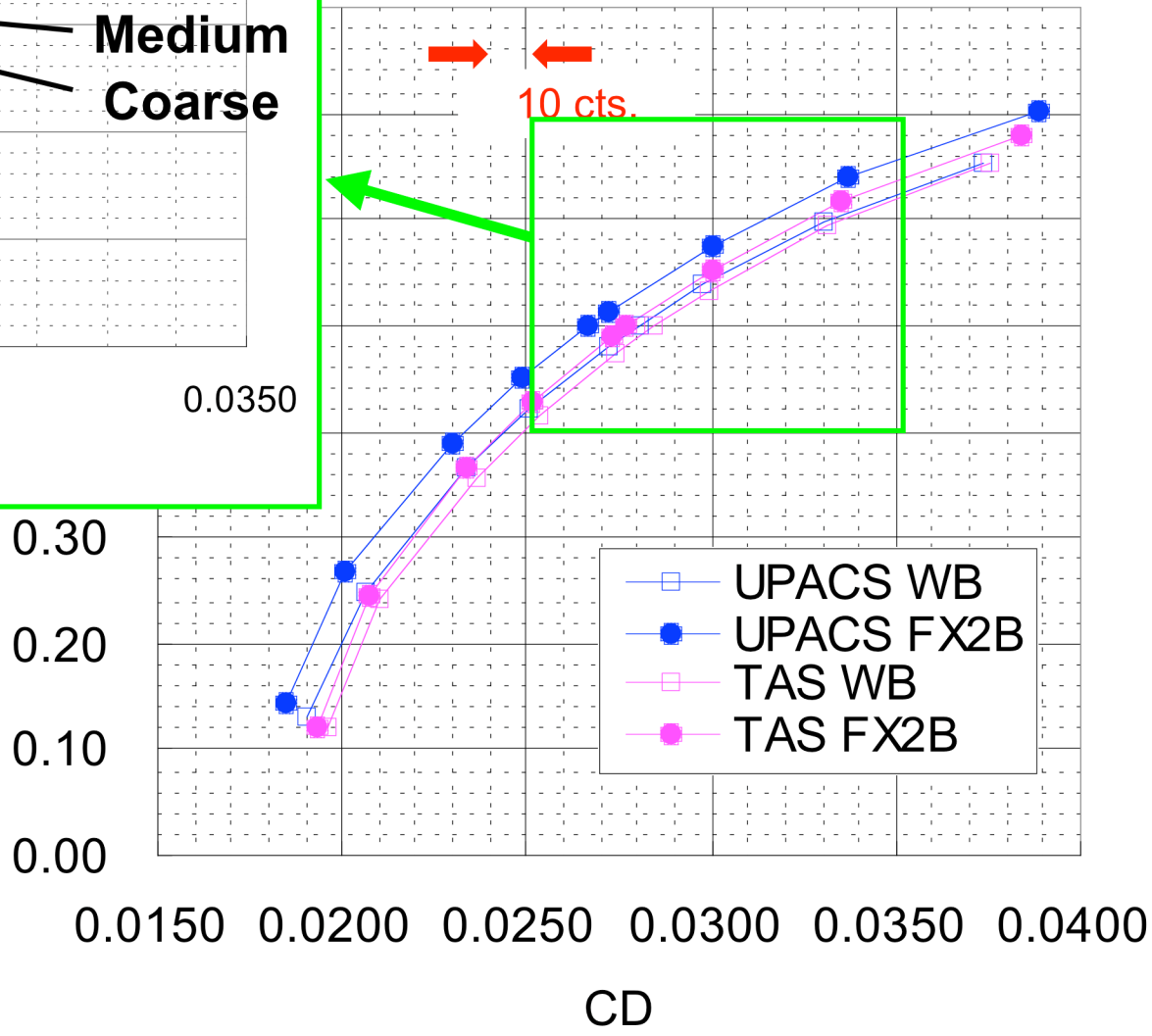
-1~-2 cts. at upper α



on medium grids

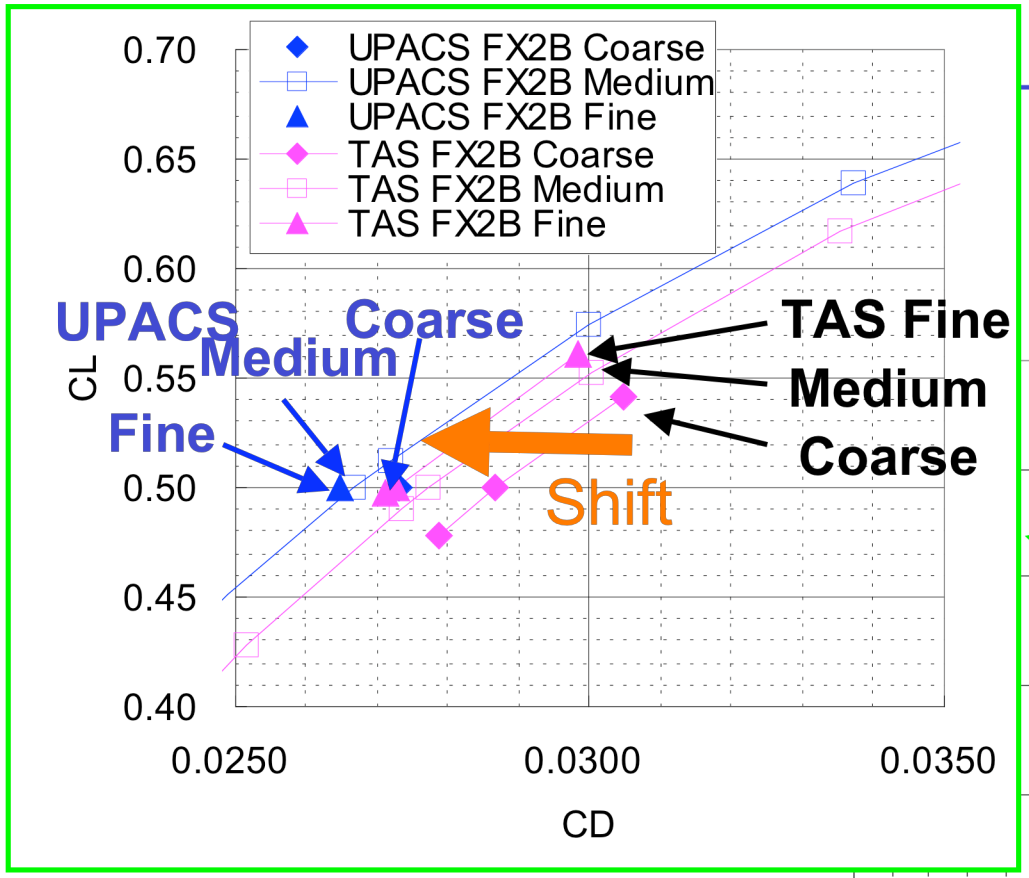
at M=0.75, Re=5x10^6, SA

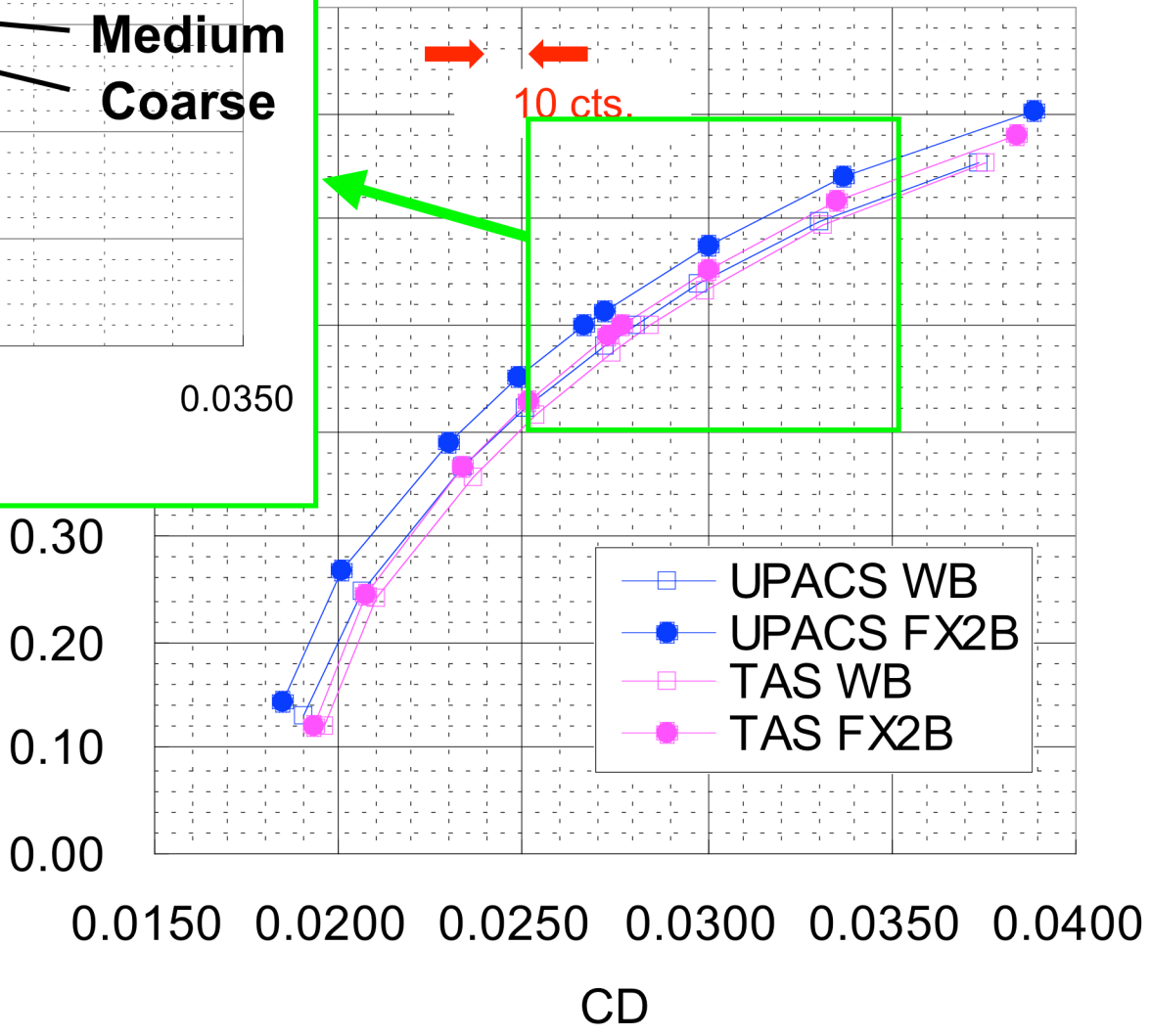




on medium grids

at M=0.75, Re=5x10^6, SA





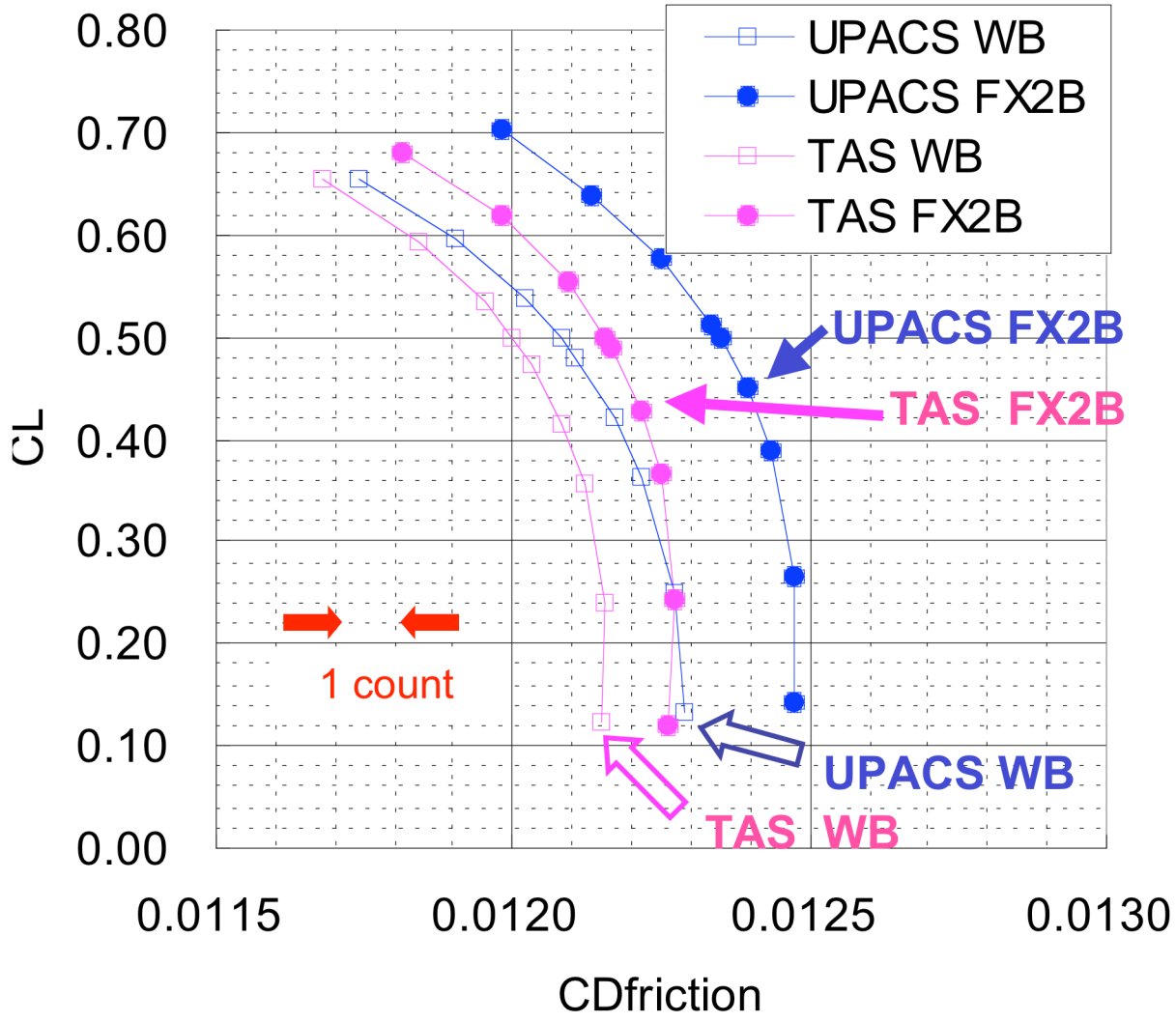
By the increase of grid resolution, TAS showed better agreement with UPACS

Comparison of CDfr on medium grids

at M=0.75, Re=5x10^6, SA

$\Delta CDfr_{FX2B\text{-}WB}$: 1~3 cts.

$\Delta CDfr_{UPACS\text{-}TAS}$: 1~2 cts.



Comparison of CL-alpha and CL-CM on medium grids

at M=0.75, Re=5x10^6, SA

CL

WB:

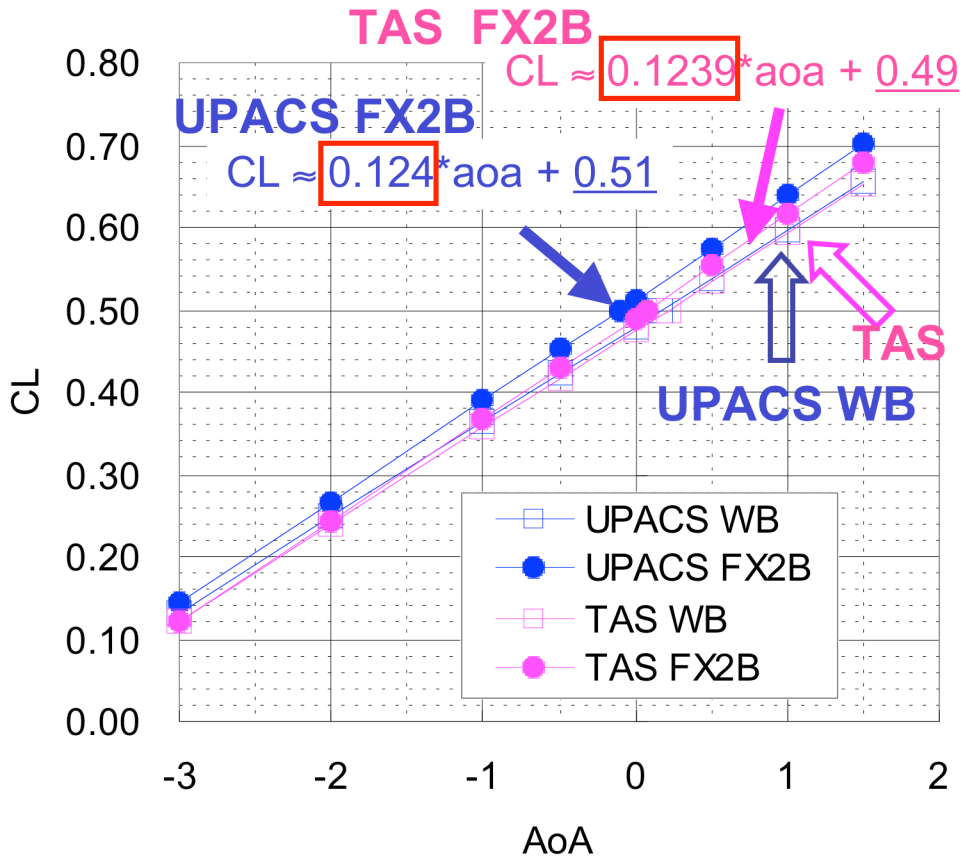
Both codes show good agreement

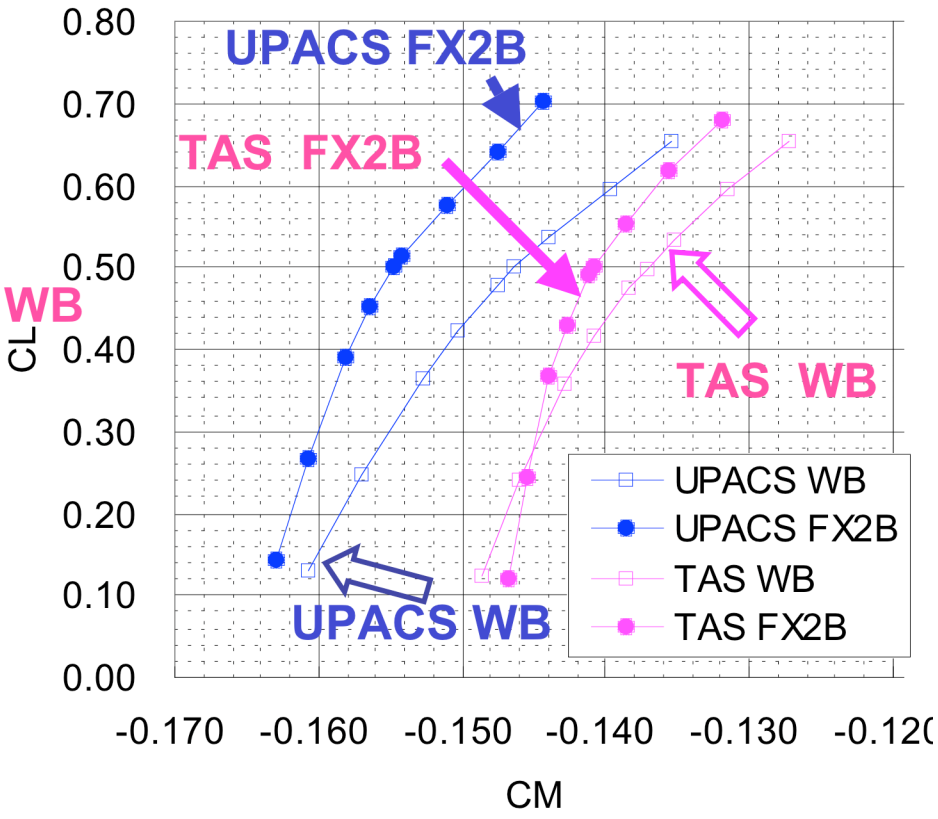
FX2B:

Shift of ΔCL≈0.02

CM

Shift of ΔCM≈0.01~0.015 between the codes

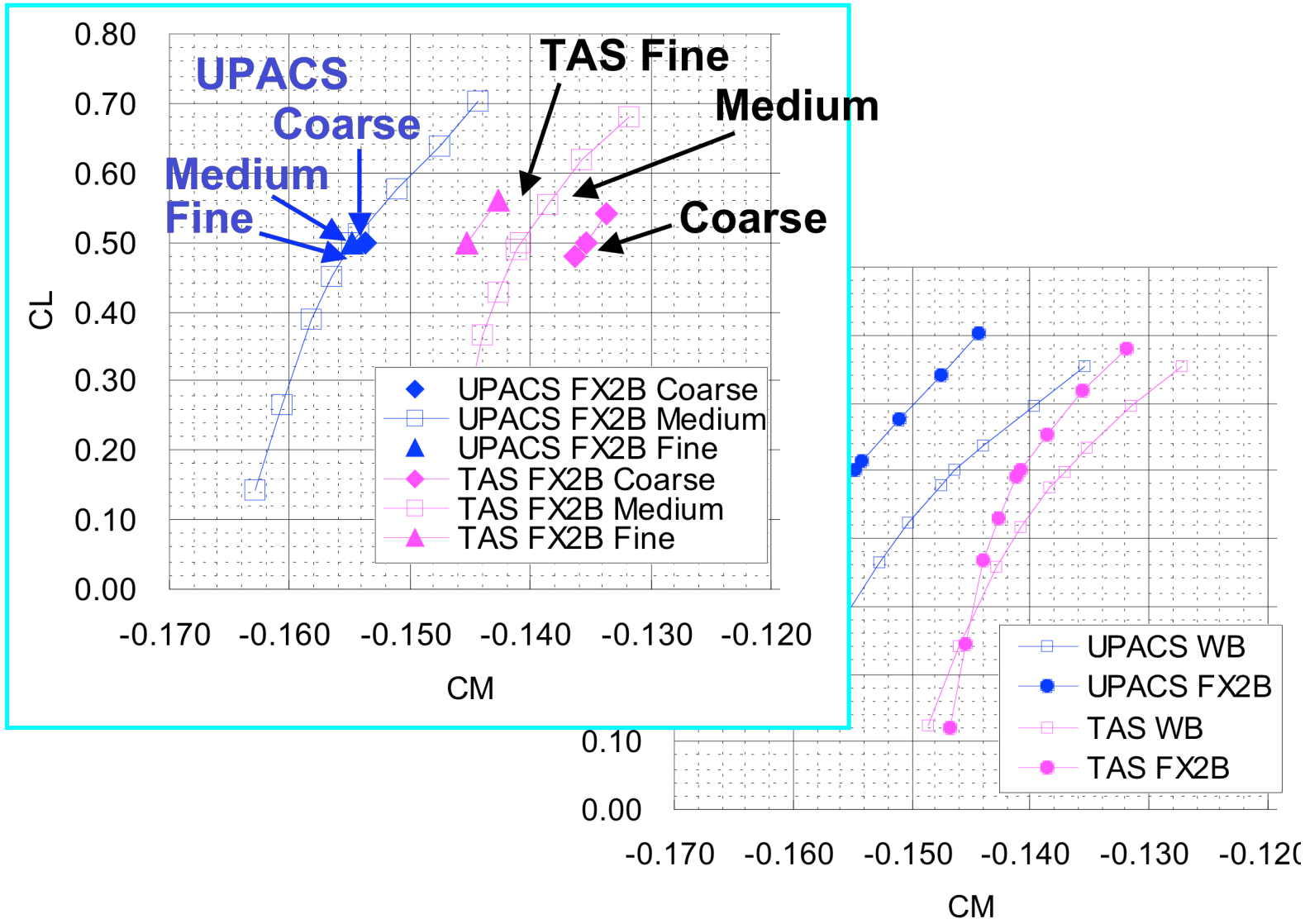




Grid dependency of CL-CM

at M=0.75, Re=5x10^6, SA

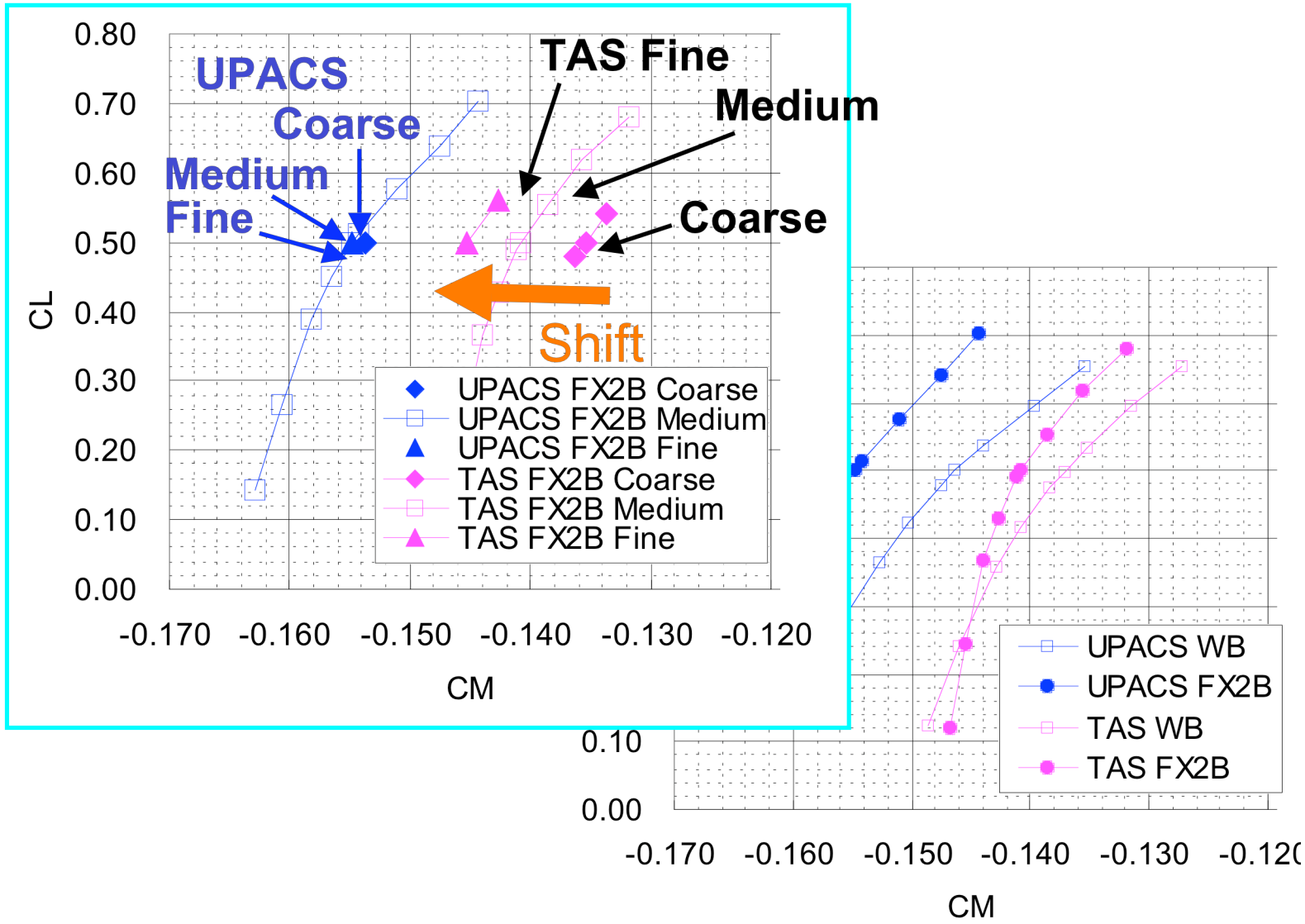
Grid dependency of unstructured grid is relatively larger



Grid dependency of CL-CM

at M=0.75, Re=5x10^6, SA

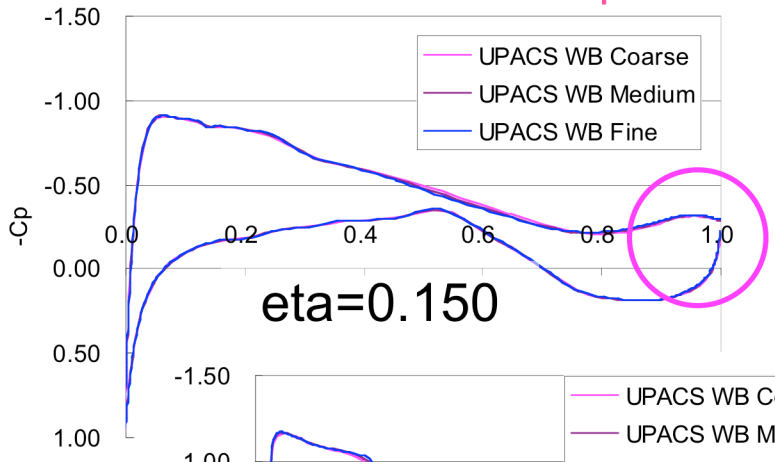
Grid dependency of unstructured grid is relatively larger

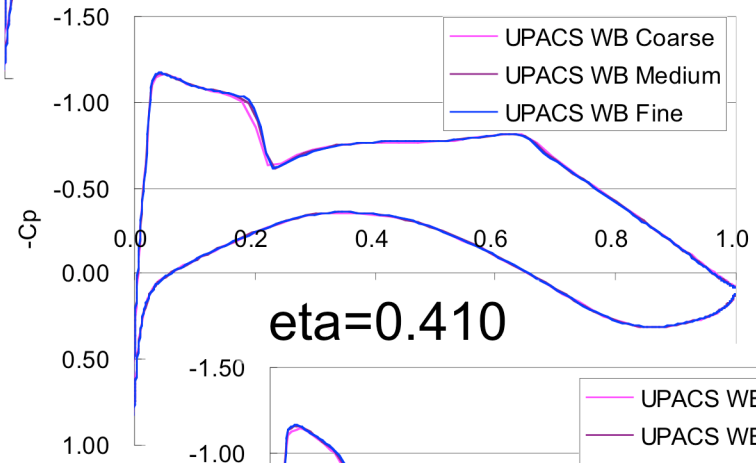


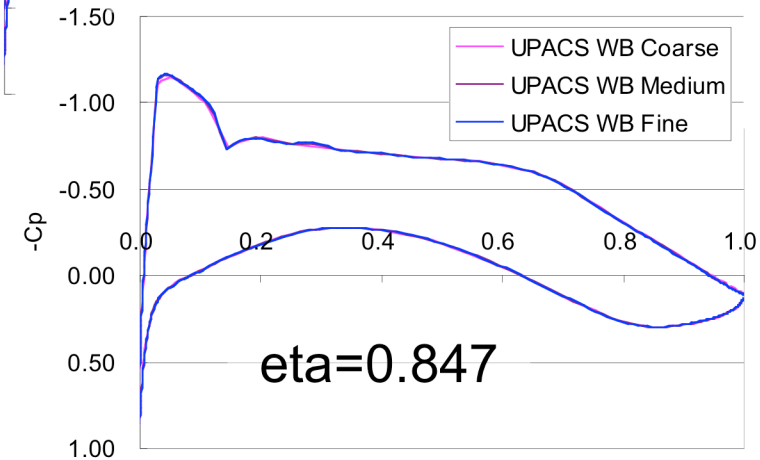
Grid dependency of Cp for WB Configuration

UPACS

Small grid dependency even for separation

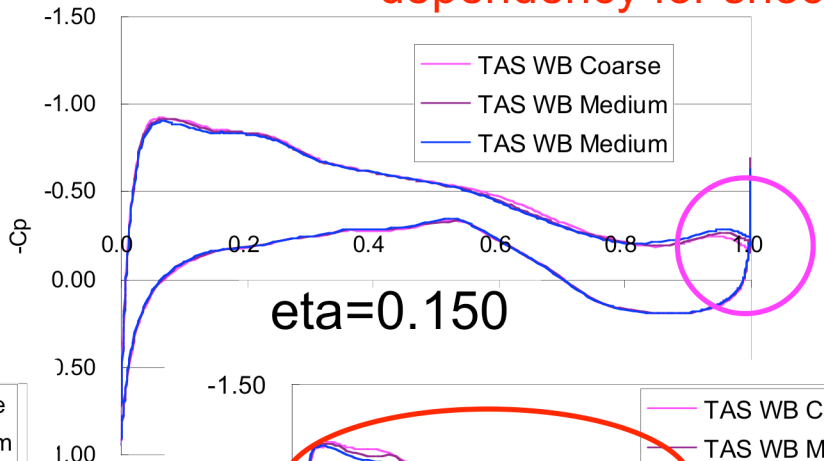


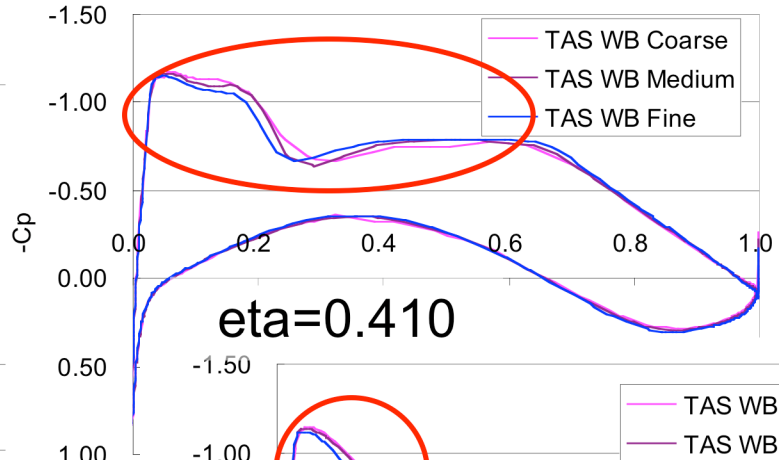


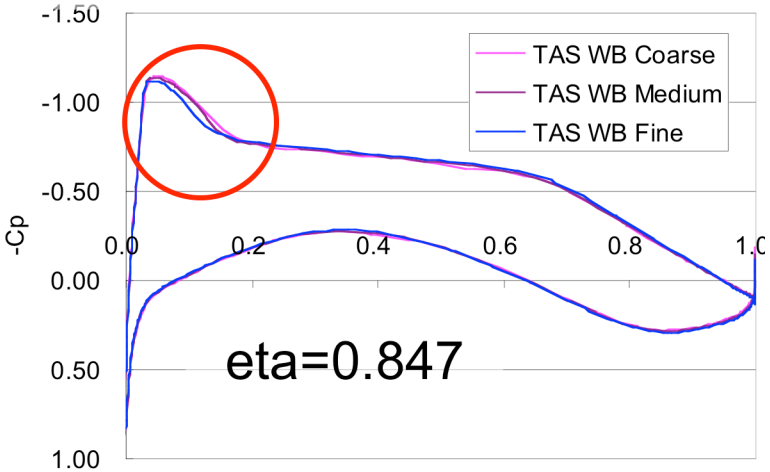


TAS

Relatively larger grid dependency for shock





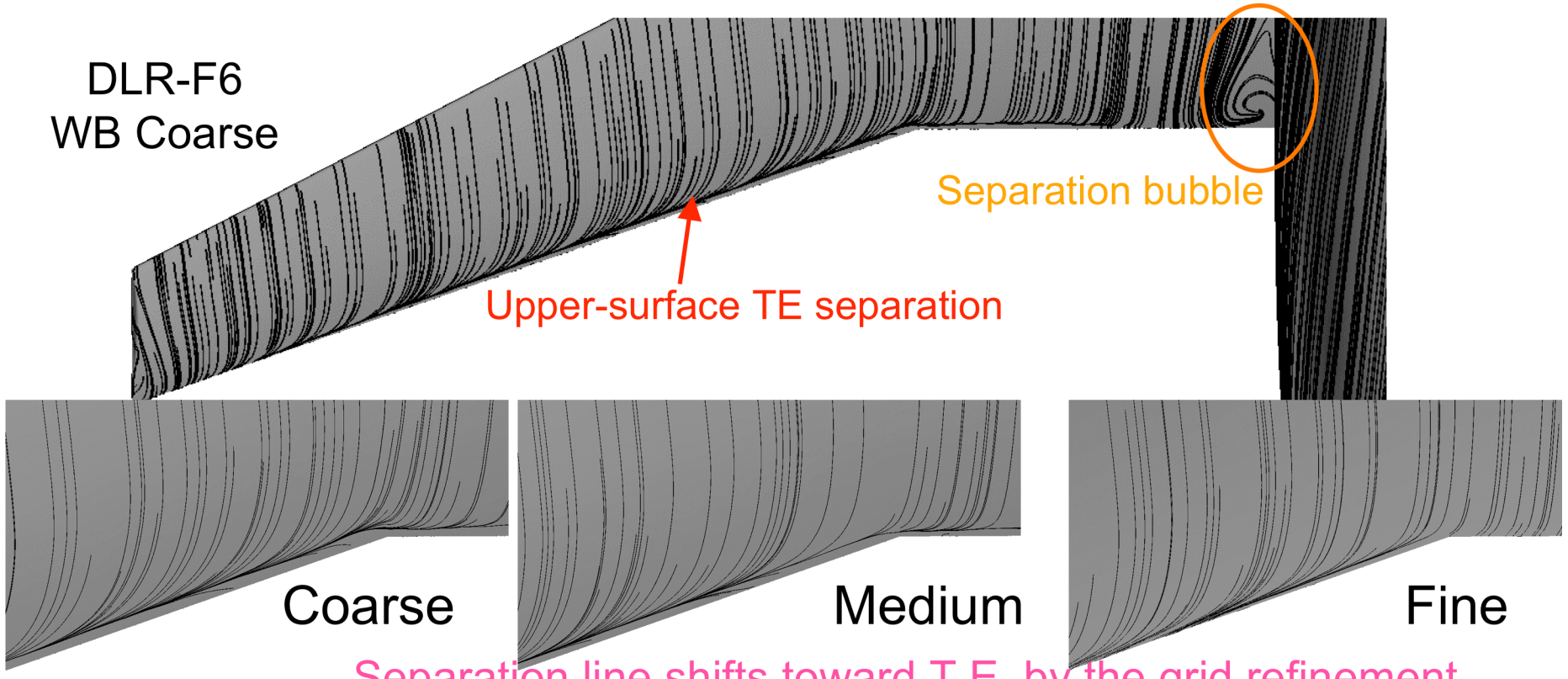


Upper-surface trailing-edge separation location

at CL=0.5, M=0.75, Re=5x10^6, SA

TAS

Y/BO2	DLR-F6 WB			DLR-F6 WB FX2B		
	Coarse(AoA0.274	Medium(AoA0.213	Fine(AoA0.104)	Coarse(AoA0.168)	Medium(AoA0.081)	Fine(AoA0.017)
0.15	0.834	0.82	0.81	1	1	1
0.239	1	1	1	0.987	1	1
0.331	0.982	0.995	1	0.981	0.984	0.986
0.377	0.984	0.99	1	0.982	0.984	0.987
0.411	0.972	0.985	0.987	0.967	0.976	0.979
0.514	0.971	0.981	0.997	0.967	0.968	0.978
0.638	0.979	0.981	0.999	0.973	0.973	0.975



Separation line shifts toward T.E. by the grid refinement

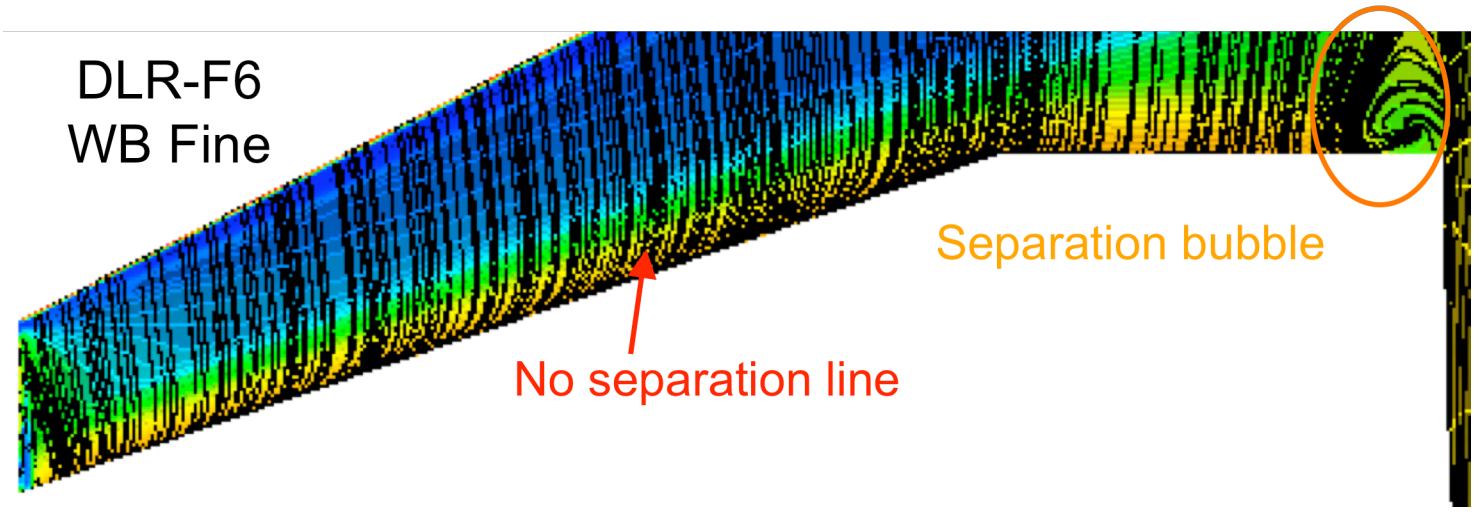
Upper-surface trailing-edge separation location

at CL=0.5, M=0.75, Re=5x10^6, SA

UPACS

Y/BO2	DLR-F6 WB			DLR-F6 WB FX2B		
	Coarse(AoA0.151	Medium(AoA0.174	Fine(AoA0.188)	Coarse(AoA-0.104	Medium(AoA-0.104	Fine(AoA-0.096)
0.15			0.804	1	1	1
0.239	1	1	1	1	1	1
0.331	1	1	1	1	1	1
0.377	1	1	1	1	1	1
0.411	1	1	1	1	1	1
0.514	1	1	1	1	1	1
0.638	1	1	1	1	1	1

No separation line near T.E. on all grids



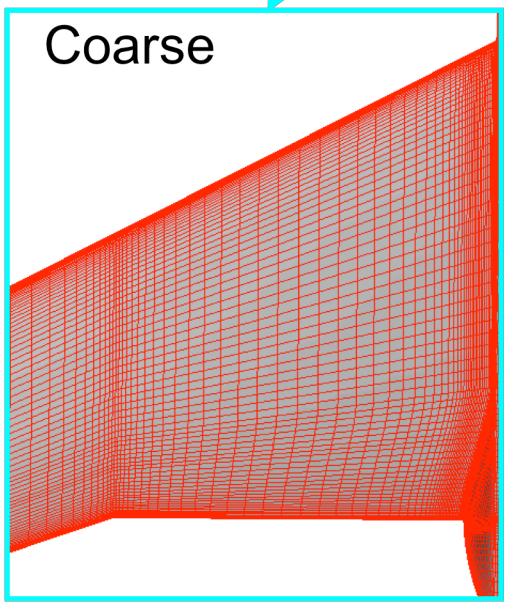
Upper-surface trailing-edge separation location

at CL=0.5, M=0.75, Re=5x10^6, SA

UPACS

Y/BO2	DLR-F6 WB			DLR-F6 WB FX2B		
	Coarse(AoA0.151	Medium(AoA0.174	Fine(AoA0.188)	Coarse(AoA-0.104)	Medium(AoA-0.104)	Fine(AoA-0.096)
0.15			0.804	1	1	1
0.239	1	1	1	1	1	1
0.331	1	1	1	1	1	1
0.377	1	1	1	1	1	1
0.411	1	1	1	1	1	1
0.514	1	1	1	1	1	1
0.638	1	1	1	1	1	1

No separation line near T.E. on all grids



Upper-surface trailing-edge separation location

at CL=0.5, M=0.75, Re=5x10^6, SA

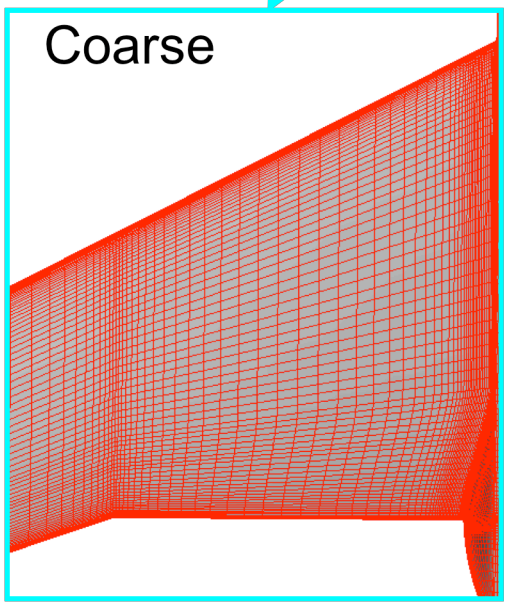
UPACS

Y/BO2	DLR-F6 WB			DLR-F6 WB FX2B		
	Coarse(AoA0.151	Medium(AoA0.174	Fine(AoA0.188)	Coarse(AoA-0.104)	Medium(AoA-0.104)	Fine(AoA-0.096)
0.15			0.804	1	1	1
0.239	1	1	1	1	1	1
0.331	1	1	1	1	1	1
0.377	1	1	1	1	1	1
0.411	1	1	1	1	1	1
0.514	1	1	1	1	1	1
0.638	1	1	1	1	1	1

No separation line near T.E. on all grids

Spanwise refinement to decrease aspect ratio of grid

(Change of spanwise grid resolution by 1/2x , 4x, 8x)



Upper-surface trailing-edge separation location

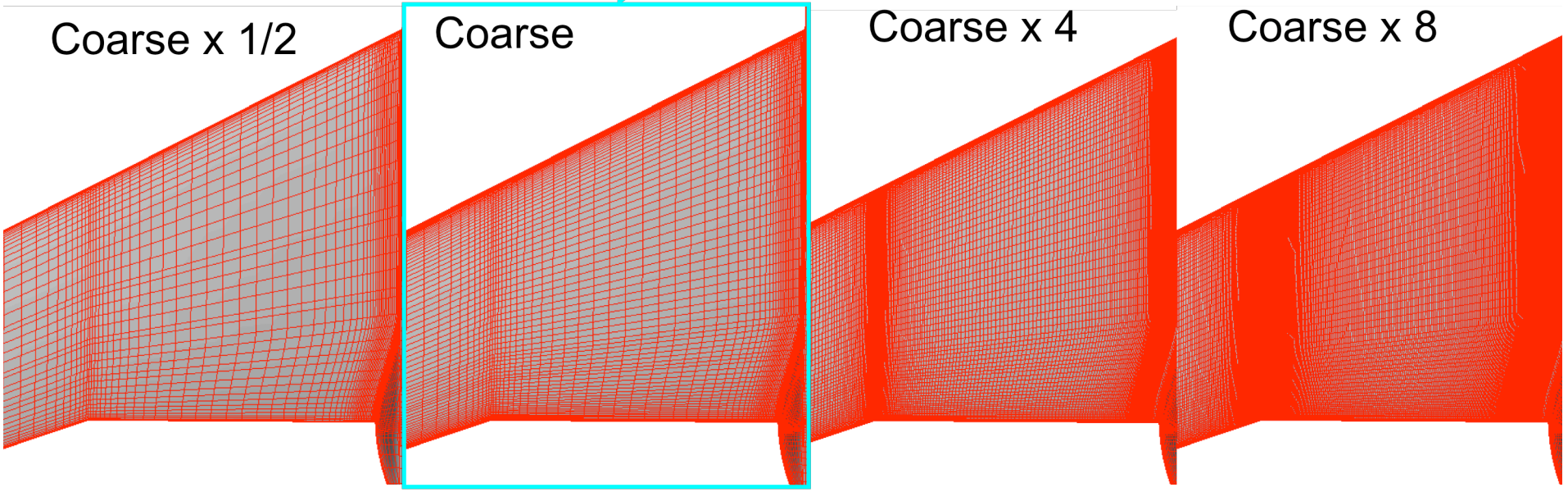
at CL=0.5, M=0.75, Re=5x10^6, SA

UPACS

Y/BO2	DLR-F6 WB			DLR-F6 WB FX2B		
	Coarse(AoA0.151	Medium(AoA0.174	Fine(AoA0.188)	Coarse(AoA-0.104	Medium(AoA-0.104	Fine(AoA-0.096)
0.15			0.804	1	1	1
0.239	1	1	1	1	1	1
0.331	1	1	1	1	1	1
0.377	1	1	1	1	1	1
0.411	1	1	1	1	1	1
0.514	1	1	1	1	1	1
0.638	1	1	1	1	1	1

No separation line near T.E. on all grids

Spanwise refinement to decrease aspect ratio of grid
(Change of spanwise grid resolution by 1/2x , 4x, 8x)



Upper-surface trailing-edge separation location

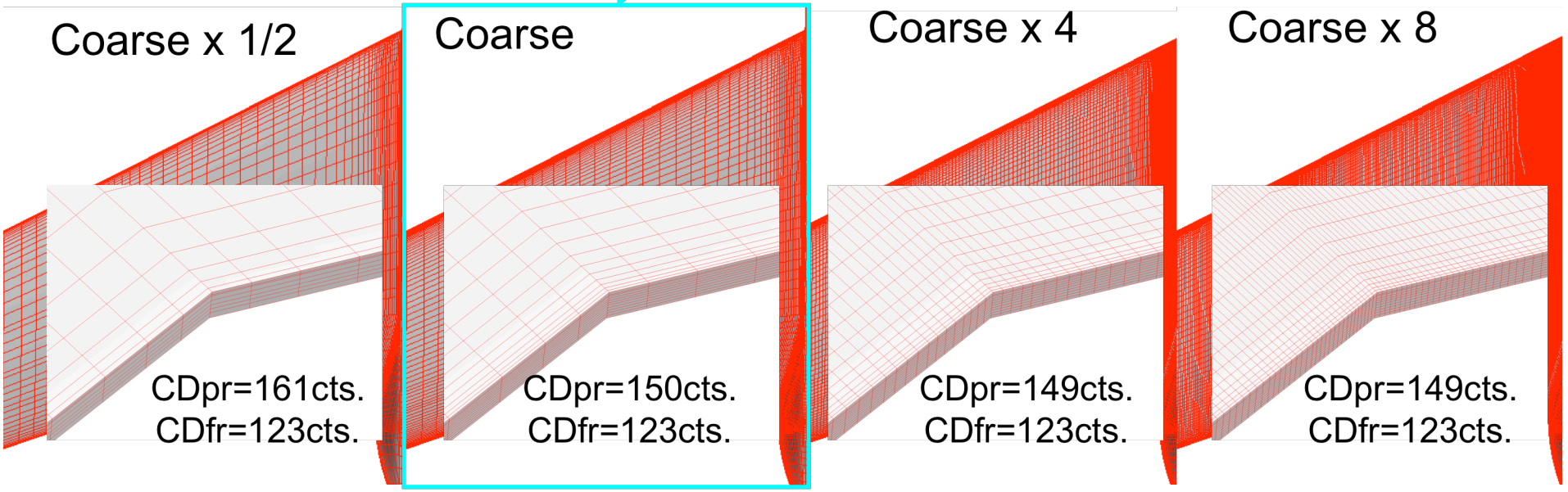
at CL=0.5, M=0.75, Re=5x10^6, SA

UPACS

Y/BO2	DLR-F6 WB			DLR-F6 WB FX2B		
	Coarse(AoA0.151	Medium(AoA0.174	Fine(AoA0.188)	Coarse(AoA-0.104	Medium(AoA-0.104	Fine(AoA-0.096)
0.15			0.804	1	1	1
0.239	1	1	1	1	1	1
0.331	1	1	1	1	1	1
0.377	1	1	1	1	1	1
0.411	1	1	1	1	1	1
0.514	1	1	1	1	1	1
0.638	1	1	1	1	1	1

No separation line near T.E. on all grids

Spanwise refinement to decrease aspect ratio of grid
(Change of spanwise grid resolution by 1/2x , 4x, 8x)



Upper-surface trailing-edge separation location

at CL=0.5, M=0.75, Re=5x10^6, SA

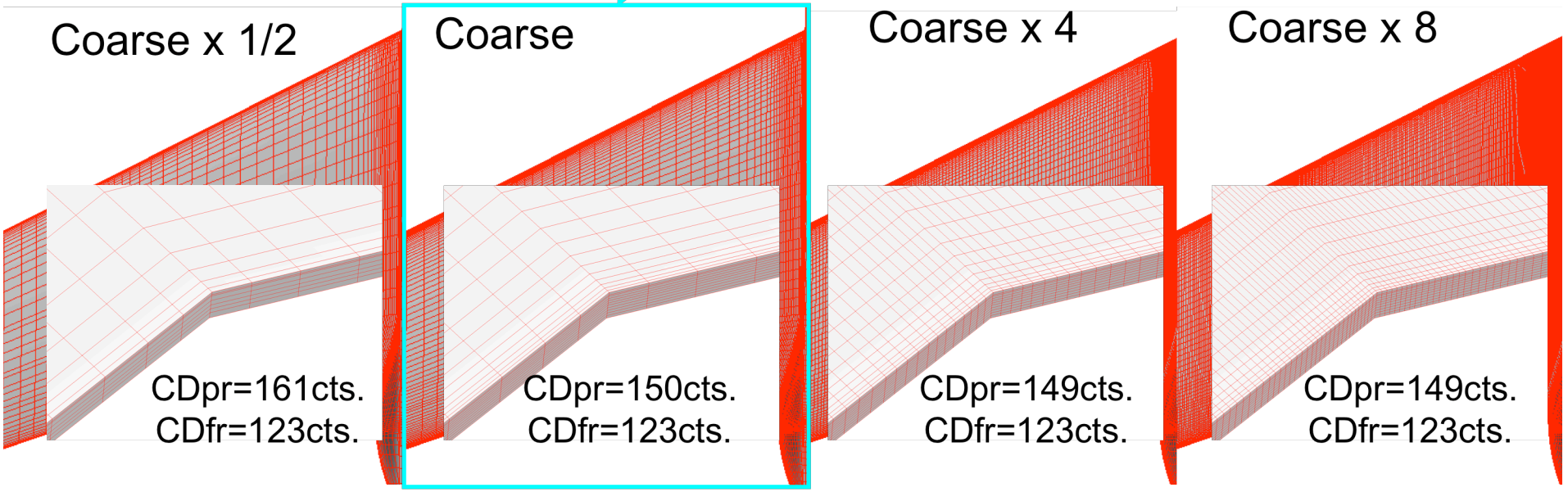
UPACS

Y/BO2	DLR-F6 WB			DLR-F6 WB FX2B		
	Coarse(AoA0.151	Medium(AoA0.174	Fine(AoA0.188)	Coarse(AoA-0.104	Medium(AoA-0.104	Fine(AoA-0.096)
0.15			0.804	1	1	1
0.239	1	1	1	1	1	1
0.331	1	1	1	1	1	1
0.377	1	1	1	1	1	1
0.411	1	1	1	1	1	1
0.514	1	1	1	1	1	1
0.638	1	1	1	1	1	1

No separation line near T.E. on all grids

Spanwise refinement to decrease aspect ratio of grid ⇨ No separation

(Change of spanwise grid resolution by 1/2x , 4x, 8x)



Separation bubble near the wing-fuselage junction

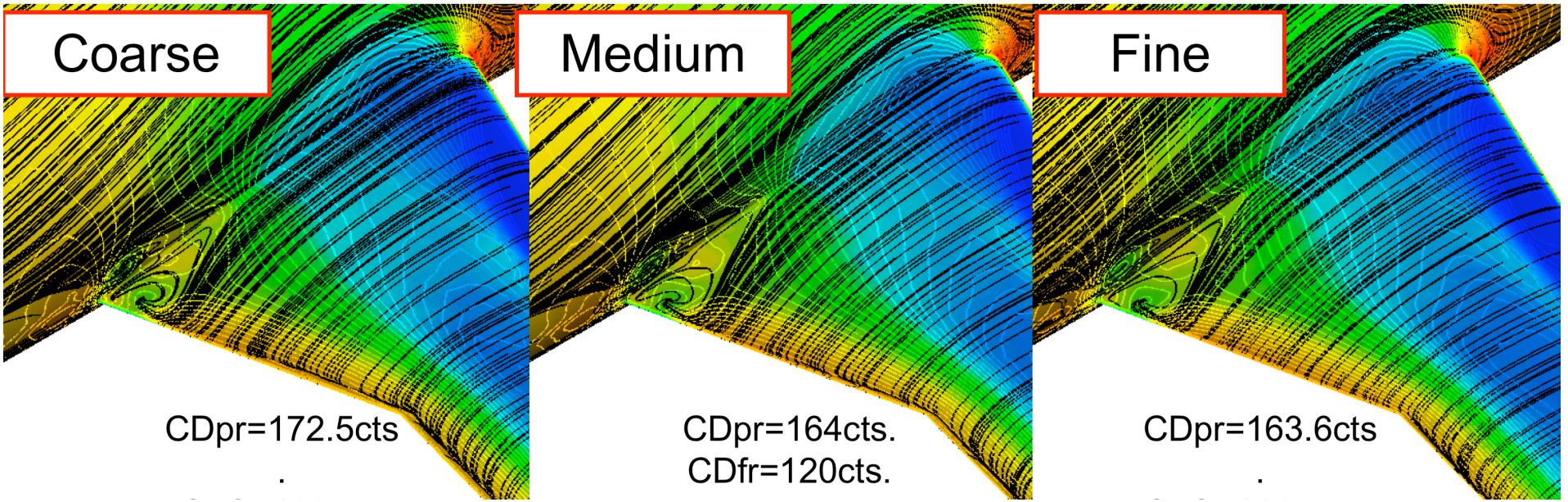
at CL=0.5, M=0.75, Re=5x10^6, SA

Comparison by the grid density

TAS

The size of the separation bubble does not change largely

GRID	FS_BUB	BL_BUB	WL_BUB	FS_EYE_W	BL_EYE_W	WL_EYE_W	FS_EYE_B	BL_EYE_B	WL_EYE_B
COARSE	170.91	84.51	5.52	232.27	81.34	-7.12	232.62	70.65	2.49
MEDIUM	165.52	85.83	5.64	233.01	82.62	-7.34	233.49	70.94	3.42
FINE	165.63	84.72	7.79	233.25	83.09	-7.17	233.86	71.19	4.25



Separation bubble near the wing-fuselage junction

at CL=0.5, M=0.75, Re=5x10^6, SA

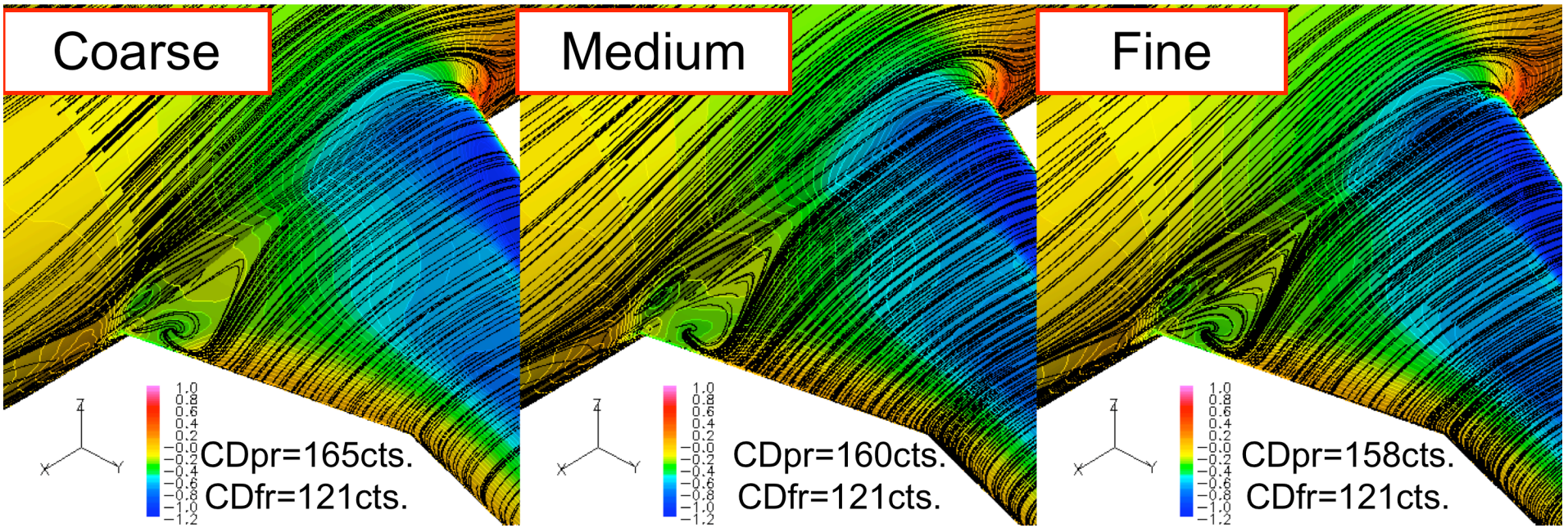
Comparison by the grid density

UPACS

The size does not change largely

The size is a little larger than that by unstructured grids

GRID	FS_BUB	BL_BUB	WL_BUB	FS_EYE_W	BL_EYE_W	WL_EYE_W	FS_EYE_B	BL_EYE_B	WL_EYE_B
COARSE	141.48	107.74	18.92	231.48	84.65	-6.3	236.28	71.97	7.33
MEDIUM	138.94	108.58	17.37	231.29	84.9	-6.19	234.96	72.24	8.04
FINE	134.14	109.22	17.37	231.19	85.34	-6.08	235.24	72.36	8.33



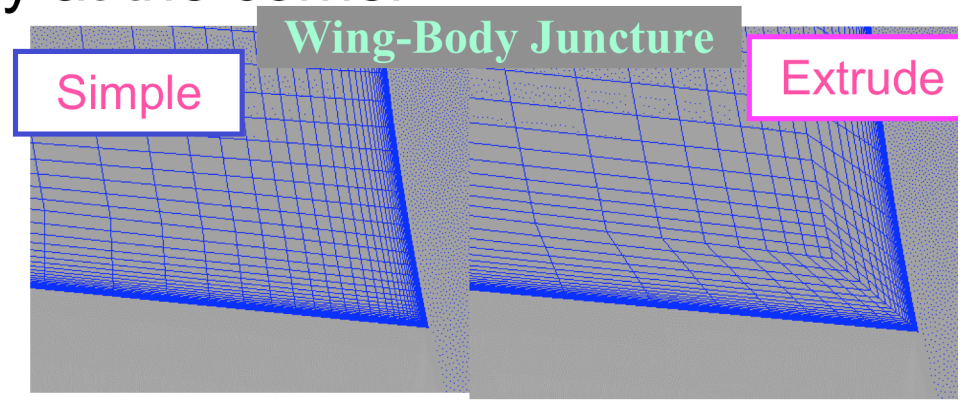
Separation bubble near the wing-fuselage junction

at CL=0.5, M=0.75, Re=5x10^6, SA

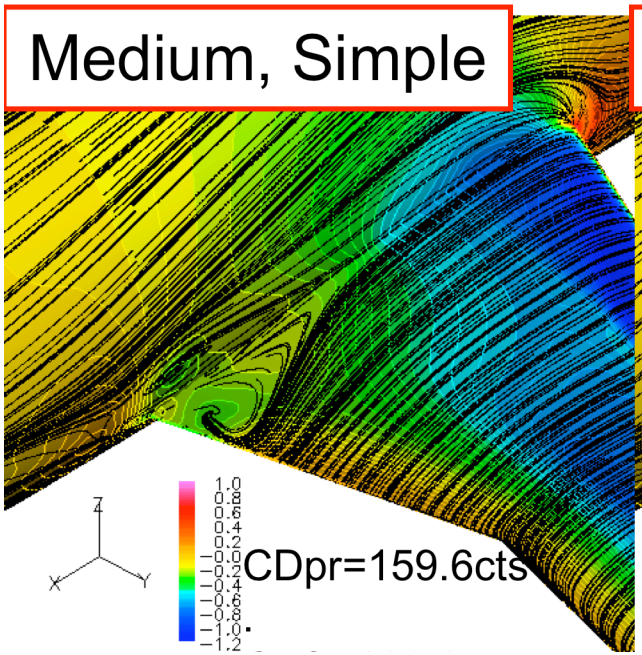
Comparison by the grid topology at the corner

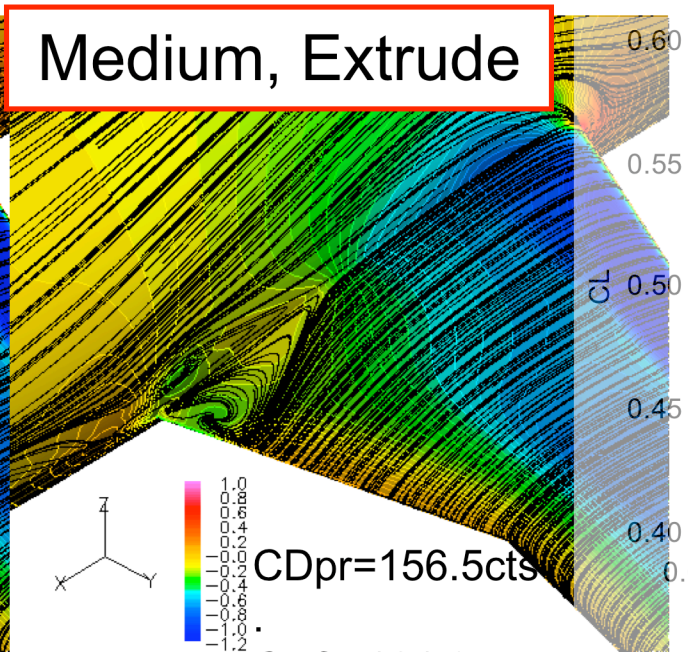
UPACS

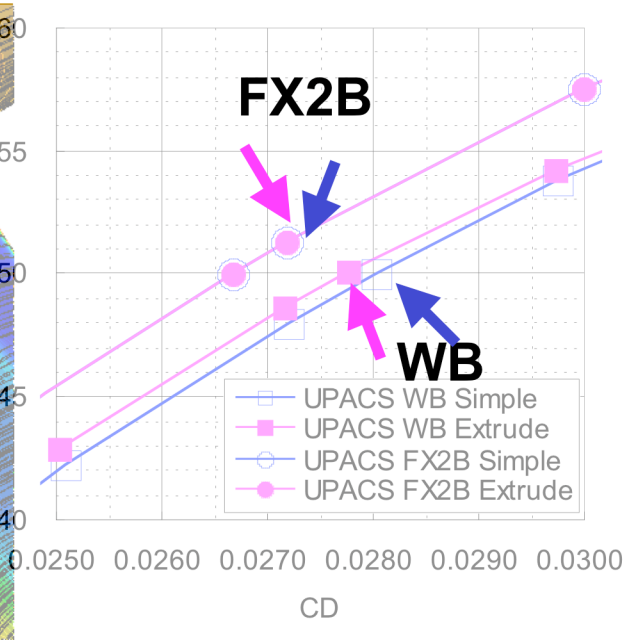
The size becomes smaller on the grid using extrude type



GRID	FS_BUB	BL_BUB	WL_BUB	FS_EYE_W	BL_EYE_W	WL_EYE_W	FS_EYE_B	BL_EYE_B	WL_EYE_B
Simple	138.94	108.58	17.37	231.29	84.9	-6.19	234.96	72.24	8.04
Extrude	166.62	104.09	17.51	233.32	83.45	-7.13	234.26	71.91	6.76







Separation bubble near the wing-fuselage junction

at CL=0.5, M=0.75, Re=5×10^6

Comparison by the turbulence model, SA and SST

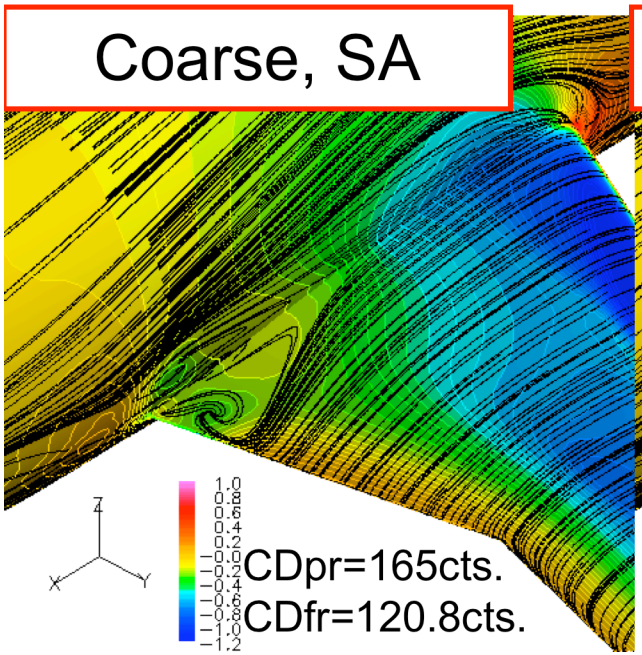
UPACS

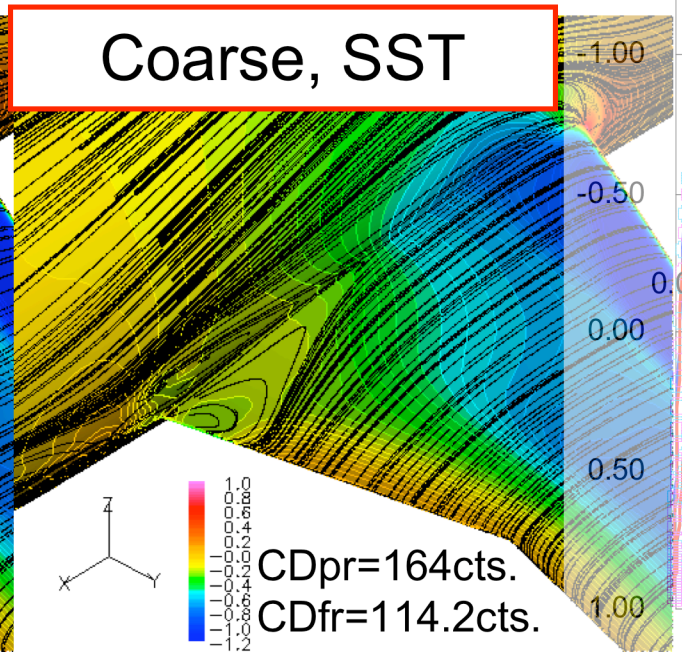
The eyes of the separation bubble change by turbulence models

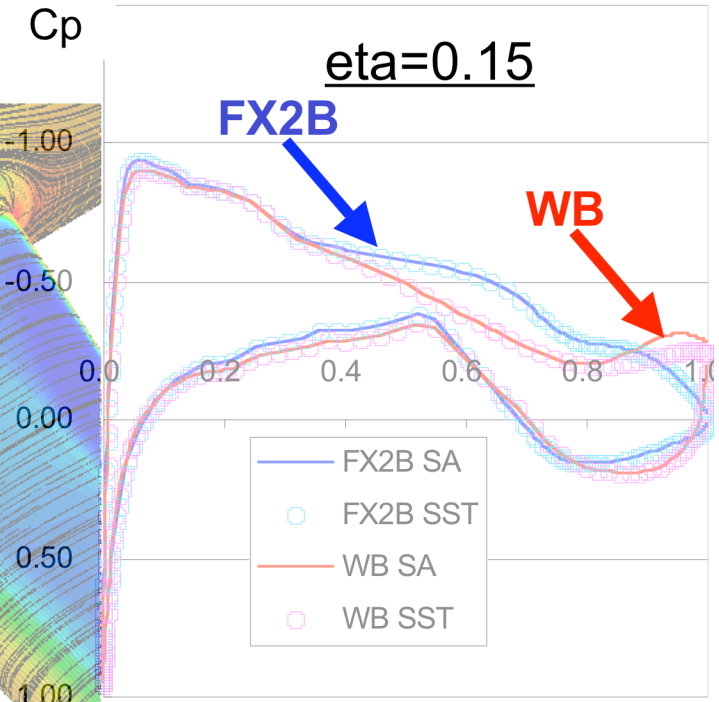
SST model shows lower CDfr

Cf. FX2B

SA	SST
CDpr=149.8cts	CDpr=149.9cts
CDfr=123.3cts.	CDfr=116.7cts.







Summary

Both UPACS and TAS codes predicted drag at a similar level when the same turbulence model was used

Discussion

Grid convergence

CDpr:

Structured grid: Good convergence

Unstructured grid: Not converged even on the self-made fine grid,
Relatively larger change with grid size

CDfr:

Small change with grid size both structured and unstructured grids

Upper-surface trailing-edge separation location

Unstructured grid: Separation line moves near TE by the grid refinement

Structured grid: No separation

Separation bubble at the corner of wing-body junction

FX2B: No separation bubble on all grids

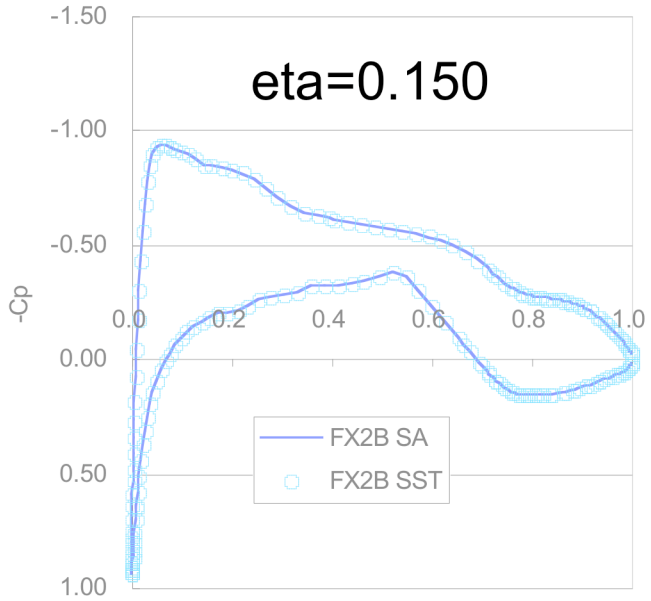
Wing-Body: Factors such as grid topology, turbulence model easily affect

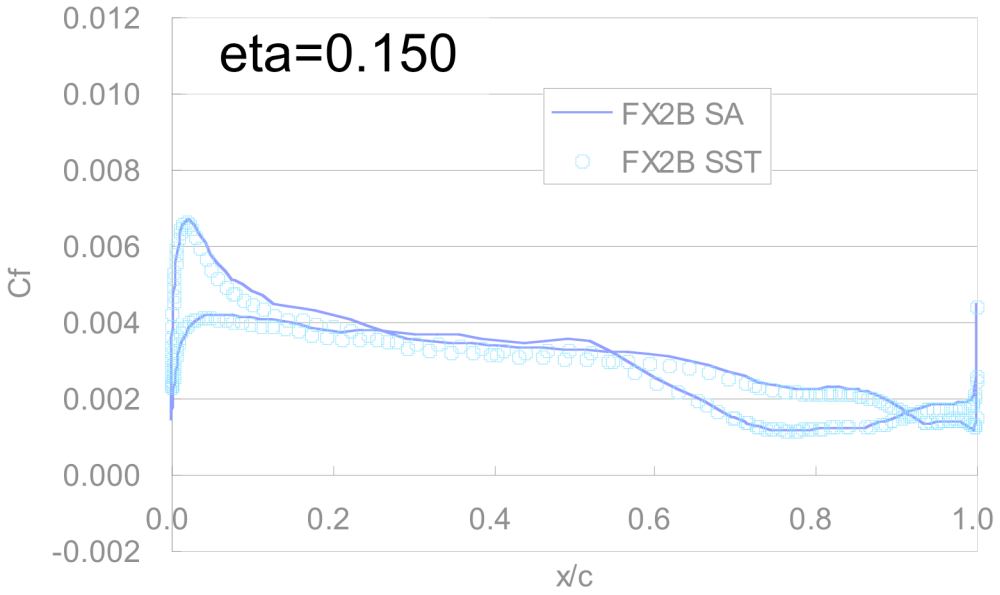
The size becomes smaller on the grid using extrude type at the corner

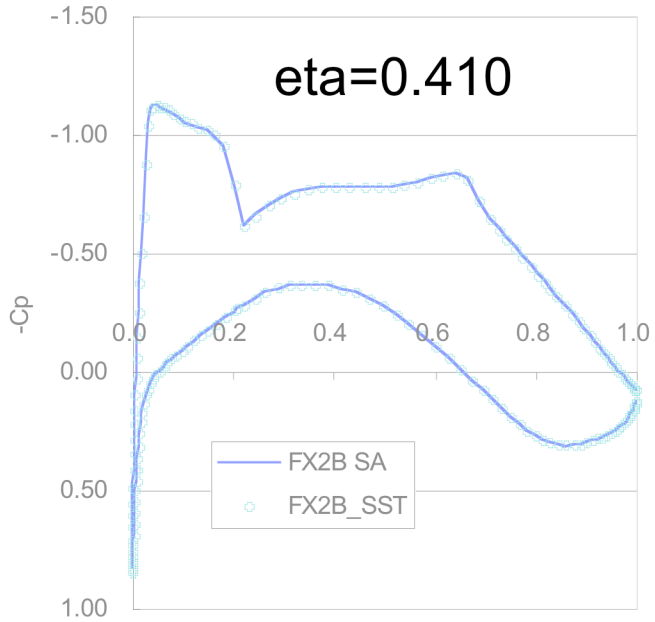
SST turbulence model shows lower CDfr than SA model

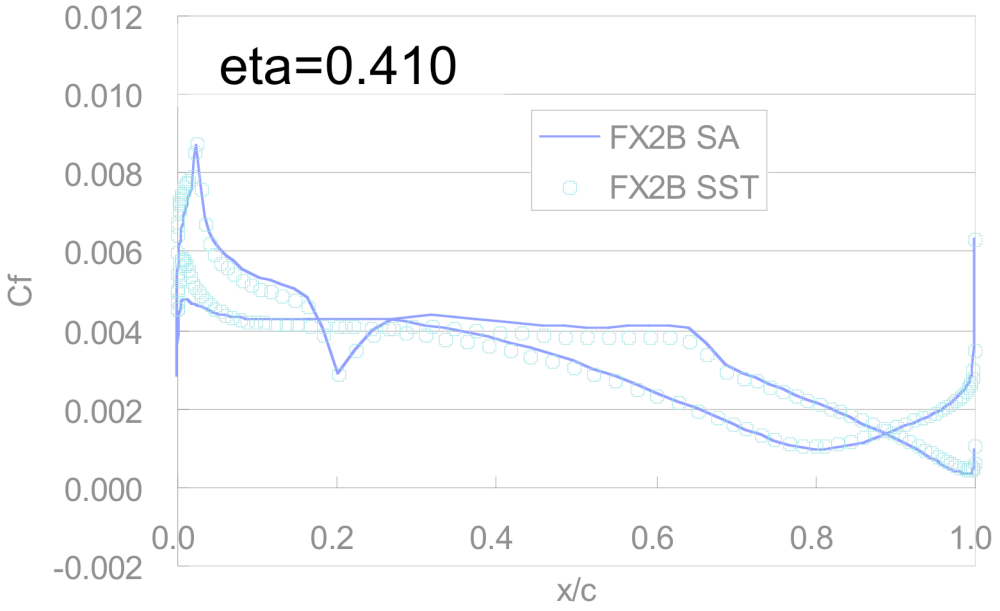
Comparison of Cp and Cf by turbulence model(FX2B)

at CL=0.5, M=0.75, Re=5x10^6, Coarse Grid



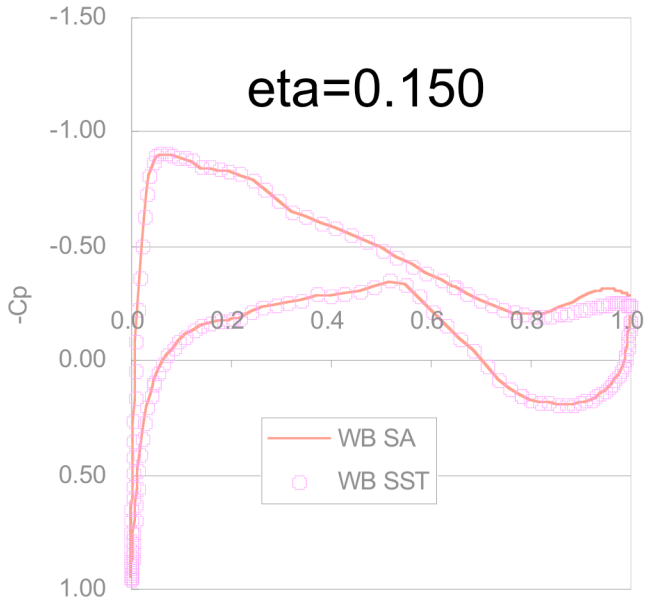


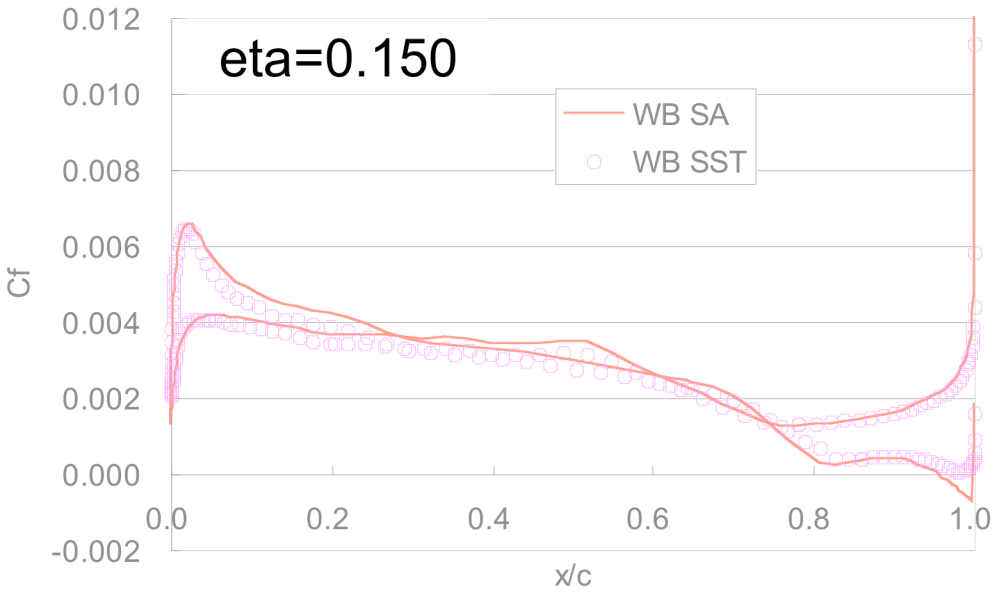


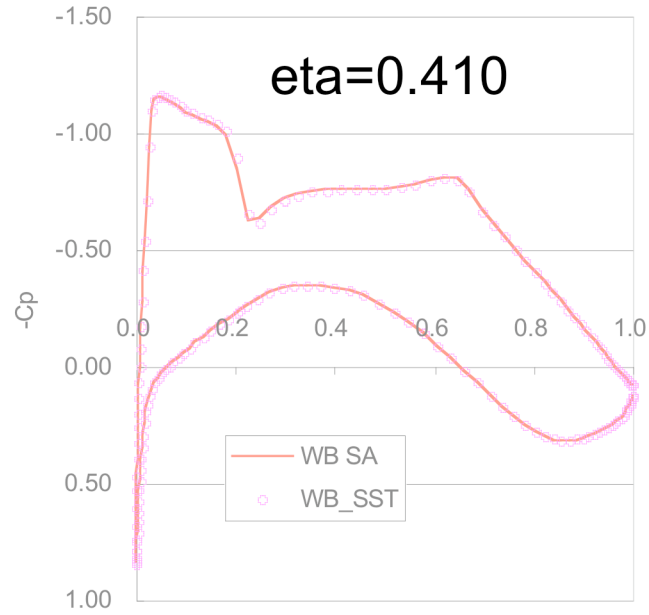


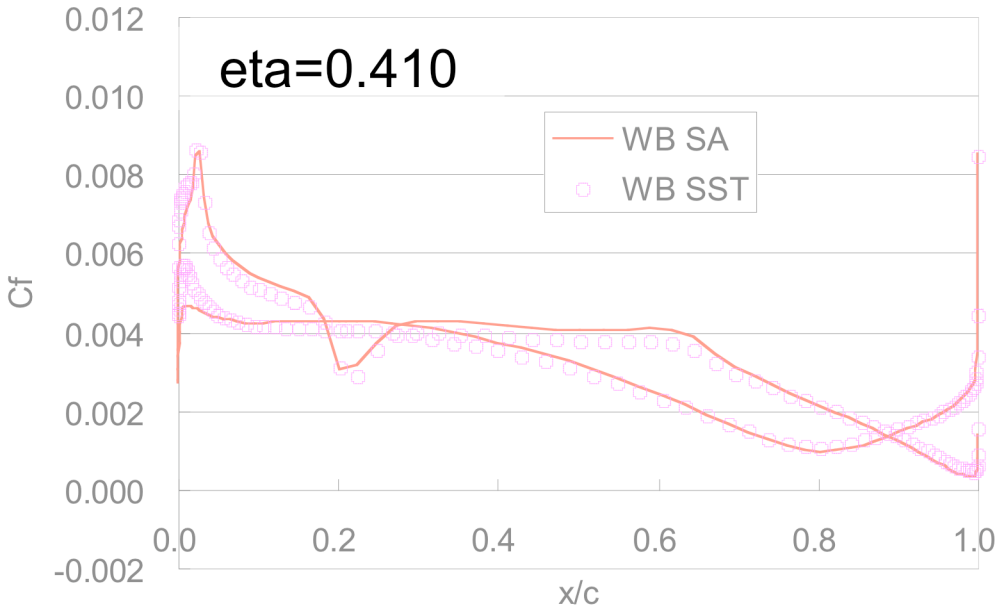
Comparison of Cp and Cf by turbulence model(WB)

at CL=0.5, M=0.75, Re=5x10^6, Coarse Grid









Solution information for typical-fine grid for DLR-F6 WB

Computational resource

Computer Platform: Fujitsu PRIMEPOWER HPC2500,
SPARC 64V 1.3GHz, 1792cpu
(Numerical Simulater III in JAXA)
Operating System: SunOS 5.8
Compiler : Fujitsu MPI Fortran

Unstructured Mesh, TAS Code (17.5M Nodes)

Processors: 64
Run Time CPU: 75 hours per 1 CPU
Run Time Wall-Clock: 150 hours per 1 CPU
Memory Requirements: 82 Gbytes per 64 CPUs

Structured Mesh, UPACS (29.8M Nodes)

Processors: 100
Run Time CPU: 71.25 hours per 1 CPU
Run Time Wall-Clock: 185.95 hours per 1 CPU
Memory Requirements: 39 Gbytes per 100 CPUs

Grid information (Detail)

Structured grid (Simple)

Config.	MeshType	Density	Zone	Nodes	Cells	Surf.Nodes	BL1stCellSize	GrowthRate	TE Cells
DLR-F6	Multi-block structured	Coarse	222	3.1M	2.7M	47K	0.0006[mm]	1.29	8
		Medium	222	9.8M	8.9M	100K	0.0004[mm]	1.17	12
		Fine	222	29.8M	28.0M	209K	0.00027[mm]	1.12	16
DLR-F6 FX2B	Multi-block structured	Coarse	222	3.3M	2.8M	49K	0.0006[mm]	1.29	8
		Meidum	222	10.0M	9.1M	103K	0.0004[mm]	1.17	12
		Fine	222	29.8M	28.0M	209K	0.00027[mm]	1.12	16

Unstructured grid

Config.	MeshType	Density	Zone	Nodes	Cells	Surf.Nodes	BL1stCellSize	GrowthRate	TE Cells
DLR-F6	Mixed Unstructured	Coarse	1	5.4M	5.0M tet, 8.9M pri	134K	0.0006[mm]	1.2	4
		Medium	1	9.4M	10.7M tet, 14.9M pri	219K	0.0004[mm]	1.2	5
		Fine	1	17.5M	25.3M tet, 25.9M pri	368K	0.00027[mm]	1.2	6
DLR-F6 FX2B	Mixed Unstructured	Coarse	1	5.4M	5.0M tet, 8.9M pri	136K	0.0006[mm]	1.2	4
		Meidum	1	9.5M	10.8M tet, 15.0M pri	223K	0.0004[mm]	1.2	5
		Fine	1	17.2M	23.9M tet, 25.8M pri	378K	0.00027[mm]	1.2	6

Grid convergence

CD versus # of nodes

at CL=0.5, M=0.75, Re=5x10^6, SA

CDpr:

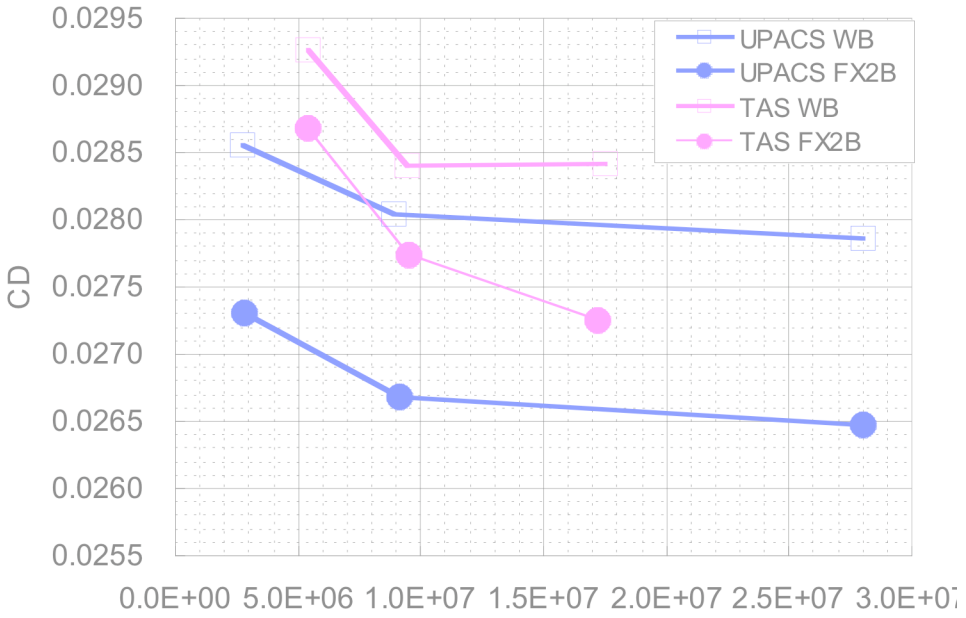
UPACS: Good convergence

TAS: Not converged even on fine grid

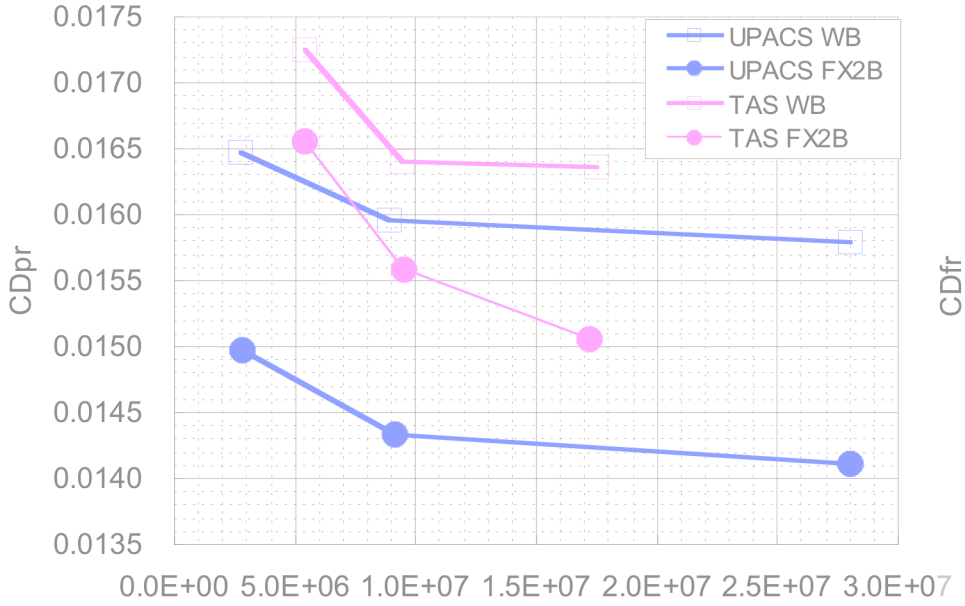
Change with grid size is larger

CDfr:

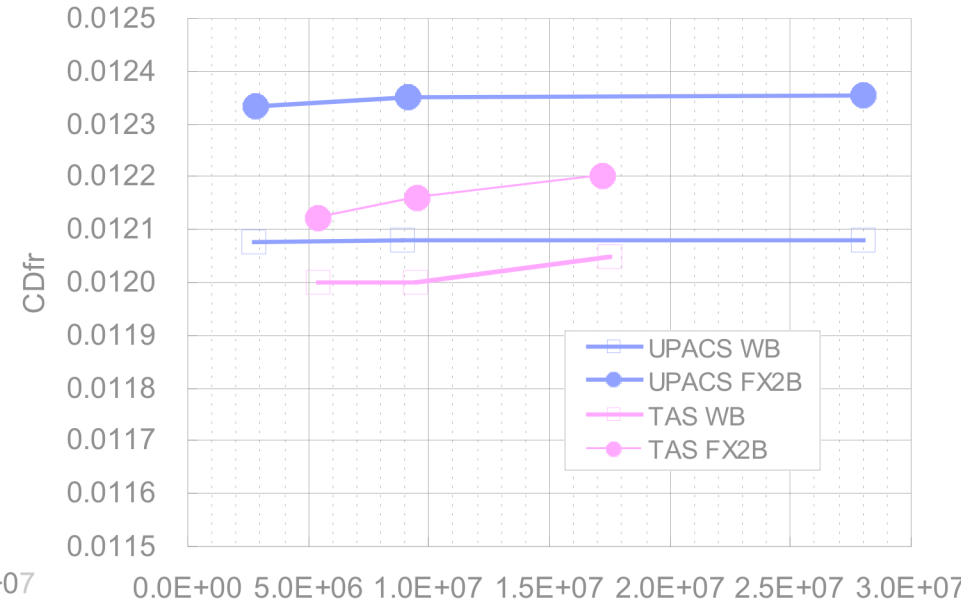
Change with grid size is small



Total drag



Pressure drag



Friction drag

Grid convergence

CD versus Log(# of nodes)

at CL=0.5, M=0.75, Re=5x10^6, SA

CDpr:

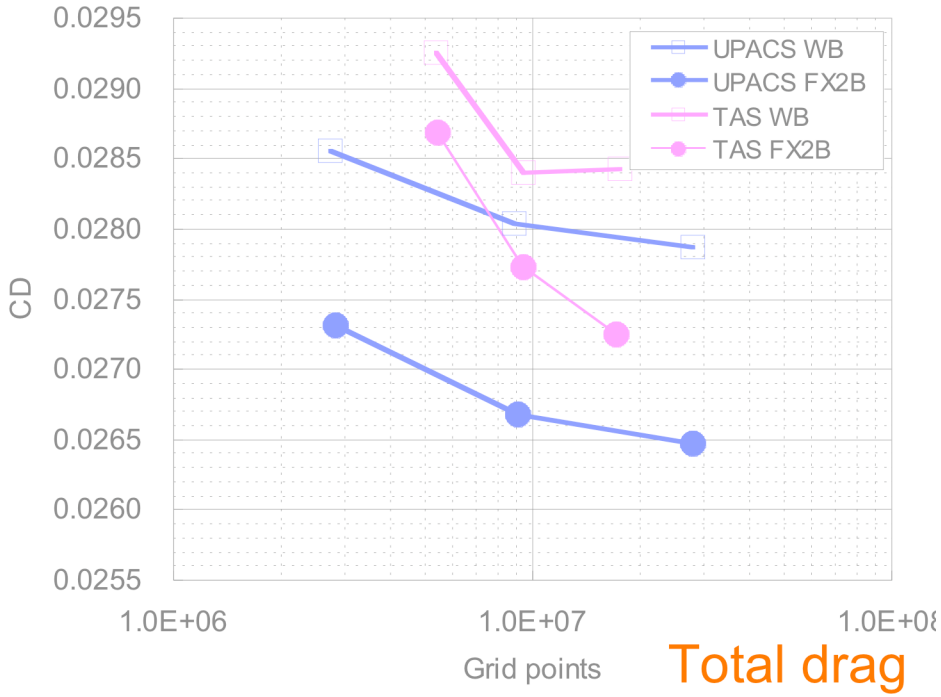
UPACS: Good convergence

TAS: Not converged even on fine grid

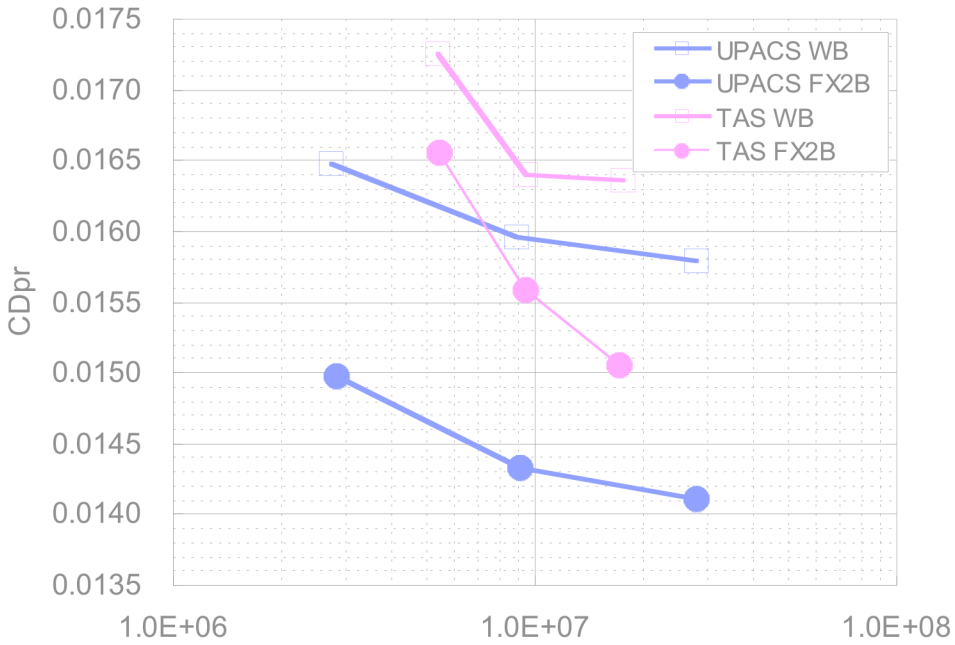
Change with grid size is larger

CDfr:

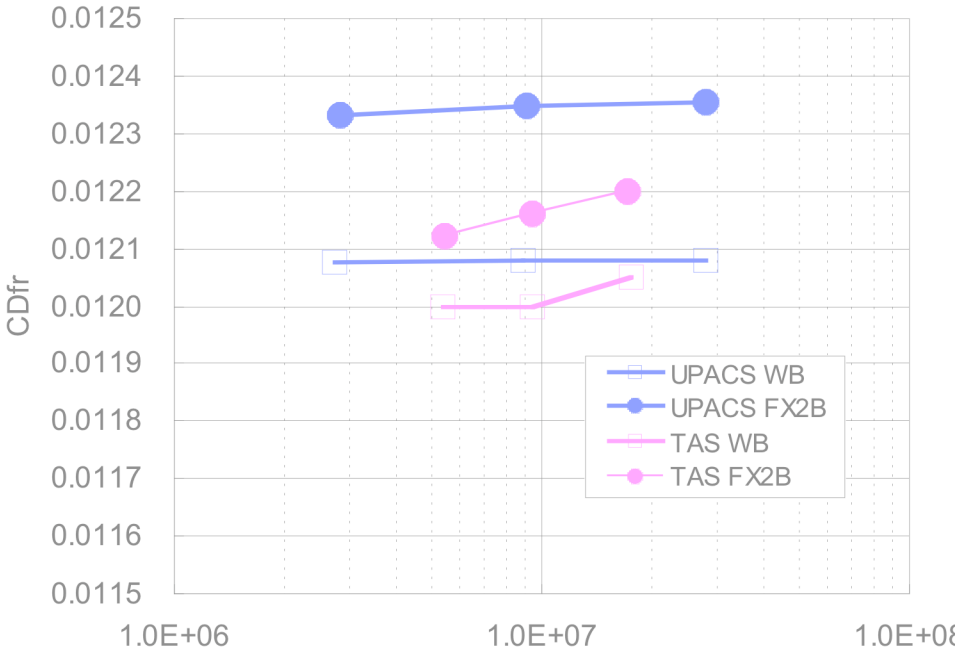
Change with grid size is small



Total drag



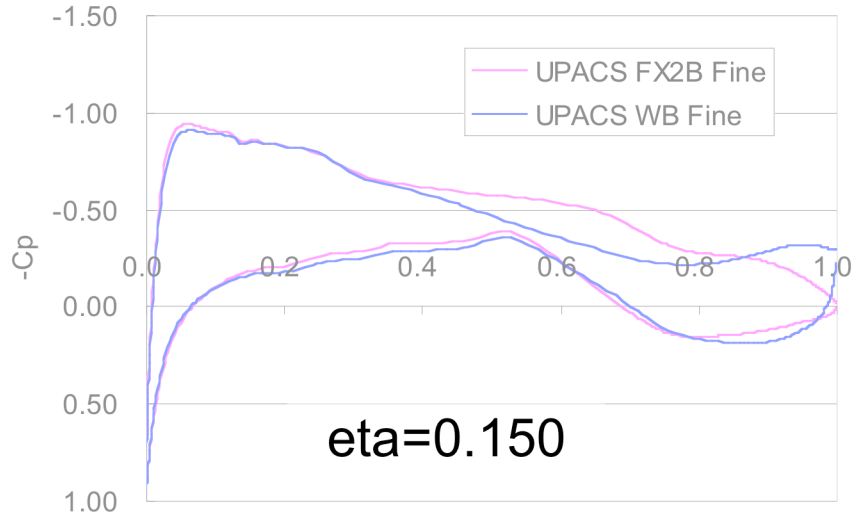
Pressure drag

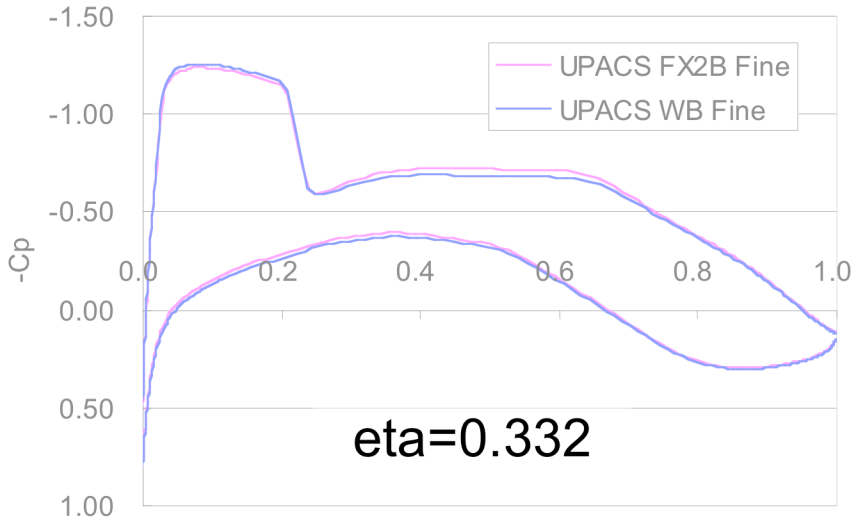


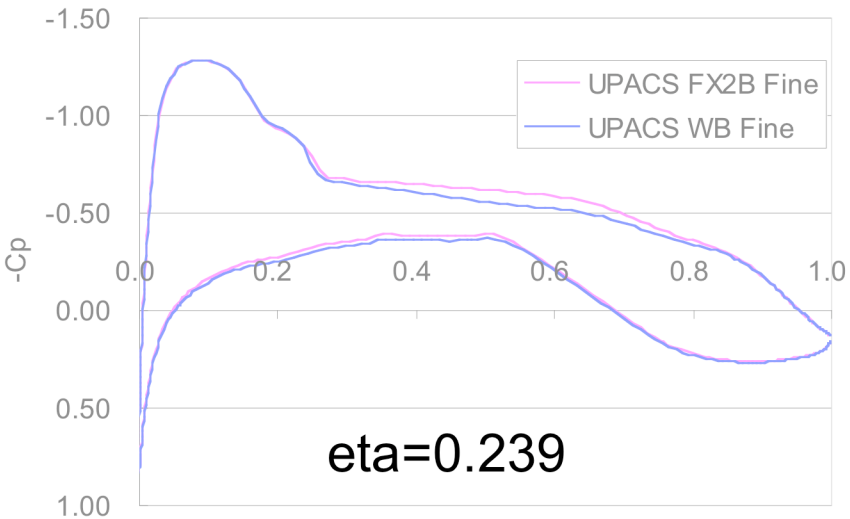
Friction drag

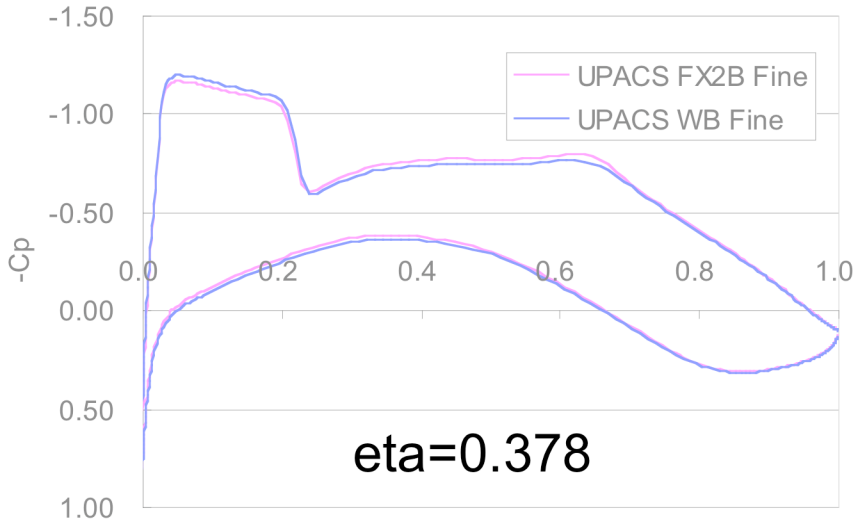
Comparison of Cp between WB and FX2B Configuration

at CL=0.5, M=0.75, Re=5x10^6, SA



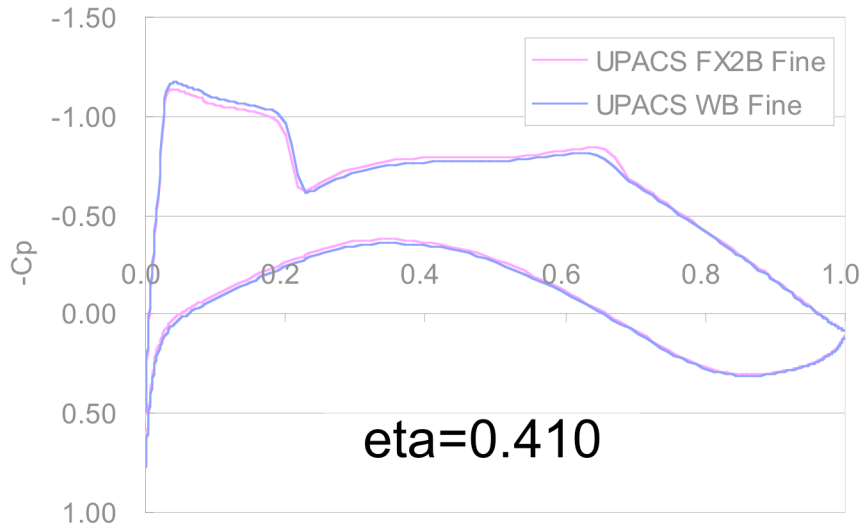


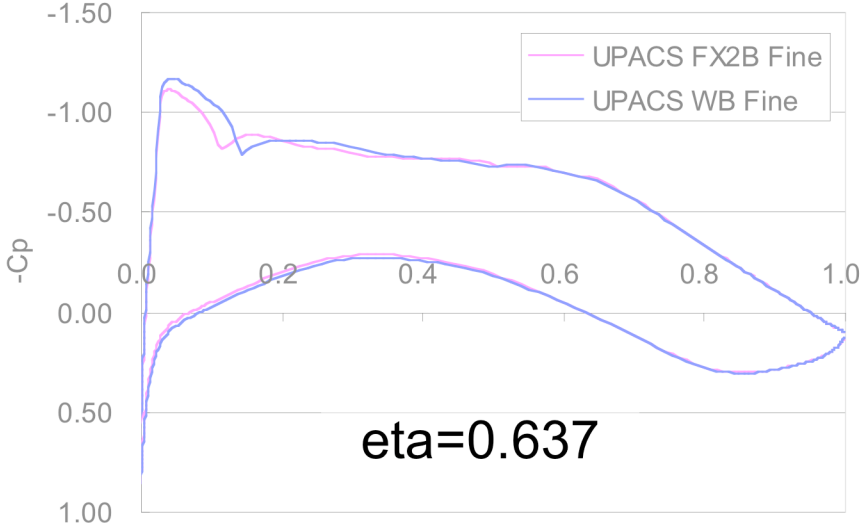


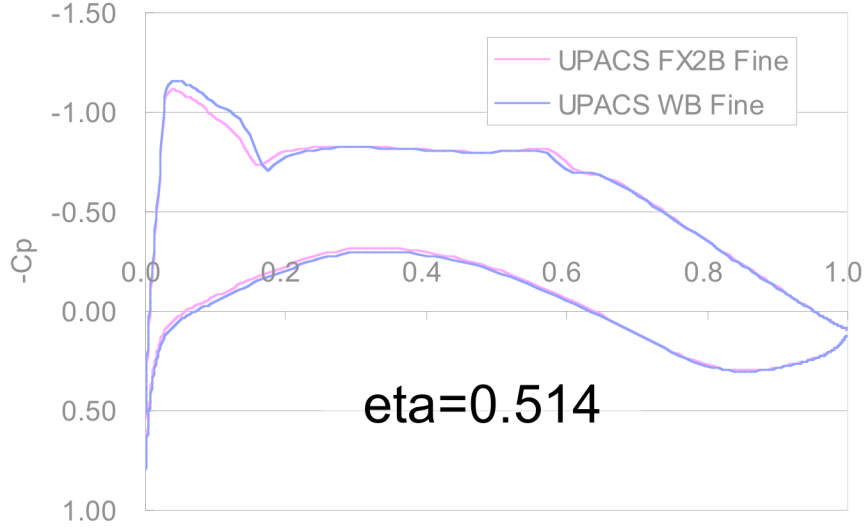


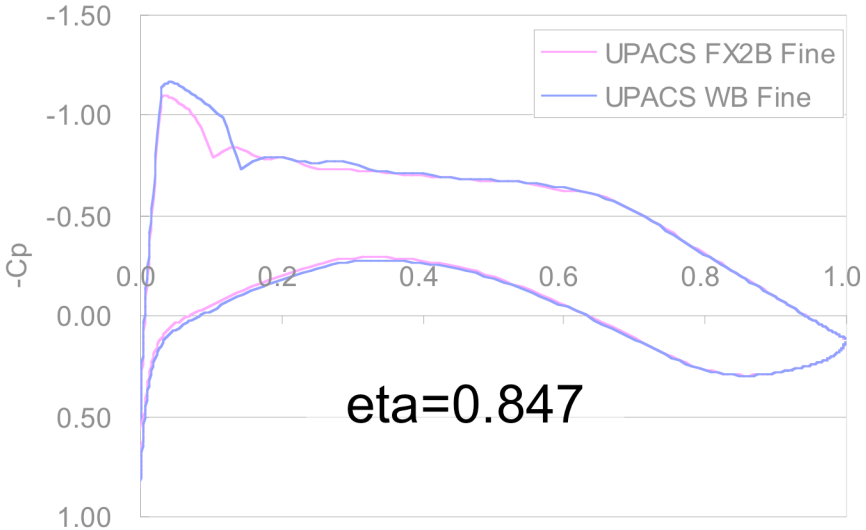
Comparison of Cp between WB and FX2B Configuration

at CL=0.5, M=0.75, Re=5x10^6, SA



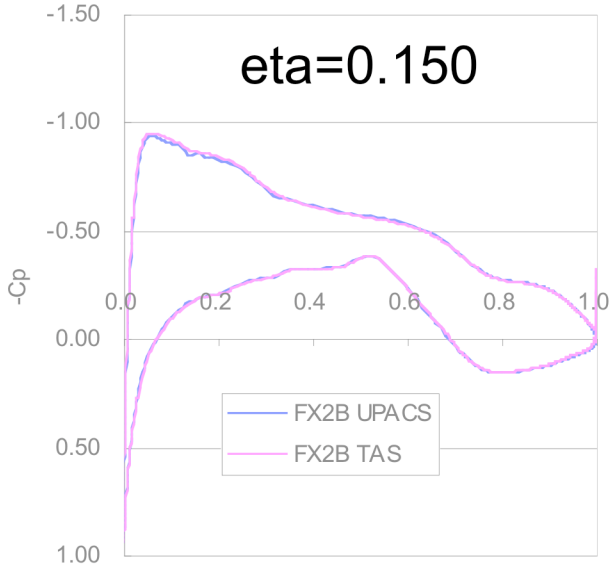


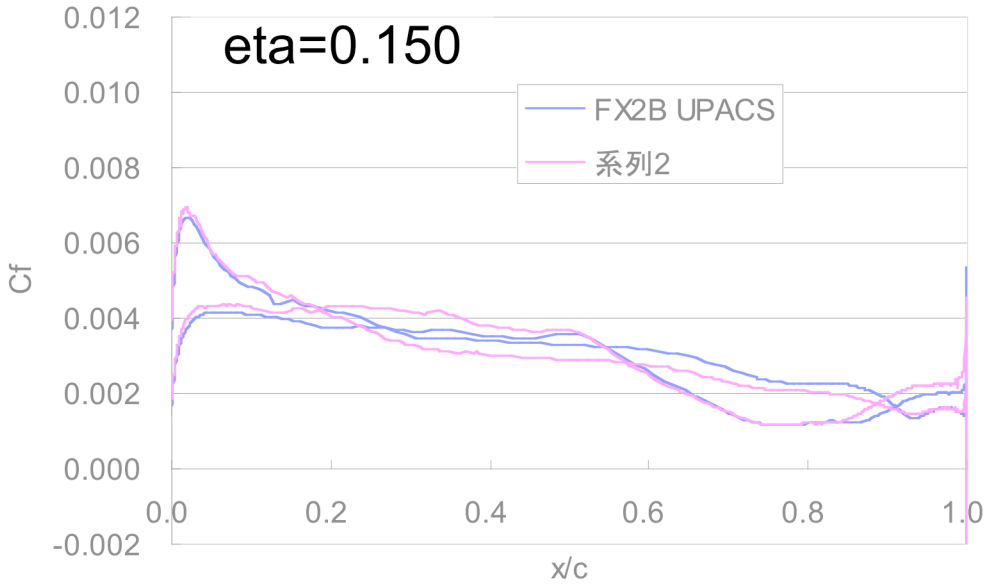


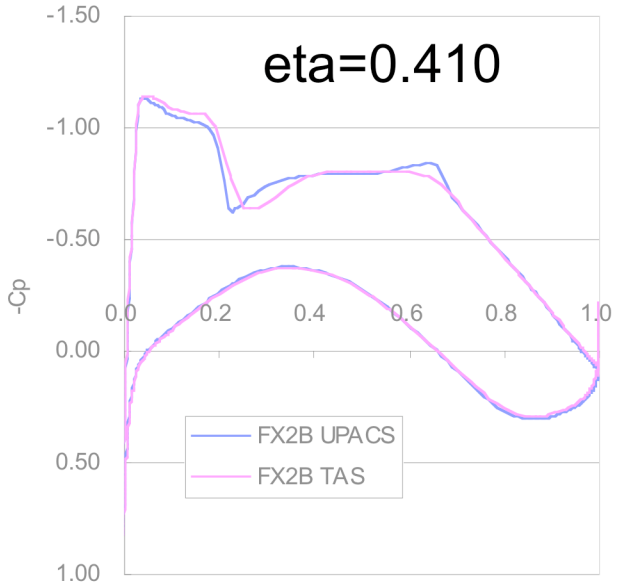


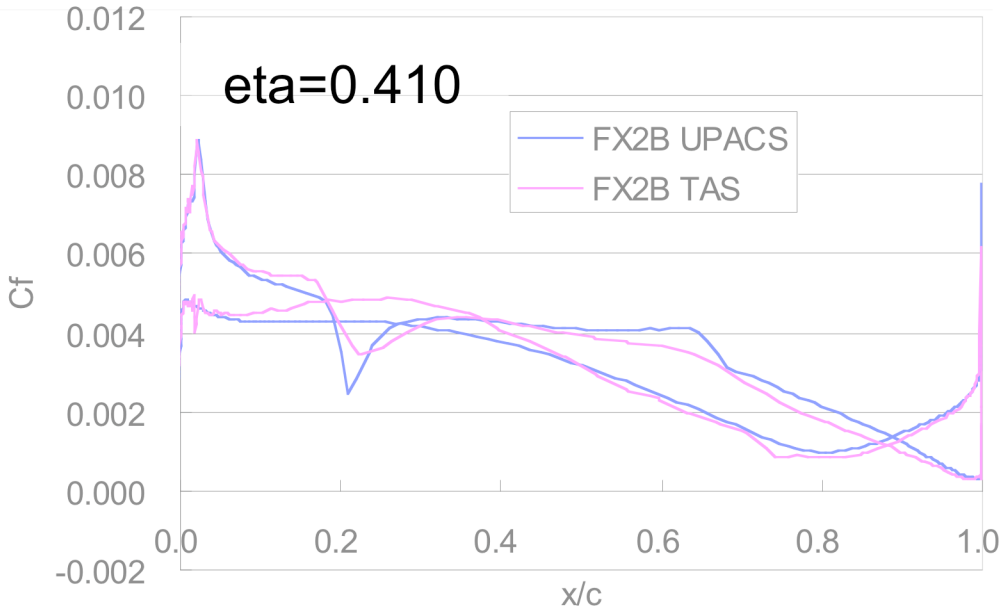
Comparison of Cp and Cf between codes (FX2B)

at CL=0.5, M=0.75, Re=5x10^6, SA, Fine Grid



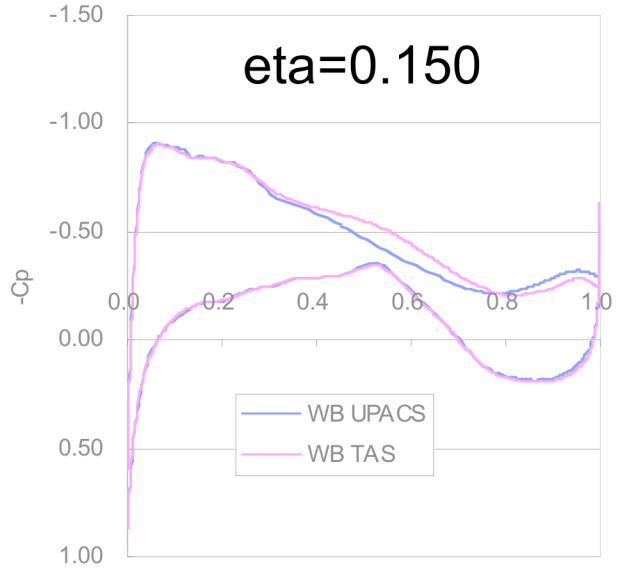


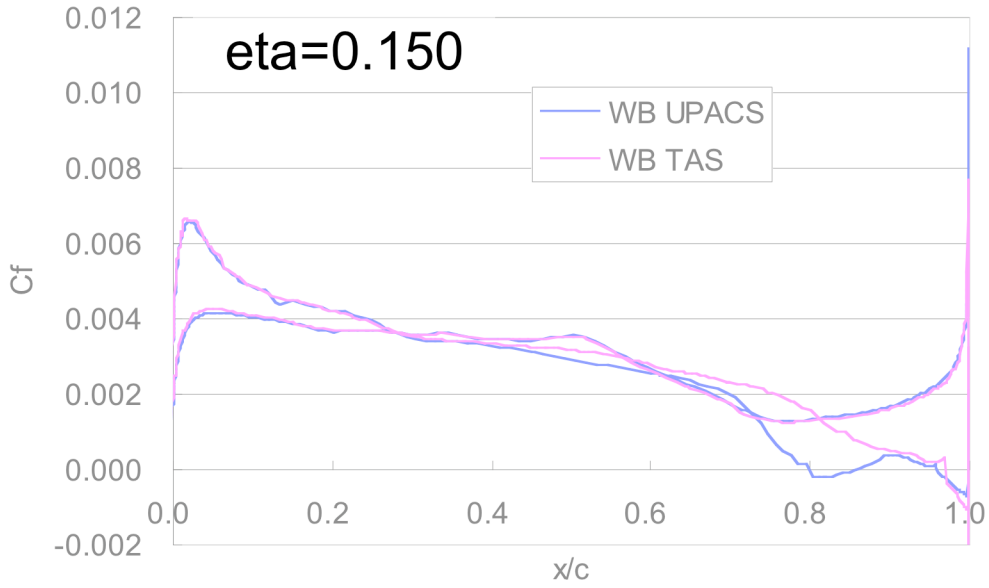


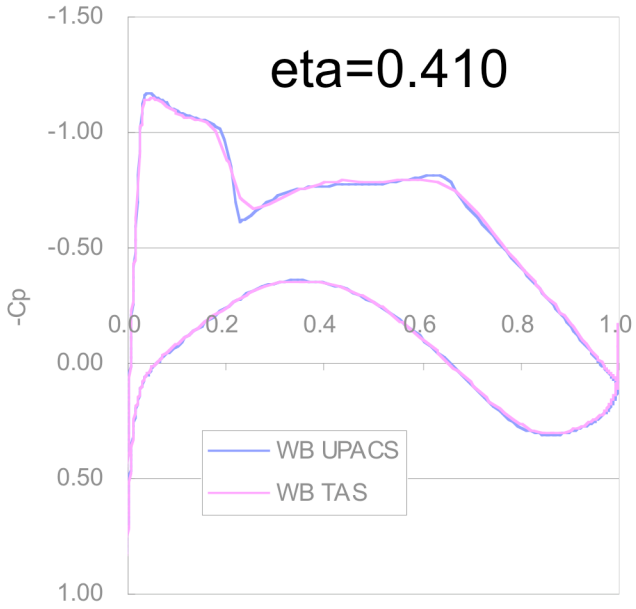


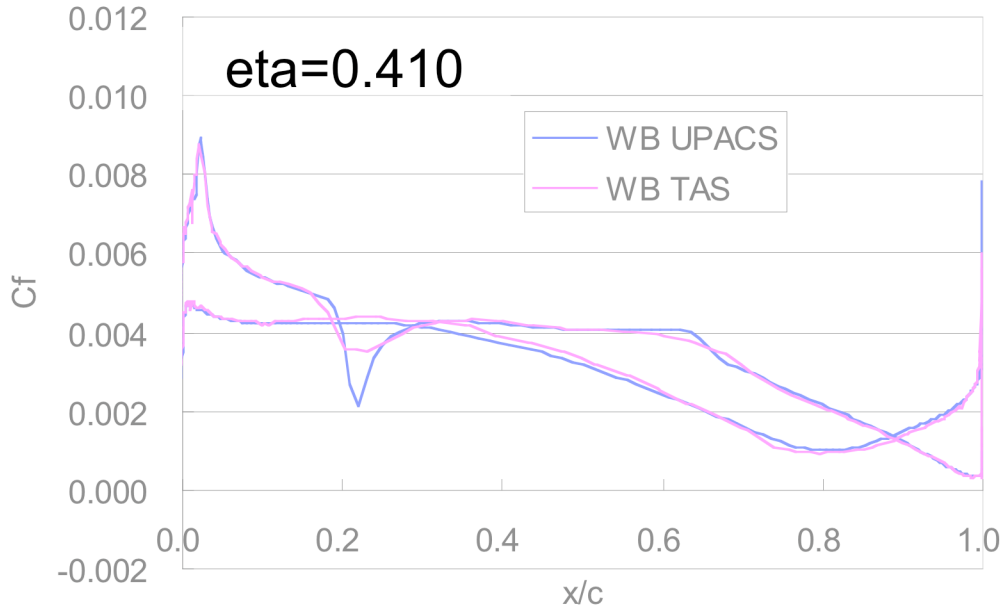
Comparison of Cp and Cf between codes (WB)

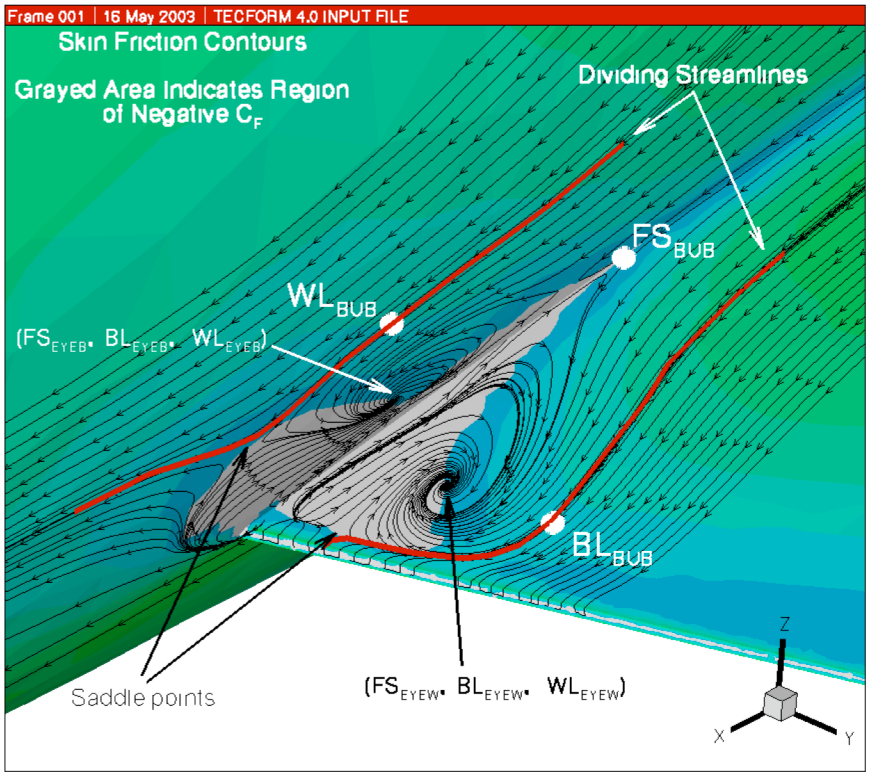
at CL=0.5, M=0.75, Re=5x10^6, SA, Fine Grid











* FS_BUB Fuselage station at the leading edge of the wing root separation bubble (W)
* BL_BUB Buttock line at the outboard edge of the wing root separation bubble (W)
* WL_BUB Water line at the top edge of the wing root separation bubble (F)

* FS_EYE_W Fuselage station at the center of the wing root separation bubble (W)
* BL_EYE_W Buttock line at the center of the wing root separation bubble (W)
* WL_EYE_W Water line at the center of the wing root separation bubble (W)

* FS_EYE_B Fuselage station at the center of the wing root separation bubble (F)
* BL_EYE_B Buttock line at the center of the wing root separation bubble (F)
* WL_EYE_B Water line at the center of the wing root separation bubble (F)

(W): measured on the wing, (F) measured on the fuselage

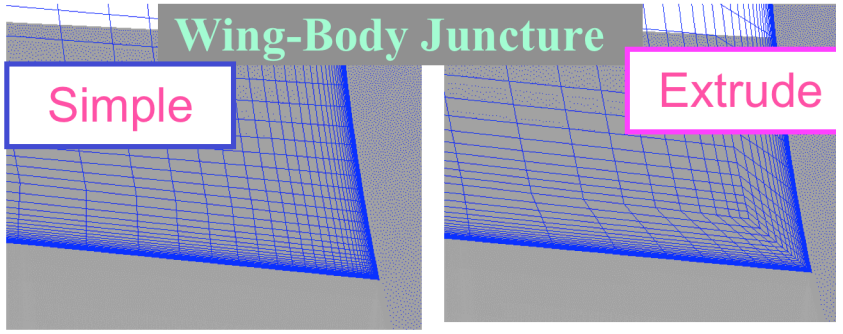
Separation bubble near the wing-fuselage junction

at CL=0.5, M=0.75, Re=5x10^6, SA

Comparison by the grid topology at the corner

UPACS

The size becomes smaller on the grid using extrude type



GRID	FS_BUB	BL_BUB	WL_BUB	FS_EYE_W	BL_EYE_W	WL_EYE_W	FS_EYE_B	BL_EYE_B	WL_EYE_B
Simple	141.48	107.74	18.92	231.48	84.65	-6.3	236.28	71.97	7.33
Extrude	173.68	100.32	16.80	234.02	81.67	-7.68	236.51	71.47	5.17