AIAA 2011-937
CFD Comparison Study for Trapezoidal High-Lift Wing Configurations by Structured and Unstructured Mesh Method

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Computational cases

- Submitted data to the workshop
  - Evaluation of CFD codes and mesh generation method used in APG/JAXA
    - Unstructured mesh code, **TAS**-code
    - Structured mesh code, **UPACS**

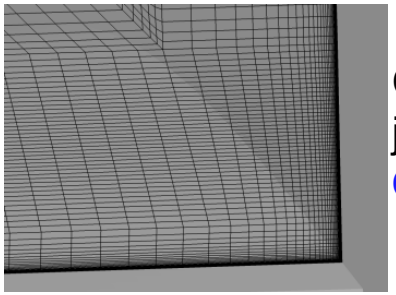
id	Code	Grid	Turb. Model	Case1 Grid convergence	Case2 Flap deflection	Case3 Bracket effect
12.01	**TAS**	**JAXA** Mixed-element Node-Centered **Unstructured**	SA(mod)	○	○	○
12.02	**UPACS**	**JAXA** Multi-block One-to-One **Structured**	SA(mod)	○	○	–

- Additional evaluations (Not submitted)
  - Other unstructured grids provided by committee
    - **Univ. of Wyoming using VGRID: Case1 &Case2**
      - Unst-Mixed-FromTet-Nodecentered-A-v1
    - **DLR using Solar: Case1 (Coarse & Medium)**
      - Unst-Mixed-Nodecentered-B-v1
  - Influence of local grid density of flap trailing-edge on flap flow separation
  - Sensitivity of turbulence model
    - **Spalart-Allmaras** and **Menter's SST**
    - **Spalart-Allmaras with some modifications**

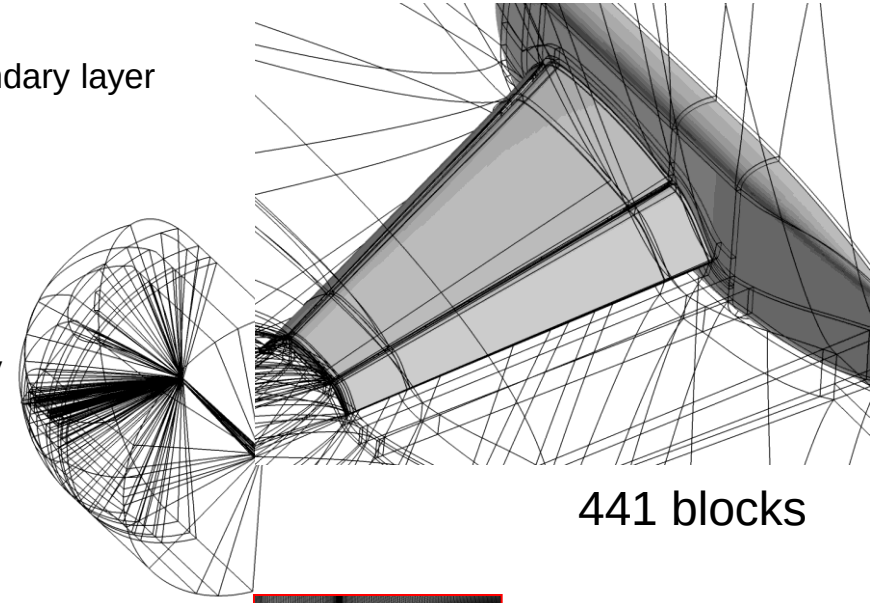
JAXA multi-block structured grids (Gridgen)

- O-O grid topology near the model surface
  - To guarantee better orthogonality within the boundary layer
- C-O grid topology at outward

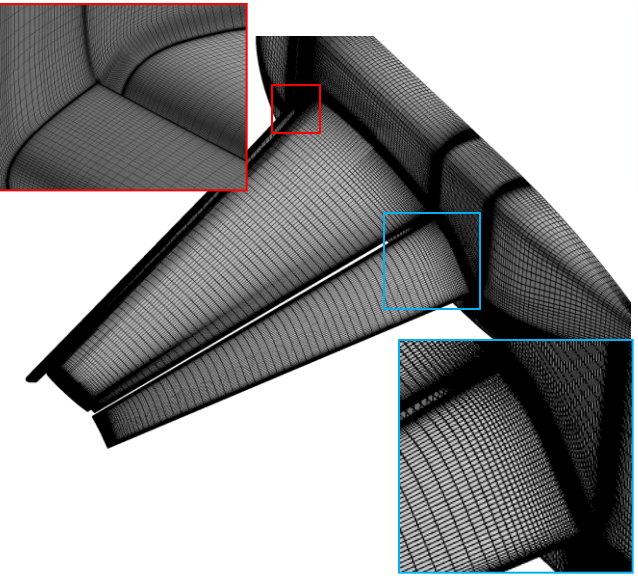
High dense grid at the corner of wing-body junction



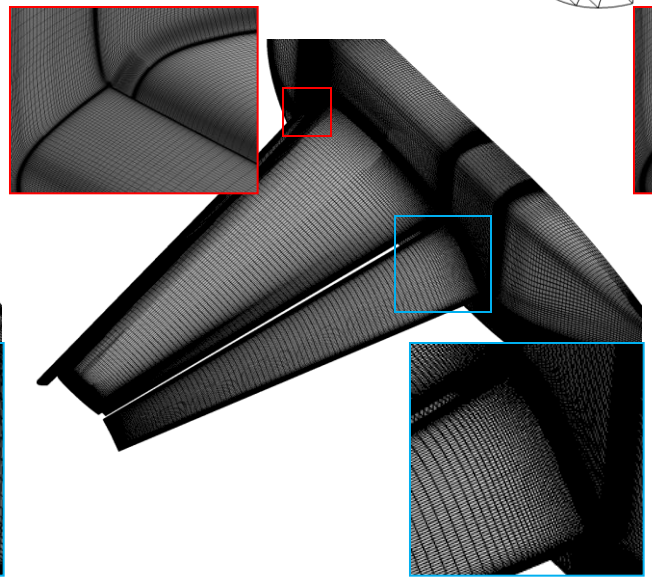
Corner of wing-body junction:
O-H grid topology



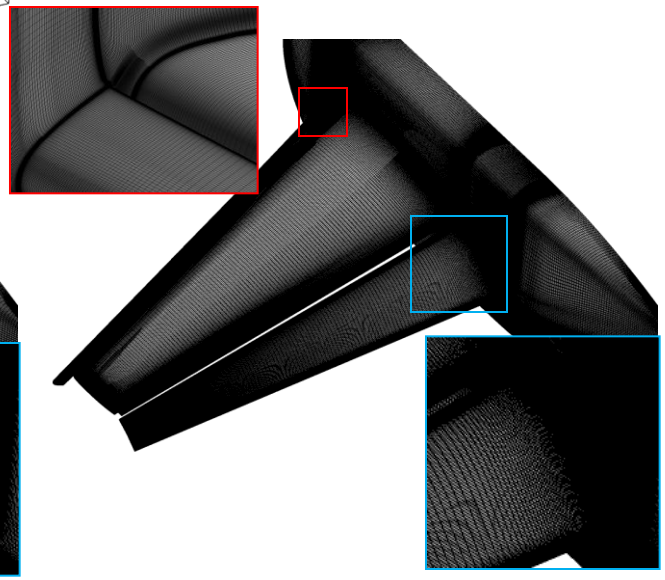
441 blocks



Coarse grid (12M)



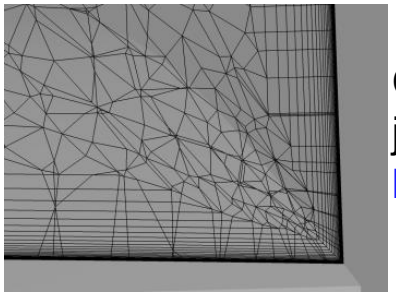
Medium grid (37M)



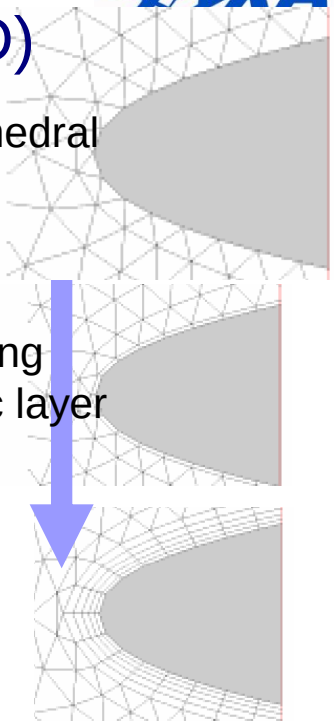
Fine grid (124M)

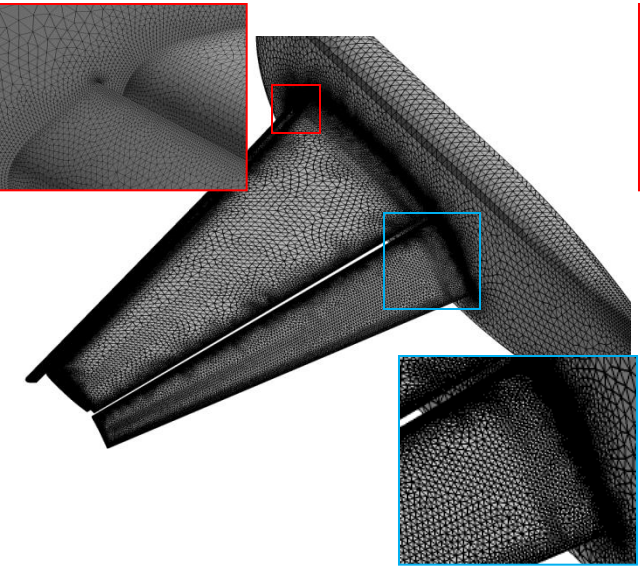
JAXA mixed-element unstructured grids (MEGG3D)

- Surface grid (Triangles)
  - Direct advancing front method employing nearly-isotropic triangles
- Volume grid (Tetrahedra, Prisms, Pyramids)
  - Delauney (tetra) → insertion of prismatic layer (prism)

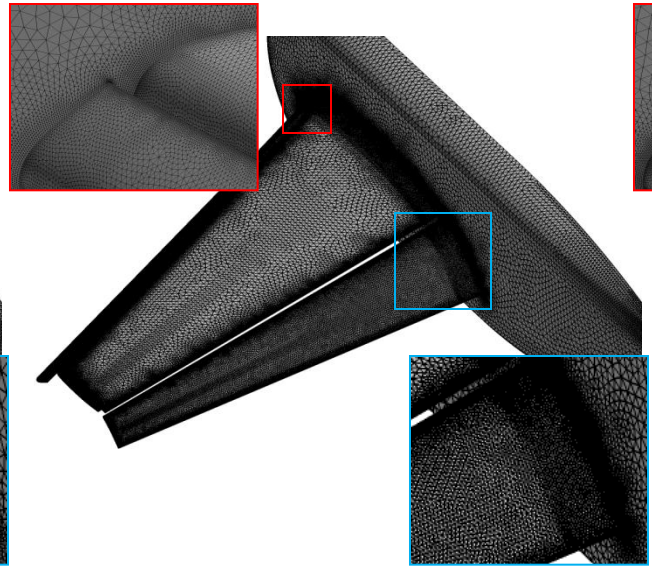


Corner of wing-body junction:
Extrude type

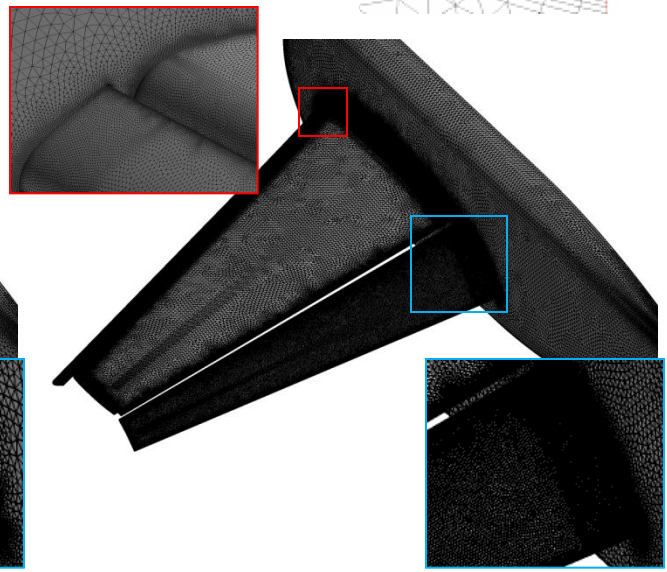




Coarse grid (12M)



Medium grid (28M)



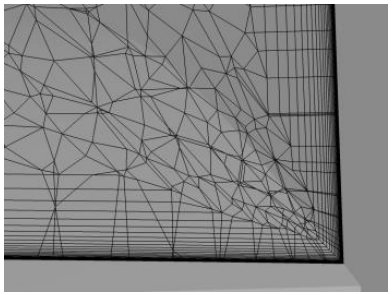
Fine grid (72M)

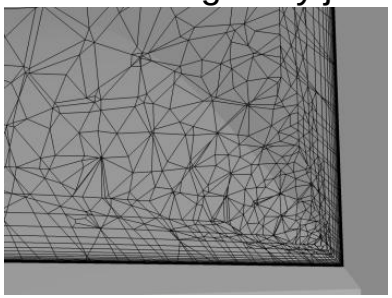
Committee-provided mixed-element unstructured grids

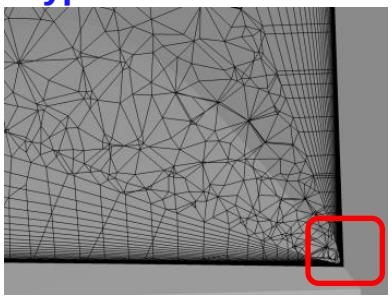
- Univ. of Wyoming using VGRID
  - Unst-Mixed-FromTet-Nodecentered-A-v1: Unst-MFTNAv1
- DLR using Solar
  - Unst-Mixed-Nodecentered-B-v1: Unst-MNBv1

Comparison of medium grids

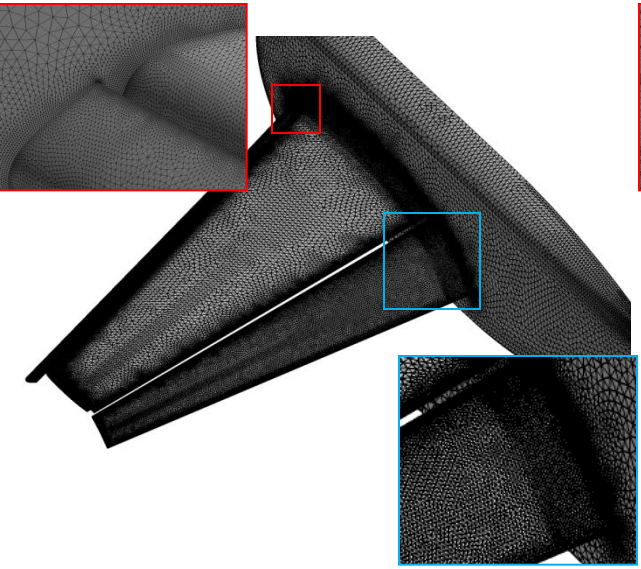
Wing-body junction: **Extrude type**

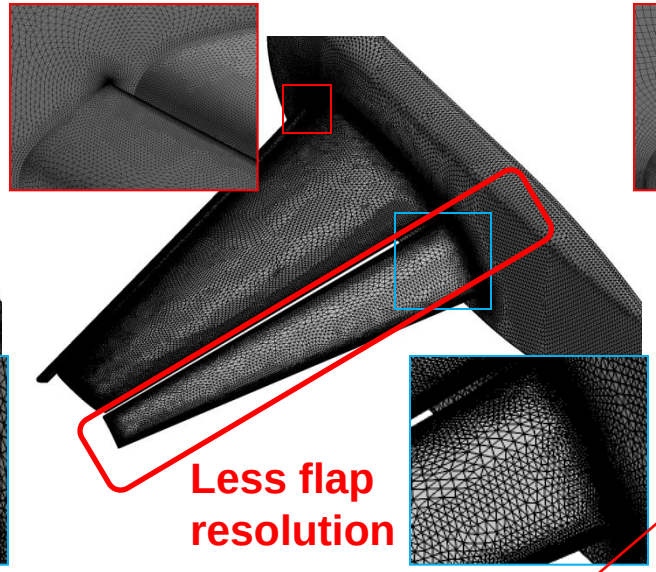




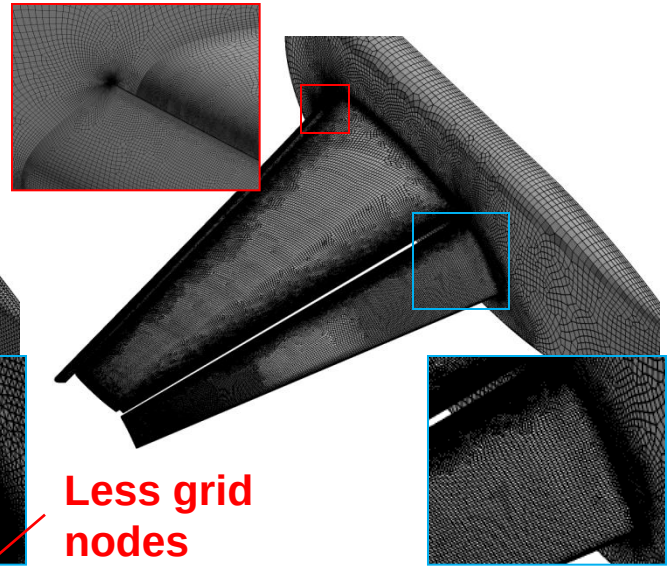


Less prism at corner





Less flap resolution



Less grid nodes

Unst-JAXA grid (28M)

Unst-Uwyo grid (11M)

Unst-DLR grid (37M)

Numerical methods: UPACS & TAS

	UPACS	TAS
Mesh type	Multi-block structured	Unstructured
Discretization	Cell-centered finite volume	Cell-vertex finite volume
Convection Flux	Roe 3rd-order (without Limiter)	HLLEW 2nd-order with Venkatakrishnan's limiter (K=1)
Time integration	Matrix-Free Gauss-Seidel	LU-Symmetric Gauss-Seidel
Turbulence model	SAmod	SAmod

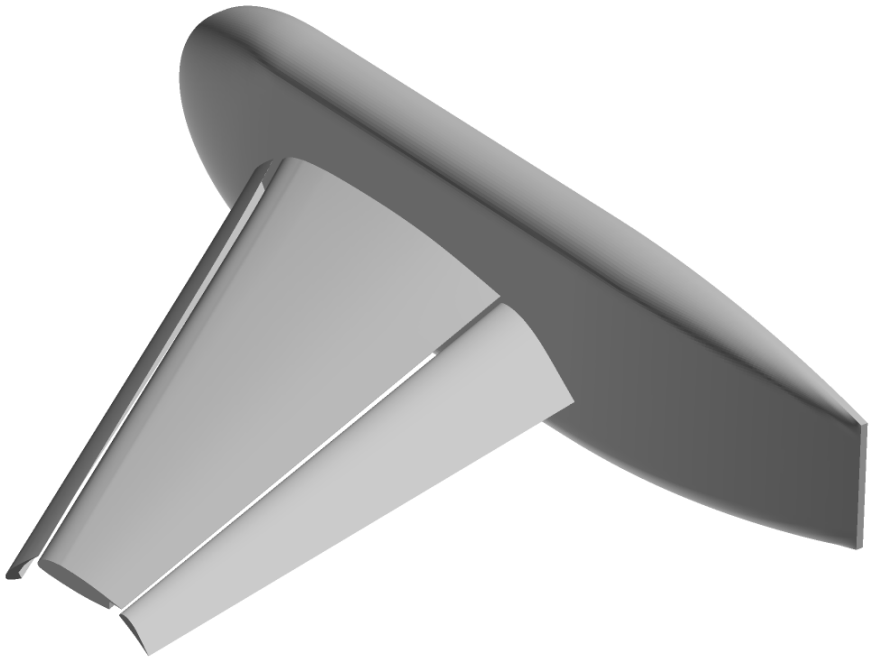
- Modification to S-A model (SAmod): to supress excessive eddy viscosity after separation
  - without trip related terms
  - with a modification to production term: $S = \min(\sqrt{2\Omega^2}, \sqrt{2S^2})$
- Restart from result at lower α to obtain results at higher α
- Computer Platform: JSS - Fujitsu FX1 (SPARC64 VII 2.5GHz,3008cpu)
  - Typical computational time (C_{Dfinal}-C_D < 2~3 cts.)

Code	Grid points		# of CPU	CPU Time(H)	Tota lCPU Time(H)	# of Iteration
TAS	Medium	28M	73	41	2,993	50,000
UPACS	Medium	37M	48	80	3,840	100,000

Results

- Case 1 Grid Convergence Study
- Case 2 Flap Deflection Prediction Study
- Case 3 Flap and Slat Support Effects Study
- Additional evaluations
  - Local grid density on flap trailing-edge
  - Sensitivity of turbulence model

	Case1 Grid convergence study
Slat & flap setting	Config. 1
Slat & flap bracket	Not-included
M	0.2
Re	4.3×10^6
T [R]	520
AOA [deg]	13, 28

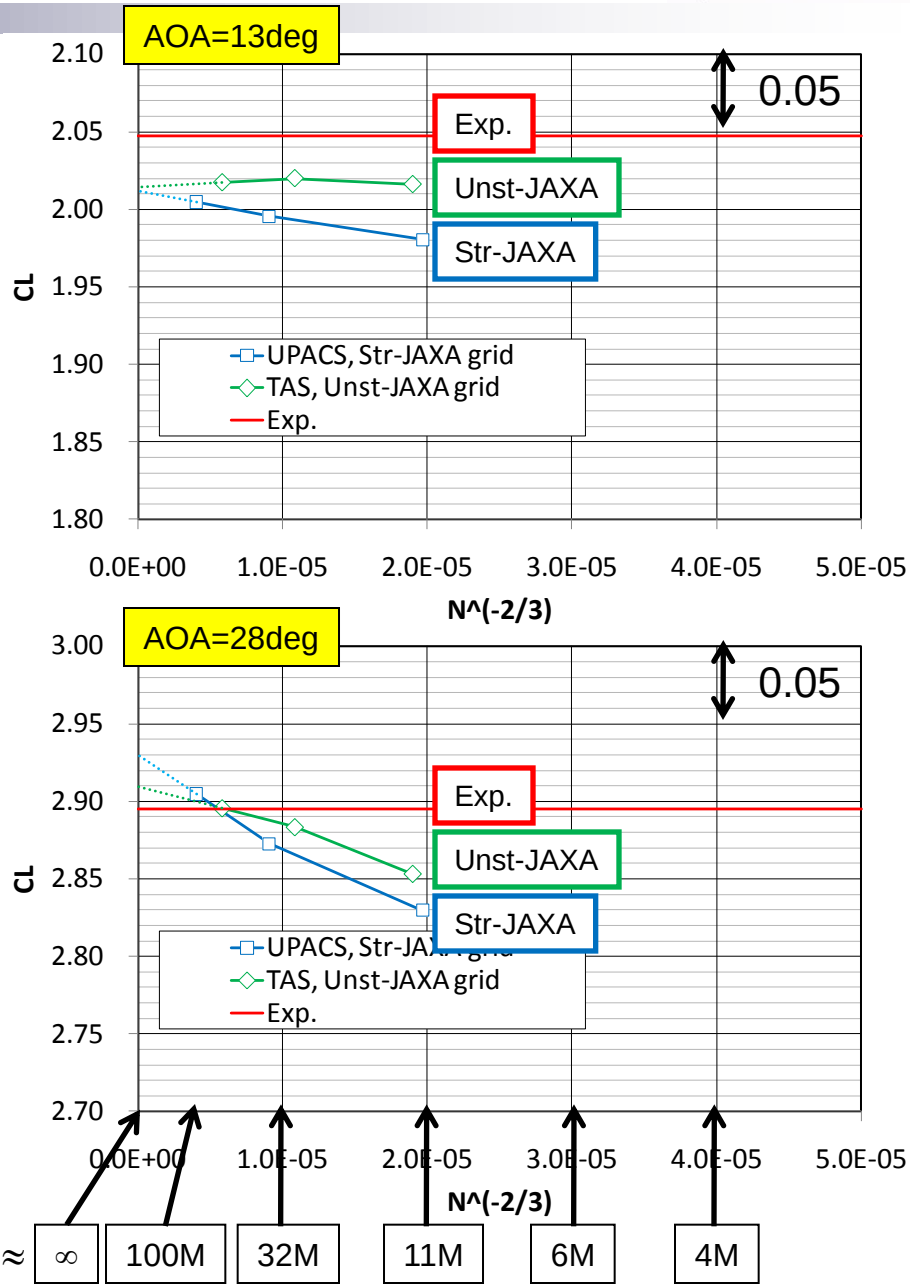


Grid convergence of C_L

- Good agreement among CFD results on finer grids
- Good correlation about grid converged solutions ($C_{L(N\to\infty)}$) by UPACS on Str-JAXA grid and TAS on Unst-JAXA grid

- AOA=13deg
  - Mild slope of grid convergence
  - Good agreement among CFD results, but lower C_L than Exp.

- AOA=28deg
  - More variations and steeper slope of grid convergence
  - Higher $C_{L(N\to\infty)}$ than Exp.



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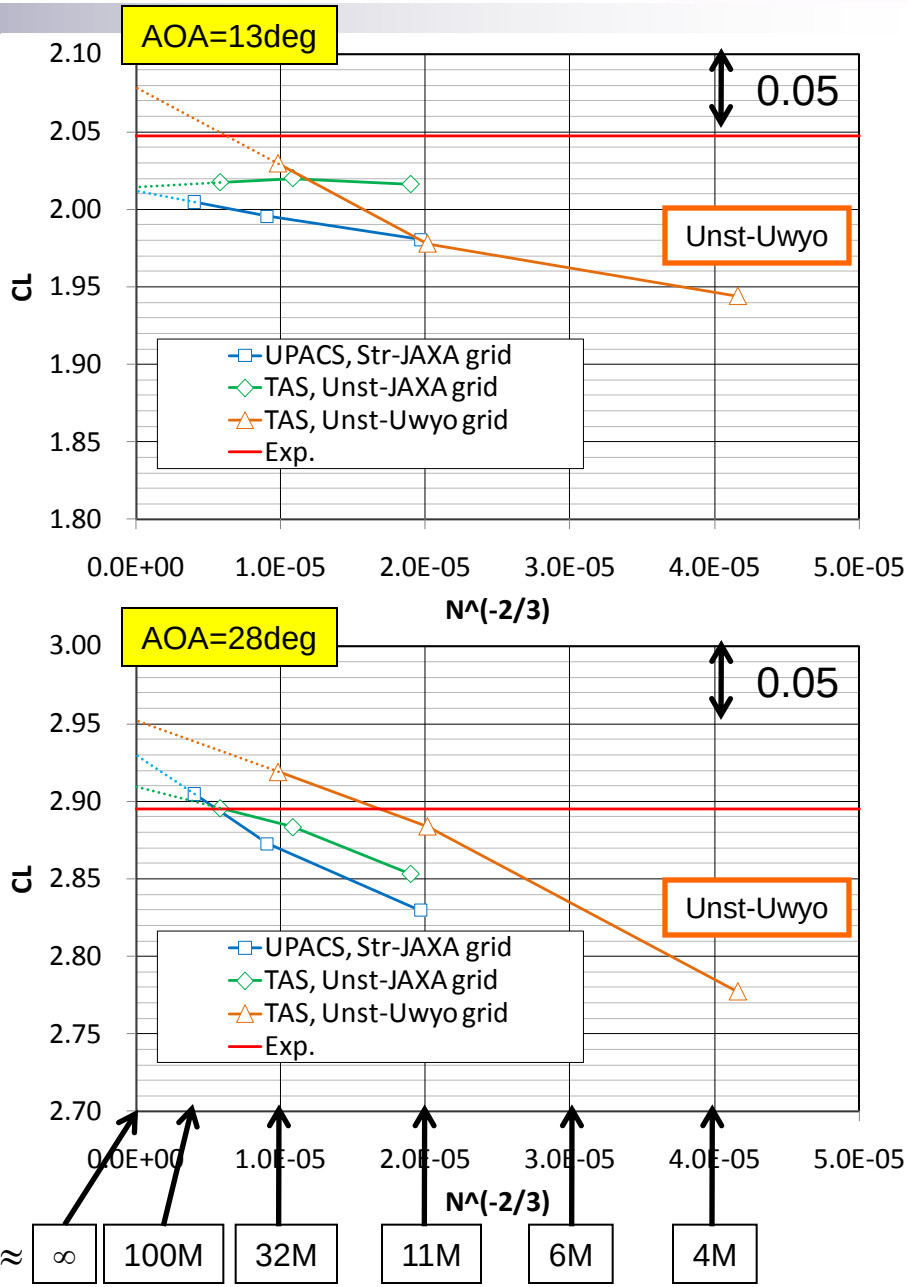

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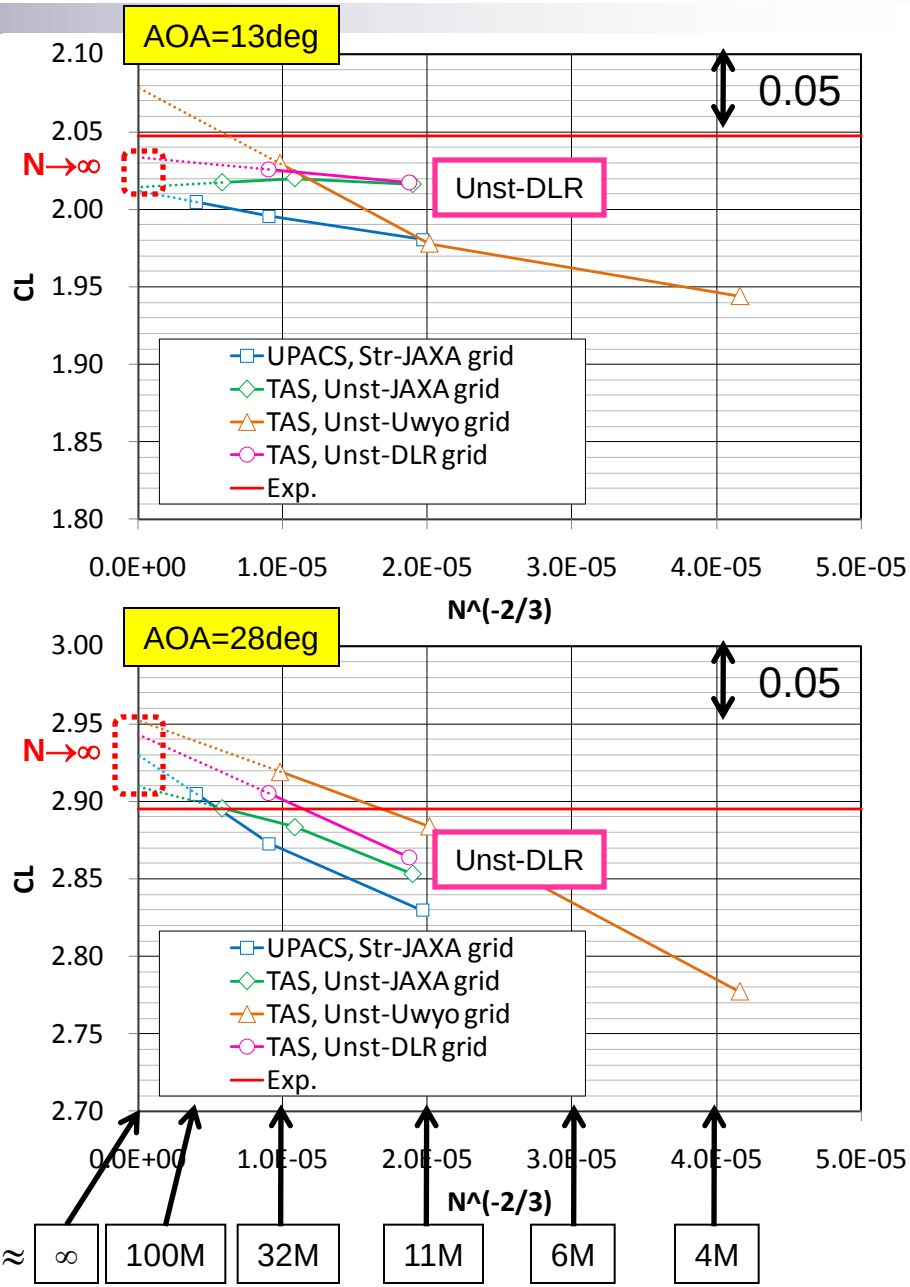
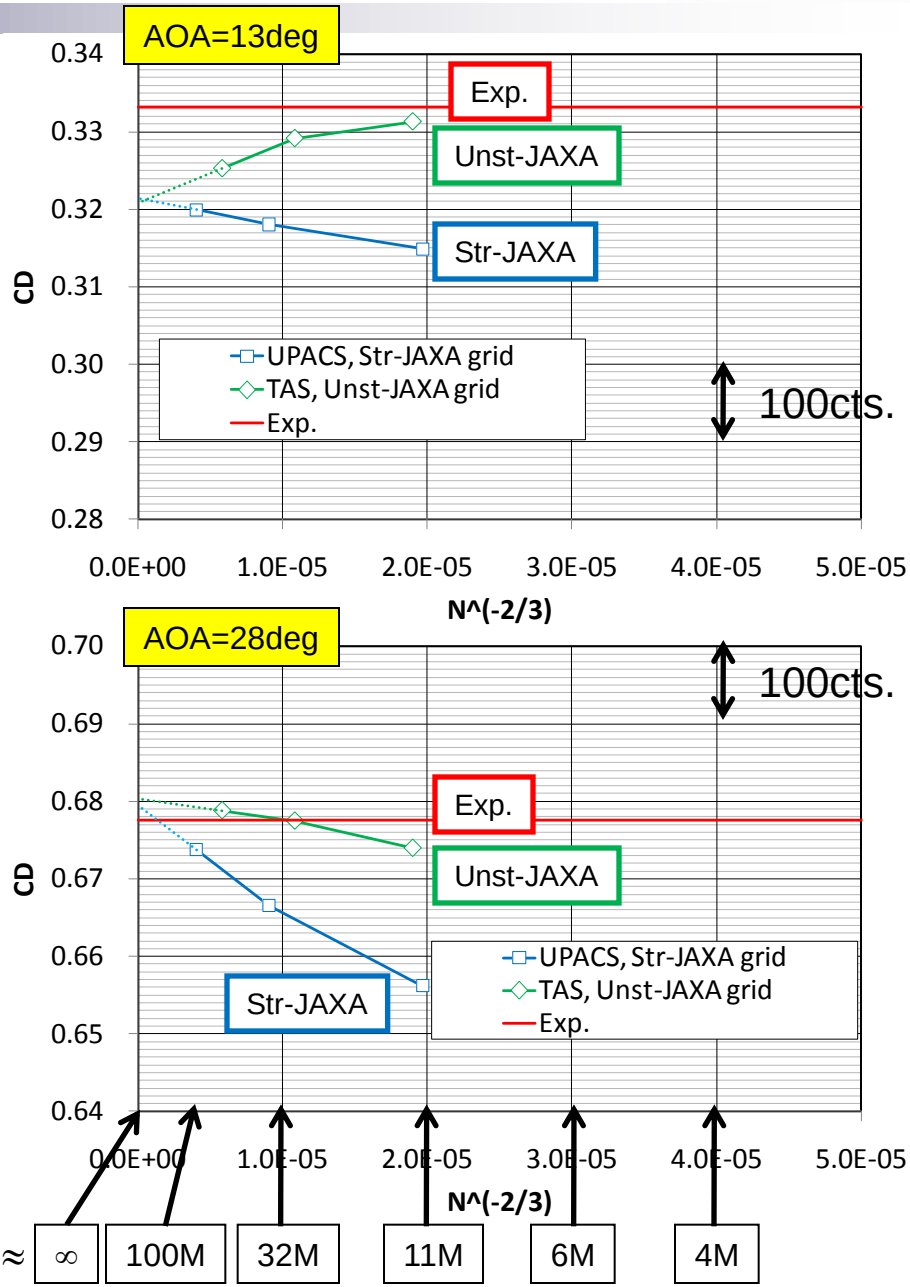


Grid convergence of C_D

- Reasonable agreement among CFD results on finer grids at AOA=13
- Good correlation about $C_{D(N\to\infty)}$ by UPACS on Str-JAXA grid and TAS on Unst-JAXA grid

- AOA=13deg
  - Mild slope of grid convergence
  - Good agreement among CFD results, but lower C_D than Exp.
- AOA=28deg
  - More variations and steeper slope of grid convergence
  - More scattering among CFD results
  - Higher $C_{D(N\to\infty)}$ than Exp.

This comparison includes influence of induced drag by difference of predicted C_L



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  - Good agreement among CFD results, but lower C_D than Exp.
- AOA=28deg
  - More variations and steeper slope of grid convergence
  - More scattering among CFD results
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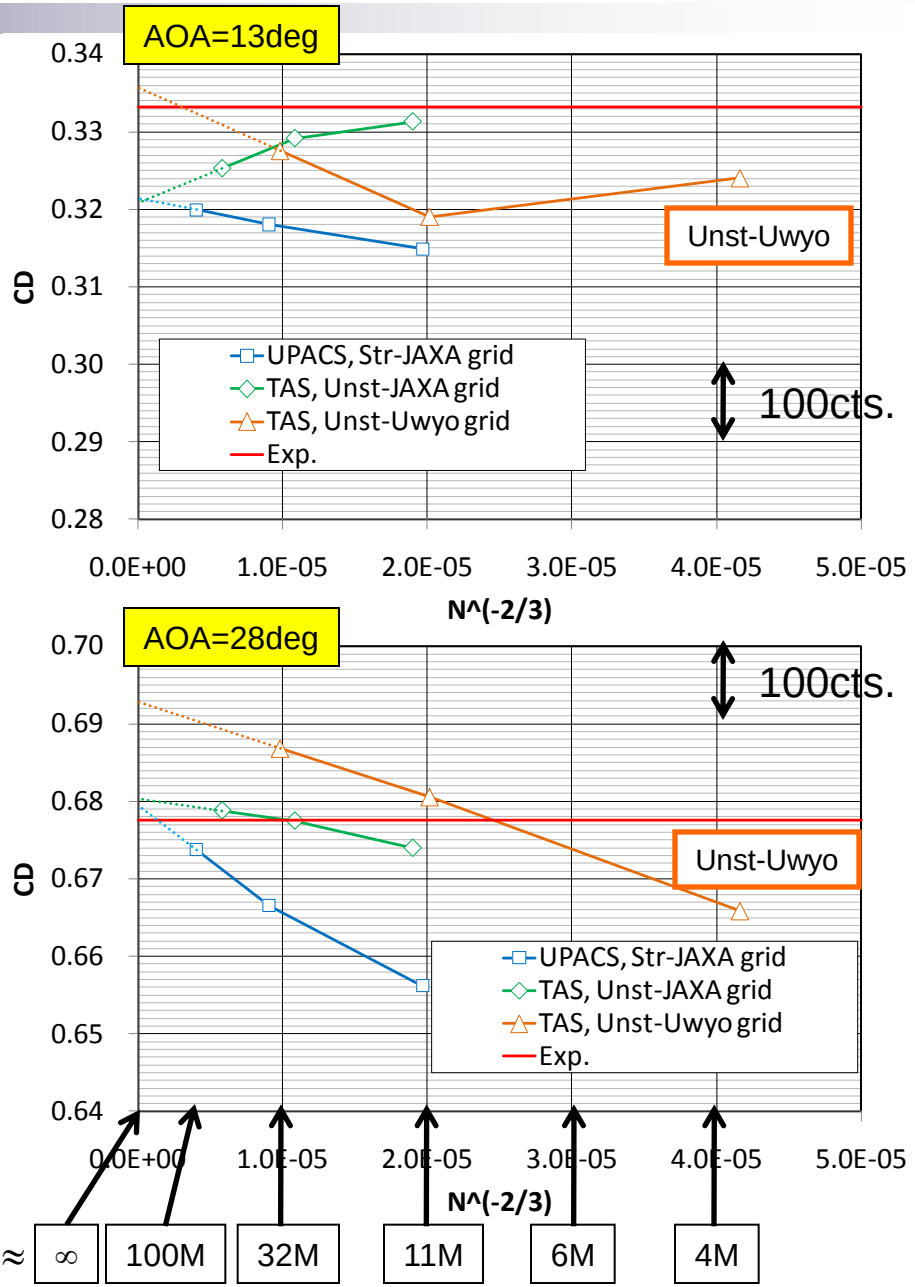

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  - Good agreement among CFD results, but lower C_D than Exp.
- AOA=28deg
  - More variations and steeper slope of grid convergence
  - More scattering of $C_{D(N\to\infty)}$ among CFD results
  - Higher $C_{D(N\to\infty)}$ than Exp.

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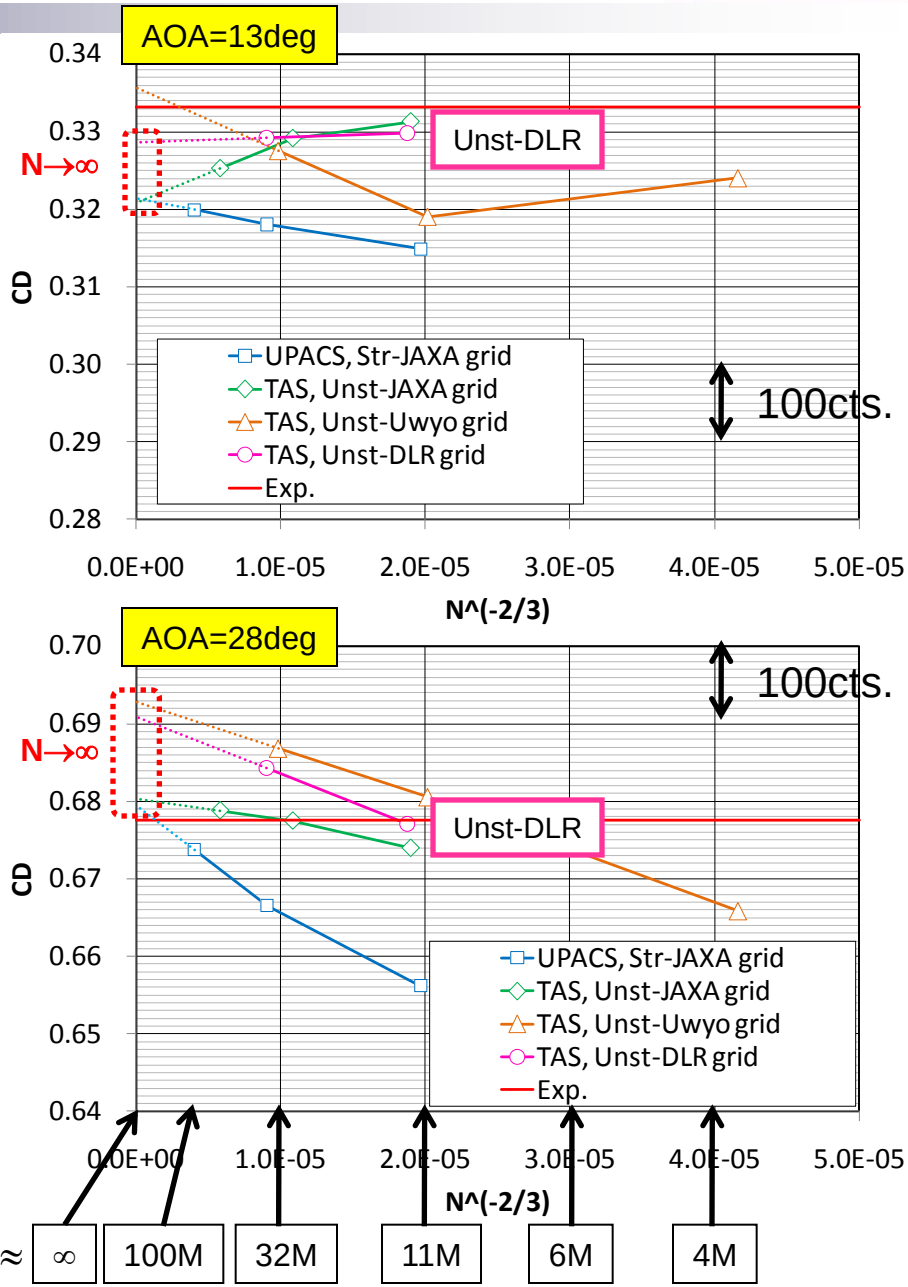
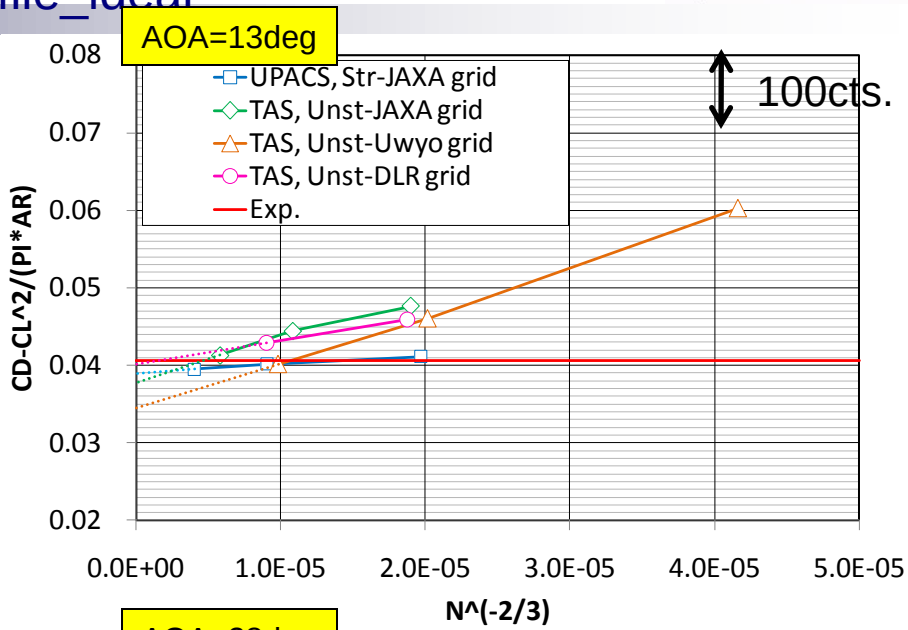
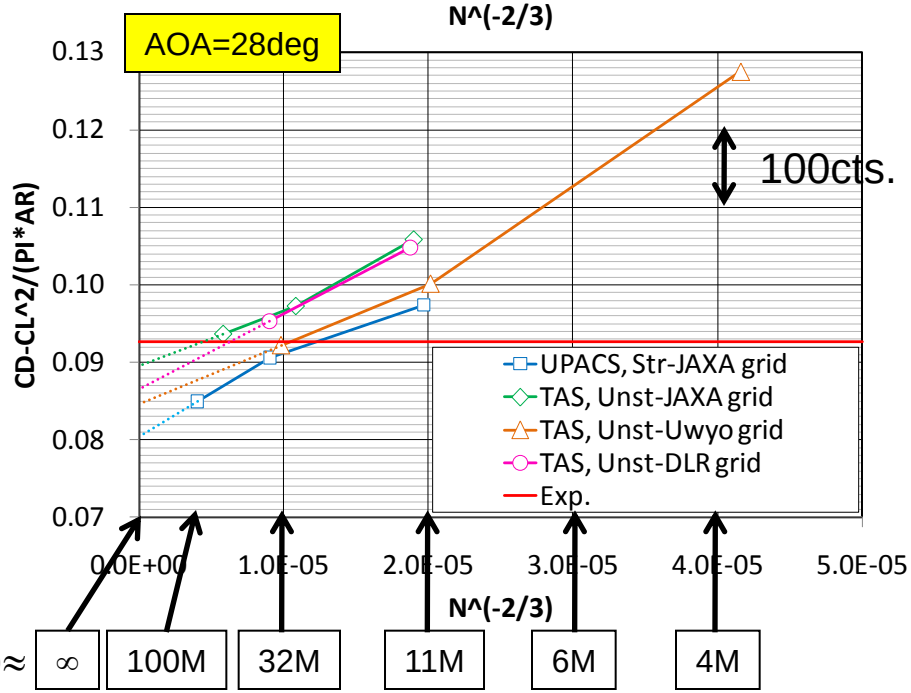


Grid convergence of $C_{Dprofile_ideal}$

- Comparison of idealized profile drag by subtracting ideal induced drag (=C_D-C_L^2/(PI*AR))
  - $C_{Dinduced}$ accounts for about 90% of C_D at high-lift conditions.
  - Better linearity of grid convergence
  - Less scattering among CFD results
  - Better agreement with experimental results

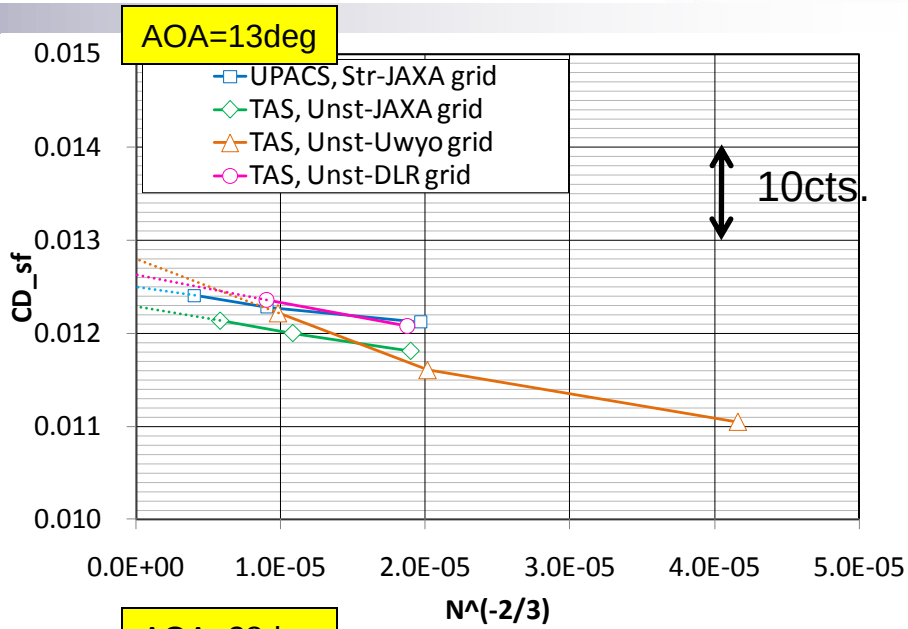


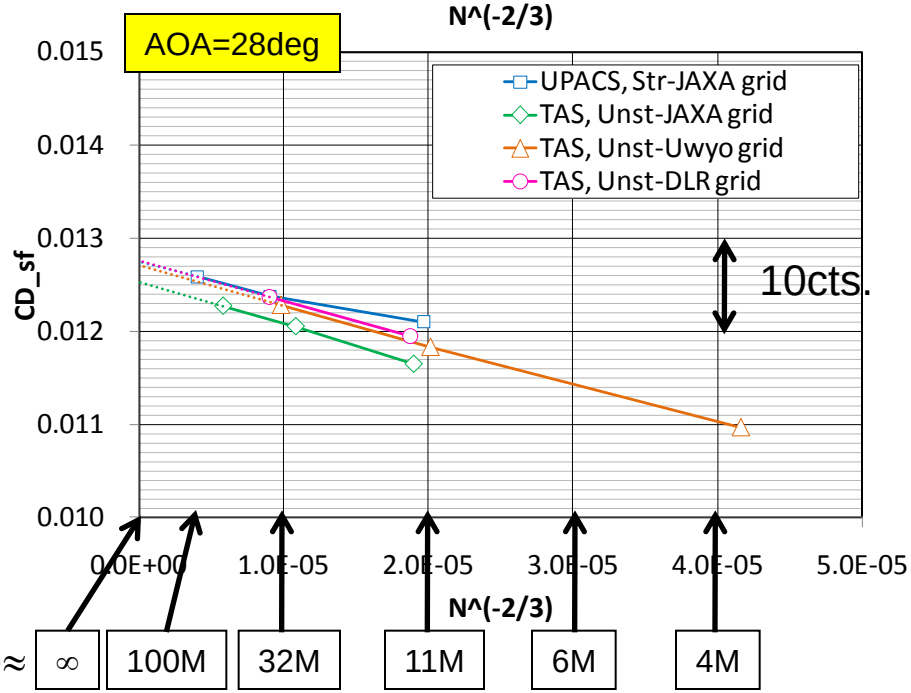


N (grid points)≈ ∞ | 100M | 32M | 11M | 6M | 4M

Grid convergence of C_{D_sf}

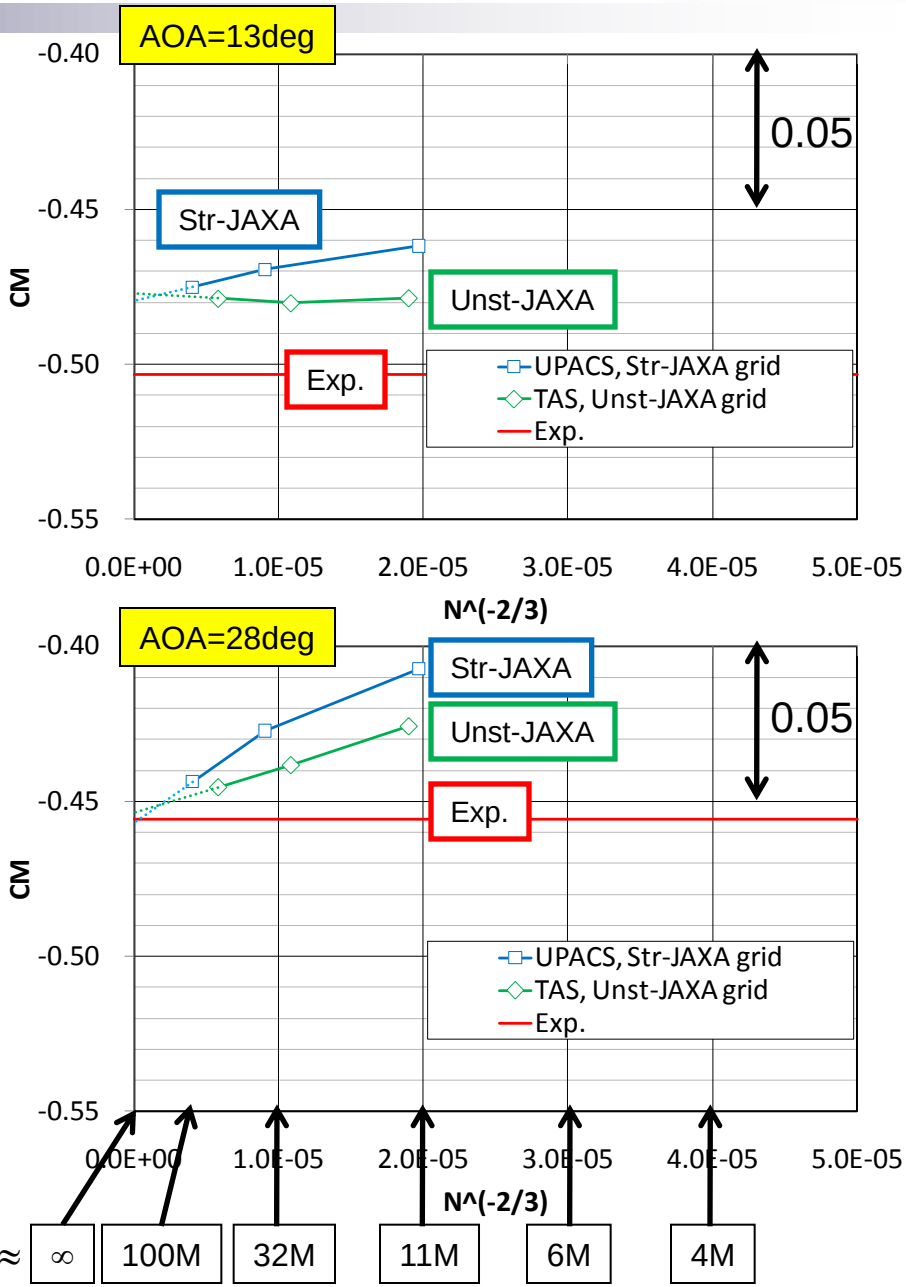
- Scattering by grid density is about 5~10cts.
- Scattering among codes and grids on the medium or fine grids is within 3 cts.
  - Total C_D
    - ≈ 3200-3400 cts. at AOA=13
    - ≈ 6750-6950 cts. at AOA=28





Grid convergence of C_M

- Similar tendency with results of grid convergence of C_L
- Good agreement among CFD results on finer grids at AOA=13
- Good correlation about $C_{M(N\to\infty)}$ by UPACS on Str-JAXA grid and TAS on Unst-JAXA grid
- AOA=13deg
  - Mild slope of grid convergence
  - Good agreement among CFD results, but more pitch-up C_M than Exp.
- AOA=28deg
  - Steeper slope of grid convergence, but better agreement with Exp. on finer grids



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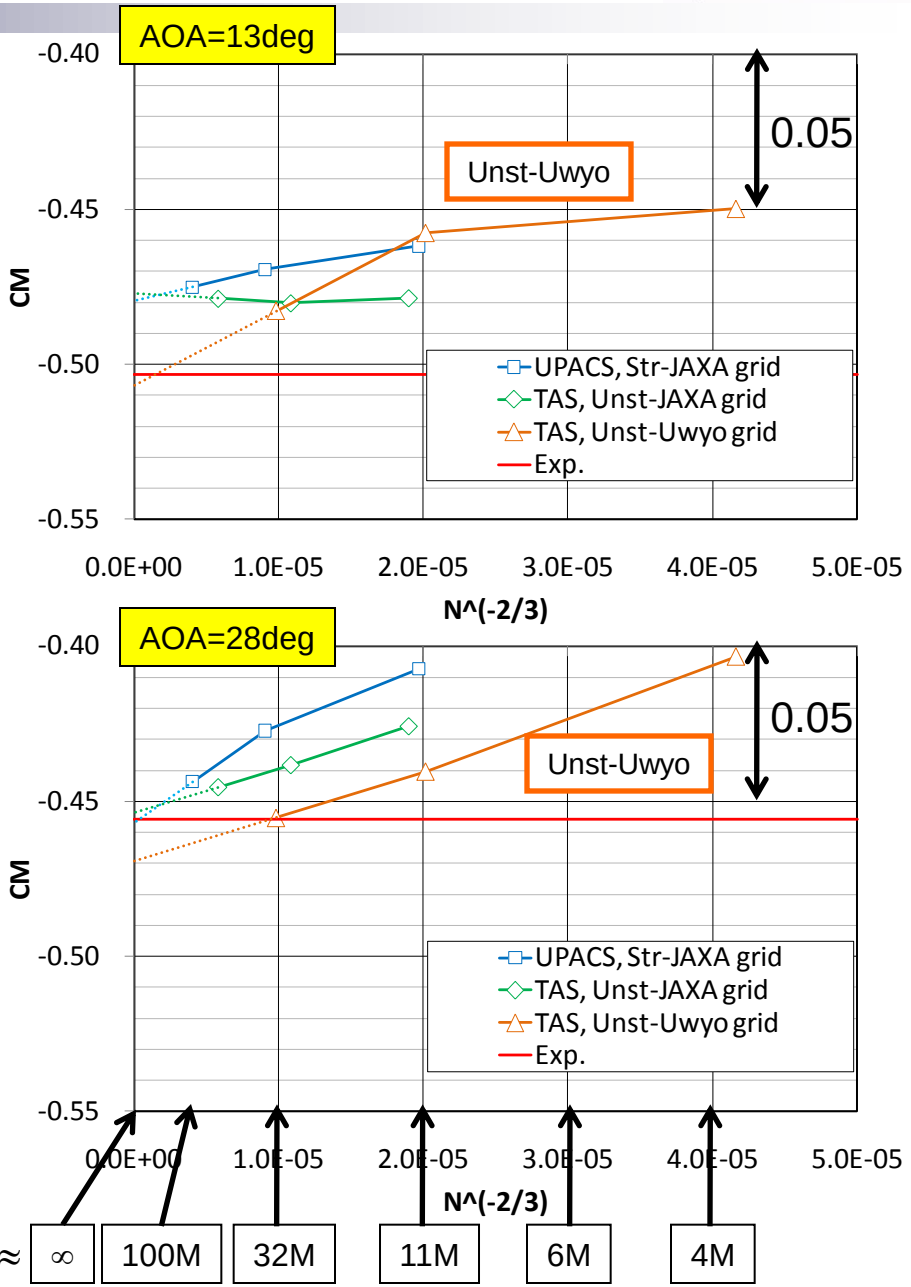

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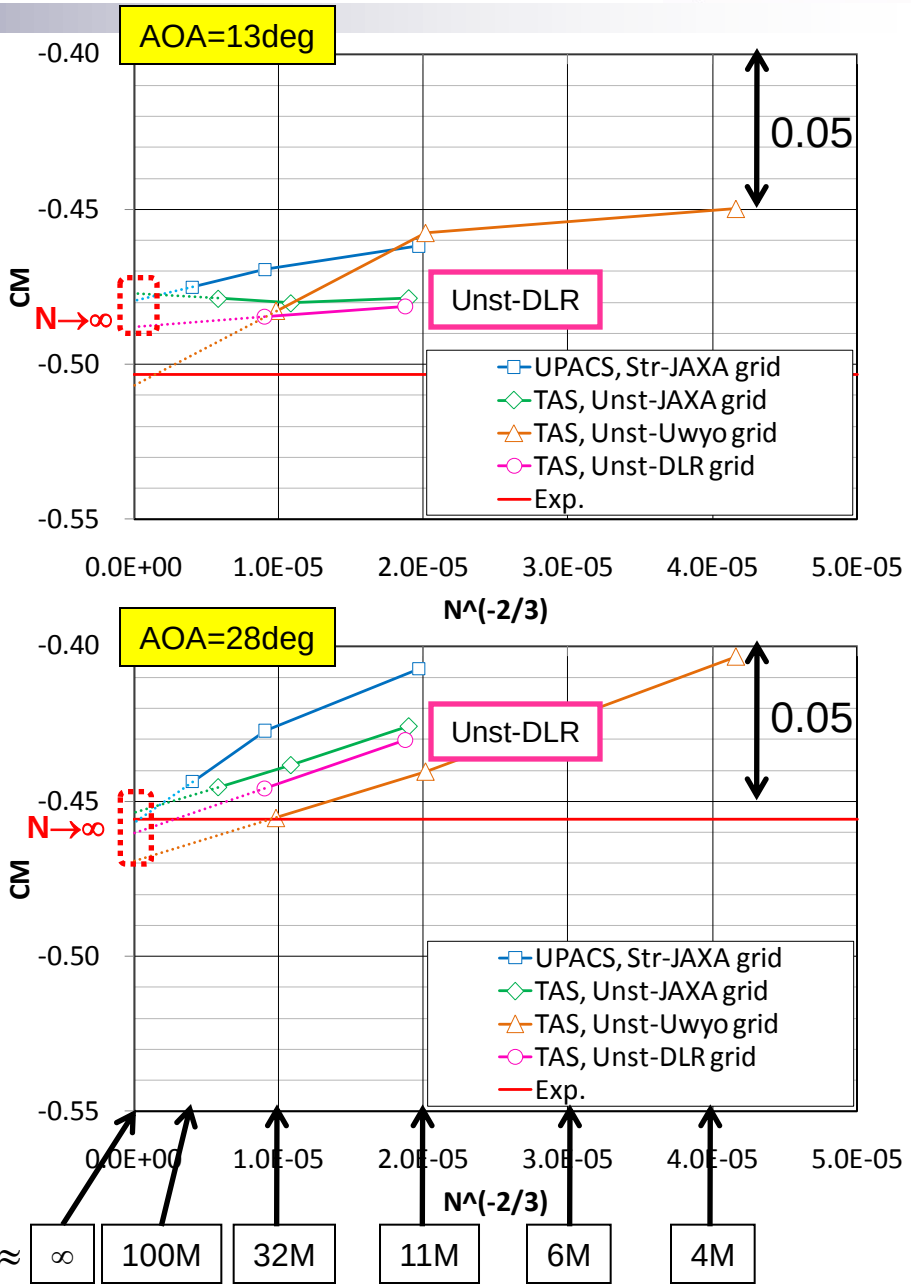
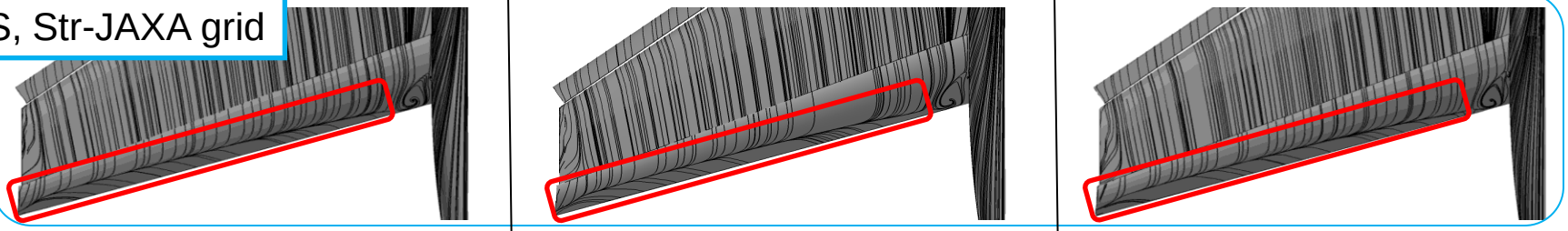


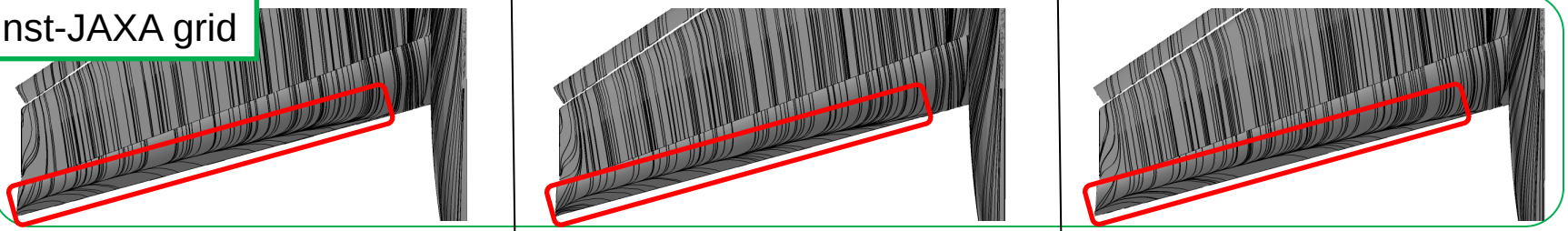
Comparison of oil flow at AOA=13deg

Low sensitivity of grid density to flap flow separation except for Unst-Uwyo grid

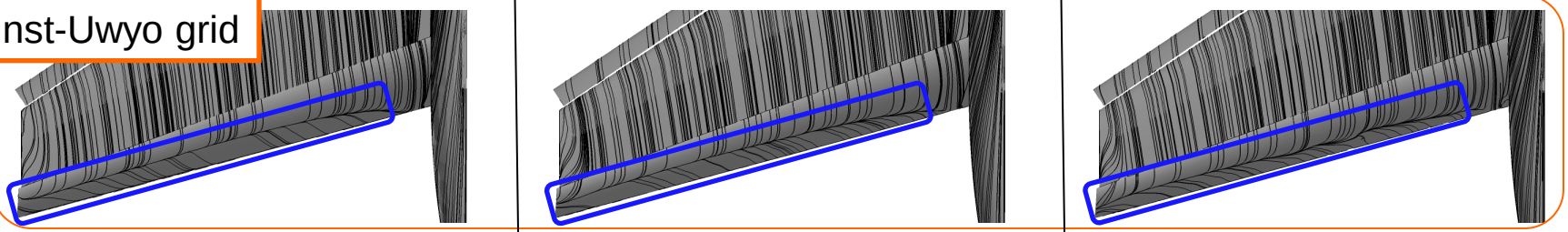
UPACS, Str-JAXA grid



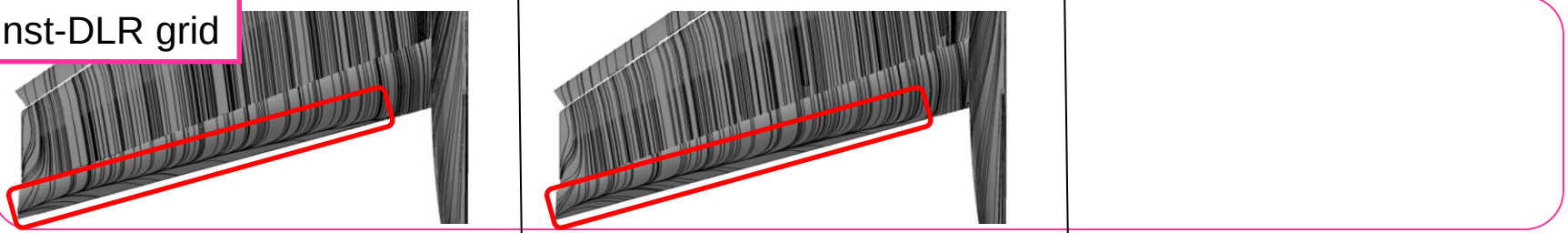
TAS, Unst-JAXA grid



TAS, Unst-Uwyo grid

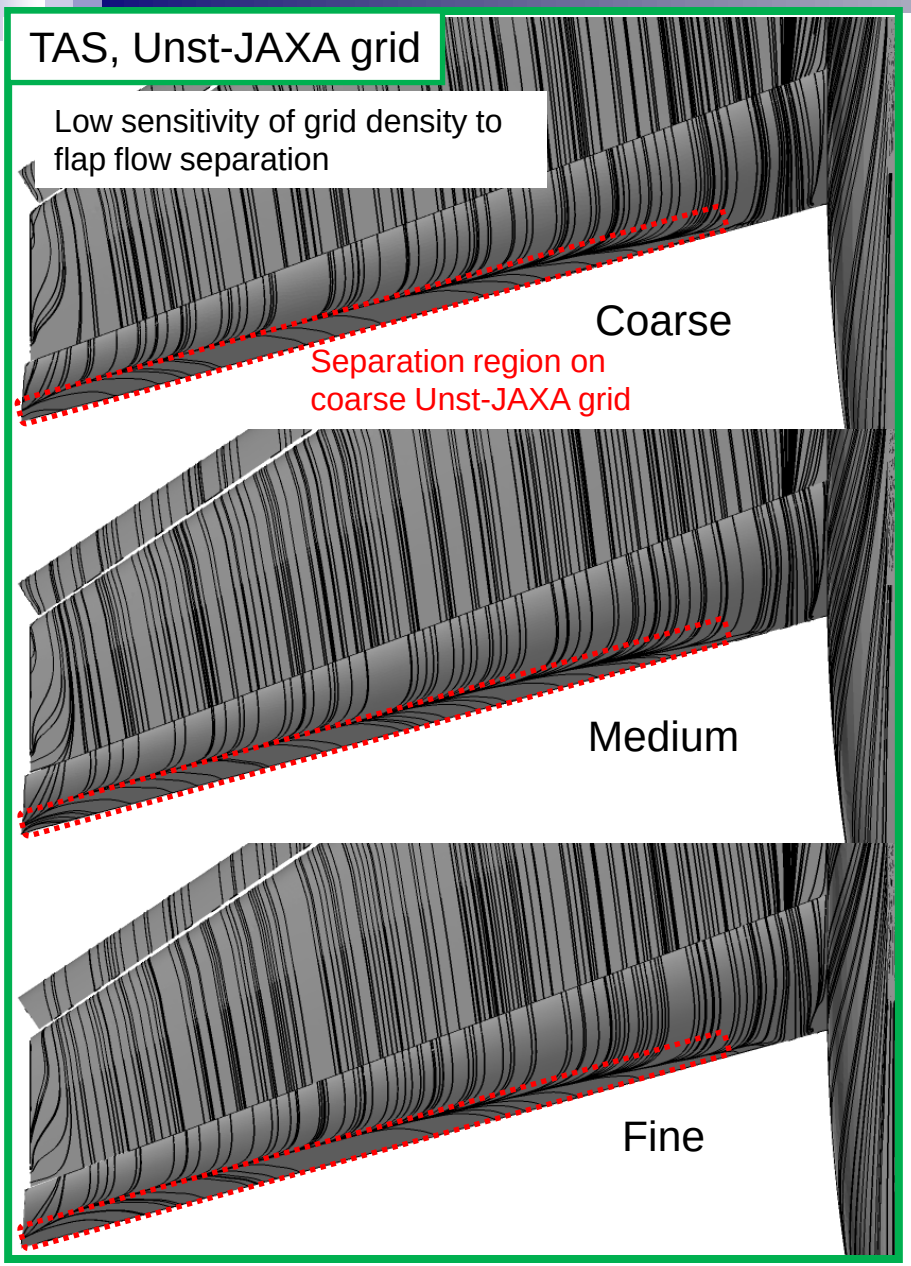


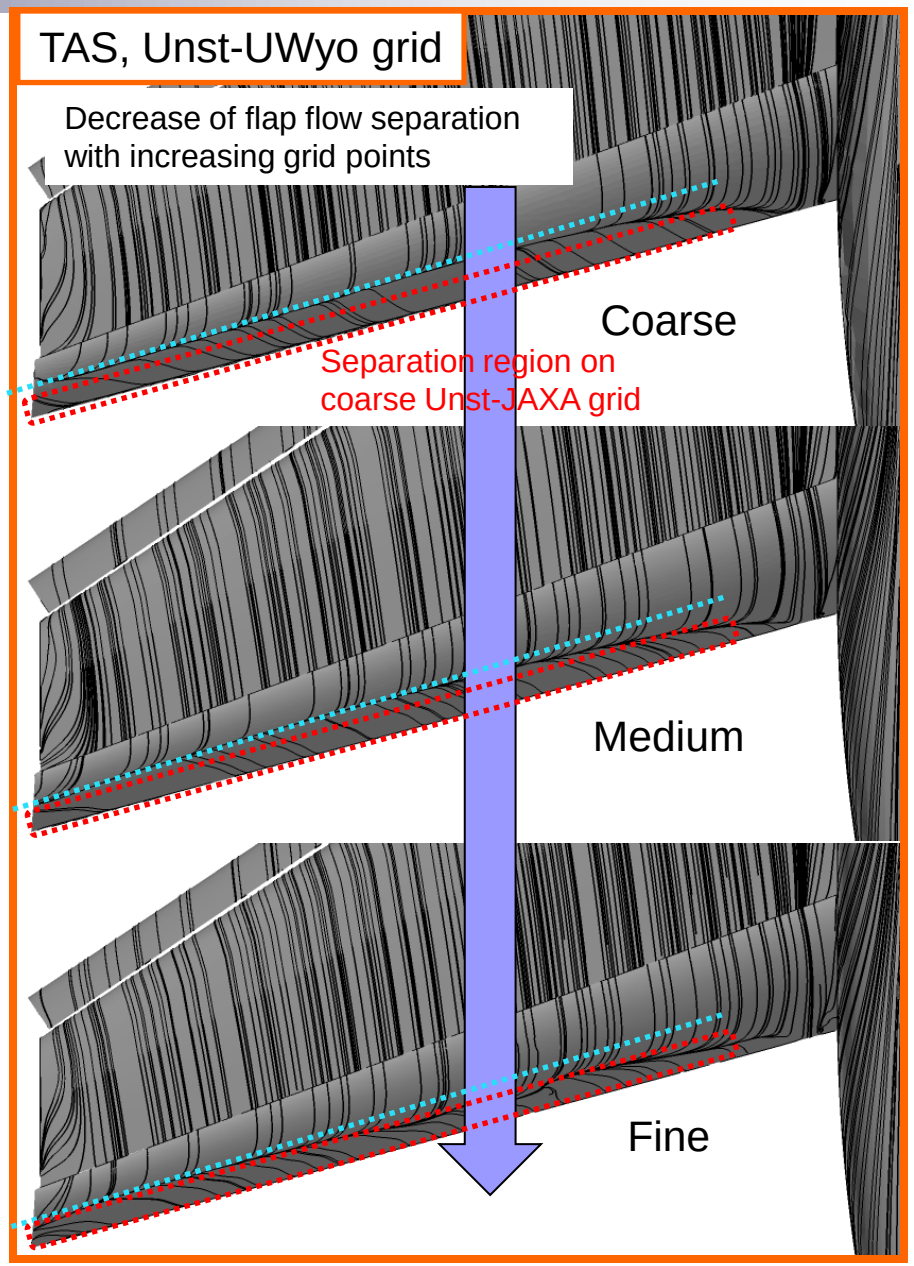
TAS, Unst-DLR grid



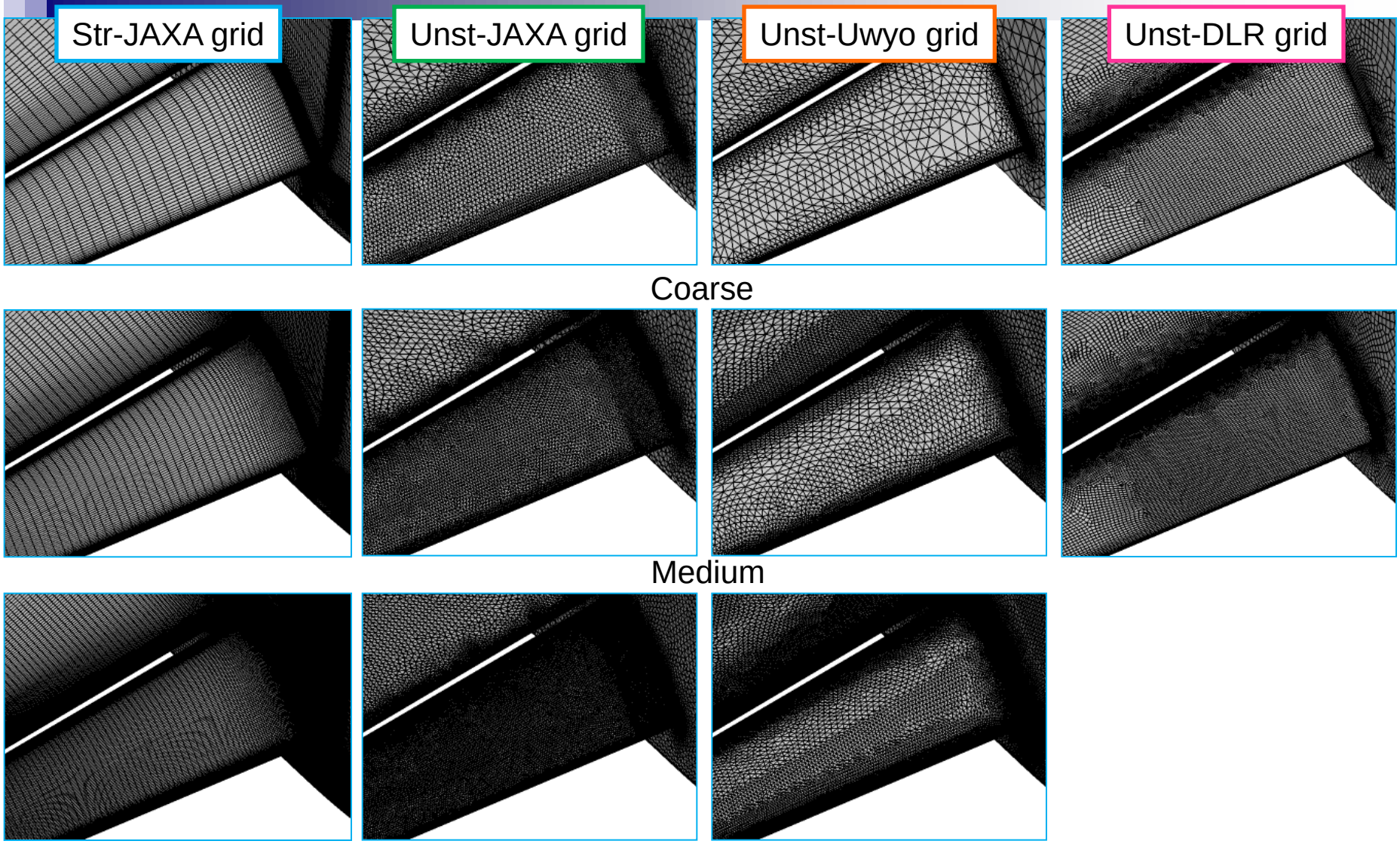
Coarse | Medium | Fine

Comparison of oil flow at AOA=13deg



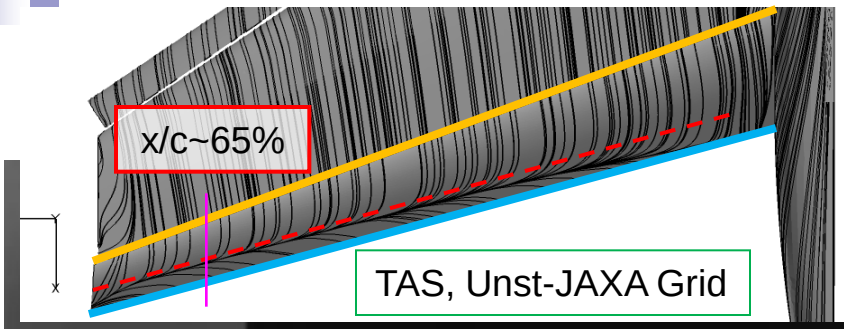


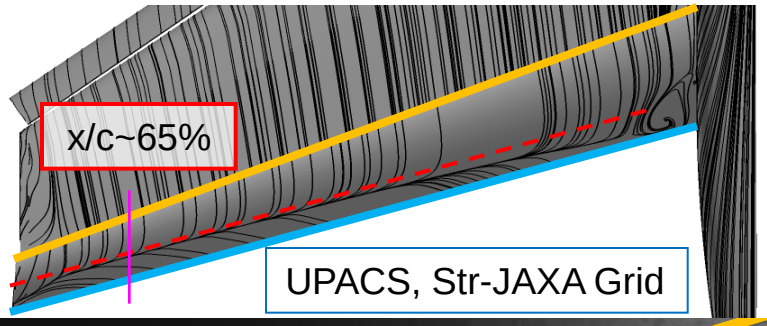
Comparison of grid resolution on the flap



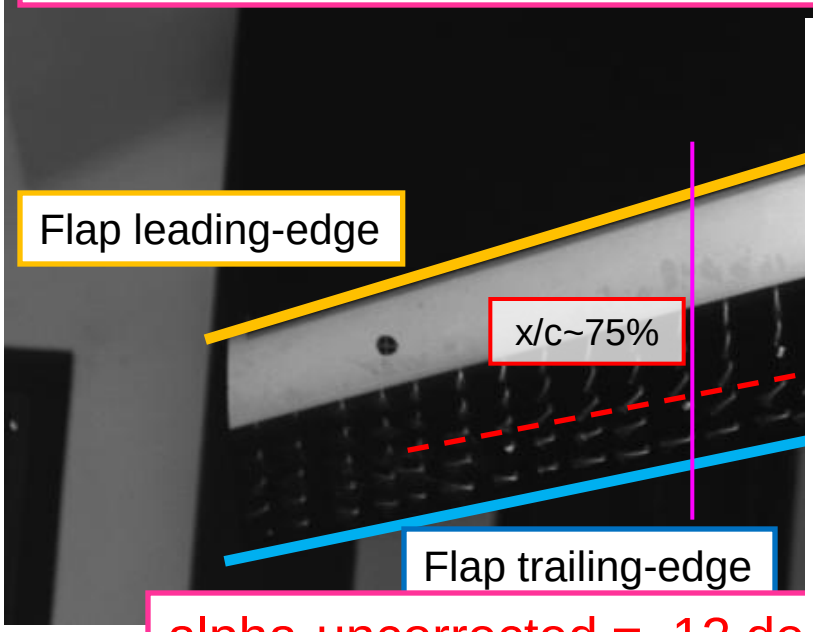
- Difference of grid resolution on the flap at each grid level (Less flap resolution on Unst-Uwyo grids)

Comparison of flow separation on flap(AOA=13, Medium)

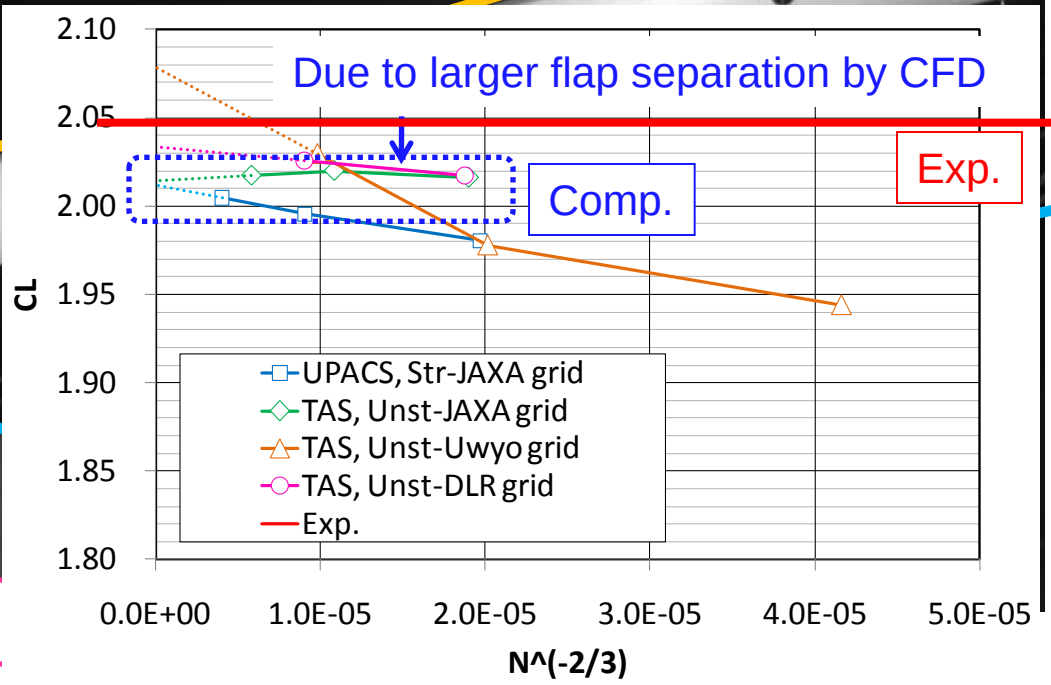




CFD results show larger flap TE flow separation than Exp.



alpha-uncorrected = 12 de

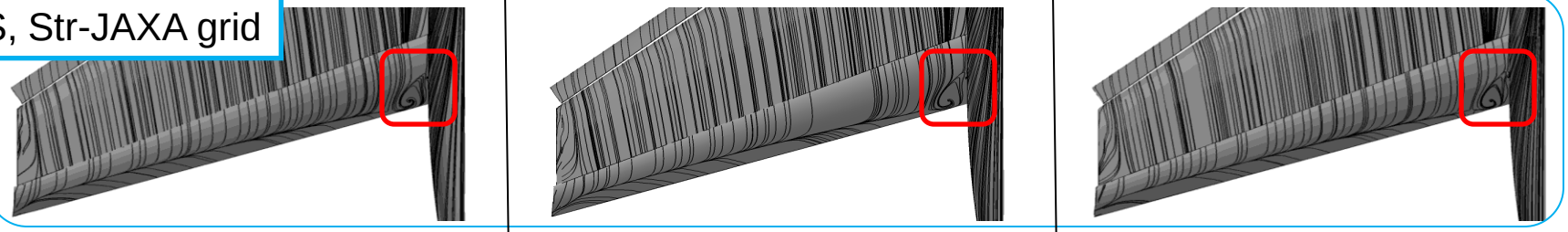


Exp. (Tuft image)

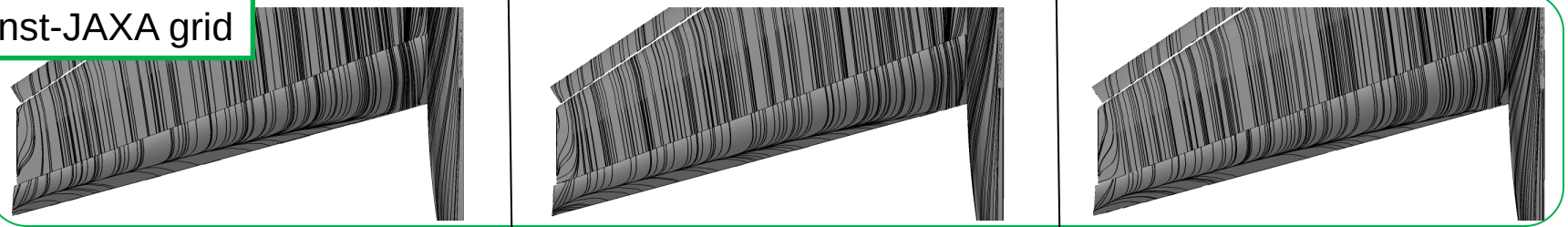
Comparison of oil flow at AOA=13deg

- Flap SOB flow separation only on Str-JAXA grid
- Low sensitive of grid density

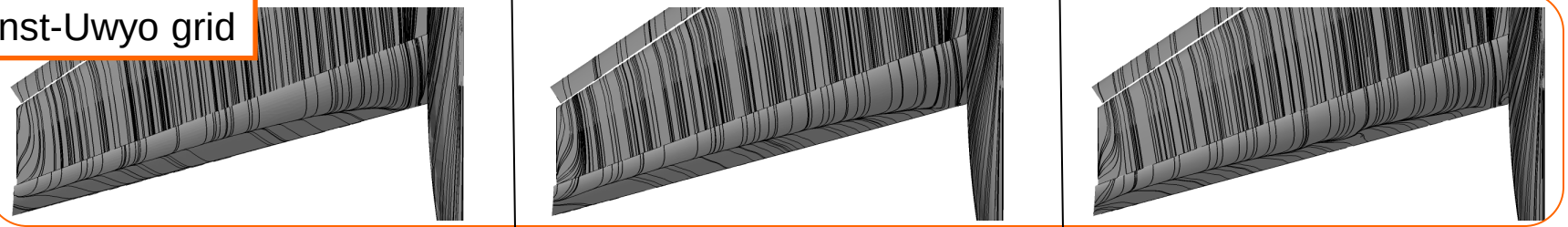
UPACS, Str-JAXA grid



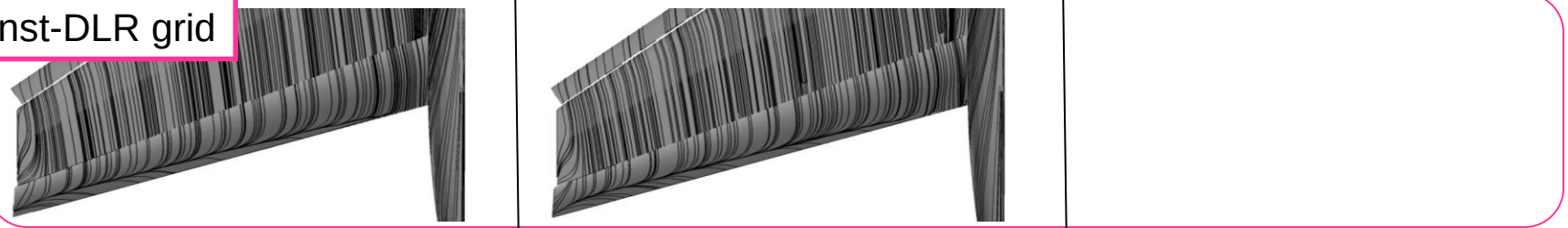
TAS, Unst-JAXA grid



TAS, Unst-Uwyo grid



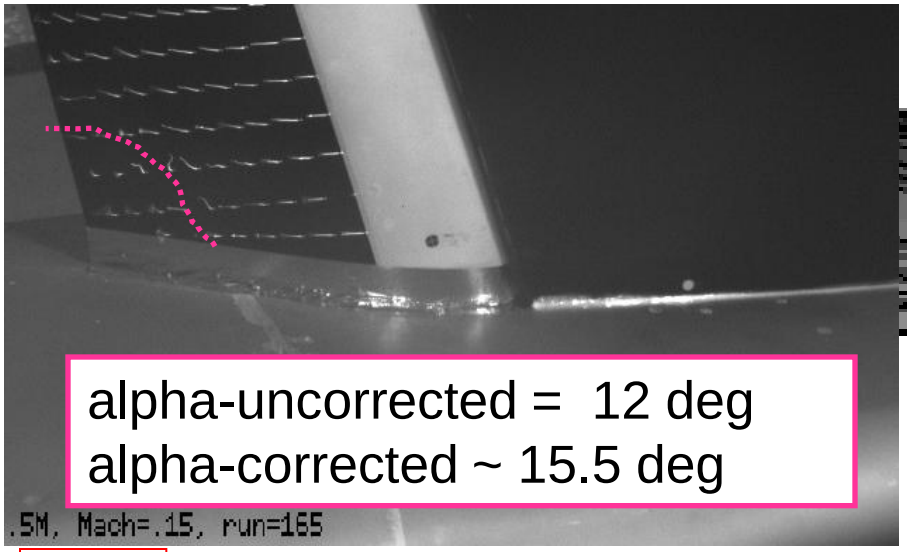
TAS, Unst-DLR grid



Coarse | Medium | Fine

Comparison of flap SOB separation(AOA=13, Medium)

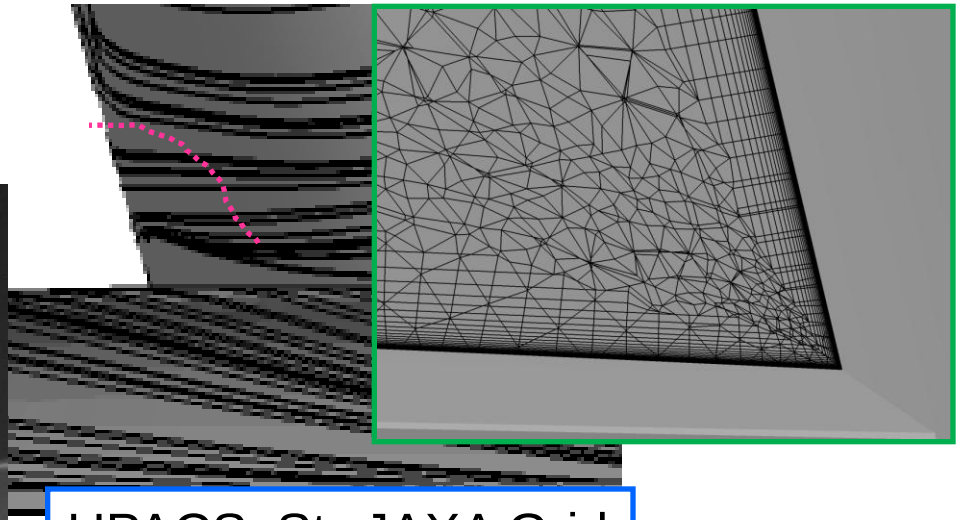
- Flap SOB flow separation by UPACS shows better agreement with Exp.



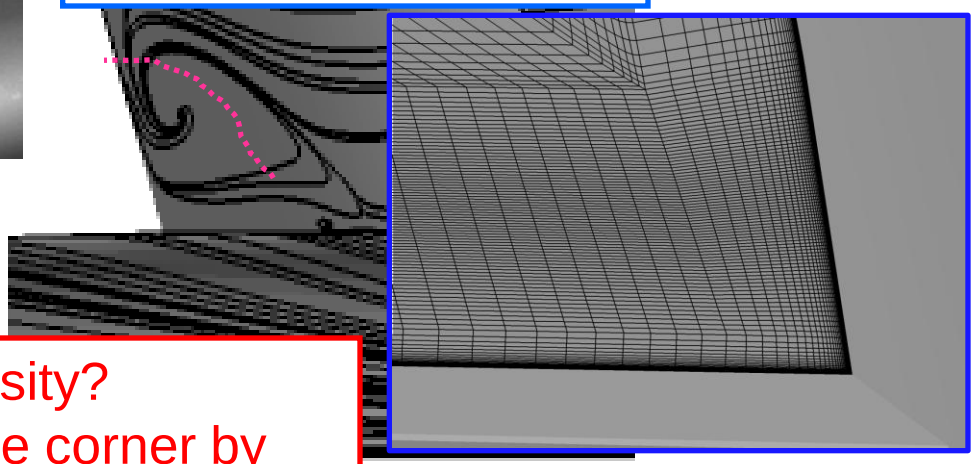
alpha-uncorrected = 12 deg
alpha-corrected ~ 15.5 deg

Exp.

TAS, Unst-JAXA Grid



UPACS, Str-JAXA Grid

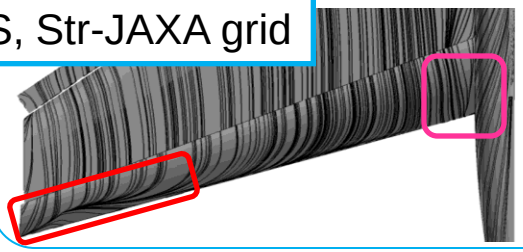
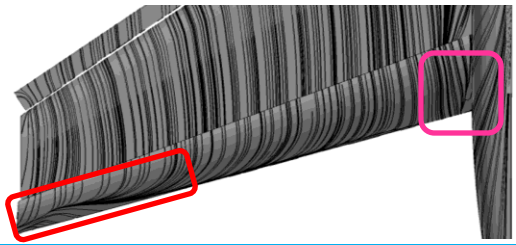
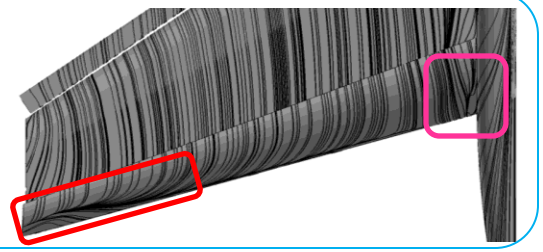


Due to difference of corner grid density?
Str-JAXA grid is extremely fine at the corner by the grid topology even for coarse Str-JAXA grid.

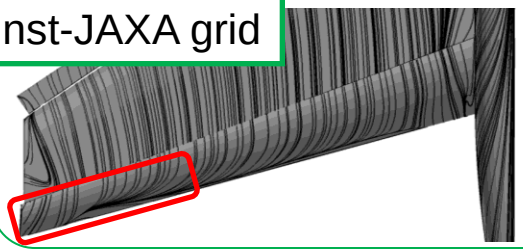
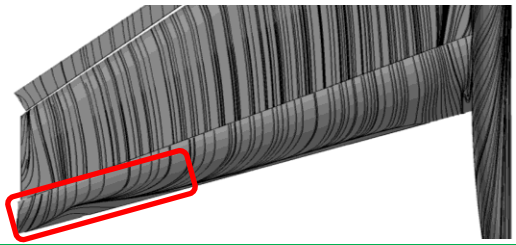
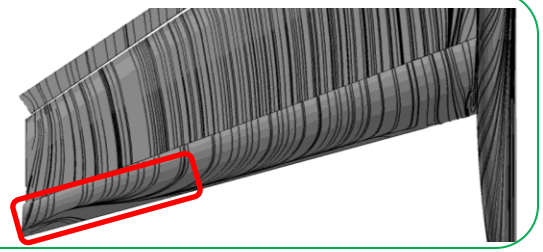
Comparison of oil flow at AOA=28deg

Decrease of **flap flow separation** and **flap SOB separation** at AOA=28

UPACS, Str-JAXA grid

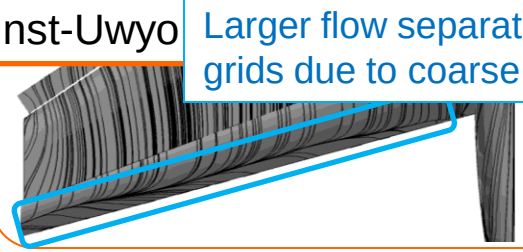
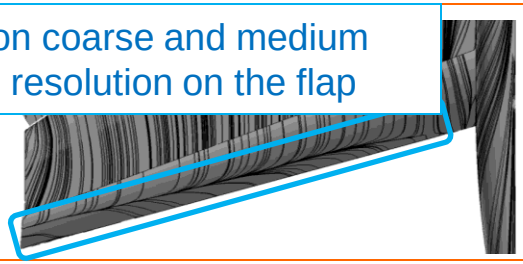
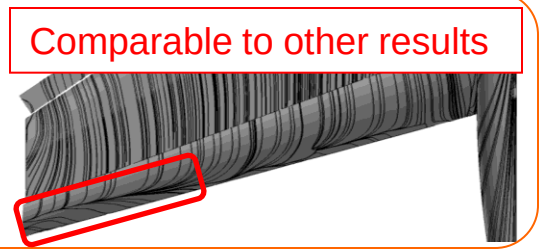
TAS, Unst-JAXA grid

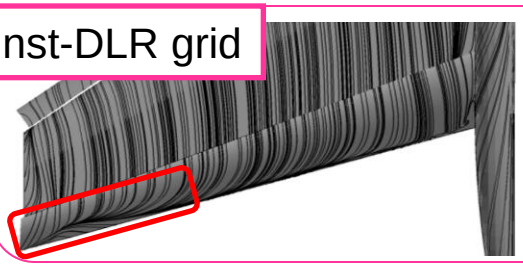
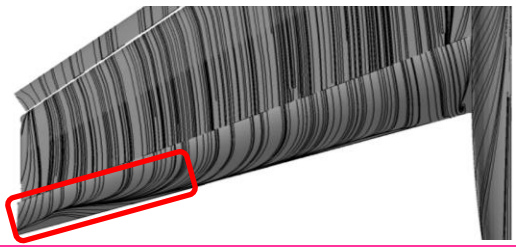
TAS, Unst-Uwyo

Larger flow separation on coarse and medium grids due to coarse grid resolution on the flap

Comparable to other results

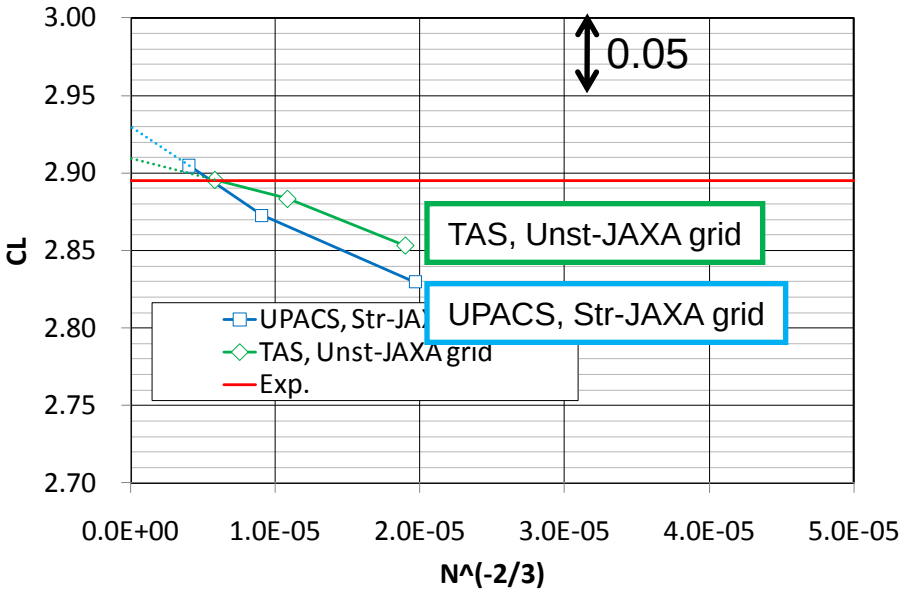




TAS, Unst-DLR grid

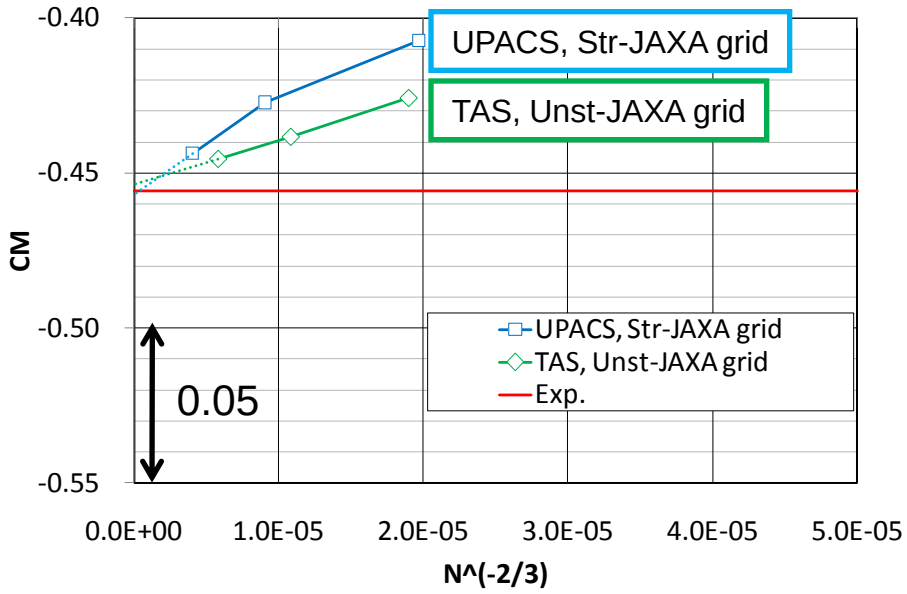



Coarse | Medium | Fine

Comparison of grid convergence at AOA=28



C_L



C_M

- UPACS on Str-JAXA grid shows relatively higher sensitivity of grid resolution at AOA=28.
  - Why ?

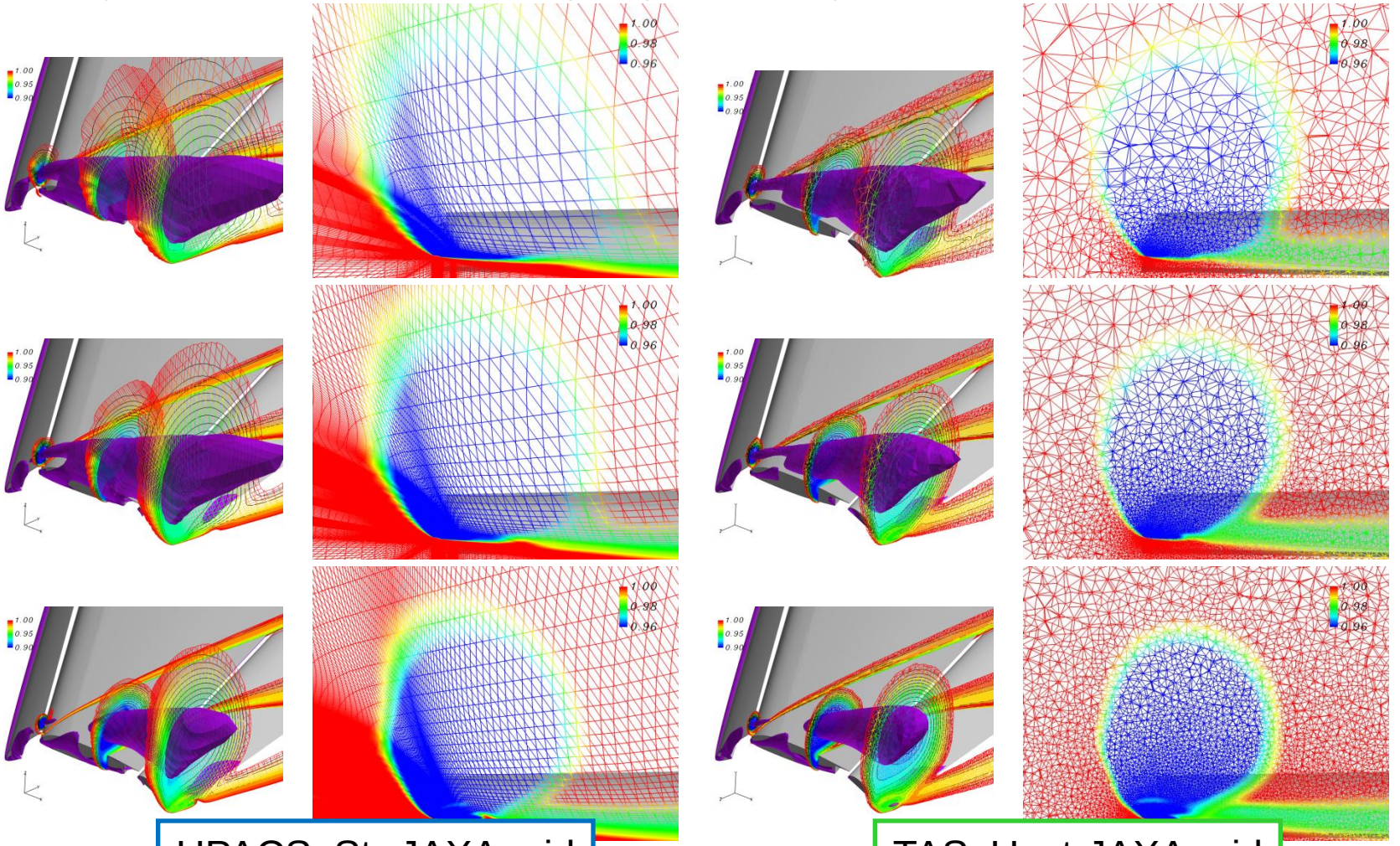
P_{total} and Iso-surface with -0.01%U_{inf} at AOA=28

- Grid spreading ratio on Str-JAXA grid is larger in the wing tip vortex regions.
- Loss of Pt is larger and onset of breakdown of tip vortices is earlier on coarse Str-JAXA grid.
- Results by UPACS on Str-JAXA show higher grid sensitivity.

Coarse

Medium

Fine



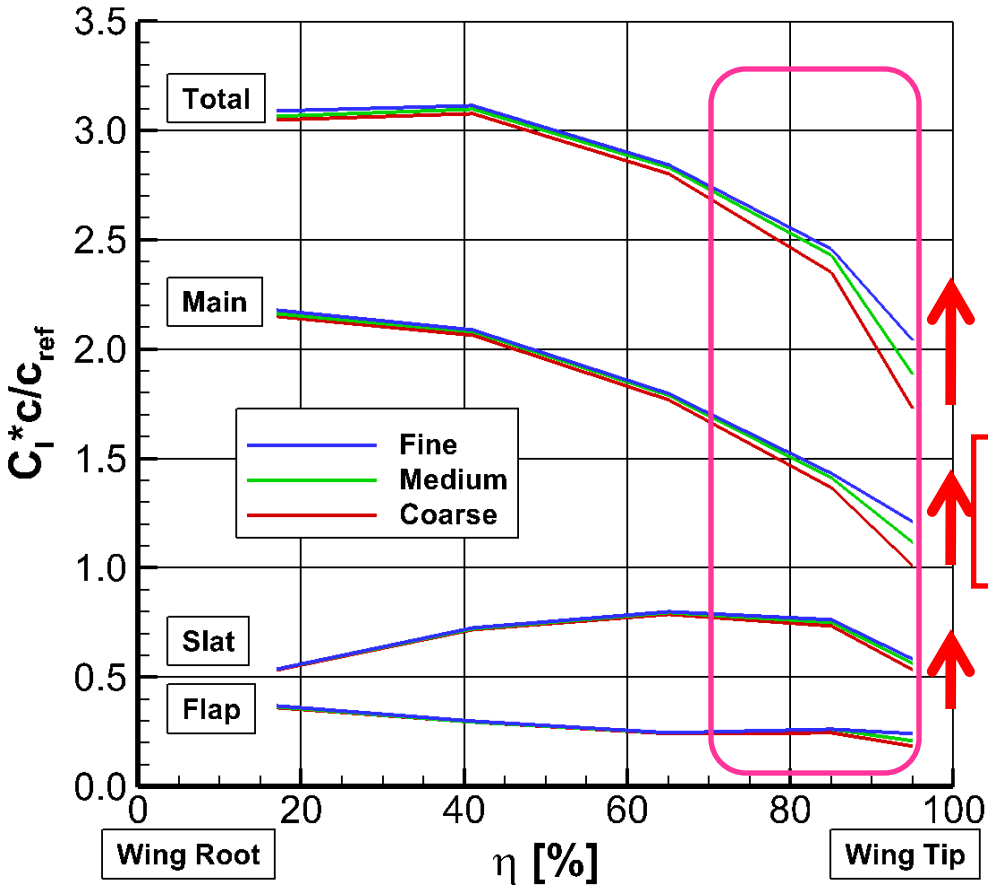
UPACS, Str-JAXA grid

TAS, Unst-JAXA grid

Load distribution in the span-wise at AOA=28

Larger loss of Pt and earlier onset of breakdown of wing tip vortices

→ Less lift near the wing tip regions



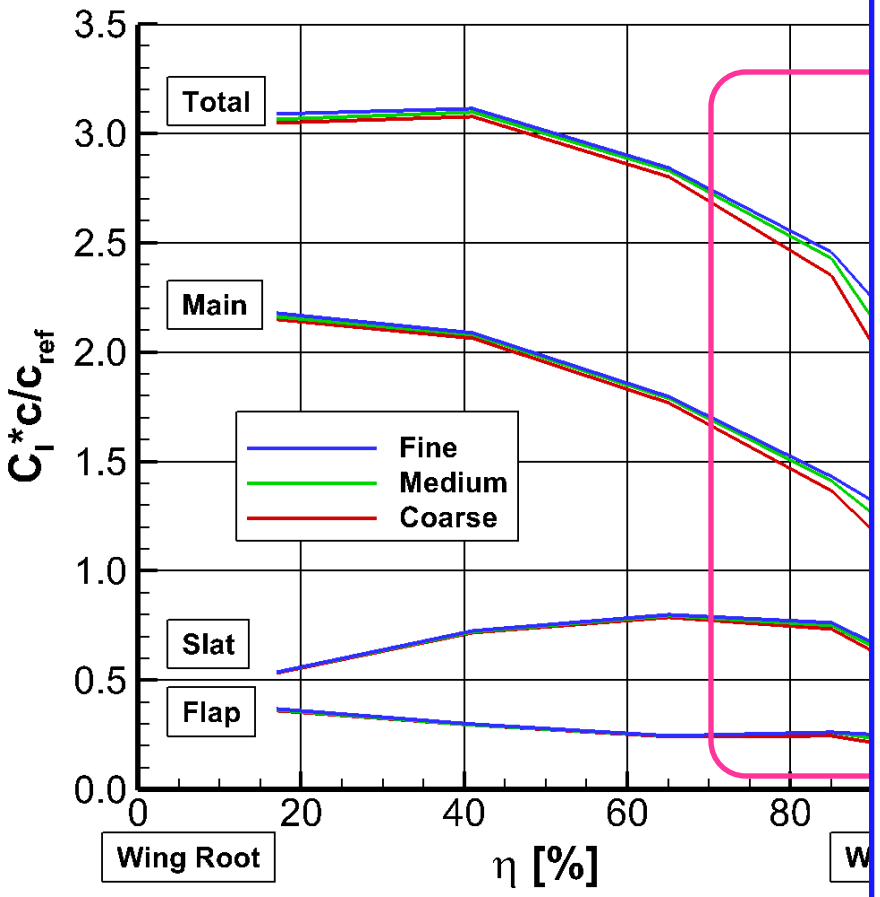
- Major change appears only near wing tip
- Load increases with higher grid resolution

UPACS Str-JAXA grid at AOA=28

Load distribution in the span-wise at AOA=28

Larger loss of Pt and earlier onset of breakdown of wing tip vortices

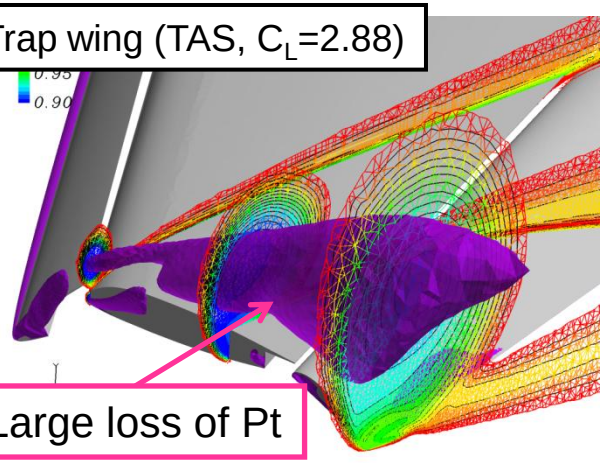
→ Less lift near the wing tip regi



UPACS Str-JAXA grid at AOA=

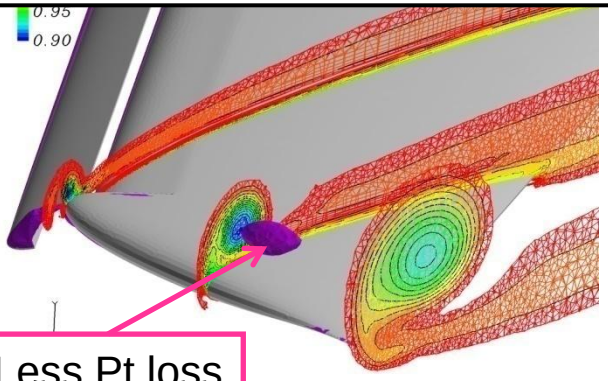
Ref. Comparison of wing tip flow with realistic aircraft model
Trap wing: Full-span slat and flap, simplified wing tip

Trap wing (TAS, C_L=2.88)



Large loss of Pt

JAXA HLD Research Model, JSM (TAS, C_L=2.89)



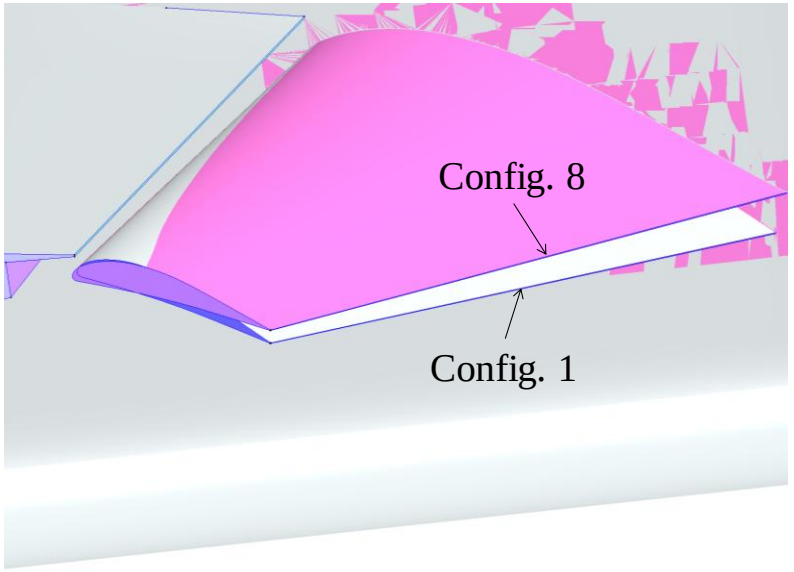
Less Pt loss

Observations in Case1

- AOA=13
  - Importance of prediction of flow separation over flap
  - Tendency to show lower $C_{L(N\rightarrow\infty)}$ and higher pitch-up $C_{M(N\rightarrow\infty)}$ than Exp. due to larger flow separation
- AOA=28
  - Importance of prediction of tip vortex behavior although difference among codes and grids will decrease with finer grids

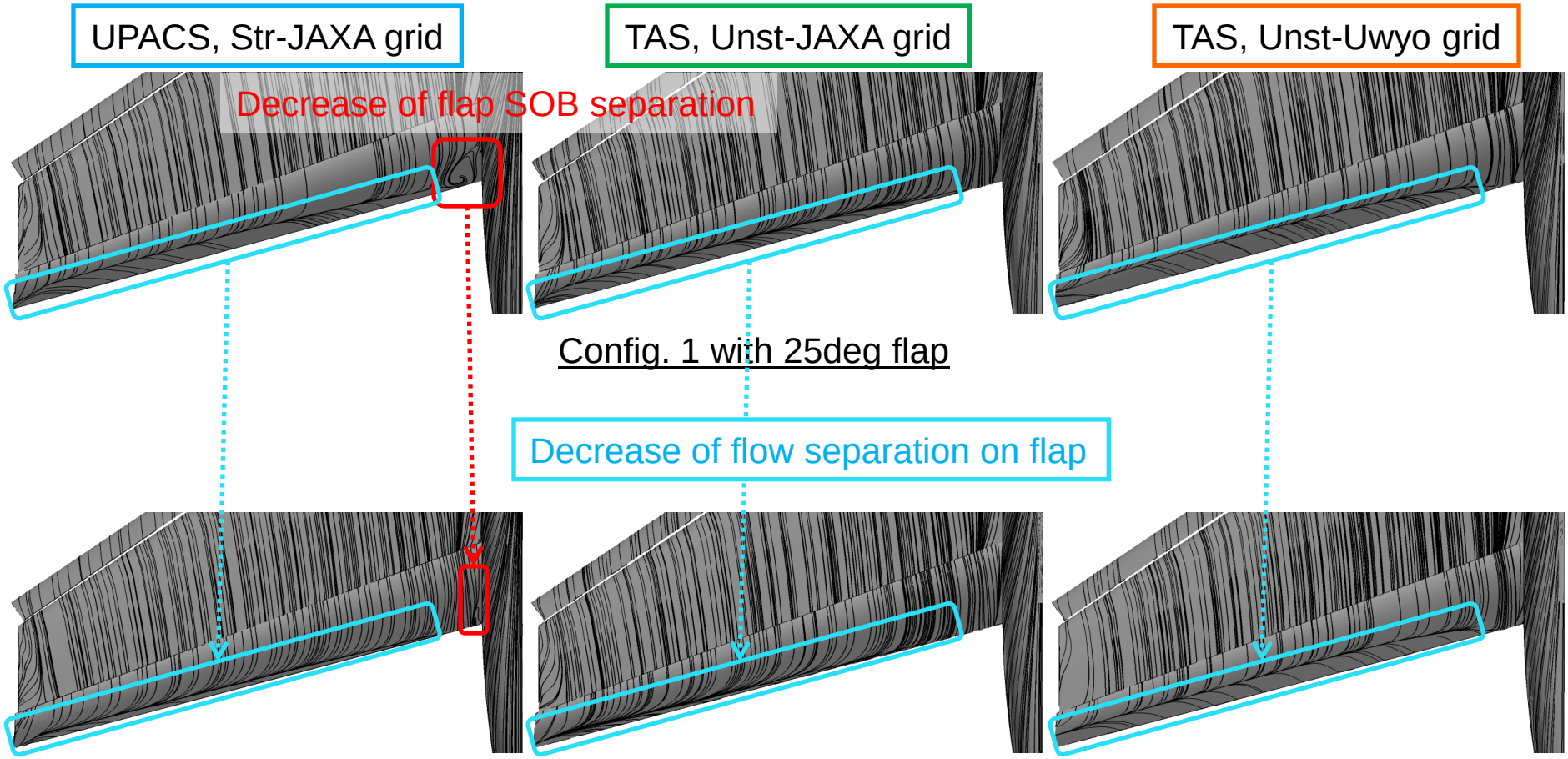
- Case 1 Grid Convergence Study
- Case 2 Flap Deflection Prediction Study
- Case 3 Flap and Slat Support Effects Study
- Additional evaluations
  - Local grid density on flap trailing-edge
  - Sensitivity of turbulence model

	Case2 Flap deflection prediction study
Slat & flap setting	Config. 1 and Config. 8
Slat & flap bracket	Not-included
M	0.2
Re	4.3×10^6
T [R]	520
AOA [deg]	6, 13, 21, 28, 32, 34, 37



	deflection [deg]	
	slat	flap
Config. 1	30	25
Config. 8		20

Comparison of oil flow at AOA=13deg



Flap deflection effect of ΔC_L (=Config.1 – Config.8)

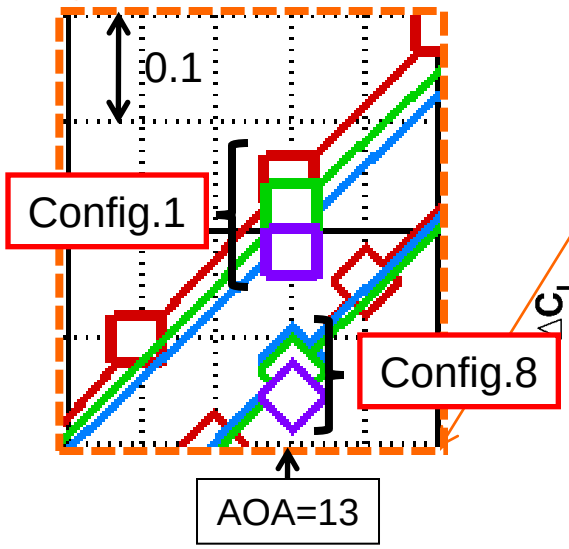
- Results for Config. 8 show less differences among codes and grids.

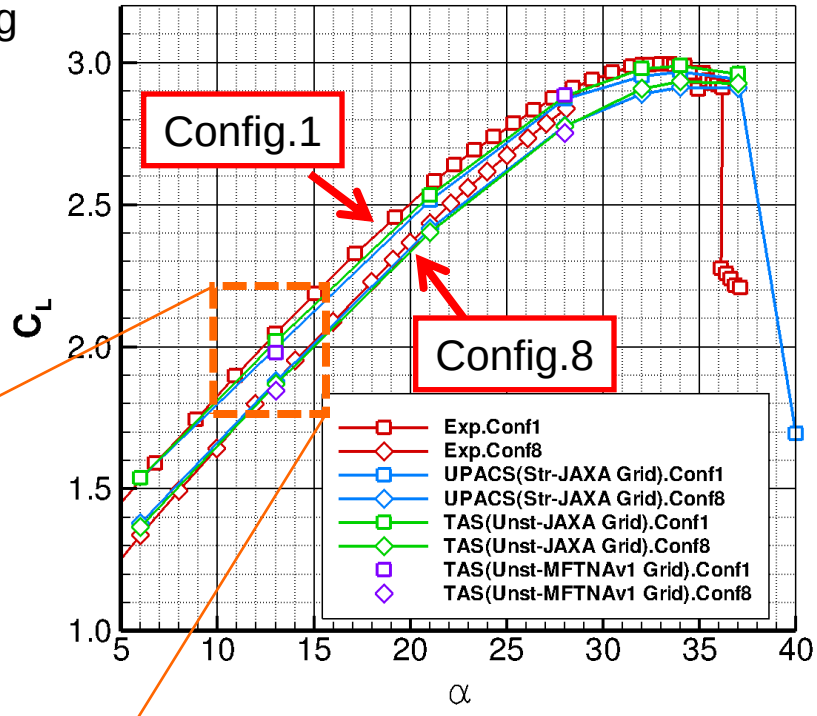
AOA=13

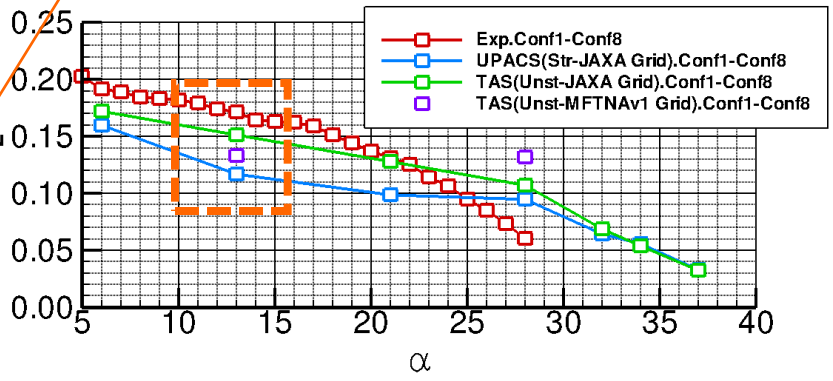
- Config. 1
  - Lower C_L
- Config. 8
  - Reasonable agreement with Exp.

→ Less ΔC_L effect than Exp.

- **Exp.**
- **Str-JAXA**
- **Unst-JAXA**
- **Unst-Uwyo**







Flap deflection effect of ΔC_L (=Config.1 – Config.8)

- Results for Config. 8 show less differences among codes and grids.

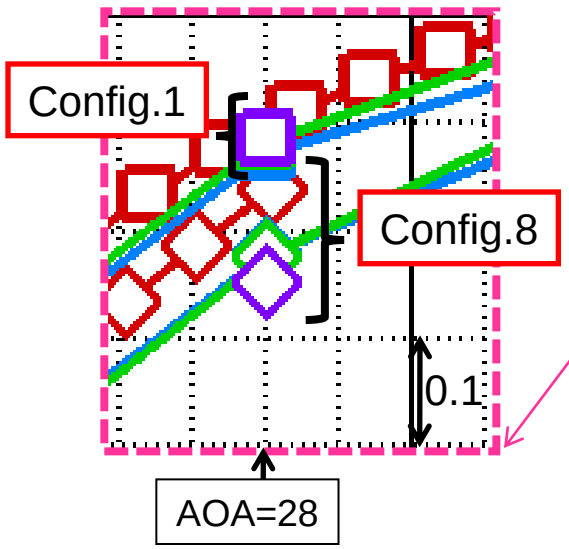
AOA=28

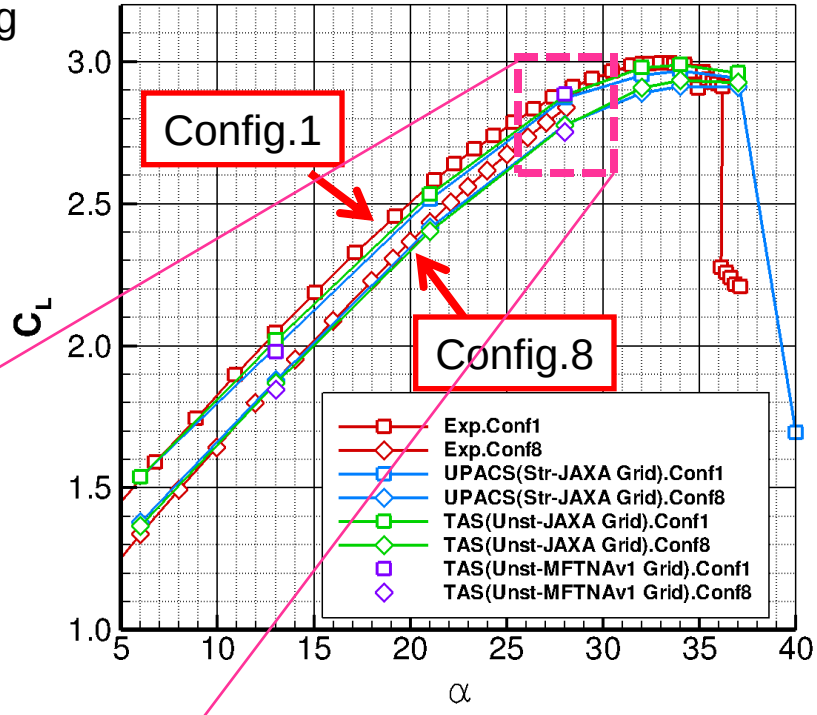
- Config.1
  - Reasonable agreement with Exp.
- Config. 8
  - Lower C_L

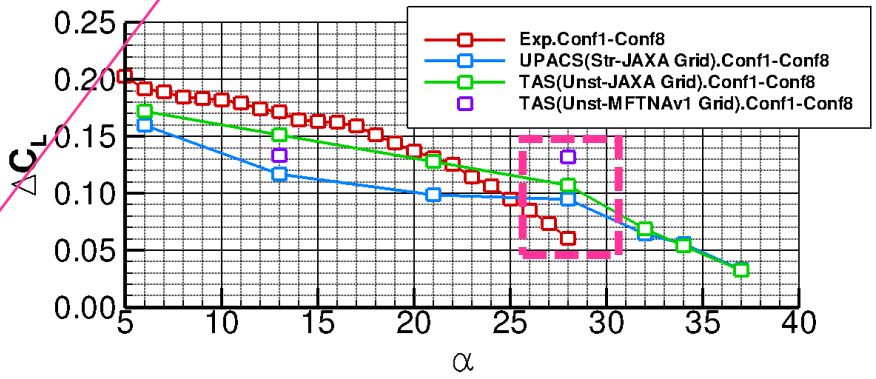
Difference of C_L-slope between Config.1 and Config.8 at high AOA was not captured.

→ More ΔC_L effect than Exp.

- Exp.
- Str-JAXA
- Unst-JAXA
- Unst-Uwyo







Flap deflection effect of ΔC_M (=Config.1 – Config.8)

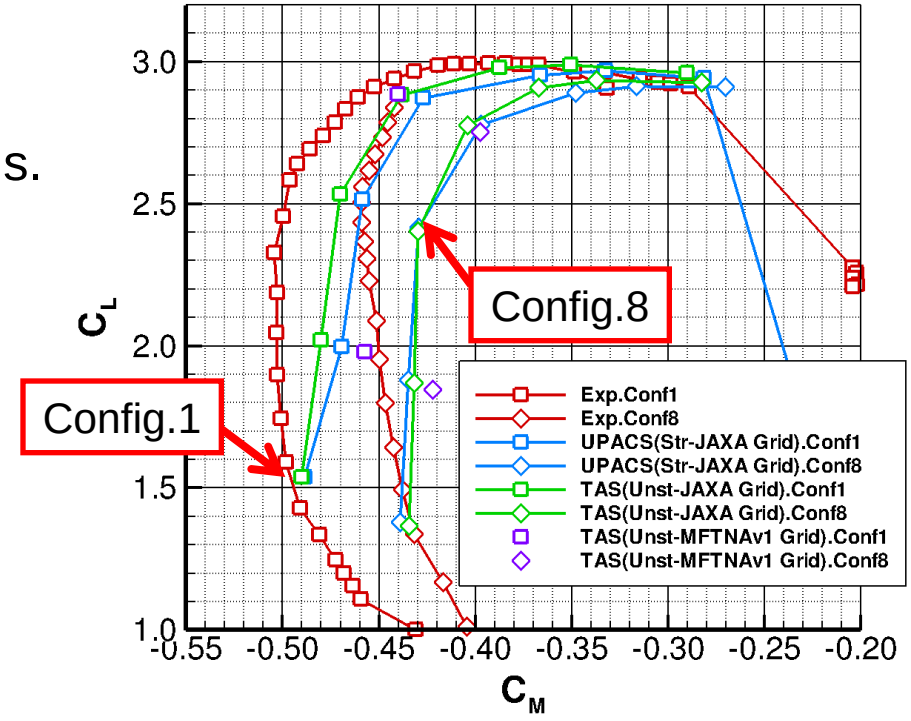
- Similar tendency with C_L
  - Results for Config. 8 show less differences among codes and grids.

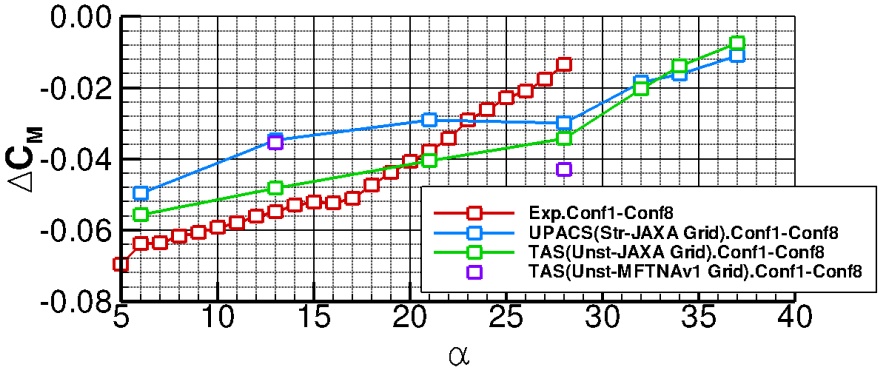
AOA=13

- Under-predict ΔC_M

AOA=28

- Over-predict ΔC_M





Observations in Case2

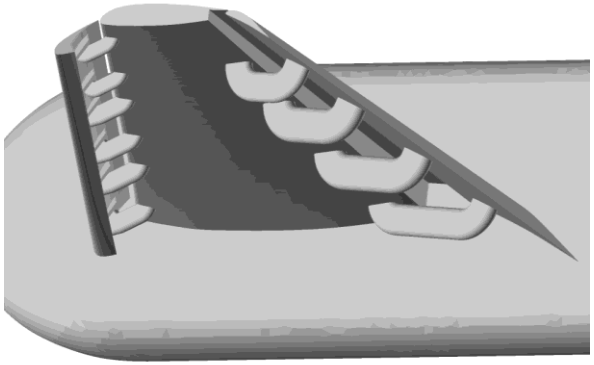
- Config.8 shows less flap separation and wingtip vortices due to lower flap deflection.

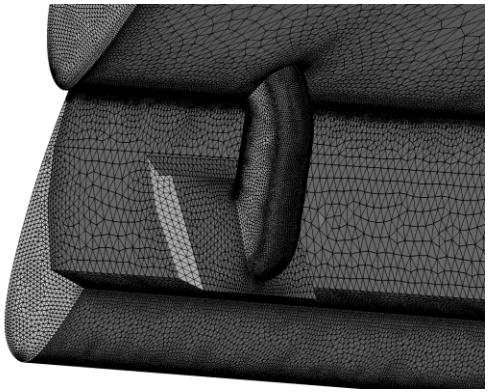
→ Less sensitivity among codes and grid density

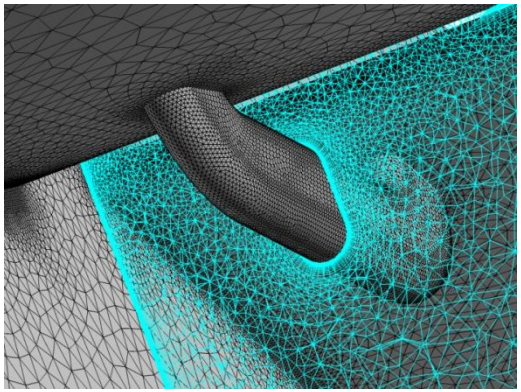
- Prediction accuracy of effectiveness of flap deflection
  - AOA=13
    - Based on the prediction accuracy of Config.1, where the flap flow separation becomes larger
  - AOA=28
    - Based on the prediction accuracy of difference of C_L-slope between Config.1 and Config.8 at high AOA (especially for Config. 8)

- Case 1 Grid Convergence Study
- Case 2 Flap Deflection Prediction Study
- Case 3 Flap and Slat Support Effects Study
- Additional evaluations
  - Local grid density on flap trailing-edge
  - Sensitivity of turbulence model

	Case3 Flap and slat support effects study
Slat & flap setting	Config. 1
Slat & flap bracket	Modeled
M	0.2
Re	4.3×10^6
T [R]	520
AOA [deg]	13, 28



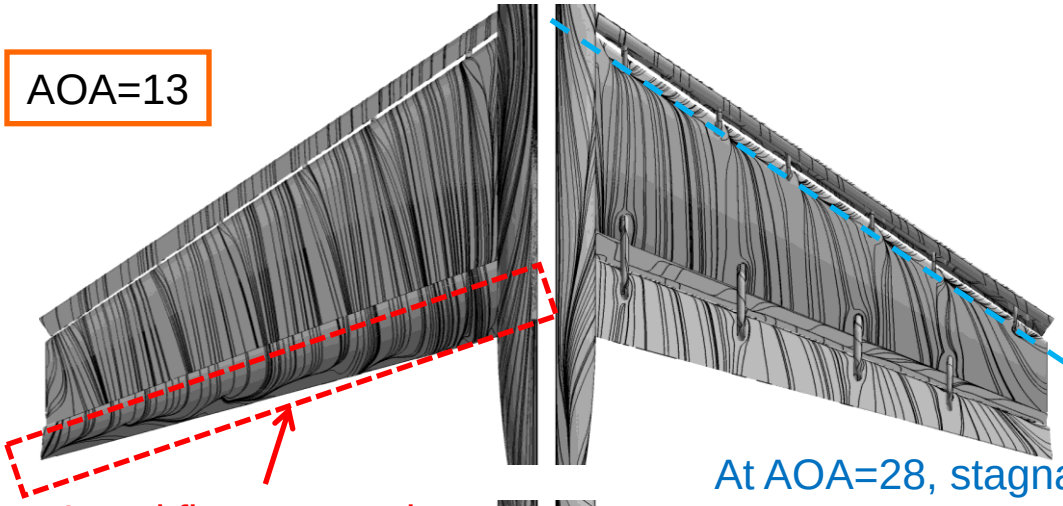


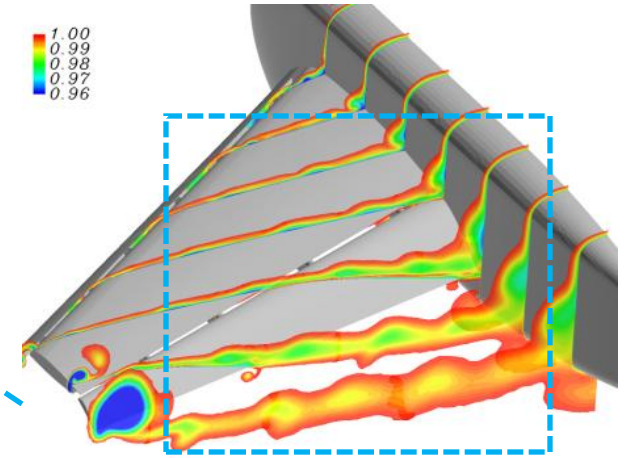


Comparison of oil flow and P_{total}

Slat brackets have influence on the flap flow separation

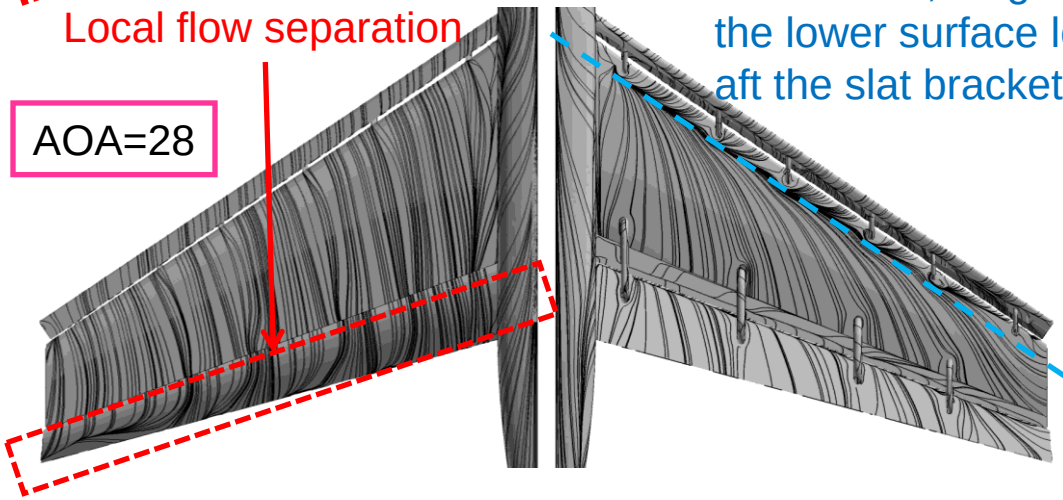
AOA=13

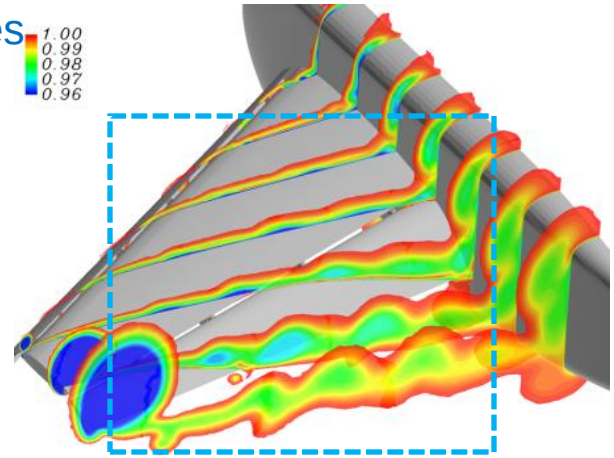




Local flow separation

AOA=28





At AOA=28, stagnation on the lower surface locates aft the slat brackets.

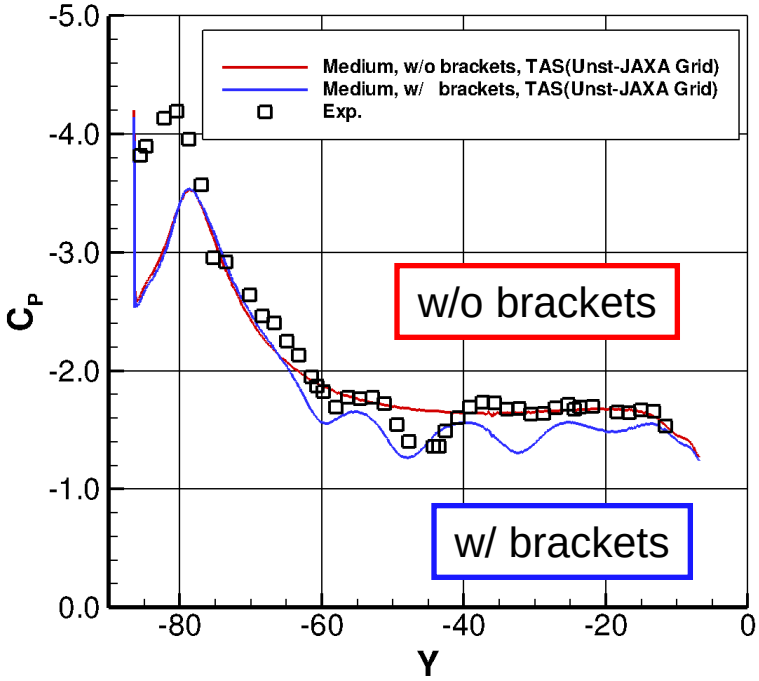
Disturbed wake flow from slat brackets is larger at AOA=28

Upper surface

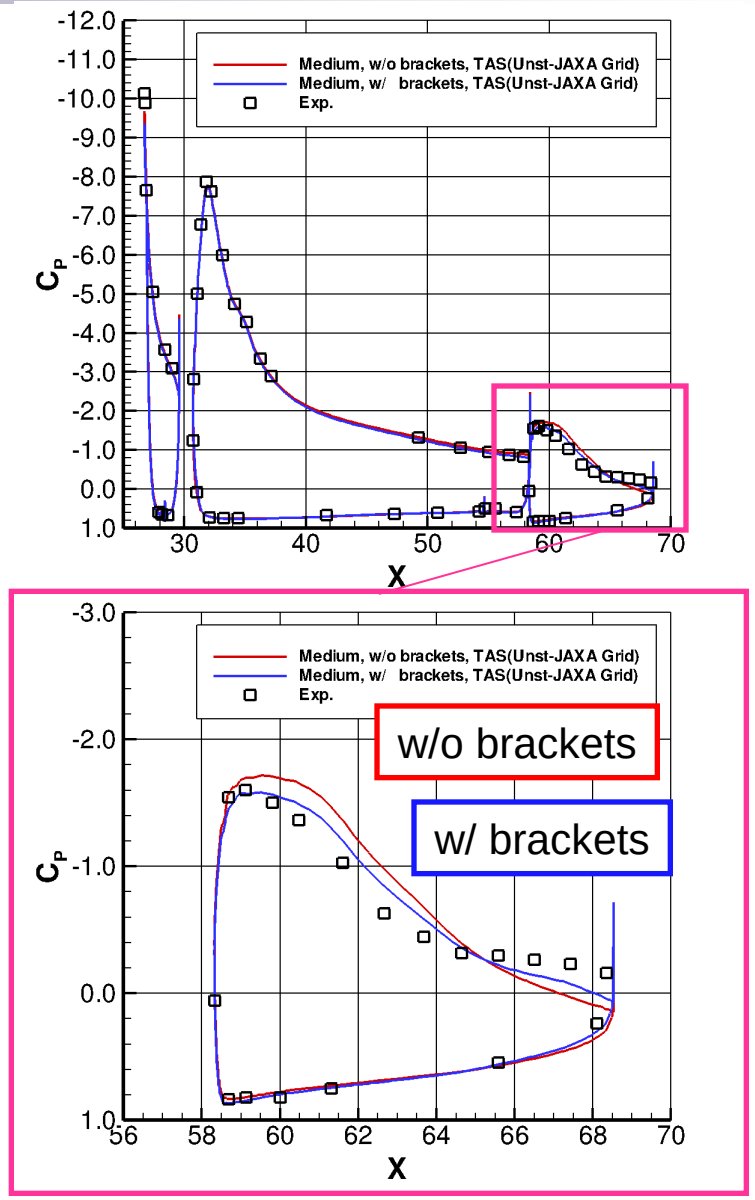
Lower surface

Comparison of Cp with/without brackets at AOA=28

- Computational results with brackets show better agreement of Cp with Exp. about flap separation.



Cp distributions in the spanwise on the upper surface of flap near the leading-edge



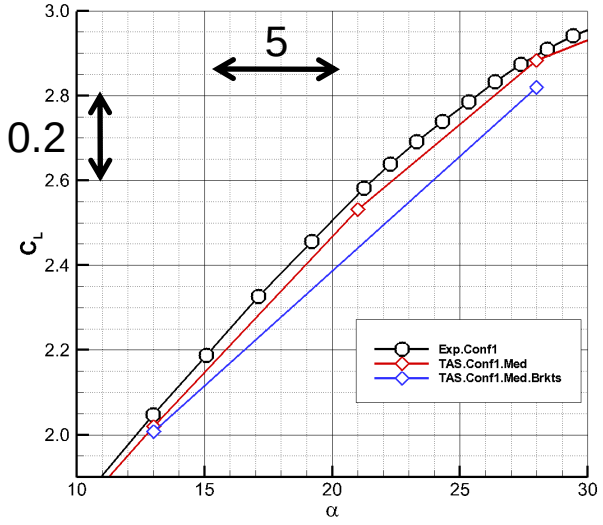
Cp at 50% semi-span location

Flap and slat support effect of C_L, C_M, C_D

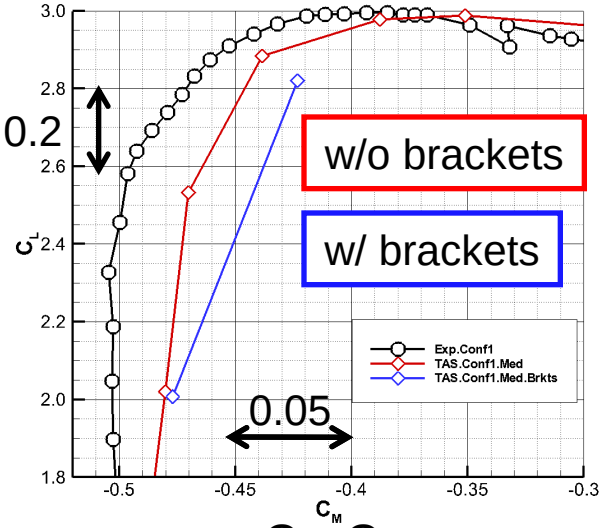
- Flap and slat support effect
  - Larger effect at AOA=28 → **Change of C_L-α slope**
    - C_L decrease
    - Pitch-up C_M
    - C_D increase **at constant C_L**
      - C_D decrease at same AOA due to decrease of $C_{Dinduced}$ according to C_L decrease

However, support effect shows a tendency to move away from Exp. results.

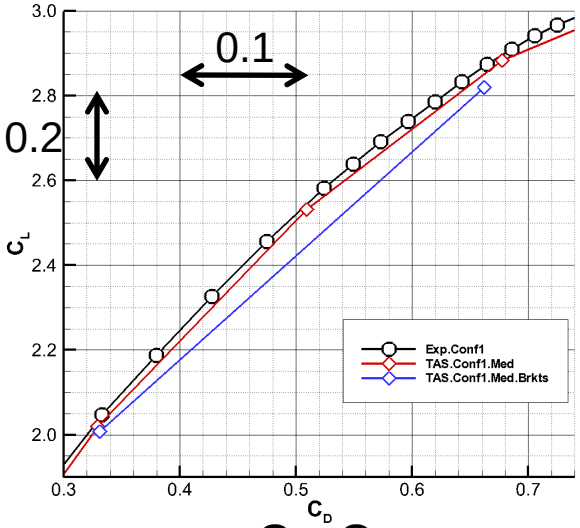
→ Results without brackets at medium size may be still not good enough.
More extensive investigation with grid refinement study will be required for quantitative agreement with Exp.



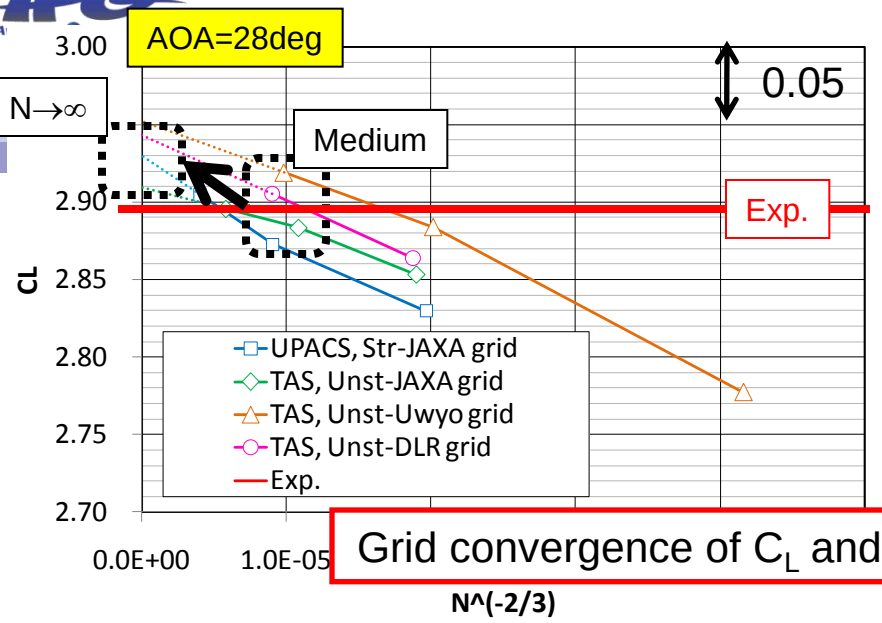
C_L- α

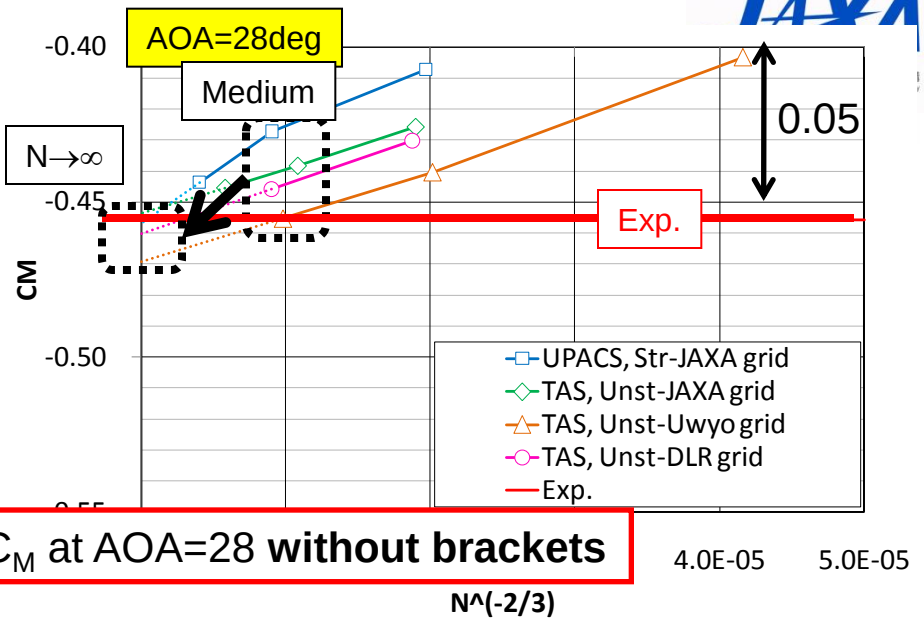


C_L- C_M



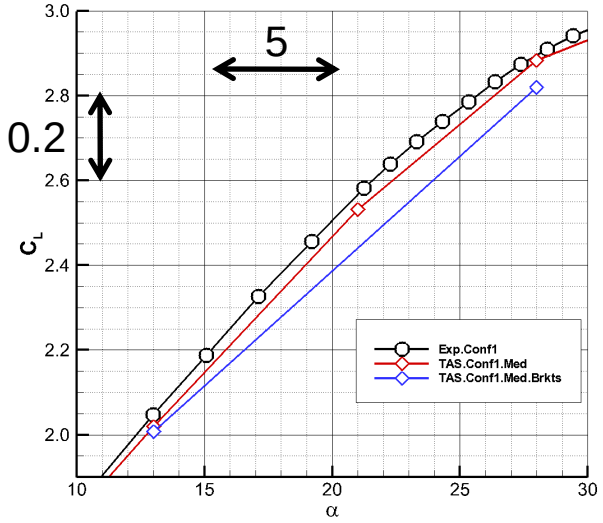
C_L- C_D



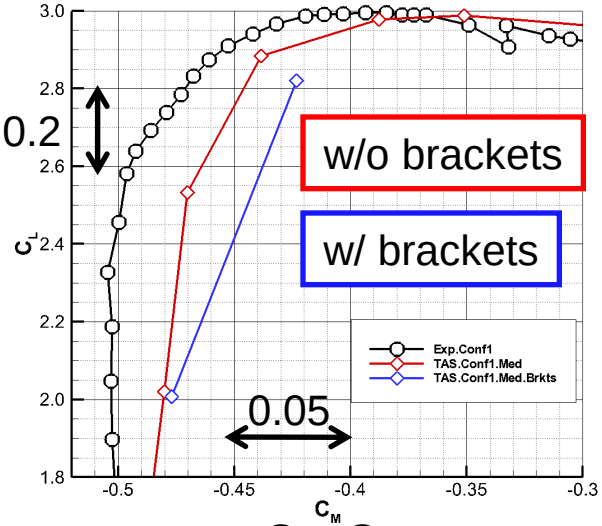


Grid convergence of C_L and C_M at AOA=28 **without brackets**

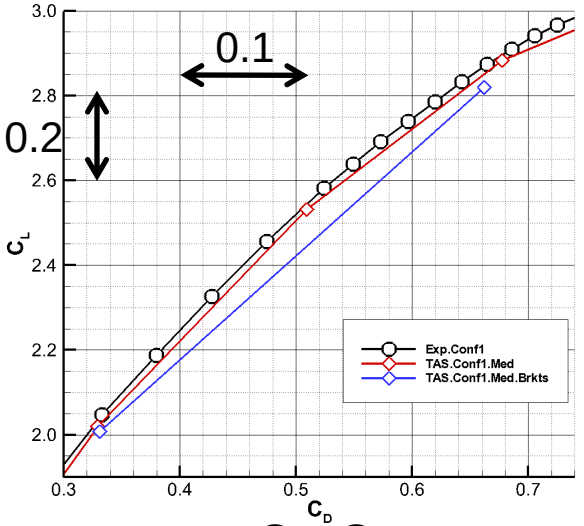
→ Results without brackets at medium size may be still not good enough.
More extensive investigation with grid refinement study will be required for quantitative agreement with Exp.



C_L- α



C_L- C_M



C_L- C_D

- Case 1 Grid Convergence Study
- Case 2 Flap Deflection Prediction Study
- Case 3 Flap and Slat Support Effects Study
- Additional evaluations
  - Local grid density on flap trailing-edge
  - Sensitivity of turbulence model
    - **Spalart-Allmaras** and **Menter's SST**
    - **Spalart-Allmaras with some modifications**

Sensitivity study of turbulence models

- Menter's SST k-ω model: Unst-JAXA coarse grid
- Variations of Spalart-Allmaras with some modifications: Str-JAXA medium grid
  - SA
  - SAmod (baseline model in JAXA's computations): To reduce excessive eddy viscosity in the regions with high-vorticity after flow separation
    - without trip related terms
    - with a modification to production term
  - SAnl: To reduce excessive corner flow separation
    - SAmod with simplified constitutive relation effect of anisotropy of Reynolds stress

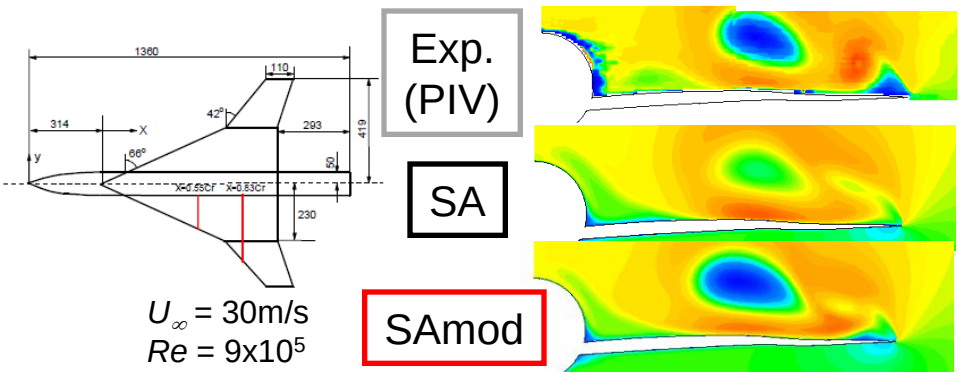
Ω:Vorticity, $\hat{S}$:Strain rate

$$S = \Omega + \min(0, \hat{S} - \Omega)$$

P.R. Spalart / Int. J. Heat and Fluid Flow 21 (2000) 252-263.

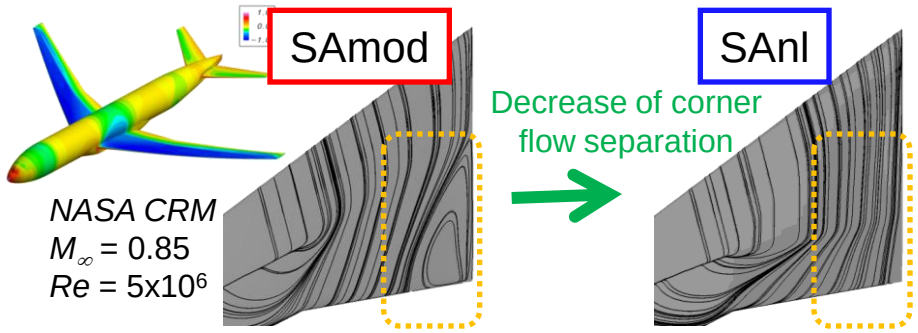
$$\tau_{ij} = \bar{\tau}_{ij} - c_{nl1}\left[O_{ik}\bar{\tau}_{jk} + O_{jk}\bar{\tau}_{ik}\right] \quad O_{ik} \equiv \frac{\partial_k U_i - \partial_i U_k}{\sqrt{\partial_n U_m \partial_n U_m}}, \quad c_{nl1} = 0.3$$

$\bar{\tau}_{ij}$ is the Reynolds stress given by linear models.



U_∞ = 30m/s
Re = 9x10^5

Lei, Z., *Trans of JSASS*, Vol. 48, Nov. 2005, pp. 150-160.

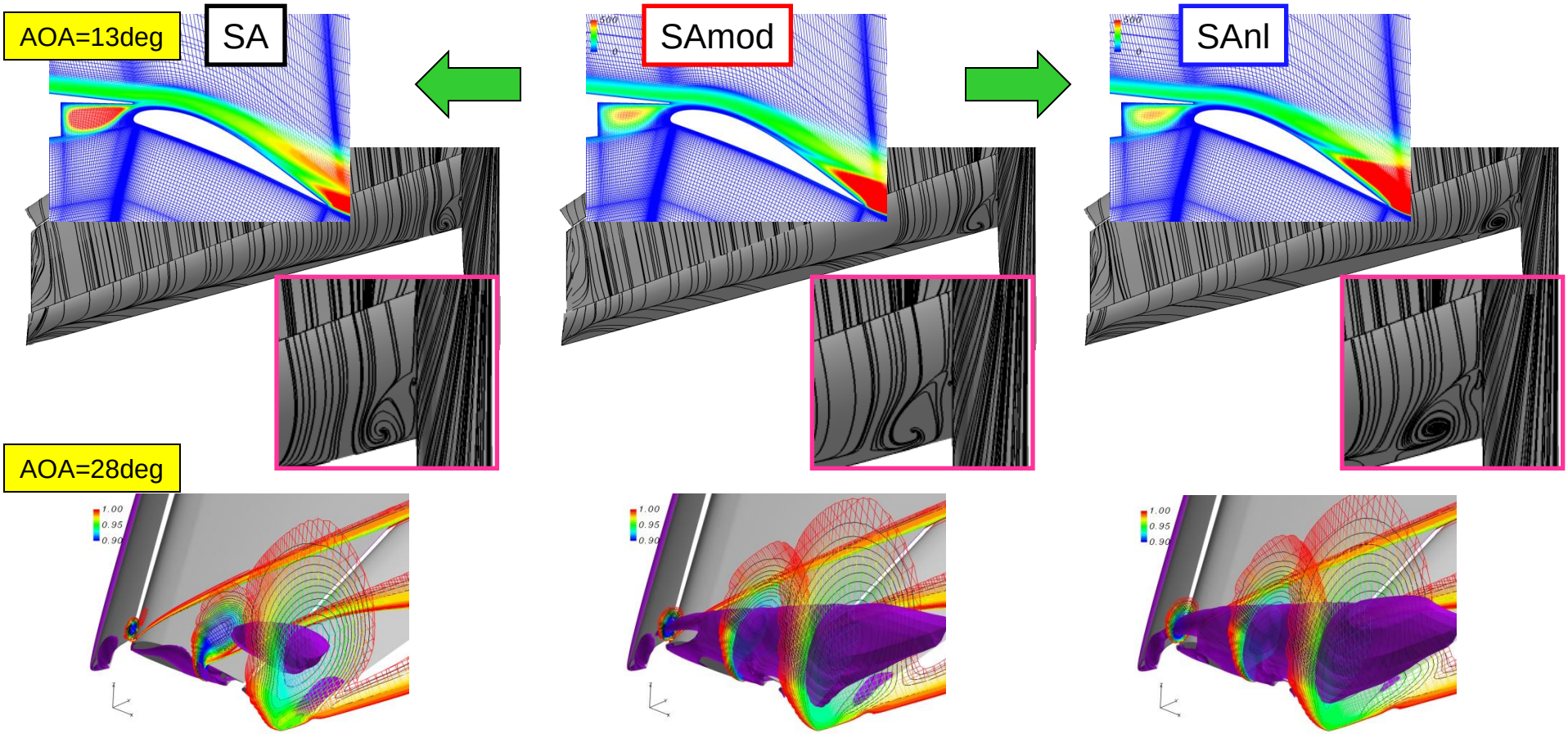


NASA CRM
M_∞ = 0.85
Re = 5x10^6

Yamamoto, K., Tanaka, K., Murayama, M., AIAA Paper 2010-4222

Variations of Spalart-Allmaras with some modifications

- SA
  - Less flap flow separation
  - Higher eddy viscosity in the cove and slat/wing wake
  - Smaller vortex breakdown regions of wing-tip vortices at AOA=28 due to higher eddy viscosity
- SAnl
  - More flap flow separation
  - The model does not necessarily suppress corner flow separation.

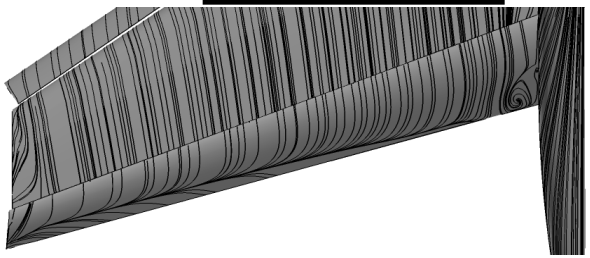


Comparison with SST k-ω model

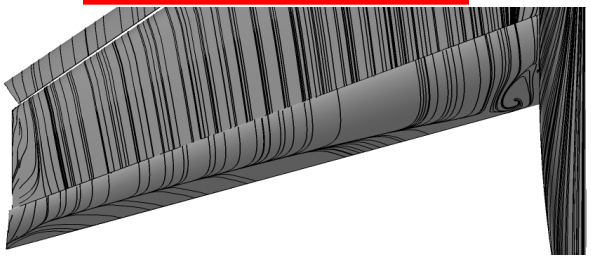
- SST model shows much larger flow separation on the flap.

AOA=13deg

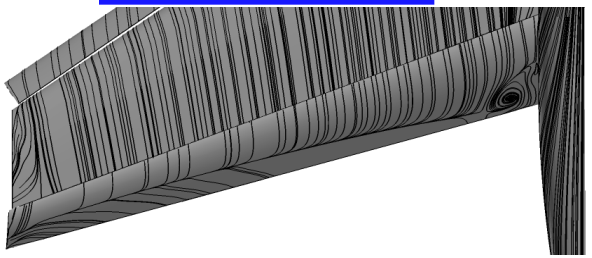
SA, Str-JAXA



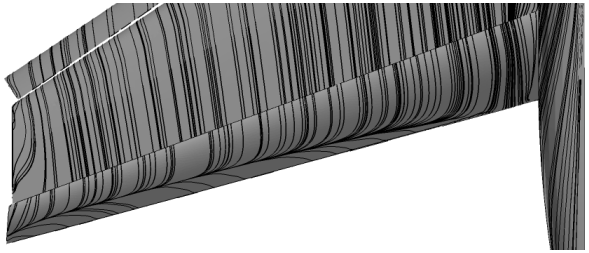
SAmod, Str-JAXA



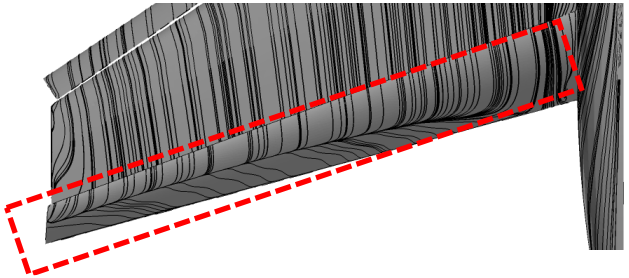
SAnl, Str-JAXA



SAmod, Unst-JAXA



SST, Unst-JAXA

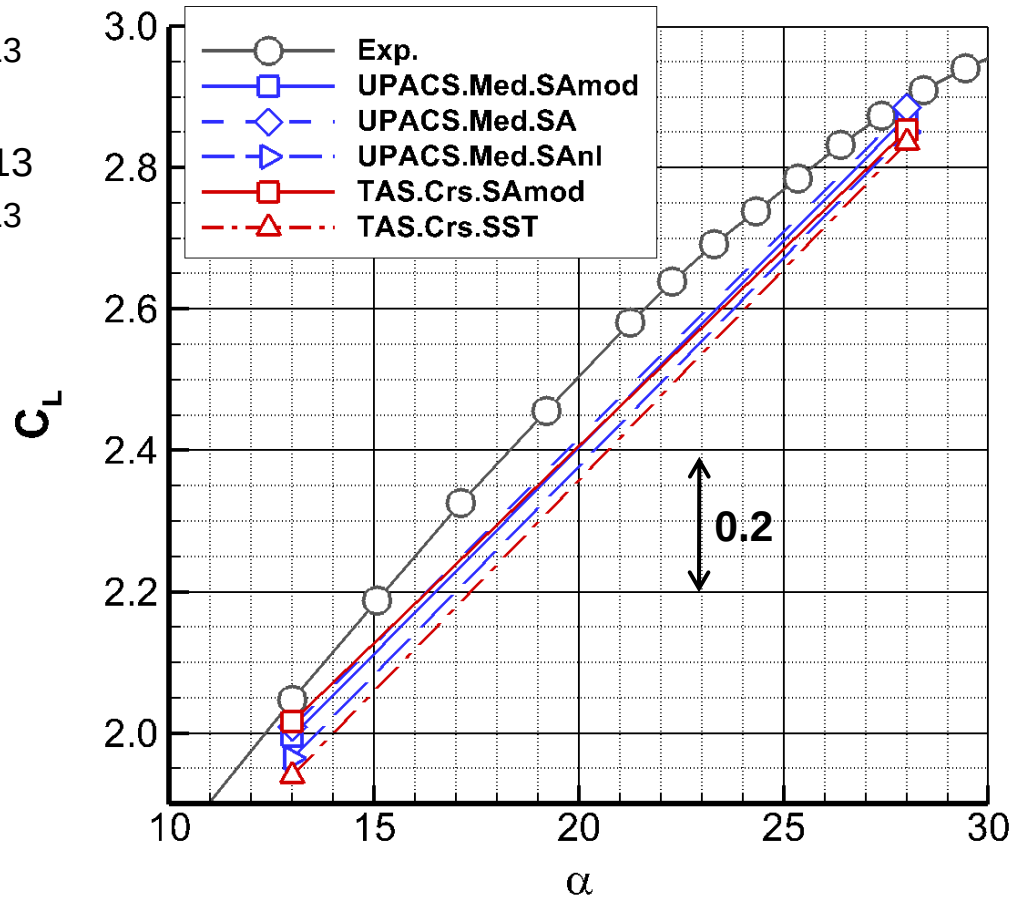


Largest flap flow separation

Comparison of C_L with different turbulence models

- SST model shows the largest variation from SAmod (ΔC_L)
  - SA: $\Delta C_L \approx +0.01$ ($+0.5\%C_L$)
    - Less flap flow separation at AOA=13
    - Less vortex breakdown of wing-tip vortices at AOA=28
  - SAnl: $\Delta C_L \approx -0.03$ ($-1.5\%C_L$)
    - More flap flow separation at AOA=13
  - SST: $\Delta C_L \approx -0.08$ ($-4\%C_L$) at AOA=13
    - More flap flow separation at AOA=13

Applicability and characteristics of turbulence models for complicated high-lift flows should be further investigated.



Summary

- Case1: Grid convergence study
  - Computational results showed reasonable agreement with each other on the fine grids.
    - Especially, results by Str-JAXA and Unst-JAXA showed good correlation.
  - **To predict flap flow separation and tip vortex behavior were important for Trap Wing.**
    - Computations at AOA=13 showed lower $C_{L(N\to\infty)}$ and higher pitch-up $C_{M(N\to\infty)}$ than Exp. due to larger flap flow separation.

- Case2: Flap deflection prediction study
  - Computations for Config.8 showed less sensitivity among codes and grids due to less flap separation and wingtip vortices by lower flap deflection.
  - Prediction accuracy of effectiveness of flap deflection angle is mainly based on the followings;
    - AOA=13: Based on the prediction accuracy of Config.1, where the **flap flow separation** becomes larger
    - AOA=28: Based on the prediction accuracy of **difference of C_L-slope between Config.1 and Config.8 at high AOA (especially for Config. 8)**

- Case3: Flap and slat support study
  - Computational results reproduced the influence of support reasonably, however, support effect showed a tendency to move away from Exp.
    - Results without brackets may be still not good enough.
    - More extensive investigation with grid refinement study will be required.

- Additional evaluations
  - Grid resolution on the trailing-edge was important for the flap separation.
    - Four cells are required at least.
  - Sensitivity of turbulence models was shown.
    - SST showed relatively larger variations and lower C_L by 4%C_L at AOA=13.

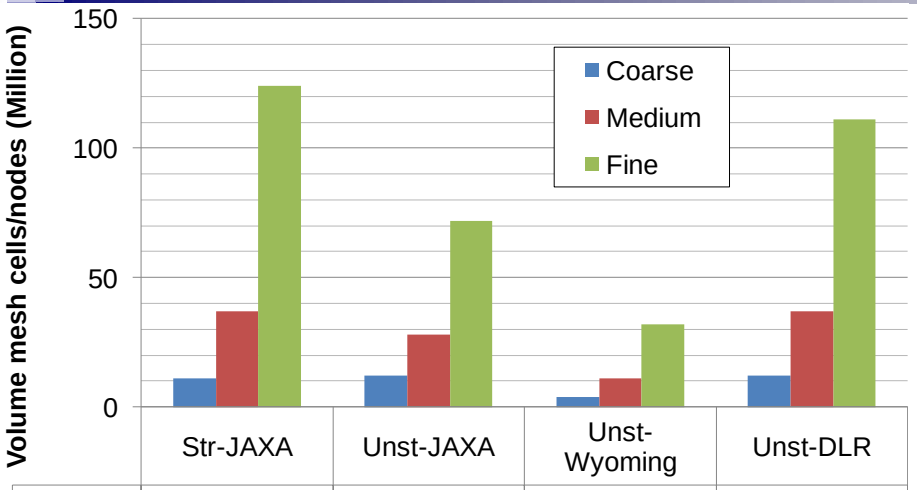
Future work

- Further grid convergence study
  - Config. 8
  - Config. 1 w/ bracket
  - C_{Lmax}
  - Extra-fine

- Turbulence model
  - Influence of boundary layer transition from laminar to turb. on flap flow separation at AOA=13
  - Systematic evaluation of applicability and characteristics of models

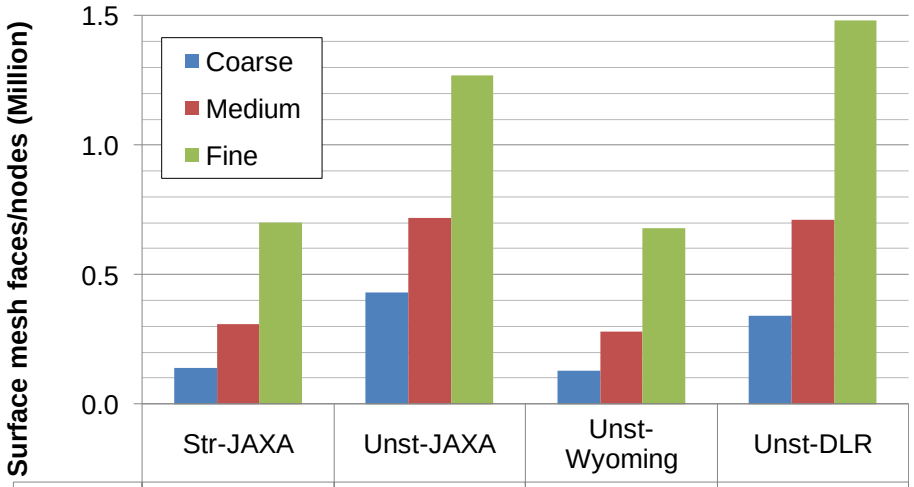
- Backup slides

Comparison of grids



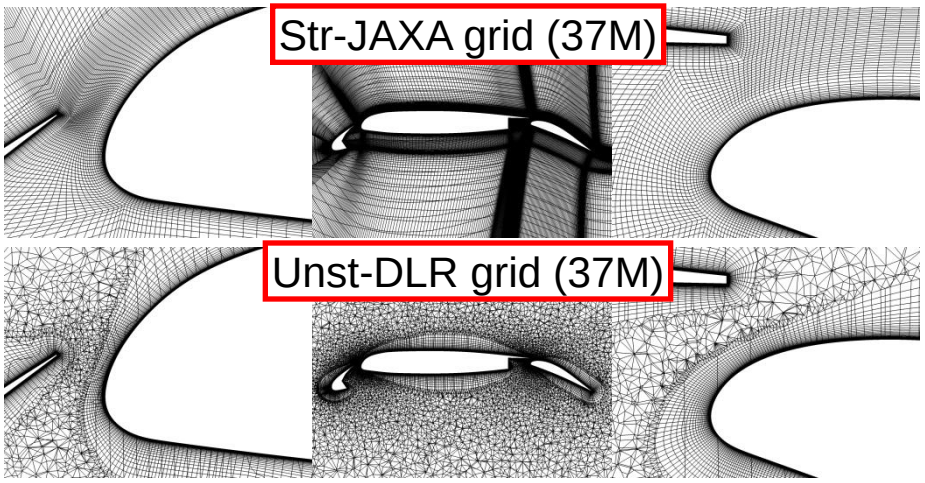
	Str-JAXA	Unst-JAXA	Unst-Wyoming	Unst-DLR
Coarse	11	12	4	12
Medium	37	28	11	37
Fine	124	72	32	111

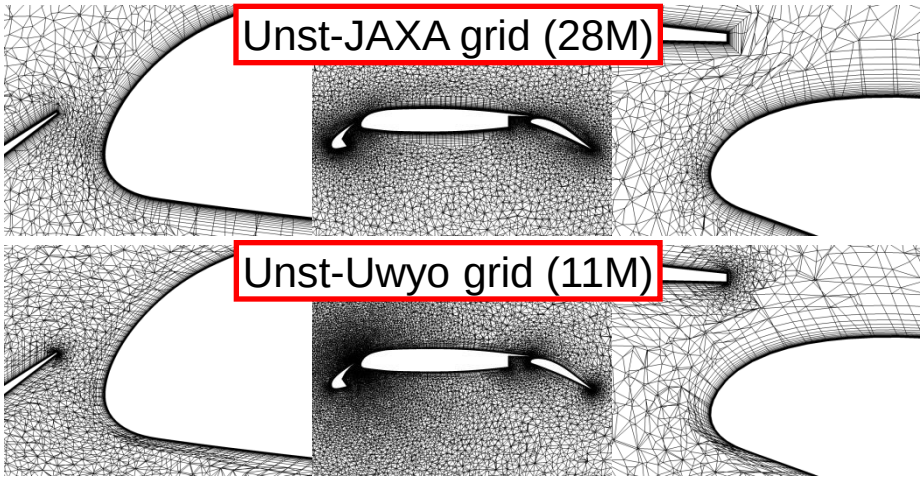
Comparison of **volume grid** cells/nodes



	Str-JAXA	Unst-JAXA	Unst-Wyoming	Unst-DLR
Coarse	0.14	0.43	0.13	0.34
Medium	0.31	0.72	0.28	0.71
Fine	0.7	1.27	0.68	1.48

Comparison of **surface grid** faces/nodes





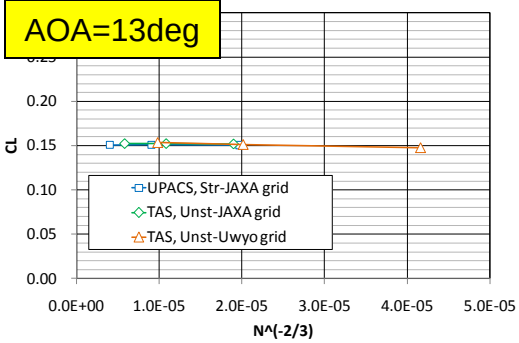
Comparison of cross-sectional view at 50% span

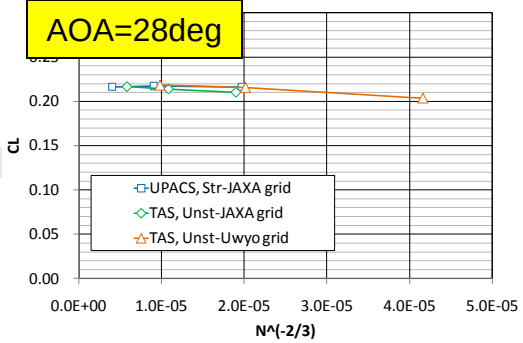
Grid conv. of CL compo.

AOA=13deg

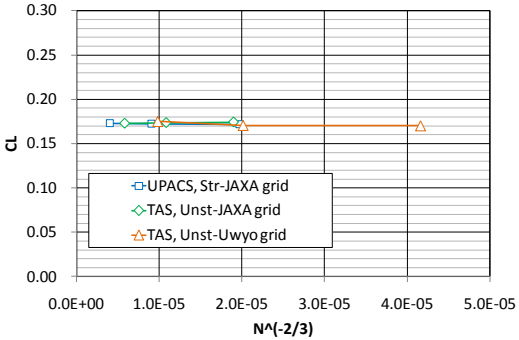
AOA=28deg

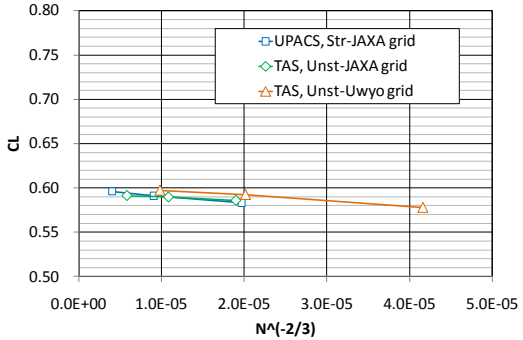
Body



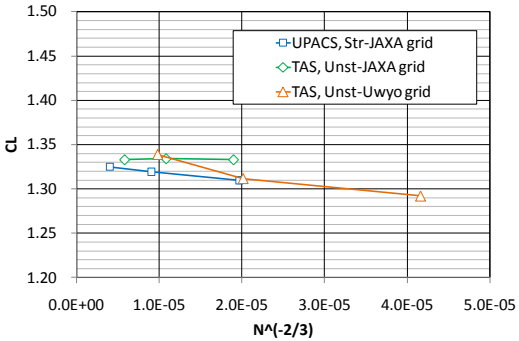


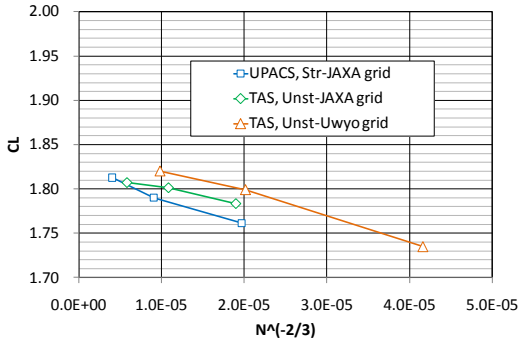
Slat



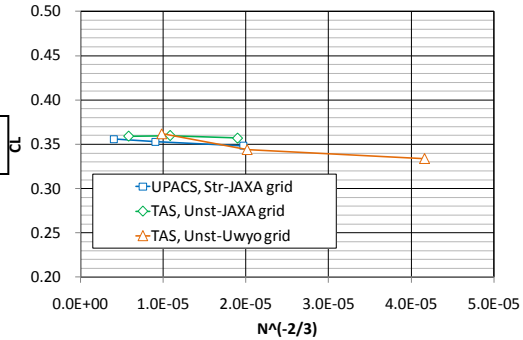


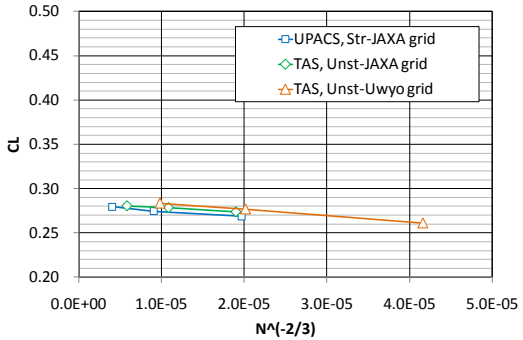
Wing





Flap



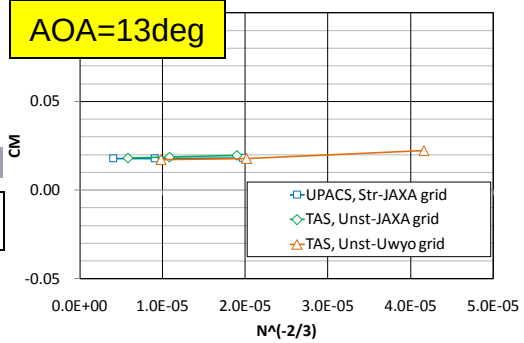


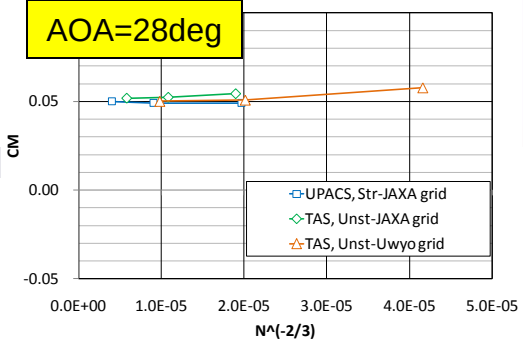
Grid conv. of CM compo.

AOA=13deg

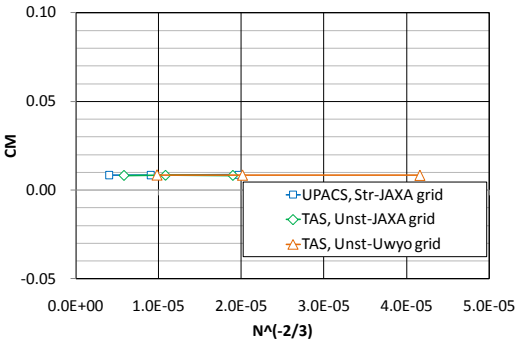
AOA=28deg

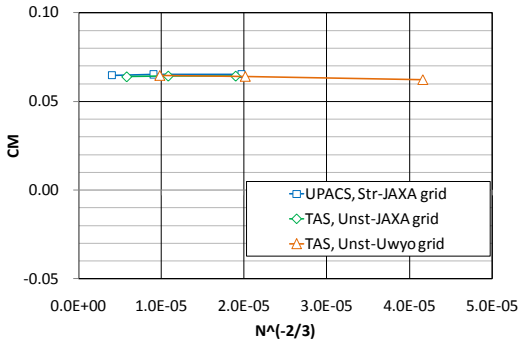
Body



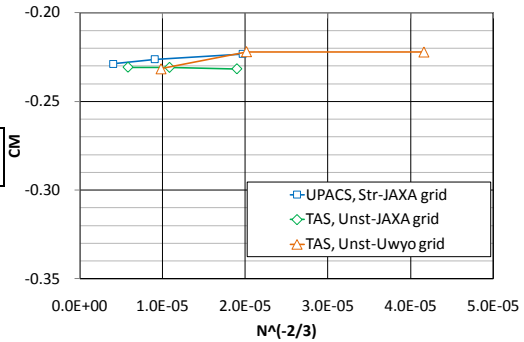


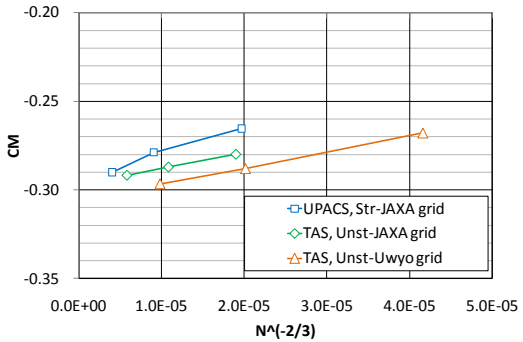
Slat



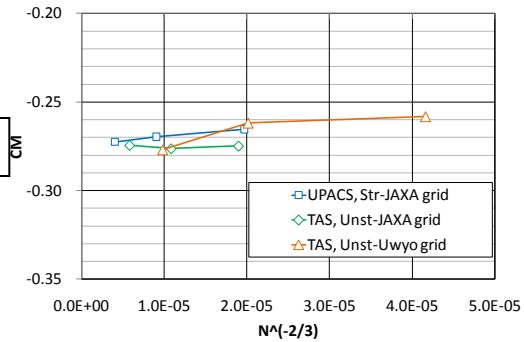


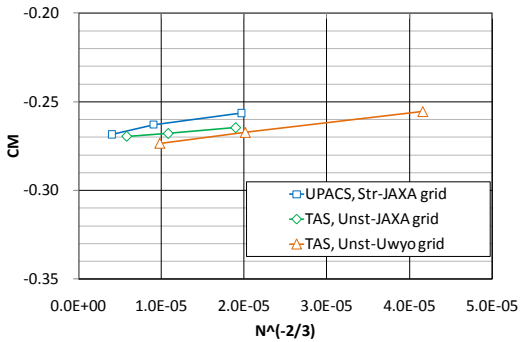
Wing





Flap



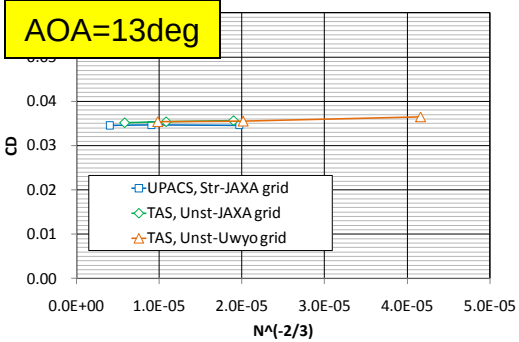


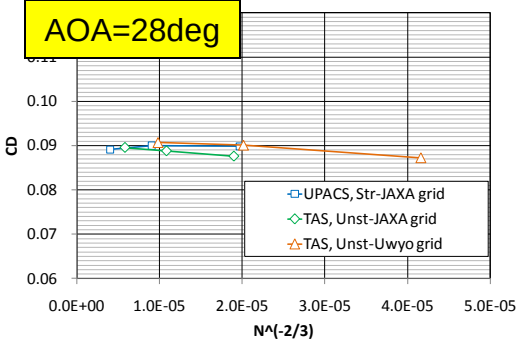
Grid conv. of CD compo.

AOA=13deg

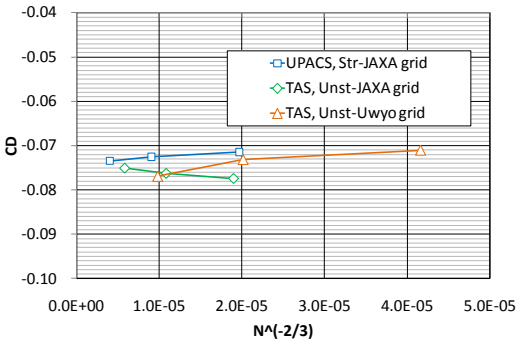
AOA=28deg

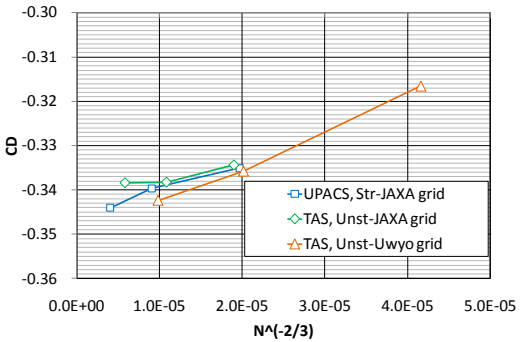
Body



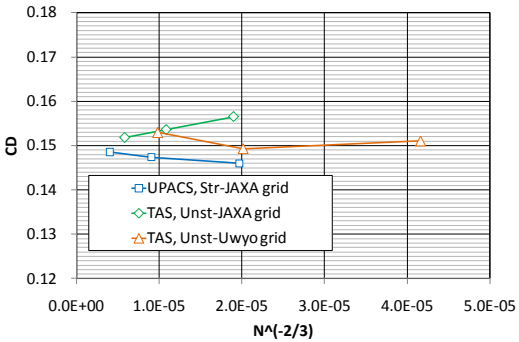


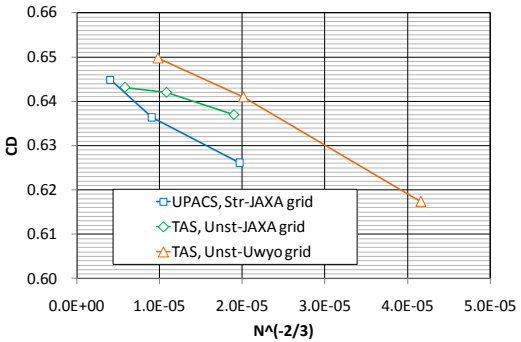
Slat



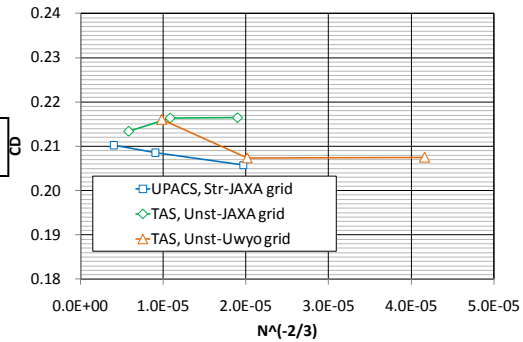


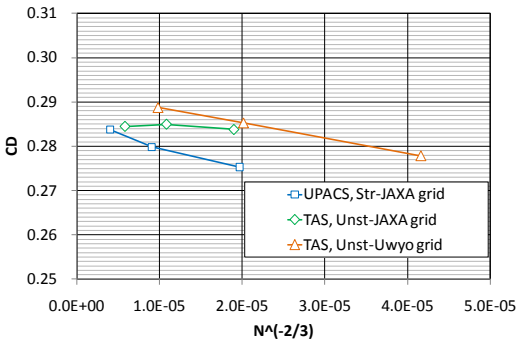
Wing



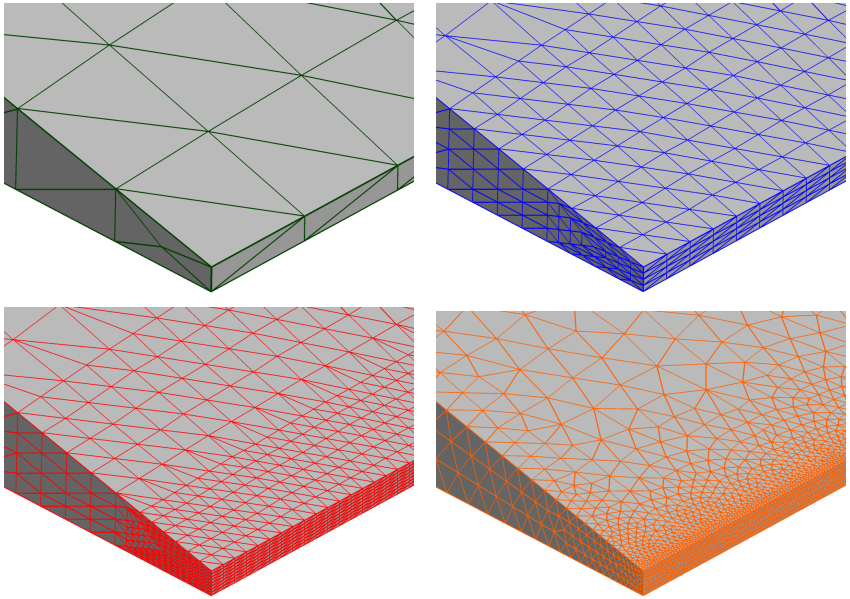


Flap





- Case 1 Grid Convergence Study
- Case 2 Flap Deflection Prediction Study
- Case 3 Flap and Slat Support Effects Study
- Additional evaluations
  - Local grid density on flap trailing-edge
  - Sensitivity of turbulence model



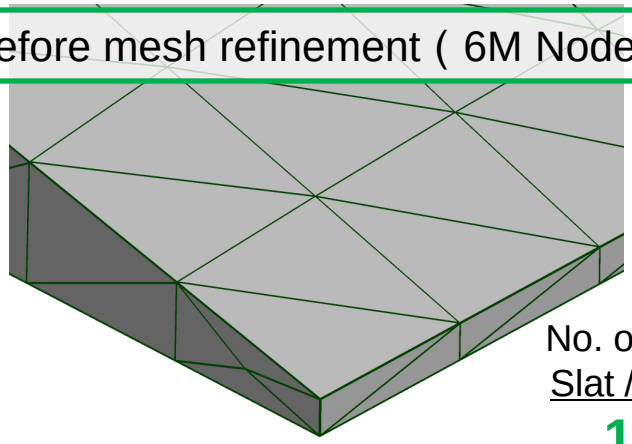
Investigation of influence of local grid density near flap trailing-edge on the flap flow separation at AOA=13

Influence of local grid density near flap trailing-edge

- Investigation of influence of local grid density near flap trailing-edge on the flap flow separation at AOA=13

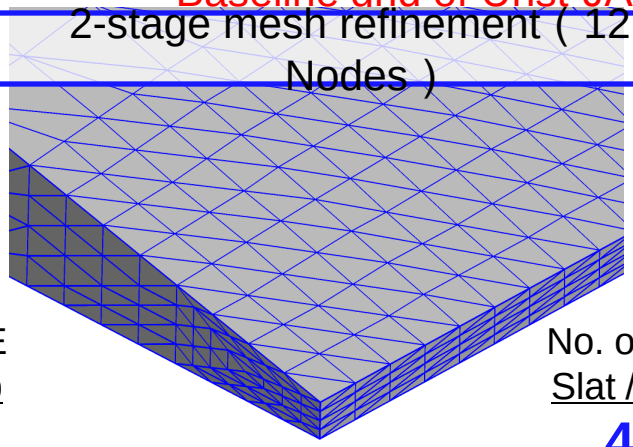
Baseline grid of Unst-JAXA grid

Before mesh refinement (6M Nodes)



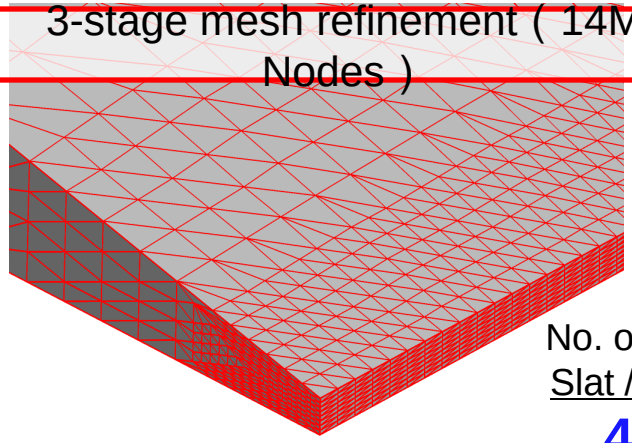
No. of cells on TE
Slat / Wing / Flap
1 / 1 / 1

2-stage mesh refinement (12M Nodes)



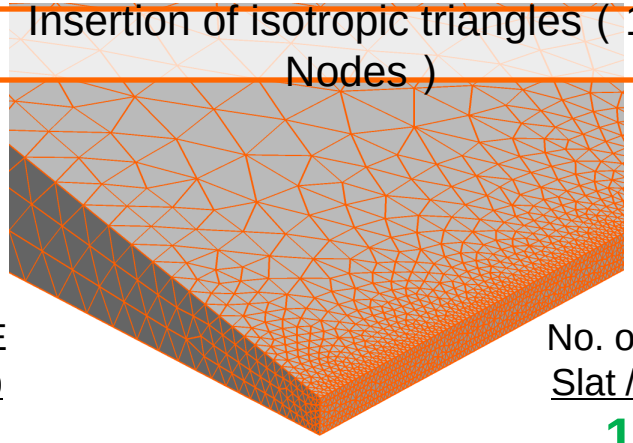
No. of cells on TE
Slat / Wing / Flap
4 / 4 / 4

3-stage mesh refinement (14M Nodes)



No. of cells on TE
Slat / Wing / Flap
4 / 4 / 8

Insertion of isotropic triangles (15M Nodes)



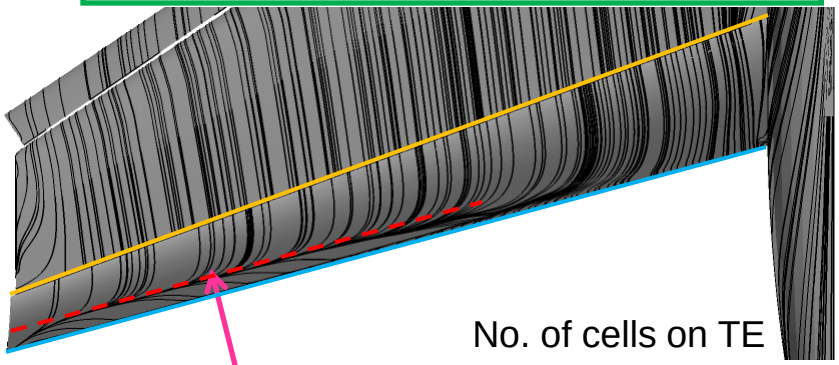
No. of cells on TE
Slat / Wing / Flap
1 / 1 / 6

Comparison of oil flow at AOA=13

- Result with only one-cell on the trailing-edge show less flow separation on the flap.
- The other results show good agreement with each other.

Baseline grid of Unst-JAXA grid

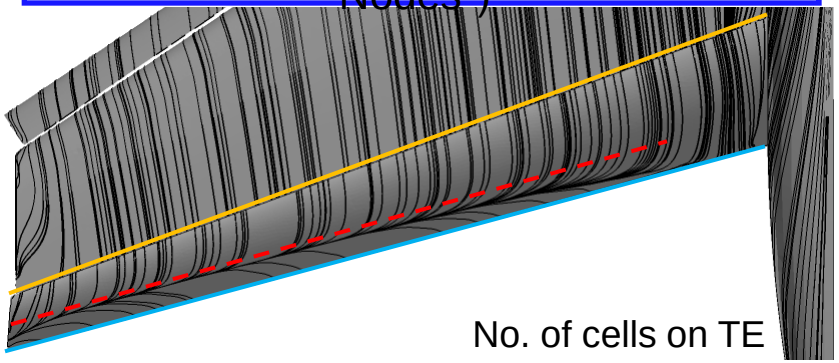
Before mesh refinement (6M Nodes)



Less flow separation

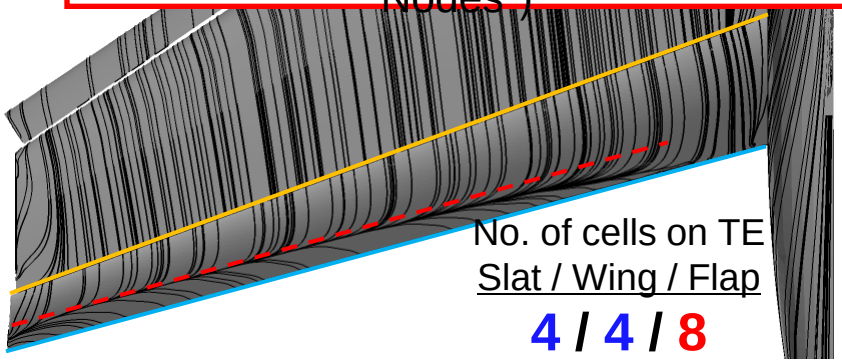
No. of cells on TE
Slat / Wing / Flap
1 / 1 / 1

2-stage mesh refinement (12M Nodes)



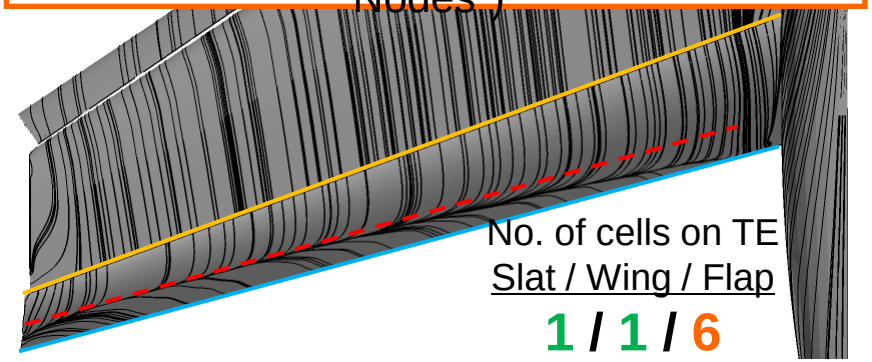
No. of cells on TE
Slat / Wing / Flap
4 / 4 / 4

3-stage mesh refinement (14M Nodes)



No. of cells on TE
Slat / Wing / Flap
4 / 4 / 8

Insertion of isotropic triangles (15M Nodes)



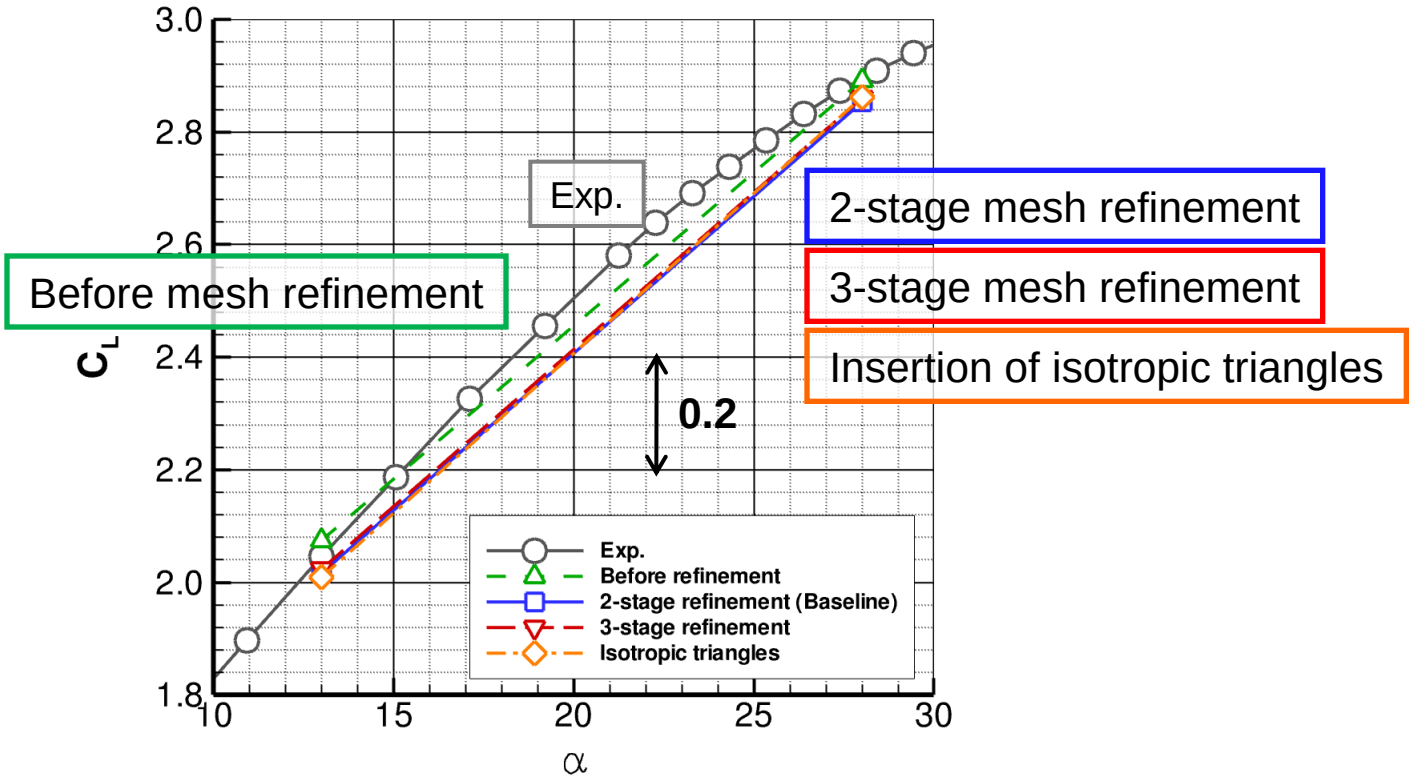
No. of cells on TE
Slat / Wing / Flap
1 / 1 / 6

Comparison of C_L-alpha

- Result with only one-cell on the trailing-edge shows higher lift due to less flow separation on the flap.
- The other results show good agreement with each other.

For the prediction of the flap flow separation,

- Four cells are required on the flap trailing-edge at least.
- Isotropy of surface triangles are not essential and moderate anisotropic triangles are acceptable.



- End of backup slides