AIAA 2012-2844

Computational Studies of the NASA High-Lift Trap Wing Using Structured and Unstructured Grid Solvers

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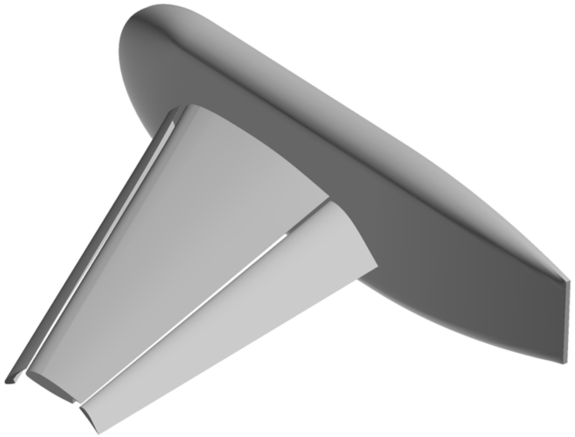
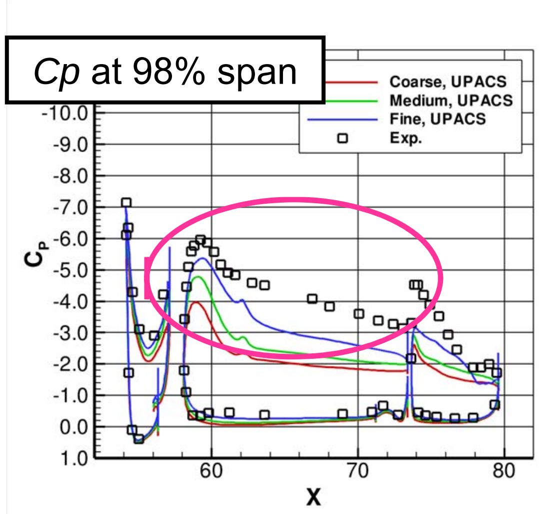
Outline

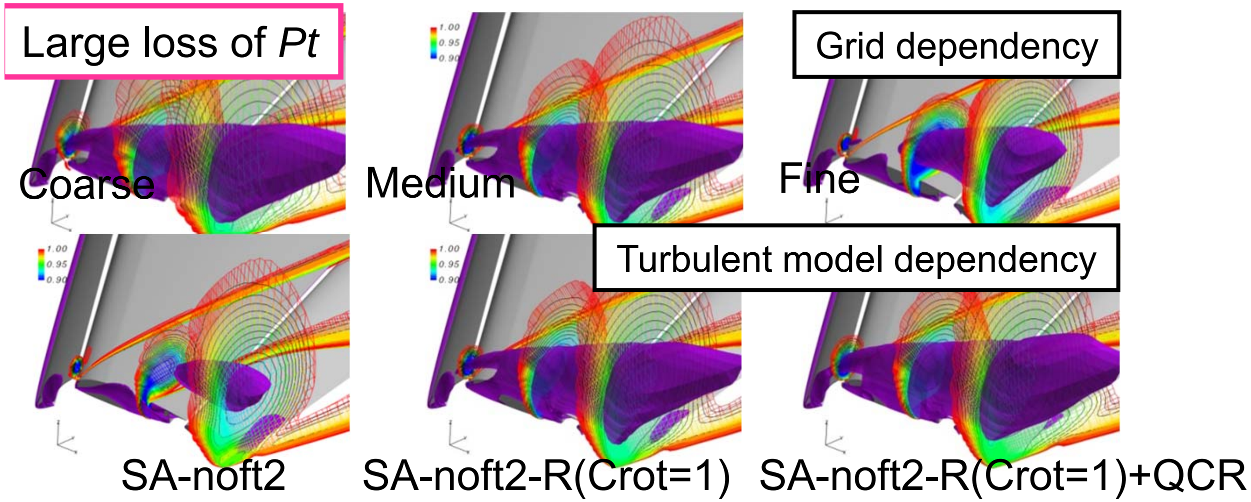
- Background
  - Lessons learned from HiLiftPW-1
- Objectives
- Grid effects
  - Unstructured hybrid mesh generation w/ suppressed marching direction method at concave corners
- Prediction of boundary layer transitions
  - LSTAB based on e^N method
- Flow solvers & flow conditions
- Results
  - Grid convergence of CL & CD
  - Transition prediction
- Concluding remarks



Background

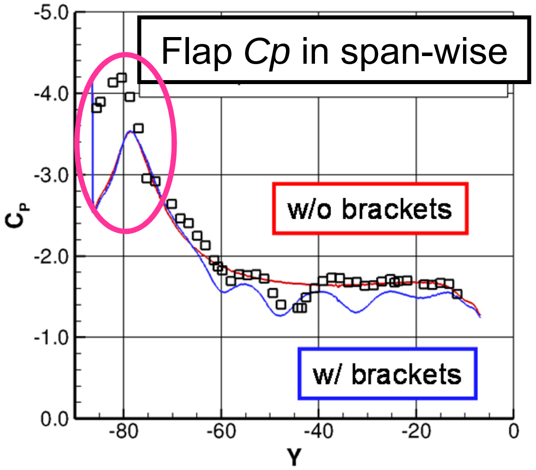
- 1st AIAA CFD High Lift Prediction Workshop in 2010
  - ☐ NASA Trap wing: Full-span slat & flap, simplified wing tip
  - ☐ Summary by Rumsey *et al*. (AIAA 2011-0939)
- Identified areas needing additional attention for CFD
  - ☐ Outboard flap trailing edge region
    - Higher variability among CFD
  - ☐ Effect of initial conditions on CFD solutions
  - ☐ Bluff wing tip region
    - Vortices from the slat & wing tip grow & burst over the wing
    - Tendency to under-predict *Cp* suction levels near the wing tip
    - Accurate prediction of behavior of the vortices, their breakdown & their interaction over the wing may be important
  - ☐ Influence of transition


Cp at 98% span


Large loss of *Pt*

Grid dependency

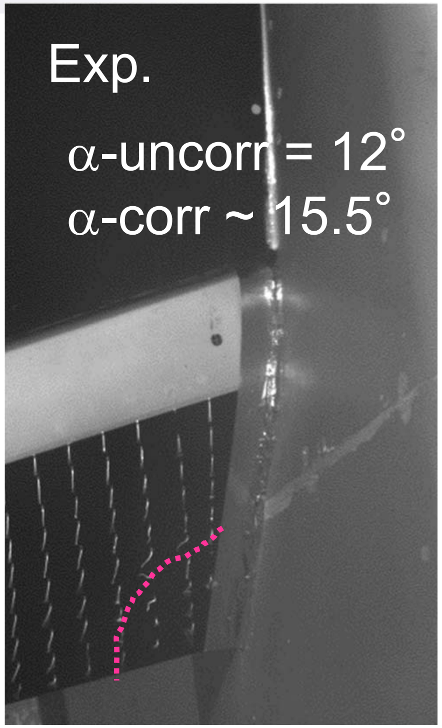
Turbulent model dependency

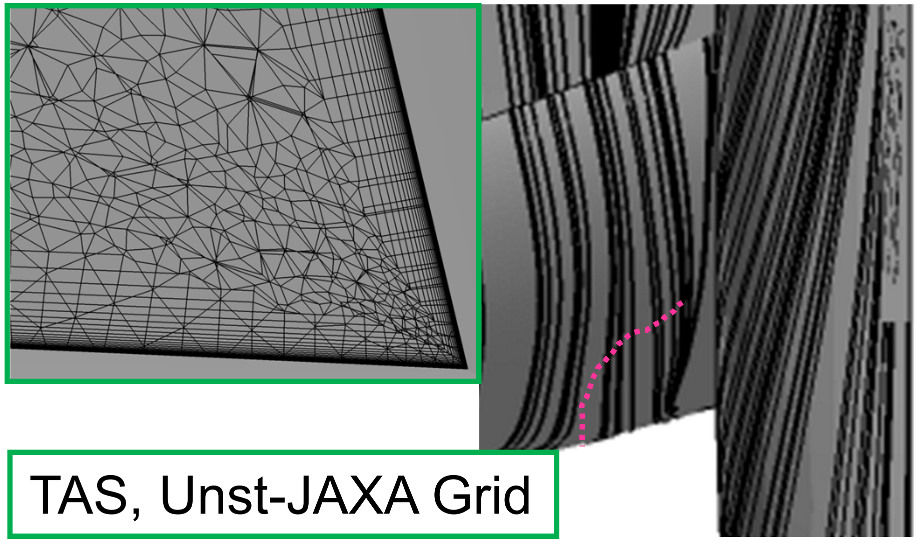

Flap *Cp* in span-wise

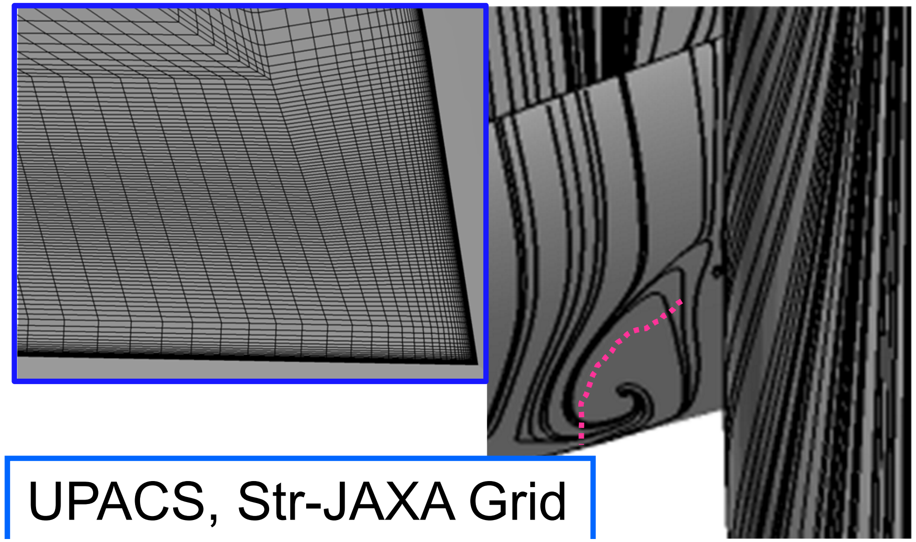
α = 28°

Comparison of flap SOB separation (α = 13º, Medium)

- CFD simulations w/ 2 solvers in JAXA
  - TAS code for unstructured grids
  - UPACS for structured grids
- Flap SOB flow separation by UPACS showing better agreement with exp.
- Due to difference in corner grid topology?
  - Str-JAXA grids are much finer



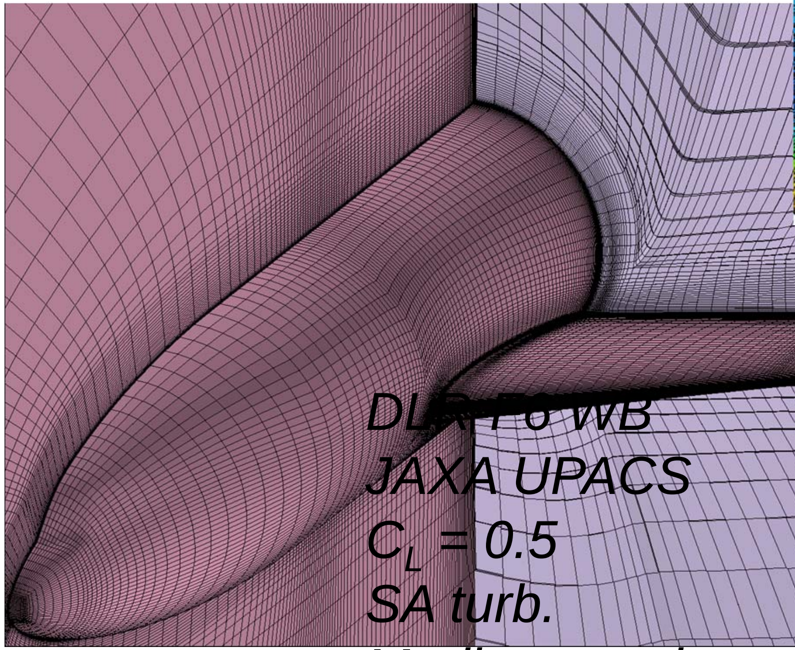

TAS, Unst-JAXA Grid


UPACS, Str-JAXA Grid

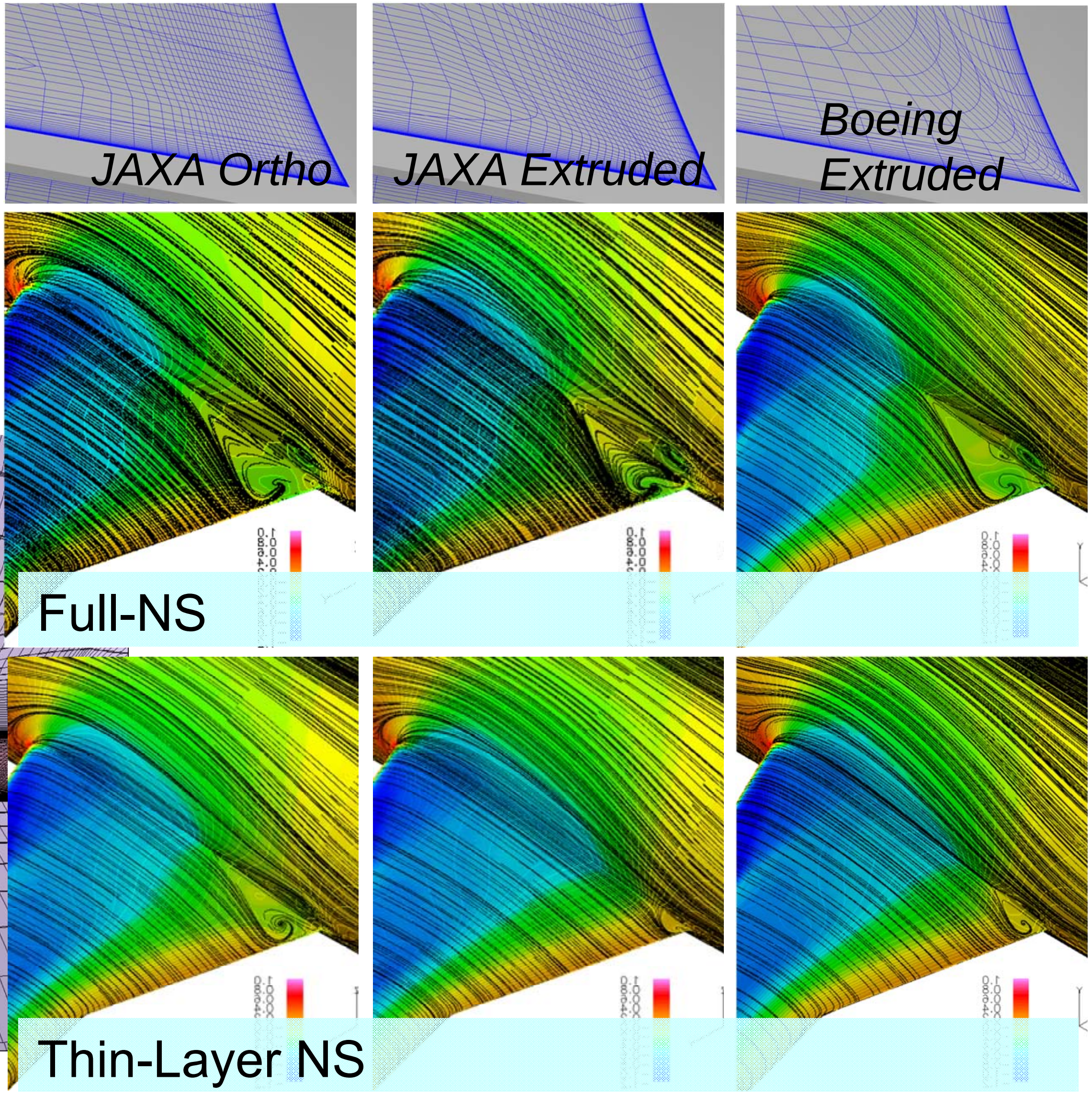
Comparison of SOB Separation in DPW-3

Murayama & Yamamoto, AIAA 2007-0258

- Orthogonal mesh is more independent of approx methods in viscous term
  - ☐ Higher-quality elements
  - ☐ Less artificial viscosity
- Similar approach in hybrid meshing?



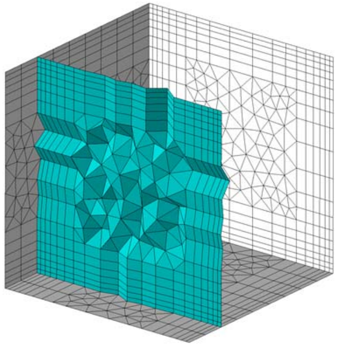
DLR-F6 WB
JAXA UPACS
$C_L = 0.5$
SA turb.
Medium meshes

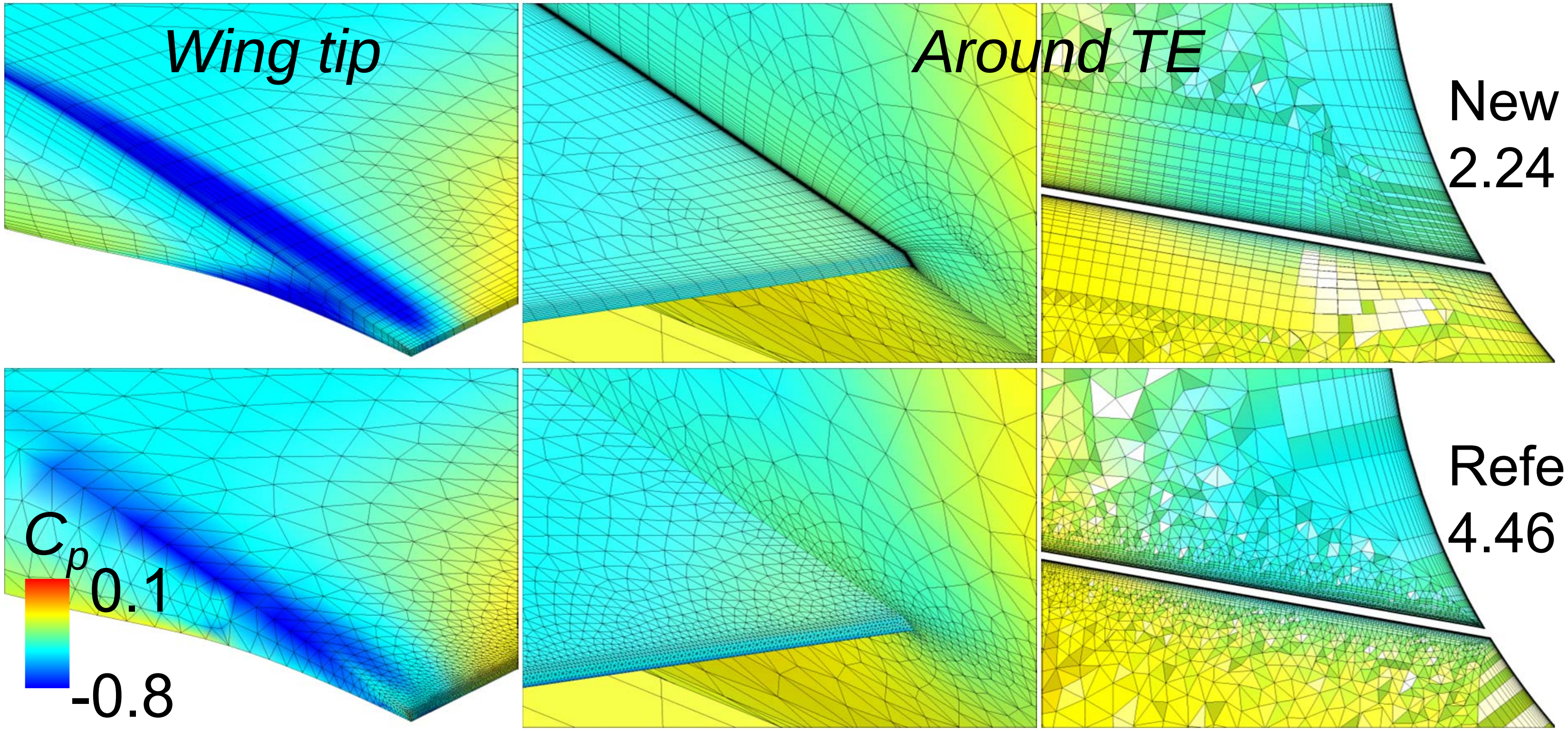


New Hybrid surface and volume meshing method

Ito *et al.*, AIAA 2011-3539

- To create good-quality semi-structured surface quads around selected ridges with minimum user-interventions
  - ☐ Advancing-layers type method & special treatment at concave corners
- To improve the hybrid volume meshing method so that good-quality elements can be easily created at concave corners
  - ☐ Suppressed marching direction method



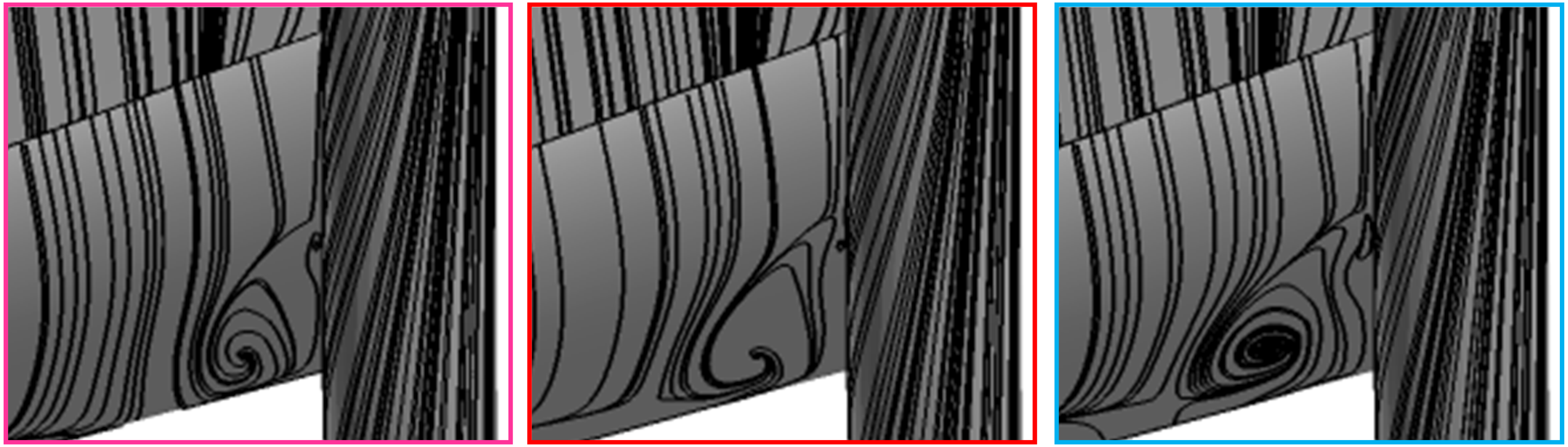


New approach
2.24 M nodes

Reference
4.46 M nodes

Comparison of flap SOB separation ($\alpha = 13^\circ$, Medium)

UPACS, Str-JAXA Grid



SA-noft2

SA-noft2-R(Crot=1)

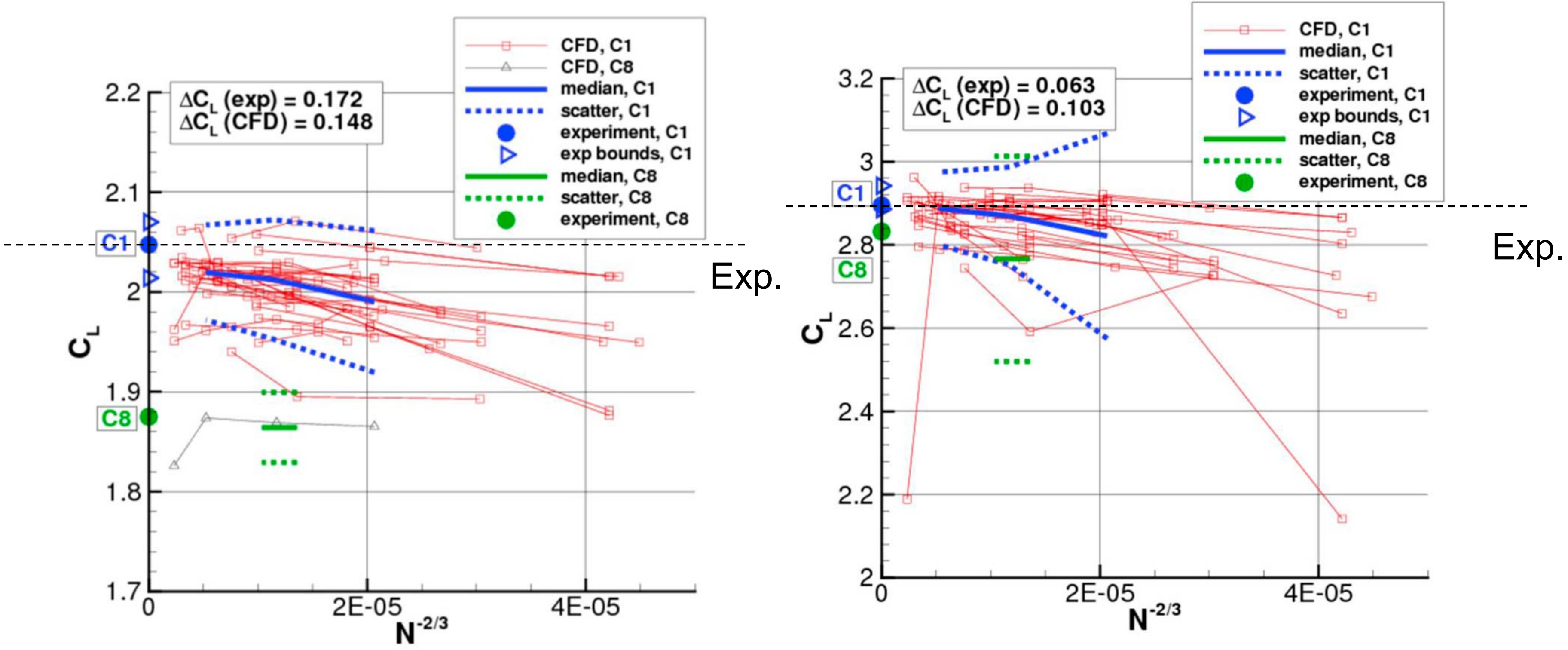
SA-noft2-R(Crot=1)+QCR

Influence of turbulent model

- Dependency of the separation to turbulent models
  - Yamamoto *et al*., AIAA-2012-2895 (11:30 AM, Tuesday, June 26)

Influence of laminar-to-turbulent transition

- Trend of under-predicted C_L especially at α = 13°
    - ☐ Several reports importance of including the transition for better comparison w/ exp
- Transition prediction method developed in JAXA will be evaluated



CL at α = 13°

CL at α = 28°

Grid convergence from summary of HiliftPW-1 (AIAA 2011-0939)

Objectives

- We have recently performed supplementary computational studies for the Trap Wing model
- (1) Grid effects
  - To compare results w/ JAXA structured grids & several unstructured hybrid grids by different mesh generators
    - Including new hybrid meshes w/ the suppressed marching direction method
  - To investigate differences in the wing tip region and the side-of body region
- (2) Prediction of boundary layer transitions
  - To evaluate a transition prediction method based on e^N method

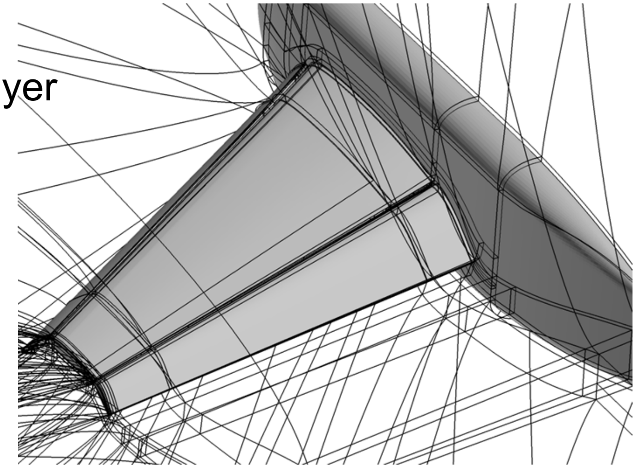
(1) Grid effects

- Comparison of JAXA structured grids and several unstructured hybrid grids by different mesh generators
- To investigate the wing tip region and the side-of body region

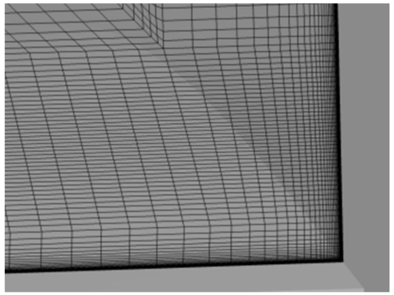
- Grids used in this study
  - ☐ JAXA multi-block structured grids using Gridgen, Str-OneTo-One-E (SX12-JAXA)
    - Coarse, Medium, Fine
  - ☐ JAXA unstructured hybrid grids, Unst-Mixed-Nodecentered-C using MEGG3D (UH16-JAXA)
    - Coarse, Medium, Fine
  - ☐ Committee-provided Uwyo unstructured hybrid grids, Unst-Mixed-FromTet-Nodecentered-A-v1 using VGRID
    - Coarse, Medium, Fine
  - ☐ Committee-provided DLR unstructured hybrid grids, Unst-Mixed-FromTet-Nodecentered-B using Solar
    - Coarse, Medium
  - ☐ New JAXA unstructured hybrid grids, Unst-Mixed-Nodecentered-JAXA New using MEGG3D
    - Coarse, Medium-coarse

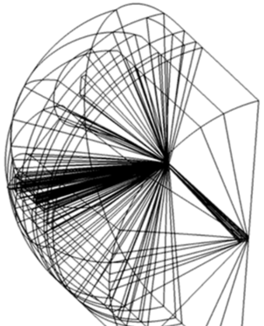
JAXA multi-block structured grids (SX12-JAXA, Gridgen)

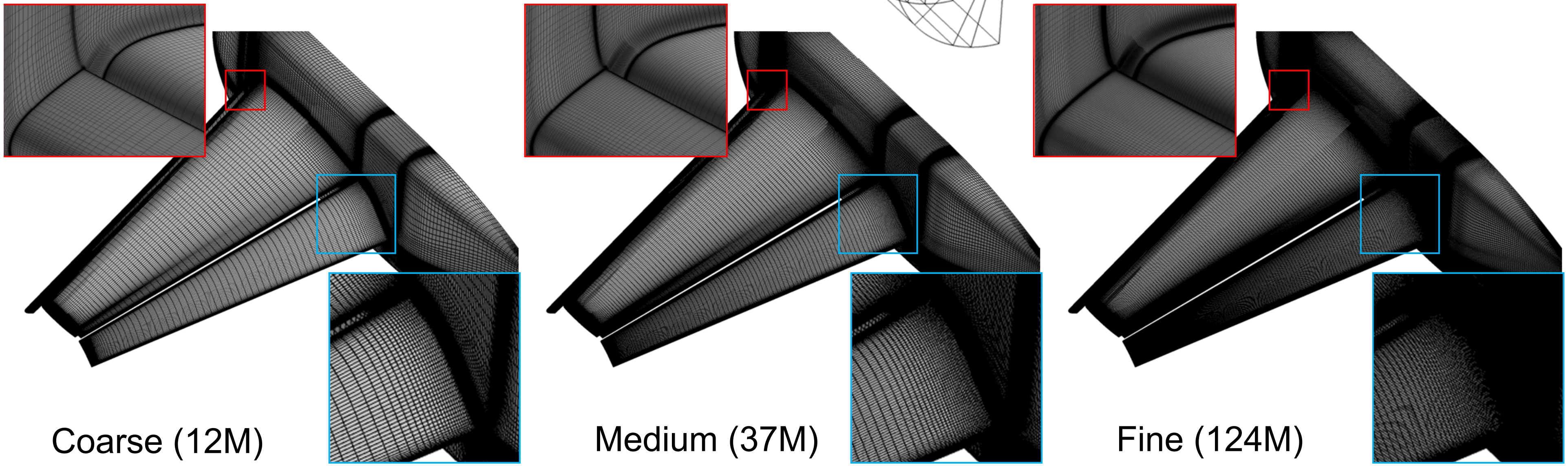
- O-O grid topology near the model surface
  - To guarantee better orthogonality within the boundary layer
- C-O grid topology at outward
- **O-H grid topology** at wing-body junction
  - High-density grid at the corner of wing-body junction



441 blocks







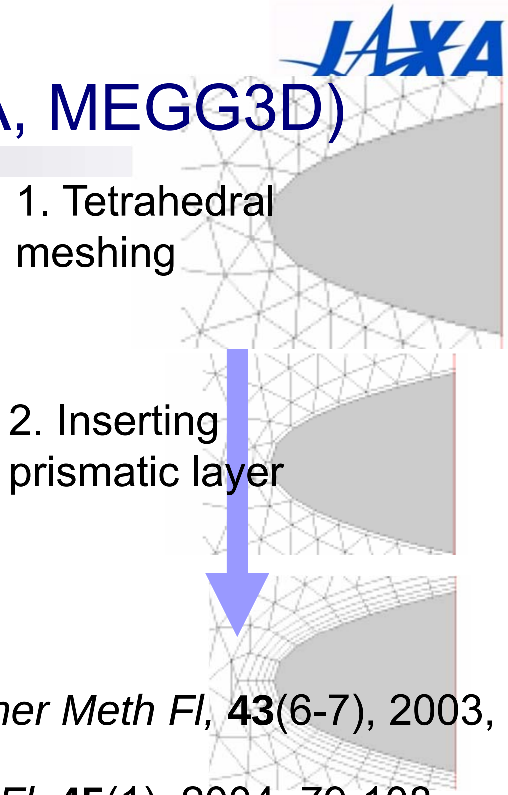
Coarse (12M)

Medium (37M)

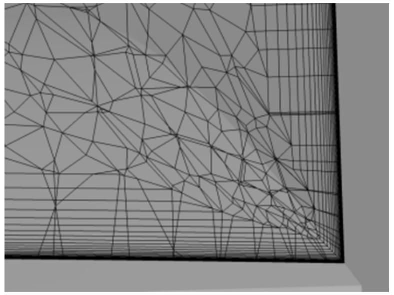
Fine (124M)

JAXA unstructured hybrid grids (UH16-JAXA, MEGG3D)

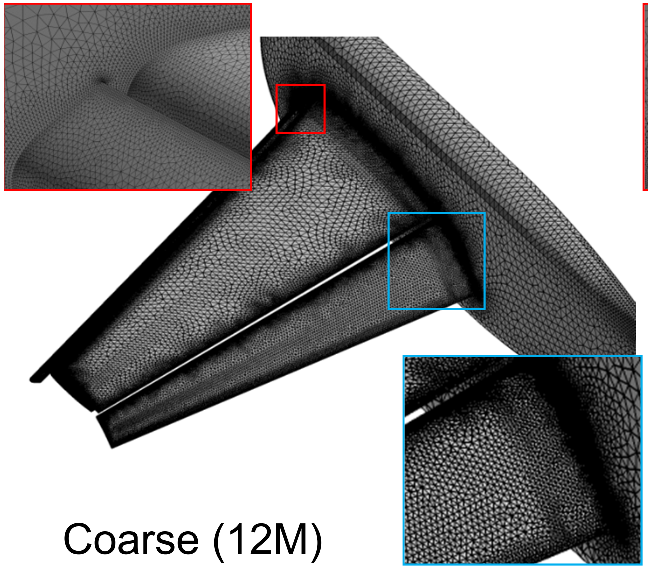
- Surface grid (Isotropic triangles)
  - ☐ Direct advancing front method by Ito *et al*.
- Volume grid (Tetrahedra, Prisms, Pyramids)
  - ☐ Delauney (tetra) → insertion of prismatic layer (prism)
- **Extruded prisms** on no-slip walls, including at wing-body junction

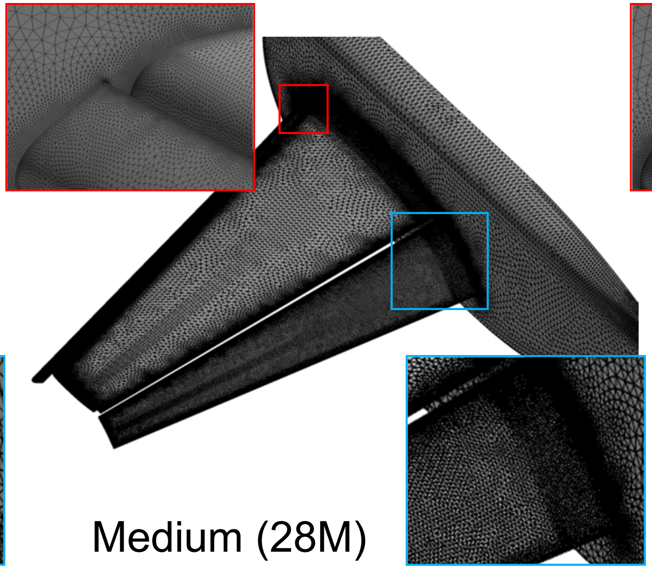

1. Tetrahedral meshing

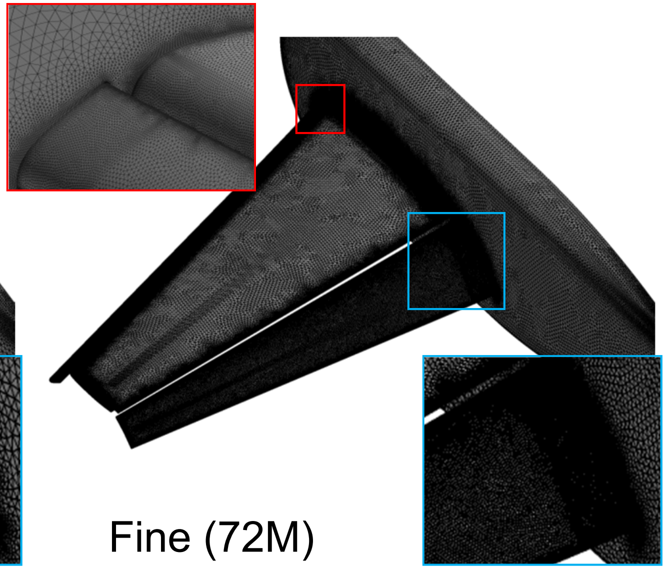
2. Inserting prismatic layer



- Nakahashi, Ito & Togashi, *Int J Numer Meth Fl*, **43**(6-7), 2003, 769-783.
- Ito & Nakahashi, *Int J Numer Meth Fl*, **45**(1), 2004, 79-108.

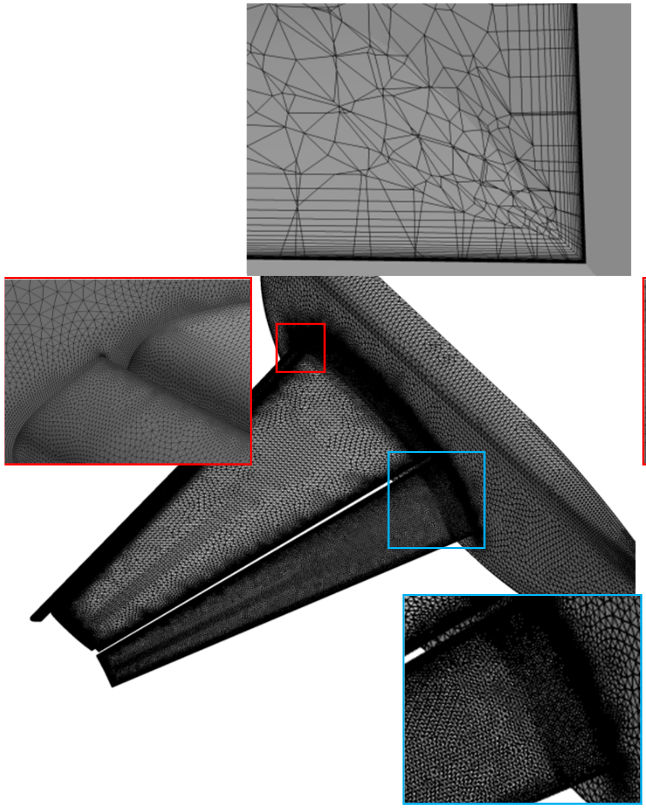

Coarse (12M)


Medium (28M)

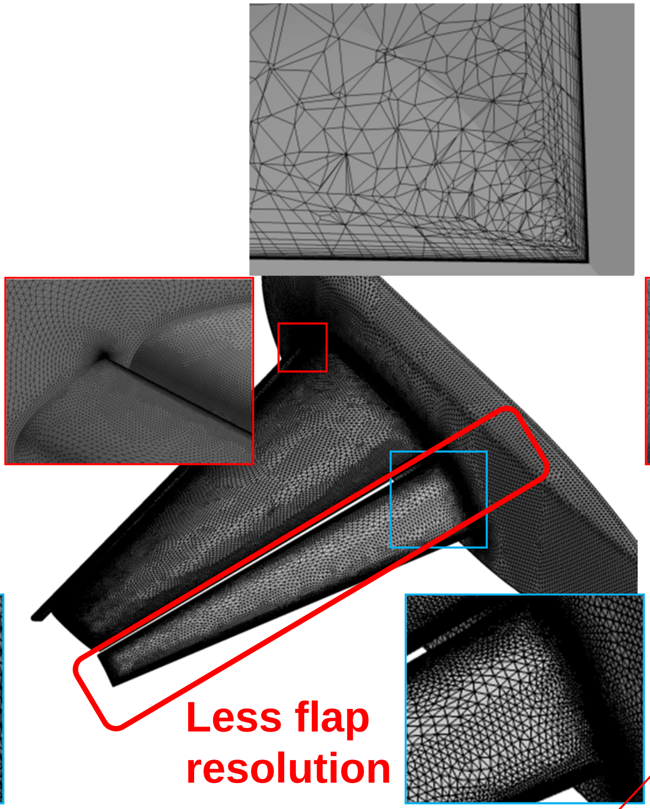

Fine (72M)

Committee-provided unstructured hybrid grids

- University 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
  - **Extruded elements** at wing-body junction



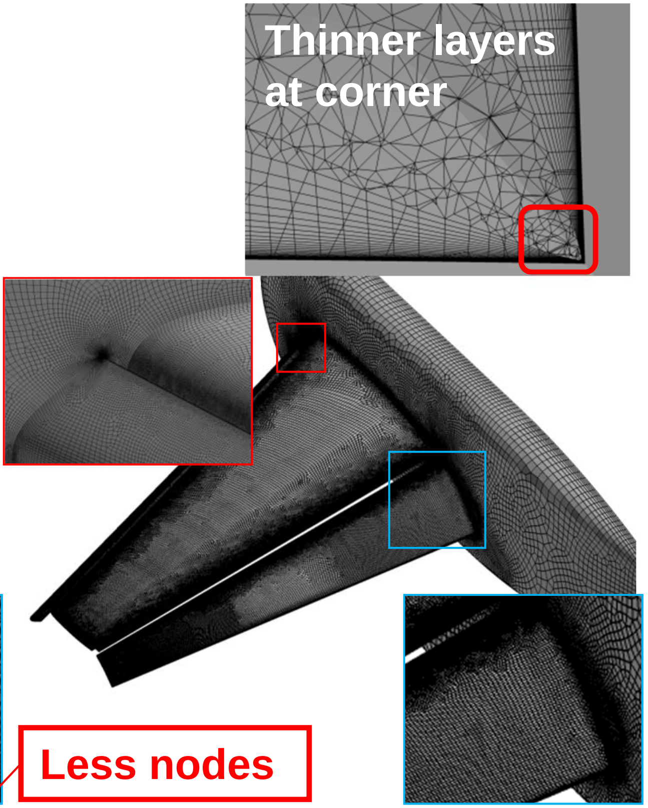
Unst-JAXA grid (UH16) (28M)



Less flap resolution

Unst-MFTNAv1 grid (11M)

Less nodes

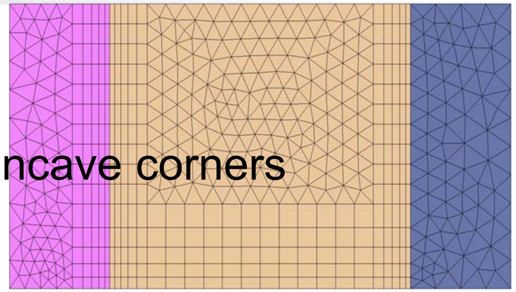


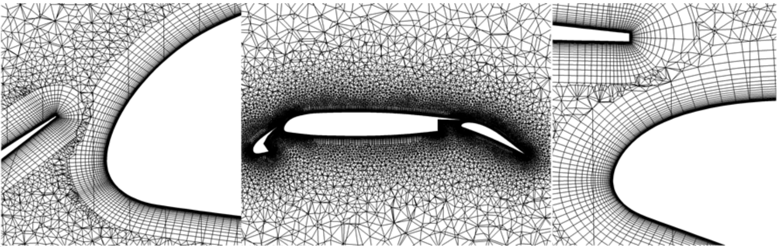
Thinner layers at corner

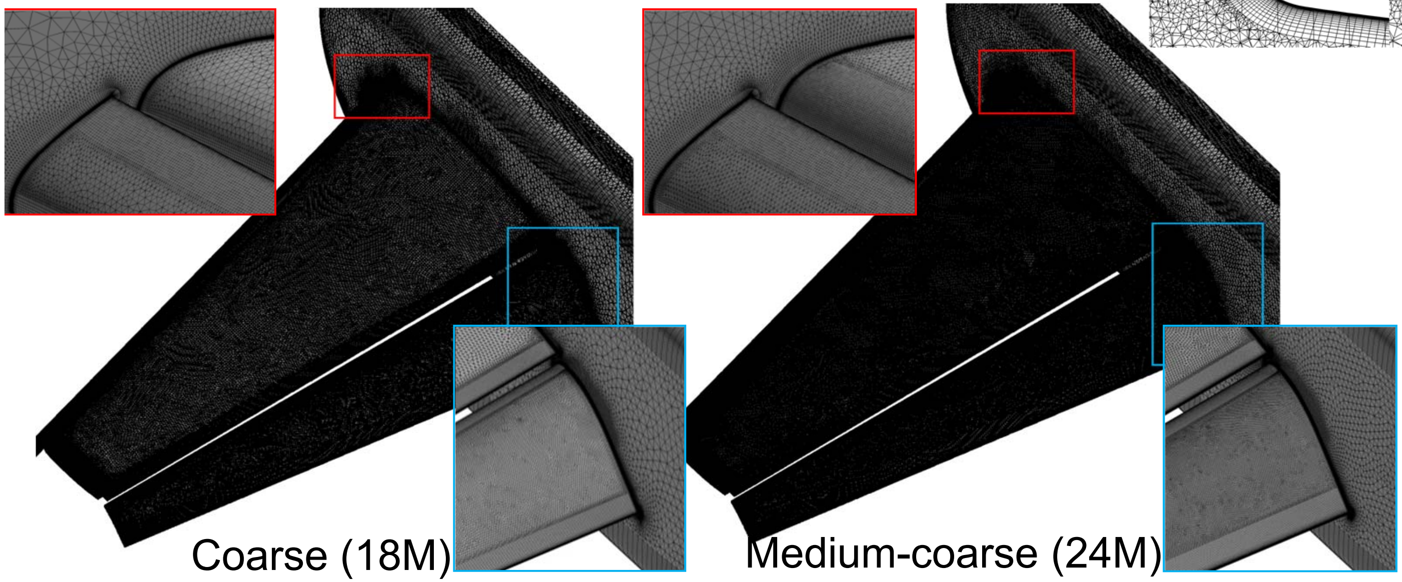
Unst-MNBv1 grid (37M)

New JAXA unstructured hybrid grids (MEGG3D)

- Surface grid
  - ☐ Advancing-layers type method w/ special treatment at concave corners
  - ☐ Direct advancing front method for surface triangulation
- Volume grid
  - ☐ Advancing-layers type method w/ suppressed marching direction method
  - ☐ Advancing front method for tetrahedral meshing
- **Orthogonal hexes** at wing-body junction

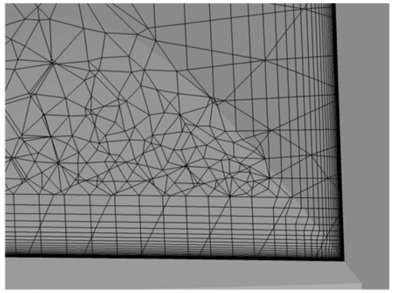






Coarse (18M)

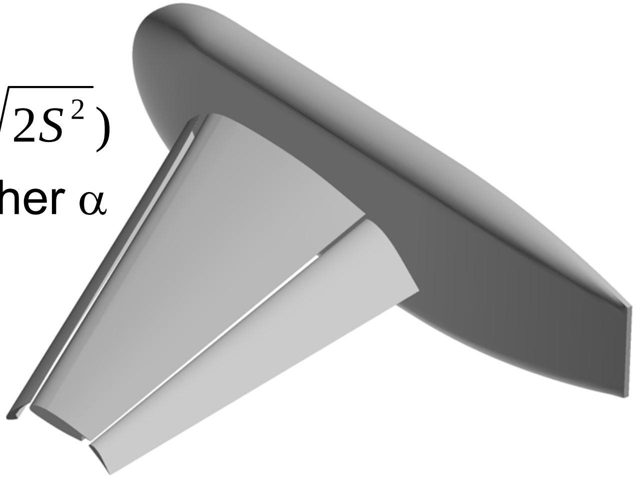
Medium-coarse (24M)



Numerical methods & flow conditions

	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	SA-noft2-R (Crot=1)	SA-noft2-R (Crot=1)

- Modification to S-A model (SA-noft2-R (Crot=1)) to suppress excessive eddy viscosity after separation
  - ☐ w/o trip related terms
  - ☐ w/ 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



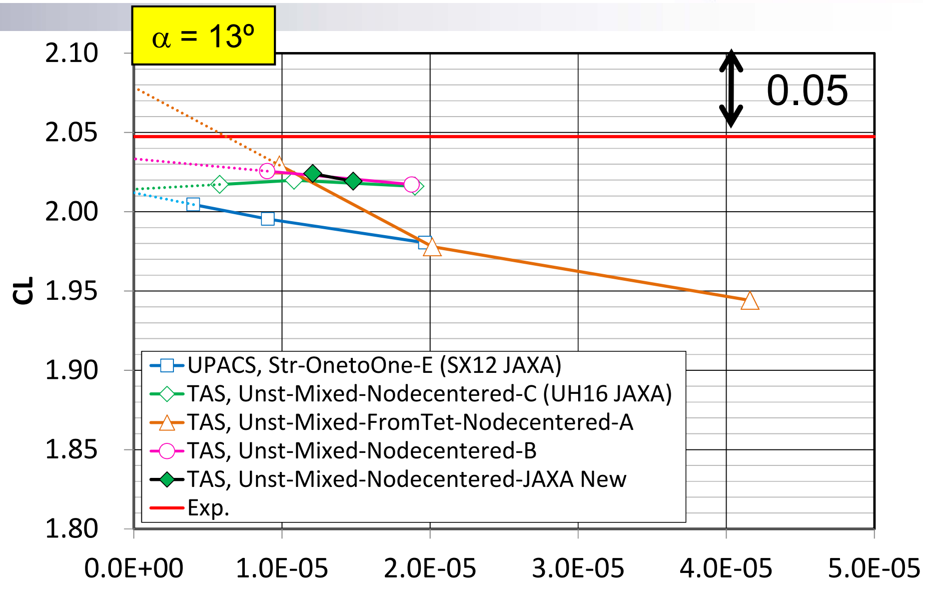
- Slat & flap setting: Config 1
- No slat & flap brackets included
- M = 0.2, Re = 4.3 x 10^6, T = 520ºR & α = 13º, 28º

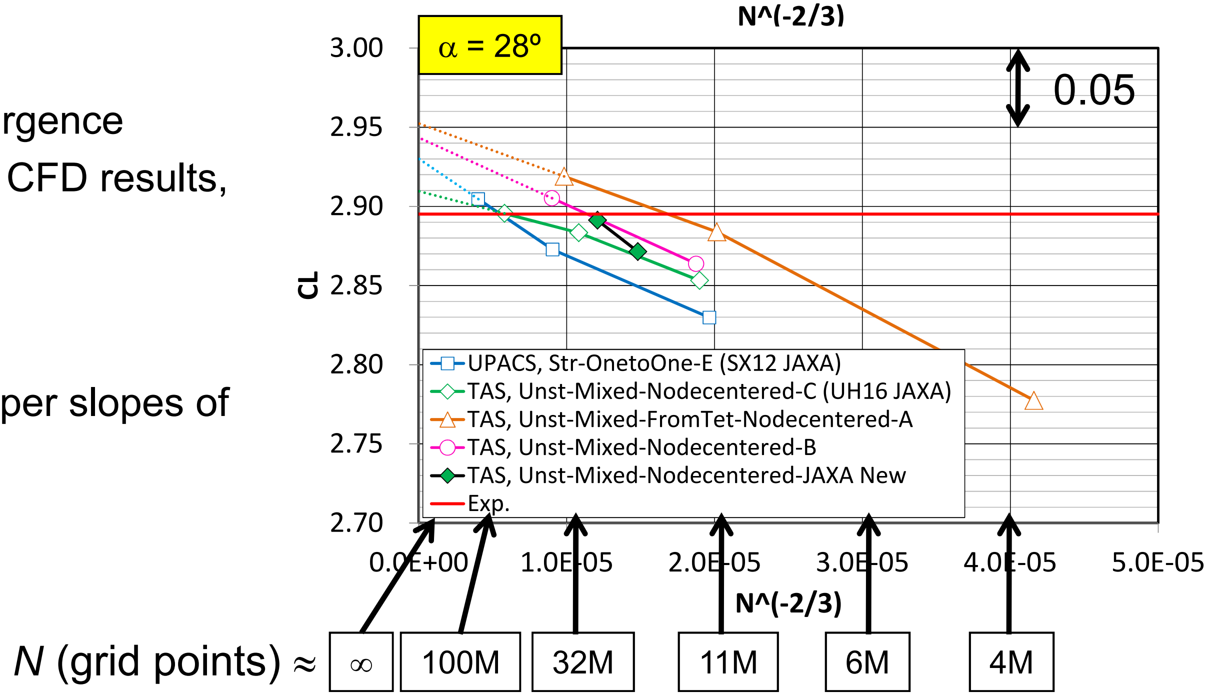
Grid convergence of C_L

- Good agreement among CFD results on finer grids
- Good correlation between UPACS for SX12-JAXA & TAS for UH16-JAXA on expected grid converged solutions, $C_{L(N\rightarrow\infty)}$
- Similar values & trends by JAXA-New & UH16-JAXA

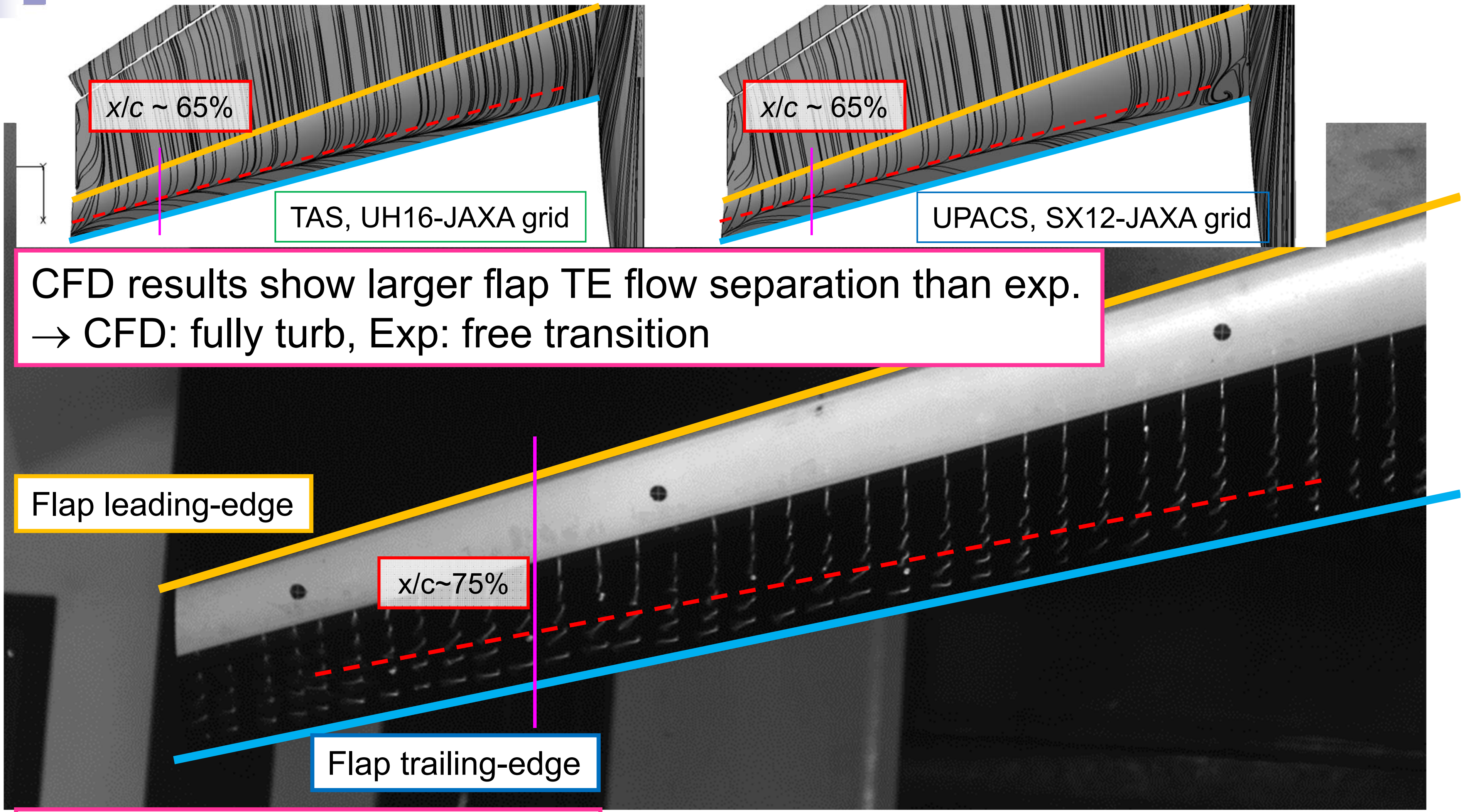
- α = 13°
  - ☐ Mild slopes of grid convergence
  - ☐ Good agreement among CFD results, but lower C_L than exp.

- α = 28°
  - ☐ More variations and steeper slopes of grid convergence
  - ☐ Higher $C_{L(N\rightarrow\infty)}$ than exp.





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

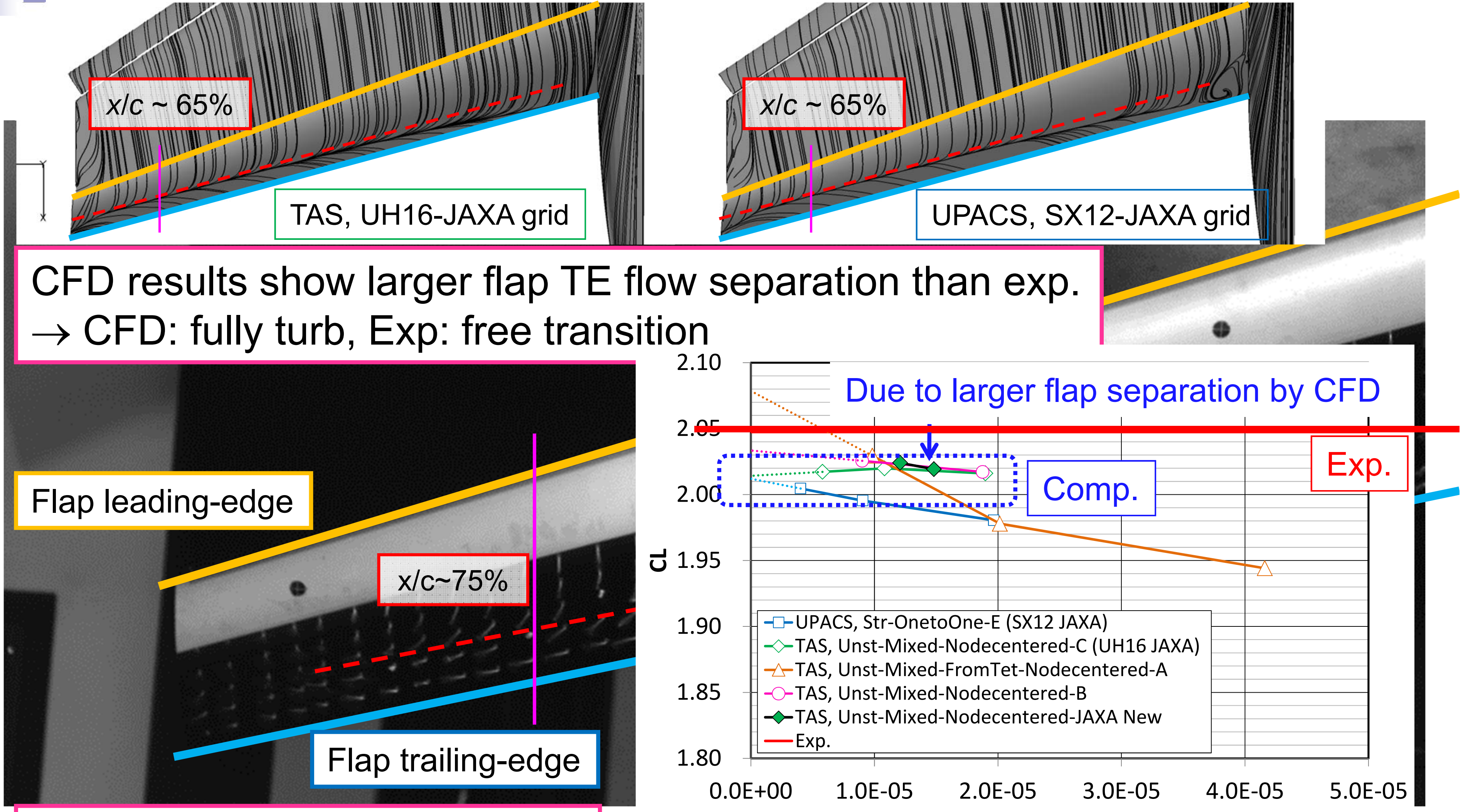


CFD results show larger flap TE flow separation than exp.
→ CFD: fully turb, Exp: free transition

α-uncorr = 12°, α-corr ~ 15.5 °

Exp. (Tuft image)

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



CFD results show larger flap TE flow separation than exp.
→ CFD: fully turb, Exp: free transition

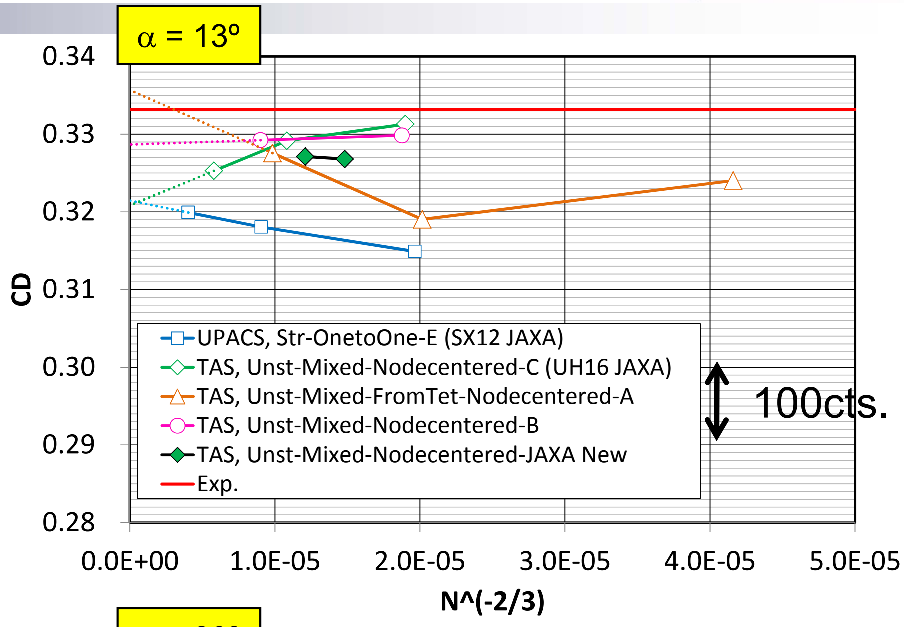
α-uncorr = 12º, α-corr ~ 15.5 º

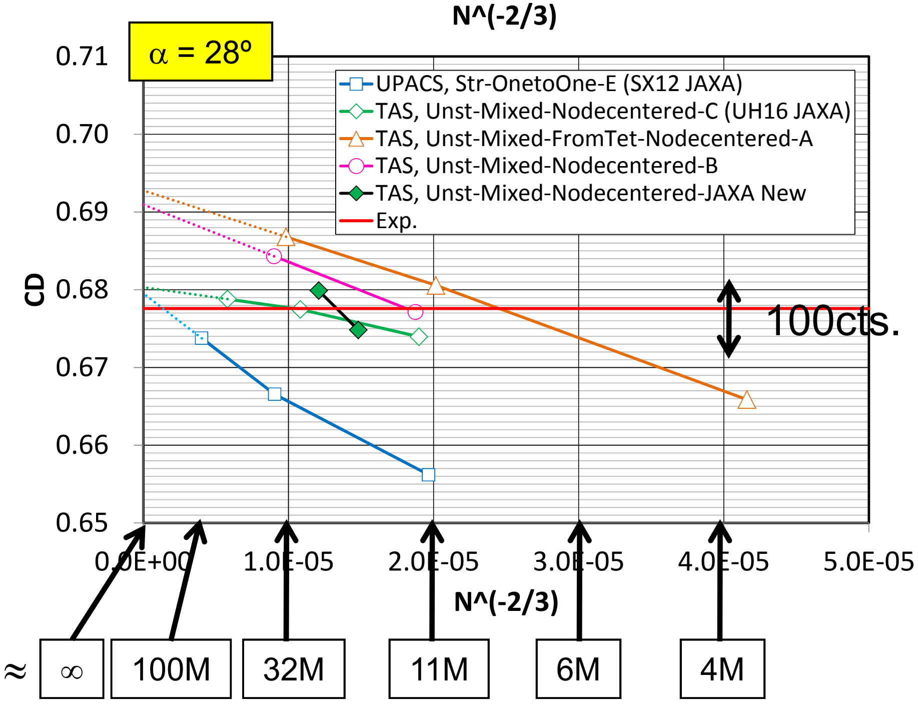
Exp. (Tuft image)

Grid convergence of C_D

- Similar trends with *CL*
- Reasonable agreement among CFD results on finer grids at α = 13°
- Good correlation between UPACS for SX12-JAXA & TAS for UH16-JAXA on expected grid converged solutions, $C_{D(N\to\infty)}$
- Similar values and trends by JAXA-New & UH16-JAXA

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

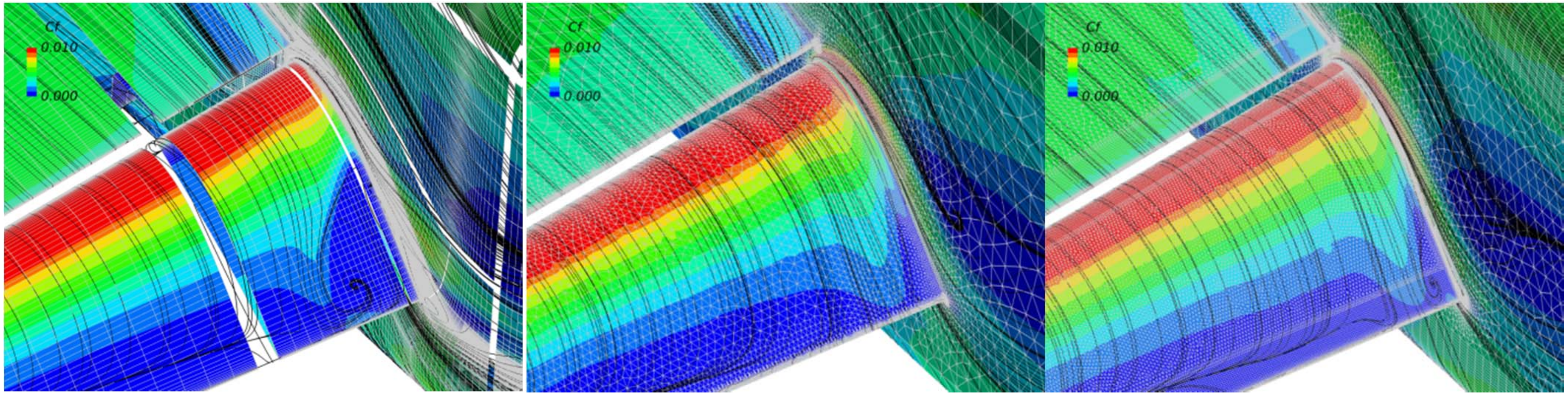




N (grid points) ≈

Comparison of flow separation at flap-body junction

- SX12-JAXA grid & JAXA-New grid have smaller, better-quality, more orthogonal hexes at the corner.
- Finer grids predicted the large corner flow separation
  - The flow separation by JAXA-New grid still remains smaller than that of SX12-JAXA grid by UPACS
  - Grid dependency will be investigated furthermore



Str-OneToOne-E
(SX12 JAXA grid)

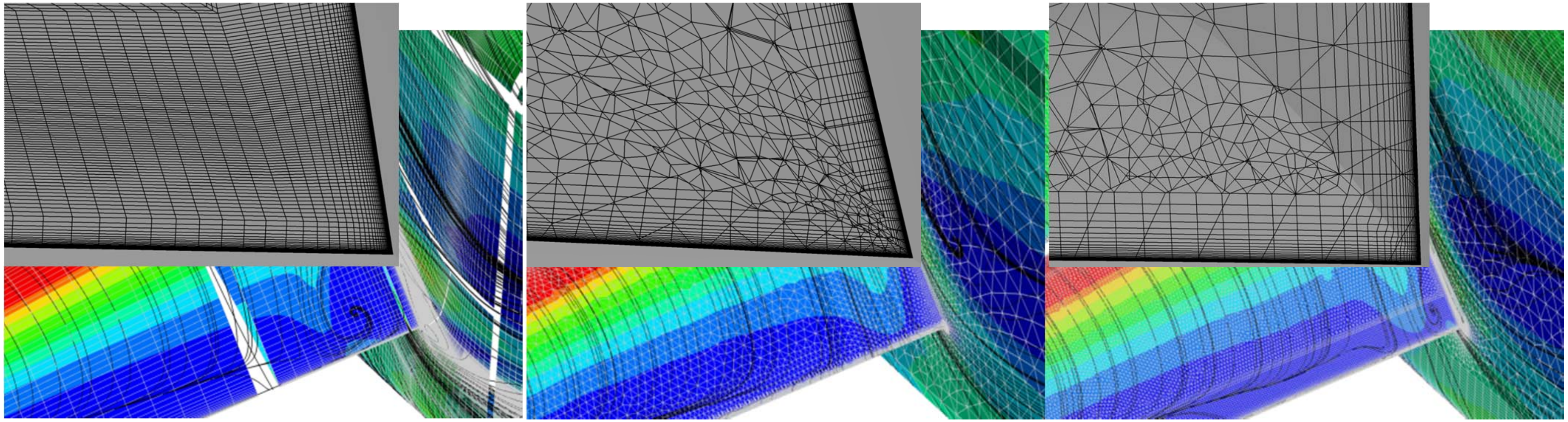
Unst-Mixed-Nodecentered-C
(UH16 JAXA grid)

JAXA New grid

C_f and grid distribution at $\alpha = 13°$

Comparison of flow separation at flap-body junction

- SX12-JAXA grid & JAXA-New grid have smaller, better-quality, more orthogonal hexes at the corner.
- Finer grids predicted the large corner flow separation
  - ☐ The flow separation by JAXA-New grid still remains smaller than that of SX12-JAXA grid by UPACS
  - ☐ Grid dependency will be investigated furthermore



Str-OneToOne-E (SX12 JAXA grid)

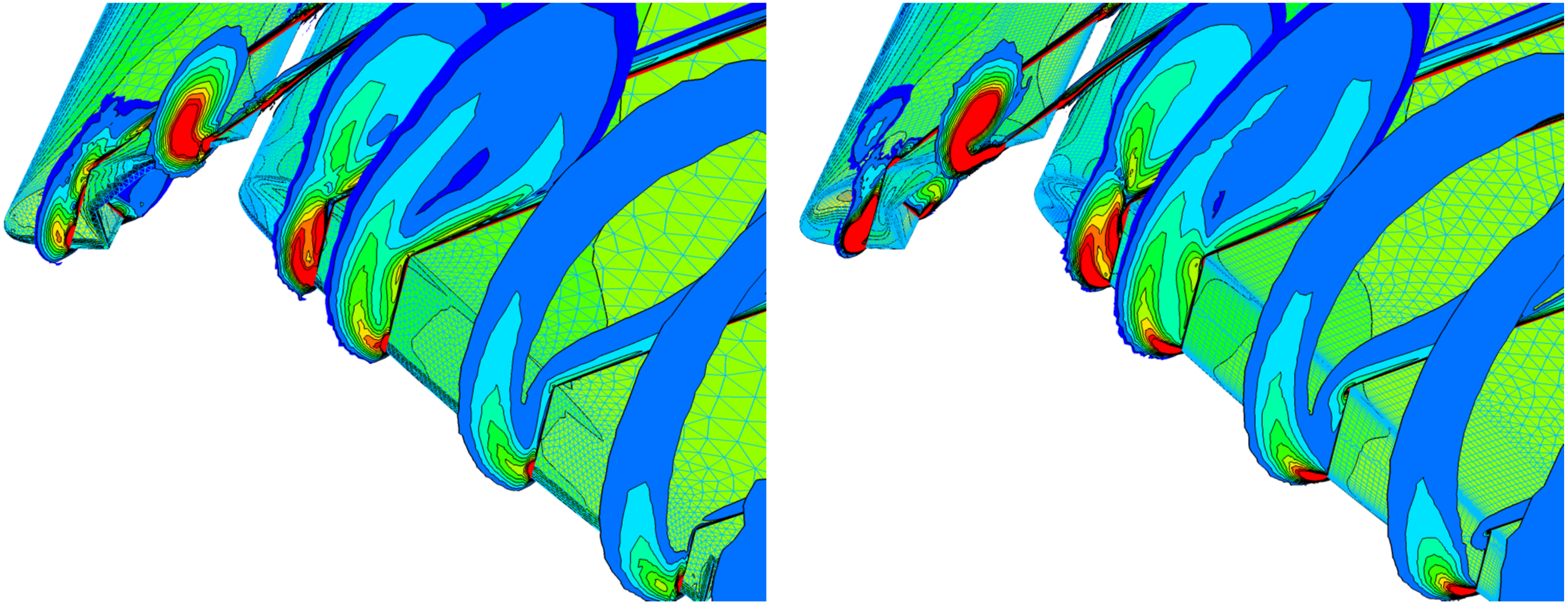
Unst-Mixed-Nodecentered-C (UH16 JAXA grid)

JAXA New grid

C_f and grid distribution at α = 13°

Comparison of tip vortices between JAXA grids

- JAXA-New grids have much finer faces on the tips and predict stronger vortices from the edges of the tips
- However, *Cp* at 98% semi-span station was not improved
  - ☐ More elements are probably needed in the volume



UH16-JAXA grids, ≤ 72M nodes

JAXA-New grids, ≤ 24M nodes

Vorticity and grid distribution at α = 28°

Comparison of tip vortices between JAXA grids

- JAXA-New grids have much finer faces on the tips and predict stronger vortices from the edges of the tips
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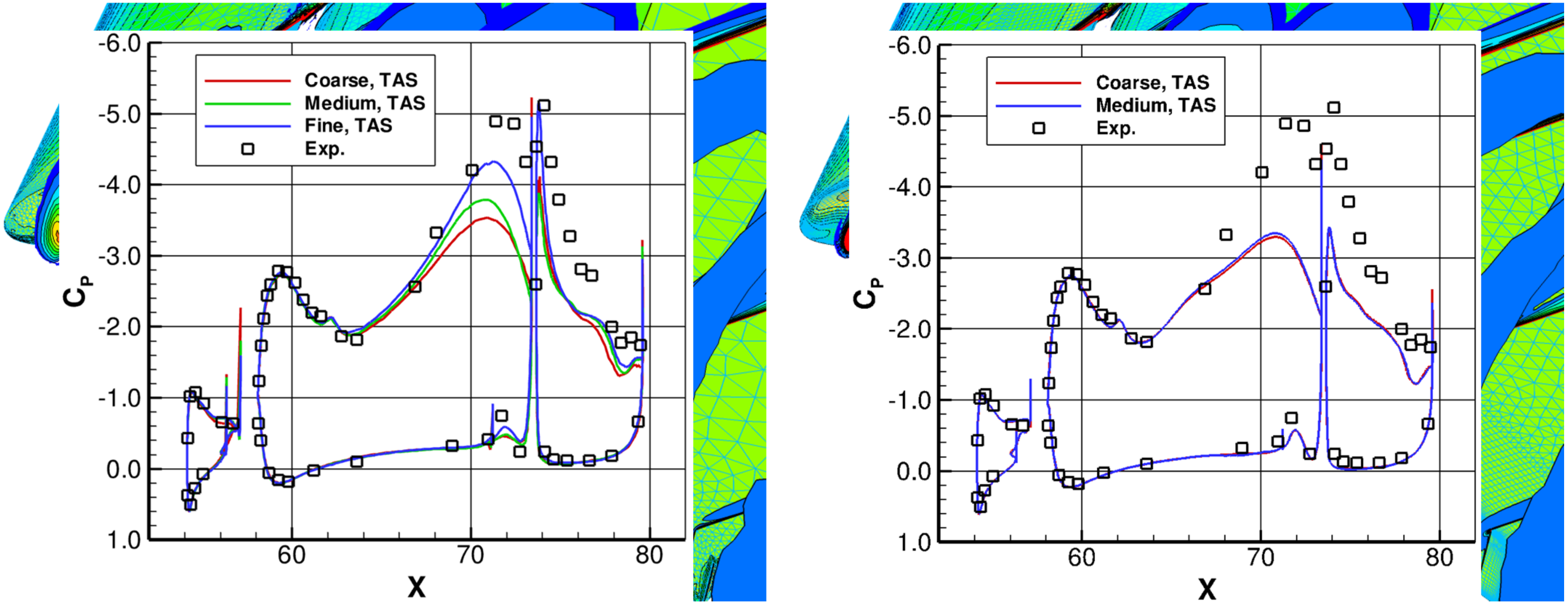


UH16-JAXA grids, ≤ 72M nodes

JAXA-New grids, ≤ 24M nodes

Vorticity and grid distribution at α = 28°

(2) Prediction of boundary layer transitions

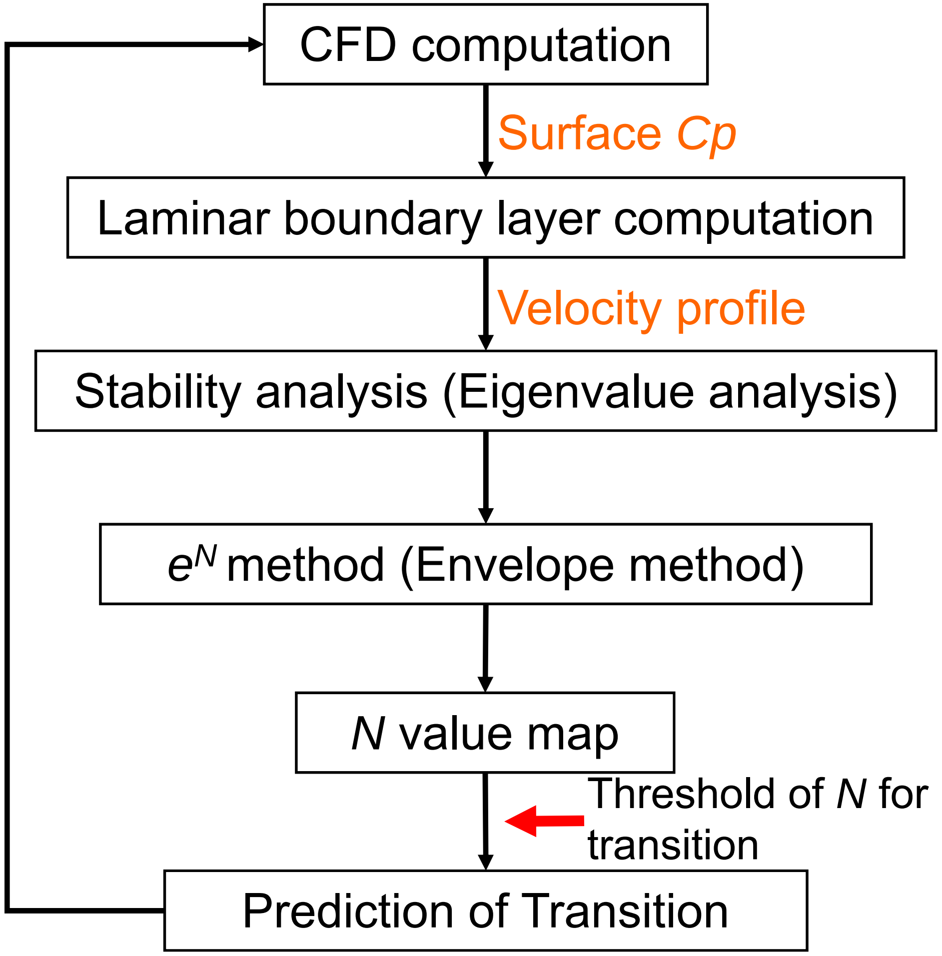
- Our approach: e^N based method using RANS CFD *Cp*
  - ☐ Tollmien-Schlichting (TS) instability
  - ☐ Cross Flow (CF) instability
  - ☐ Laminar separation bubbles (LSB)
- We have not considered
  - ☐ Attachment line contamination due to the transport of turbulence from fuselage, etc.
  - ☐ Re-laminarisation due to strong acceleration of flow
  - ☐ Bypass transition due to the wake flow of fore wing element

- Predicted locations compared w/ those by Eliasson *et al*. (AIAA 2011-3009) available on HiLiftPW website
  - ☐ Prescribed $N = 5, 7, 10$ for comparison

LSTAB code for TS, CF, Laminar separation

Developed in JAXA NEXST (National EXperimental Supersonic Transport) Projects

Yoshida *et al*.


CFD computation

Surface *Cp*

Laminar boundary layer computation

Velocity profile

Stability analysis (Eigenvalue analysis)

e^N method (Envelope method)

N value map

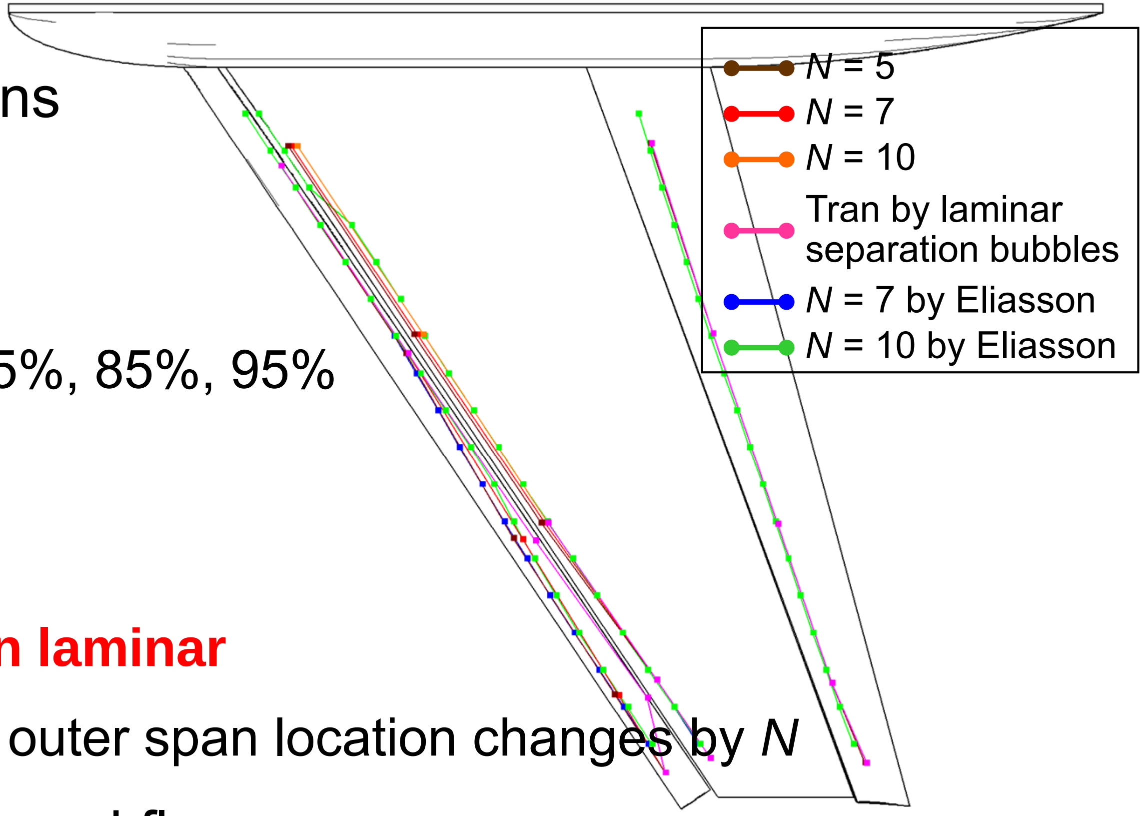
Threshold of *N* for transition

Prediction of Transition

- Stability analysis
    - Performed at several span locations
- Laminar boundary layer computation
    - Kaups & Cebeci method using *Cp*
        - Conical flow approximation
    - Laminar separation is detected based on the shape factor, *H*
- *N*-factor
    - Obtained by envelope method using integration of amplification rates of each small disturbance
- Prediction of transition
    - *N* = 5, 7, 10
    - If transition due to TS and CF does not occur before the laminar separation, transition starts just before the separation location

\# Results after only one cycle are presented
\# First CFD comp. is performed assuming fully turbulent flow

Predicted transition location: $\alpha = 13^\circ$, upper surf

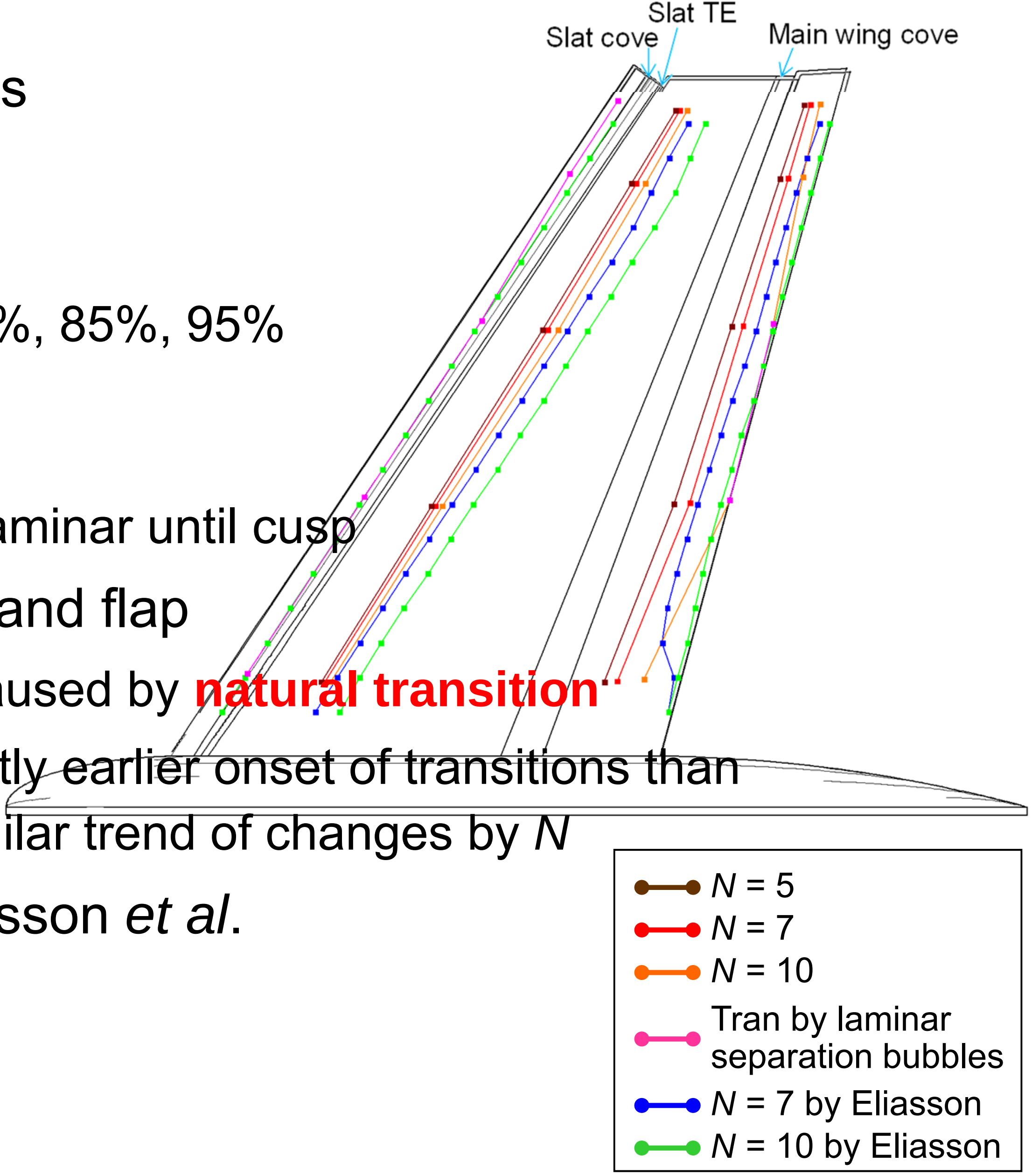


- Computational conditions
  - SX12-JAXA grid
  - $N = 5, 7, 10$
  - Span = 17%, 41%, 65%, 85%, 95%
- Upper surface of slat
  - **Most regions remain laminar**
  - Transition location at outer span location changes by N
- Upper surfaces of main and flap
  - Most transitions are caused by **laminar separation bubble**
- Good agreement w/ Eliasson *et al*.

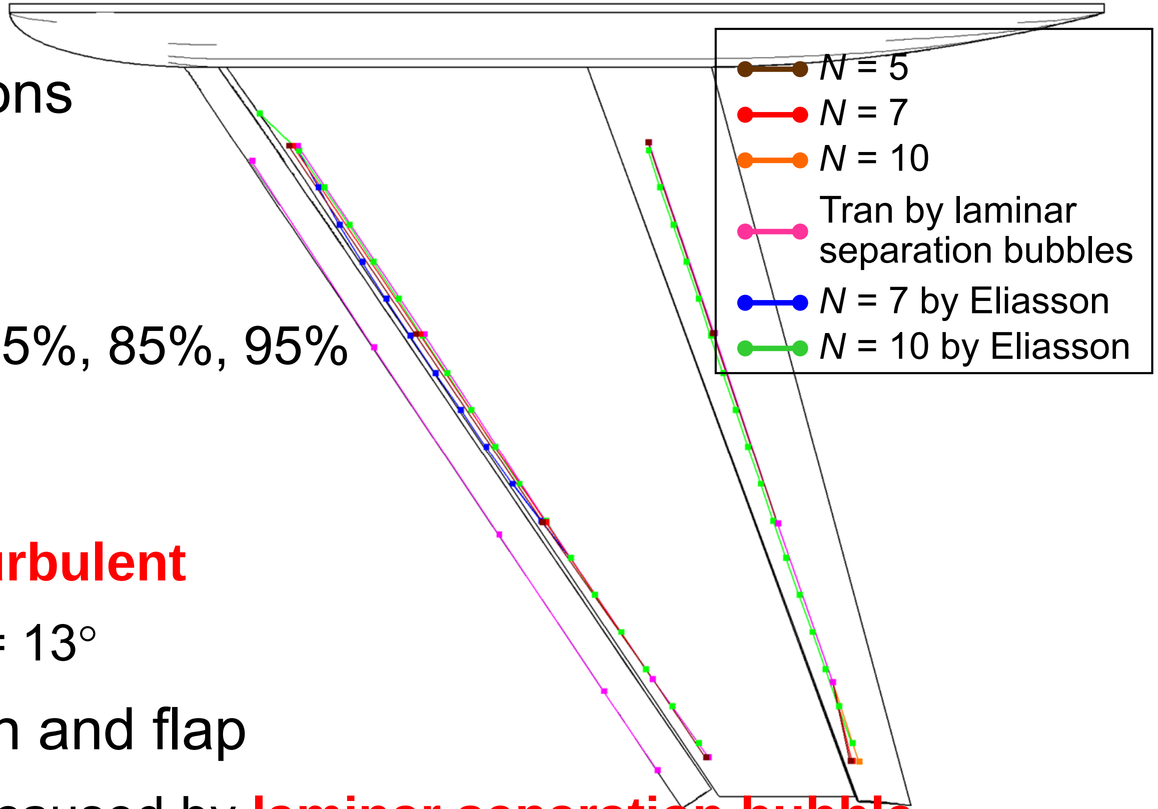
Predicted transition location: $\alpha = 13°$, lower surf

- Computational conditions
  - SX12-JAXA grid
  - *N* = 5, 7, 10
  - Span = 17%, 41%, 65%, 85%, 95%

- Lower surface of slat
  - Most regions remain laminar until cusp
- Lower surfaces of main and flap
  - Most transitions are caused by **natural transition**
  - The results show slightly earlier onset of transitions than Eliasson *et al*., but similar trend of changes by *N*
- Good correlation w/ Eliasson *et al*.



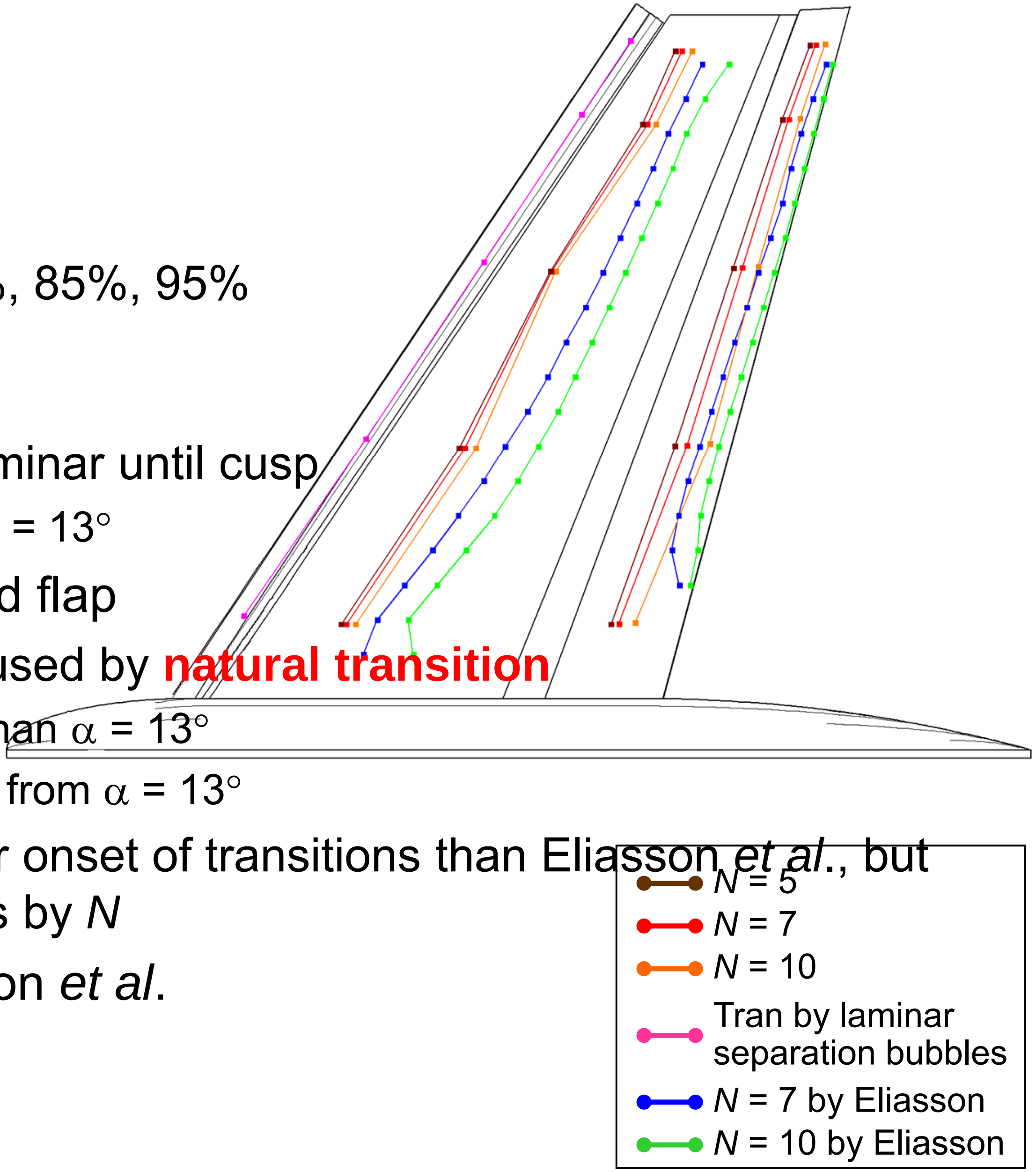
Predicted transition location: α = 28°, upper surf



- Computational conditions
  - ☐ SX12-JAXA grid
  - ☐ N = 5, 7, 10
  - ☐ Span = 17%, 41%, 65%, 85%, 95%
- Upper surface of slat
  - ☐ **Most regions are turbulent**
    - *Cf*. Laminar at α = 13°
- Upper surfaces of main and flap
  - ☐ Most transitions are caused by **laminar separation bubble**
  - ☐ Similar to the result at α = 13°
- Good agreement w/ Eliasson *et al*.

Predicted transition location: α = 28°, lower surf

- Computational conditions
  - SX12-JAXA grid
  - *N* = 5, 7, 10
  - Span = 17%, 41%, 65%, 85%, 95%
- Lower surface of slat
  - Most regions remain laminar until cusp
    - Nearly identical with α = 13°
- Lower surfaces of main and flap
  - Most transitions are caused by **natural transition**
    - Main: delayed onset than α = 13°
    - Flap: slightly changed from α = 13°
  - The results show earlier onset of transitions than Eliasson *et al.*, but similar trend of changes by *N*
- Good correlation w/ Eliasson *et al*.



Concluding Remarks

- Computational studies have recently been performed to supplement HiLiftPW-1
- The influence of grid resolution around wing tip & SOB regions were investigated with two new unstructured hybrid grids
  - Finer, high-quality near-field meshes around the flap-body junction generated larger corner flow separation
  - The improvement of grid resolution on the surface around wing tip was not effective to improve the under-predicted C_p suction peaks
  - Further studies on more extensive grid refinement & influence of turbulence models may be required to capture flow physics in those regions
- A transition prediction method based on e^N method was evaluated by compared with data from Eliasson *et al*.
  - Predicted transition locations caused by laminar separation bubbles agreed well
  - Overall tendency of the transition patterns & locations agreed reasonably well with each other