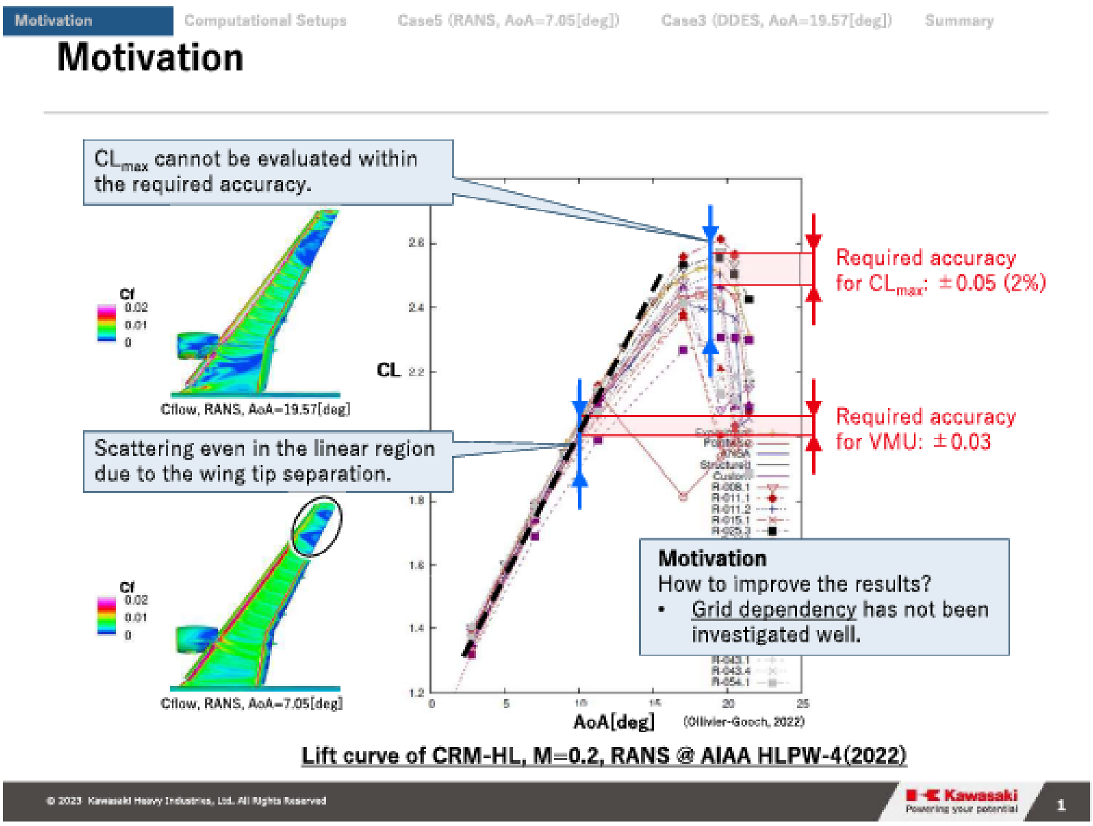
CflowによるCRM-HLの検証解析 − 格子解像度の影響・安田 英将, 澤木 悠太, 山内 優果, 浅野 宏佳 (川崎重工)



Computational cases

Grid dependencies are focused on.

1. Case 5: **Required grid resolution** for RANS simulation is investigated.
2. Case 3: **Grid resolution effects** in DDES are evaluated.

Because DDES requires grid resolution of at least enough for RANS to resolve the flow field, the required grid resolution is investigated in the Case 5.

Computational cases

(O: conducted cases)

Grid(*1)	HLPW-4 No. (*2)	Type	Case 5	Case 3	
			7.05[deg]	17.05[deg]	19.57[deg]
Cflow-C1	140.C	Hex	O		
Cflow-C2	N/A	Hex	O		
Cflow-C3	N/A	Hex	O	O	O
Cflow-C6	N/A	Hex	O	O	O
ANSA-C	101.C	Hex	O		
PW-A	1.3.A	Tet+Prism	O		
PW-C	1.3.C	Tet+Prism	O		
JAXA-C	240.C	Tet+Prism	O		

(*1) "-A" or "-C" represent grid levels defined in the HLPW-4 gridding guidelines.
(*2) Provided in the HLPW-4 web site: https://hiliftpw.larc.nasa.gov/Workshop4/grids_downloads.html

Numerical methods

Numerical methods used in Cflow are summarized in the table below.

- RANS simulation was started from uniform flow condition (cold start).
- DDES was started from RANS results at the same flow condition (warm start).

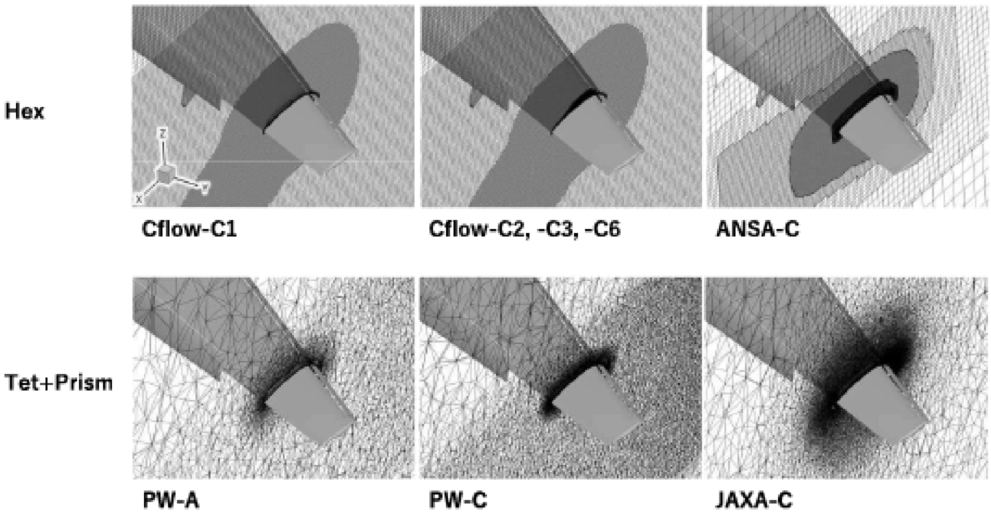
Numerical methods

	Case 5 (RANS)	Case 3 (DDES)
Governing equations	Compressible Reynolds-averaged Navier-Stokes equations	
Spatial discretization	Cell-centered finite volume method	
Flux reconstruction	**2nd-order** accurate reconstruction based on MUSCL	
Gradient	Green-Gauss	
Inviscid flux	Simple low-dissipation AUSM scheme (**SLAU**)	
Slope limiter	minmod	
Viscous flux	2nd-order accurate central difference	
Turbulence modeling	**SA-neg**	SA-neg-based Delayed Detached Eddy Simulation (DDES)
Time integration	Matrix-free Gauss Seidel (MFGS) implicit method	
	local time-stepping method	1st order, dt=0.01[-] (CFL≈1 around bracket wake region)

Computational grids

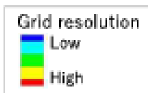
Effects of both grid type and grid resolution are investigated.

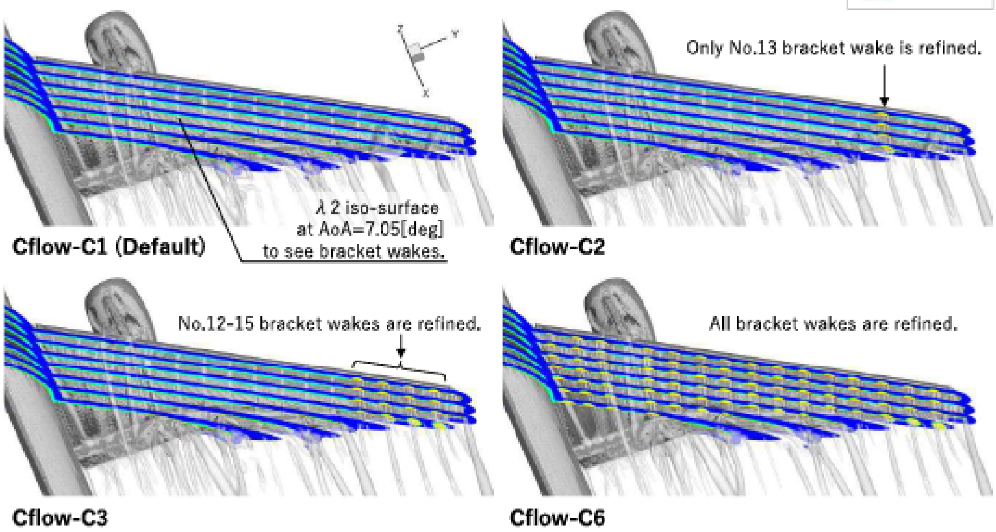
- Hex-dominant: 5 types, Tet+Prism: 3 types
  - Cflow-C2, -C3, and –C6 have finer grid around bracket wake than Cflow-C1. (→Next slide.)
- Spatial grid resolution is different even in the same grid level C.



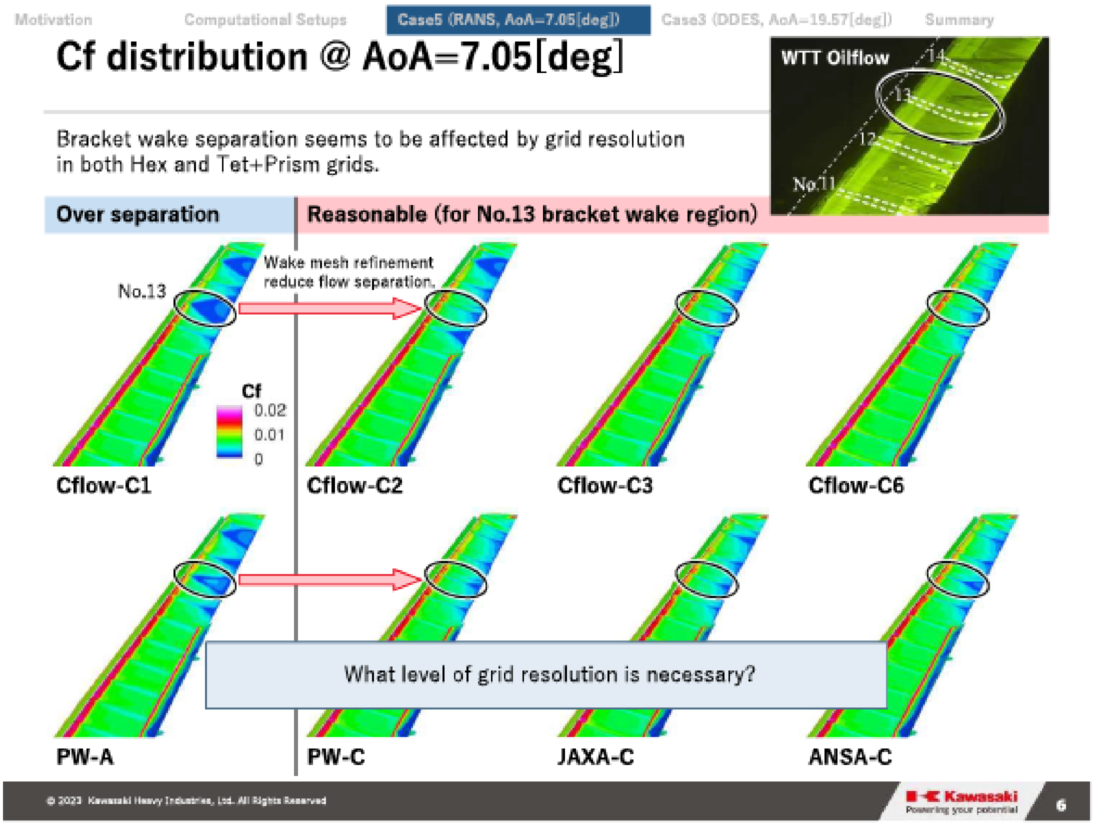
Computational grids – Cflow-grid family

Grid resolution around the bracket wake is different in the Cflow grid family.





Spatial-grid-resolution distributions of the Cflow grids


Motivation
Computational Setups
Case5 (RANS, AoA=7.05[deg])
Case3 (DDES, AoA=19.57[deg])
Summary
Cf distribution @ AoA=7.05[deg]
WTT Oilflow
14
13
12
No.11
Bracket wake separation seems to be affected by grid resolution in both Hex and Tet+Prism grids.
Over separation
Reasonable (for No.13 bracket wake region)
No.13
Wake mesh refinement reduce flow separation.
Cf
0.02
0.01
0
Cflow-C1
Cflow-C2
Cflow-C3
Cflow-C6
What level of grid resolution is necessary?
PW-A
PW-C
JAXA-C
ANSA-C
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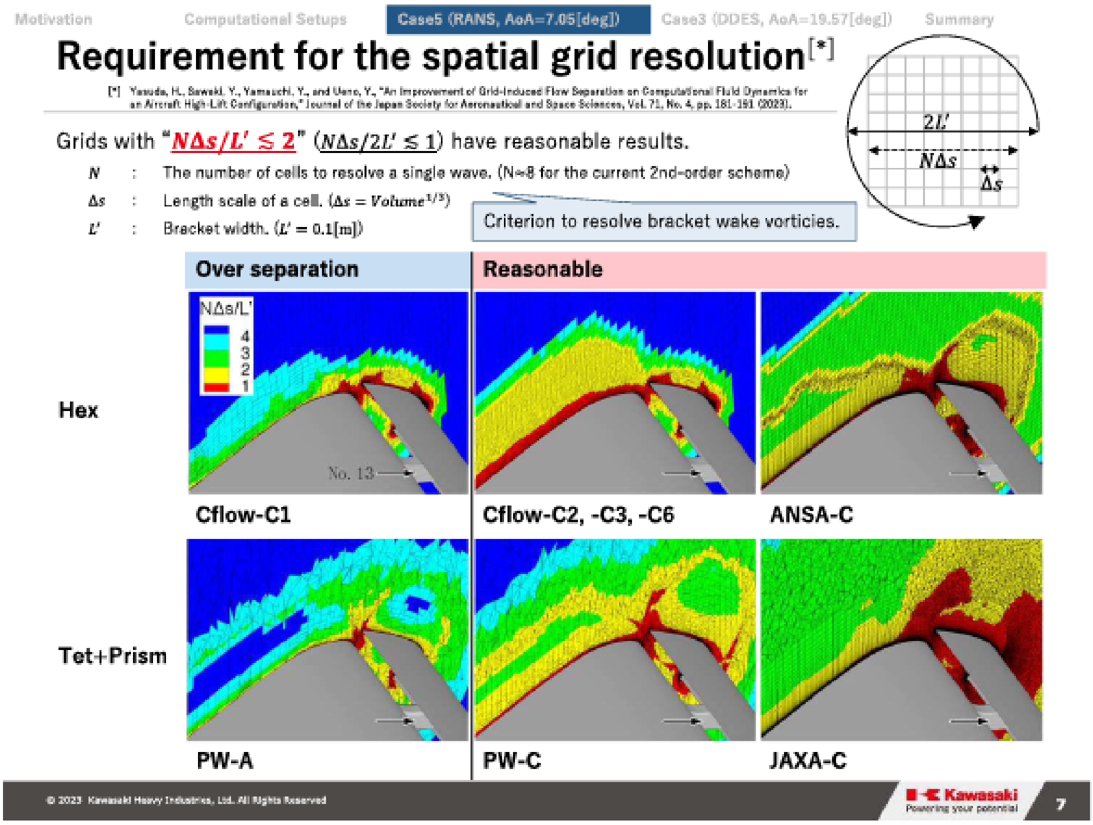
Motivation
Computational Setups
Case5 (RANS, AoA=7.05[deg])
Case3 (DDES, AoA=19.57[deg])
Summary
Requirement for the spatial grid resolution[*]
[*] Yasuda, H., Sawaki, Y., Yamauchi, Y., and Ueno, Y., "An Improvement of Grid-Induced Flow Separation on Computational Fluid Dynamics for an Aircraft High-Lift Configuration," Journal of the Japan Society for Aeronautical and Space Sciences, Vol. 71, No. 4, pp. 181-191 (2023).
Grids with "$N\Delta s/L' \lesssim 2$" ($N\Delta s/2L' \lesssim 1$) have reasonable results.
N : The number of cells to resolve a single wave. (N≈8 for the current 2nd-order scheme)
Δs : Length scale of a cell. ($\Delta s = Volume^{1/3}$)
L' : Bracket width. ($L' = 0.1[m]$)
Criterion to resolve bracket wake vorticies.
$2L'$
$N\Delta s$
Δs
Over separation
Reasonable
NΔs/L'
4
3
2
1
Hex
No. 13
Cflow-C1
Cflow-C2, -C3, -C6
ANSA-C
Tet+Prism
PW-A
PW-C
JAXA-C
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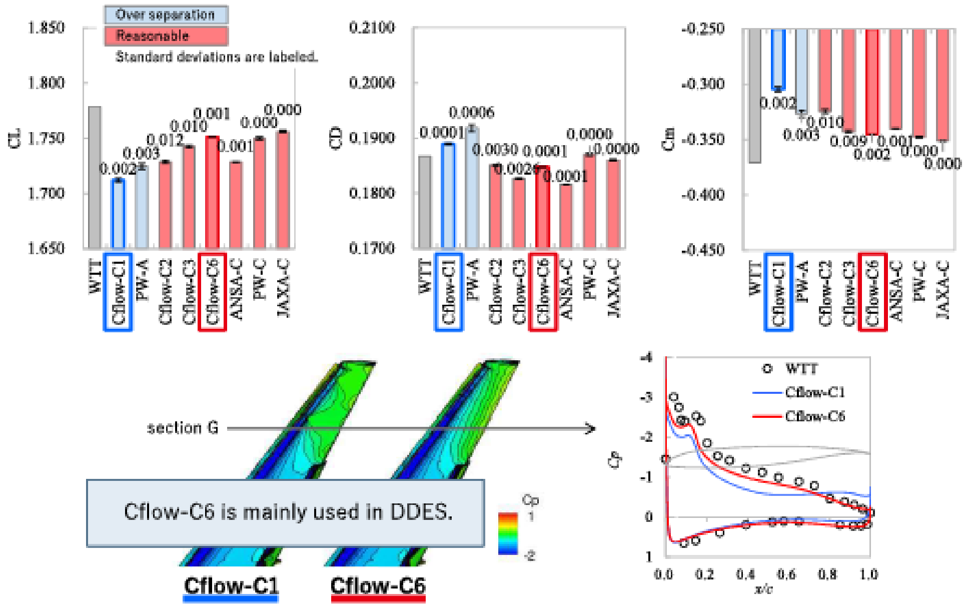
Forces, Moment, Cp distribution

Forces, moment and Cp distribution are improved by bracket-wake mesh refinement.

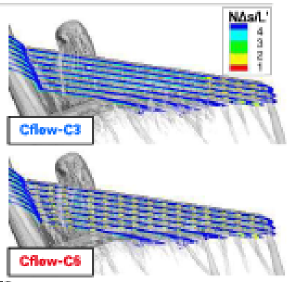


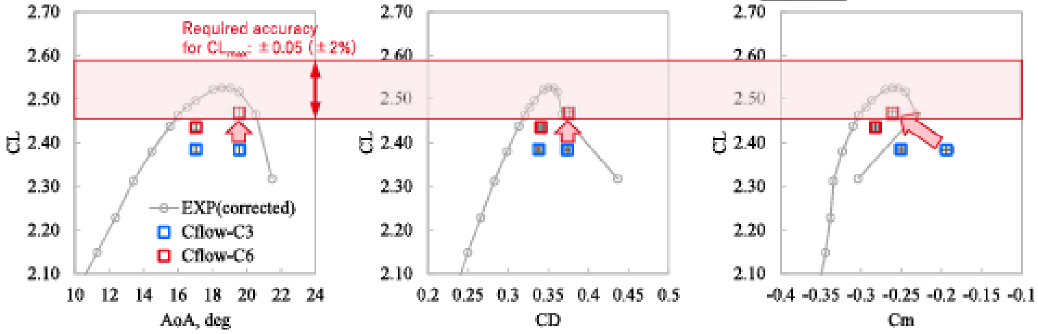
DDES at AoA=19.57[deg]

CL, CD, and Cm of Cflow-C3/-C6 are compared to WTT results.

- Cflow-C3 underestimates CL_{max} by approximately 4%.
- Cflow-C6 has closer results than Cflow-C3.
    - CL improves to the level of the required accuracy (2%).
    - CD and Cm also improve.

→ The bracket wake's grid resolution is important for CL_{max} estimation.





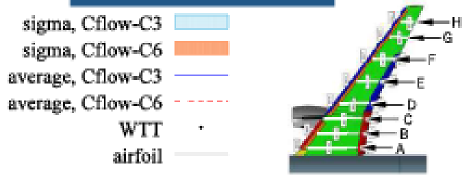
- AoA=17.05[deg] is also shown for Cflow-C3 as a reference.
- CL, CD, and Cm are averaged in 10000step (flow through approximately 2.8*MAC).
- Each CFD result is plotted with standard deviation.

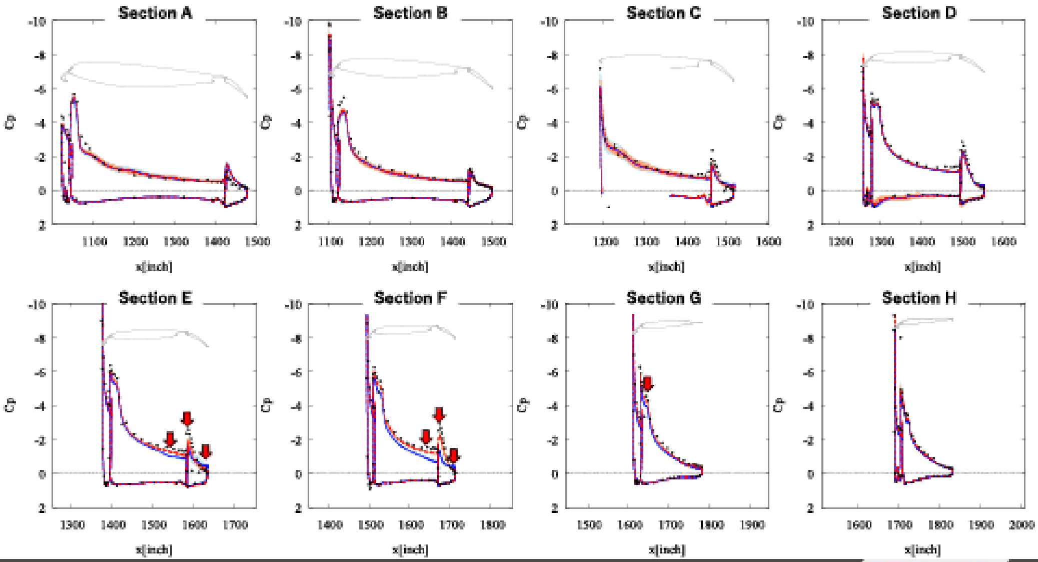
Motivation Computational Setups Case5 (RANS, AoA=7.05[deg]) **Case3 (DDES, AoA=19.57[deg])** Summary

Sectional Cp distribution

Grid dependency is observed at "⬇".

- Cflow-C6 is closer to WTT than Cflow-C3.



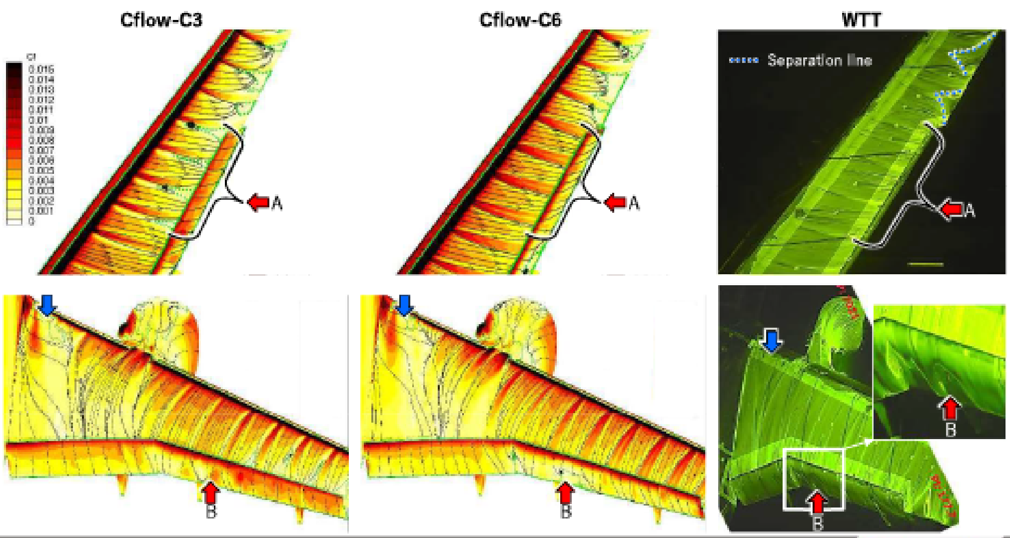


Motivation Computational Setups Case5 (RANS, AoA=7.05[deg]) **Case3 (DDES, AoA=19.57[deg])** Summary

Mean surface flow at AoA=19.57[deg]

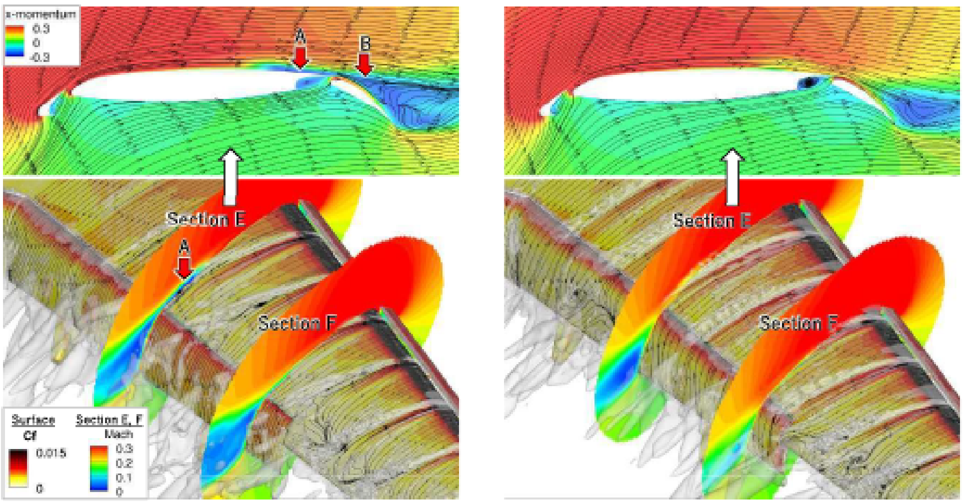
Mean Cf and surface stream line are compared to WTT oilflow.

- Wake refined grid (Cflow-C6) captures flow separation more precisely. (⬅ A, B)
  - Cflow-C3 overestimate flow separation around bracket wakes (A) and underestimate around flap (B).
- Surface flow at LE of wing root does not match WTT. (⬅)



Flow fields around section E, F

- Wake refined grid (Cflow-C6) captures bracket wakes well.
- Bracket wake separation (A) affect flow field over the flap (B).
- Capturing bracket wake is also important for the flow field around the flap.



Cflow-C3　　Cflow-C6

Surface Cf, streamline, Section Mach (E, F), $\lambda 2$ iso-surface

Summary

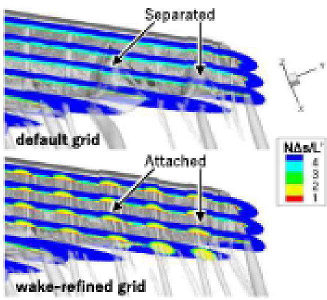
Case 5: Required grid resolution in RANS at AoA=7.05[deg]

- Flow field could be well captured by bracket wake refinement.
- Grids satisfying a criterion "$N\Delta s/L' \lesssim 2$" ($N\Delta s/2L' \lesssim 1$) showed reasonable agreement with the WTT flow fields around the wing tip.

N : The number on cells to resolve a single wave. ($N \approx 8$ for the current 2nd-order scheme)

Δs : Length scale of a cell. ($\Delta s = Volume^{1/3}$)

L' : Bracket width. ($L' = 0.1[\mathrm{m}]$)



Case 3: Grid resolution effects in DDES at AoA=19.57[deg]

- Bracket wake refined grid showed better results for both the aerodynamic coefficients and flow fields.
- The grid resolution criterion seems to be effective for DDES.

Enough grid resolution to capture bracket wakes is important for both RANS and DDES to improve the simulation accuracy.