1A21

Flux-Reconstruction法と壁面モデルを用いたNASA-CRMの低速・高迎角流の非定常解析

Unsteady Flow Analysis for NASA-CRM at Low-speed and High Angle-of-attack Conditions Using Flux-reconstruction Method and Wall-Model

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Objective

- To assess the prediction capability of the state-of-the-art high-order scheme (Split-FR) and the wall-stress model for practical unsteady flows, which is realized by LS-FLOW-HO solver.
- Grid dependency for WMLES
- Overset grid approach to satisfy the grid requirement with minimal increase of grid cells.
- Case 2：Unsteady flow analysis

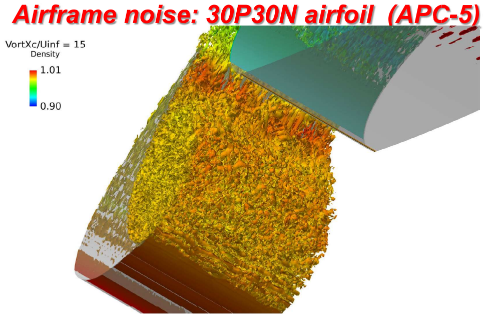
  Flow conditions: $M_\infty = 0.168$, $Re = 1.06 \times 10^6$
  Angle of attack: 11.05 [deg]

Solver: LS-FLOW-HO

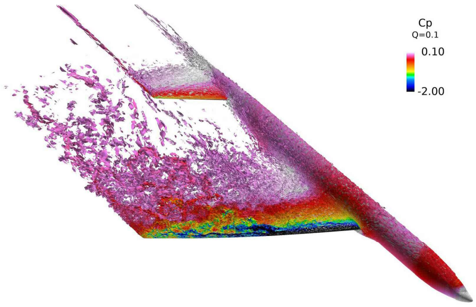
Discretization	**Split-FR (p0-15) [1]**
Inviscid Flux	Roe
Viscous Flux	BR2 $(\eta_{BR2} = 6.0)$
SGS Model	None (Implicit LES)
Time Integration	3rd-order TVD Runge-Kutta
Shock Capturing	LAD [2] (not used in this study)
Wall Stress Model	**Equilibrium BL eqs. [3]**
Parallelism	MPI & OpenMP/OpenACC
Grid	Hex cell, **Overset**

[1] Y. Abe, et al., JCP 353 193-227 (2018)
[2] T. Haga and S. Kawai, JCP 376 534-563 (2019)
[3] T. Haga and S. Kawai, The 31st CFD symposium (2017) (in Japanese)

Airframe noise: 30P30N airfoil (APC-5)

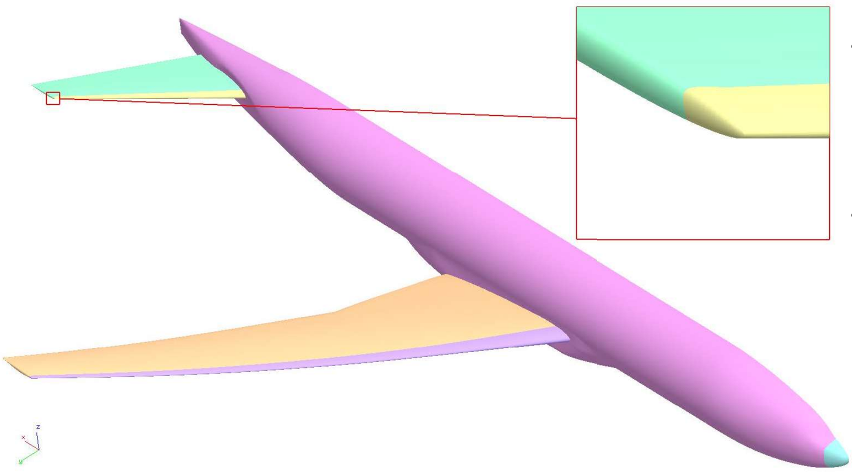


High lift flow WMLES: CRM (APC-6)



Transition Treatment

- According to the locations of trip-dot in the wind-tunnel test, **laminar (no-slip)** or **turbulent (wall-modeled)** BCs are prescribed.

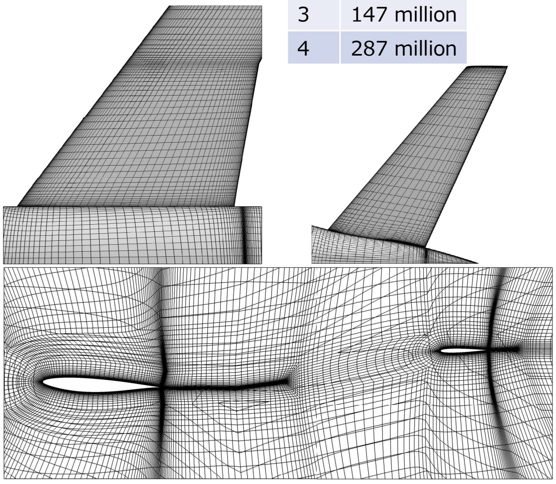


- In Exp.
  - Wings: 10% of each chord length
  - Body: 1.5% of the fuselage length
- In CFD
  - Boundary surface is split by the grid line that is close to the 10% of MAC (wings).

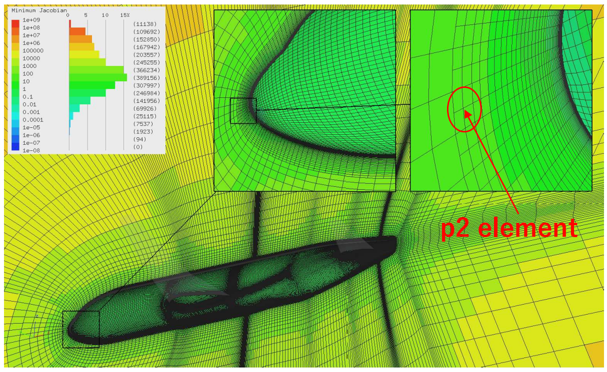
Computational Mesh (Structured)

- Modified the AIAA-DPW4 RNAS mesh (JAXA-Multiblock-Coarse) 2,293,988 cells

P	Points
2	62 million
3	147 million
4	287 million



- Enlarged cell-height for WM: $\frac{\Delta h_{wall}}{c}$ =7.25e-5(y^+<10)
- Each hex was subdivided into 8 hex by ***Pointwise*** Glyph script. (Feature lines are kept exactlly)
- In the near wall (24 layers), the 8 hex were combined into a p2-element by ***QuickMesh***.
  - ➤ p2-p1 mixed mesh in Gmsh format



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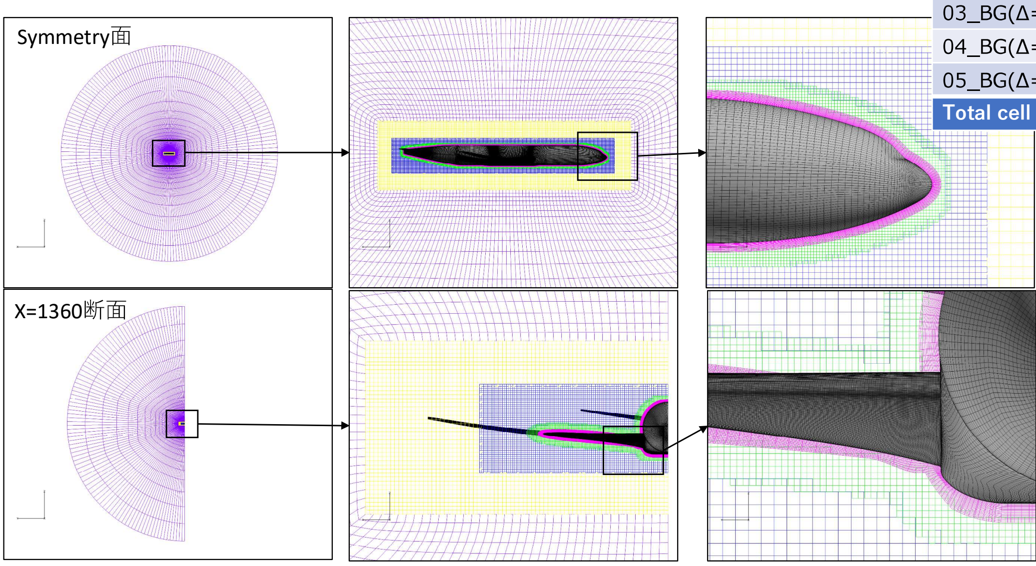
Overset Grid Approach

Overset Grids	Cells
01_Layer(BodyFitted)	1,004,157
02_BG(Δ=5inch)	503,401
03_BG(Δ=7inch)	792,120
04_BG(Δ=20inch)	378,906
05_BG(Δ=40～4000inch)	266,070
Total cell	2,944,654

P	Points
2	111 million
3	264 million



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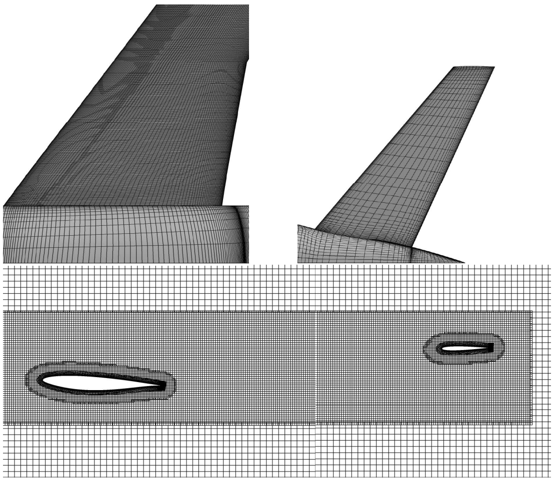
Computational Mesh (Overset)

- Controlled grid resolution for the layer grid (body-fitted)

LE: x/c~0.1: h_w =0.2 δ_{max}/c_{MAC}



Grid Requirements by Prof. Larsson
https://wmles.umd.edu/wall-stress-models/grid-requirements/

APC7

$$\Delta x \lesssim \begin{cases} 0.05\delta\text{–}0.10\delta & \text{, outer layer} \\ 0.6h_{\mathrm{wm}}\text{–}1.0h_{\mathrm{wm}} & \text{, log – layer} \end{cases}$$

APC6

$$\Delta y \lesssim \begin{cases} 0.01\delta\text{–}0.04\delta & \text{, outer layer} \\ 0.2h_{\mathrm{wm}}\text{–}0.3h_{\mathrm{wm}} & \text{, log – layer} \end{cases}$$

$$\Delta z \lesssim \begin{cases} 0.04\delta\text{–}0.08\delta & \text{, outer layer} \\ 0.4h_{\mathrm{wm}}\text{–}0.8h_{\mathrm{wm}} & \text{, log – layer} \end{cases}$$

FR-p3 was validated for parallel channel flow
$\Delta x_e/\delta \approx 0.08, \Delta y_{\min,e}/\delta \approx 0.02, \Delta z_e/\delta \approx 0.05$

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Cases and Costs

JAXA 4.32% scale model: C_{ref}=0.30262 [m], Flow through time: $C_{\mathrm{ref}}/U_\infty$=0.005104 [s]

Case	Grid	$h_{\mathrm{smp}}/C_{\mathrm{ref}}$	$\Delta t \cdot a_\infty/C_{\mathrm{ref}}$	Timesteps for $10\,C_{\mathrm{ref}}/U_\infty$	Cores (CPUs) Fujitsu FX1000	Actual elapse time [hours] for (X $C_{\mathrm{ref}}/U_\infty$)	Estimated elapse time [hours] for $10\,C_{\mathrm{ref}}/U_\infty$	Restart
P2 w/ WM	Str-2020	5.0e-4	3.0e-6	1.98e+7	4096 (128)	282 (7.46)	378	Uniform
P3 w/ WM	Str-2021	2.0e-3	↑	↑	12288 (256)	325 (6.05)	537	Uniform
P4 w/ WM	↑	↑	↑	↑	12288 (256)	368 (4.23)	868	From p3
P2 w/ WM	Overset	4.0e-3	1.2e-4	4.95e+5	12000 (250)	27.9 (9.07)	30.8	Uniform
P3 w/ WM	↑	↑	0.8e-4	7.43e+5	12000 (250)	35.0 (3.76)	93.0	Uniform

Str-2021
- Enlarged minimum edge length : slight larger dt than APC6
- Higher h_w : based on the BL thickness from p3-WM result.

Overset grid
- 26.6-40 times larger dt than Str-2021

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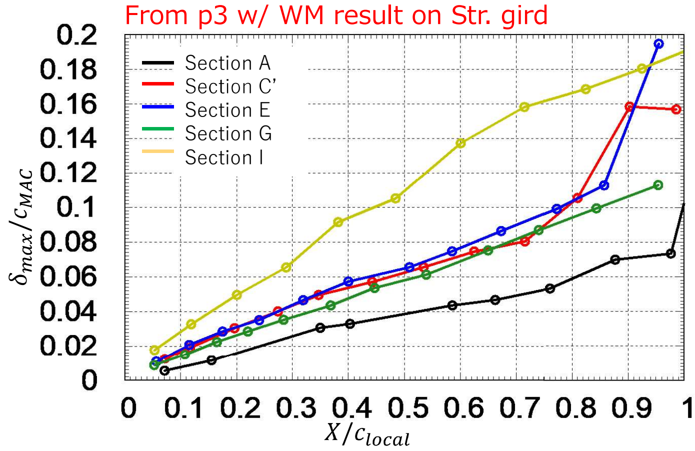
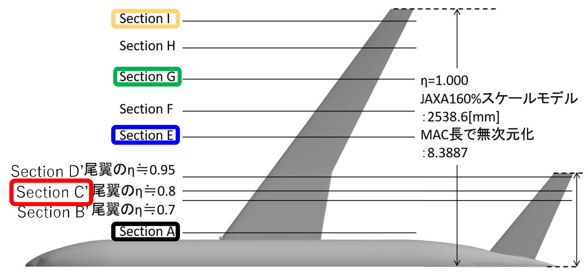
Boundary Layer Thickness

From p3 w/ WM result on Str. gird





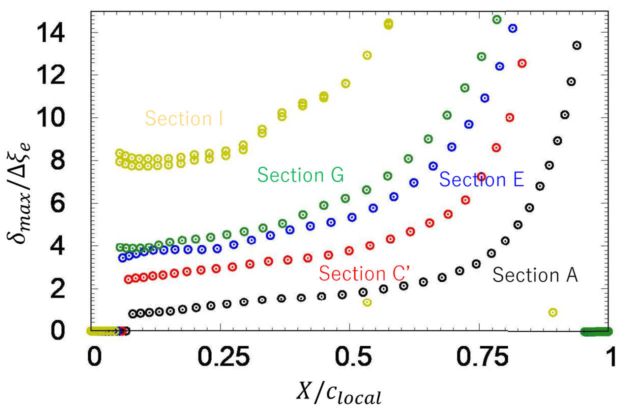
Estimated boundary layer thickness

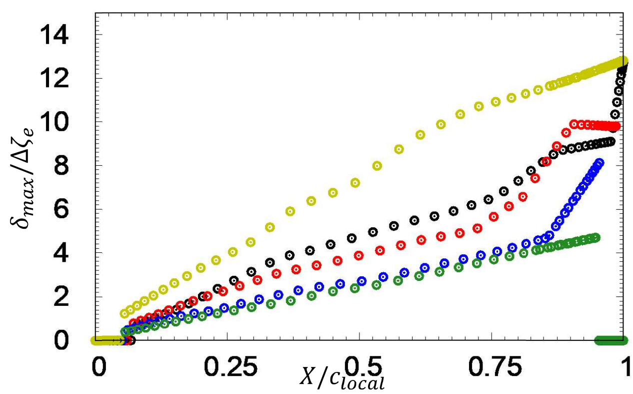
- LE (x/c~0.1): δ_{max}/c_{MAC} ~0.02
- TE (x/c~1.0): δ_{max}/c_{MAC} ~0.1

WM sampling point（loosened grid requirement）

- LE (x/c~0.1): 0.2 δ_{max}/c_{MAC}
- TE (x/c~1.0): 0.1 δ_{max}/c_{MAC}

Effective resolutions in parallel directions

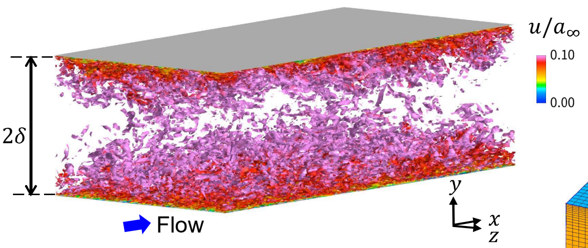


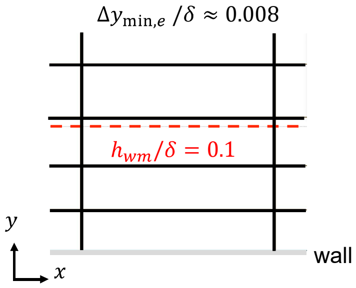


WMLES on very coarse grids

Coarse Grid WMLES(Channel flow)

- $M_b = 0.3$, $Re_\tau \approx 5{,}200$ Lee and Moser (2015)

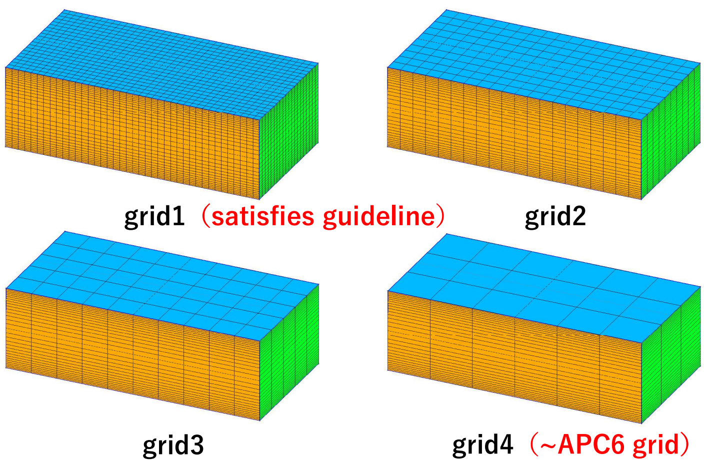




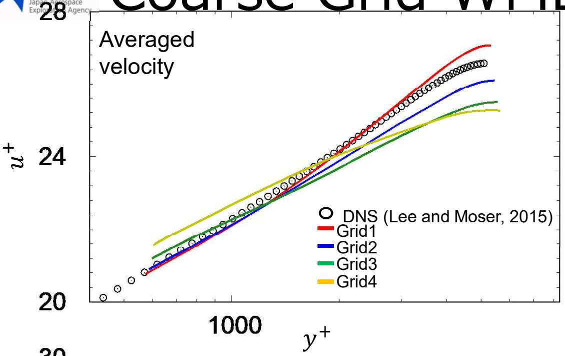
h_{wm}/δ and grid lines

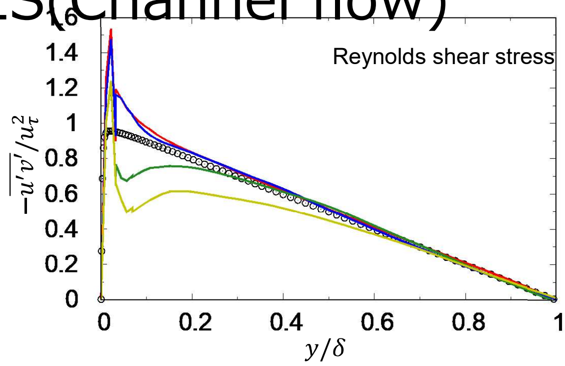
	$\Delta x_e/\delta$	$\Delta y_e/\delta$	$\Delta z_e/\delta$	$\delta/\Delta x_e = \delta/\Delta z_e$
grid1	0.04	0.008-0.029	0.04	25
grid2	0.08	0.008-0.029	0.08	12.5
grid3	0.16	0.008-0.029	0.16	6.25
grid4	0.32	0.008-0.029	0.32	3.75
Larsson et al. (2016)	≲0.05-0.1	≲0.01-0.04	≲0.04-0.08	

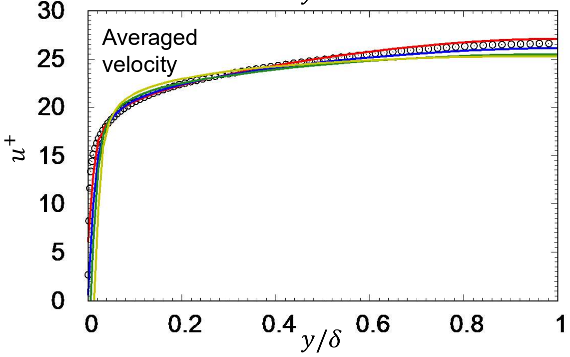
Subscript e indicates effective resolution : grid cell size is divided by the number of solution point 4 (p3 scheme).



Coarse Grid WMLES(Channel flow)







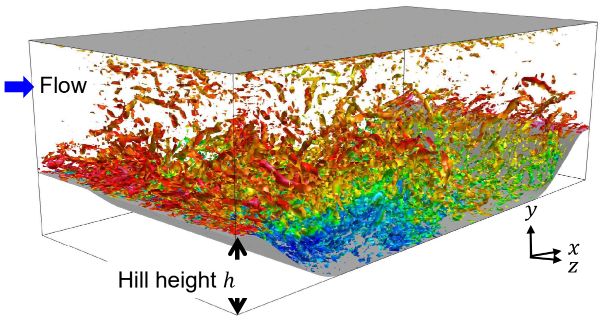
Grid information for channel flow

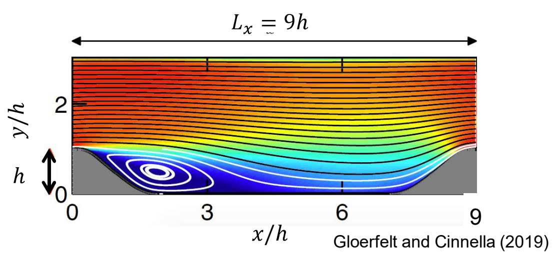
	$\Delta x_e/\delta$	$\Delta y_e/\delta$	$\Delta z_e/\delta$	$\delta/\Delta x_e = \delta/\Delta z_e$	C_f (DNS: 3.44×10^{-3})
grid1	0.04	0.008-0.029	0.04	25	3.39×10^{-3}
grid2	0.08	0.008-0.029	0.08	12.5	3.55×10^{-3}
grid3	0.16	0.008-0.029	0.16	6.25	3.65×10^{-3}
grid4	0.32	0.008-0.029	0.32	3.125	3.70×10^{-3}
Larsson et al. (2016)	≲0.05-0.1	≲0.01-0.04	≲0.04-0.08		

Subscript e indicates effective resolution : grid cell size is divided by the number of solution point 4 (p3 scheme).

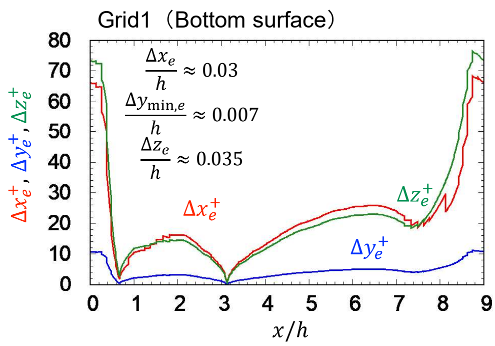
Coarse Grid WMLES(periodic hill)

- $u_b = 0.2$, $Re_h \approx 37{,}000$ Gloerfelt and Cinnella (2019)
- $h_{wm}/h = 0.1$





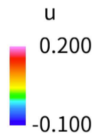
Gloerfelt and Cinnella (2019)

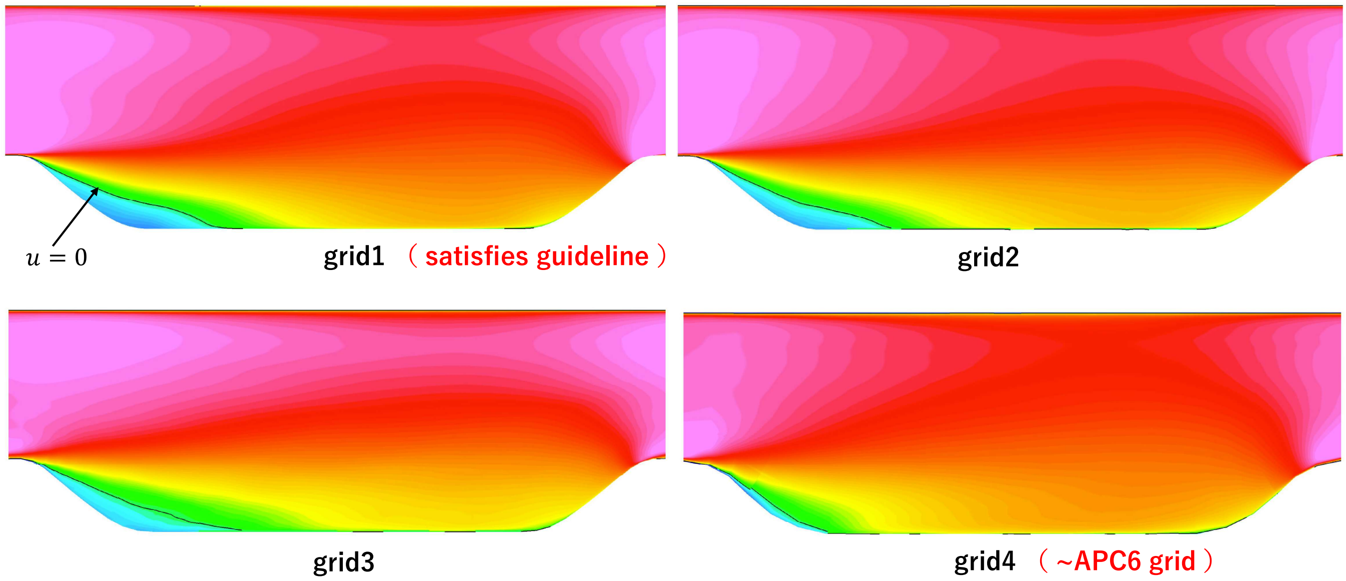


	$\Delta x_e/h$	$\Delta y_{\min,e}/h$	$\Delta z_e/h$	$h/\Delta x_e$	$h/\Delta z_e$
grid1	0.03	0.007	0.035	33.3	28.5
grid2	0.06	0.007	0.07	16.6	14.3
grid3	0.12	0.007	0.14	8.3	7.1
grid4	0.24	0.007	0.28	4.15	3.55
Larsson et al. (2016)	≲0.05-0.1	≲0.01-0.04	≲0.04-0.08		

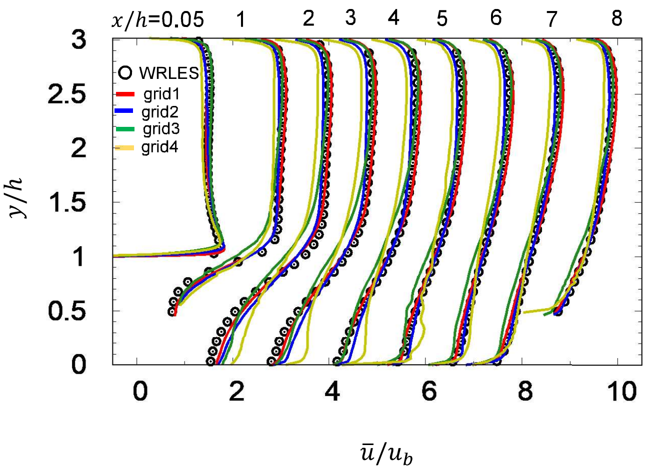
Subscript e indicates effective resolution : grid cell size is divided by the number of solution point 4 (p3 scheme).

Coarse Grid WMLES(periodic hill)

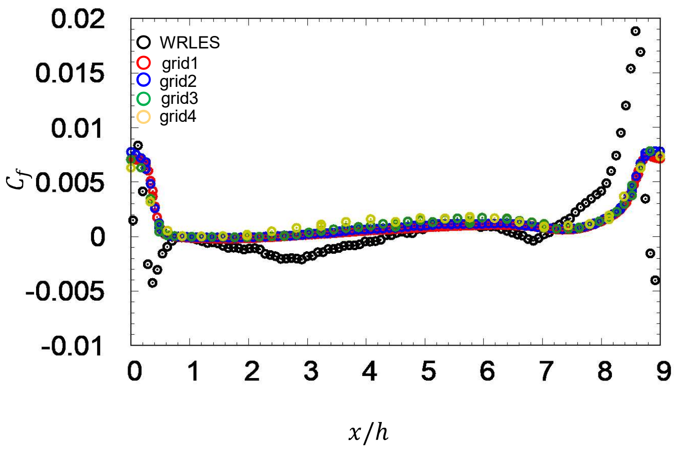




Coarse Grid WMLES(periodic hill)



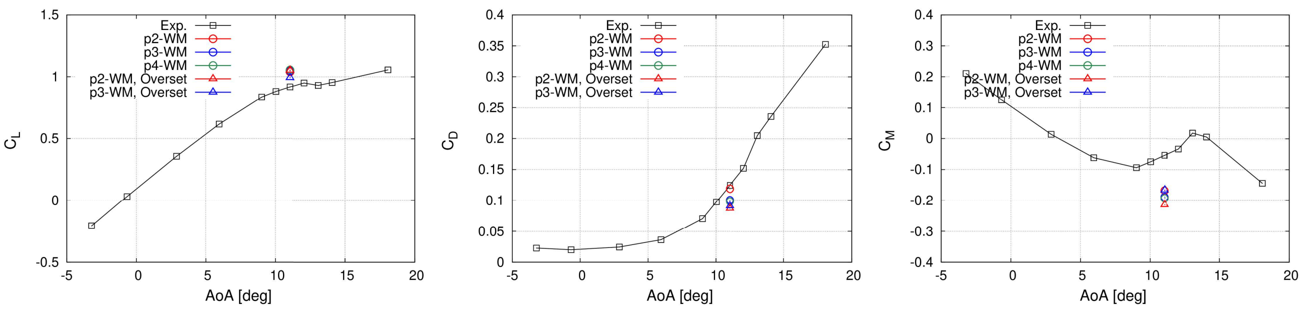
・Velocity profile: grid1 agrees well with WRLES



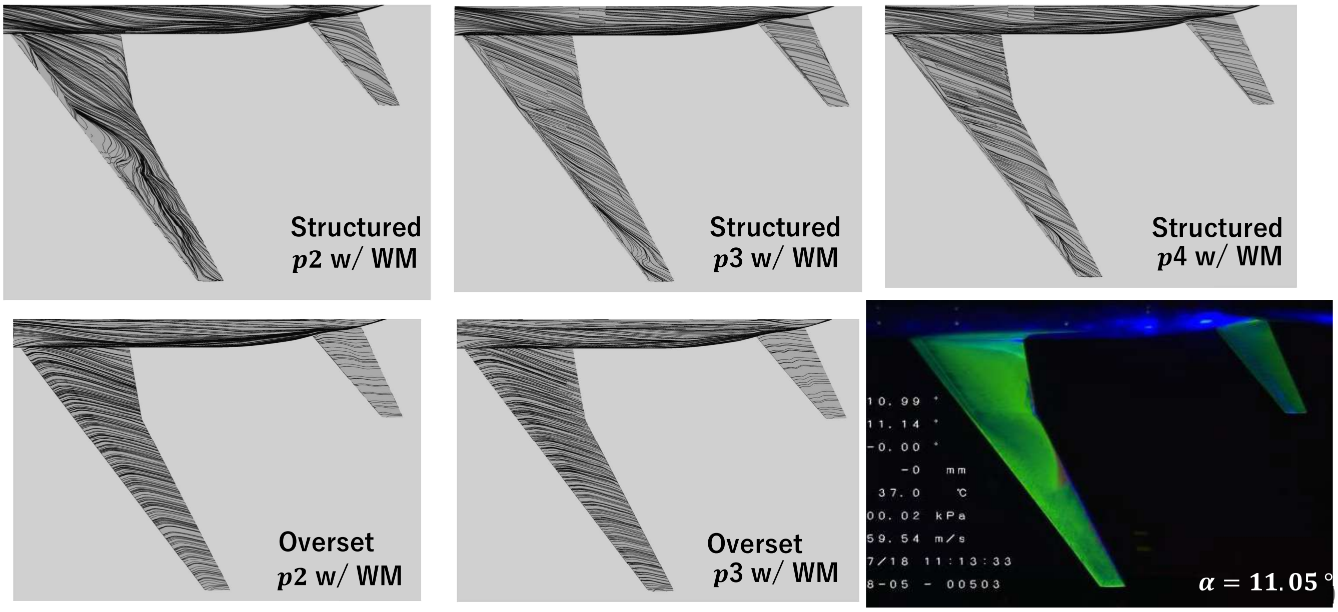
・Skin friction: discrepancy between WMLES and WRLES. Need improvement of the wall-model for separated flows.

APC7 Results

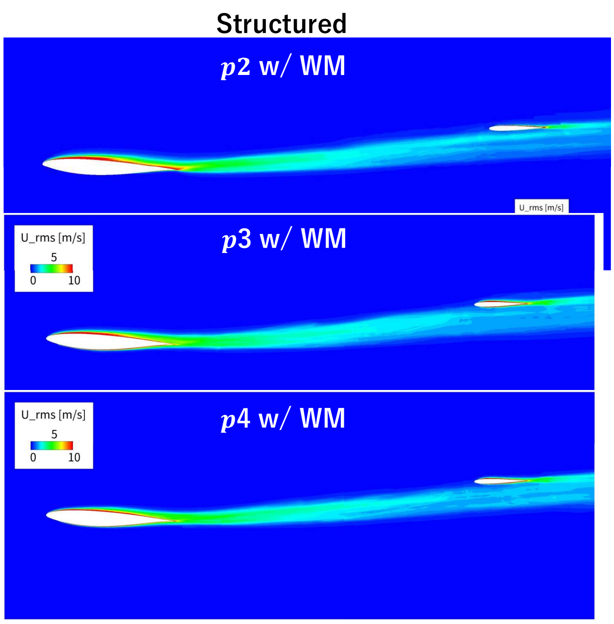
Force Coefficients (Averaged)

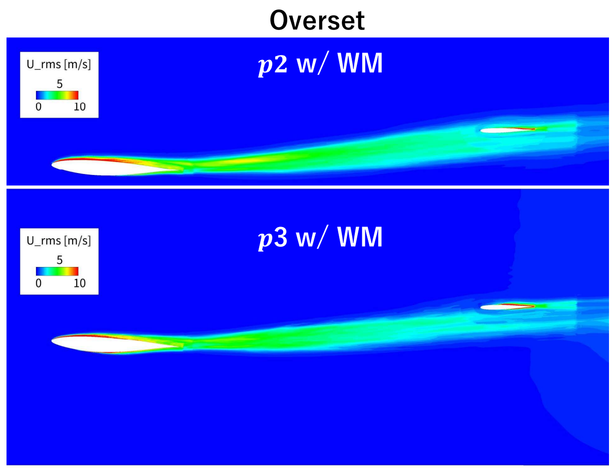


Oil Flow (Comparison with Exp.)



U-rms (Section HA)





- Main wing: smaller U-rms with higher resolution.
- Tail wing: Difference between Str. vs Overset (same surface grid but larger cell height in overset).

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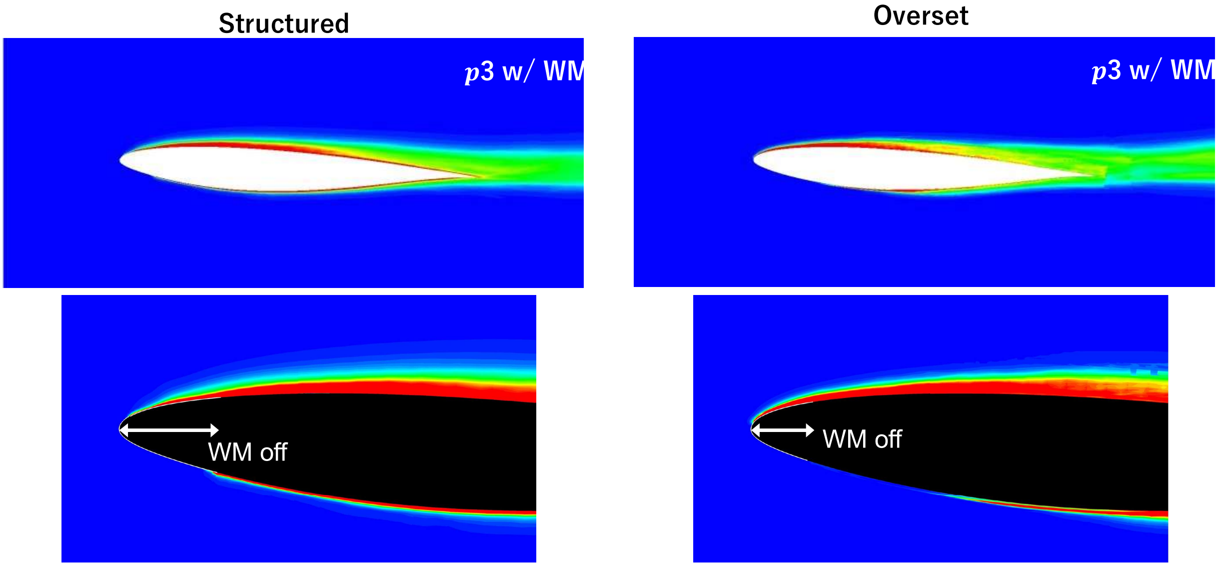
U-rms near main wing (Section HA)



- Width of laminar B.C. depends on the grid surface. (split by a grid line close to 10% of MAC)
- Higher U-rms near L.E. on overset grid（due to insufficient grid resolution?）

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Summary

- Robust WMLES computations for CRM were performed by LS-FLOW-HO（upto p4 (5^{th}-order), no parameter tuning of the scheme).
- Grid dependency for WMLES was studied especially for very coarse grids. The following trend was observed:
  - Overestimate of Cf for channel flow case
  - Small separation for periodic hill case
- Overset grid is very effective to reduce total grid cells while keeping the grid requirement
- Reasonable CL, CD prediction comparing to RANS results in APC6. Slight improvement by Overset-p3 case.
- Difficult to predict oil flows in the present cases. (No separation by Overset results) Further grid dependency study is needed (strictly satisfy the guideline, near LE?)
  - h/p adaptive solver will be more effective?

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Acknowledgments

- JAXA Supercomputing System (JSS3) was used for the computations.
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