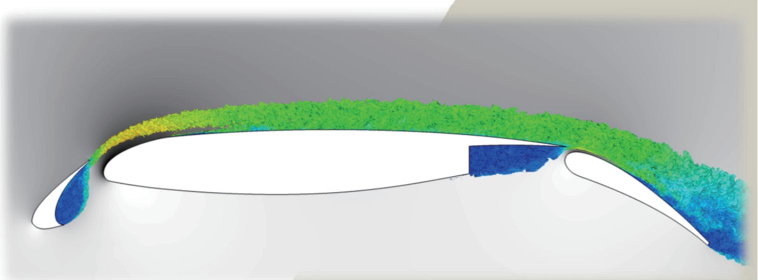
2018.07.04 @ Miyazaki Citizen's Plaza

4th Aerodynamics Prediction Challenge

Validation of aerodynamic characteristics around 3-element high-lift configuration using Cflow

Cflowによる三翼素高揚力翼型の空力特性検証解析

Hidemasa Yasuda, Yosuke Ueno, Akio Ochi
Kawasaki Heavy Industries, Ltd.
Aerospace Systems Company



18KT011417

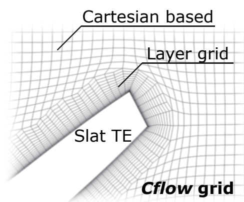
Kawasaki
Powering your potential

Introduction of "*Cflow*"

Kawasaki original CFD tool

Cflow = Grid Generator + Flow Solver

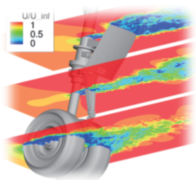
Cartesian based AMR
+layered grid



highly complicated | unsteady | large-scale

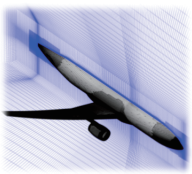
- *Cflow* has been validated in various workshops.

2010-2016
BANC I-IV



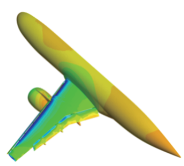
* Unsteady flow
* Complicated geometry gridding

2016
DPW6



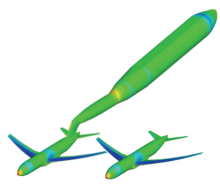
* Cruise drag

2013, 2017
HiLift-PW1, 3



* Low speed & high-lift aero

2015-2017
APC-I, II, III



* High speed aero
* WTT data correction
* Re number effect

 18KT011417 Kawasaki Powering your potential 2

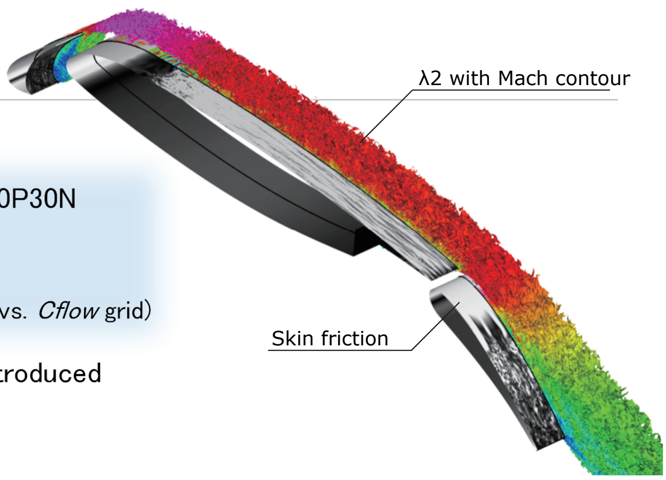
KHI's Participation on the APC-IV

Grid \ Subject		30P30N 2D Steady Sub.1-1	30P30N 2.5D Steady Sub.1-2	30P30N 2.5D Unsteady Sub.1-3 /Sub.3	30P35N 2D Steady Sub.2-1	30P35N 2.5D Steady Sub.2-2	30P35N 2.5D Unsteady Sub.2-3
Provided	L1 (Coarse)		5.5/9.5/14	5.5/9.5		5.5	5.5
Provided	L2 (Medium)	α-sweep	α-sweep	5.5/9.5	5.5	5.5	5.5
Provided	L3 (Fine)	α-sweep	α-sweep*1	5.5	5.5	5.5	5.5
Provided	L4 (Ex. Fine)						
Provided	L5 (Su. Fine)						
Cflow	Cflow-L2 (M)		α-sweep*1	5.5/9.5		5.5	5.5
Cflow	Cflow-L3 (F)		5.5				

Annotations: 2D .vs. 2.5D; Flap angle; Grid density; Steady .vs. Unsteady; Grid dependency

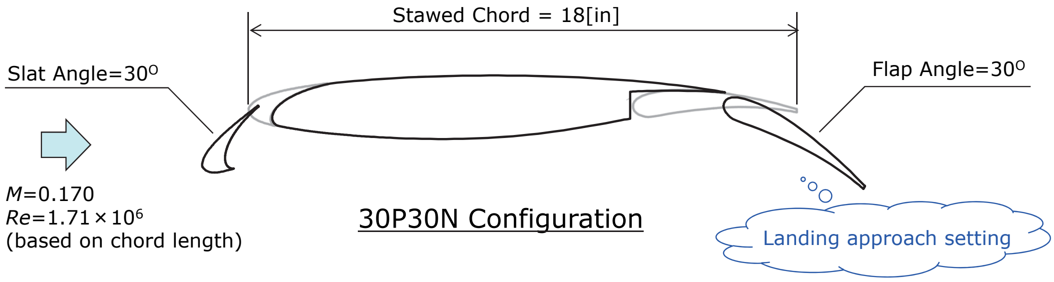
*1 Requested AoA only

Outline



Following topics will be presented.

- Aerodynamic characteristics of 30P30N predicted using *Cflow*.
  - Steady .vs. Unsteady
  - Grid dependency (Provided grid .vs. *Cflow* grid)
- Result of noise analysis will be introduced in the next presentation.



30P30N Configuration

Summary of Code and Numerics Used

	***Cflow* Solver methods**
Governing Equations	**RANS** (Raynolds Averaged Navier-Stokes equations)
Spatial Discretization	Cell-centerd finite volume method with pseudo 3rd-order accurate reconstruction based on MUSCL
Inviscid Flux	**SLAU** (Simple Low-dissipation AUSM scheme)
Viscous Flux	2nd-order accurate central difference
Time Integration	MFGS (Matrix Free Gauss Seidel) implicit method (2nd order for unsteady computation)
Turbulence Model	**SA-noft2** / **DDES** (Sub grid scale = Δ_{max})

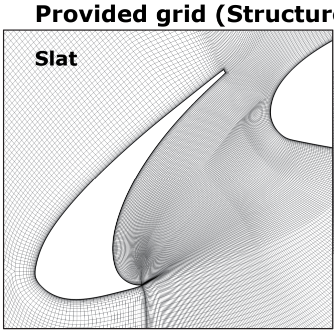
■ Reference for *Cflow* details

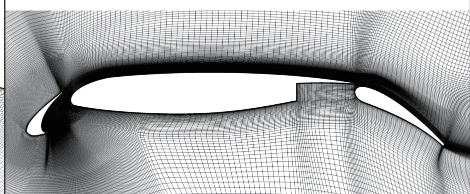
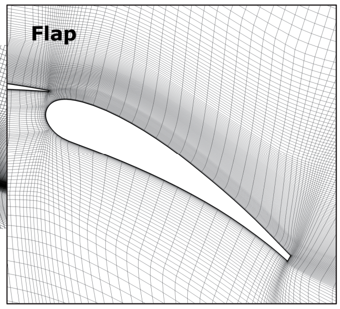
1. Nagata, T., Ueno, Y., and Ochi, A., "*Validation of new CFD tool using Non-orthogonal Octree with Boundary-fitted Layer Unstructured Grid,*" 50th AIAA Aerospace Sciences Meeting, (AIAA 2012-1259).
2. Ueno, Y., Nagata, T., and Ochi, A., "*Aeroacoustic Analysis of the Rudimentary Landing Gear Using Octree Unstructured Grid with Boundary-fitted Layer,*" 18th AIAA/CEAS Aeroacoustics Conference, (AIAA 2012-2284).
3. Yasushi Ito, Mitsuhiro Murayama, Atsushi Hashimoto, Takashi Ishida, Kazuomi Yamamoto, Takashi Aoyama, Kentaro Tanaka, Kenji Hayashi, Keiji Ueshima, Taku Nagata and Akio Ochi, "*TAS Code, FaSTAR and Cflow Results for the Sixth Drag Prediction Workshop,*" 55th AIAA Aerospace Sciences Meeting, AIAA SciTech, (AIAA 2017-0959).
4. Atsushi Hashimoto, Takashi Aoyama, Yuichi Matsuo, Makoto Ueno, Kazuyuki Nakakita, Shigeru Hamamoto, Keisuke Sawada, Kisa Matsushima, Taro Imamura, Akio Ochi, and Minoru Yoshimoto. "*Summary of First Aerodynamics Prediction Challenge (APC-I)*", 54th AIAA Aerospace Sciences Meeting, AIAA SciTech, (AIAA 2016-1780).

Sub.1-2, 3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 / *Cflow* L2 Solver=*Cflow*

Computational Grid

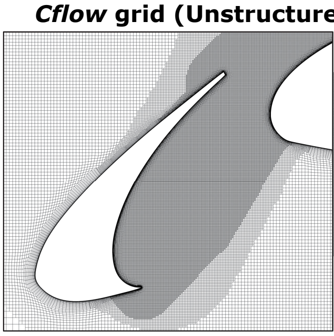
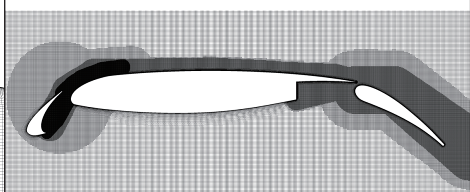
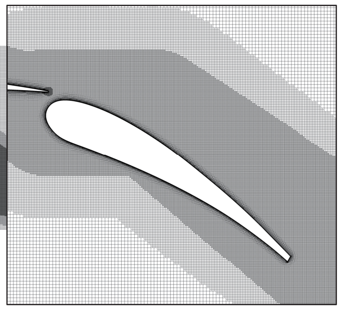
Provided grid (Structured)



nCell = 20.2 mln.
$y_1^+{}_{avg}$~0.5
Slat TE : 8 cells
Surf Δx_{min}=0.07%c

***Cflow* grid (Unstructured, Cartesian-based)**

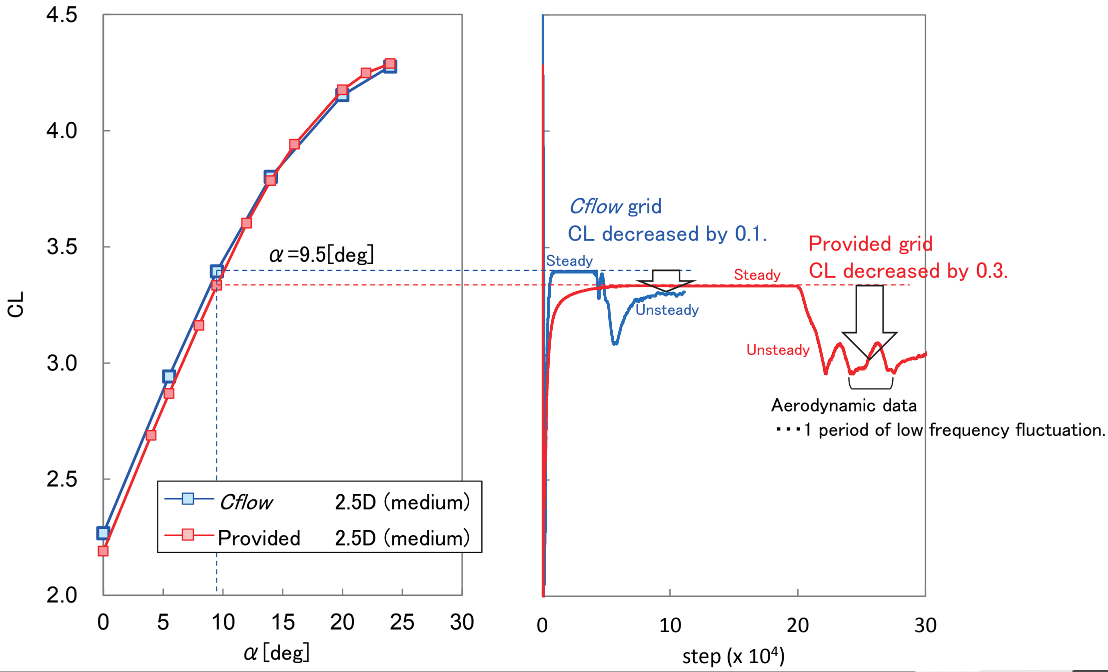




nCell = 61.0 mln.
$y_1^+{}_{avg}$~0.5
Slat TE : 6 cells
Surf Δx_{min}=0.04%c

Sub.1-2, 3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 / *Cflow* L2 Solver=*Cflow*

Steady .vs. Unsteady – CL

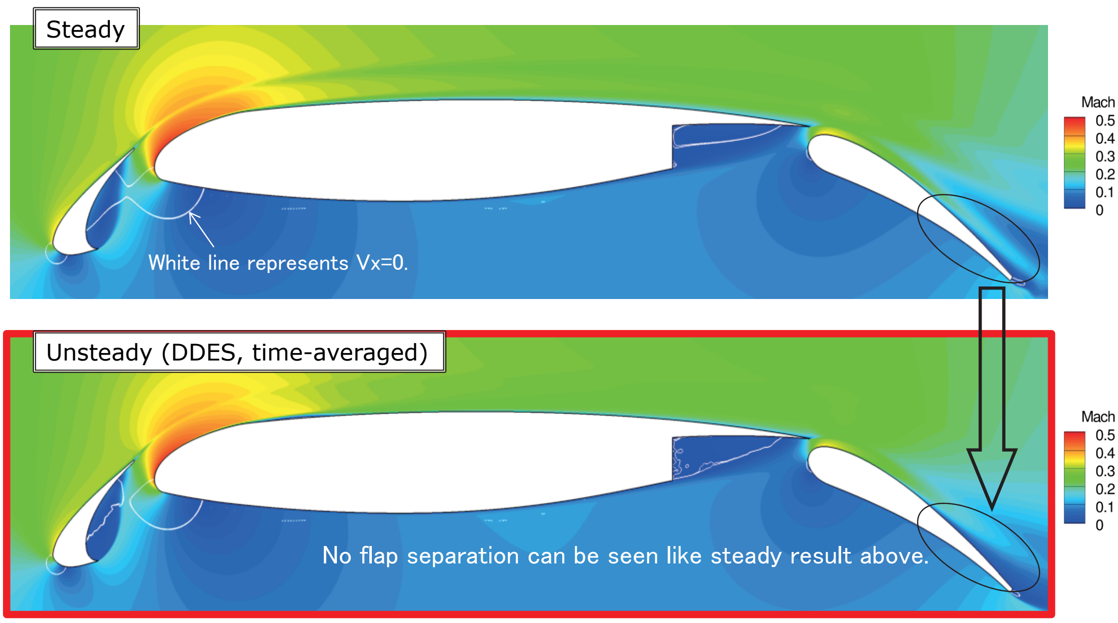
Lift curve (Steady) / Time history of CL



Sub.1-2, 3 30P30N 2.5D Steady / Unsteady Grid=*Cflow* L2 Solver=*Cflow*

Steady .vs. Unsteady – Mach, *Cflow* grid

α=9.5[deg]



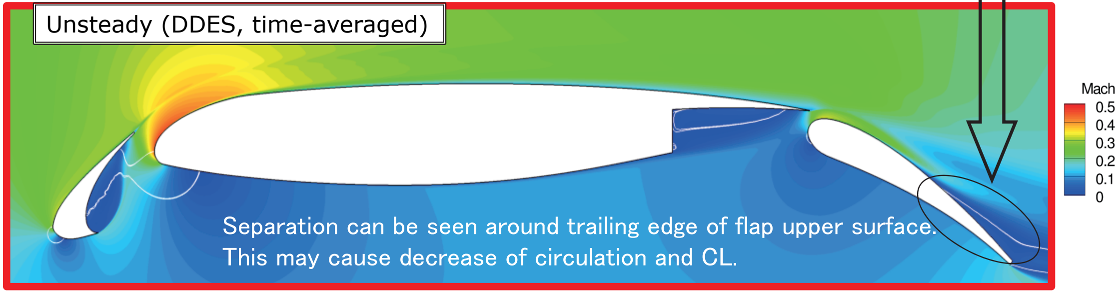
Sub.1-2, 3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 Solver=*Cflow*

Steady .vs. Unsteady – Mach, Provided grid

α=9.5[deg]

Steady

Unsteady (DDES, time-averaged)

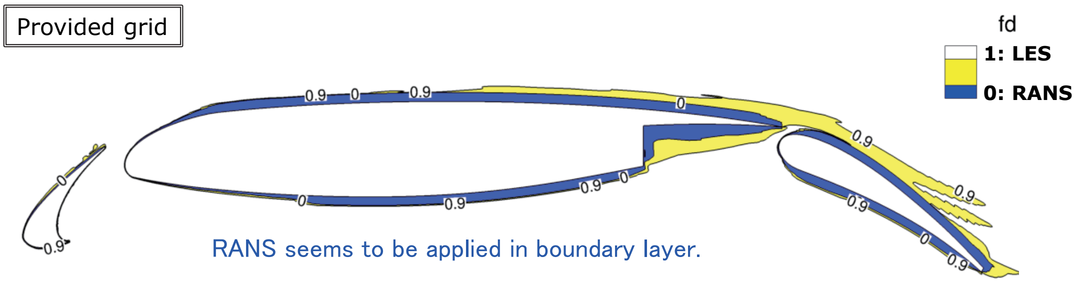


Sub.1-3 30P30N 2.5D Unsteady Grid=Provided L2 / *Cflow* L2 Solver=*Cflow*

Grid Dependency – RANS/LES region

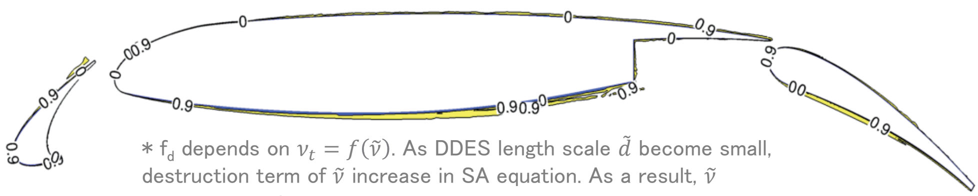
α=9.5[deg] (instantaneous result)

Provided grid



Cflow grid

Cflow has less RANS region and LES is applied to almost all region.
WMLES-like approach?

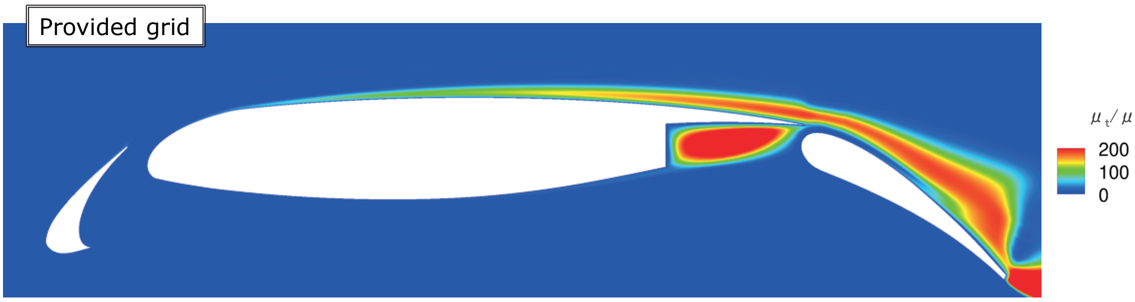


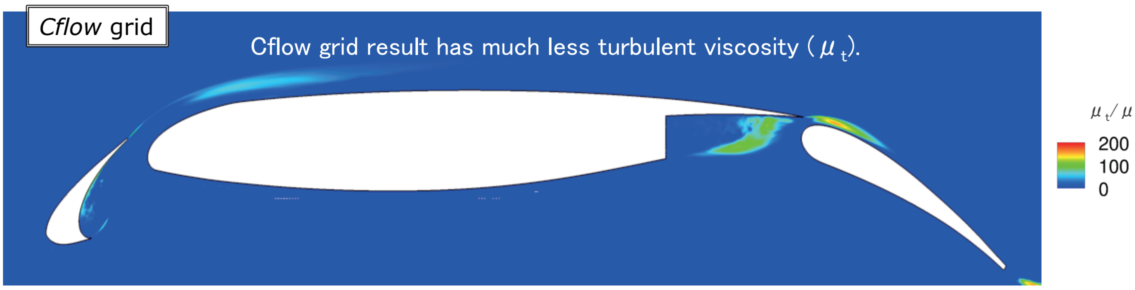
* f_d depends on $\nu_t = f(\tilde{\nu})$. As DDES length scale $\tilde{d}$ become small, destruction term of $\tilde{\nu}$ increase in SA equation. As a result, $\tilde{\nu}$ decrease and f_d approaches unity.
DDES length scale $\tilde{d} = d - fd * \max(0, Cdes * \Delta_{max})$

Sub.1-3 30P30N 2.5D Unsteady Grid=Provided L2 / *Cflow* L2 Solver=*Cflow*

Grid Dependency – μ_t/μ Modeled turbulence in RANS

α=9.5[deg] (time-averaged)



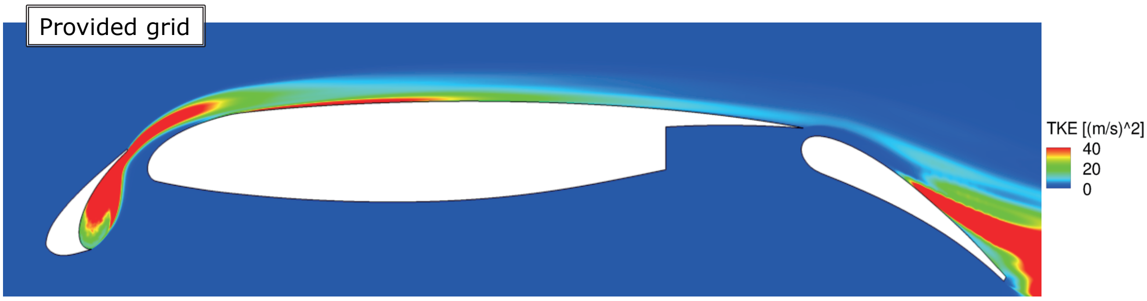


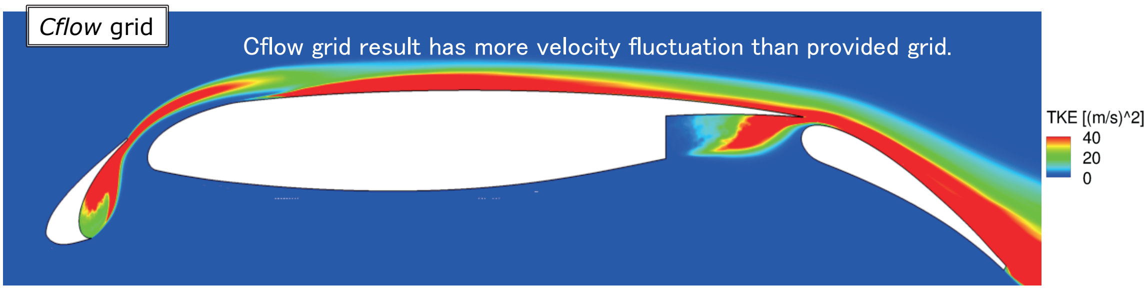
Sub.1-3 30P30N 2.5D Unsteady Grid=Provided L2 / *Cflow* L2 Solver=*Cflow*

Grid Dependency – TKE* Resolved turbulence in RANS

＊Turbulent Kinetic Energy

α=9.5[deg]





Sub.1-2, 3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 Solver=*Cflow*

Steady .vs. Unsteady – Provided grid

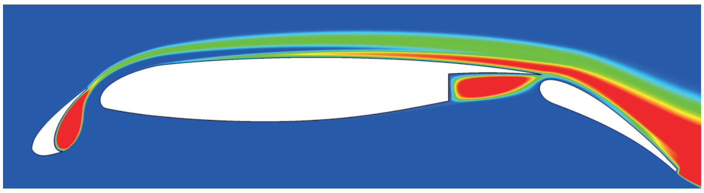
＊Turbulent Kinetic Energy

α=9.5[deg]

Steady

SA-noft2

μ_t/μ

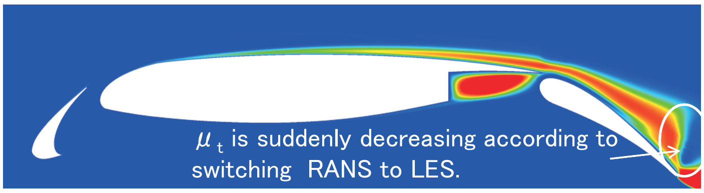


μ_t/μ: 200, 100, 0

Unsteady

DDES

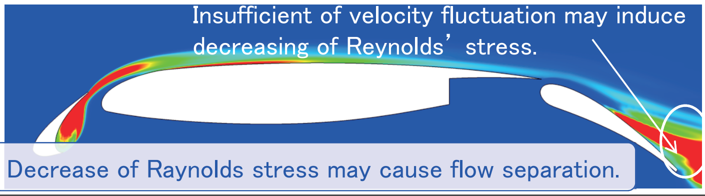
μ_t/μ



μ_t/μ: 200, 100, 0

RANS $\tau_{ij} = 2\frac{\mu_t}{\rho}S_{ij}$

TKE



TKE [(m/s)^2]: 40, 20, 0

LES $\tau_{ij} = -\rho\overline{u_i' u_j'}$

Summary

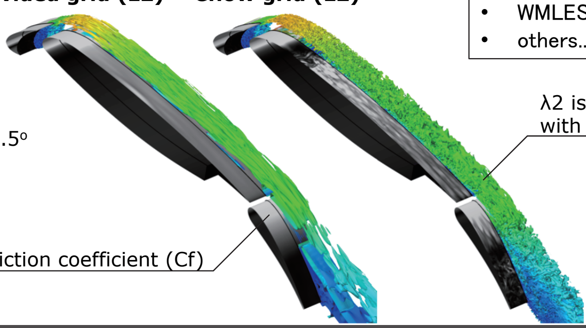
- CL decreased in DDES (unsteady) analysis started from RANS (steady) result.
  - In the unsteady analysis, provided grid had flow separation on the flap upper surface, while *Cflow* grid result had no flap separation like steady result.
  - Velocity fluctuation seemed insufficient in the provided grid result, which caused decrease of Reynolds stress and induce flow separation.

It seemed important to transfer Reynolds stress properly at the boundary between RANS and LES in the DDES approach.

Possible solutions
- Modify/adjust f_d function (e.g. DDES-p)
- Give velocity fluctuation at RANS/LES boundary
- WMLES
- others... modeling or resolving flow field.

Provided grid (L2) **Cflow grid (L2)**

α=9.5°



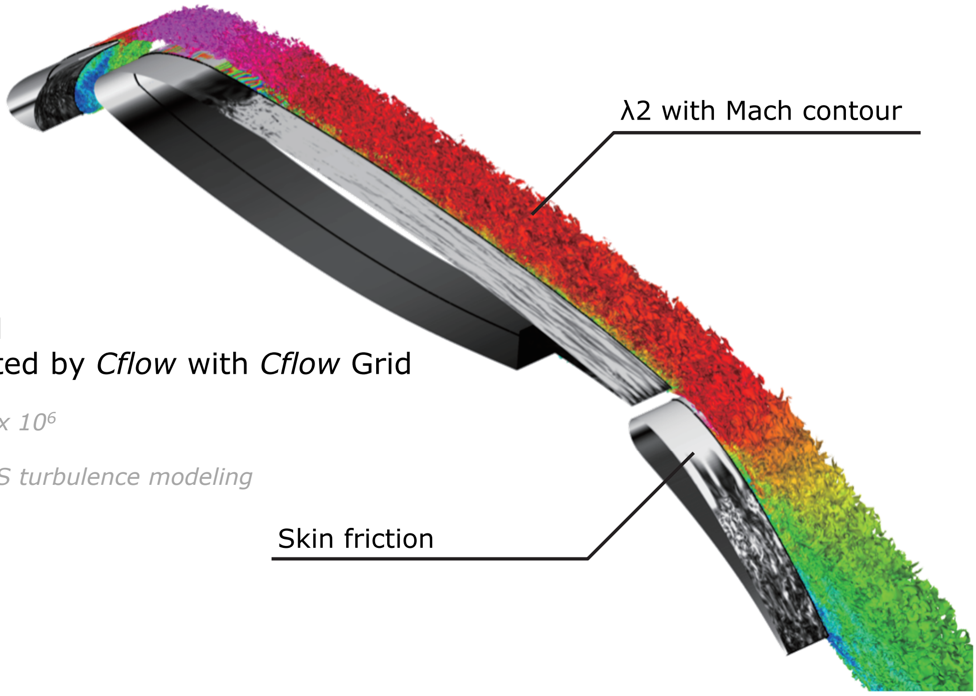
λ2 iso surface (0.01) with Mach contour

Skin friction coefficient (Cf)

Cf: 0.01, 0

Mach: 0.5, 0

Thank you for your attention!



30P30N
Computed by *Cflow* with *Cflow* Grid
M=0.170
Re=1.71 x 10^6
AoA=5.5º
SA / DDES turbulence modeling

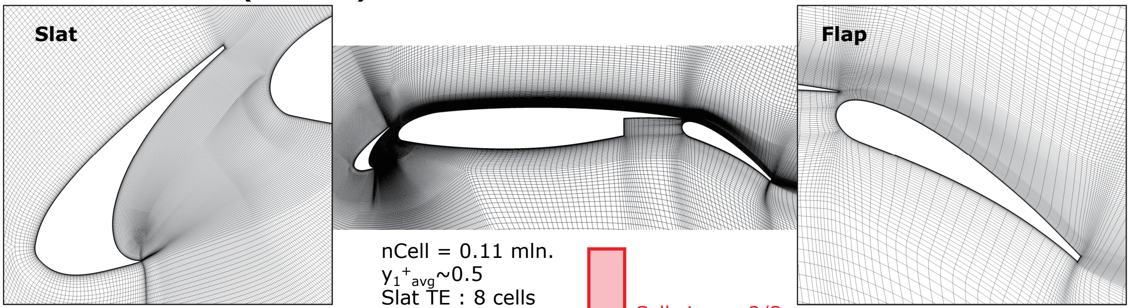
Appendix

1. Effect of Grid Resolution (30P30N, Provided Grid)
2. 2D .vs. 2.5D (30P30N, Provided Grid)
3. Grid Dependency – Steady Analysis (30P30N, Cflow Grid)
4. Unsteady Analysis (30P30N/30P35N, Cflow Grid)

Sub.1-1 30P30N 2D Steady-RANS Grid=Provided L2/L3 Solver=Cflow

Grid Resolution – Computational Grid

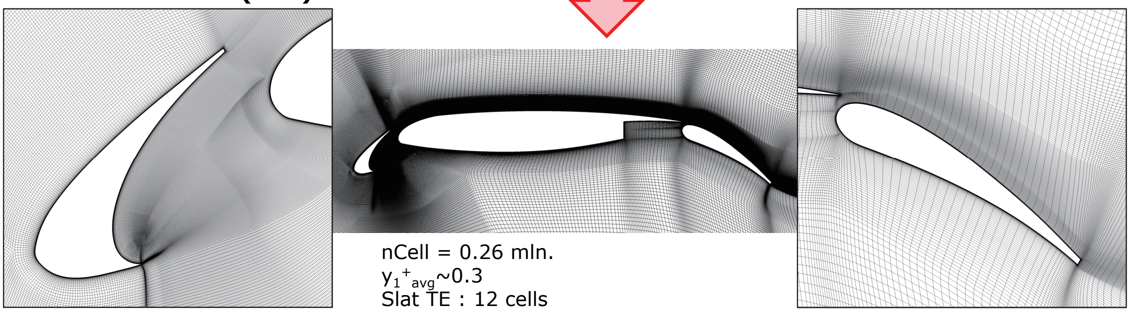
Provided 2D-L2 (medium) Grid



nCell = 0.11 mln.
$y_{1\,avg}^{+}$~0.5
Slat TE : 8 cells
Surf Δx_{min}=0.07%c

Cell size ~x2/3

Provided 2D-L3 (fine) Grid



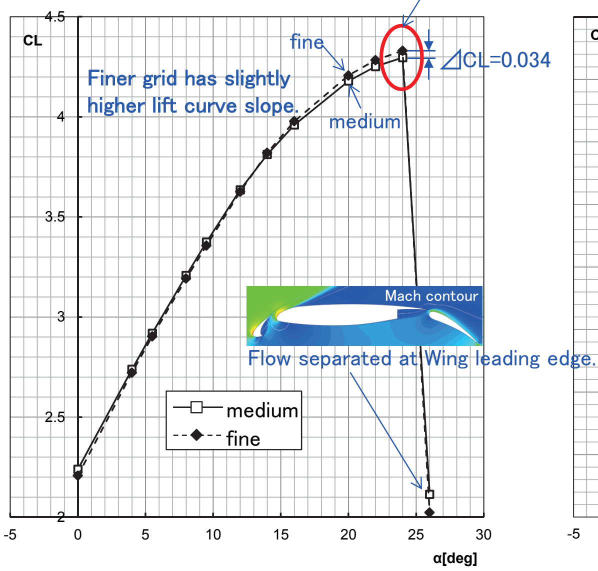
nCell = 0.26 mln.
$y_{1\,avg}^{+}$~0.3
Slat TE : 12 cells
Surf Δx_{min}=0.04%c

Sub.1-1 30P30N 2D Steady-RANS Grid=Provided L2/L3 Solver=Cflow

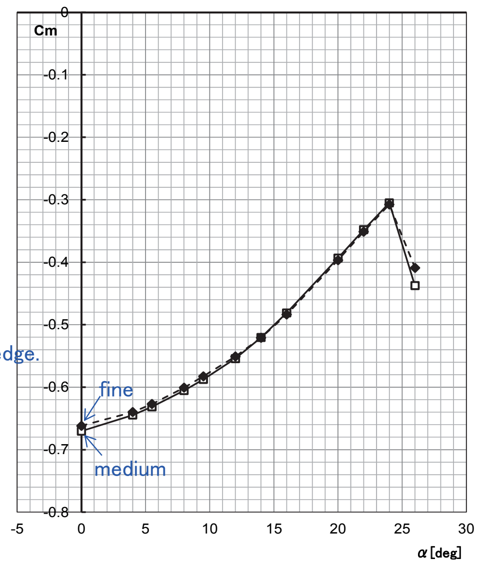
Grid Resolution – CL, Cm

Lift Curve

Compare flow field in the next page.



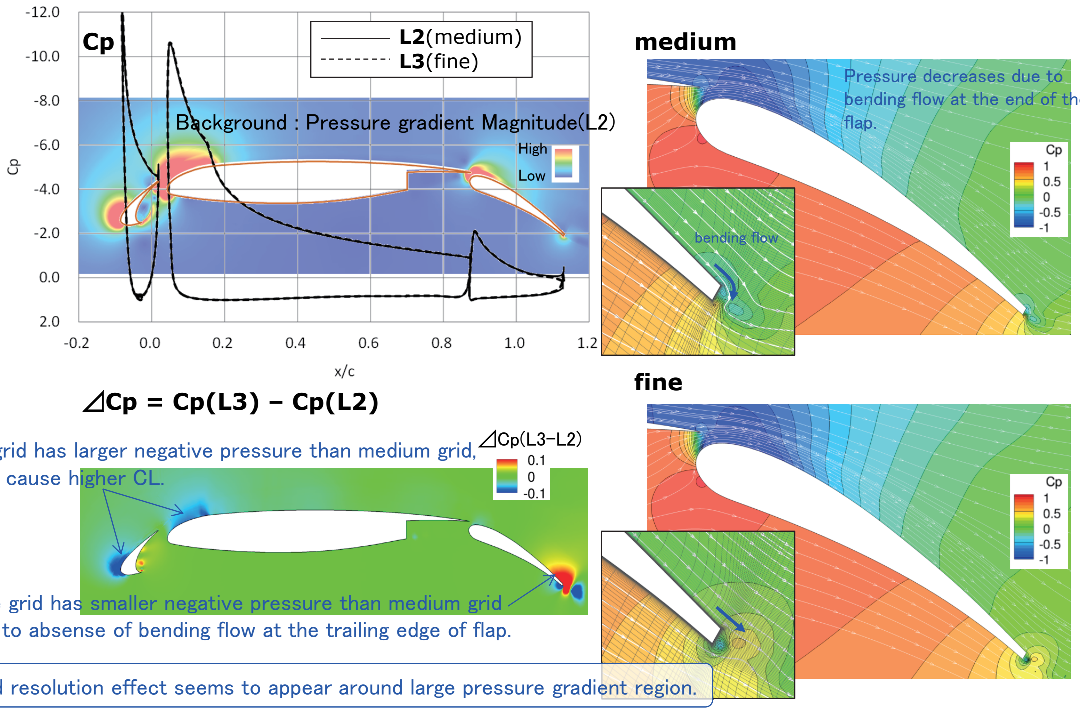
Pitching Moment



Each AoA result was obtained by impulsive start (start from uniform flow condition).

Sub.1-1 30P30N 2D Steady-RANS Grid=Provided L2/L3 Solver=Cflow

Grid Resolution – Cp @ α=24[deg]



Grid resolution effect seems to appear around large pressure gradient region.

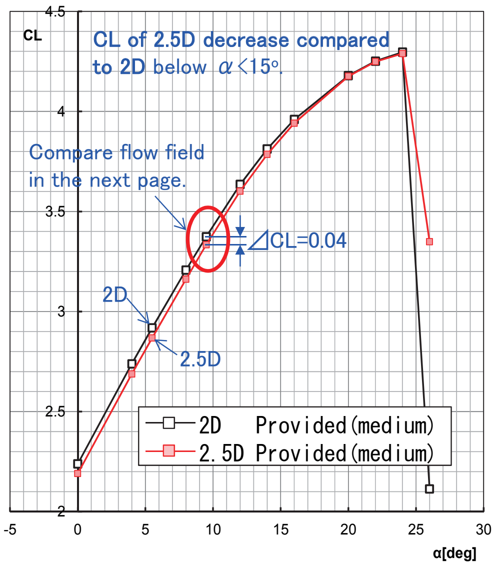
Appendix

Sub.1-2 30P30N 2D/2.5D Steady-RANS Grid=Provided L2 Solver=Cflow

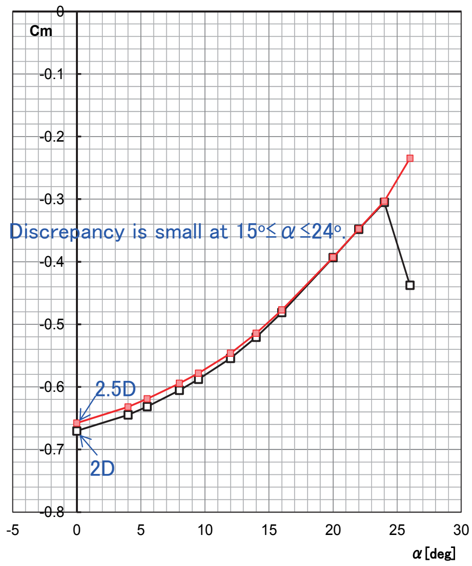
2D .vs. 2.5D* – CL, Cm

* Periodic boundary condition is applied for span-wise direction.
* Aerodynamic coefficients of 2.5D are obtained by integrating all area (including span-wise region).

Lift Curve



Pitching Moment



Sub.1-2 30P30N 2D/2.5D Steady-RANS Grid=Provided L2 Solver=Cflow

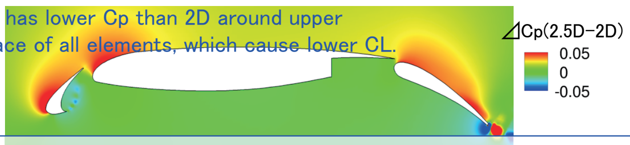
2D .vs. 2.5D* - Cp @ α=9.5[deg]

←CL(2.5D) < CL(2D)

* 2.5D-result represents mid-span section. (2.5D-Steady result is almost uniform along span-wise direction.)

⊿Cp = Cp(2.5D) – Cp(2D)

2.5D has lower Cp than 2D around upper surface of all elements, which cause lower CL.



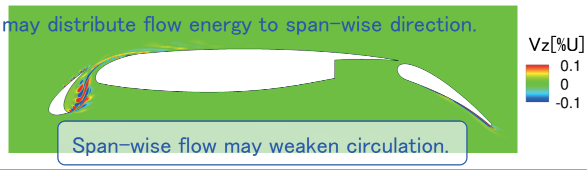
Span-wise(3D) effect can be seen on the upper surface of each component, especially around the leading edge.

⊿M = M(2.5D) – M(2D)

Mach difference seems corresponding to ⊿Cp.
→ Circulation decreases in the 2.5D analysis.

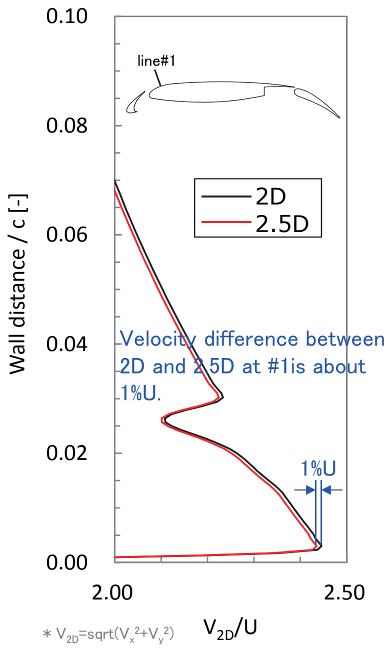
Span-wise Velocity (V_z)

V_z may distribute flow energy to span-wise direction.



Span-wise flow may weaken circulation.

Velocity Profile @ line#1



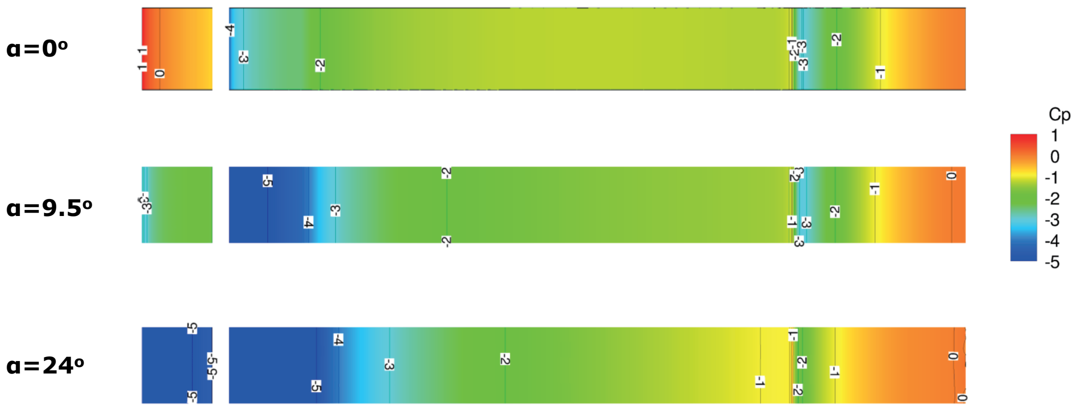
* V_{2D}=sqrt($V_x^2+V_y^2$)

Sub.1-2 30P30N 2D/2.5D Steady-RANS Grid=Provided L2 Solver=Cflow

2.5D – Spanwise Distribution

■ Cp distribution on the upper surface

Cp distribution is almost uniform along span-wise direction.



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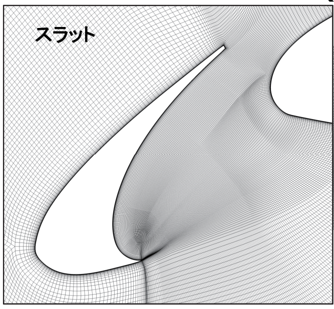
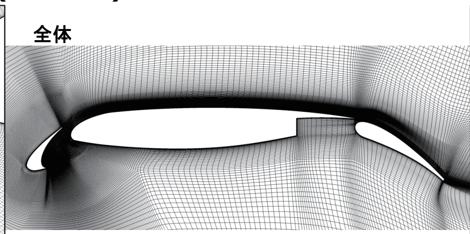
2. 2D .vs. 2.5D (30P30N, Provided Grid)
3. Grid Dependency – Steady Analysis (30P30N, Cflow Grid)
4. Steady .vs. Unsteady (30P30N/30P35N, Cflow Grid)

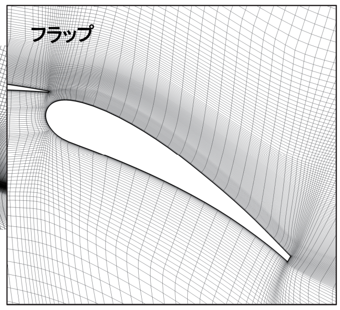
Sub.1-2 30P30N 2.5D Steady-RANS Grid=Provided L2 / Cflow L2 Solver=Cflow

Provided .vs. Cflow Grid – Grid

Provided Grid 2.5D L2 (medium)

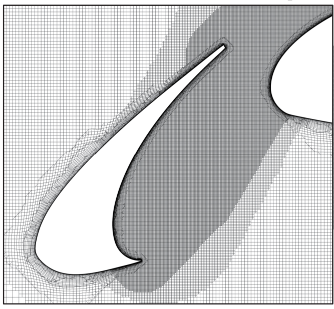


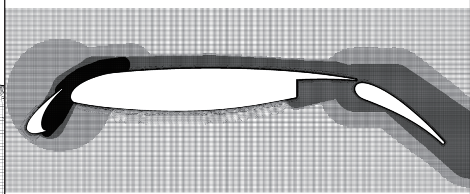


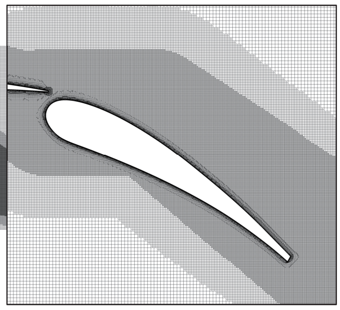


nCell = 20.2 mln.
$y_1^+{}_{avg}$~0.5
Slat TE : 8 cells
Surf Δx_{min}=0.07%c

Cflow Grid 2.5D L2 (medium)







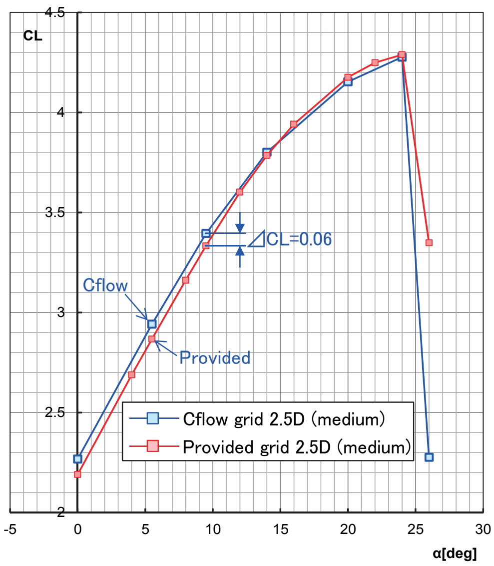
nCell = 61.0 mln.
$y_1^+{}_{avg}$~0.5
Slat TE : 6 cells
Surf Δx_{min}=0.044%c

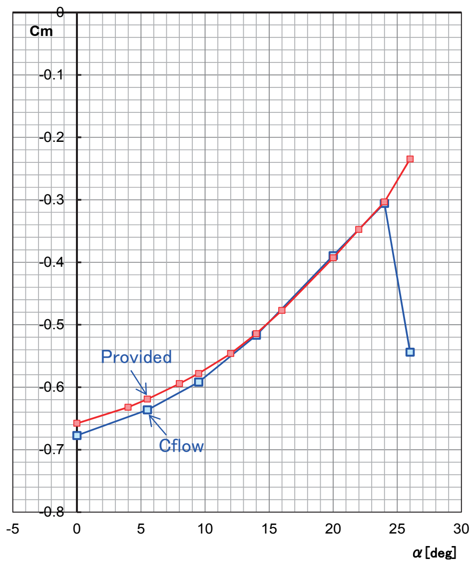
Sub.1-2 30P30N 2.5D Steady-RANS Grid=Provided L2 / Cflow L2 Solver=Cflow

Provided .vs. Cflow Grid – CL, Cm

＊ Periodic boundary condition is applied for span-wise direction.
＊ Aerodynamic coefficients of 2.5D are obtained by integrating all area (including span-wise region).

Lift Curve **Pitching Moment**

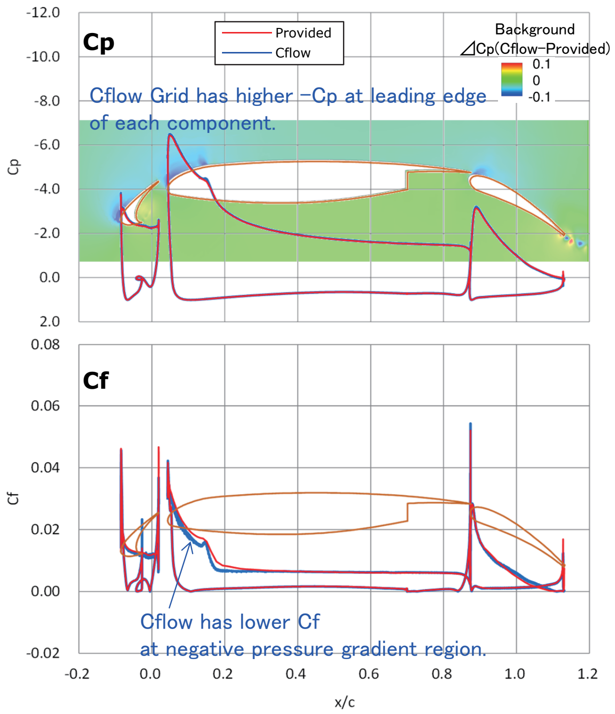


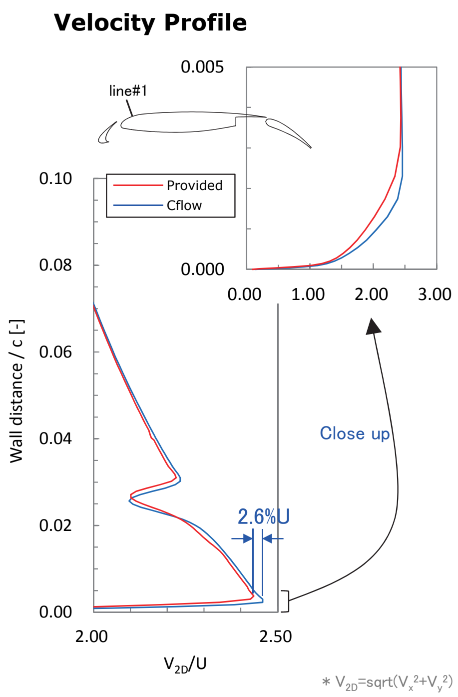


Sub.1-2 30P30N 2.5D Steady-RANS Grid=Provided L2 / Cflow L2 Solver=Cflow

Provided .vs. Cflow Grid - Cp/Cf @ α=9.5[deg]

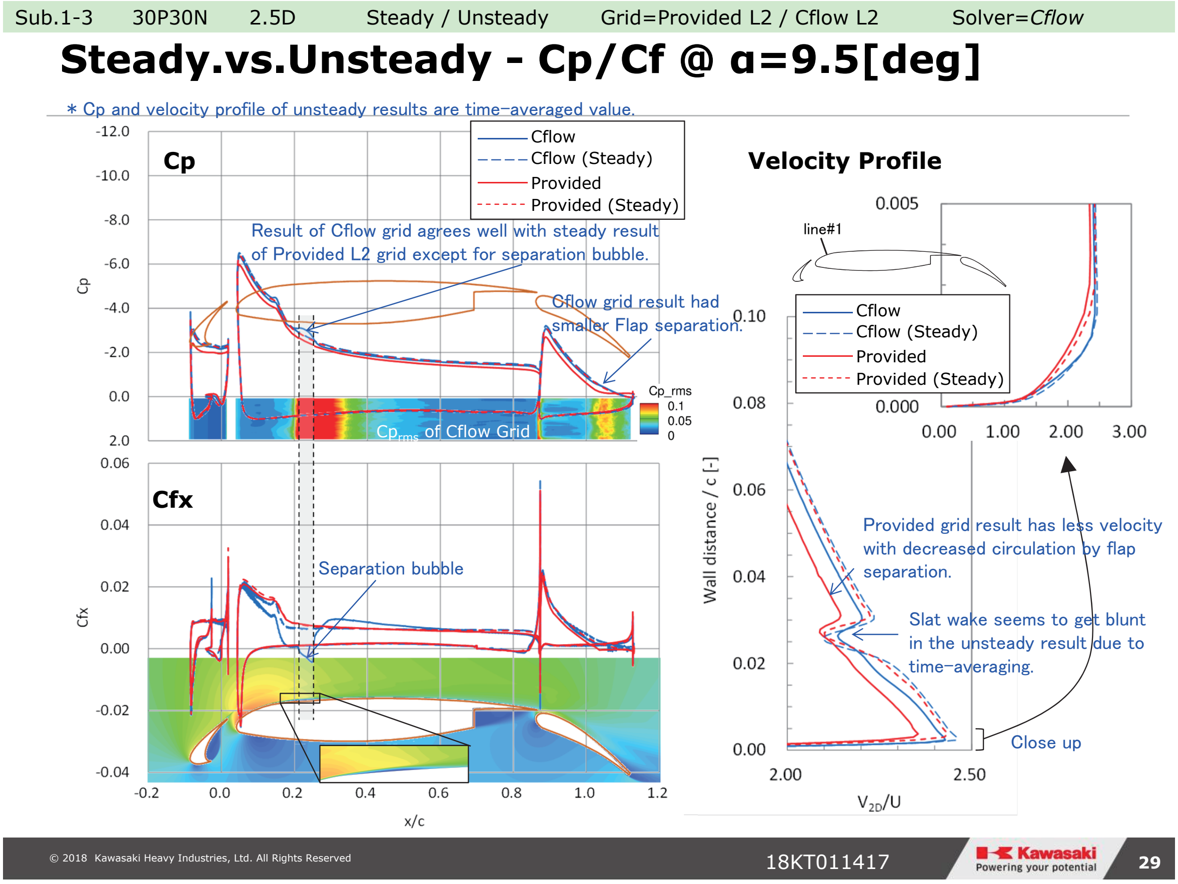
＊Cp/Cf was obtained at mid-span section (Not span-wise average). ↑CL(Provided) < CL(Cflow)





Appendix

1. Effect of Grid Resolution (30P30N, Provided Grid)
2. 2D .vs. 2.5D (30P30N, Provided Grid)
3. Grid Dependency – Steady Analysis (30P30N, Cflow Grid)
4. Unsteady Analysis (30P30N/30P35N, Cflow Grid)


Sub.1-3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 / Cflow L2 Solver=Cflow
Steady.vs.Unsteady - Cp/Cf @ α=9.5[deg]
＊Cp and velocity profile of unsteady results are time-averaged value.
Cp
Cflow
Cflow (Steady)
Provided
Provided (Steady)
Result of Cflow grid agrees well with steady result of Provided L2 grid except for separation bubble.
Cflow grid result had smaller Flap separation.
Cp_rms of Cflow Grid
Cfx
Separation bubble
x/c
Velocity Profile
line#1
Provided grid result has less velocity with decreased circulation by flap separation.
Slat wake seems to get blunt in the unsteady result due to time-averaging.
Close up
Wall distance / c [-]
V2D/U
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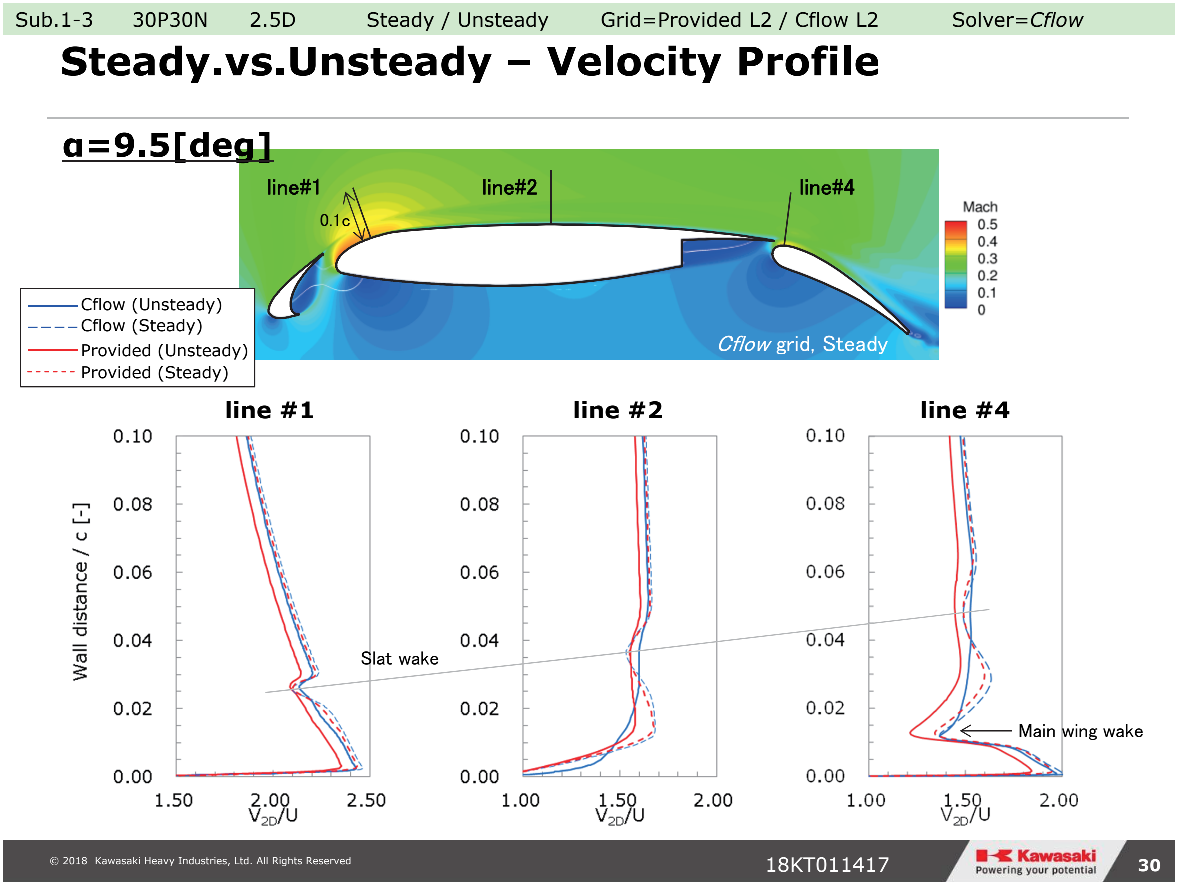
Sub.1-3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 / Cflow L2 Solver=Cflow
Steady.vs.Unsteady – Velocity Profile
α=9.5[deg]
line#1
0.1c
line#2
line#4
Mach
Cflow grid, Steady
Cflow (Unsteady)
Cflow (Steady)
Provided (Unsteady)
Provided (Steady)
line #1
line #2
line #4
Wall distance / c [-]
Slat wake
Main wing wake
V2D/U
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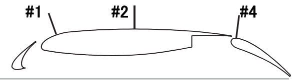
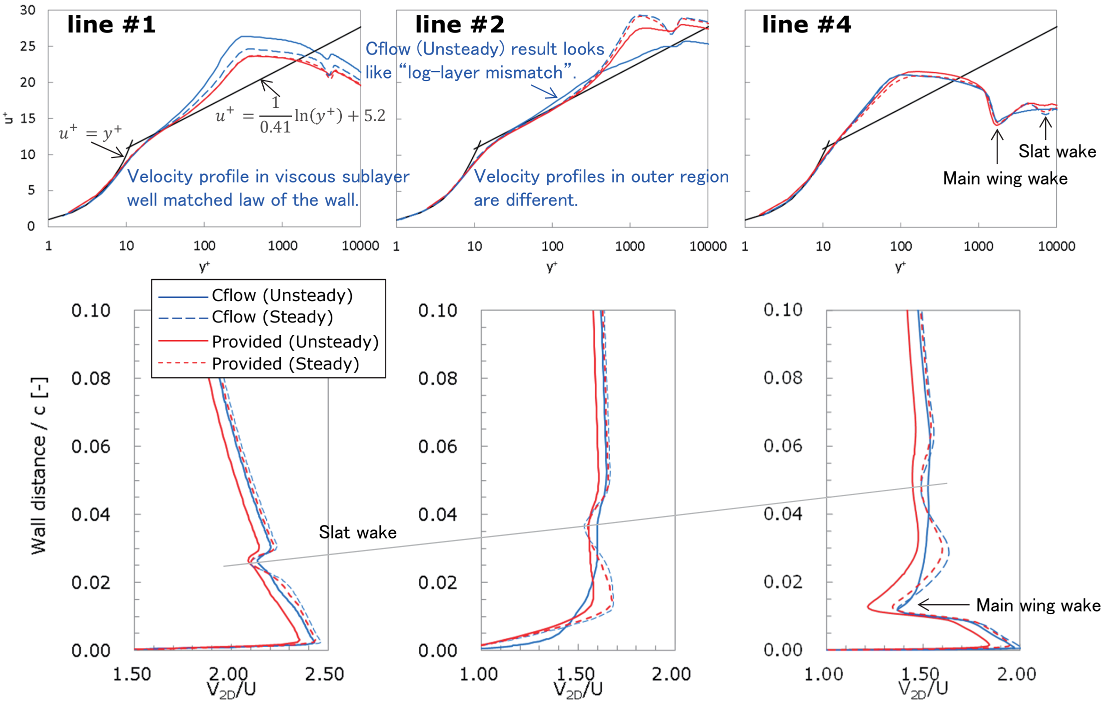
Sub.1-3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 / Cflow L2 Solver=*Cflow*

Steady .vs. Unsteady - u⁺-y⁺

α=9.5[deg]





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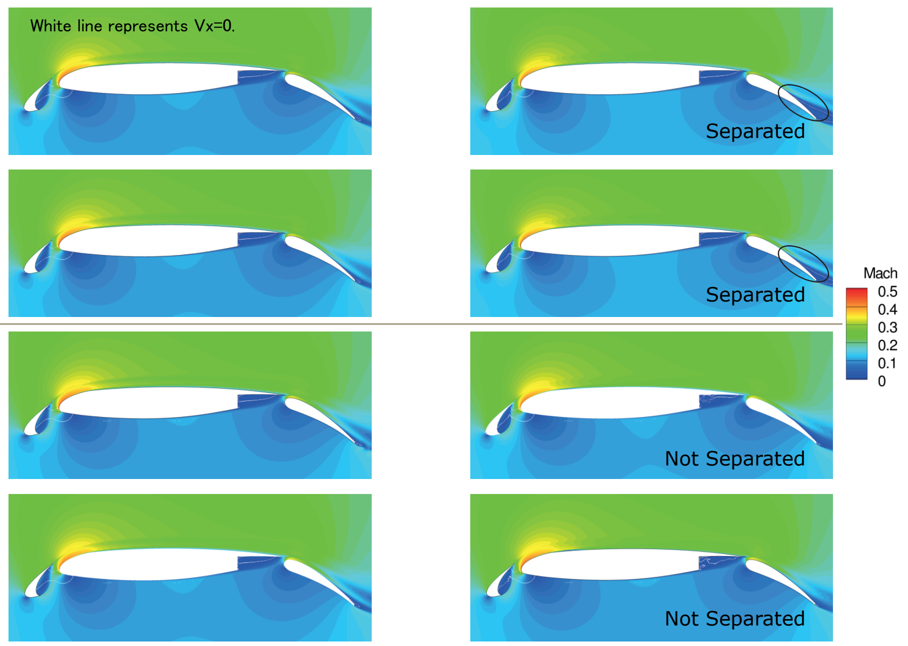
Sub.1-3 30P30N 2.5D Steady / Unsteady Grid=Provided L2 / Cflow L2 Solver=*Cflow*

Steady .vs. Unsteady - Flap separation

α=5.5[deg]

＊Unsteady analysis was started from the result of steady analysis.

	Steady	Unsteady(time-average)
Provided (L2)		
Provided (L3)		
Cflow (L2)		
Cflow (L3)		



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Sub.2-3 30P35N 2.5D Steady / Unsteady Grid=Provided L2 / Cflow L2 Solver=*Cflow*

Steady .vs. Unsteady - Flap separation

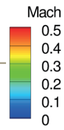
α=5.5[deg]

＊Unsteady analysis was started from the result of steady analysis.

	Steady	**Unsteady(time-average)**

Provided (L2)

Flap separation area expanded with provided L2 grid switching from steady to unsteady analysis.

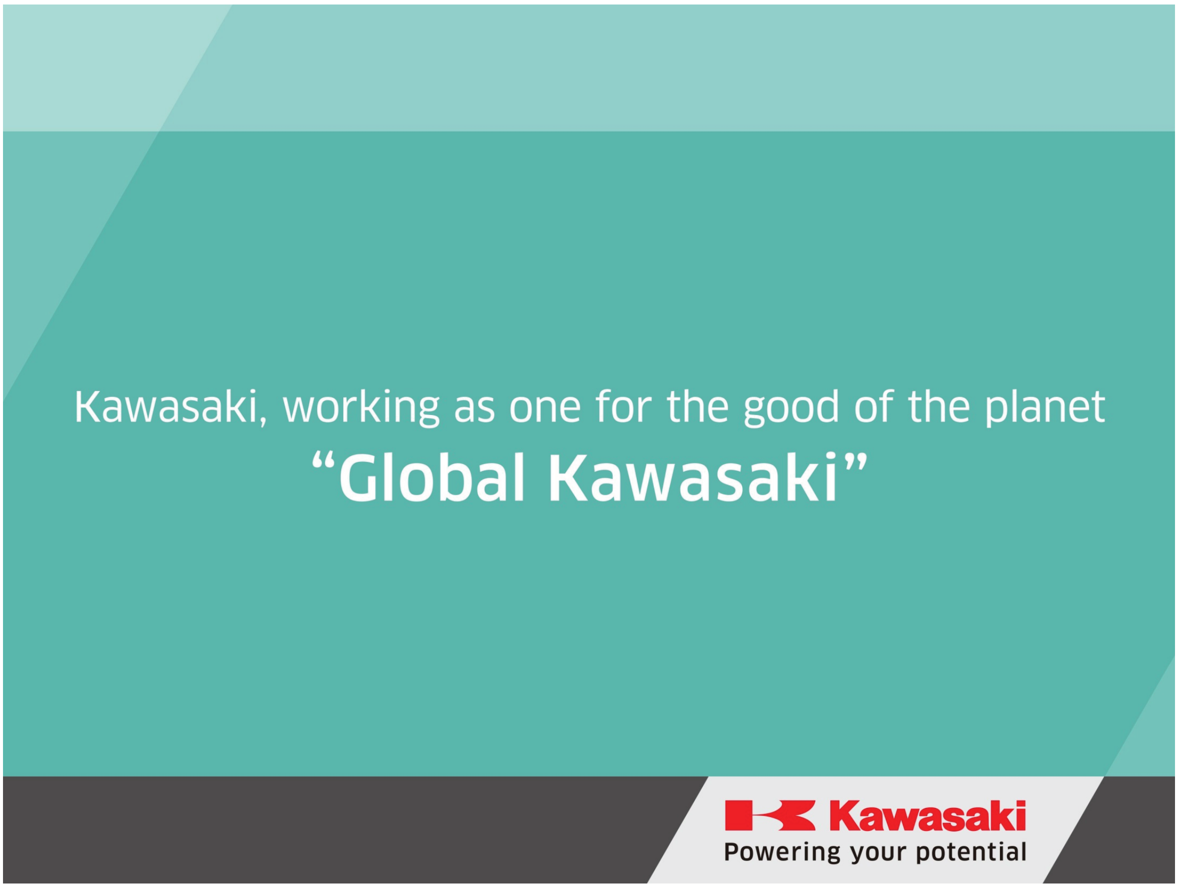


Cflow (L2)

Small difference between steady and unsteady result with Cflow grid.

Appendix Summary

1. Effect of Grid Resolution (30P30N, Provided Grid)
   - Grid resolution effect seemed to appear around region where were large pressure gradient.
2. 2D .vs. 2.5D (30P30N, Provided Grid)
   - Cl decreased in the 2.5D analysis compared to 2D analysis.
   - Span-wise flow may weaken circulation by distributing energy to span-wise direction.
3. Grid Dependency – Steady Analysis (30P30N, Cflow Grid)
   - Cflow Grid result had higher Cl than Provided Grid.
   - Cflow Grid had lower Cp than Provided Grid at leading edge of slat/wing/flap due to higer velocity.
4. Steady .vs. Unsteady (30P30N/30P35N, Cflow Grid)
   - Result of Cflow Grid had smaller flap separation than Provided Grid in the unsteady analysis.
   - Velocity profile in the viscous sublayer well matched law of the wall. Difference of velocity profile was seen in the outer region.
     → Grid resolution near wall may be sufficient with L2 grid. Spatial grid resolution in the slat/wing wake region may affect on the flow field around flap.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