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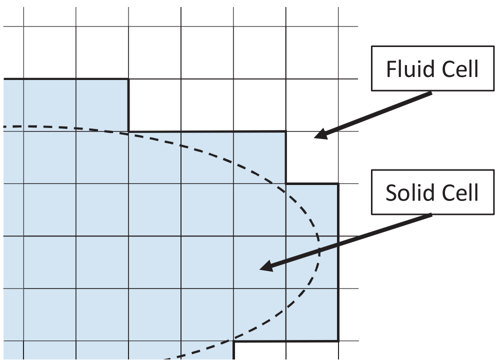
Numerical Simulations of Compressible Flow around the 30P30N using Wall-Modeled Cartesian Cut-Cell Method

壁面モデルを適用した直交カットセル法による 30P30Nまわりの圧縮性流れの数値解析

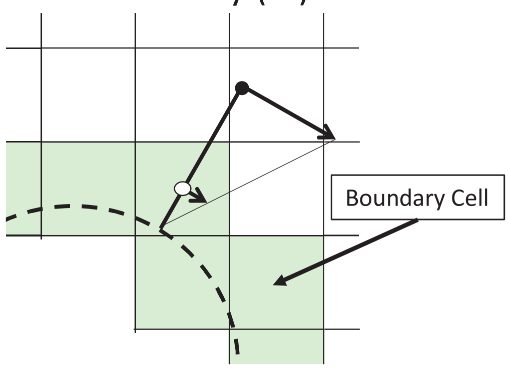
ISHIKAWA Tatsuya, TAKEDA Yuki
UENO Kazuyuki, OKUDERA Tomohiro
(Iwate University)

Typical Methods using Cartesian Grid

Voxel Method



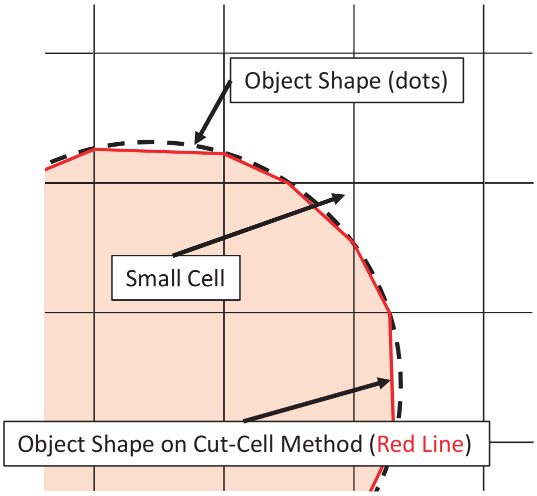
Immersed Boundary (IB) Method



- Easy for implement.
- Need many cells to perform smooth surface.

- Boundary condition on the boundary cells.
- Mass is not conserved in each boundary cell.

Cartesian Cut-Cell Method



Cut cell method cuts the computation cells according to object shape.

- Smoother surface.
- Satisfy the mass conservation law.

On the other hand…

- Many cutting patterns.

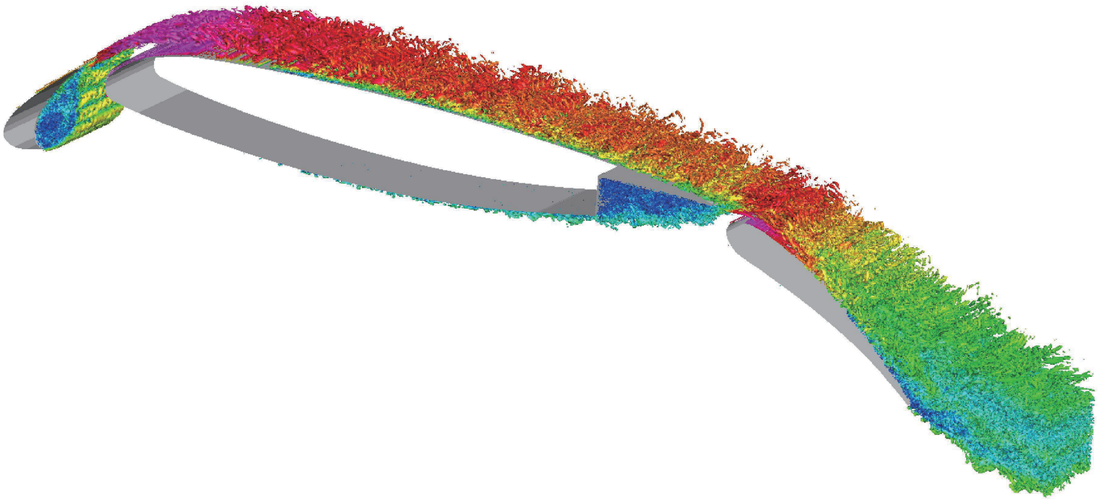
Objective

Research on the prediction performance of
Wall-Modeled Cartesian Cut-Cell Method
in high Reynolds number unsteady flow simulation.

Test case

Case1 : Prediction of aerodynamics

1-3 : 2.5D unsteady flow simulation

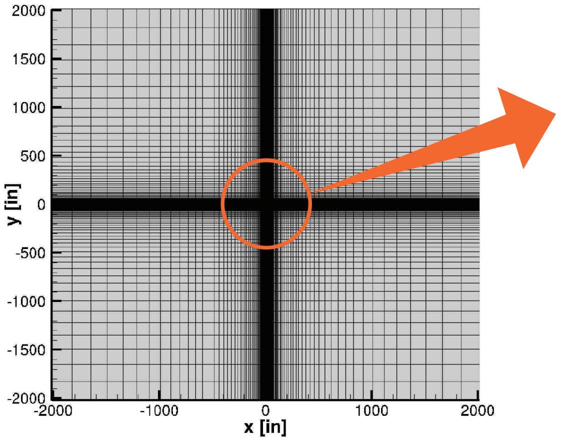


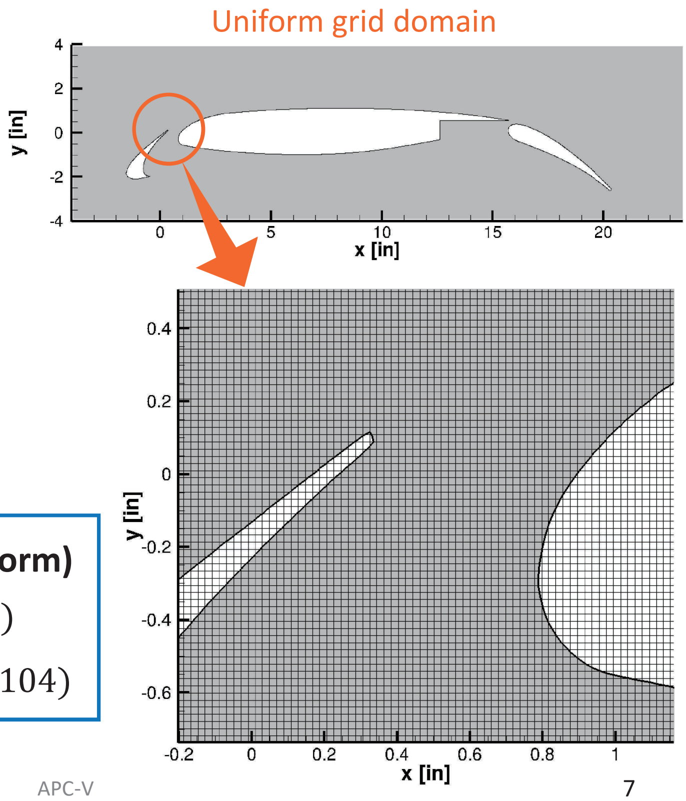
Simulation Method

Conservation Equation	Compressible Navier-Stokes Eq.
Wall Shear Stress	Wall Model [1]
Discretization Method	Cell-Centered Finite Volume Method
Wall Treatment	Cartesian Cut-Cell Method
Inviscid Flux	SLAU (5th-Order MUSCL + Thornber's Modification)
Viscous Flux	2nd-Order Central Difference
Time Integration	2nd-Order TVD Runge-Kutta Method
Turbulence Model	Implicit LES

[1] S. Kawai *et al.* , "Wall-modeling in large eddy simulation: Length scales, grid resolution, and accuracy ", Physics of Fluids **24**, 2012.

Computational Grid

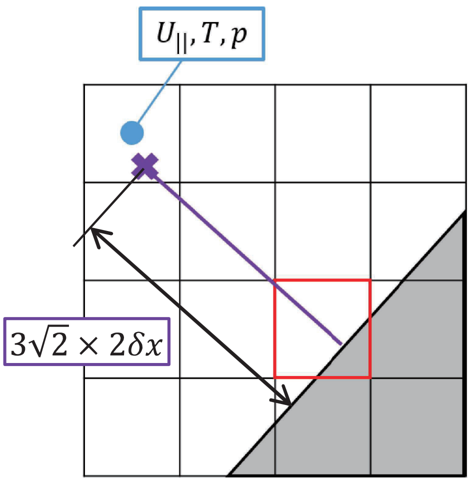


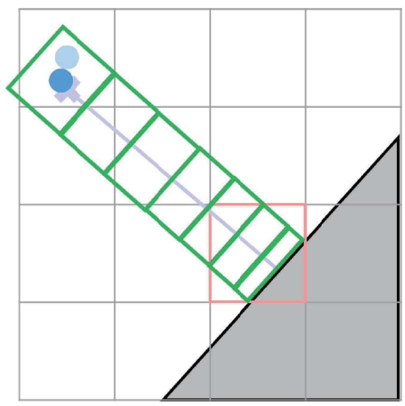


Cartesian grid (Uniform + Non-Uniform)

- $2\Delta x/c \approx 1.0 \times 10^{-3} \quad (y^{+} < 200)$
- 93,515,136 cells $(1572 \times 572 \times 104)$

Wall Model for Cut-Cell Method





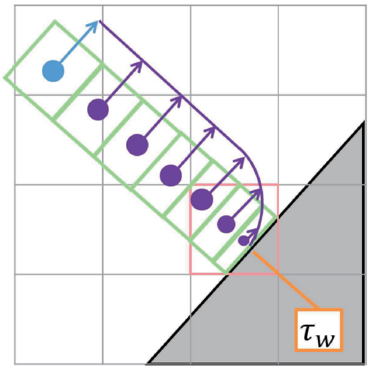
1) Extend the probe vertically from the wall.

2) Search the nearest cell center from the probe tip.

3) Generate virtual grid system (1D) in the vertical direction of the wall.

4) Input the nearest cell center value from the probe tip to the Wall Model.

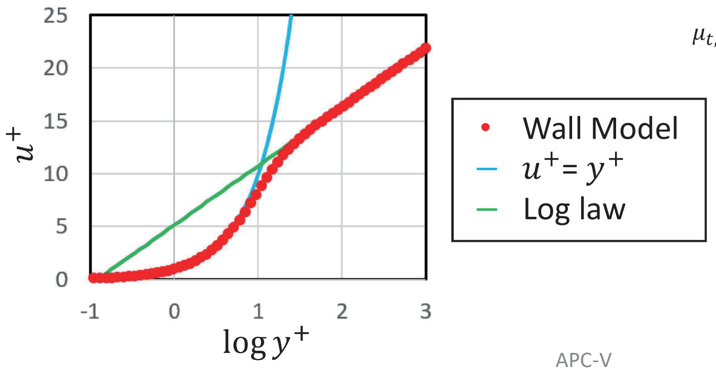
Wall Model for Cut-Cell Method



5) Solve the Wall Model equations to obtain τ_w, and apply τ_w to the cut cell as the wall flux.

$$\frac{d}{d\eta}\left[(\mu+\mu_{t,\mathrm{wm}})\frac{dU_{||}}{d\eta}\right]=0$$

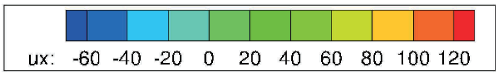
$$\frac{d}{d\eta}\left[(\mu+\mu_{t,\mathrm{wm}})U_{||}\frac{dU_{||}}{d\eta}\right]+\frac{d}{d\eta}\left[c_p\left(\frac{\mu}{Pr}+\frac{\mu_{t,\mathrm{wm}}}{Pr_{t,\mathrm{wm}}}\right)\frac{dT}{d\eta}\right]=0$$

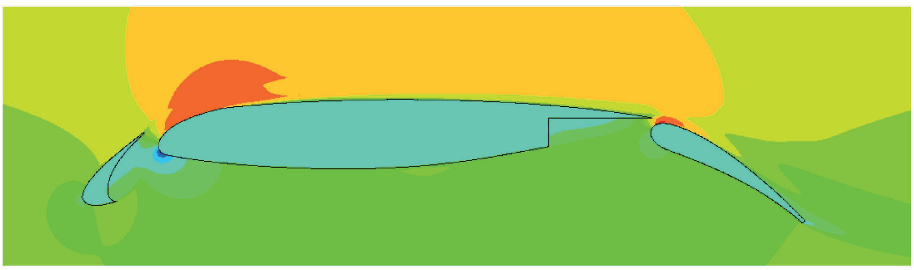


$$\mu_{t,\mathrm{wm}}=\kappa\rho y\sqrt{\frac{\tau_w}{\rho}}D \qquad D=\left[1-\exp\left(-\frac{y^+}{A^+}\right)\right]^2$$

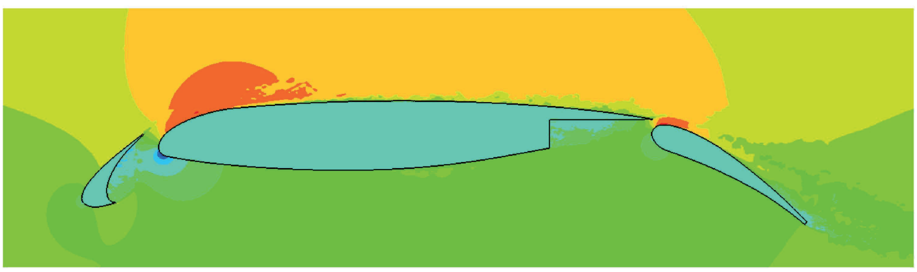
Results : Flow Field ($\alpha = 5.5°$)

Time-averaged flow field



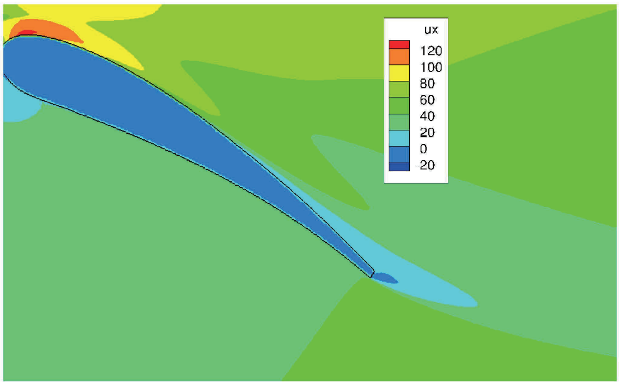


Instantaneous flow field



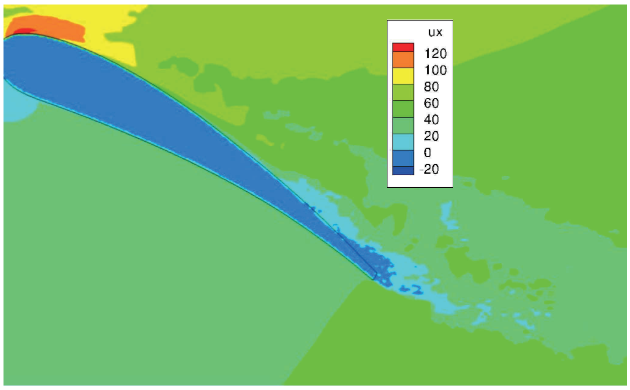
Results : Flow Field ($\alpha = 5.5°$)

Time-averaged flow field



No separation can be seen.

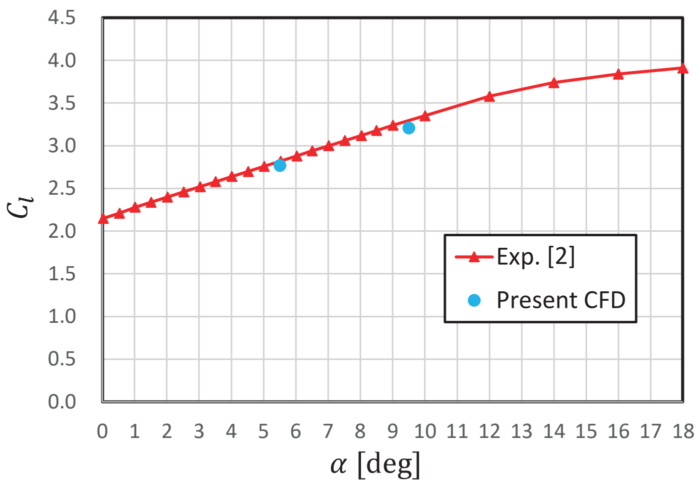
Instantaneous flow field



Separation can be seen slightly.

Results : C_l

● $C_l - \alpha$ curves

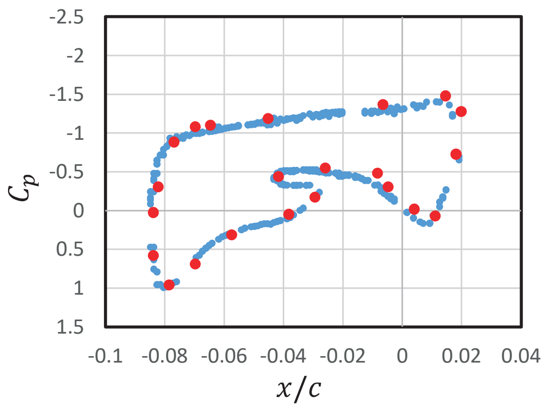


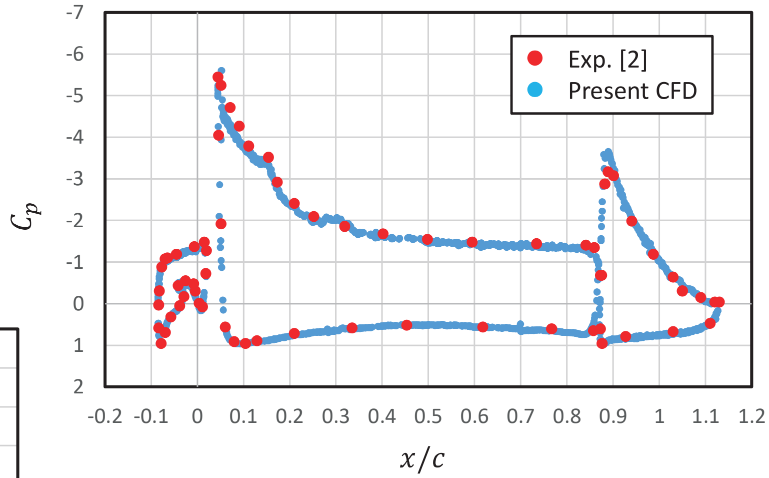
● Comparison results

α [deg]	5.5	9.5
Exp. [2]	2.82	3.30
Present CFD	2.77	3.21

[2] M. Murayama *et al.* , "Experimental Study on Slat Noise from 30P30N Three-Element High-Lift Airfoil at JAXA Hard-Wall Low-Speed Wind Tunnel", AIAA 2014-2080.

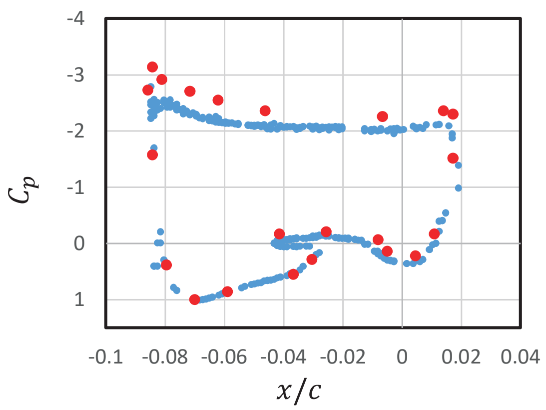
Results : $C_p(\alpha = 5.5°)$

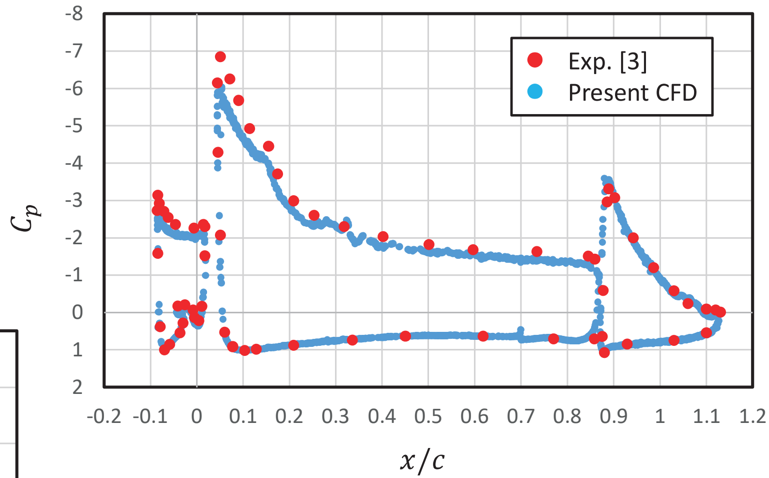




[2] M. Murayama *et al.* , "Experimental Study on Slat Noise from 30P30N Three-Element High-Lift Airfoil at JAXA Hard-Wall Low-Speed Wind Tunnel", AIAA 2014-2080.

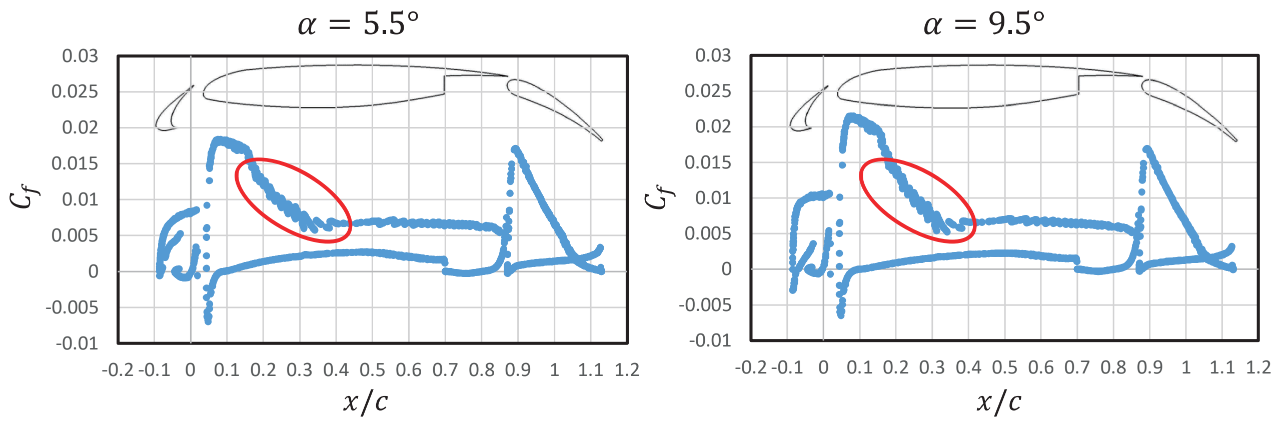
Results : $C_p(\alpha = 9.5°)$





[3] "JAXA Special Publication Fourth Aerodynamics Prediction Challenge(APC-IV)", JAXA-SP-18-008

Results : C_f



Unnatural distribution appeared in both conditions.
→ Input method of Wall Model is capable of improvement.

Conclusion

Unsteady flow simulations around 30P30N with Wall-Modeled Cartesian Cut-Cell Method were performed.
The prediction performance of this calculation method was evaluated.

Flow Field

In time-averaged flow field, flow separation didn't appear at flap. However, flow separation at flap appeared intermittently in instantaneous flow field.

Lift Coefficient

C_l values in two conditions were good agreement with experimental data.

Pressure Coefficient

Good agreement with the experiment for C_p distribution. However, C_p values on the slat and the main wing LE were slightly different from experimental values when $\alpha = 9.5°$.

Friction Coefficient

Unnatural distribution appeared at main wing SS in two conditions.

Future works

- Improve the grid resolution.
- Reconsider input method of Wall Model.