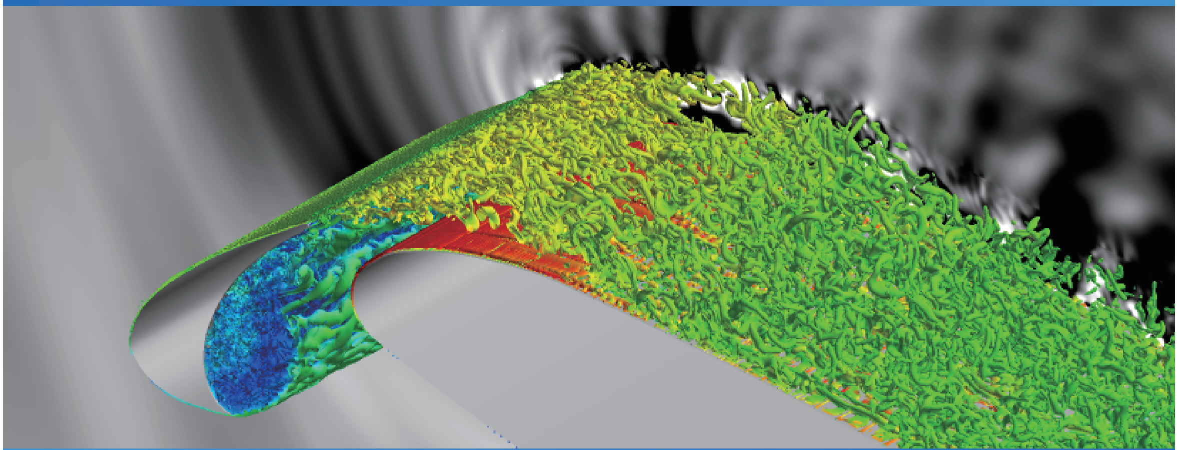
APC4@36th ANSS

Unsteady Flow Simulation around 30P30N by Cascaded LBM



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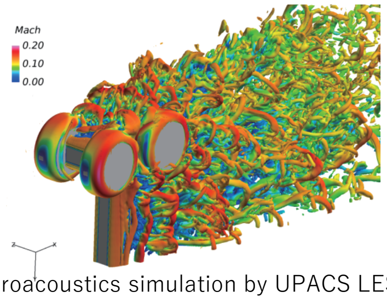
Outline

- Numerical Method
  - Lattice Boltzmann Method
    - Cascaded LBM
  - Boundary condition
    - Wall boundary
    - Outer boundary
  - Building-Cube Method
- Numerical Results
  - Problem category 1-1 (2D)
  - Problem category 1-3 (3D)
  - Problem category 3-1 (3D)
- Conclusions

Background

- CFD use：
  - understanding the flow physics
  - engineering design (especially in steady state)

- Problems in current CFD
  - Cost for unsteady flow simulation
    - High resolution/High order schemes
    - Restriction for Δt
    - Inner iteration of implicit time integration
    - Handling of massive output data
  - Model dependency
    - DES, DDES, IDDES, Zonal DES, …
    - RANS/LES switching parameter



Aeroacoustics simulation by UPACS LES
(~1month computation with PC cluster)

- It is difficult to directly apply unsteady flow simulation for engineering design.

- Lattice Boltzmann Method has capability to overcome current CFD problem (?)

Algorithms of LBM

- Governing equation: Boltzmann transport equation

$$\frac{\partial f_i}{\partial t} + \mathbf{e}_i \cdot \nabla f_i = \mathbf{\Omega}_i \qquad (i = 1, \cdots, b)$$

f :probability distribution function

$\mathbf{e}$:discrete set of velocities

$\mathbf{\Omega}$:collision operator

Ludwig Eduard Boltzmann
(1844–1906)

- Discretization on lattice:

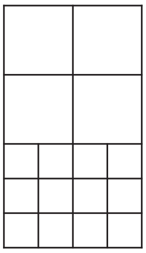
$$f_i(\mathbf{r} + \mathbf{e}_i dt, t + dt) = f_i(\mathbf{r}, t) + dt \times \mathbf{\Omega}_i(f_1, \cdots, f_b)$$
$$(i = 1, \cdots, b)$$

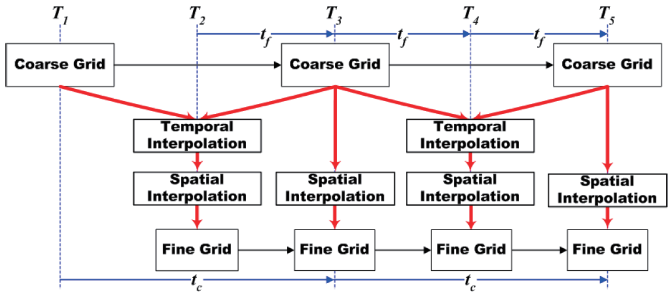
- Lattice model used in this research: D2Q9, D3Q27

Algorithms of LBM

- Relaxation parameter τ depends on the local grid size Δx.
  - $\frac{\Delta x_{coarse}}{\Delta x_{fine}} = n$ leads $\frac{\Delta t_{coarse}}{\Delta t_{fine}} = n$
- Temporal/spatial interpolation are necessary among difference size cells.
- Usually, non-equilibrium part of f is rescaled.

$$f_i^{fine} = \widehat{f_i}^{eq,coarse} + \left(\widehat{f_i}^{coarse} - \widehat{f_i}^{eq,coarse}\right) \frac{\Delta x_{fine} \tau_{fine}}{\Delta x_{coarse} \tau_{coarse}}$$





Ye Zhao et.al. "Flow Simulation with Locally-Refined LBM"

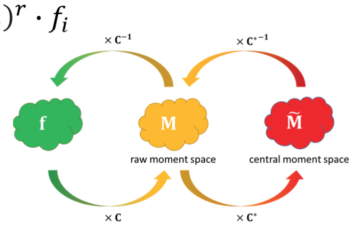
Algorithms of LBM

- Cascaded LBM is used for collision operator.
  - Satisfy Galilean invariance and has better accuracy/stability
  - Compute central moment defined by moving coordinate:

$$\widetilde{\mathbf{M}}_{p,q,r} = \sum_i (e_{ix} - u_x)^p \cdot (e_{iy} - u_y)^q \cdot (e_{iz} - u_z)^r \cdot f_i$$

  - Relation between Raw moment/Central moment

$$\widetilde{\mathbf{M}} = \boldsymbol{C}^* \mathbf{M}$$



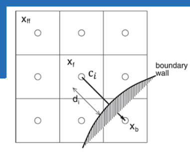
- 27 Central moments used in this research:

M_ρ, M_x, M_y, M_z, K_{xy}, K_{xz}, K_{yz}, K_{xx-yy}, K_{xx-zz}, $\mathrm{K}_{xx+yy+zz}$, $\mathrm{K}_{xyy+xzz}$, $\mathrm{K}_{xxy+yzz}$, $\mathrm{K}_{xxz+yyz}$, $\mathrm{K}_{xyy-xzz}$, $\mathrm{K}_{yzz-xxy}$, $\mathrm{K}_{xxz-yyz}$, K_{xyz}, $\mathrm{K}_{xxyy+xxzz+yyzz}$, $\mathrm{K}_{xxyy+xxzz-yyzz}$, $\mathrm{K}_{xxyy-xxzz}$, K_{xxyz}, K_{xyyz}, K_{xyzz}, K_{xyyzz}, K_{xxyzz}, K_{xxyyz}, and K_{xxyyzz}.

  - $\tau = 1$ is used for the above moments to enhance stability.
  - Our approach is Implicit LES.

Martin Geier, et. al., "Cascaded digital lattice Boltzmann automata for high Reynolds number flow"

Wall/Outer boundary



- Interpolated Bounce-Back (IBB) Scheme (1st order)

$$f_{-i}(\mathbf{x}, t+\Delta t) = 2q\tilde{f}_i(\mathbf{x}, t) + (1-2q)\tilde{f}_i(\boldsymbol{x}-\mathbf{c}_i\Delta t, t) - 2w_i\rho(\mathbf{x}, t)\frac{\boldsymbol{e}_i \cdot u_w}{c_s^2} \quad \left(q_i < \frac{1}{2}\right)$$

$$f_{-i}(\mathbf{x}, t+\Delta t) = \frac{1}{2q}\tilde{f}_i(\mathbf{x}, t) + \frac{2q-1}{2q}\tilde{f}_{-i}(\mathbf{x}, t) - \frac{1}{q}w_i\rho(\mathbf{x}, t)\frac{\boldsymbol{e}_i \cdot u_w}{c_s^2} \quad \left(q_i \geq \frac{1}{2}\right)$$

where $q_i = \frac{d_i}{|\mathbf{c}_i|\Delta t}$, non-dimensional distance

※No wall function is used.

G. Eitel-Amor et.al. "A lattice-Boltzmann method with hierarchically refined meshes"

- Damping function is used for the outer boundary condition.

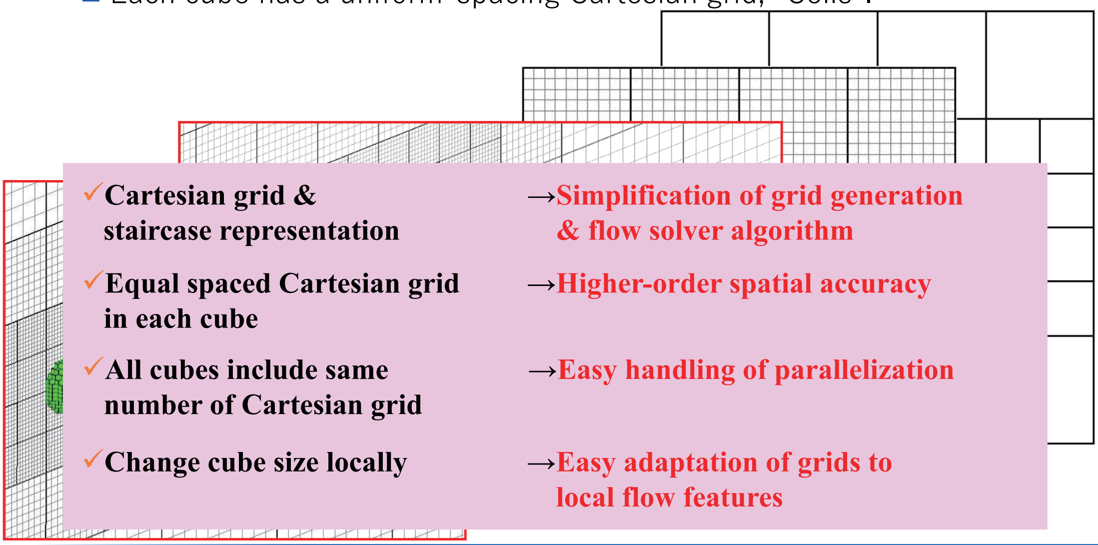
$$f^{outer} = f - \alpha * (f - f_{eq}^{target})$$

$$\alpha = 0.5 \times \left(\frac{d-r}{R-r}\right)^2$$

where r/R are inner/outer radius of damping region, d is distance from inner radius r

Building-Cube Method

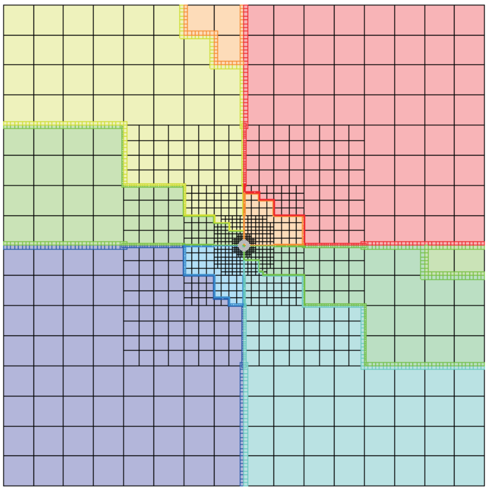
- BCM is a block-structured Cartesian grid approach proposed by prof. Nakahashi.
  - Computational domain is divided into "Cubes".
  - Each cube has a uniform-spacing Cartesian grid, "Cells".



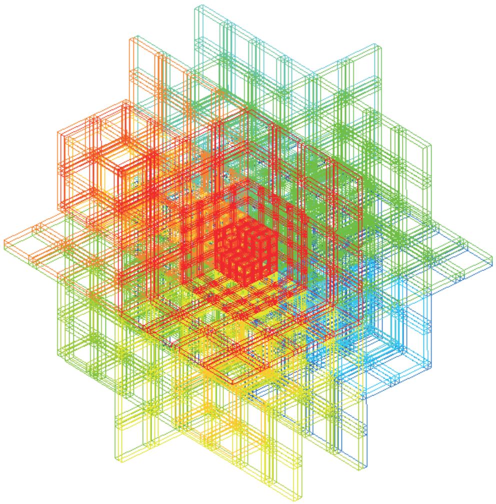
✓**Cartesian grid & staircase representation**	→**Simplification of grid generation & flow solver algorithm**
✓**Equal spaced Cartesian grid in each cube**	→**Higher-order spatial accuracy**
✓**All cubes include same number of Cartesian grid**	→**Easy handling of parallelization**
✓**Change cube size locally**	→**Easy adaptation of grids to local flow features**

Domain Partition

- BCM framework use both OpenMP/MPI parallelization.
- Z-ordering is used for MPI parallelization.



2D



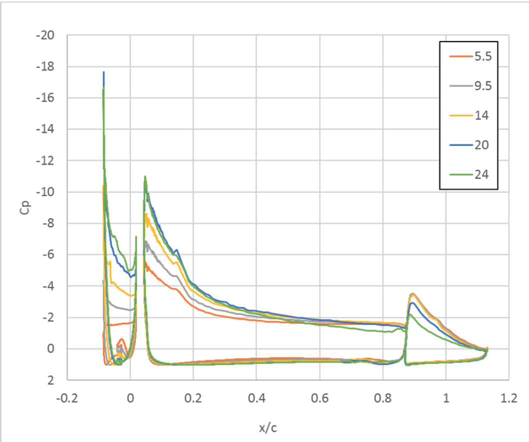
3D

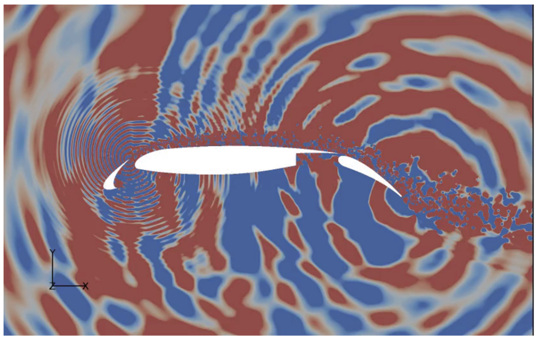
Grid information

Details		
dimension	2D	3D
Re	1.71×10^6	
M_∞	0.17	
α	5.5	
Domain	$32L_\infty \times 32L_\infty$	$16L_\infty \times 16L_\infty \times 0.125L_\infty$
Cube	6535	77326
Cell	32^2	$4^3, 8^3, 16^3, 32^3$
Total cells	$6.7M$	$4.9M, 40M, 317M, 2.5B$
Δx_{min}	$1.22 \times 10^{-4} L_\infty$	$2.44 \times 10^{-4} L_\infty$

Periodic boundary condition is applied in spanwise direction.

2D results





dp field@AoA=5.5

- Flow separation is different at slat-cove compared to NS(RANS) results.
  ⇒due to 2D computation with ILES.
- LBM overestimated Cp compared to NS(RANS) results.

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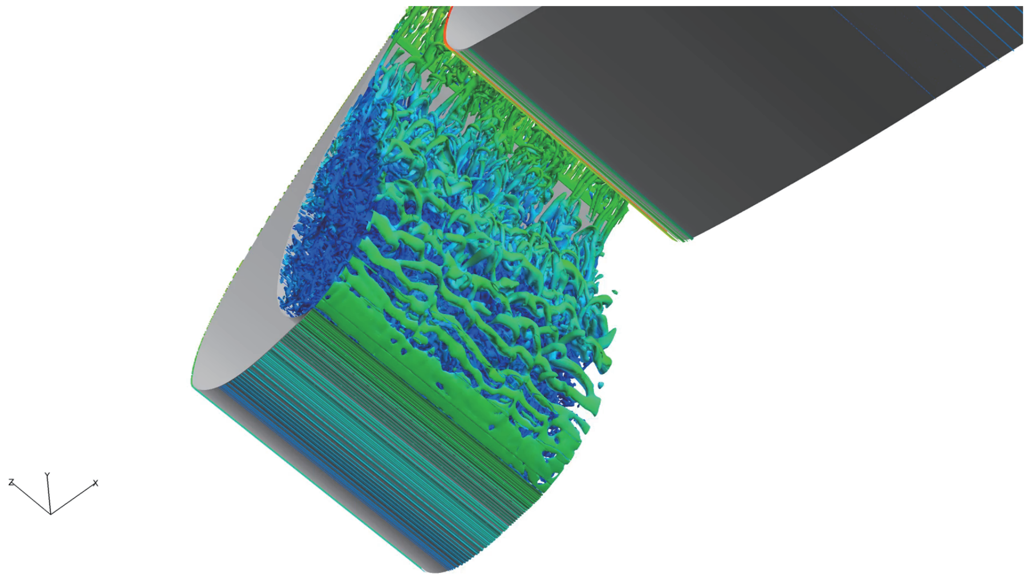
3D results



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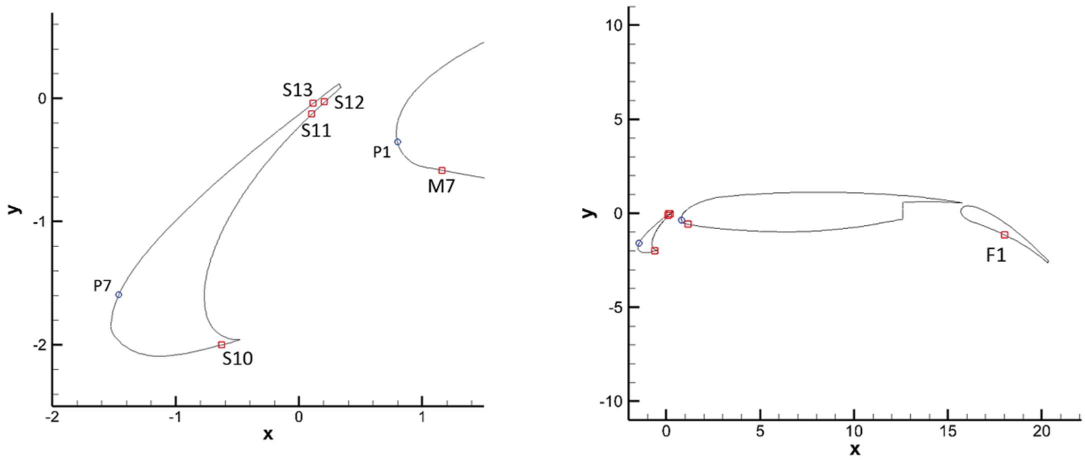
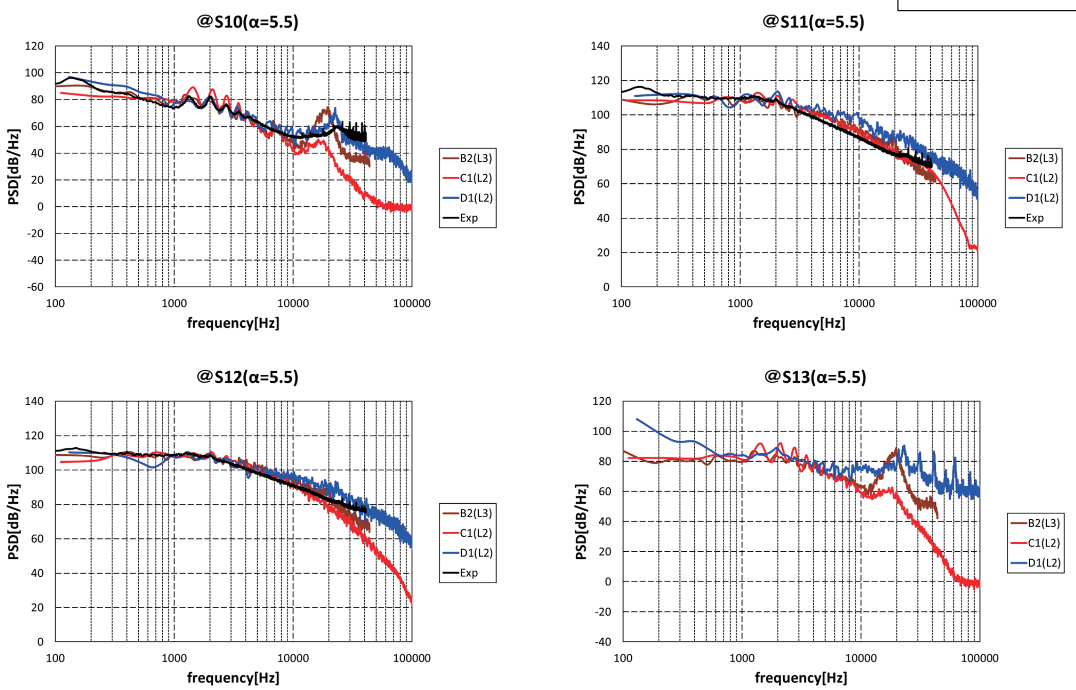
PSD data position



PSD comparison

B2:FaSTAR(L3)
C1:FaSTAR(L2)
D1:Present



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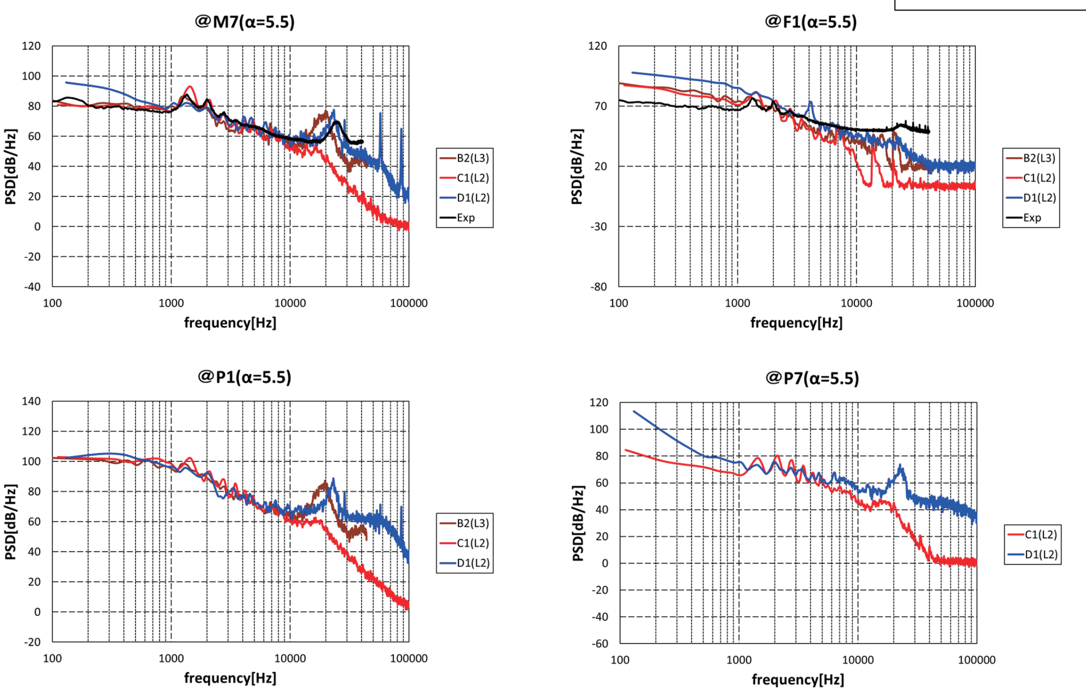
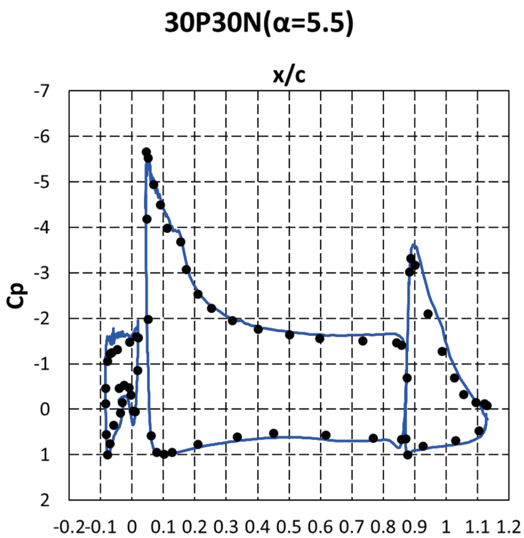
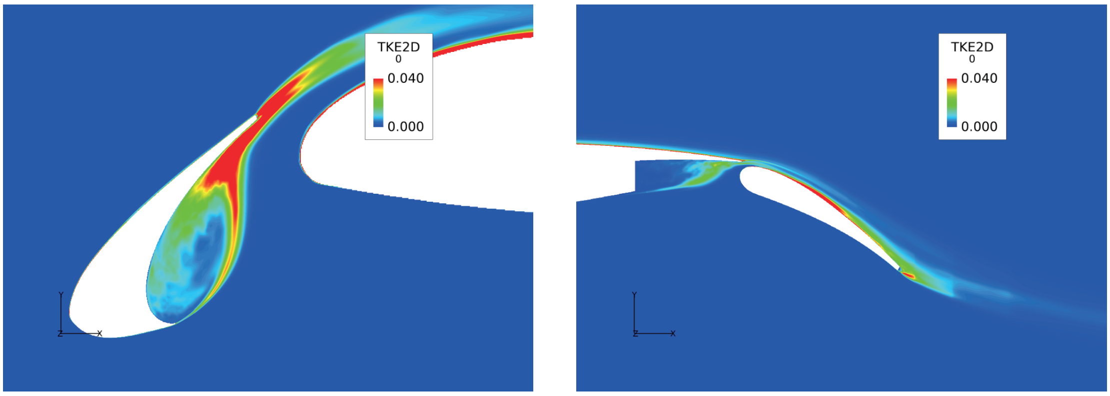


Time-averaged Cp



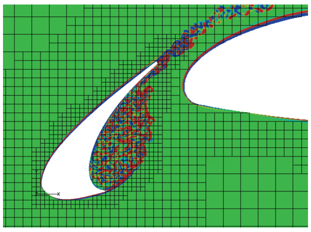
- LBM overestimated Cp at slat and flap ⇒ due to the outer domain size?
- BL thickness at slat-TE may be changed slightly compared other CFD results due to the flow acceleration at flap suction.

TKE2D



Conclusions

- NBPs were well captured by present approach.
- The peak from slat-TE was slightly shifted to higher region compared to NS results, but reasonable agreement was obtained with experimental data.
- Future works
  - Grid convergence
  - Effect of local mesh refinement based on flow field



Thank you for your kind attention.