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マルチブロック型の直交格子を用いた格子ボルツマン法によるNASA-CRMの非定常流体解析

Unsteady Flow Simulation around NASA-CRM by Lattice Boltzmann Method with Multi-Block Cartesian Grid

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Outline

- Background/Objectives
- Numerical Method
  - Lattice Boltzmann Method
  - Building-Cube Method
  - Wall Model in Present Approach
- Numerical Results
- Summary/Conclusion

Background/Objectives

- These days, Lattice Boltzmann Method（LBM） has achieved a significant progress in turbulent flow simulations.
  - PowerFlow, Xflow, LaBS, LAVA, OpenLB, etc

- Characteristics of Lattice Boltzmann Method:
  - No non-linear term in governing equation
  - Asymptotic to Navier-Stokes equation (Kn<<1, M<<1)
  - Weak compression
  - Explicit scheme only, but CFL=1
  - Easy to program/parallelize, Compact stencils, Fast computation

- Research objectives:
  - To realize “One Day Solution” of unsteady flow simulation.
  - To investigate the capability of present approach through APC-6.

Lattice Boltzmann Method

- Lattice Boltzmann equation
  - Collision: $f_i^*(\mathbf{r},t) = f_i(\mathbf{r},t) - \omega_i(f_i(\mathbf{r},t) - f_i^{eq}(\mathbf{r},t))$
  - Stream: $f_i(\mathbf{r}+\mathbf{c}_i\Delta t, t+\Delta t) = f_i^*(\mathbf{r},t)$

f_i	: Distribution function
f_i^{eq}	: Equilibrium function
$\mathbf{c}_i$	: Particle velocity
ω_i	: Relaxation frequency
τ	: Relaxation time coefficient

- Macroscopic variables
  - density: $\rho = \sum_i f_i$
  - momentum: $\rho\mathbf{u} = \sum_i \mathbf{c}_i f_i$

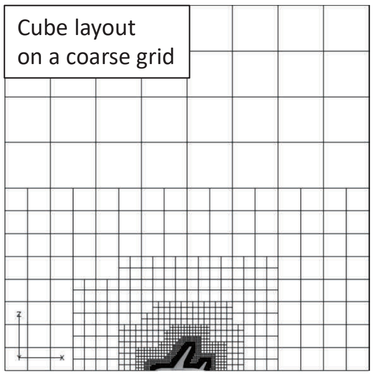
- Cumulant LBM is used for the collision operator[1].
  - Cumulant: $c_{\alpha\beta\gamma} = e^{-(\alpha+\beta+\gamma)} \frac{\partial^{\alpha+\beta+\gamma}}{\partial\Xi_x^\alpha \partial\Xi_y^\beta \partial\Xi_z^\gamma} \ln\{F(\Xi_x,\Xi_y,\Xi_z)\}\big|_{\Xi_x,\Xi_y,\Xi_z=0}$ $(\alpha,\beta,\gamma = 0,1,2)$
  - Collision of cumulant: $c^*_{\alpha\beta\gamma} = c_{\alpha\beta\gamma} - \omega_{\alpha\beta\gamma}\left(c_{\alpha\beta\gamma} - c^{eq}_{\alpha\beta\gamma}\right)$
  - This approach is the implicit LES.

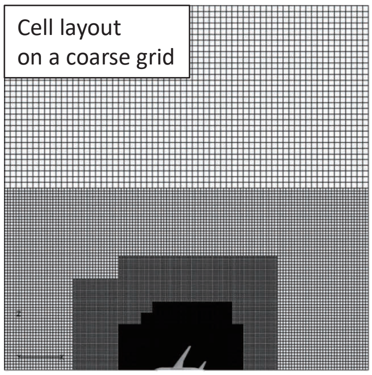
[1] Geier, M., et al., Comput. Math. with Appl.(2015)

Building-Cube Method

- Computational domain is divided into “Cubes”.
- Each cube has a uniform-spacing Cartesian grid, “Cells”.
- Grid information （Custom Grid）

Grid	Coarse	Fine
Cube	65,899	219,948
Cell	8^3	8^3
Total points	33,740,288	112,613,376
Δx_{min}	$7.81 \times 10^{-3} L$	$3.91 \times 10^{-3} L$
Dimain size	$64L \times 64L \times 64L$	$64L \times 64L \times 64L$





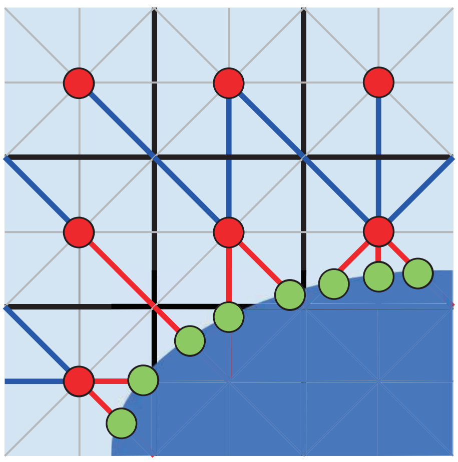
Wall Boundary Treatment

- Following bounce-back boundary condition is used[2].

$$f_{\bar{i}\bar{j}\bar{k}xyz(t+\Delta t)} = \frac{1}{q_{ijk}+1} f^{w}_{\bar{i}\bar{j}\bar{k}t} + \frac{q_{ijk}}{q_{ijk}+1} f_{\bar{i}\bar{j}\bar{k}(x+\bar{i}c\Delta t)(y+\bar{j}c\Delta t)(z+\bar{k}c\Delta t)(t+\Delta t)}$$

$$f^{w}_{\bar{i}\bar{j}\bar{k}t} = f^{w}_{ijkt} - 6\omega_{ijk}(iu_w + jv_w + kw_w)$$

$$f^{w}_{ijkt} = (1-q_{ijk}) f_{ijkxyzt} + q_{ijk} f_{ijk(x+ic\Delta t)(y+jc\Delta t)(z+kc\Delta t)(t+\Delta t)}$$

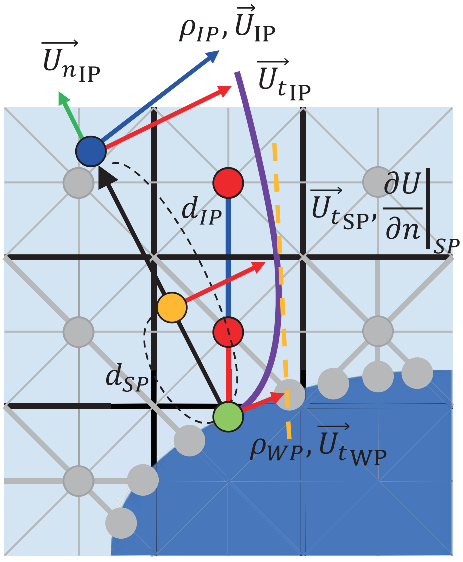


Slip wall velocity：(u_w, v_w, w_w)

[2] Geier, M., et al., Comput. Math. with Appl.(2015)

Wall Model in Present Approach

- Slip wall velocity is introduced at wall boundary[3].
- Eddy viscosity is introduced near wall boundary to reproduce realistic flow near wall boundary[3].



Slip wall velocity

- $d_{IP} = \alpha\, \Delta x_{min}\ (\alpha = 1.75)$
- $\rho_{WP} = \rho_{IP}$
- $y_{IP}^{+} = F_{Spalding}(u_{IP}^{+}) \rightarrow u_\tau$
- $y_{SP}^{+} = \max(100, y_{IP}^{+}) \rightarrow y_{SP}^{+}, u_{SP}^{+}, d_{SP}, \vec{U}_{tSP}, \frac{\partial U}{\partial n}\Big|_{SP}$
- $\vec{U}_{tWP} = (u_w, v_w, w_w) = \vec{U}_{tSP} - \frac{\partial U}{\partial n}\Big|_{SP} \cdot d_{SP}$

Eddy viscosity

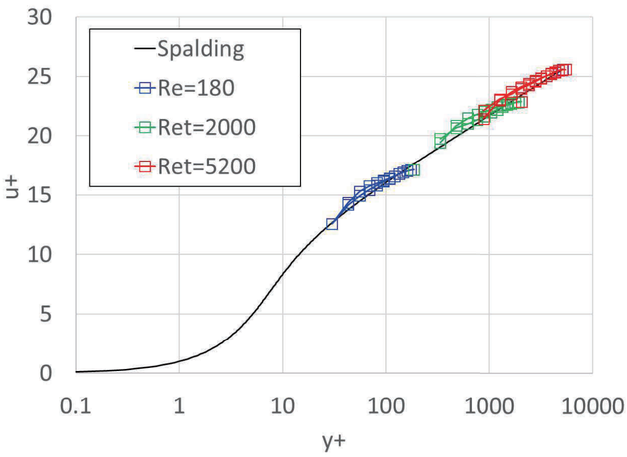
- $\nu_t = \kappa u_\tau d_{IP} \beta$

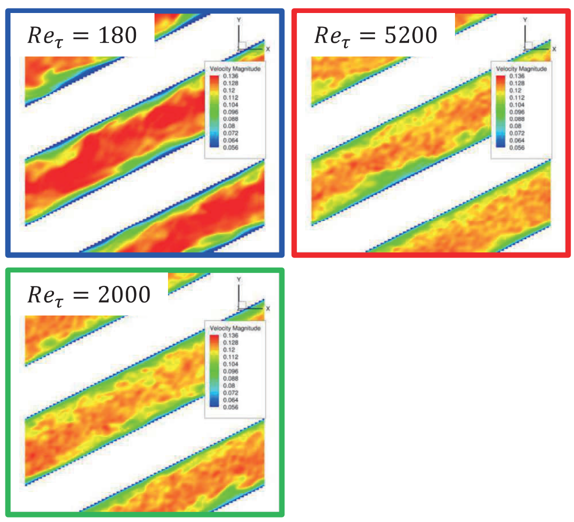
$$\beta = \left(\min\left(\frac{d_{IP} - d}{d_{IP} - 0.5 d_{IP}}, 1\right)\right)^2 \quad (0 \le d \le d_{IP})$$

[3] Maeyama, H., et al., AIAA AVIATION Forum (2020)

Validation of Current Wall Model

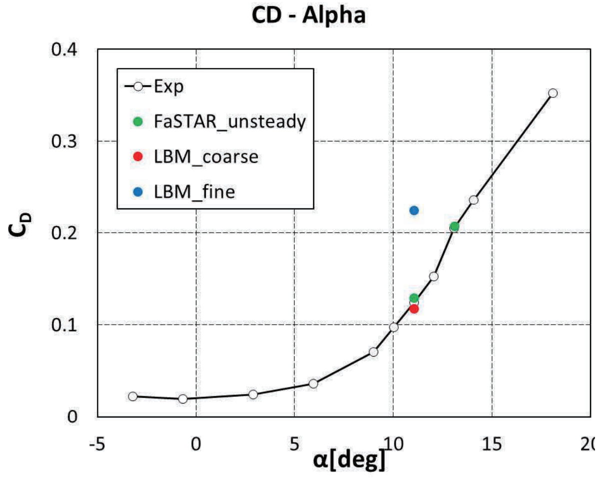
- Oblique periodic turbulent channel flow was computed at $Re_\tau = 180, 2000, and\ 5200$.
  - $\theta = atan(0.5) \approx 27°, M_\infty = 0.2, \Delta x = 1/16$

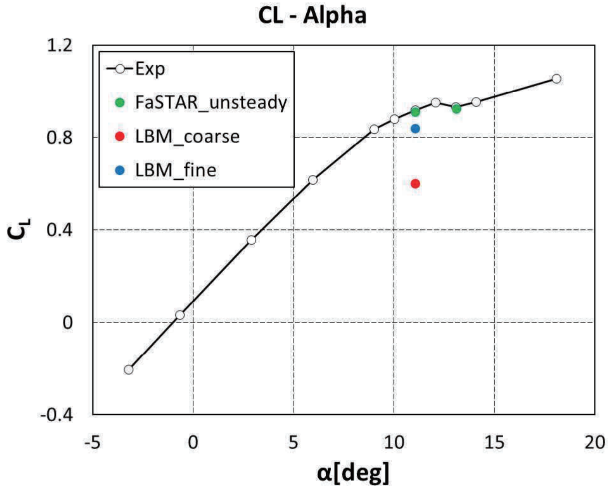




Aerodynamic Coefficients

- Flow Conditions（APC-6 Conditions）
  - Mach number $M = 0.168$
  - Reynolds number $Re = 1.06 \times 10^6$
  - Angle of attack $\alpha = 11.05\mathrm{deg}$





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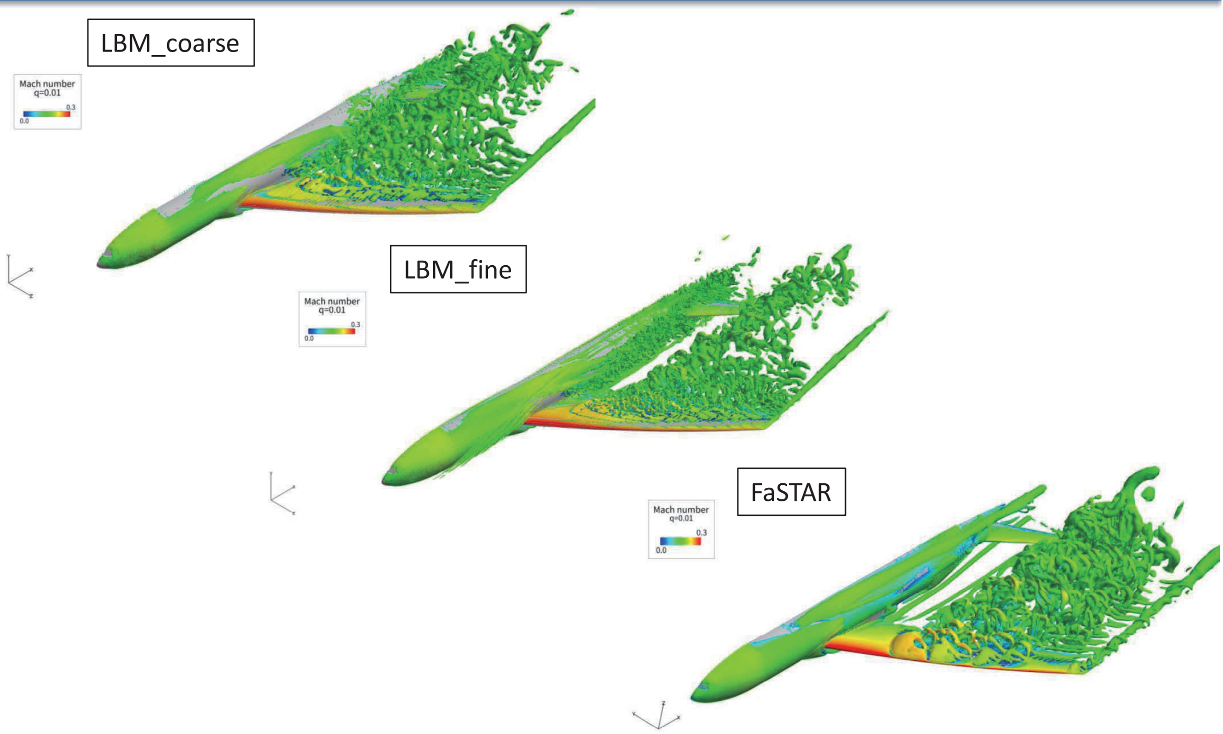
Q-Criterion



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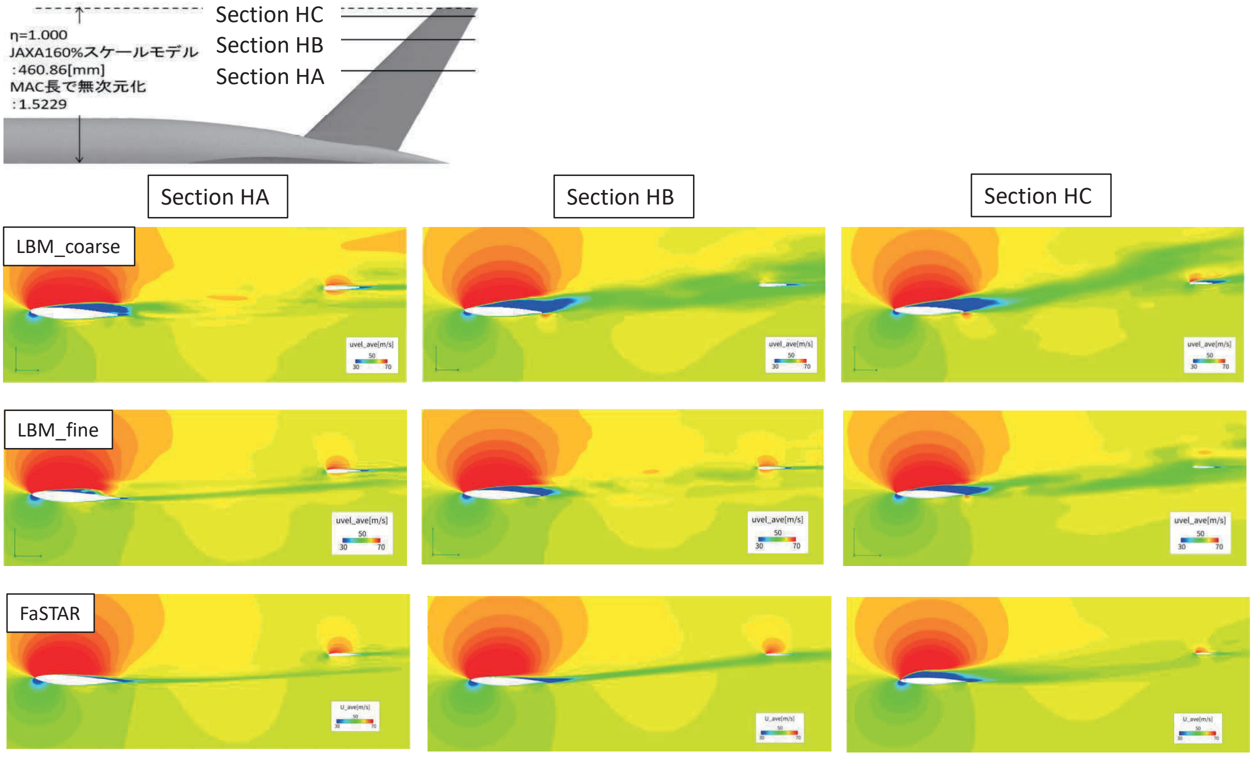
Time-Averaged Flow Field



Summary/Conclusion

- Wall model was implemented in the current LBM framework.
  - Slip wall velocity and eddy viscosity were introduced near wall boundary.
  - WMLES was conducted for oblique turbulent channel flow and its results showed reasonable agreement with law of the wall.

- WMLES around NASA-CRM was conducted.
  - Separated flow around complex geometry was captured stably.
  - Separated region differed from FaSTAR.
  - In the coarse grid analysis, CL was underestimated compared to CL of the experimental data and FaSTAR.
  - In the fine grid analysis, CD was overestimated compared to CD of the experimental data and FaSTAR.