Numerical Simulations of Compressible Flow around the NASA-CRM using Cartesian Cut-Cell Method with Wall-Stress Model

壁面応力モデルを適用した直交カットセル法によるNASA-CRMまわりの圧縮性流れの数値解析

Yuta Takahashi, Yuki Takeda,
Karin Matsubara, Kazuyuki Ueno
(Iwate University)

Cartesian Grid Method

Characteristics of Cartesian grid
- Easy grid generation and full automation
- Fast and robust grid generation

→ One of the most useful computational methods for complex shaped object

Typical Cartesian grid method
- Cartesian Cut-Cell Method
- Voxel Method
- Immersed Boundary Method

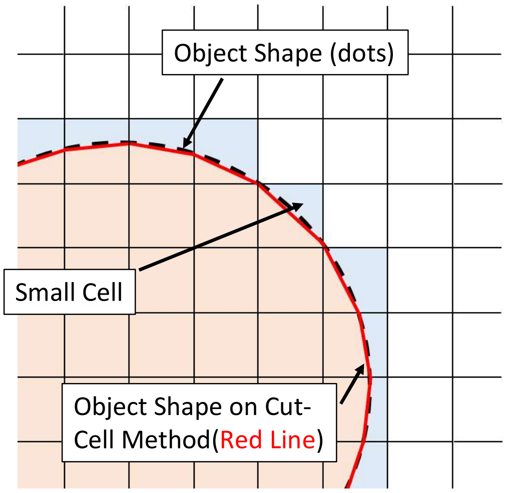
Cartesian Cut-Cell Method

Cut-Cell method cuts the computation cells according to object shape.

- Smoother surface than voxel method.
- Satisfy the mass conservation law.
  (IB method is not satisfy.)

On the other hand…

- Need to be divided into a large number of cases depending on many cutting patterns.
- Problem of CFL condition in small cells.



Objective

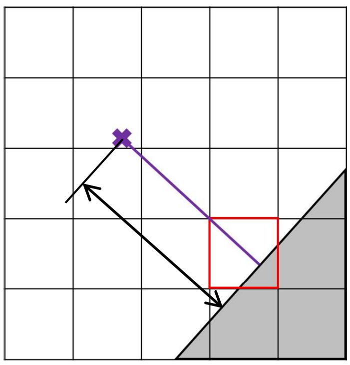
Aerodynamic prediction on the NASA-CRM using Cartesian Cut-Cell Method with Wall-Stress Model is performed.

Simulation Method

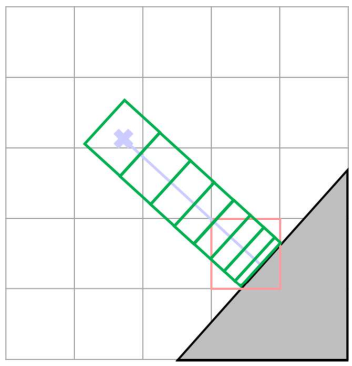
Conservation Equation	Compressible Navier-Stokes Equation
Wall Shear Stress	Wall-Stress Model[1]
Discretization Method	Cell-Centered Finite Volume Method
Wall Treatment	Cartesian Cut-Cell Method
Inviscid Flux	SLAU （5th-Order MUSCL + Thornber's Modification）
Viscous Flux	2nd-Order Central Difference
Time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

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

Wall-Stress Model for Cut-Cell Method

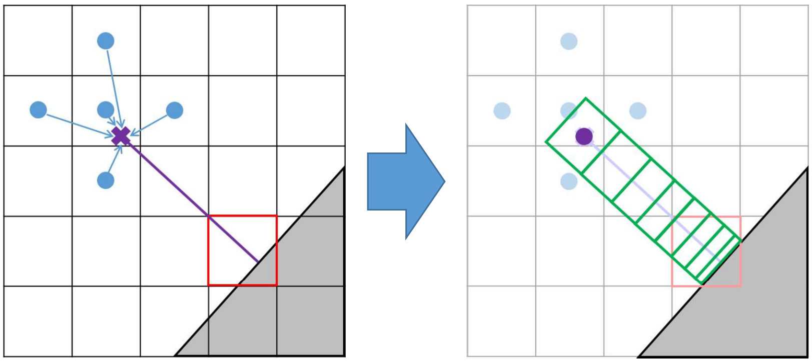


1) Extend the probe vertically from the wall.



2) Generate virtual grid system (1D) in the vertical direction of the wall, based on the extended probe.

Wall-Stress Model for Cut-Cell Method



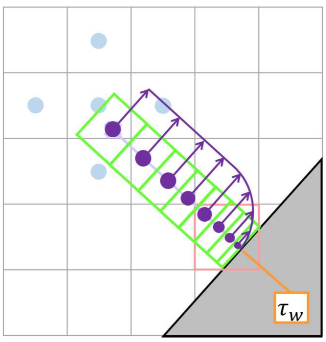
Inverse Distance Weighted Interpolation

$$Q = \frac{\sum_{i=1}^{n} w_i Q_i}{\sum_{i=1}^{n} w_i}$$

$$w_i = \frac{1}{\sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}}$$

3) The values at the probe tip are interpolated from the neighboring cell-centers by Inverse Distance Weighted Interpolation, and input as a boundary condition for Wall-Stress Model.

Wall-Stress Model for Cut-Cell Method

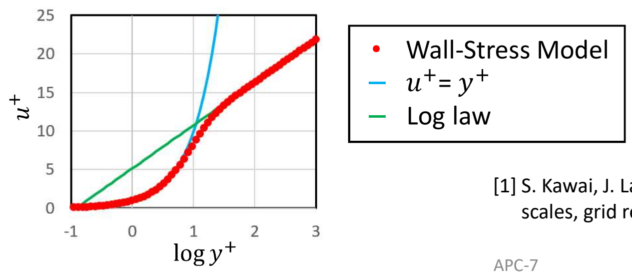


4) Solve the Wall-Stress Model Equation[1] to obtain τ_w, and apply τ_w to the Cut-Cell as the wall flux.

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

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

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



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

Computational Conditions

Case2 : Unsteady computation

-Mach number : $M_\infty = 0.168$

-Reynolds number : $Re_c = 1.06 \times 10^6$

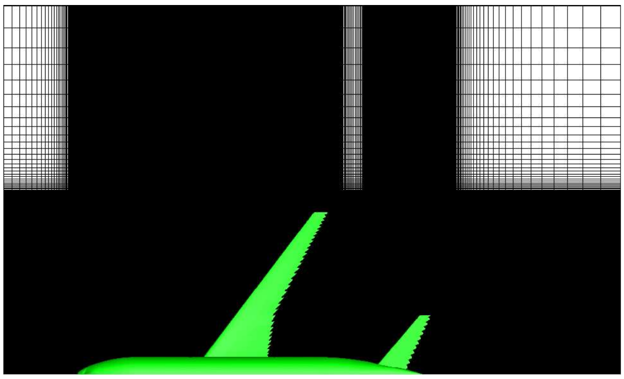
-Reference temperature : $T_{ref} = 310$ K

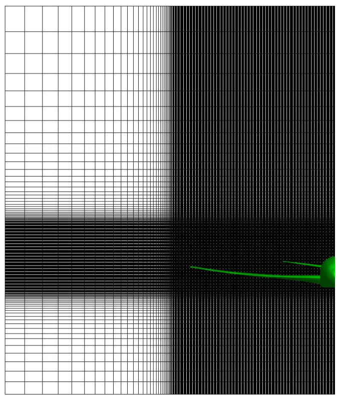
-Angle of attack : $\alpha = 11.05°$

Computational Grid

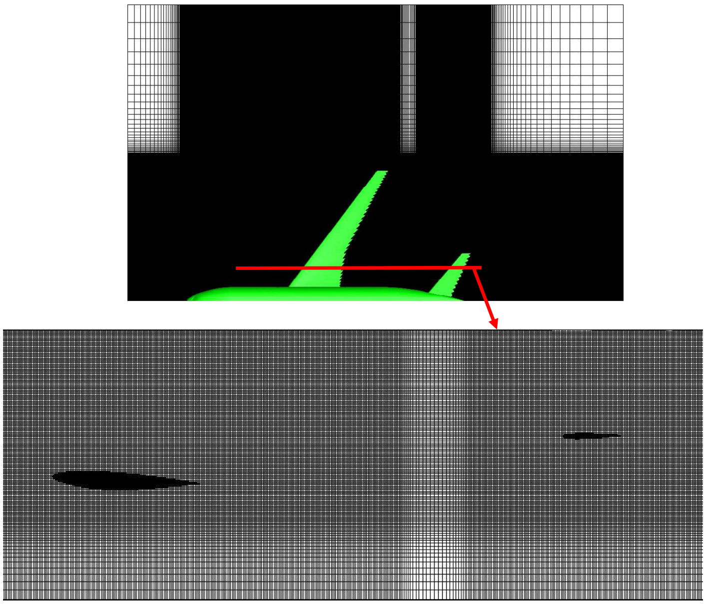
Cartesian grid（Uniform＋Non-Uniform）

	Minimum cell size Δx ($\Delta x / C_{ref}$)	Total cell number
Coarse	0.1 m (1.43×10^{-2})	54,737,280 cells（$731 \times 360 \times 208$）
Fine	0.05 m (7.14×10^{-3})	379,011,072 cells($1402 \times 704 \times 384$)

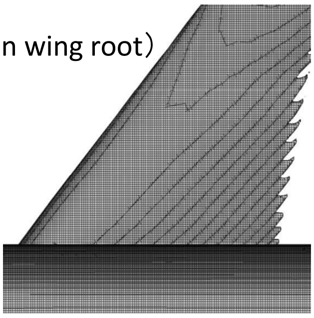




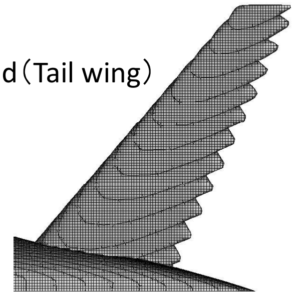
Computational Grid (Coarse)



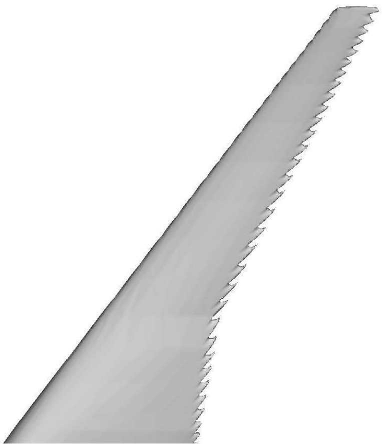
Surface grid（Main wing root）



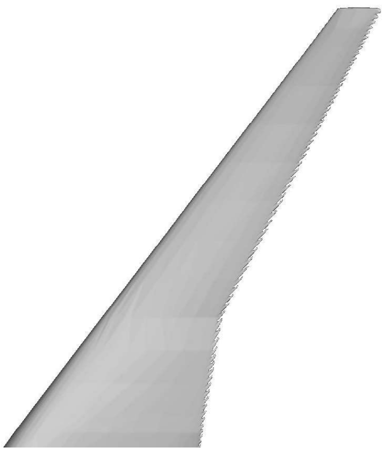
Surface grid（Tail wing）



Shape of Wing Trailing Edge

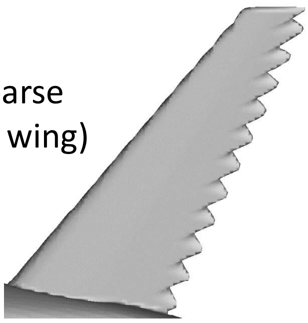


Coarse (Main wing)

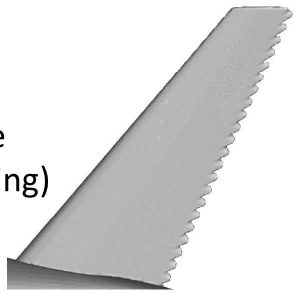


Fine (Main wing)

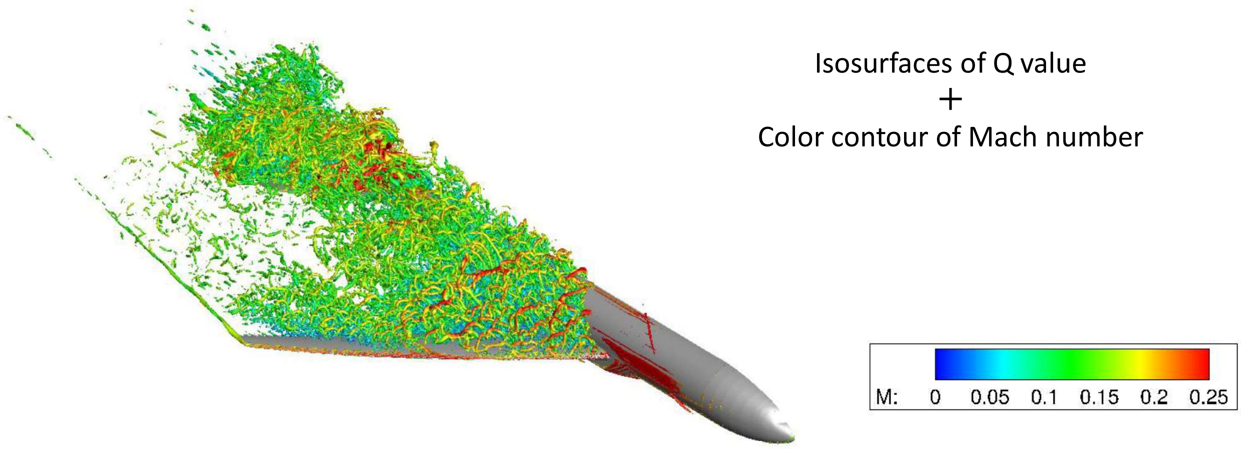
Coarse
(Tail wing)



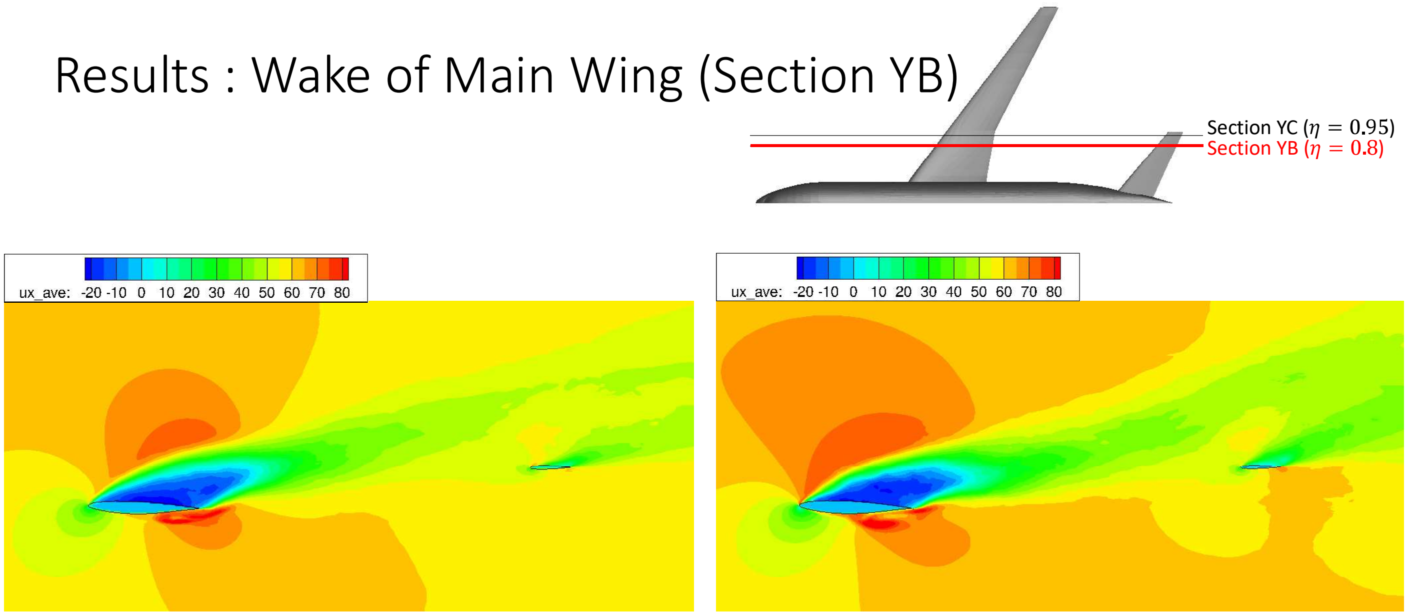
Fine
(Tail wing)



Results : Flow Field (Coarse)



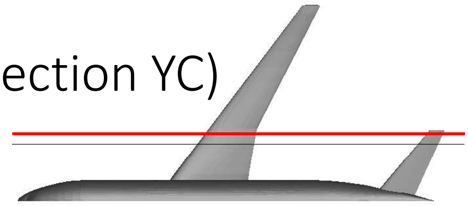
Results : Wake of Main Wing (Section YB)

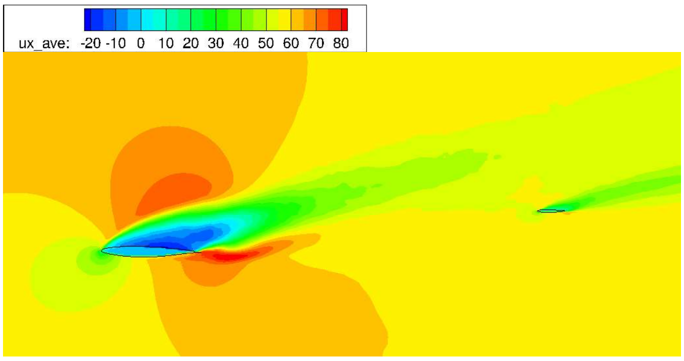


Time-averaged flow field (Coarse)

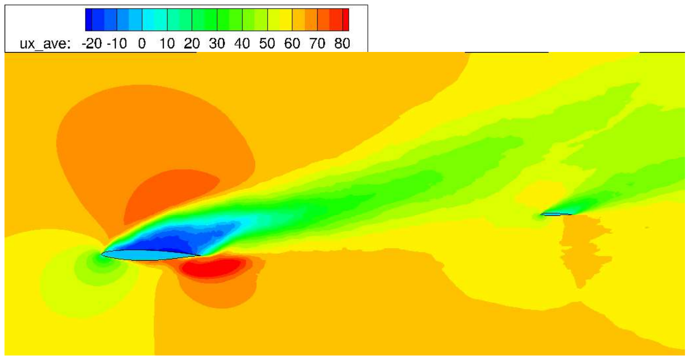
Time-averaged flow field (Fine)

Results : Wake of Main Wing (Section YC)



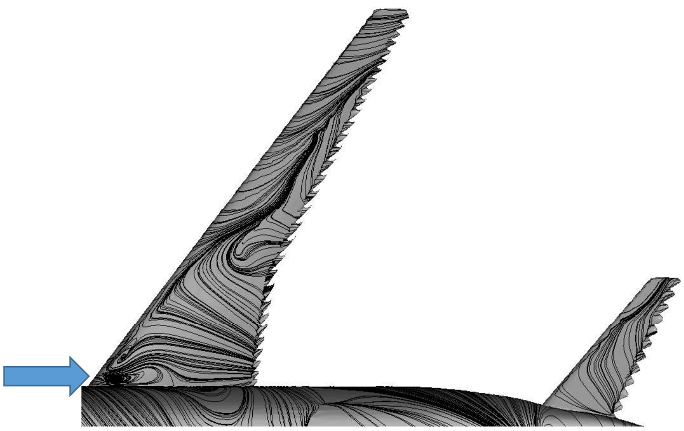


Time-averaged flow field (Coarse)

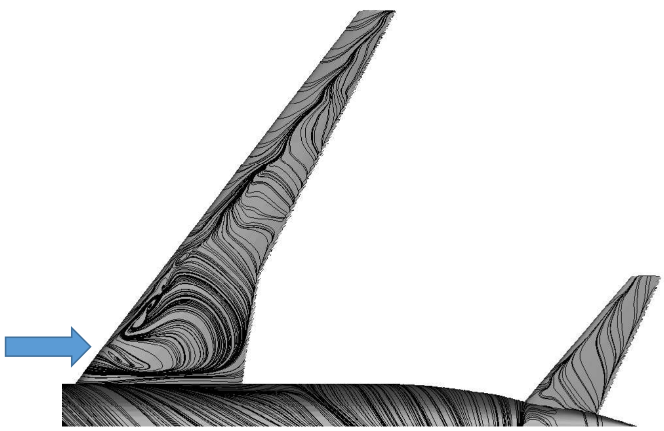


Time-averaged flow field (Fine)

Results : Surface Streamline (Time-averaged)



Coarse



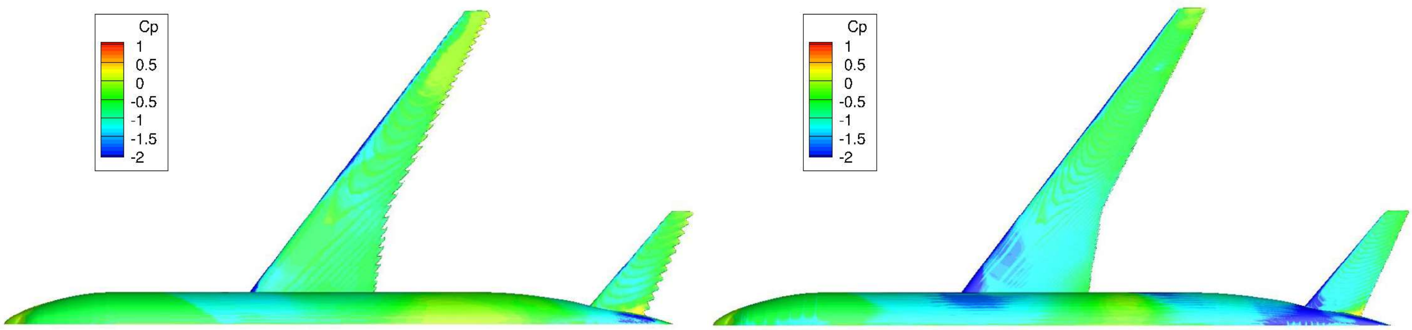
Fine

Results : Aerodynamic Coefficients (C_L, C_D, C_M)

	C_L	C_D	C_M
Exp. [2]	0.9172	0.1247	-0.0537
Coarse	0.9687	0.1440	-0.1601
Fine	1.300	0.2884	-0.4612

[2] T. Uchiyama et al. , “Experimental Investigation of 160% Scaled NASA Common Research Model at Low Speed Conditions ", 7-11 January 2019, San Diego, California, AIAA Scitech 2019 Forum, AIAA 2019-2190.

Result : Pressure Coefficient C_p



Coarse　Fine

Conclusion

Numerical simulations of compressible flow around the NASA-CRM using Cartesian Cut-Cell Method with Wall-Stress Model were performed.

- The position of leading edge separation of main wing approaches the experiment by increasing grid resolution.
- Both Coarse grid and Fine grid, wake of main wing passed above the tail wing.
- Lift coefficient and Drag coefficient of Coarse grid were close to that of the experiment.
- Lift coefficient and Drag coefficient of Fine grid was overestimated compared to Coarse grid and experiment.