階層直交格子フレームワークCUBEによる空気力学予測チャレンジ・金 相元（理研），

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佐々木 大輔（大阪公立大），坪倉 誠（理研），橋本 和典（金沢工大）

2023.7.12 Ninth Aerodynamics Prediction Challenge (APC-9)

Aerodynamics Prediction Challenge with CUBE, Hierarchical Mesh Framework

階層直交格子フレームワークCUBEによる空気力学予測チャレンジ

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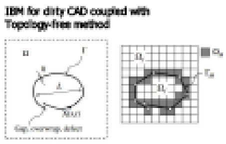
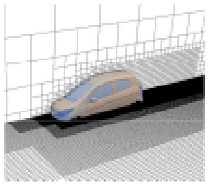
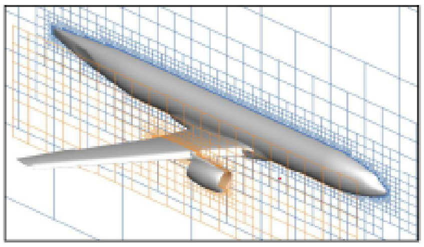
Background and Objectives

- CUBE (Complex Unified Building cubE)
  - Hierarchically structured FVM (Jansson et al., 2018).
    - Building Cube Method : Discretized into hierarchical cubic units
    - Immersed Boundary Method for dirty CAD object
- Recently implemented KEEP Scheme for Acoustic applications
  - Original framework (FFVHC-ACE) used same BCM method
    - Implement of KEEP scheme didn't take much time
  - While, used different method for objects (FFVHC-ACE : Solid)
    - Other models (Turbulent and wall models, etc)
    - Under validation and verification of KEEP scheme for CUBE







FFVHC-ACE (H. Asada et al., 2023)

Acoustic problem on external flow of car

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Numerical condition

◆Kinetic Energy and Entropy Preserving (KEEP) Scheme (Y. Kuya, 2018, Y. Kuya, 2020)

- Convective Flux scheme for satisfying Primary and secondary conservative parameters
  - Primary conservative parameters (Mass, Momentum, and Total energy)
  - Secondary conservative parameters (Kinetic energy and Entropy)
- 2nd order central difference / Stable calculated without artificial viscosity
- Hanging nodes (Changing size from cube interface) also satisfy conservated

Primary conservative parameter

Mass ρ, Momentumρu, Total Energy$E$

$$\frac{\partial Q}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}+\frac{\partial H}{\partial z}=0$$

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ E\end{bmatrix},F=\begin{bmatrix}\rho\\ \rho uu+p\\ \rho uv\\ \rho uw\\ (E+p)u\end{bmatrix},F=\begin{bmatrix}\rho v\\ \rho uv\\ \rho vv+p\\ \rho vw\\ (E+p)v\end{bmatrix},H=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho ww+p\\ (E+p)w\end{bmatrix}$$

$$E=\rho k+\rho e, k=\frac{u^2+v^2+w^2}{2}$$

Secondary conservative parameter

Kinetic Energy ρk(1D)

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho k u}{\partial x}+u\frac{\partial p}{\partial x}=0$$

Entropy ρs (1D)

$$\frac{\partial \rho s}{\partial t}+\frac{\partial \rho s u}{\partial x}=0$$

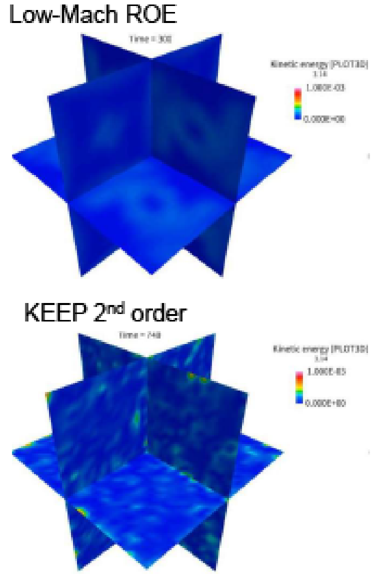
if

In incompressible limit,

$$\frac{\partial u}{\partial x}=0, u\frac{\partial p}{\partial x}=\frac{\partial (up)}{\partial x}$$

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}=0$$

$$\frac{\partial \rho e}{\partial t}+\frac{\partial \rho e u}{\partial x}+p\frac{\partial u}{\partial x}=0$$



Y. Kuya, K. Totani, and S. Kawai, "Kinetic energy and entropy preserving schemes for compressible flows by split convective forms", J. Comput. Phys., 375, (2018) 823-853.
Y. Kuya, K. Totani, and S. Kawai, "A stable and non-dissipative kinetic energy and entropy preserving (KEEP) scheme for non- conforming block boundaries on Cartesian grids", Computers and Fluids, 200, 104427, (2020).

Numerical condition

◆Numerical Filter for KEEP scheme (Asada and Kawai, 2023)

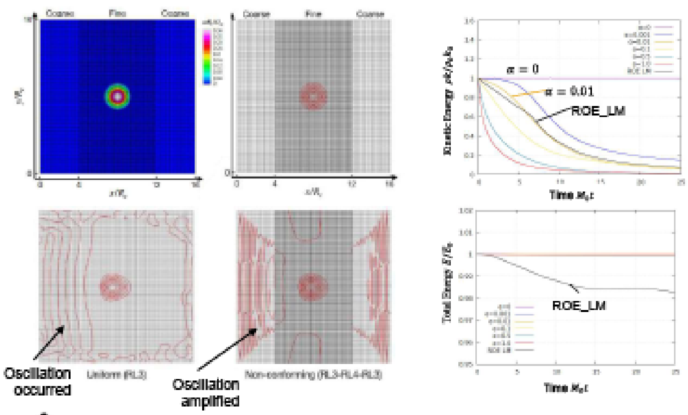
- Phase error and numerical oscillation due to 2nd-order central difference scheme
  - Amplitude from hanging node and object shape
- Finite-volume-concept Padé-type filtering schemes (In this study, 4th-order scheme)
- Low-pass filtering schemes to maintain numerical stability (filter strength, α=0~1)

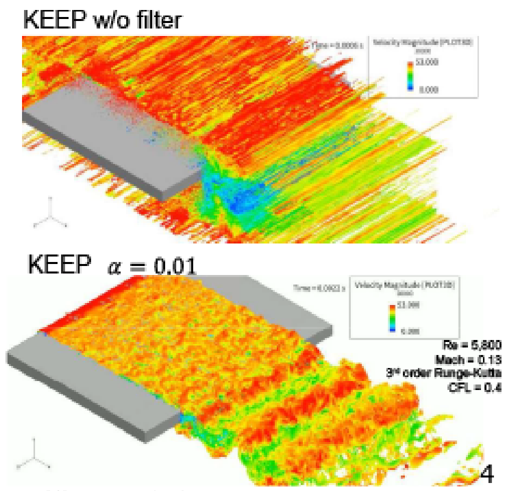
$\bar{q}$: filtered conservative properties $(\rho,\rho u,\rho v,\rho w,E)$

$$\bar{q}_i=q_i-\alpha\left(f_{i+1/2}-f_{i-1/2}\right)$$

$$f_{i+1/2}=\left[b_0(q_{i+1}-q_i)+b_1(q_{i+2}-q_{i-1})\right]$$

2D Inviscid vortex convection (Y. Kuya, 2020)





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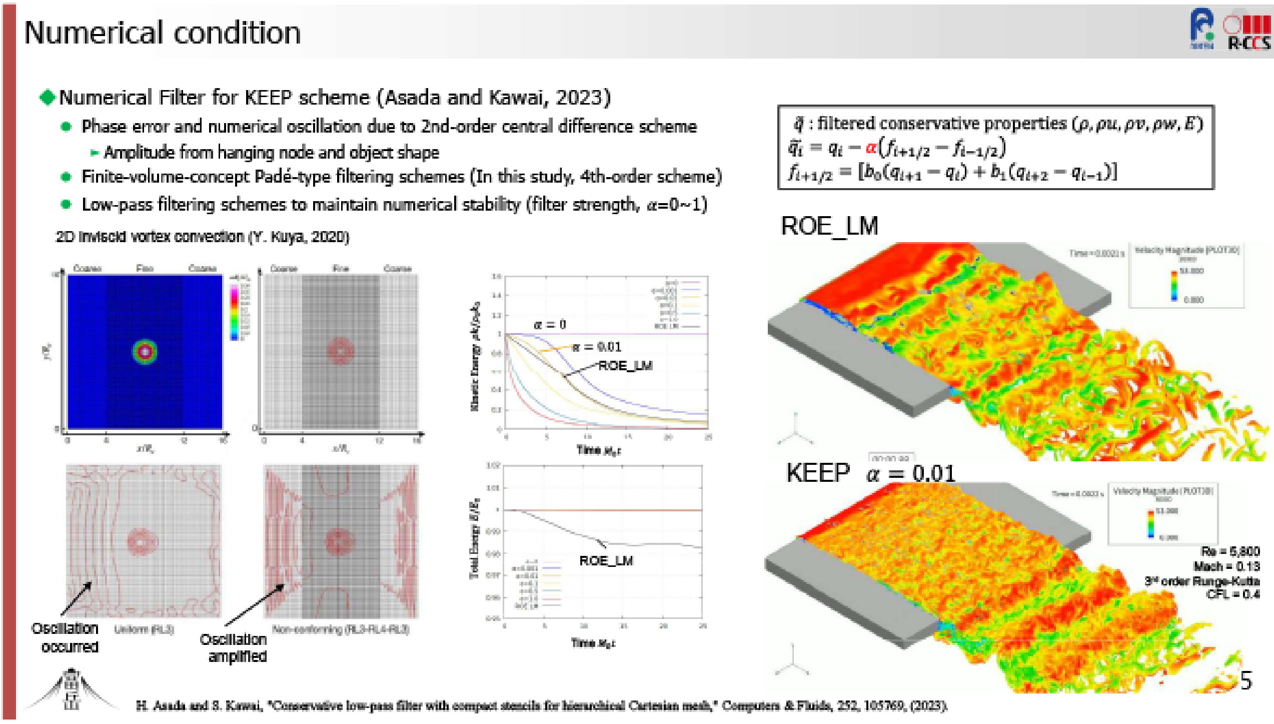
H. Asada and S. Kawai, "Conservative low-pass filter with compact stencils for hierarchical Cartesian mesh," Computers & Fluids, 252, 105769, (2023).


Numerical condition
Numerical Filter for KEEP scheme (Asada and Kawai, 2023)
Phase error and numerical oscillation due to 2nd-order central difference scheme
Amplitude from hanging node and object shape
Finite-volume-concept Padé-type filtering schemes (In this study, 4th-order scheme)
Low-pass filtering schemes to maintain numerical stability (filter strength, α=0~1)
$\tilde{q}$: filtered conservative properties $(\rho, \rho u, \rho v, \rho w, E)$
$\tilde{q}_i = q_i - \alpha(f_{i+1/2} - f_{i-1/2})$
$f_{i+1/2} = [b_0(q_{i+1} - q_i) + b_1(q_{i+2} - q_{i-1})]$
2D Inviscid vortex convection (Y. Kuya, 2020)
Oscillation occurred
Uniform (RL3)
Oscillation amplified
Non-conforming (RL3-RL4-RL3)
$\alpha = 0$
$\alpha = 0.01$
ROE_LM
ROE_LM
KEEP $\alpha = 0.01$
Re = 5,800
Mach = 0.13
3rd order Runge-Kutta
CFL = 0.4
H. Asada and S. Kawai, "Conservative low-pass filter with compact stencils for hierarchical Cartesian mesh," Computers & Fluids, 252, 105769, (2023).
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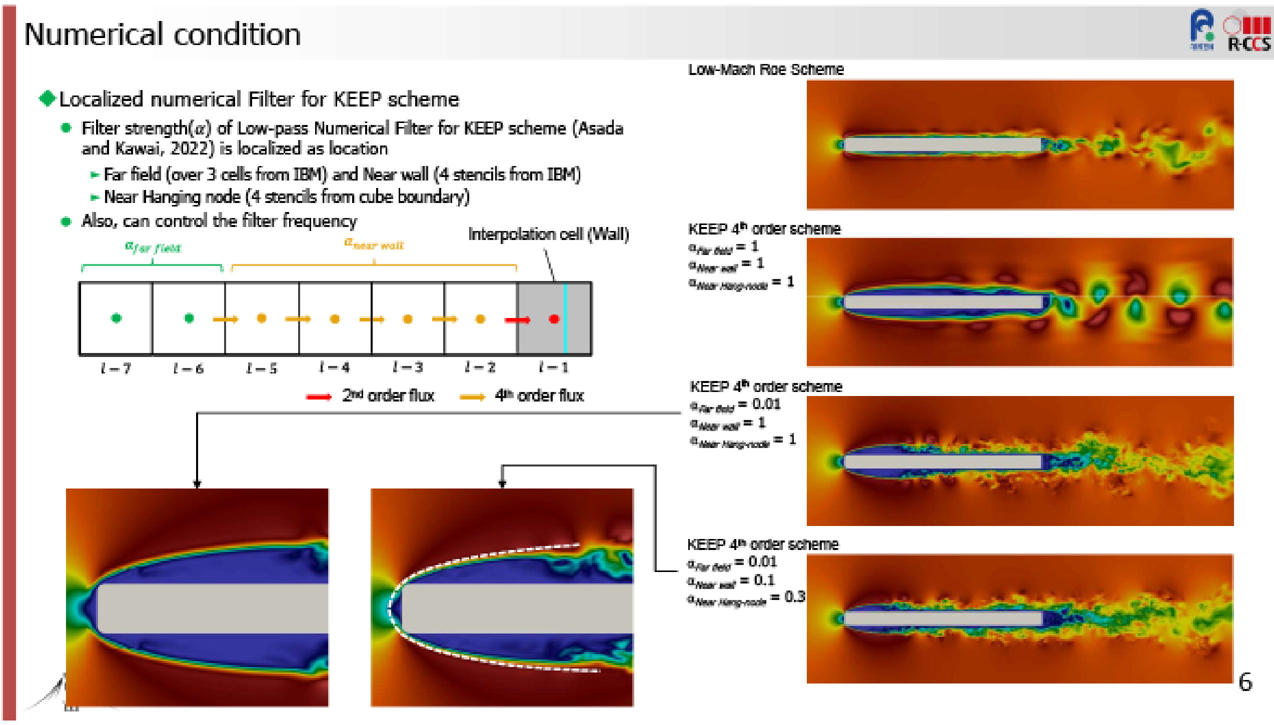
Numerical condition
Localized numerical Filter for KEEP scheme
Filter strength(α) of Low-pass Numerical Filter for KEEP scheme (Asada and Kawai, 2022) is localized as location
Far field (over 3 cells from IBM) and Near wall (4 stencils from IBM)
Near Hanging node (4 stencils from cube boundary)
Also, can control the filter frequency
Interpolation cell (Wall)
$\alpha_{far\ field}$
$\alpha_{near\ wall}$
$i-7$ $i-6$ $i-5$ $i-4$ $i-3$ $i-2$ $i-1$
2nd order flux
4th order flux
Low-Mach Roe Scheme
KEEP 4th order scheme
$\alpha_{Far\ field} = 1$
$\alpha_{Near\ wall} = 1$
$\alpha_{Near\ Hang\text{-}node} = 1$
KEEP 4th order scheme
$\alpha_{Far\ field} = 0.01$
$\alpha_{Near\ wall} = 1$
$\alpha_{Near\ Hang\text{-}node} = 1$
KEEP 4th order scheme
$\alpha_{Far\ field} = 0.01$
$\alpha_{Near\ wall} = 0.1$
$\alpha_{Near\ Hang\text{-}node} = 0.3$
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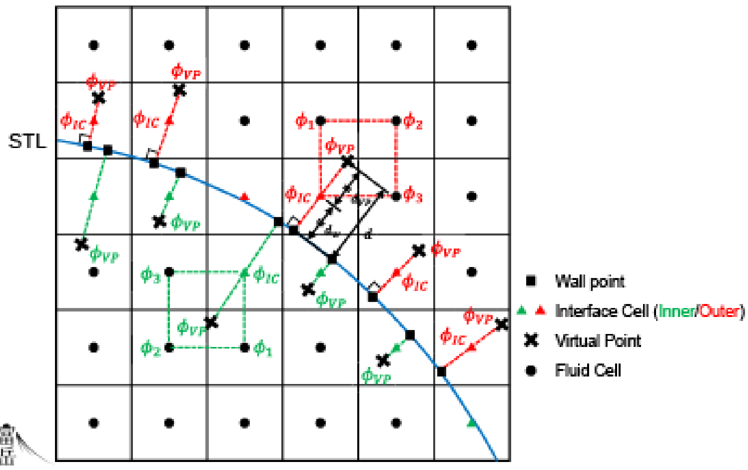
Numerical condition

◆ Immersed boundary method for Compressible solver (Li et al. 2016, 2023)

- Interface cell (IC) : closest cells to the triangle of STL, Must evaluated using interpolation
- Virtual point(VP) : Symmetrically positioned to the wall point (WP) with respect to IC
  - ► By bilinear interpolation surrounding cells
- Depend on the assigned conditions (Dirichlet, Neumann), interface cell is calculated



Dirichlet ($\phi_w = \phi_{assign}$)

$$\phi_{IC} = \frac{1}{2}(\phi_{VP} + \phi_{assign}) = \frac{w_1\phi_1 + w_2\phi_2 + w_3\phi_3 + \phi_{assign}}{2 - w_{IC}}$$

Neumann ($\phi_w = \phi_{IC} = \phi_{VP}$)

$$\phi_{IC} = \phi_{VP} = \frac{w_1\phi_1 + w_2\phi_2 + w_3\phi_3}{1 - w_{IC} + \epsilon}$$

ρ, p : Neumann(Adiabatic)
v : Dirichlet($v_{assign} = 0$)

$$\phi_{VP} = w_1\phi_1 + w_2\phi_2 + w_3\phi_3 + w_{IC}\phi_{IC}$$
$$\phi_{IC} = \frac{1}{2}(\phi_{VP} + \phi_w)$$
$$\phi_w = \phi_{IC} - \frac{\partial\phi}{\partial n}d$$
$$\frac{\partial\phi}{\partial n} = \frac{\phi_{VP} - \phi_w}{d}$$

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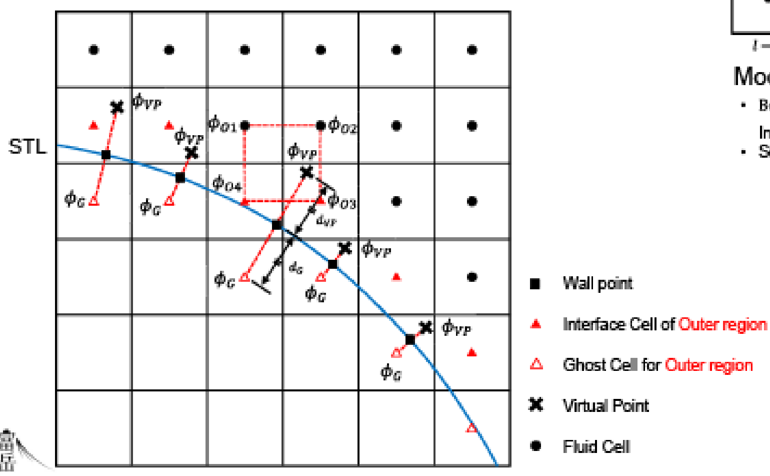
Numerical condition

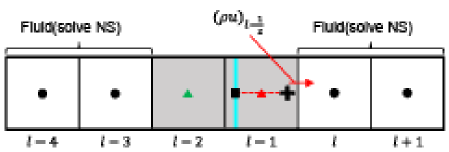
◆ Modified Immersed boundary method for mass conservation

- IC of original IBM are located between WP and VP
  - ► Not solve Navier Stokes at cell located WP → Not satisfy conservation.
- IC of modified IBM located outside WP → ghost cell (GC)
  - ► Solve Navier Stokes at cell located WP → conservation is expected to improve.



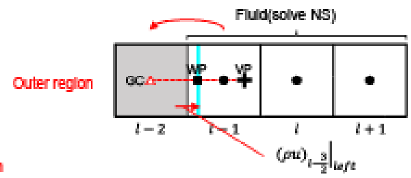
Original IBM

- Boundary flux = $(\rho u)_{i-\frac{1}{2}}$ $u_i > 0 \Rightarrow$ inflow, $u_i < 0 \Rightarrow$ outflow
- Not solve NS at interface cell



Modified IBM

- Boundary flux $(\rho u)_{i-\frac{1}{2}}$
  Inflow or outflow is judged by the distance between WP and GC
- Solve NS at interface cell



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Numerical condition

◆ Modified Immersed boundary method for mass conservation

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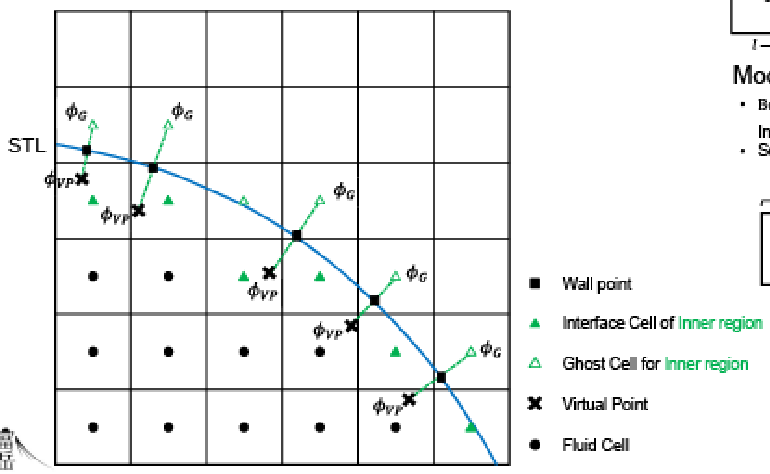
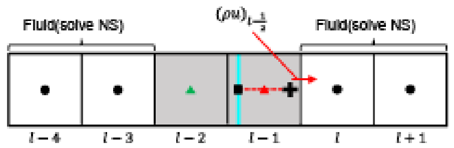
  - Solve Navier Stokes at cell located WP → conservation is expected to improve.



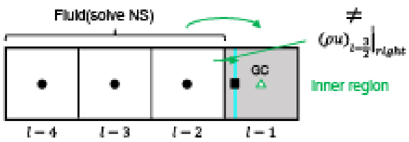
Original IBM

- Boundary flux = $(\rho u)_{i-\frac{1}{2}}$ $u_i > 0 \Rightarrow$ inflow, $u_i < 0 \Rightarrow$ outflow
- Not solve NS at interface cell



Modified IBM

- Boundary flux $(\rho u)_{i-\frac{3}{2}}$
  Inflow or outflow is judged by the distance between WP and GC
- Solve NS at interface cell



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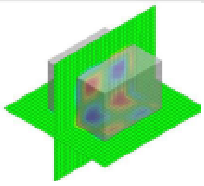
Numerical condition

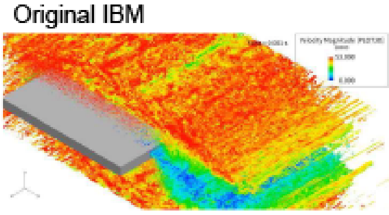
◆ Modified Immersed boundary method for mass conservation

- Taylor-Green Vortex in Solid box
  - Modified IBM conserved mass and energy properly
- Horizontal plate
  - Original IBM showed large numerical oscillation in all direction, boundary layer on IBM are disturbed so that barely developed
  - Numerical oscillation from modified IBM suppressed somewhat, boundary layer on IBM also start to developed

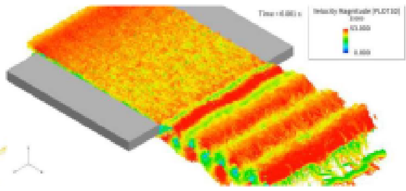


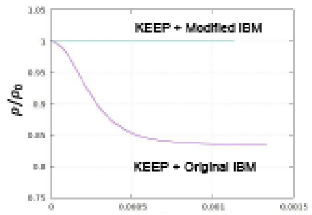
Taylor-Green Vortex in Solid box

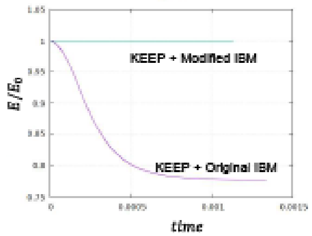
Original IBM



Modified IBM







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9th Aerodynamics Prediction Challenge (APC-9)

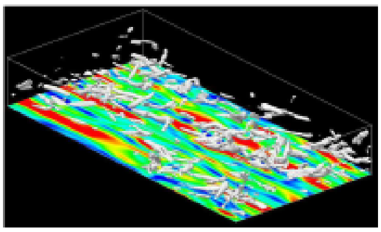
◆ List of Challenge

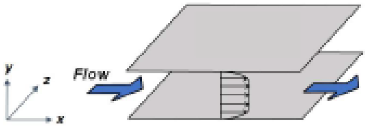
- Challenge 1: Validation Case
  - Verification of Wall-Resolved LES (for those who participate in Challenge 3 and 4)
- Challenge 2: 3D CRM-HL, Wind Tunnel Wall, Steady Analysis (RANS)
- Challenge 3: 3D CRM-HL, uniform flow, unsteady analysis (HRLES, WMLES, etc.) (optional)
- Challenge 4: 3D CRM-HL, wind tunnel wall, unsteady analysis (HRLES, WMLES, etc.) (optional)
- Challenge 5: 3D CRM-HL, uniform flow, steady analysis (RANS), lattice dependency survey (optional)

  *Participation may be limited to some of the above issues

◆ Challenge 1: Verification of Wall-Resolved LES (for Challenge 3 and 4)

- Methodology: WRLES
- Target: Channel Flow
- Grid: Free
- Reynolds number: Re_τ=395
- Comparison data: u+ vs. y+, u_{rms}, v_{rms}, w_{rms}
- DNS Data for Turbulent Channel Flow
- References: R. D. Moser, J. Kim & N. N. Mansour, "Direct numerical simulation of turbulent channel flow up to Re_T=590", Phys. Fluids, Vol. 11, pp 943-945 (1999).

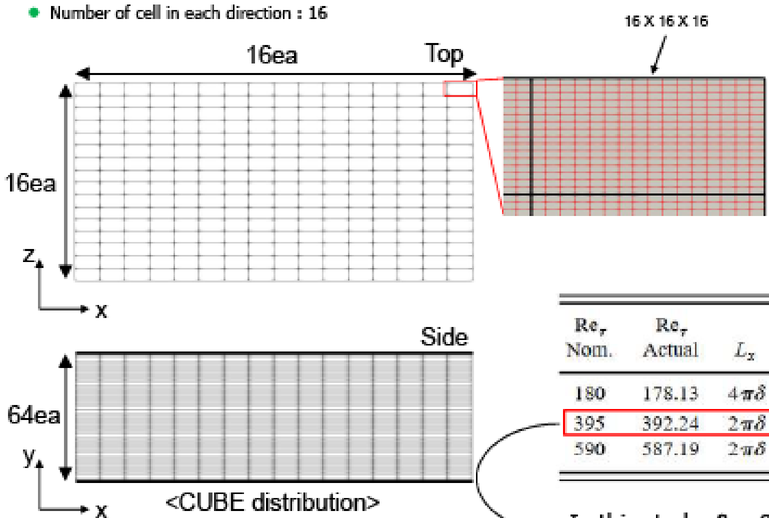




Challenge 1: Validation Case

◆ Numerical conditions

- Mesh : 0.61mm($\Delta x^+ \approx 9.7$), 0.048mm($\Delta y^+ \approx 0.77$), 0.31mm ($\Delta z^+ \approx 4.8$)
- Number of cell in each direction : 16



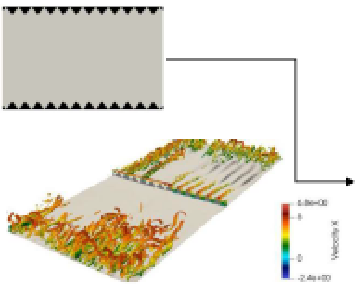
	Scheme
Flux	KEEP (2nd, 4th, 6th, 8th) Low-Mach Roe
Time step	1e-5s
Time integration	LUSGS_SLTS_MIX
Num. CUBE (Num. cell)	16,384 (Approx. 67 Million)
BC	X(Periodic), Z(Periodic) Y(NoSlip)

Re_τ Nom.	Re_τ Actual	L_x	L_z	$N_x \times N_y \times N_z$	Δx^+	Δz^+	Δy_c^+
180	178.13	$4\pi\delta$	$\frac{4}{3}\pi\delta$	128×129×128	17.7	5.9	4.4
395	392.24	$2\pi\delta$	$\pi\delta$	256×193×192	10.0	6.5	6.5
590	587.19	$2\pi\delta$	$\pi\delta$	384×257×384	9.7	4.8	7.2

In this study, δ = 0.05m (Channel height)
Lx : Ly : Lz = 0.157m : 0.05m : 0.0785m

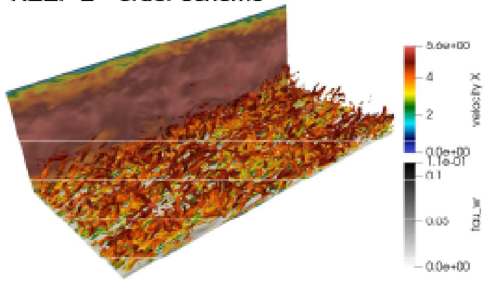
Challenge 1: Validation Case

- Calculation procedure
  - Generated initial perturbation by wedge shape object
  - Main simulation are performed with KEEP 2nd order scheme firstly
  - Turbulent structure is generated properly
- Comparison of Mean velocity / velocity fluctuation
  - Compared with DNS (Moser, Kim, Mansour, 1999) results
  - Current results are perfectly matched with DNS results
    - Velocity fluctuation on both close wall region and far field are matched well

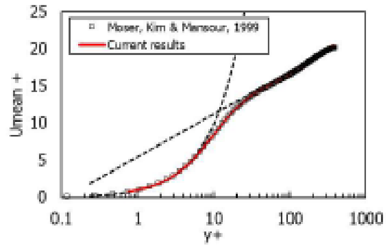


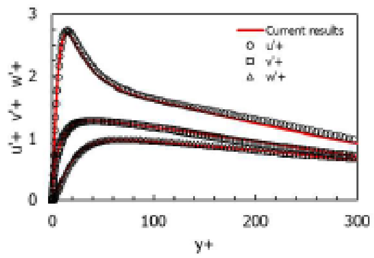
Initial perturbation by Object

KEEP 2nd order scheme



Iso-surface of $Q = 10^5\ s^{-2}$





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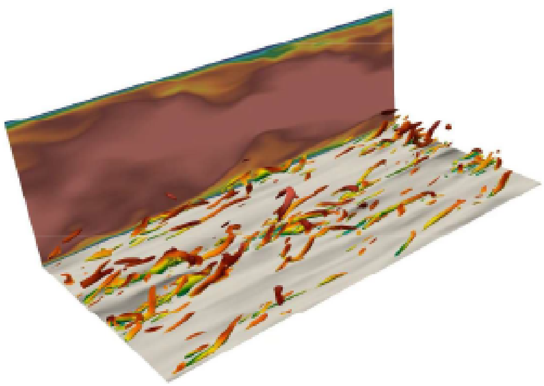
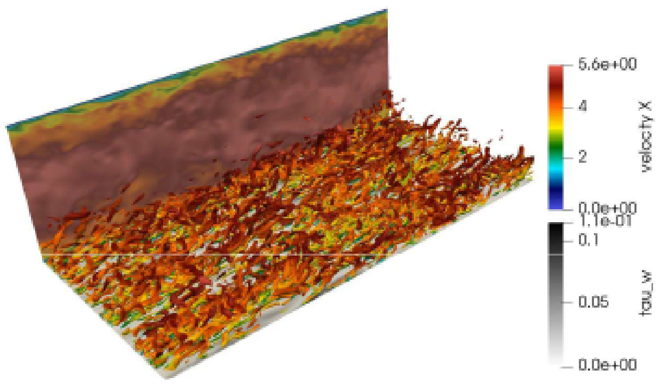
Challenge 1: Validation Case

- Comparison iso-surface of $Q = 10^5\ s^{-2}$ as numerical scheme
  - Low-Mach Roe scheme shows less turbulent structures due to its large dissipation rate
    - Velocity fluctuation on bulk region is barely shown
    - Considered overestimation on bulk flow due to higher velocity
  - KEEP scheme shows finer turbulent structures and velocity fluctuation on bulk region



Low-Mach Roe scheme



KEEP 2nd order scheme

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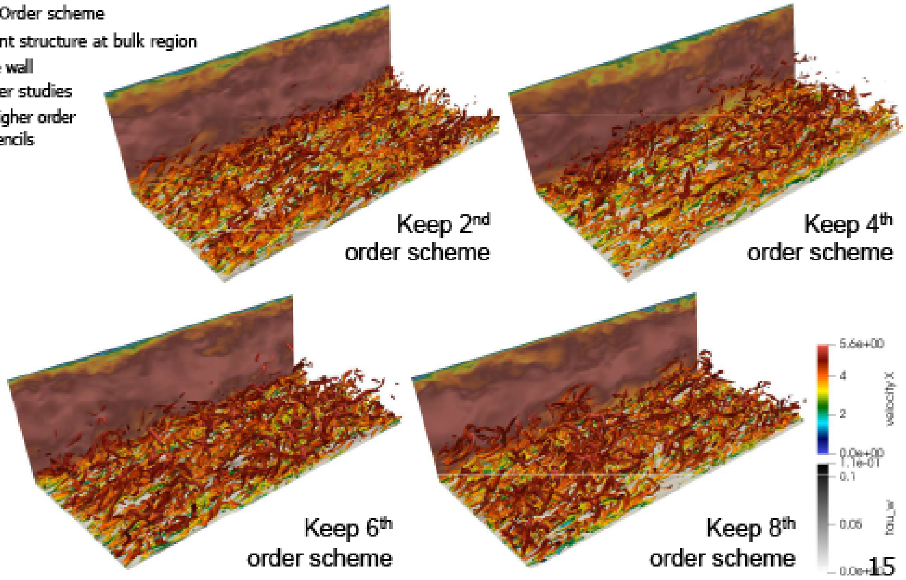
Challenge 1: Validation Case

- Comparison on KEEP scheme as Different order
  - Based on the results from KEEP 2nd Order scheme
  - Higher Order scheme shows turbulent structure at bulk region
    - Denser field of hair structure on the wall
  - 4th order scheme is utilized for further studies
    - Computational cost increase from higher order
    - Due to requirement of additional stencils



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Progress : 9th Aerodynamics Prediction Challenge (APC-9)

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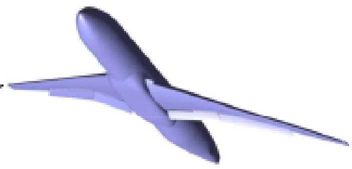

<High Lift version of Common Research Model (CRM-HL)>

- Challenge 3: 3D CRM-HL, wind tunnel wall, unsteady analysis (HRLES, WMLES, etc.) (optional)Methodology: WRLES
  - Target: 3D CRM-HL flap angle: 40°/37° (inboard/outboard), wind tunnel wall consideration
  - Grid: Free
  - Mach Count: M = 0.2
  - Reynolds number: $Re=5.49 \times 10^6$ (C_{ref}=275.8 inches)
  - Static temperature: T_{ref}=521°R
  - Angle of attack: 17.05, ~~19.57~~ deg
    - Computational cost was limited for whole cases

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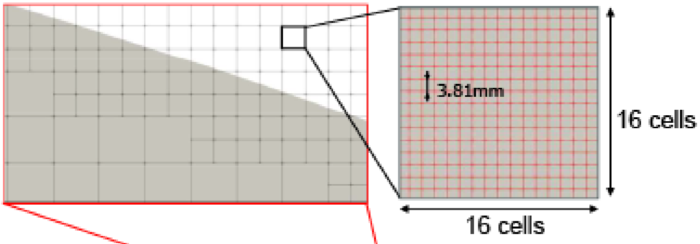
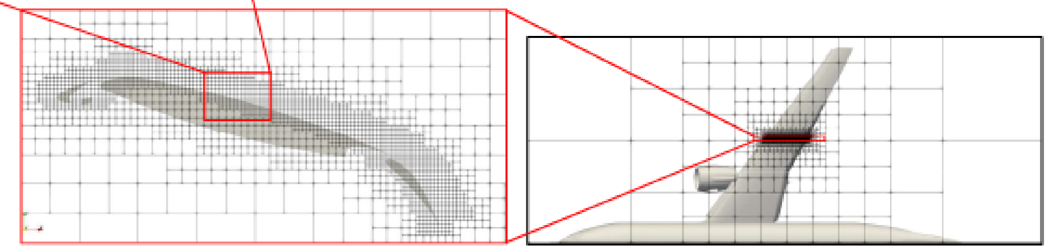
Challenge 3: 3D CRM-HL, uniform flow, unsteady analysis (HRLES, WMLES, etc.)

- Numerical conditions
  - Numerical simulations were performed for locally refined models (Local wing region)
  - Number of cell in each direction : 16
  - Applied numerical filter (Low-pass filter for KEEP scheme)
    - Filter strength applied differently as regions

	Scheme
Flux	KEEP (4th) or ROE Low Mach
Numerical filter	$\alpha_{near\ wall} = 0.1$, $\alpha_{near\ hang\text{-}node} = 0.3$, $\alpha_{far\ field} = 0.01$, Filter Freq. = 4
Time step	1e-5s
Time integration	LUSGS_SLTS_MIX
Num. CUBE (Num. cell)	17,728 (72,600,000)
BC	X(Free), Z(Slip) Y(Slip)





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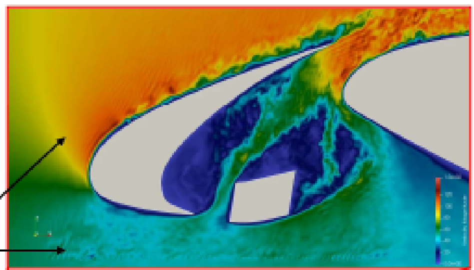
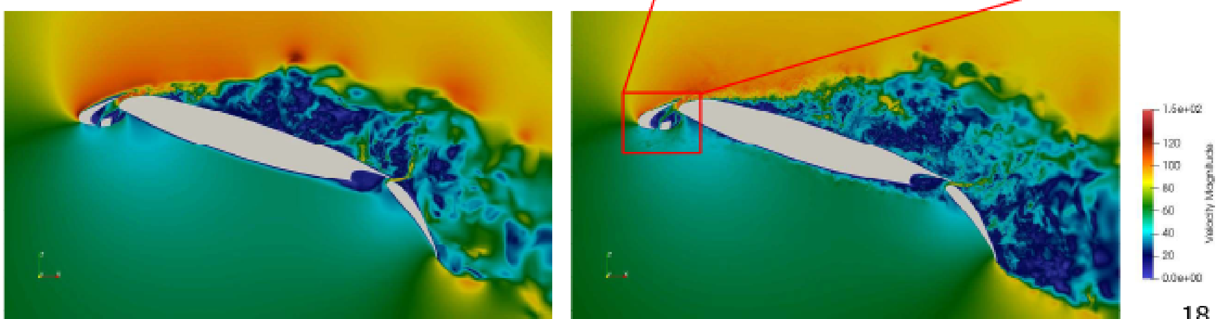
Challenge 3: 3D CRM-HL, uniform flow, unsteady analysis (HRLES, WMLES, etc.)

- Comparison velocity contour as numerical scheme
  - Visualized section view at y=15.9 m
  - Low-Mach Reo scheme shows only large turbulent structures from large recirculation region of upper surface
  - KEEP 4th order scheme shows fine turbulent structure in whole region
    - Meanwhile, numerical oscillation was occurred around the slat

Periodic numerical oscillation in streamwise direction





Low-Mach Roe scheme　　KEEP 4th order scheme

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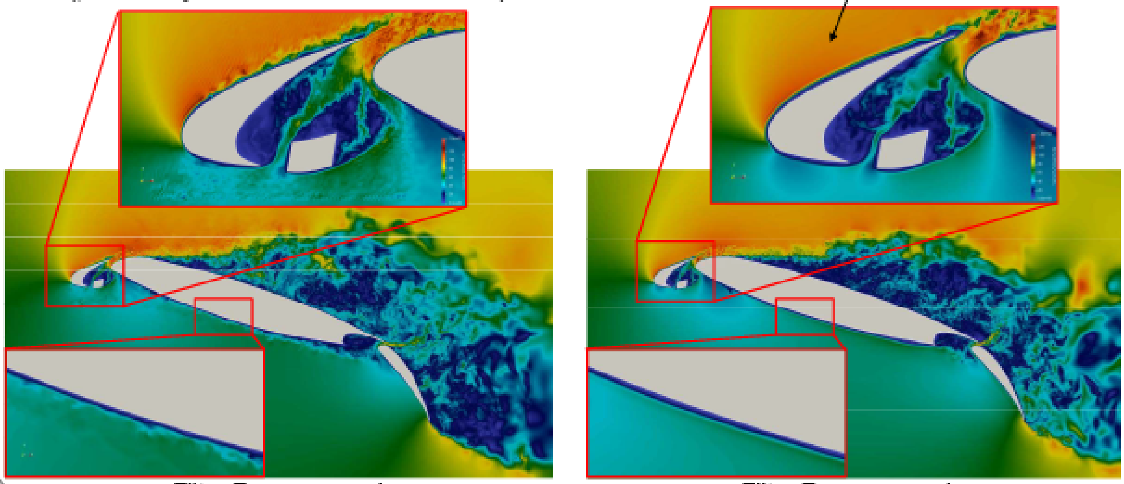
Challenge 3: 3D CRM-HL, uniform flow, unsteady analysis (HRLES, WMLES, etc.)

- Comparison velocity contour as numerical filter frequency for KEEP scheme
  - As applying filter freq. = 1, numerical oscillation around slat was disappeared
    - Meanwhile, Boundary layer in some region is thicken with constant thickness (e.g., slat, bottom surface)
    - This phenomenon enhanced from coarser mesh like bottom surface
    - Currently, we couldn't figure the reason on that → Need further study



Filter Frequency = 4   Filter Frequency = 1

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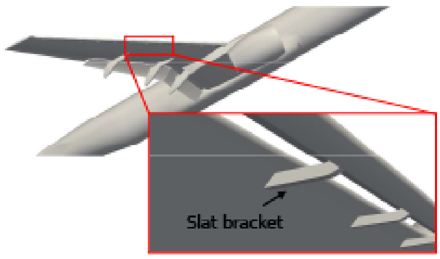
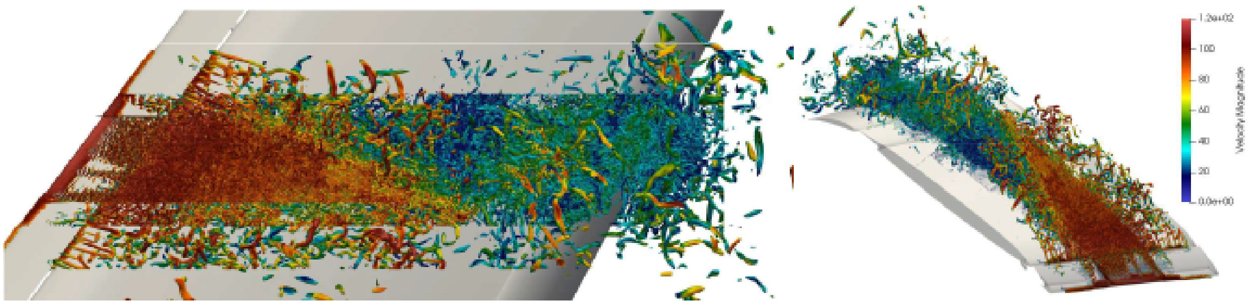
Challenge 3: 3D CRM-HL, uniform flow, unsteady analysis (HRLES, WMLES, etc.)

- Comparison iso-surface of Q = 4×10^5 s^{-2} as numerical scheme
  - Large separation on upper surface in both scheme
    - Expected due to different mesh size
  - Low-Mach Roe scheme
    - Longitudinal turbulent structures from slat bracket are observed
    - Turbulent flow from trailing edge of slat is looks like suppressed
  - KEEP 4th order scheme
    - Finer turbulent structure from both slat bracket and trailing edge of slat are observed





KEEP 4th order scheme

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Challenge 3: 3D CRM-HL, uniform flow, unsteady analysis (HRLES, WMLES, etc.)

- Comparison iso-surface of Q = 4×10^5 s^{-2} as numerical scheme
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  - Low-Mach Roe scheme
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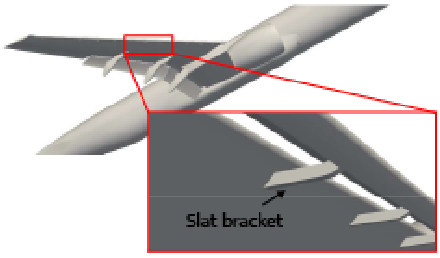

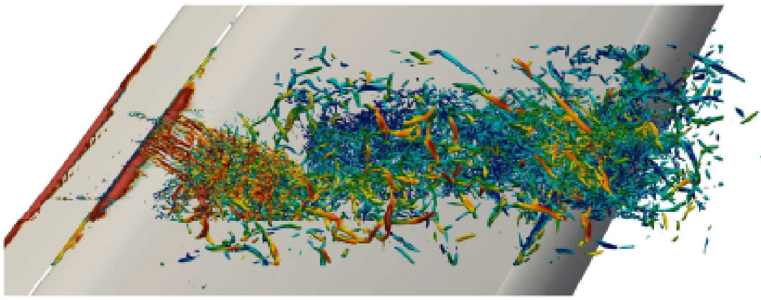

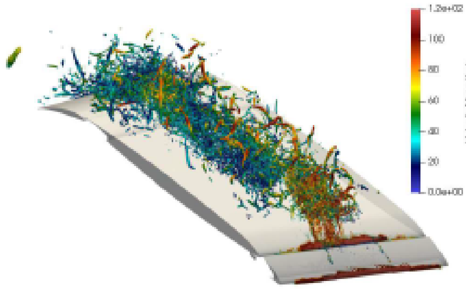

Low-Mach Roe scheme

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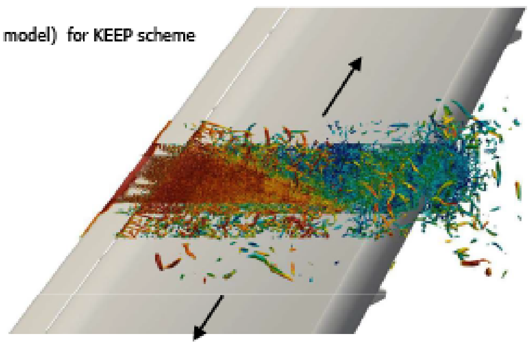
Conclusions & Future work

- Conclusions
  - Verification study of CRM-HL with implemented KEEP scheme of CUBE solver was performed
    - We revised original IBM and implemented numerical filter for stabilize the results from KEEP scheme
    - Comparing to Low-Mach Roe scheme, KEEP scheme was excellently resolved turbulent structures on where the mesh refined quite enough
  - Current problem
    - Meanwhile, we still faced unphysical phenomenon such thickened boundary layer with constant thickness compared to Low-Mach Roe scheme
    - Numerical filter is need to tuning for further study
    - Currently, some of numerical model is not available for KEEP scheme, because most of implemented model is tuned for Low-Mach Roe scheme
    - Additional numerical model for KEEP scheme (Such as, wall model, LES SGS model) is need to implement

- Future work
  - Implement of auxiliary numerical models (wall model, LES SGS model) for KEEP scheme
  - Tuning of numerical filter for solving current problem
  - Extend refinement area of CRM-HL model



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THANK YOU