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Aeroacoustic Simulation of 30P30N High-Lift Configuration using Lattice Boltzmann Method

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Outline

- **Background/Objective**
- **MHI-LBM solver**
  - Overview
  - Cumulant collision model
  - Equilibrium wall model
- **Computational condition/mesh**
- **Results**
- **Summary**

Background/Objective

- **Challenge of Industrial CFD**
  - Unsteady phenomena(e.g. CAA)
  - Complex geometry
  - **Low computational cost**

  (Wall clock time to solution : Less than a week with O(100) cores)

- **Lattice Boltzmann Method**
  - Lower dissipation error than DRP scheme with 6th order RK※
    (but higher dispersion error)
  - 10 – 50 times speed up can be achieved with LBM

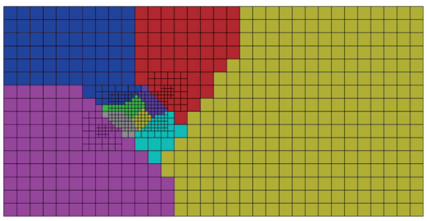
Objective:
Development of practical LBM solver for industrial use

※Marié, Simon, Denis Ricot, and Pierre Sagaut. "Comparison between lattice Boltzmann method and Navier–Stokes high order schemes for computational aeroacoustics." Journal of Computational Physics 228.4 (2009): 1056-1070.
Denis Ricot, "Application of Lattice Boltzmann Method in automotive industry with focus on aeroacoustic simulations", Inst. H. Poincaré, 19 January 2010

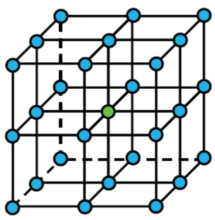
MHI-LBM solver [Overview]

Developed from scratch and now …

- D3Q27 model
- Building Cube Method
- Cumulant collision model
- Interpolated Bounced Back
- Implicit LES
- Equilibrium wall model(Conventional stress model)



Building Cube Method



D3Q27

MHI-LBM solver [Cumulant collision model]

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・Cumulant collision model

The biggest issue of LBM was numerical instability at High Re.

$$f_i(t+\Delta t, \mathbf{x}+\mathbf{e}_i\Delta t) = f_i(t,\mathbf{x})+\Omega_i, \quad i=0,\ldots,b-1$$

Collision Operator

- LBGK model(i.e. Single relaxation model)
- Multiple relaxation model
  - Raw moments
  - Central moments

From Static frame to Moving frame

$$raw\ moments = \sum \frac{f_i}{\rho} e_{ix}^m \quad \Rightarrow \quad central\ moments = \sum \frac{f_i}{\rho}(e_{ix} - v_x)^m$$

The Galilean invariance and the numerical stability is greatly improved!

MHI-LBM solver [Equilibrium wall model]

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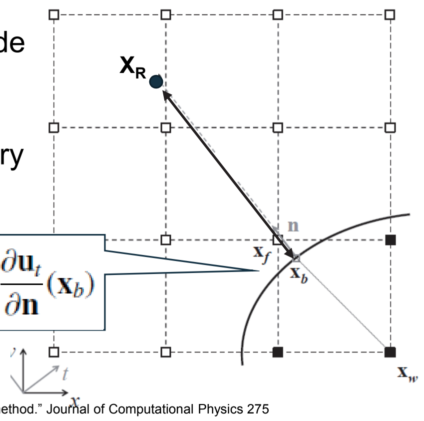
・ Equilibrium wall model

Similar to implementation presented in Ref[1] or Ref[2]

1. Choose reference point X_R (length = 1.75Δx) ← *Not good choice*
2. Interpolation rho and V at X_R
3. Calculation U_τ by Spalding law with newton iteration
4. Calculation tangential velocity at boundary node (1st order approximation)
5. Interpolated bounced back for moving boundary

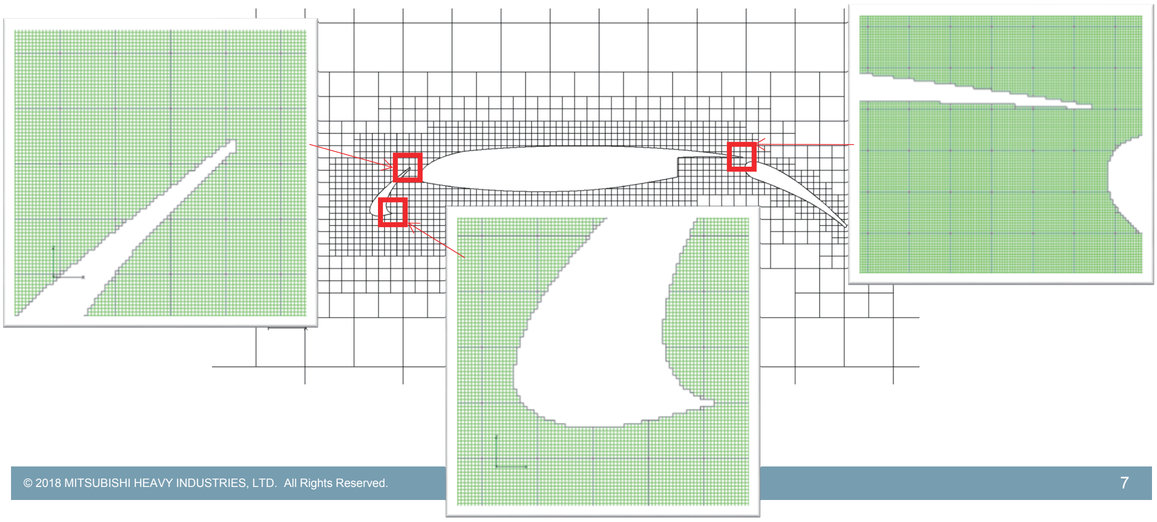
$$\mathbf{u}_t(\mathbf{x}_b) = \mathbf{u}_t(\mathbf{x}_{I_1}) - \Delta x \frac{\partial \mathbf{u}_t}{\partial \mathbf{n}}(\mathbf{x}_b)$$



Ref[1] Malaspinas, Orestis, and Pierre Sagaut. "Wall model for large-eddy simulation based on the lattice Boltzmann method." Journal of Computational Physics 275 (2014): 25-40.
Ref[2] Schneider, A. (2015). A Consistent Large Eddy Approach for Lattice Boltzmann Methods and its Application to Complex Flows.

Computational details

- Total # of cells : 150 million
- Minimum grid space : 1.0×10^{-3}C
  =>Insufficient mesh resolution to resolve trailing edge noise of slat
- Span length : 0.25C
- y^+ : ≈ 200(at 5.5 deg)
- Upper limit of resolved frequency : about 6KHz
  [PPW ≈ 10 and Rossiter mode is assumed]



Computational details

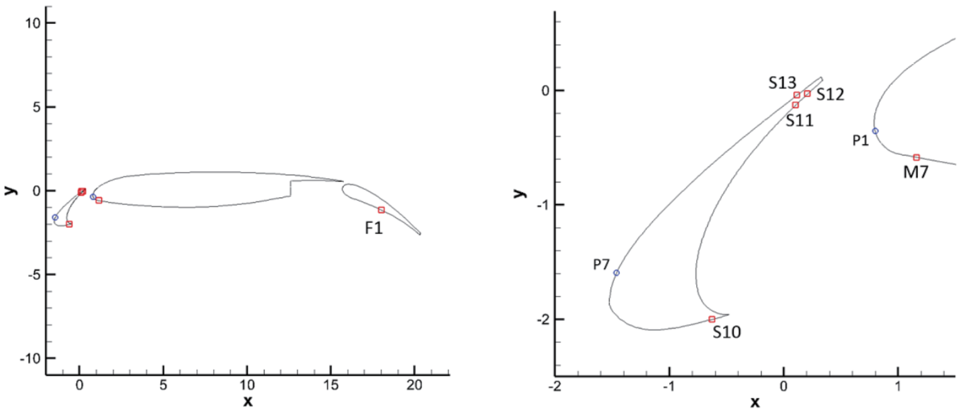
Data sampling

- # of iteration for unsteady data sampling : 98304

(Total # of iteration including transient simulation : 320000)

- Δt : 7.48×10^{-7}sec
- Total sampling time: 0.074 sec
- # of averages for spectrum : 11

Wall clock time to solution : 3.5 days with 640 cores



Results [Cp distributions]

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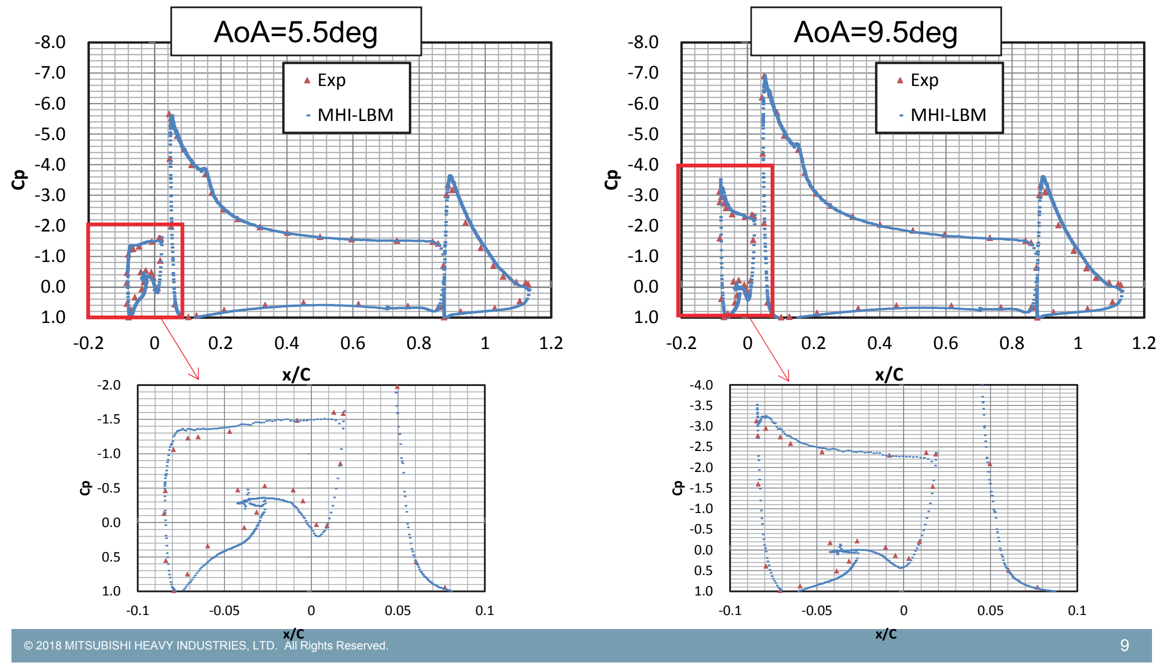
- ➤ Cp distributions agree with Exp.



Results [PSD at AoA=5.5deg]

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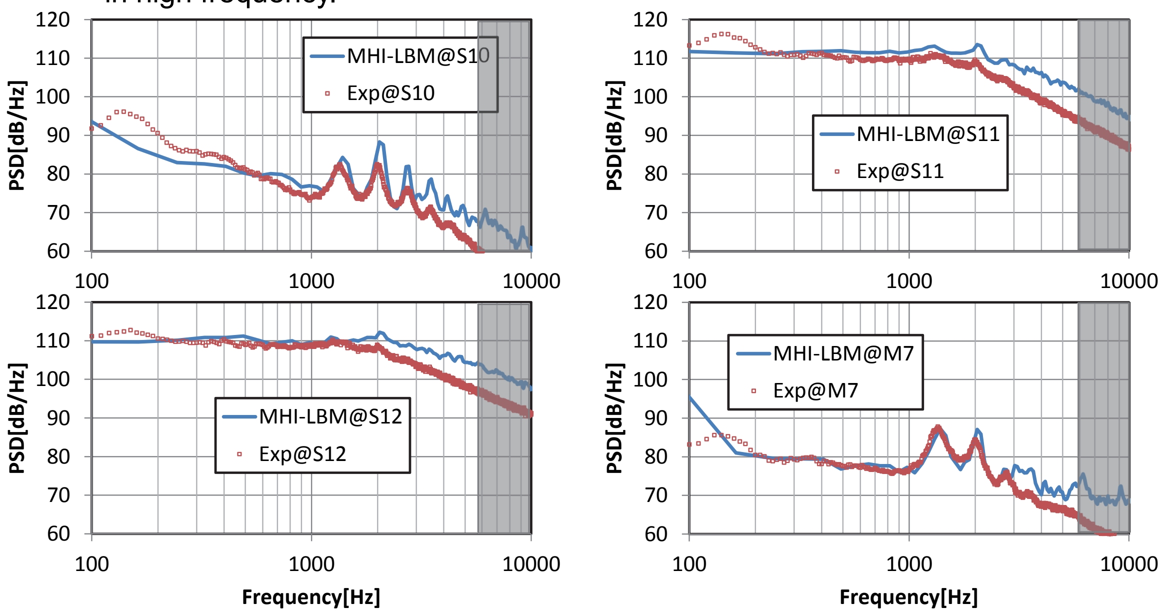
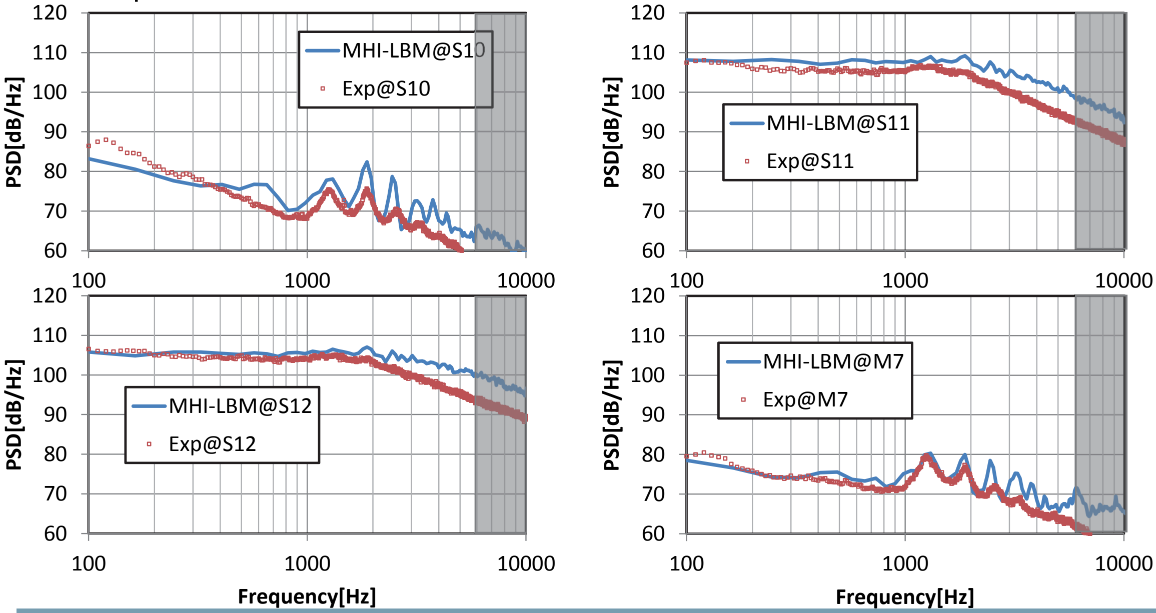
- ➤ Spectrums reasonably agree with experimental results.
- ➤ Simulation tends to be overestimated at every sampling points especially in high frequency.



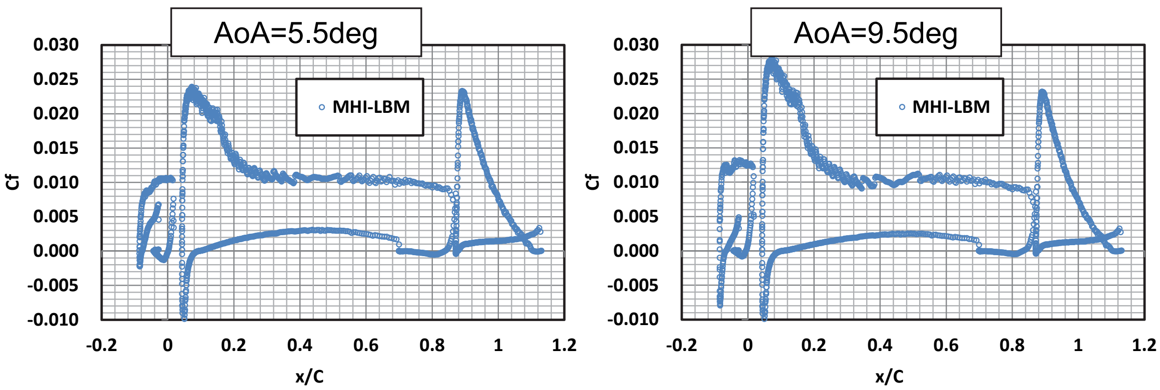
Results [PSD at AoA=9.5deg]

- Spectrums are reasonably agreement with Exp.
- The effects of AoA(Tonal frequency shift and reduction of PSD) are well captured.



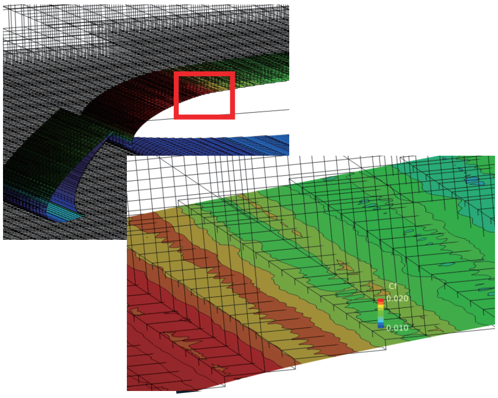
Results [Cf distributions]

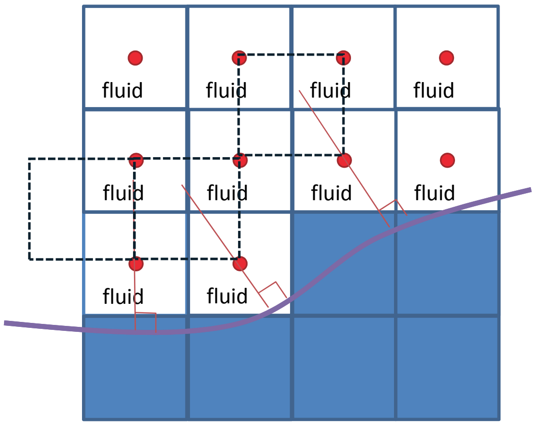
- Cf distributions unphysically oscillated.



Results [Cf distributions]

- Oscillation occurs at steps
- Stair geometric representation may cause Cf oscillation.





Interpolation procedure must be modified.
(e.g. Increase interpolation data)

Summary

・Efficient and practical MHI-LBM code has been developed

- MHI-LBM code can stably compute for 30P30N even if high Re number flow. Cumulant collision model and equilibrium wall model worked well.
- Cp distributions agree with Exp.
- PSD shows reasonable agreement with Exp.
- Cf is oscillated due to stair geometry representation.