Fifth Aerodynamics Prediction Challenge (APC-V)
1 July 2019

2次精度低散逸スキームと直交ハイブリッド格子による30P30Nの高解像度空力音響解析

Aeroacoustic Simulation of 30P30N Airfoil using Second-Order Low-Dissipation scheme on Cartesian Hybrid Grid

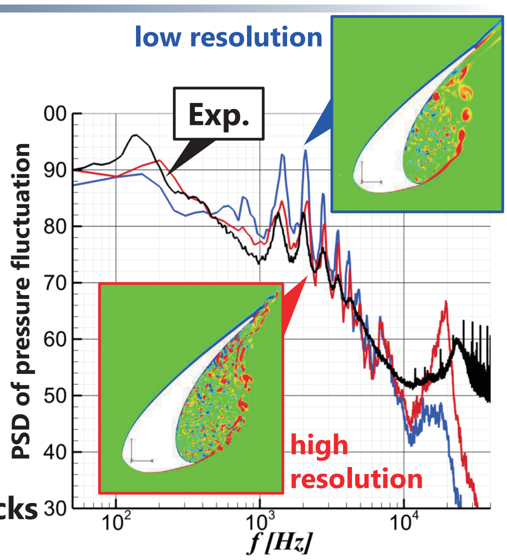
Outline
- **Background & Objective**
- **Computational Setups**
  - Flow solver
  - Computational grids
  - Reduced dissipation approach
- **Computational Results**
- **Summary**

SAKAI Ryotaro
ISHIDA Takashi
MURAYAMA Mitsuhiro
ITO Yasushi
YAMAMOTO Kazuomi
Japan Aerospace Exploration Agency

Background & Objective: Numerical simulation of slat noise

2

- **Slat has been recognized as the primal source of airframe noise**



- **Challenges in slat noise simulation**
  1. **To resolve shear layer from the slat cusp**
     - Insufficient resolution leads to **overestimation of narrow-band peaks**
  2. **To treat complex geometries such as slat tracks**
     - **Unstructured grid** is promising due to its grid flexibility

→ **Improvement of numerical resolution on unstructured grid is desirable**

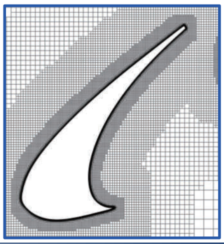
Background & Objective: Reduced dissipation approach

3

- **High-resolution by reducing numerical dissipation in discretization scheme**
- **Past studies on reduced dissipation approach**
  - Large Eddy Simulation (LES) around an airfoil [1]
  - **Airframe noise analyses** by Delayed Detached Eddy Simulation (DDES)
    - **Flap side edge** [2]
    - **Landing gear** [3]
  - DDES around a cylinder with a new approach proposed in JAXA [4]

[1] Dahlstroem, AIAA Paper 2003-0776, 2003.
[2] Winkler, C. et al., AIAA Paper 2012-0570, 2012.
[3] Winkler, C. et al., AIAA Paper 2012-2288, 2012.
[4] Ikeda, T. et al., AIAA Paper 2018-3784, 2018.

- **Objective**
  - To apply a **reduced dissipation approach** to our **unstructured CFD solver**, and assess it in the aeroacoustic simulation for the slat noise on both **structured-type grid** and **unstructured (Cartesian hybrid) grid**



Computational Setups: Flow solver

4

- **FaSTAR (unstructured CFD code in JAXA)**

FaSTAR - Fast Unstructured CFD Code -

Governing equation	3D compressible Navier-Stokes equations
Method	Cell-centered finite volume method
Turbulence model	**Delayed Detached Eddy Simulation** based on Spalart-Allmaras (**SA-noft2-R**)
Transition model	None (fully turbulent)

- **Numerical Schemes**

Discretization of inviscid term	**SLAU** (Simple Low-dissipation AUSM) [1] **with reduced dissipation approach**
Reconstruction method	2nd order Unstructured MUSCL [2]
Gradient calculation	GLSQ (Green-Gauss/Weighted-Least-Square hybrid) [3]
Time integration	LU-SGS with 2nd order dual-time stepping method

[1] Shima et al., AIAA Journal 49 (8) pp. 1693-1709, 2011.
[2] Hishida et al., JAXA-SP-10-012.
[3] Shima et al., AIAA Journal 51 (11) pp. 2740-2747, 2013.

Computational Setups: Computational grids

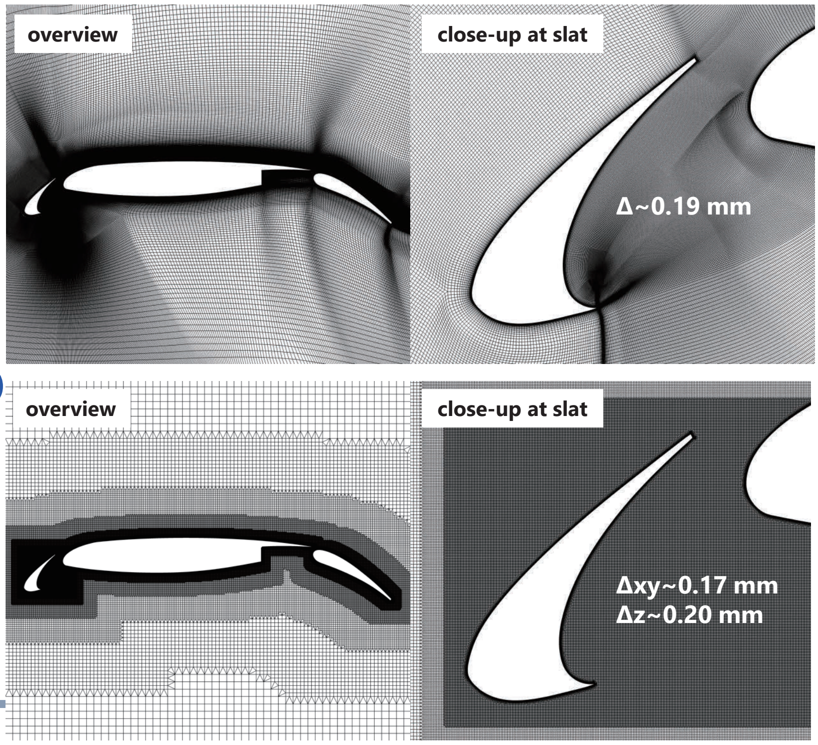
$c_{stowed} = 457.2\,mm$

5

- Both **structured-type grid** and **unstructured (BOXFUN) grid** are used

- **Structured-type**
  - provided; fine (L3)
  - cubic grids in slat cove
  - L_z = **0.11**C_{stowed}
  - **70.4** million grid points

- **Unstructured (BOXFUN)**
  - background Cartesian + hexahedral layer
  - cubic grids in slat cove
  - L_z = **0.11**C_{stowed}
  - **111** million grid points



Computational Setups: Reduced dissipation approach (1/3)

6

- **Discretization scheme for inviscid term: SLAU** [1]
  - $\tilde{\mathbf{F}} = \boxed{\frac{\dot{m}+|\dot{m}|}{2}\mathbf{\Phi}^{+} + \frac{\dot{m}-|\dot{m}|}{2}\mathbf{\Phi}^{-}} + \boxed{\tilde{p}\mathbf{N}}$ **pressure flux (incl. numerical dissipation)**

    momentum flux (incl. numerical dissipation)
  - $\tilde{p} = \frac{p^{+}+p^{-}}{2} + \frac{\beta_{+}+\beta_{-}}{2}(p^{+}-p^{-}) + (1-\chi)(\beta_{+}+\beta_{-}-1)\frac{p^{+}+p^{-}}{2}$

- **High-Resolution SLAU (HR-SLAU)** [2]
  - $\tilde{p} = \frac{p^{+}+p^{-}}{2} + \frac{\beta_{+}+\beta_{-}}{2}(p^{+}-p^{-}) + \gamma_{HR}(1-\chi)(\beta_{+}+\beta_{-}-1)\frac{p^{+}+p^{-}}{2}$
  - γ_{HR} = **1** if the numerical dissipation is needed for computational stability
  - γ_{HR} = **0** to improve the numerical resolution
  - γ_{HR} is determined by the **sign-based wiggle detector** [3]

- **In this study, reduced dissipation is applied based on the approach of HR-SLAU:**
  1. **The numerical dissipation in the momentum flux** is also reduced
  2. **Sign-based wiggle detector** is replaced by **diffusion-based wiggle detector** [4]

[1] Shima et al., AIAA Journal 49 (8), pp. 1693-1709, 2011.
[2] Kitamura, K., Computers & Fluids 126, pp. 41-57, 2016.
[3] Winkler, C. et al., AIAA Paper 2012-0570, 2012.
[4] Ikeda, T. et al., AIAA Paper 2018-3784, 2018.

Computational Setups: Reduced dissipation approach (2/3)

7

- **High-Resolution SLAU (HR-SLAU)**
  - $\tilde{\mathbf{F}} = \frac{\dot{m}+|\dot{m}|}{2}\mathbf{\Phi}^+ + \frac{\dot{m}-|\dot{m}|}{2}\mathbf{\Phi}^- + \tilde{p}\mathbf{N}$
  - $\tilde{p} = \frac{p^+ + p^-}{2} + \frac{\beta_+ + \beta_-}{2}(p^+ - p^-) + \gamma_{HR}(1-\chi)(\beta_+ + \beta_- - 1)\frac{p^+ + p^-}{2}$
- **γ_{HR} is introduced into the definition of χ_{UMUSCL} in U-MUSCL**
  - $\chi_{UMUSCL} = 1 - 0.5\gamma_{HR}$
    - $\chi_{UMUSCL} = 0.5\ if\ \gamma_{HR} = 1 \Rightarrow$ a third-order variable extrapolation to the cell face
    - $\chi_{UMUSCL} = 1\ if\ \gamma_{HR} = 0 \Rightarrow$ the cell interface is the arithmetic average between cells

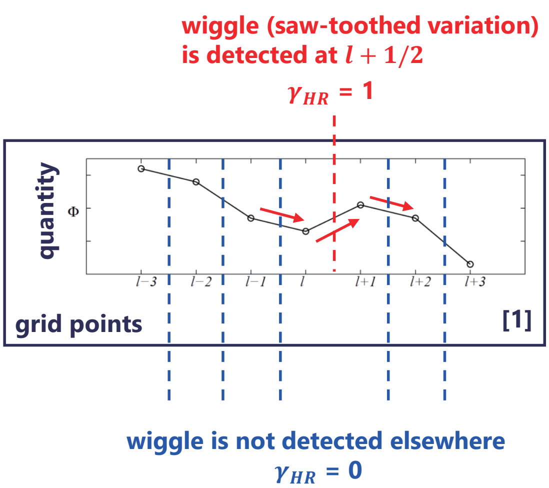
$$\Rightarrow q^+ = q^- = \frac{1}{2}(q_{j+1} + q_j)$$

- **Thus, $\gamma_{HR} = 0$ gives the following formulation without numerical dissipation**
  - $\tilde{\mathbf{F}} = \dot{m} \cdot \frac{1}{2}(\mathbf{\Phi}_{j+1} + \mathbf{\Phi}_j) + \tilde{p}\mathbf{N}$
  - $\tilde{p} = \frac{1}{2}(p_{j+1} + p_j)$
- **$\gamma_{HR} = 1$ recovers the original SLAU scheme**
  - $\tilde{\mathbf{F}} = \frac{\dot{m}+|\dot{m}|}{2}\mathbf{\Phi}^+ + \frac{\dot{m}-|\dot{m}|}{2}\mathbf{\Phi}^- + \tilde{p}\mathbf{N}$
  - $\tilde{p} = \frac{p^+ + p^-}{2} + \frac{\beta_+ + \beta_-}{2}(p^+ - p^-) + (1-\chi)(\beta_+ + \beta_- - 1)\frac{p^+ + p^-}{2}$

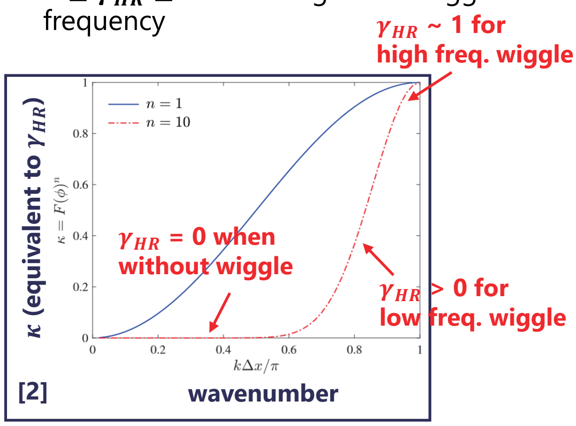
Computational Setups: Reduced dissipation approach (3/3)

8

- **Sign-based wiggle detector [1]: binary function that returns 0 or 1**
  - γ_{HR} = **1** if a wiggle is detected
  - Otherwise, γ_{HR} = **0**



- **Diffusion-based wiggle detector [2][3]: continuous function that returns value from 0 to 1**
  - $0 \le \gamma_{HR} \le 1$ according to the wiggle frequency

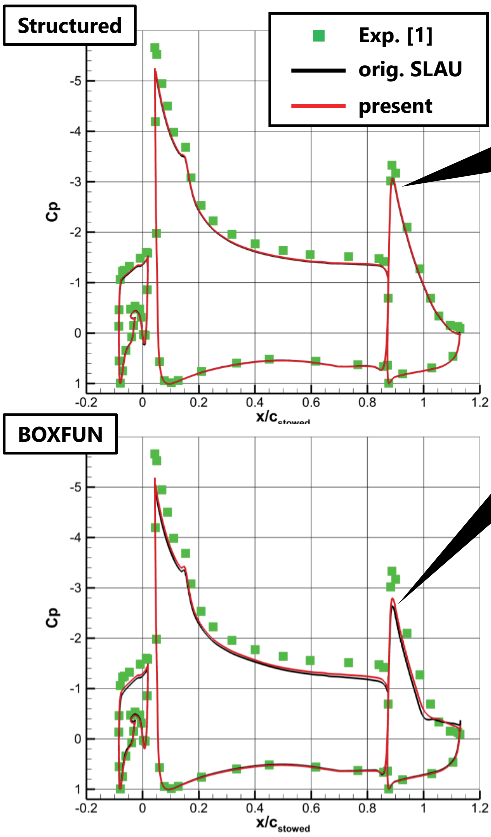


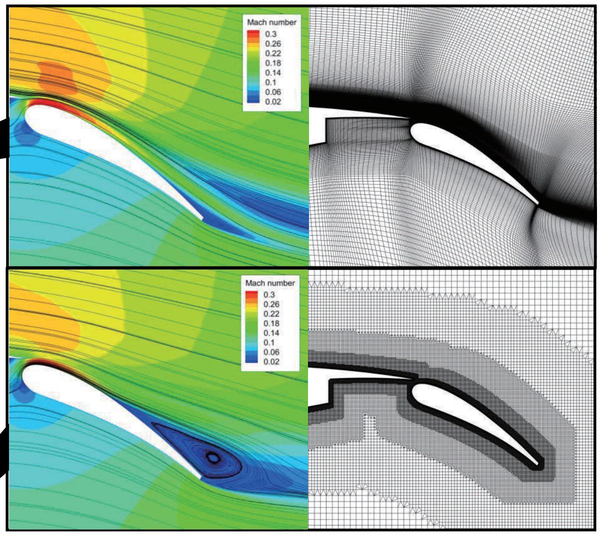
  - n = **10** is employed according to the previous study in JAXA [2]

[1] Dahlstroem, AIAA Paper 2003-0776, 2003.
[2] Ikeda, T. et al., AIAA Paper 2018-3784, 2018.
[3] Shima, E., AIAA Paper 2013-2696, 2013.

[1] Murayama, M. et al., AIAA Paper 2018-3460, 2018.

Time-averaged surface C_p distribution 9

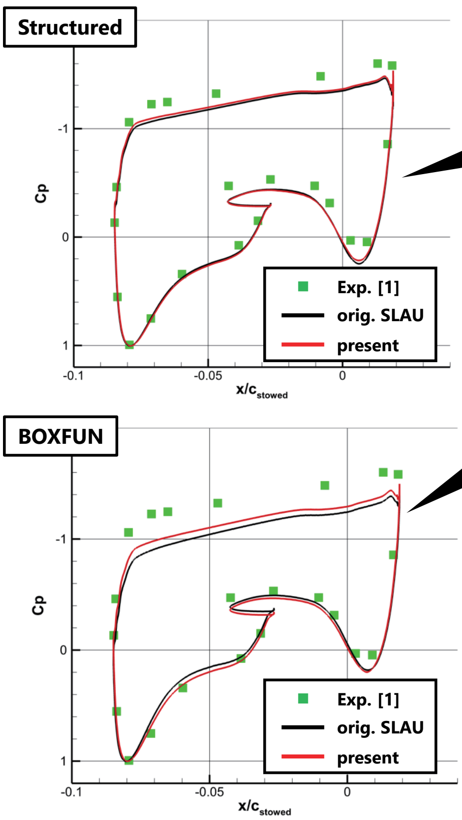


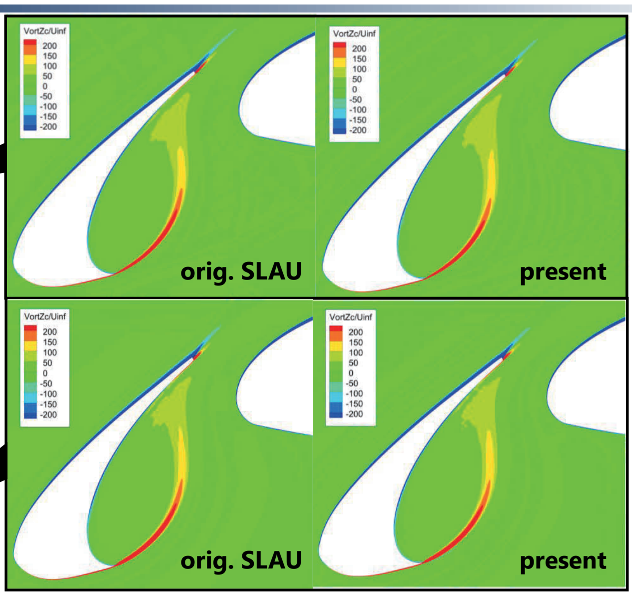


- **Structured grid shows agreement with the experimental result**
  - Both the original SLAU and present scheme show almost the same result
- **Flow separation occurs on the BOXFUN grid at the flap, due to coarse mesh over there**

[1] Murayama, M. et al., AIAA Paper 2018-3460, 2018.

Time-averaged Ω_z distribution around slat 10

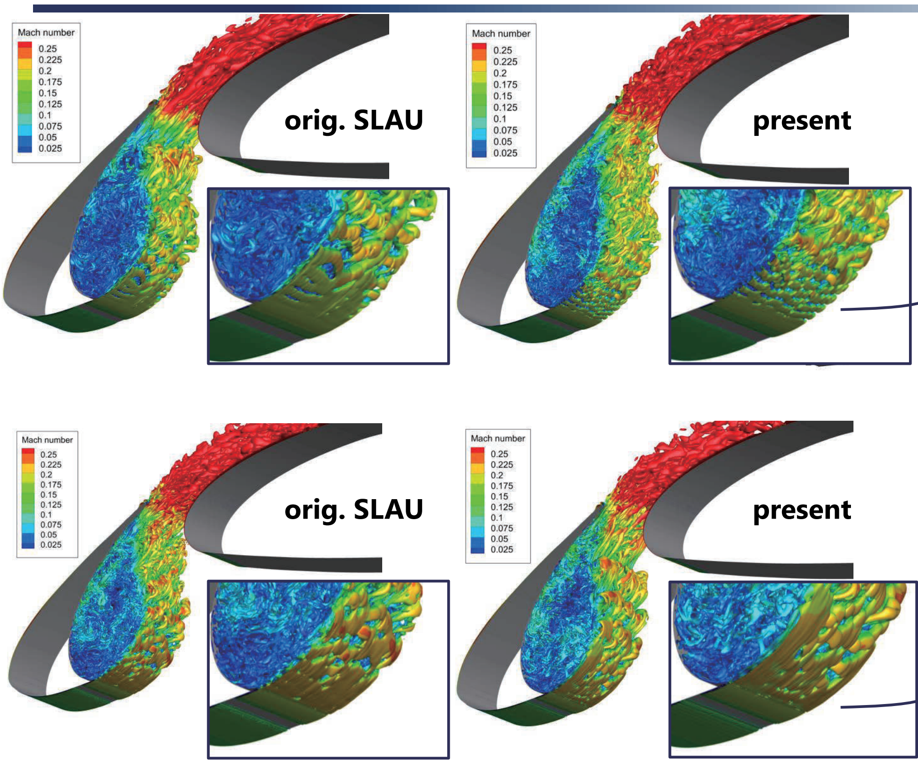




- **Qualitative similar distribution between structured grid and BOXFUN grid**

Q-isosurface (colored by Mach number) (upper: structured grid, lower: BOXFUN grid)

11

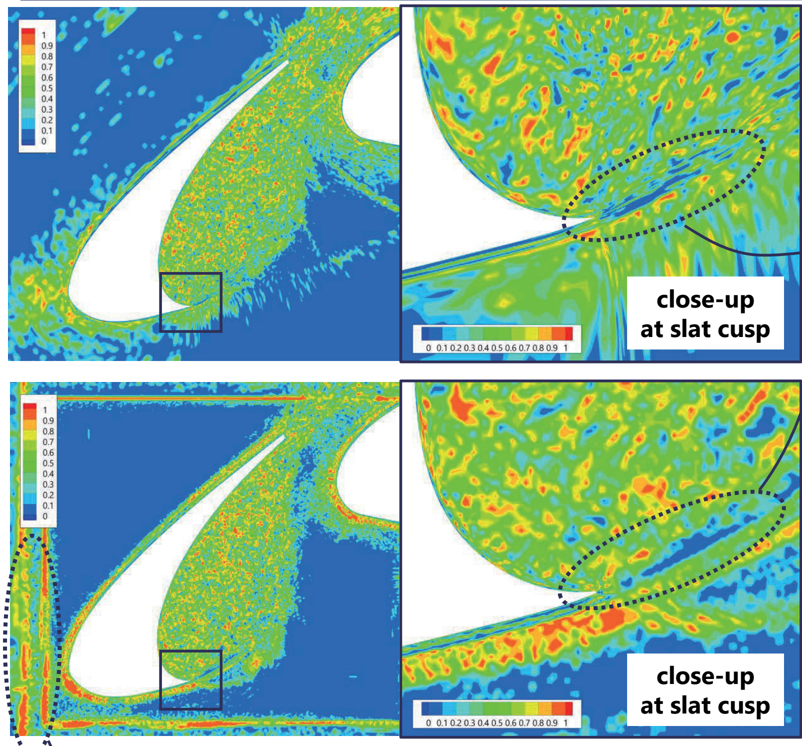


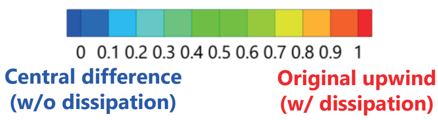
Mixing of the shear layer is facilitated with the present approach

Improvement is not obvious when compared with the structured mesh

Instantaneous snapshot of γ_{HR} (upper: structured grid, lower: BOXFUN grid)

12





Dissipation is reduced at the downstream of the slat cusp

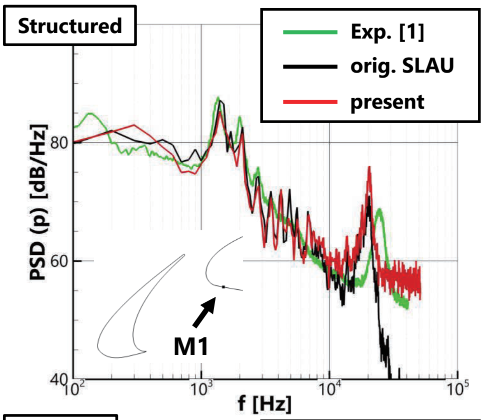
- **The present approach improves numerical resolution in the shear layer**
  - Region of the reduced dissipation is limited to just the beginning of the shear layer

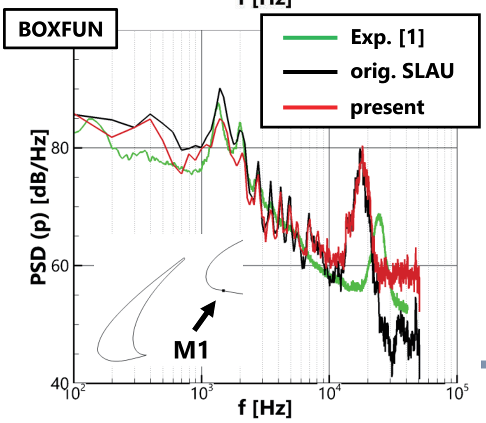
- **Large values of γ_{HR} appears at the boundary where the grid resolution is changed**

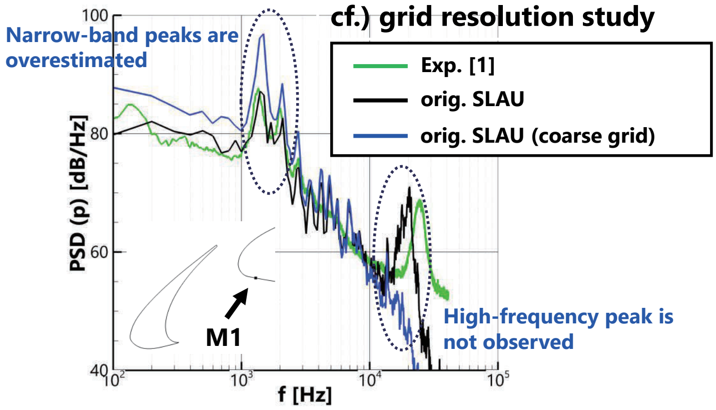
[1] Murayama, M. et al., AIAA Paper 2018-3460, 2018.

PSD of pressure fluctuation @ M1

13







- **In grid resolution study, high grid resolution gives**
  - Decreased narrow band peaks
  - Increased high-frequency peak
- **Similar tendency to grid resolution study can be observed in both grids**
  - However, improvement by the present approach is moderate

Summary

14

- **The reduced dissipation approach has been applied in an unstructured CFD code, and assessed in the slat noise simulation of the 30P30N airfoil**
- **The present approach improves numerical resolution at the beginning of the shear layer**
  - region of the reduced dissipation is limited to the beginning of the shear layer
- **The present approach shows similar tendency to grid resolution study in PSD of pressure fluctuation, which indicates improvement of numerical resolution**
  - improvement by the present approach is moderate
- **On the BOXFUN grid,**
  - flow separation occurs on the flap due to coarse mesh over the flap
  - large values of γ_{HR} appears at the boundary where the grid resolution changes