Fourth Aerodynamics Prediction Challenge (APC-IV)
4 July 2018

Investigation of Effect of Subgrid Length Scale in DDES through Unsteady Flow Simulation of 30P30N Airfoil
（30P30N非定常解析を通したDDESサブグリッド長さスケールの影響調査）

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Computations in APC-IV

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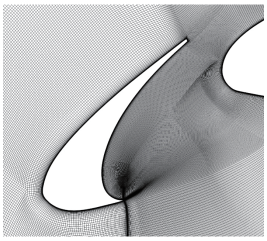
- **Computational grid**
  - Provided by JAXA: /apc/grids/3element_highlift_airfoil/30P30N_modified_slat_configF/fastar/3D_L3_fine_r1.fsgrid
  - **73.6M** cells (**0.27M** cells in 2D x **270** cells in spanwise)
  - Spanwise length: **2** inch
  - Wall-normal cell spacing on the surface $\Delta y^+ \sim$ **0.54**
  - **Nearly isotropic cells** in the slat cove region



enlarged view of grid at slat cove region

- **Computational cases**

		DDES by FaSTAR L3 (fine)			
Airfoil/Re/Ma	AoA	Δ_{max}	Δ_{vol}	Δ_{SLA}	
30P30N Re=1.7e6 Ma=0.17	5.5	✓	✓	✓	課題1-3 課題3-1, 3-2
	9.5	✓	-	-	課題1-3 課題3-1, 3-2
	14	✓	-	-	課題3-1, 3-2

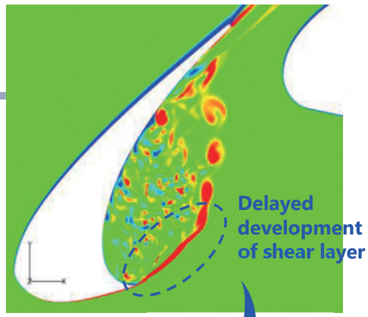
present topic: comparison of subgrid length scales in the context of DDES

Background

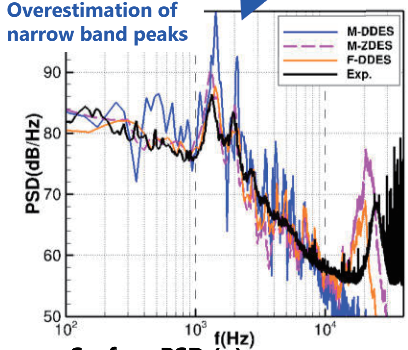
- **Length scale definition in DDES**
  - $L_{DDES} = L_{RANS} - f_d \max(0, L_{RANS} - L_{LES})$
    - $L_{RANS} = d_w$
    - $L_{LES} = \Psi C_{DES} \Delta$ subgrid length scale
    - $\Delta = \max(\Delta x, \Delta y, \Delta z)$ [Spalart, 1997]

- **Aeroacoustic simulation around a slat using DDES by UPACS [Murayama, 2015]**
  - w/ original definition of Δ (= $\max(\Delta x, \Delta y, \Delta z)$)
  - Shear layer development was delayed
  - Narrow band peaks were overestimated

- **New definitions of Δ have been proposed**
  - Δ_ω for Axial jet [Chauvet, 2007]
  - Δ_{SLA} for free shear layer [Shur, 2015]
  - <u>Few applications to a high-lift airfoil</u>
  - <u>Few systematic comparisons among them</u>



ω_z distribution [Murayama, 2015]



Surface PSD (p) [Murayama, 2015]

Objective

- **To evaluate the effect of subgrid length scale in DDES for aerodynamic and aeroacoustic analysis of 30P30N airfoil**
  - mainly on slat

Definitions of subgrid length scale in DDES 5

- **Length scale definition in DDES**
  - $L_{DDES} = L_{RANS} - f_d \max(0, L_{RANS} - L_{LES})$
    - $L_{RANS} = d_w$
    - $L_{LES} = \Psi C_{DES} \Delta$ **subgrid length scale**

f_d : DDES shielding function
d_w : wall distance
Ψ : correction parameter for low Reynolds number term [Shur, 2003]
C_{DES}: constant value

1. Definition in original DES [Spalart, 1997]

- $\Delta = \Delta_{max} = \max(\Delta x, \Delta y, \Delta z)$

$\Delta x, \Delta y, \Delta z$: cell spacing in each coordinate direction

2. Subgrid scale typically used in LES [Deardroff, 1970]

- $\Delta = \Delta_{vol} = (\Delta x \Delta y \Delta z)^{1/3}$

3. Vorticity-dependent maximum cell length [Shur, 2015]

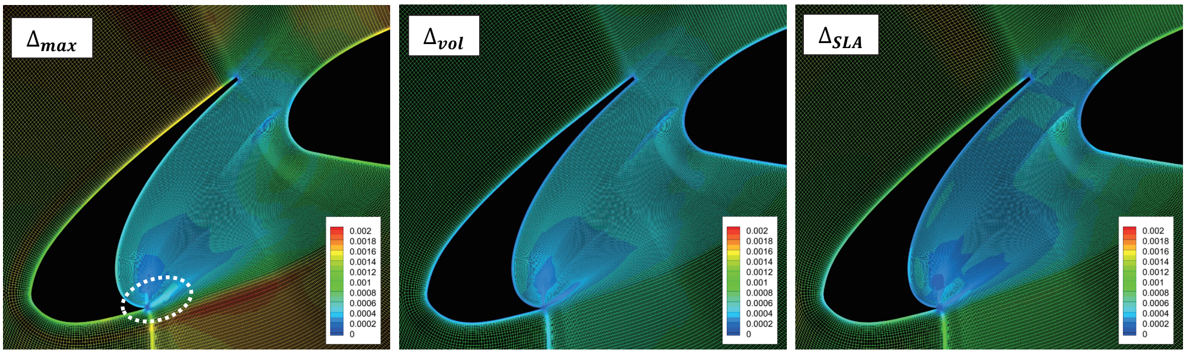
- $\Delta = \Delta_{SLA} = \tilde{\Delta}_\omega F_{KH}^{lim}$
- $\tilde{\Delta}_\omega = \frac{1}{\sqrt{3}} \max_{n,m=1,8} |(\boldsymbol{l}_n - \boldsymbol{l}_m)|$
- $F_{KH}^{lim} = \begin{cases} 1 & if\ f_d < (1-\varepsilon) \\ F_{KH} & if\ f_d \geq (1-\varepsilon) \end{cases}$
  - $\varepsilon = 0.01$

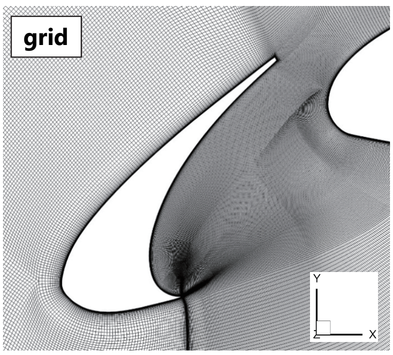
$\boldsymbol{l}_n = \boldsymbol{n}_\omega \times \boldsymbol{r}_n$
$\boldsymbol{n}_\omega = (n_x, n_y, n_z)$: unit vector aligned with the vorticity vector
$\boldsymbol{r}_n$: position vector (n is corresponding to cell vertices)

$0.1 < F_{KH} < 1.0$
$F_{KH} < 1.0$ facilitates K-H instability by making Δ small

F_{KH}^{lim} is modified F_{KH} for DDES [Shur, 2015] to prevent activation of F_{KH} inside attached boundary layer

Visualization of subgrid length scales: slat 6





(assumption of F_{KH} = 1 and n_ω=(0,0,1); only Δx and Δy are considered for max function)

- **Δ_{max} shows slightly larger values at the slat cusp**
- **Δ_{vol} is smaller than the other two scales in the entire region around slat**
- **Due to nearly isotropic mesh in the slat cove region, differences among three cases are not so large**

Visualization of subgrid length scales: flap

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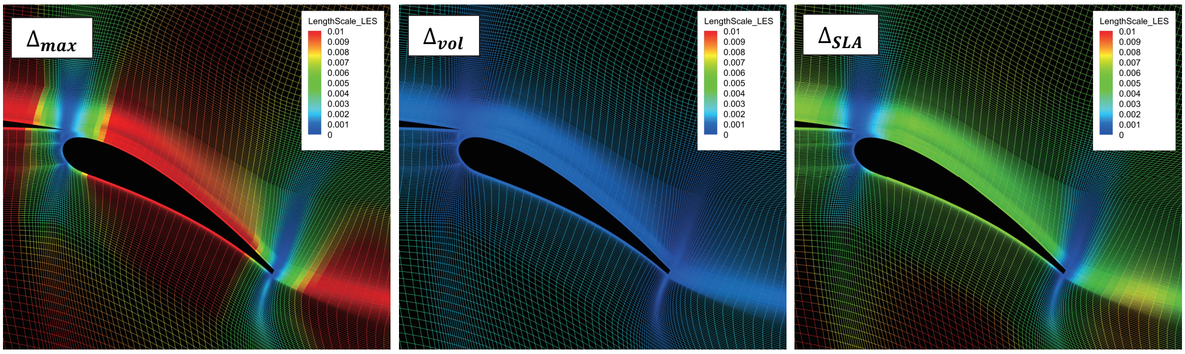

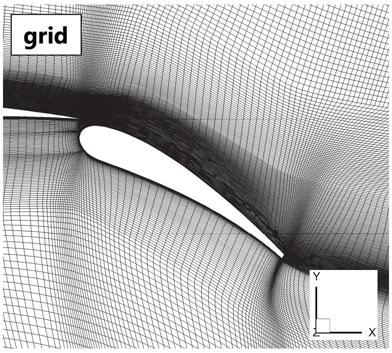

(assumption of F_{KH} = 1 and n_{ω}=(0,0,1); only Δx and Δy are considered for max function)

- **Highly stretched mesh derived from RANS simulation on the flap**
- **Δ_{max} shows larger values around the flap**
- **Δ_{vol} is smaller than the other two scales in the entire region around the flap**
- **Investigation of effect by these differences is future work**

Numerical method

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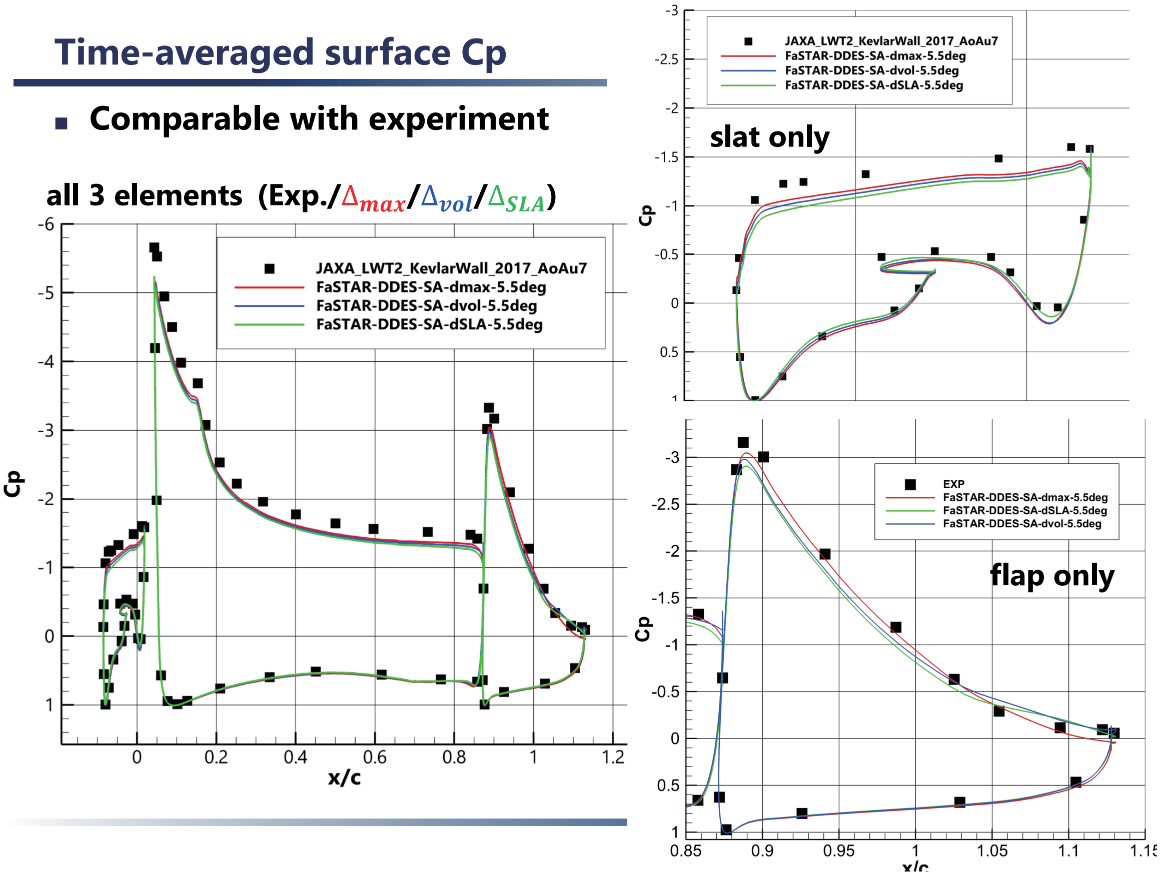
- **Near-field flow analysis: FaSTAR (Unstructured CFD code)**

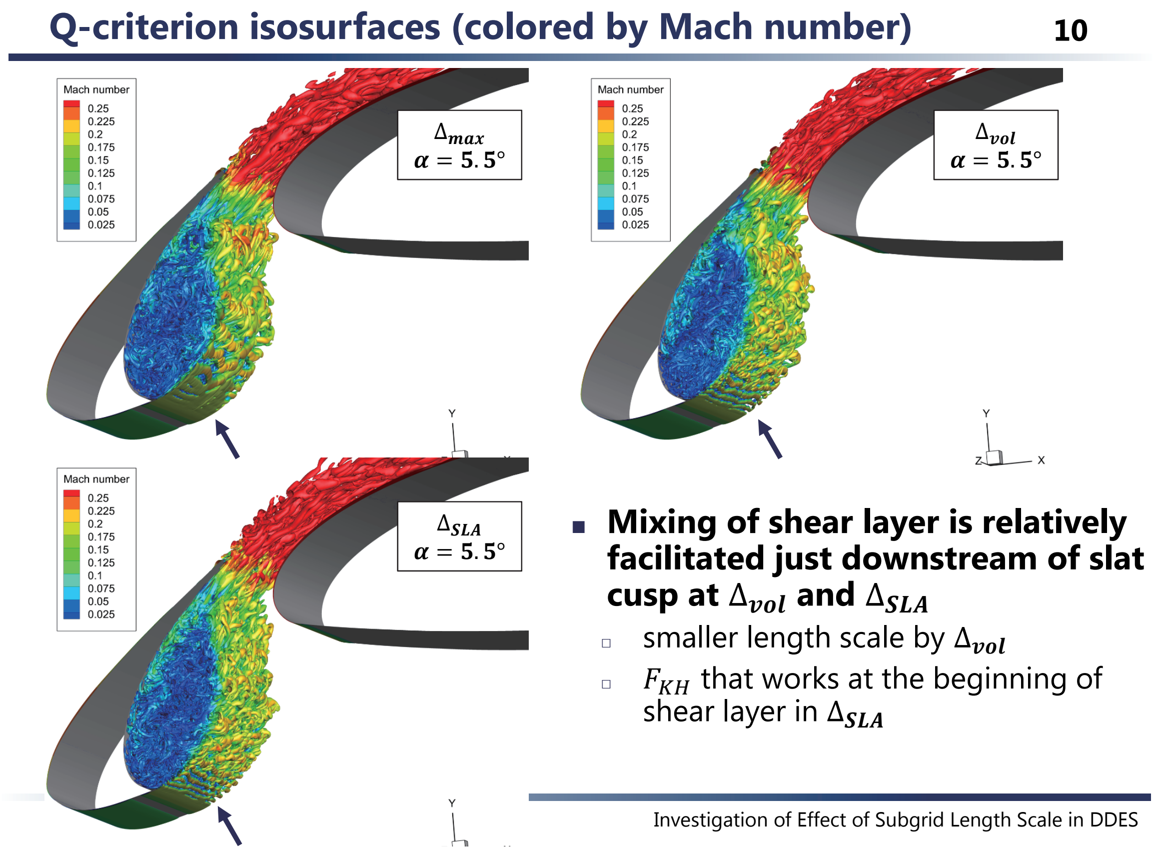
Governing equation	3D compressible Navier-Stokes equations
Method	Cell-centered finite volume method
Turbulence model	**SA-noft2-R DDES**
Discretization of inviscid term	SLAU (Simple Low-dissipation AUSM) [1]
Reconstruction method	2nd order Unstructured MUSCL
Limiter	**Hishida limiter** [2]
Gradient calculation	GLSQ (Green-Gauss/Weighted-Least-Square hybrid) [3]
Time integration	LU-SGS with dual-time stepping method
#inner iterations	**5 (fixed)**

- **Far-field sound pressure evaluation: UPACS-Acoustics**

Governing equation	Ffowcs Williams-Hawkings equation
FW-H surface	Solid wall surface of the airfoil [4]

[1] Shima et al., AIAA Journal 49 (8) pp. 1693-1709, 2011.
[2] Hishida et al., JAXA-SP-10-012. (in Japanese)
[3] Shima et al., AIAA Journal 51 (11) pp. 2740-2747, 2013.
[4] Terracol et al., AIAA Paper 2015-3132, 2015.


Time-averaged surface Cp
Comparable with experiment
all 3 elements (Exp./Δ_{max}/Δ_{vol}/Δ_{SLA})
JAXA_LWT2_KevlarWall_2017_AoAu7
FaSTAR-DDES-SA-dmax-5.5deg
FaSTAR-DDES-SA-dvol-5.5deg
FaSTAR-DDES-SA-dSLA-5.5deg
Cp
x/c
slat only
EXP
FaSTAR-DDES-SA-dmax-5.5deg
FaSTAR-DDES-SA-dSLA-5.5deg
FaSTAR-DDES-SA-dvol-5.5deg
flap only


Q-criterion isosurfaces (colored by Mach number)
10
Mach number
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
Δ_{max}
$\alpha = 5.5°$
Δ_{vol}
$\alpha = 5.5°$
Δ_{SLA}
$\alpha = 5.5°$
Mixing of shear layer is relatively facilitated just downstream of slat cusp at Δ_{vol} and Δ_{SLA}
smaller length scale by Δ_{vol}
F_{KH} that works at the beginning of shear layer in Δ_{SLA}
Investigation of Effect of Subgrid Length Scale in DDES

2D TKE distributions

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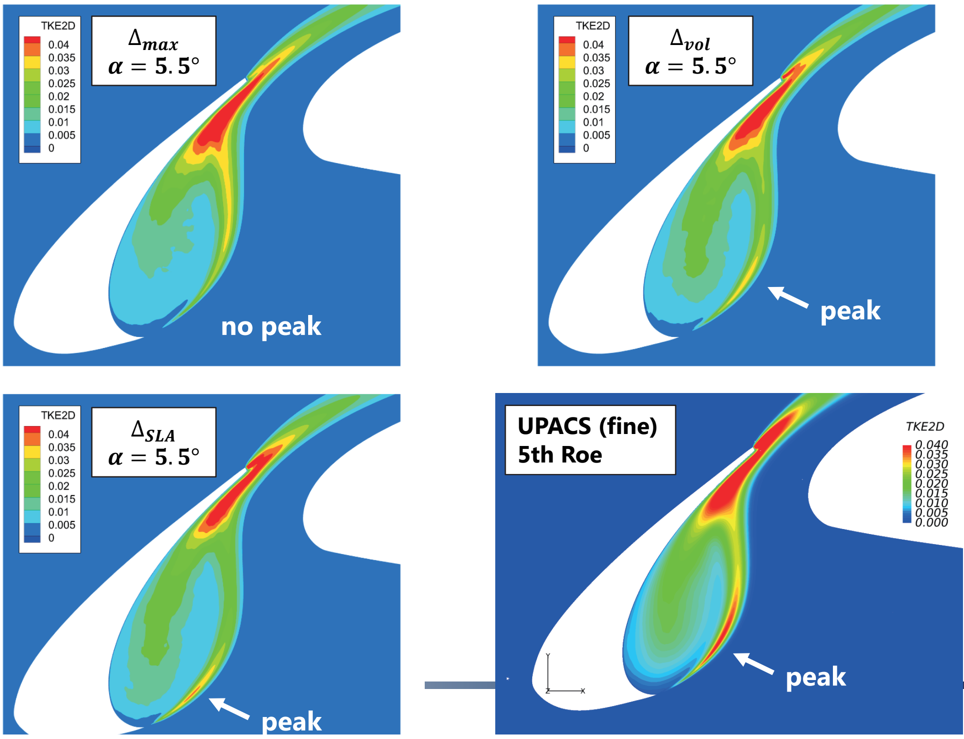
- **Different peak positions are observed among three cases**



2D TKE profiles

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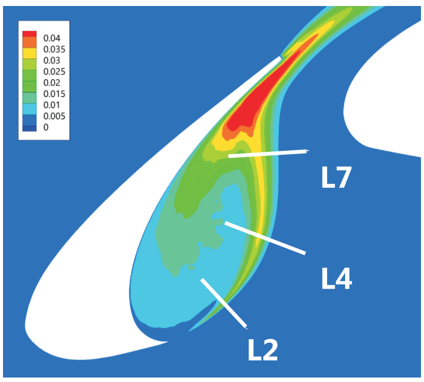
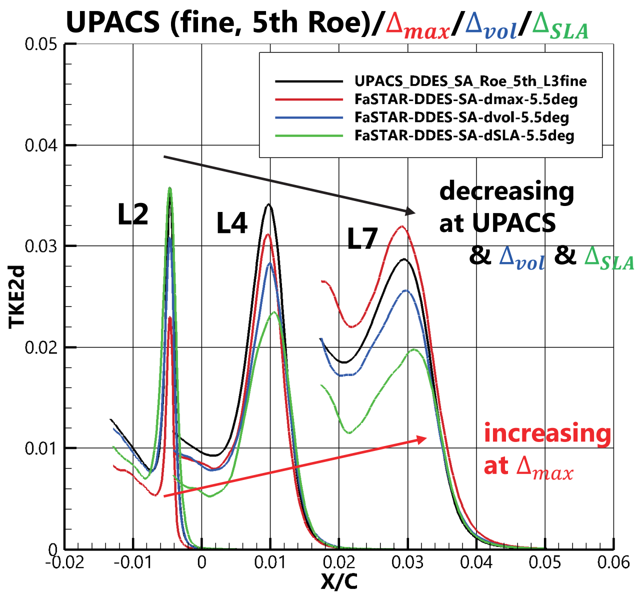


sampling locations (L2, L4, and L7)



- **Δ_{vol} and Δ_{SLA} show similar trend to UPACS**
  - Δ_{SLA} shows steep decrease at L7
- **Adverse trend to UPACS at Δ_{max}**

Surface Pressure Spectra at PMP1

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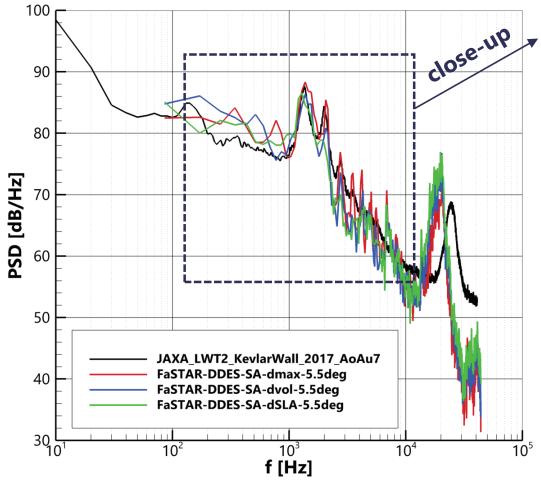

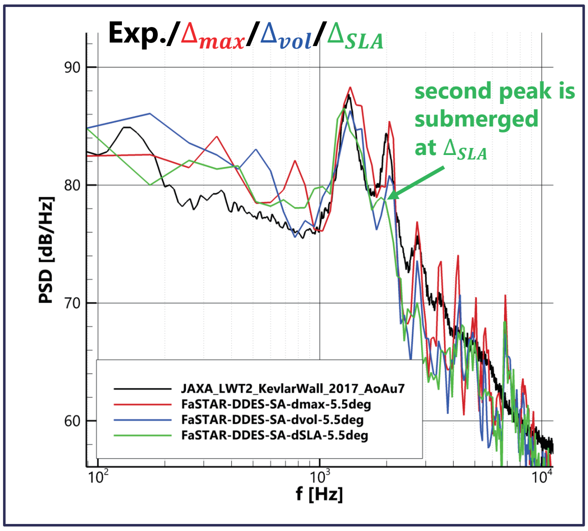

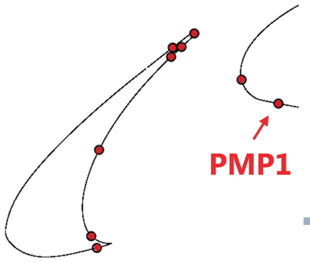

- first peak is estimated by all the three cases
- second peak is submerged by Δ_{SLA}

Investigation of Effect of Subgrid Length Scale in DDES

Farfield Pressure Spectra at 291 deg.

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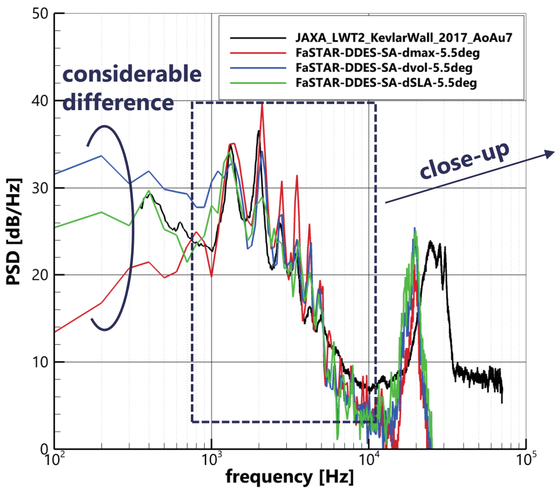
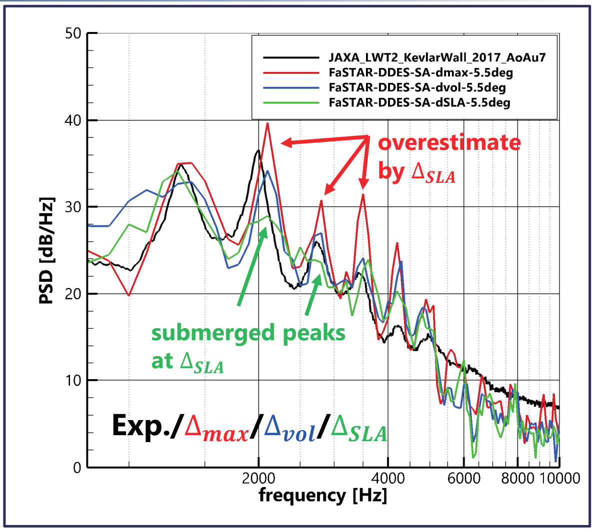
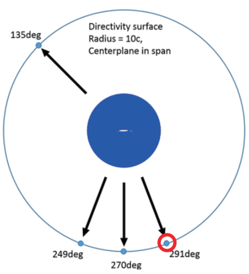


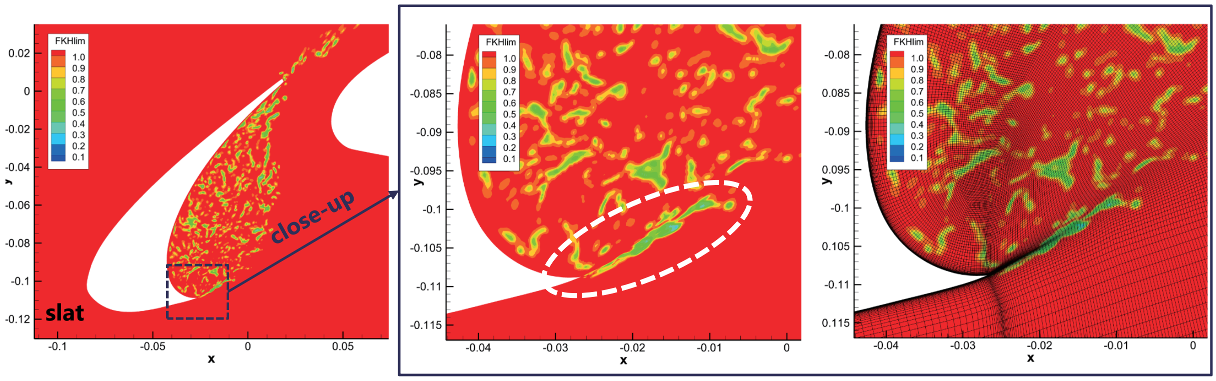


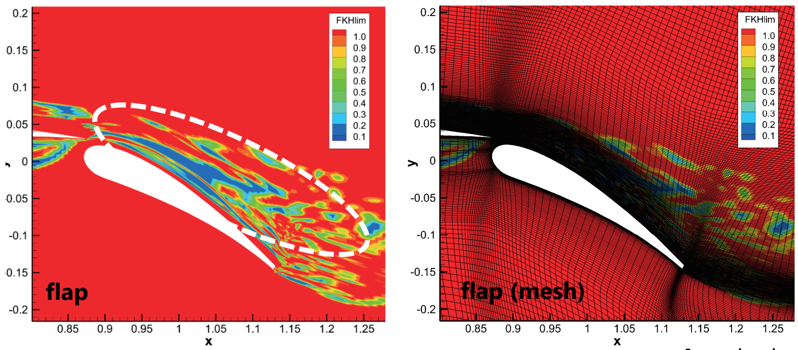


- overestimated NBPs at Δ_{max}
- submerged NBPs at Δ_{SLA}
- considerable difference in low-frequency range
  - another noise source related to main element or flap?

Investigation of Effect of Subgrid Length Scale in DDES

Visualization of F_{KH}^{lim} in Δ_{SLA}





- F_{KH}^{lim} **is less than 1.0 just downstream at slat cusp, which facilitates mixing of shear layer**
- F_{KH}^{lim} **is also less than 1.0 in the region on the flap that is not expected to be the beginning of the shear layer**

Summary

- **Comparsion of subgrid length scales at DDES for 30P30N airfoil**
  - $\Delta_{max}/\Delta_{vol}/\Delta_{SLA}$
- **Small effect on time-averaged Cp**
- Δ_{vol} **and** Δ_{SLA} **facilitates mixing of shear layer from the slat cusp, compared with** Δ_{max}
  - rapid mixing in Q-criterion isosurface at the slat cusp
  - trend of decreasing peak magnitudes in 2DTKE profile
  - reduced peak values in NPBs in surface/farfield pressure spectra
- **Observations for** Δ_{SLA}
  - steep decrease in 2DTKE
  - submerged NBPs in surface/farfield pressure spectra
  - expected activation of F_{KH} at the slat cusp; unexpected activation on the flap

- **Future work**
  - to investigate effect of subgrid length scale on the main element and the flap