流束再構築法による三翼素高揚力翼型の空力騒音解析

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Objective

- To assess the high-order FR solver for aerodynamic and aeroacoustic prediction based on the following approach:
  - Kinetic energy preserving scheme for under resolved LES
  - Wall stress modeled LES for high Re number flow
  - HO-mesh for curved airfoil geometry
- Case 3-1 : Prediction of aeroacoustics（near field）

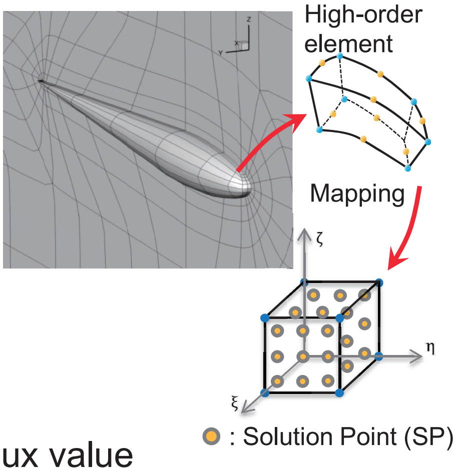
  Flow conditions: $M_\infty = 0.17$, $Re = 1.71 \times 10^6$
  Angle of attack: 5.5 [deg.]

Flux Reconstruction (FR)（Huynh, 2007）

- NS eqs. in conservative form

$$\frac{\partial \hat{Q}}{\partial t}+\frac{\partial \hat{E}}{\partial \xi}+\frac{\partial \hat{F}}{\partial \eta}+\frac{\partial \hat{G}}{\partial \zeta}=0,$$

$$\hat{Q}=JQ \quad \hat{E}=J\nabla\xi\cdot\vec{F} \quad J:=\left|\frac{\partial(x,y,z)}{\partial(\xi,\eta,\varsigma)}\right|$$



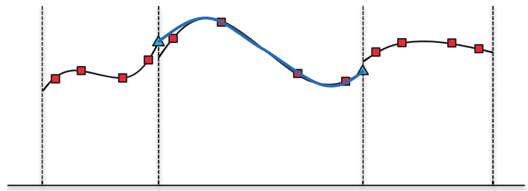
- Approximate flux by polynomial

$$\hat{E}_i(\xi,\eta,\zeta)=\sum_{j,k,l=0}^{K}\hat{E}_{i;j,k,l}\,\phi_j(\xi)\,\phi_k(\eta)\phi_l(\zeta)$$

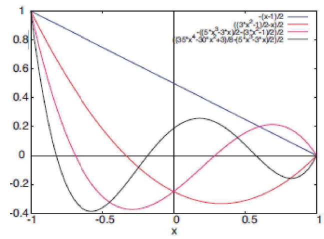
- Correct the flux polynomial by the interface flux value

$$\partial_\xi \hat{E}_i^C=\partial_\xi \hat{E}_i+\left[\hat{E}_{i-1/2}^{com}-\hat{E}_i(-1)\right]\partial_\xi g_L+\left[\hat{E}_{i+1/2}^{com}-\hat{E}_i(1)\right]\partial_\xi g_R$$

$\hat{E}_i(\xi)\in \boldsymbol{P}_K$ correction→ $\hat{E}_i^C(\xi)\in \boldsymbol{P}_{K+1}$



$g_L(\xi)\in \boldsymbol{P}_{K+1}$

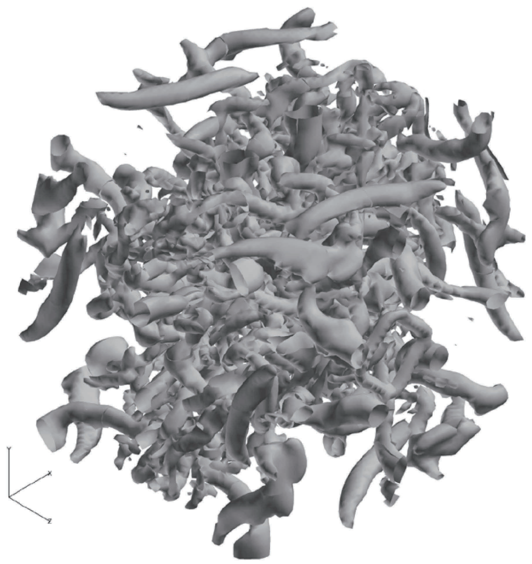


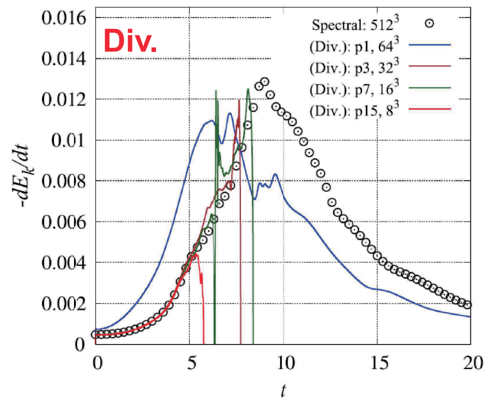
Numerical Methods

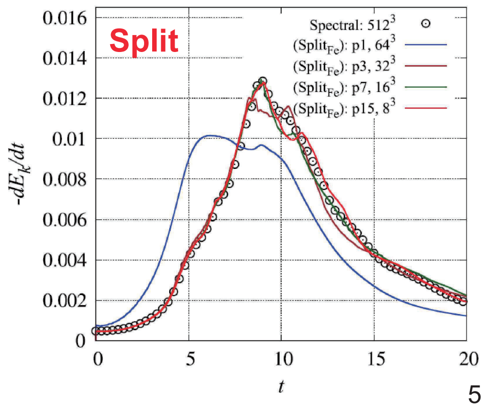
Solver	***LS-FLOW-HO***
Discretization	Split FR (p0-15) [1]
Inviscid Flux	Roe
Viscous Flux	BR2
SGS Model	None (Implicit LES)
Time Integration	3rd-order TVD Runge-Kutta
Shock Capturing	LAD [2] (not used in this study)
Wall Stress Model	Equilibrium BL eqs. [3]
Parallelism	MPI & OpenMP/OpenACC

[1] Y. Abe, I. Morinaka, T. Haga, T. Nonomura, H. Shibata, K. Miyaji, “Stable, non-dissipative, and conservative flux-reconstruction schemes in split forms,” Journal of Computational Physics 353 193-227 (2018)
[2] T. Haga and S. Kawai, “On a robust and accurate localized artificial diffusivity scheme for the high-order flux-reconstruction method,” Journal of Computational Physics 376 534-563 (2019)
[3] 芳賀臣紀, 河合宗司, “高次精度流束再構築法による壁面モデルLES” 第 31 回数値流体力学シンポジウム (2017)

Improved Robustness by Split-form







Taylor-Green Vortex (Re=1600, M=0.1)
P15 (16^{th}-order), 8x8x8 Cells (DOFs=128^3)

(Only $1/8$ domain ($0 \leq x, y, z \leq \pi L$) is shown due to symmetry)

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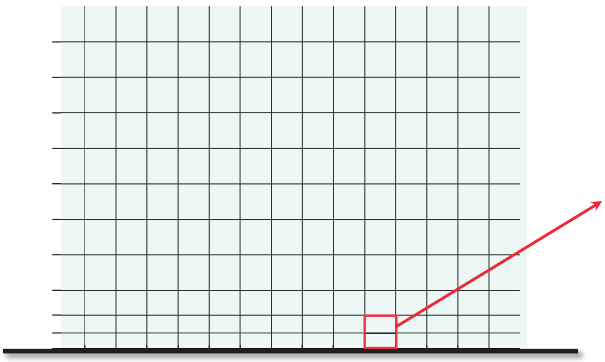
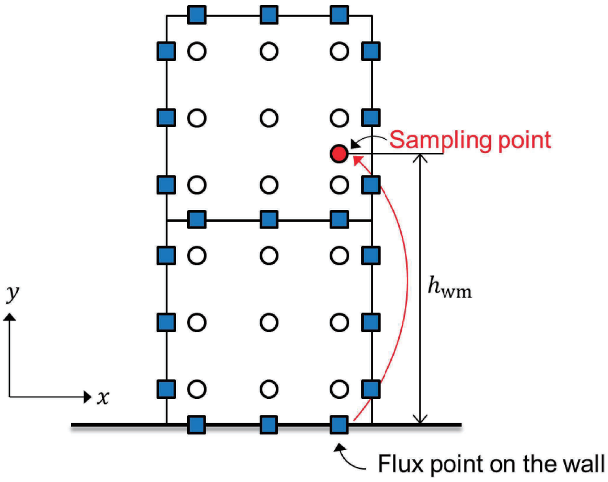
Wall Modeled LES

LES mesh without resolving BL inner layer (~10% of BL thickness)



Wall shear stress: τ_w?



Inner layer model : 1D ODE (Kawai & Larsson 2012)

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

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

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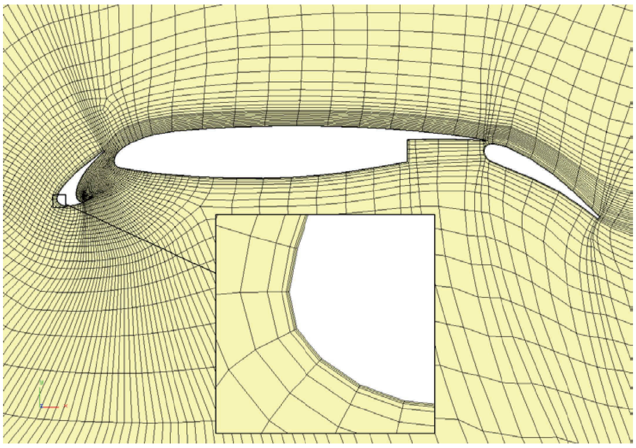
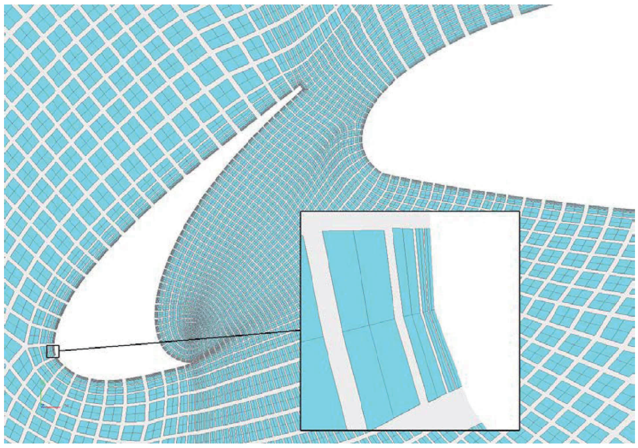
Computational Mesh



Linear mesh
- 6475 quad cells in 2D
- 291,375 hex cells in 3D (45 cells in span))

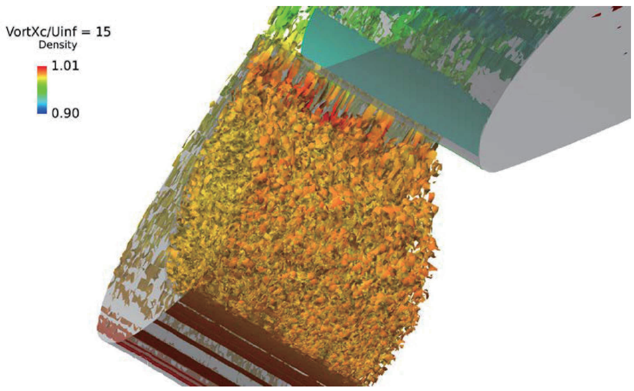


High-order (P2) mesh
(Each cell is shrink-displayed)

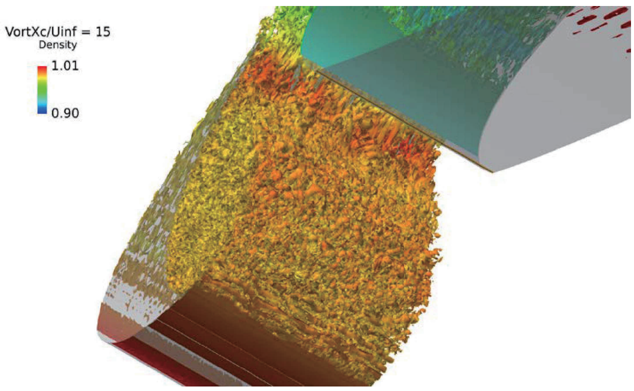
- The APC workshop mesh (L2, medium) was modified (1/4 coarser in each direction)
- $\Delta x_{Wall}/c = 2 \times 10^{-4}$ $(y^{+} < 20)$ (~$0.04\,\delta$ by assuming $\delta = 0.005$ c)
- HO mesh is generated by converting the linear mesh using *QuickMesh*

Computational Cost

Iso-surface of Streamwise Vorticity



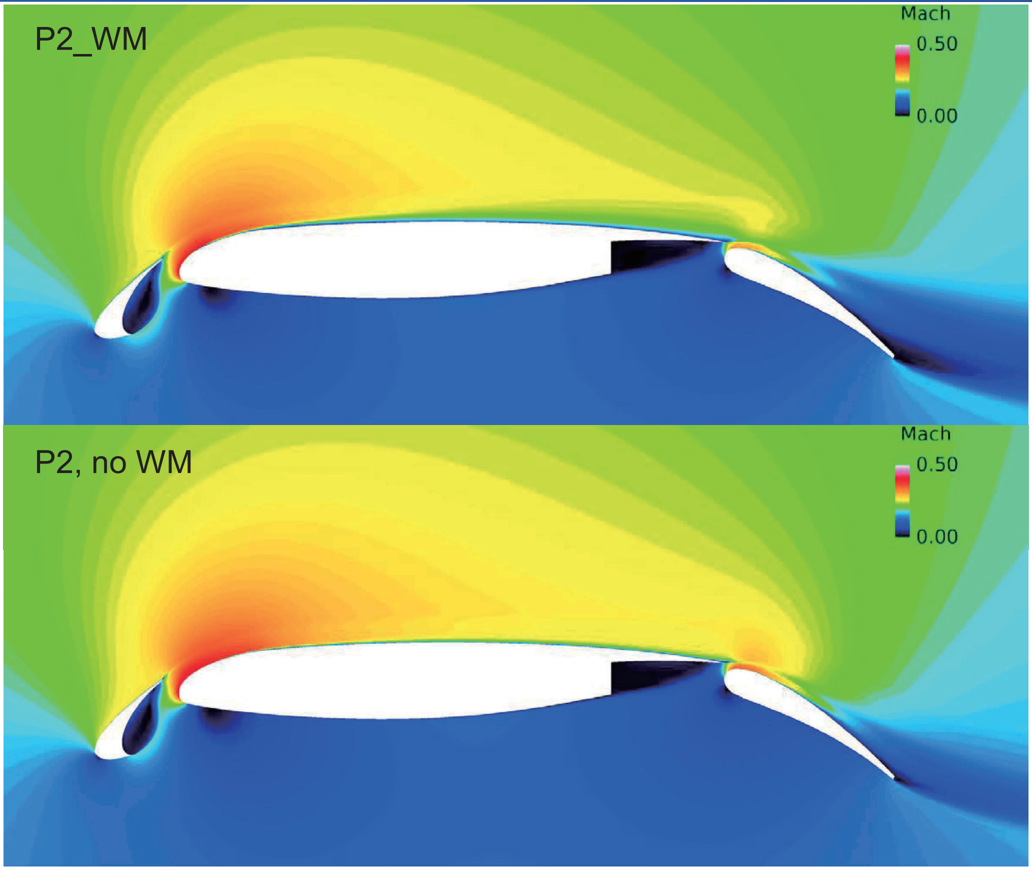
P2, 7.9M DoFs



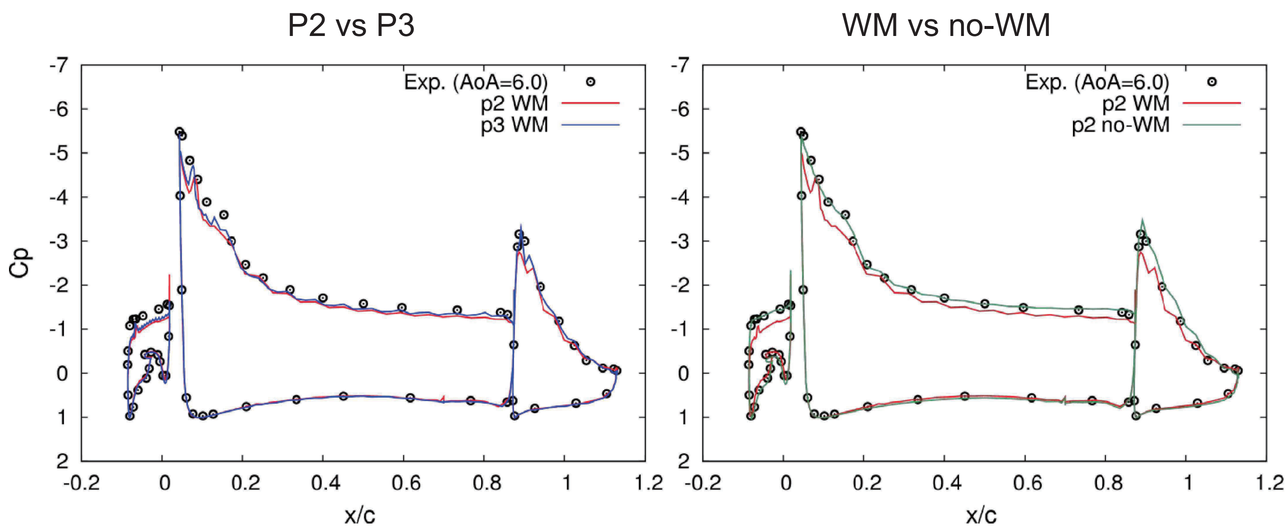
P3,18.7M DoFs

Case	$\Delta t \cdot a_{\infty}/c$	Timesteps for $10\,c/U_{\infty}$	Cores (Nodes) Fujitsu FX100	Elapse time [hours] for $10\,c/U_{\infty}$
P2_wm	4.0e-5	1.51E+06	480 (15)	7.32E+01
P3_wm	2.5e-5	2.41E+06	1440 (45)	1.32E+02

Time Averaged Flowfield (Mach Number)

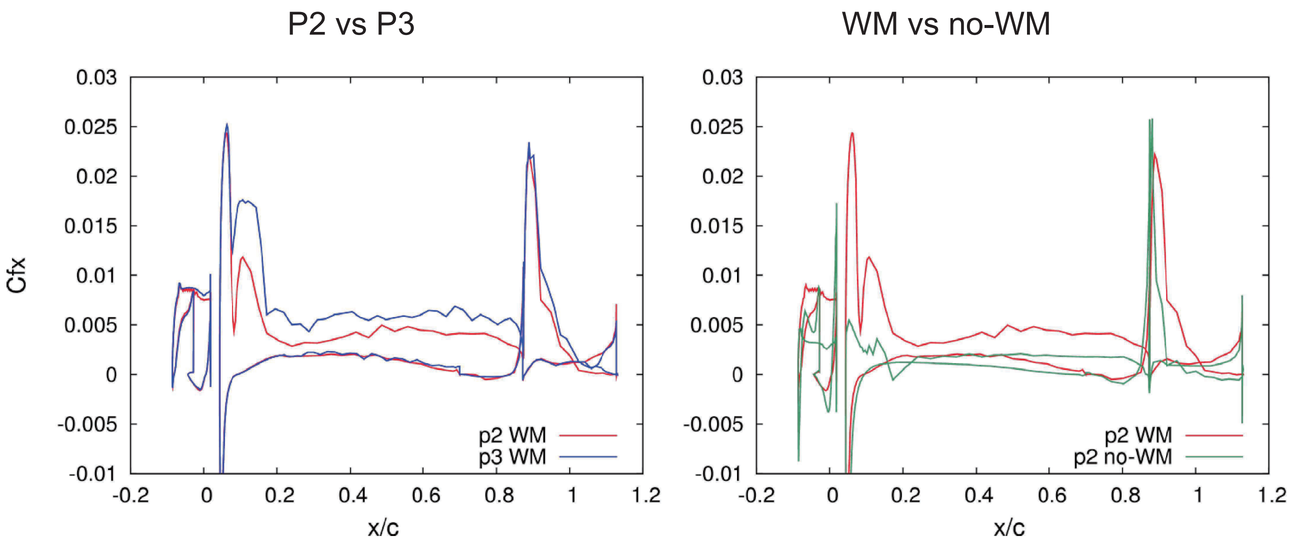


Pressure Coefficient (Averaged)



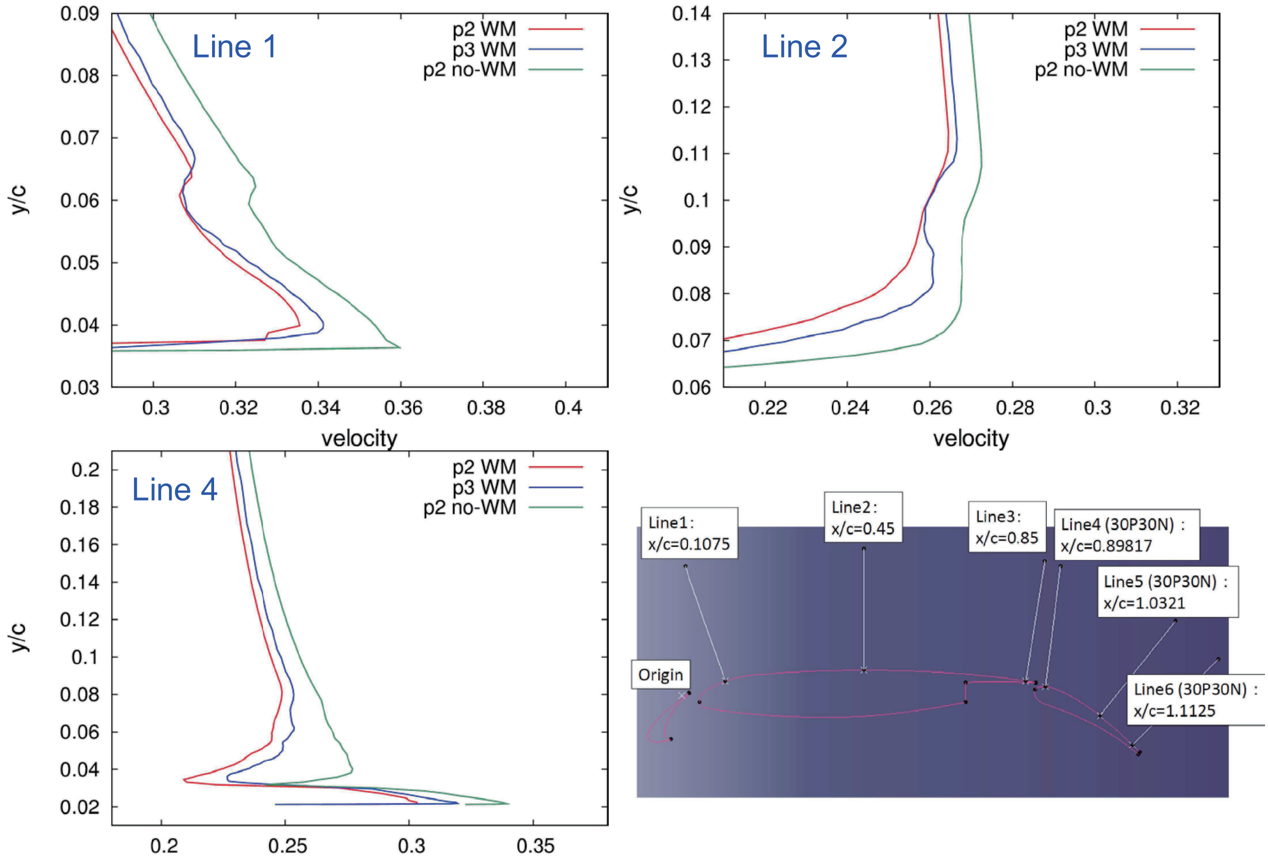
- "no-WM" agrees better with the experiment

Skin Friction Coefficient (Averaged)

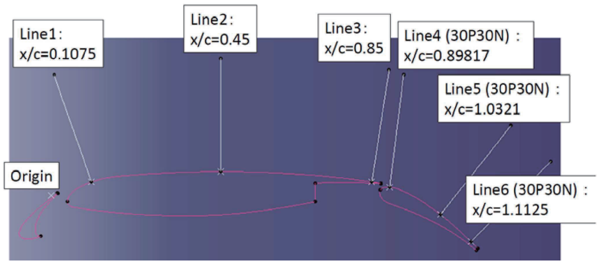


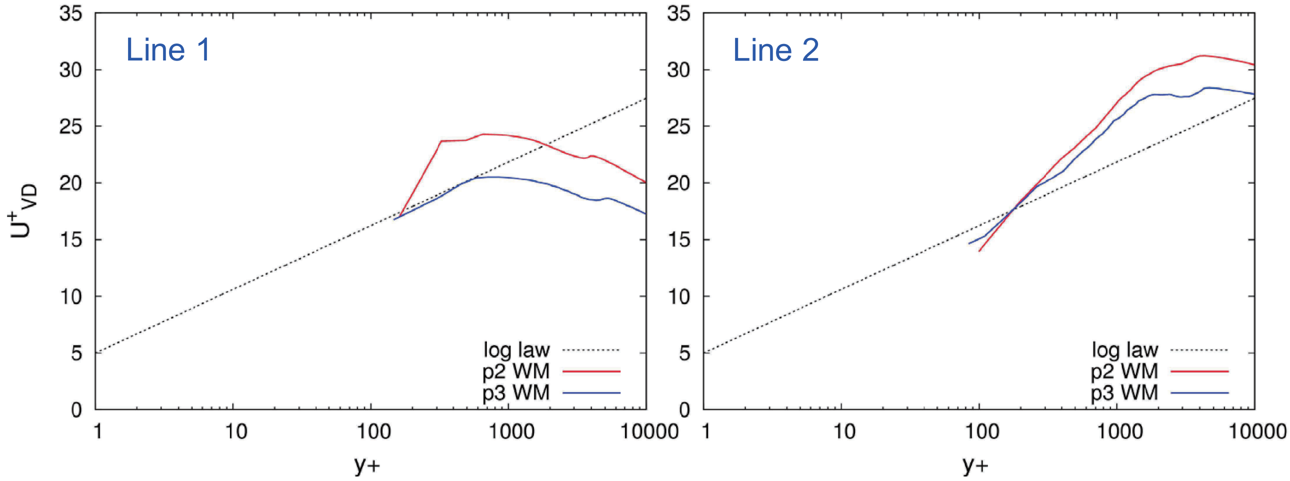
- “WM” improves skin friction prediction

Velocity Profiles (Averaged)



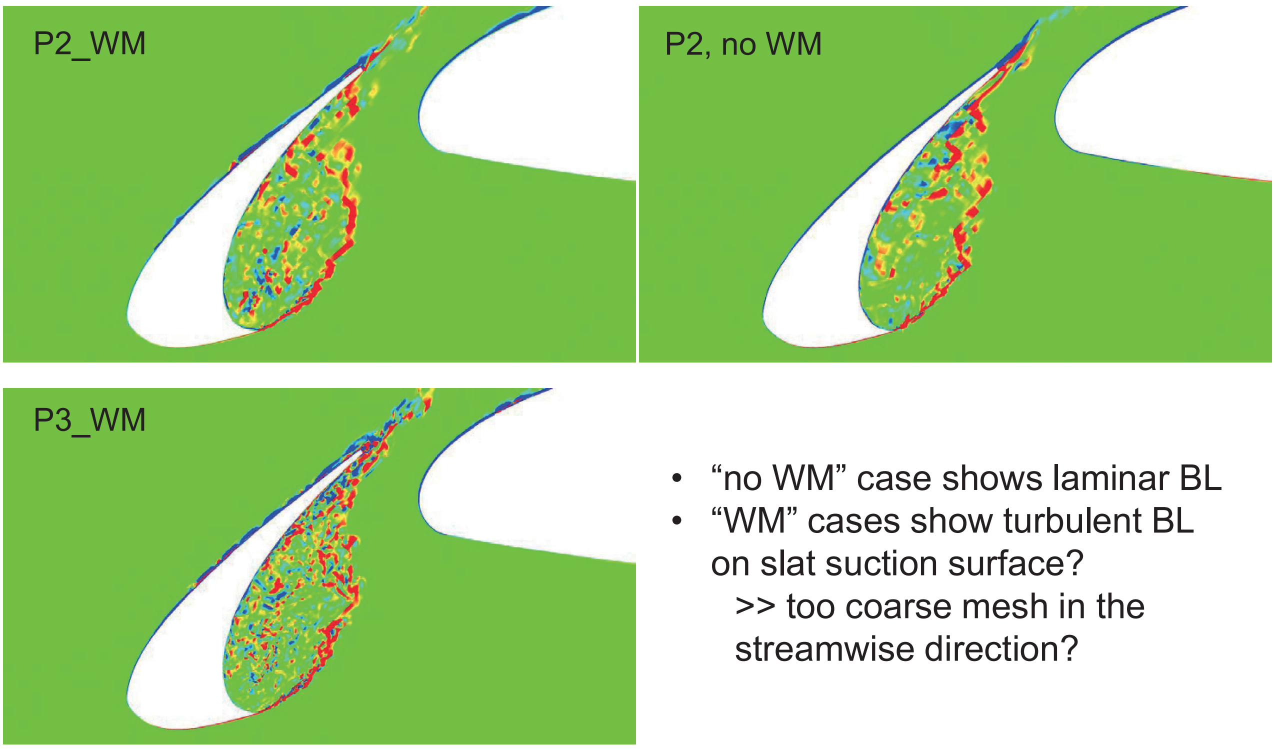
Velocity Profiles (Averaged)





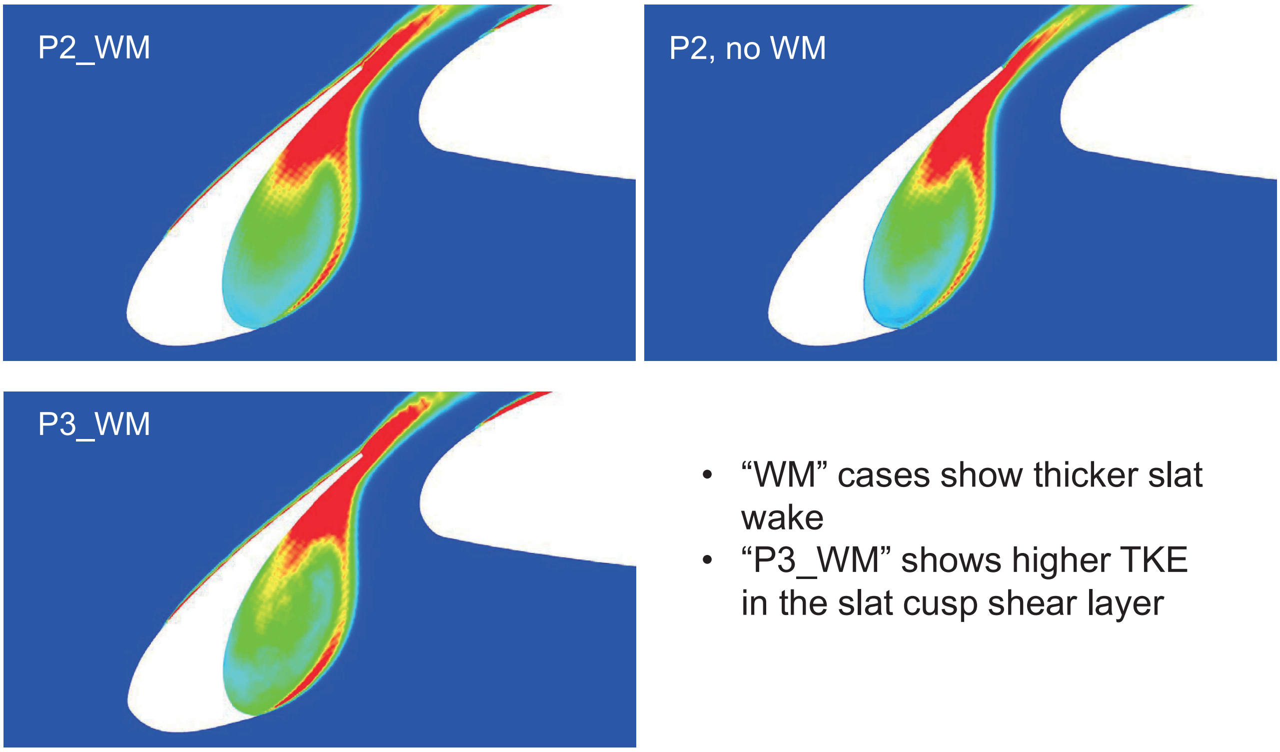
- Too coarse mesh (in the flow direction) to resolve BL even with the wall-model
- Higher order (p3) result shows some improvement

Spanwise Vorticity



- “no WM” case shows laminar BL
- “WM” cases show turbulent BL on slat suction surface?
  >> too coarse mesh in the streamwise direction?

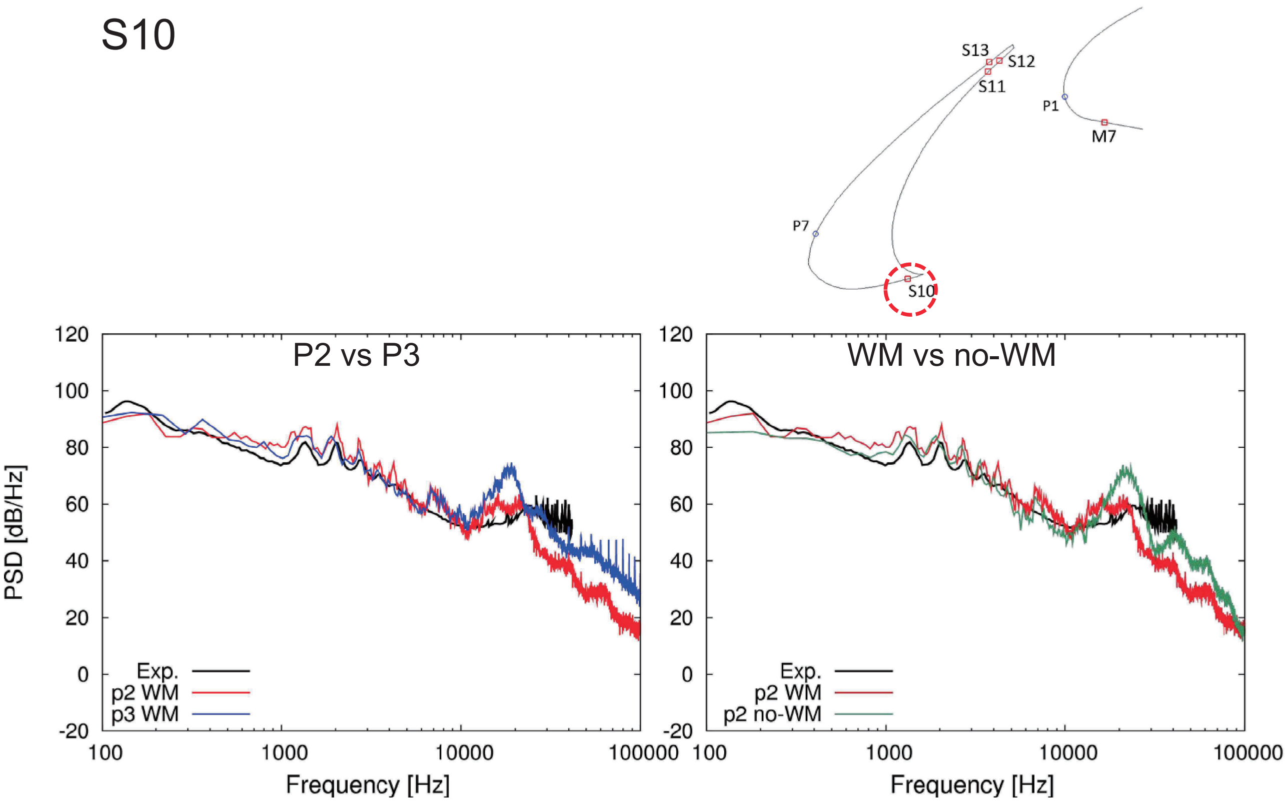
Turbulent Kinetic Energy



- “WM” cases show thicker slat wake
- “P3_WM” shows higher TKE in the slat cusp shear layer

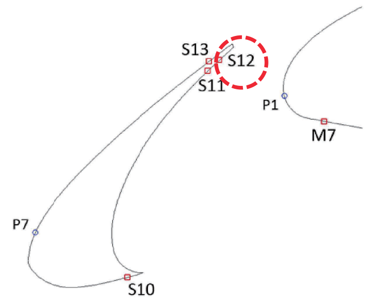
Nearfield PSD

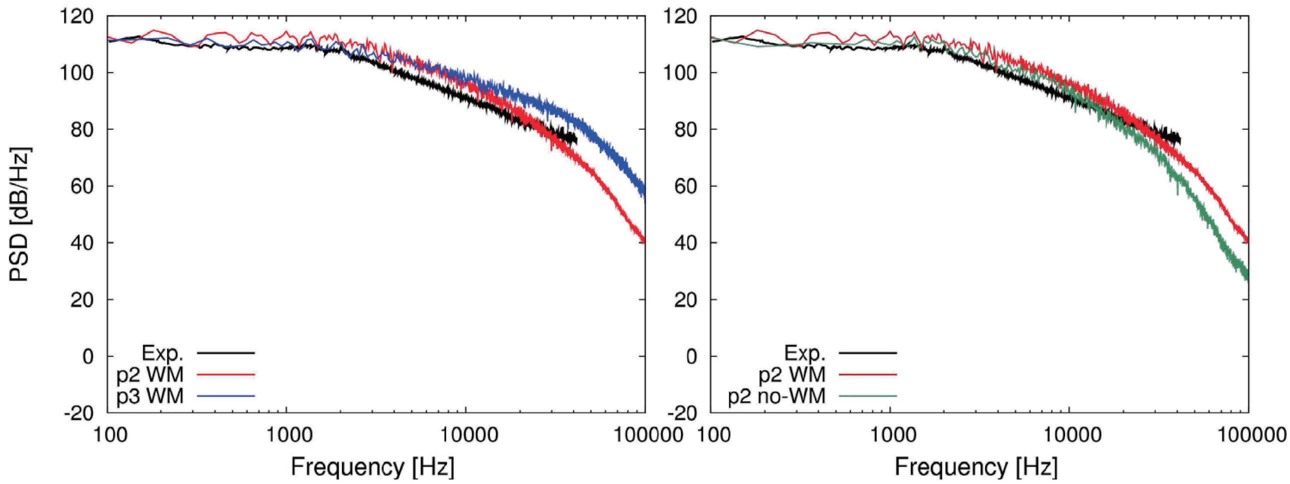
S10



Nearfield PSD

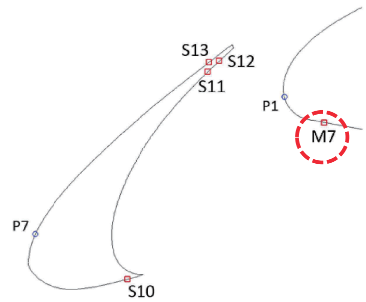
S12

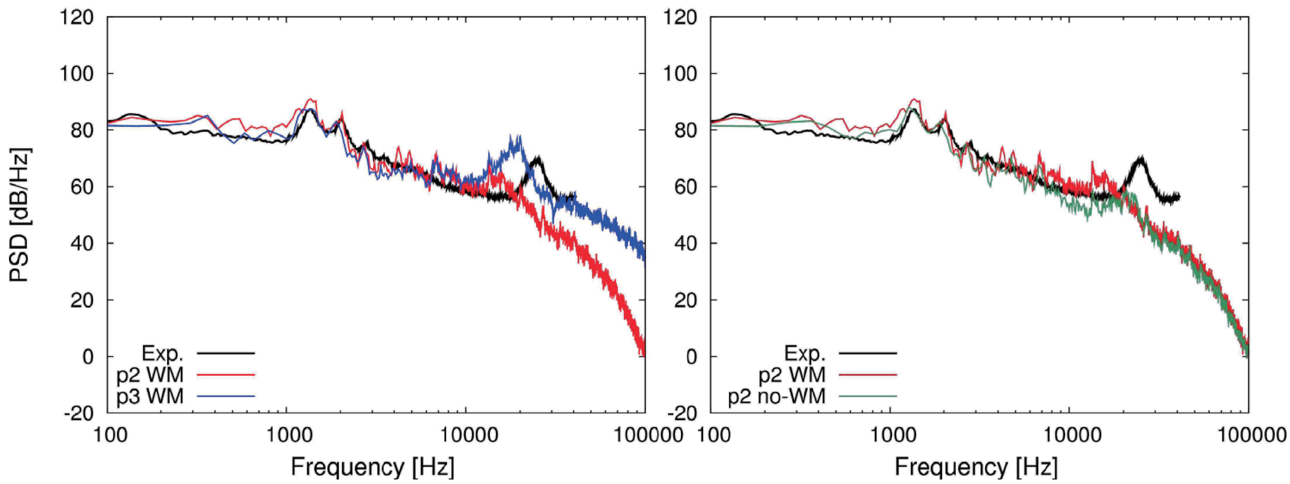




Nearfield PSD

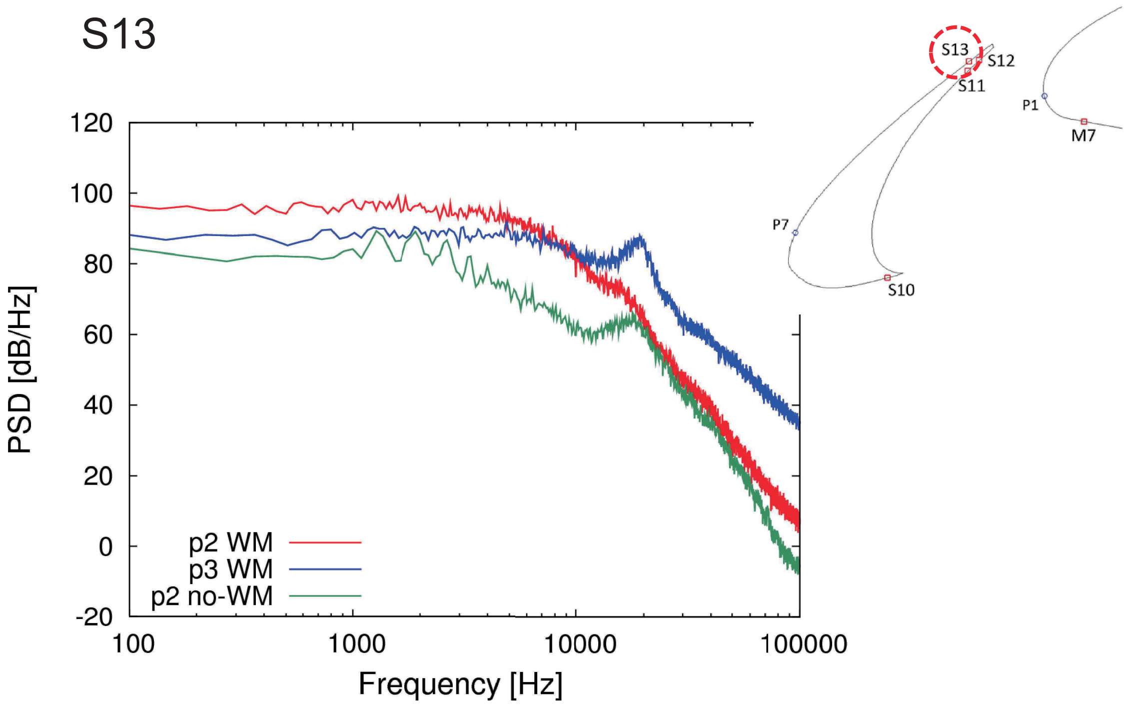
M7





Nearfield PSD

S13



- “WM” results show higher PSD level due to the spurious BL separation on the slat suction side

Summary

- Proposed approach offers robust LES even on a very coarse mesh and a high Re number condition
- The wall model (assuming fully turbulent BL) fails to predict laminar BL on the slat
  - ➢ Needs grid convergence study
  - ➢ Adopts laminar/turbulence switch with a sensor?
- Correct BL prediction on the slat is important for Cp, but its effect on the near field PSD (except for S13) may not be significant
  - ➢ Needs further investigation on far field PSD
- Overall, higher order (p3) results show better PSD in the slat cove. Also, p2 results with 7.9M DOFs were in good agreement with the experimental data.

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