Fifth Aerodynamics Prediction Challenge (APC-V)
2019/7/1 Tokyo

レイノルズ応力モデルを用いた 30P30Nの空力予測

Aerodynamic prediction of 30P30N using a Reynolds stress model

k-ω SST遷移モデルを用いた 30P35Nのフラップ剥離予測

Flap separating prediction of 30P35N using a SST transition model

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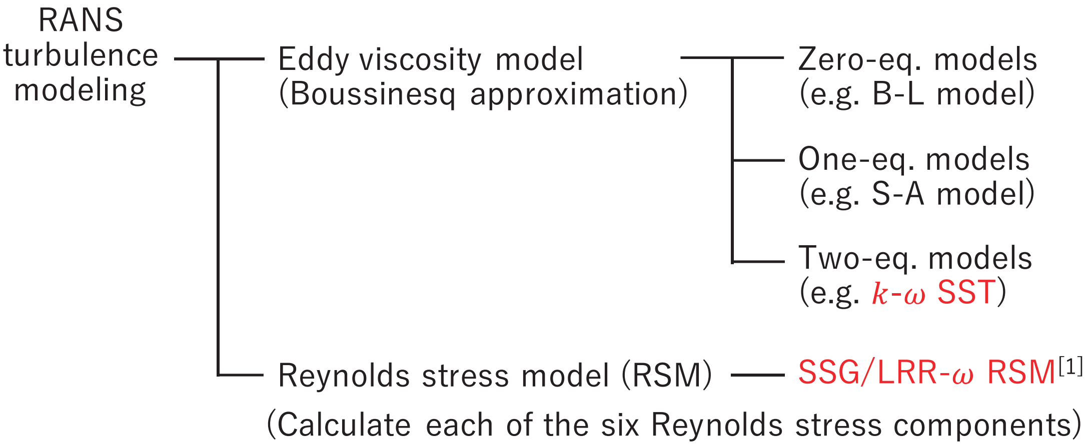
1. Overview of turbulence model
2. Computational settings
3. Results: comparison with k-ω SST
4. Concluding remarks

Turbulence model

$$\frac{\partial(\bar{\rho}\hat{u}_i)}{\partial t} + \frac{\partial(\hat{u}_j\bar{\rho}\hat{u}_i)}{\partial x_j} = -\frac{\partial\overline{p}}{\partial x_i} + \frac{\partial\overline{\sigma_{ij}}}{\partial x_j} + \frac{\partial\overline{\tau_{ij}}}{\partial x_j}$$

$\overline{\sigma_{ij}}$: Molecular viscous stress
$\overline{\tau_{ij}}$: Reynolds stress



RANS turbulence modeling

Eddy viscosity model
(Boussinesq approximation)

Zero-eq. models
(e.g. B-L model)

One-eq. models
(e.g. S-A model)

Two-eq. models
(e.g. k-ω SST)

Reynolds stress model (RSM)
(Calculate each of the six Reynolds stress components)

SSG/LRR-ω RSM[1]

[1] Eisfeld et al., 2003

Reynolds stress model

SSG/LRR-ω RSM: Reynolds stress model proposed by Eisfeld et al.

Governing eq.

$$\frac{\partial(\bar{\rho}\hat{u}_i)}{\partial t} + \frac{\partial(\hat{u}_j\bar{\rho}\hat{u}_i)}{\partial x_j} = -\frac{\partial\overline{p}}{\partial x_i} + \frac{\partial\overline{\sigma_{ij}}}{\partial x_j} + \frac{\partial\overline{\tau_{ij}}}{\partial x_j} \quad \longleftarrow \boxed{\tau_{ij}}$$

Turbulence model

The six Reynolds stress equations and one length scale equation are given by:

$$\left.\begin{aligned}
&\frac{\partial\bar{\rho}\hat{R}_{ij}}{\partial t} + \frac{(\partial\bar{\rho}\hat{u}_l\hat{R}_{ij})}{\partial x_l} = \bar{\rho}P_{ij} + \bar{\rho}\Pi_{ij} - \bar{\rho}\epsilon_{ij} + \bar{\rho}D_{ij} \qquad (\bar{\tau_{ij}} = -\bar{\rho}\hat{R}_{ij}) \\
&\frac{\partial\bar{\rho}\omega}{\partial t} + \frac{\partial(\bar{\rho}\hat{u}_l\omega)}{\partial x_l} = \frac{\alpha_\omega\omega}{\hat{k}}\frac{\bar{\rho}P_{ll}}{2} - \beta_\omega\omega^2 + \frac{\partial}{\partial x_l}\left[\left(\bar{\mu} + \sigma_\omega\frac{\bar{\rho}\hat{k}}{\omega}\right)\frac{\partial\omega}{\partial x_l}\right] + \sigma_d\frac{\bar{\rho}}{\omega}\max\left(\frac{\partial\hat{k}}{\partial x_j}\frac{\partial\omega}{\partial x_j}, 0\right)
\end{aligned}\right]$$

P_{ij}: production Π_{ij}: pressure-strain ϵ_{ij}: dissipation D_{ij}: diffusion

Case 1-2: Aerodynamic prediction of 30P30N airfoil

Numerical method	
Governing eqs.	Compressible N-S eqs.
Discretization	Cell-centered finite volume
Inviscid flux	SLAU with 3rd-order U-MUSCL
Viscous flux	2nd-order
Time integration	LU-SGS dual-time stepping
Turbulence model	SSG/LRR-ω RSM, k-ω SST model

Flow condition	
M_∞	0.17
Re_c	1.71×10^6
T_∞	295.56 K
α	0 ~ 24 deg

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1. Overview of Turbulence model

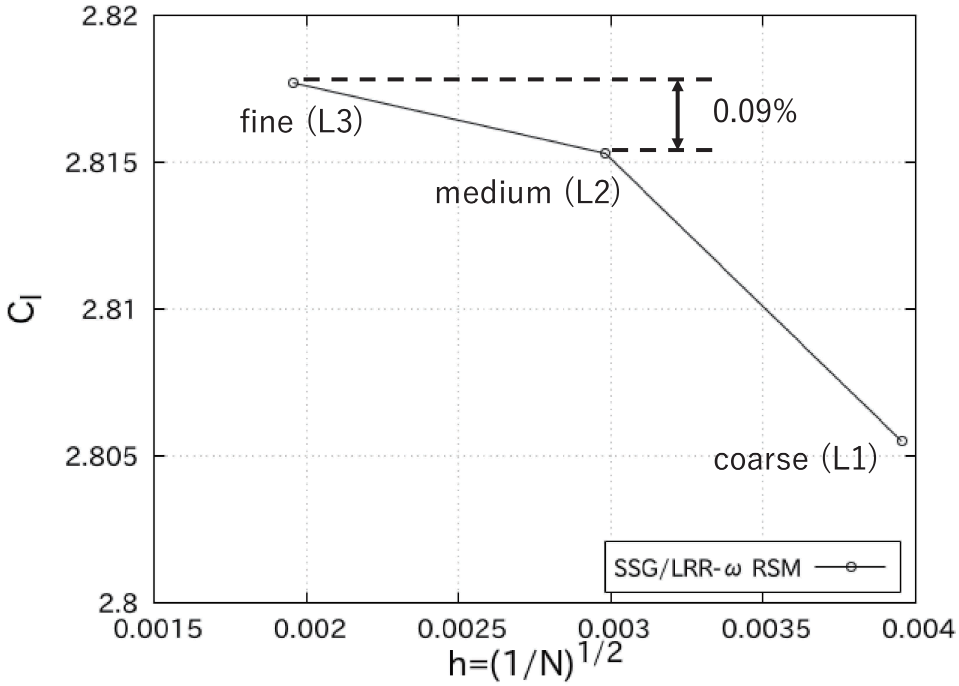
2. Computational settings

3. Results: comparison with k-ω SST model

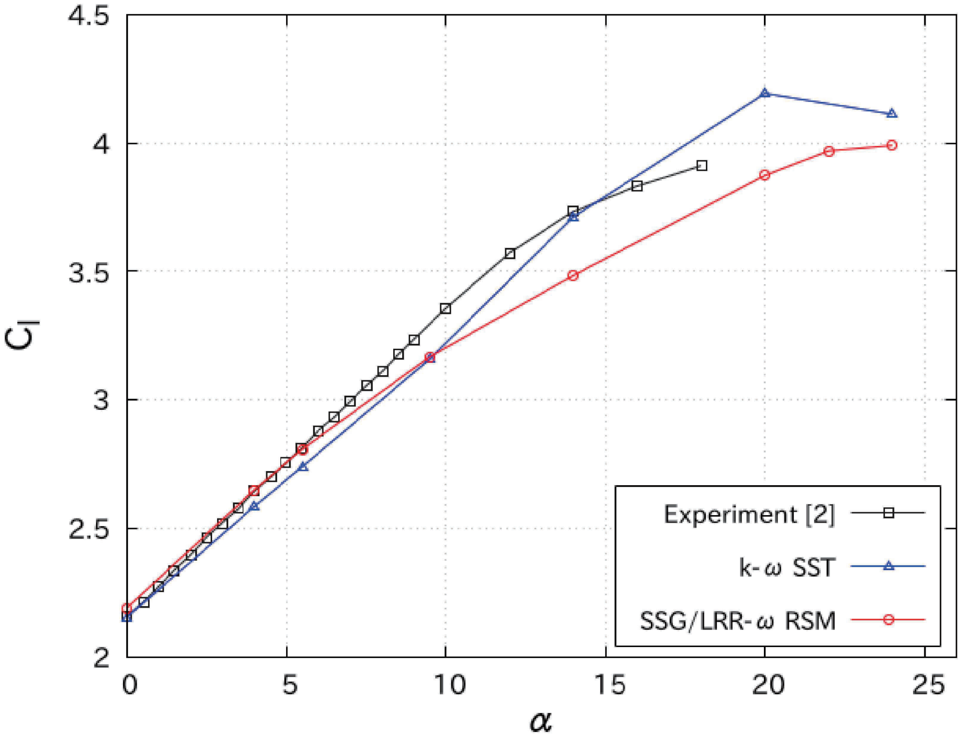
    - Grid convergence study
    - Lift coefficient C_l
    - α=5.5 deg
    - α=14 deg

4. Concluding remarks

Grid convergence study (α=5.5 deg)

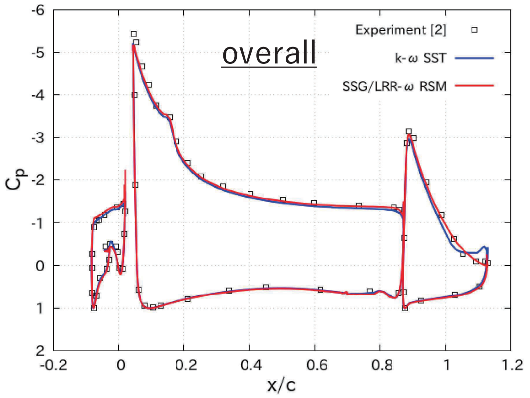


Lift coefficient C_l



[2] Murayama et al., 2014

Pressure coefficient C_p (α=5.5 deg)

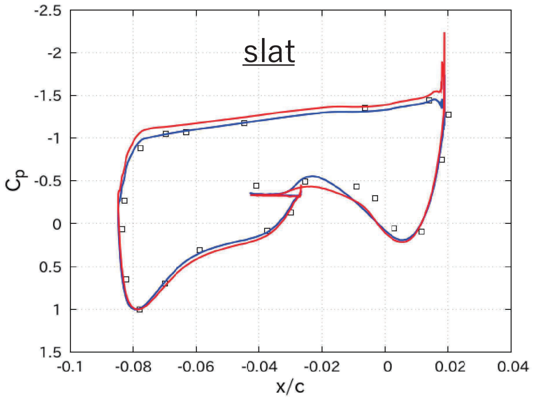


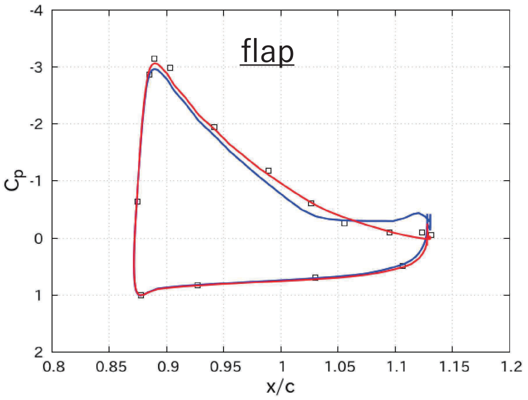
Lift coefficient: C_l

Experiment: 2.81

k-ω SST: 2.74

SSG/LRR-ω RSM: 2.80

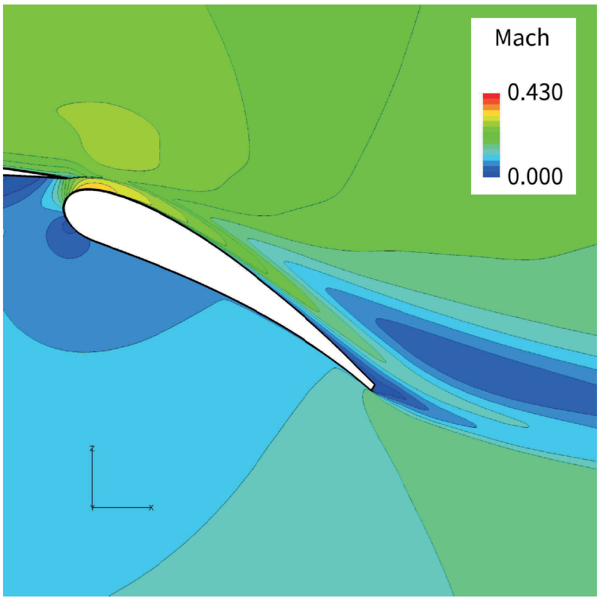




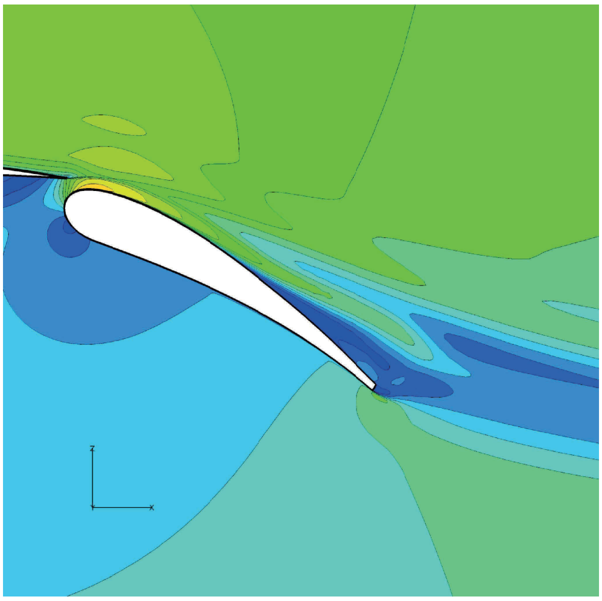
[2] Murayama et al., 2014

Mach number (α=5.5 deg)

SSG/LRR-ω RSM

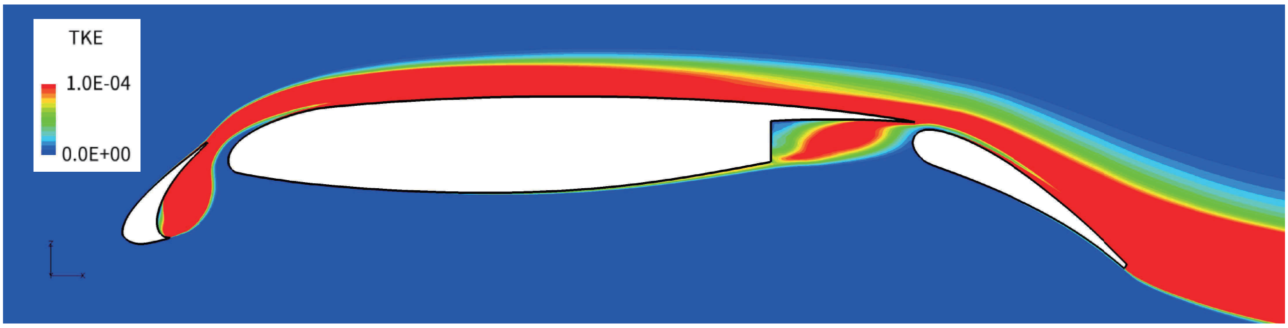


k-ω SST

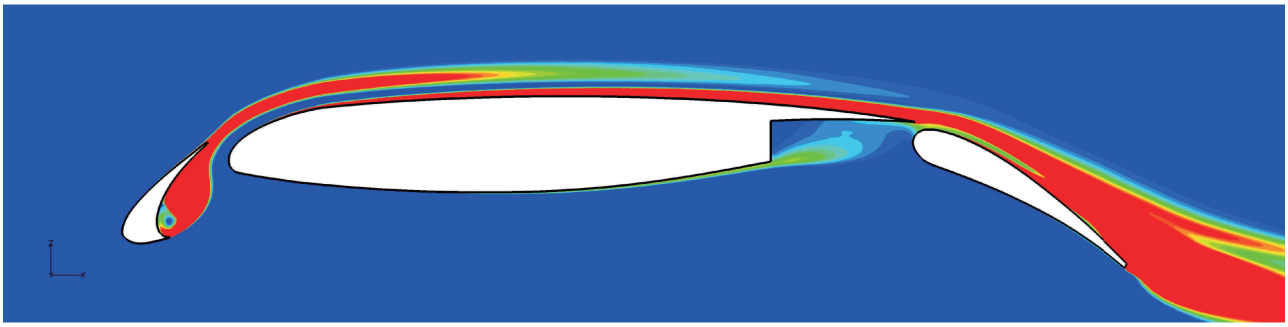


Turbulence kinetic enegy k (α=5.5 deg)

SSG/LRR-ω RSM

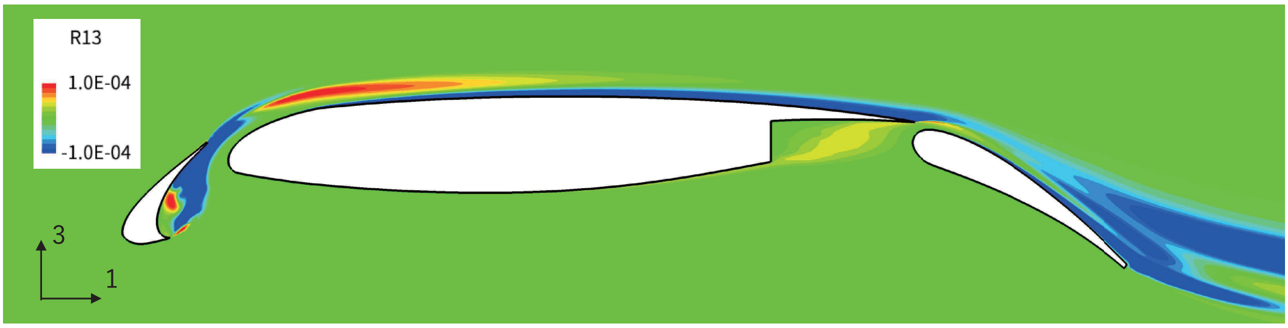


k-ω SST

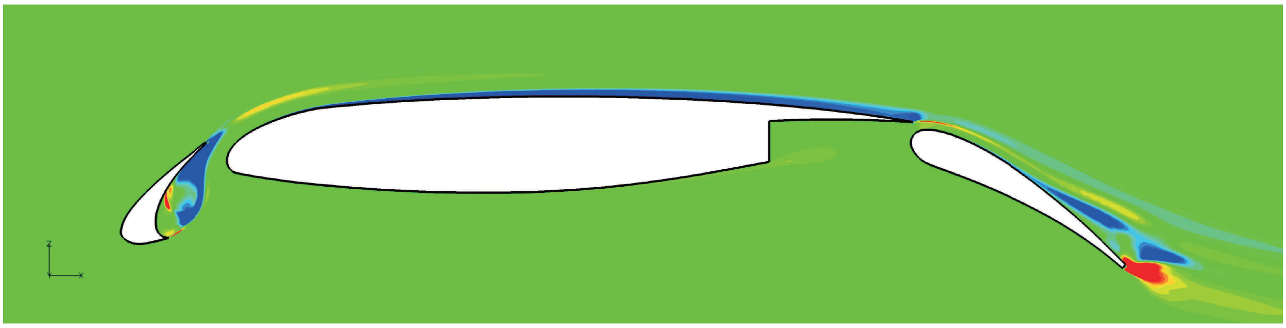


Reynolds stress R_{13} (α=5.5 deg)

SSG/LRR-ω RSM



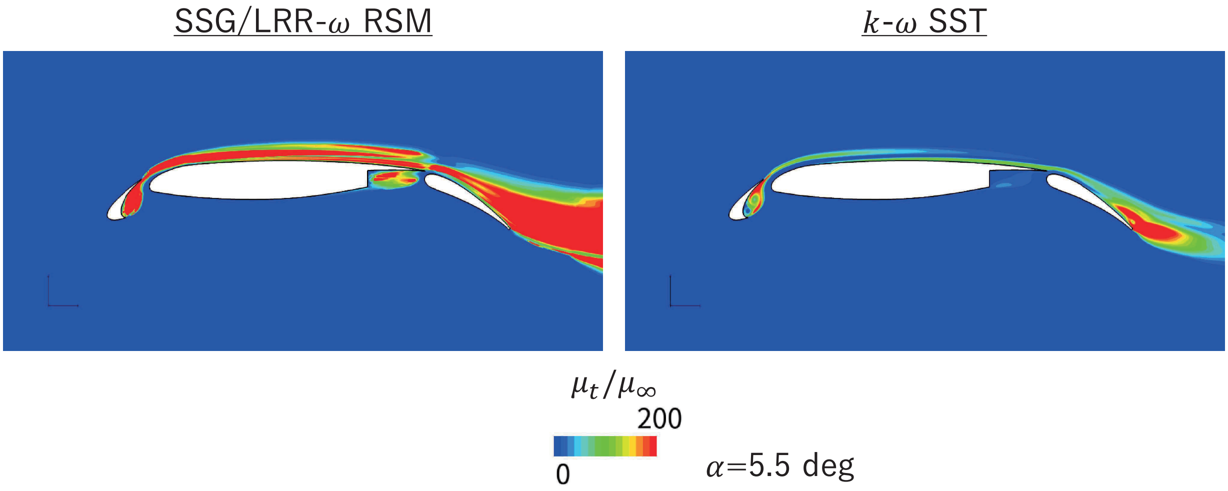
k-ω SST



Estimated μ_t in RSM

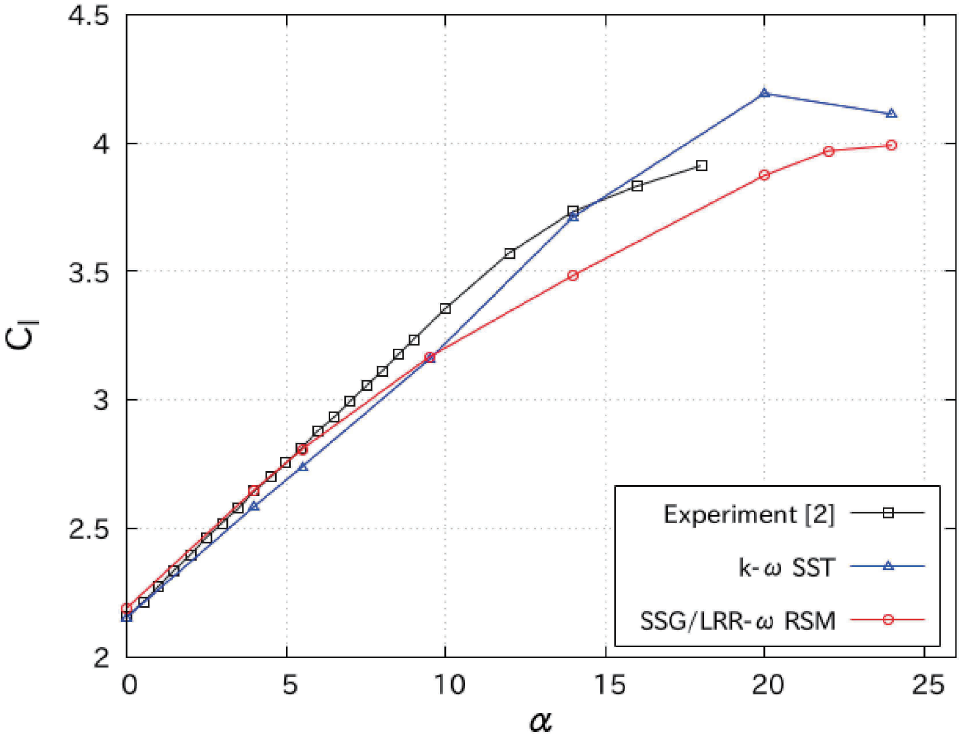
$$\tau_{ij} = -\rho R_{ij} = \mu_t \left(2S_{ij} - \frac{2}{3}\frac{\partial u_l}{\partial x_l}\delta_{ij}\right) - \frac{2}{3}\rho k \delta_{ij} \quad \text{in } k\text{-}\omega \text{ SST}$$

$$\longrightarrow \quad \mu_t = \frac{\rho}{2}\sqrt{\frac{\left(R_{ij} - \frac{2}{3}k\delta_{ij}\right)^2}{\left(S_{ij} - \frac{1}{3}\frac{\partial u_l}{\partial x_l}\delta_{ij}\right)^2}}$$



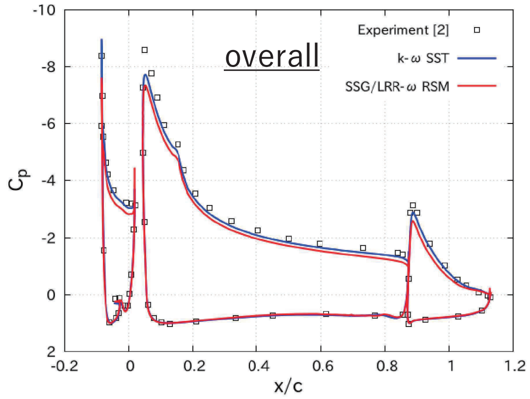
α=5.5 deg

Lift coefficient C_l



[2] Murayama et al., 2014

Pressure coefficient C_p (α=14 deg)

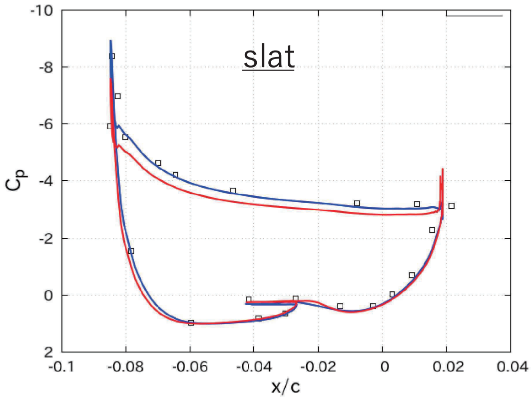


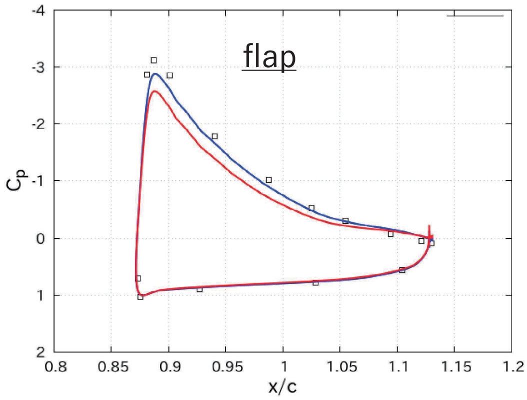
Lift coefficient: C_l

Experiment: 3.73

k-ω SST: 3.71

SSG/LRR-ω RSM: 3.48

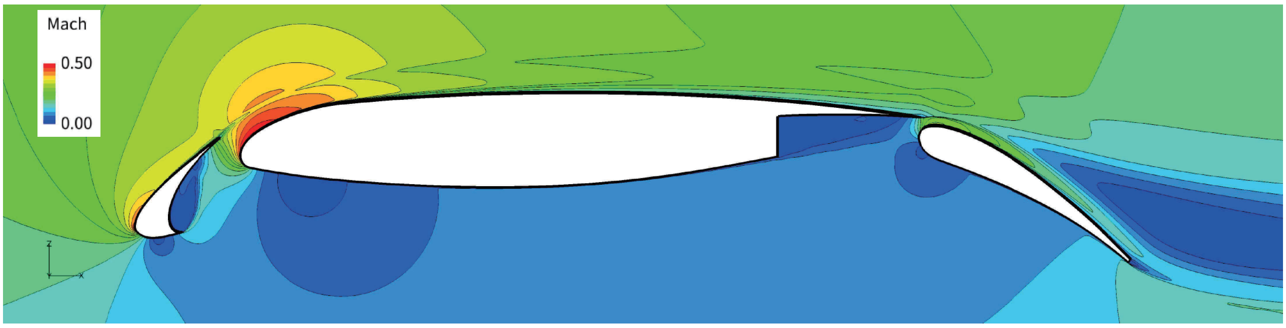




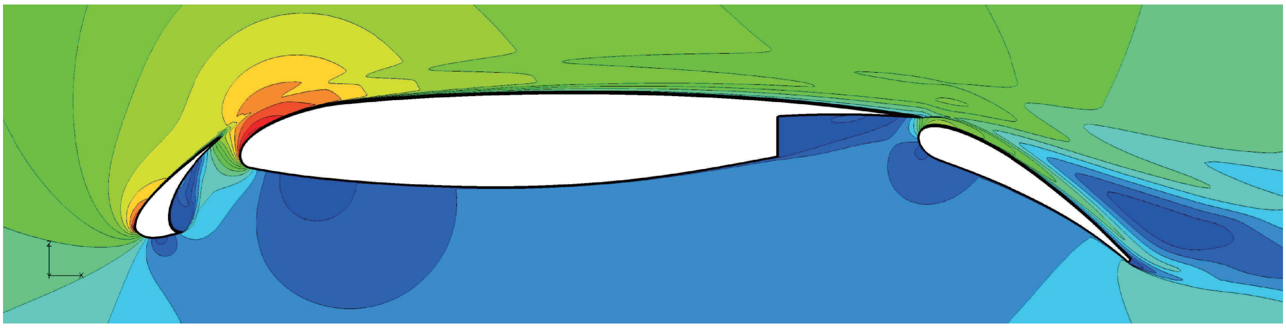
[2] Murayama et al., 2014

Mach number (α=14 deg)

SSG/LRR-ω RSM



k-ω SST



Concluding remarks

We analyzed 30P30N airfoil by RSM

・Pressure coefficient C_p obtained by the RSM is in good agreement with the experimental result (α=5.5 deg), in particular around the flap

・The k-ω SST clearly shows separation around the flap trailing edge, where the RSM predicts relatively smaller separation

・At α=14 deg , lift coefficient C_l is different, but no significant change is found in the flow field