49th Fluid Dynamics Conference / 35th Aerospace Numerical Simulation Symposium
28 June 2017

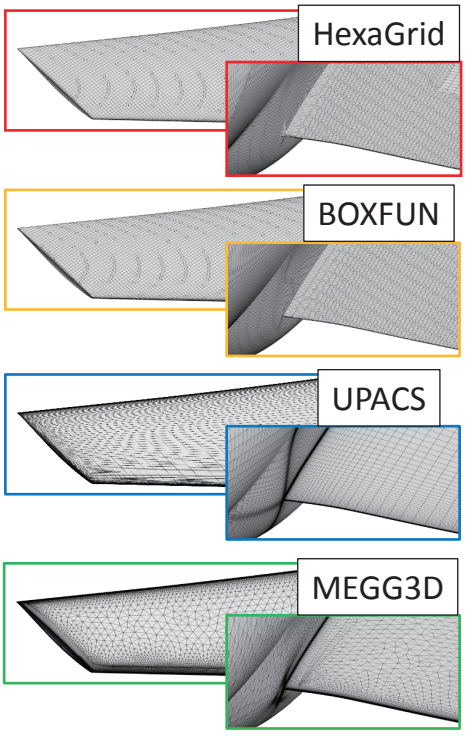
FaSTAR results with Various Grids and Turbulence models

○Takahiro Yamamoto, Kenji Hayashi, Keiji Ueshima
(Ryoyu Systems Co., Ltd.)

Takashi Ishida, Atsushi Hashimoto, Takashi Aoyama
(JAXA)

Task1 Computational Method

- Flow solver: FaSTAR
  - Grid: HexaGrid,BOXFUN,UPACS,MEGG3D
  - Turbulence model: 3 SST models,
    3 EARSM models,
    + 1 SA model (APC2 result)
  - Discretization
    - Cell-Vertex: MEGG3D
    - Cell-Center: HexaGrid, UPACS, BOXFUN
  - Inviscid flux: HLLEW
  - Reconstruction: U-MUSCL(χ=0.5)
  - Gradient: GLSQ
  - Slope limiter: Hishida(van Leer-type)
  - Time integration: LU-SGS(Local time stepping)



Turbulence models (1)

- **SAQCR**: SA-noft2-R-QCR2000
  - This is used for APC-I and APC-II.
  - No Ft2 term, rotation correction, nonlinear QCR model

  QCRモデル $\tau_{ij,QCR} = \underbrace{\tau_{ij}}_{\text{Linear}} \underbrace{- C_{cr1}\left[O_{ik}\tau_{jk} + O_{jk}\tau_{ik}\right]}_{\text{Nonlinear（QCR model）}}$
- **SST**: SST2003
  - Menter's SST proposed in 2003
- **SSTsust**: SST-2003-sust
  - k and ω do not decay in free stream（controlled decay）
- **SSTsustQCR**: SST-2003-sust-QCR2000
  - Add QCR model to the above SSTsust model

Controlled decay model

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^*\rho\omega k + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right] + \beta^*\rho\omega_{amb}k_{amb}$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho u_j\omega)}{\partial x_j} = \frac{\gamma}{\nu_t}P - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega\mu_t)\frac{\partial\omega}{\partial x_j}\right] + 2(1-F_1)\frac{\rho\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} + \beta\rho\omega_{amb}^2$$

$$k_{amb} = 10^{-6}U_\infty^2$$

$$\omega_{amb} = \frac{5U_\infty}{L}$$

The destruction terms are canceled when $k=k_{amb}$, $\omega=\omega_{amb}$

3

Turbulence models (2)

- **EARSM**: EARSMko2005a
  - Hellsten's k-ω based explicit algebraic Reynolds stress model

$$\tau_{ij} = 2\frac{M_\infty}{Re_\infty}\mu_t\left(S_{ij} - \frac{1}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right) - \frac{1}{3}\rho k\delta_{ij} - \underbrace{a_{ij}^{(ex)}\rho k}_{\text{Nonlinear term}}$$

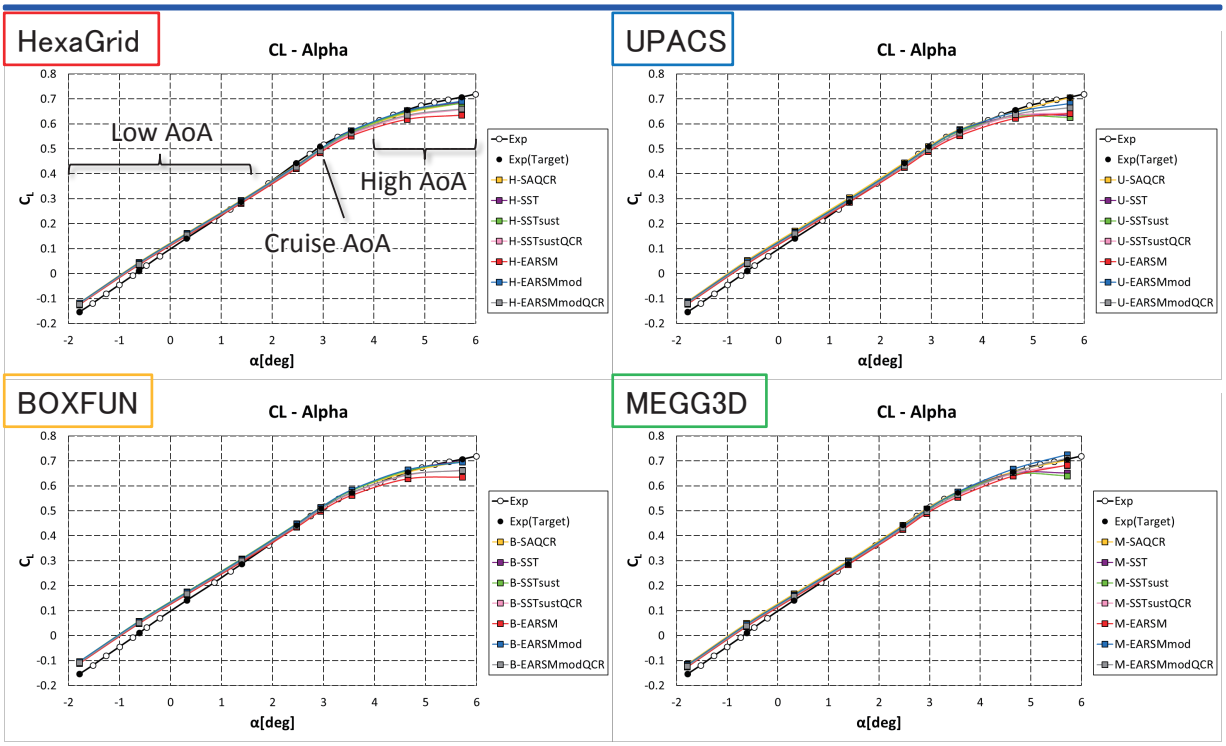
$$a_{ij}^{(ex)} = \beta_3\left(W_{ik}^*W_{kj}^* - \frac{1}{3}II_\Omega\delta_{ij}\right) + \beta_4\left(S_{ik}^*W_{kj}^* - W_{ik}^*S_{kj}^*\right) + \beta_6\left(S_{ik}^*W_{kl}^*W_{lj}^* + W_{ik}^*W_{kl}^*S_{lj}^* - II_\Omega S_{ij}^* - \frac{2}{3}IV\delta_{ij}\right)$$
$$+ \beta_9\left(W_{ik}^*S_{kl}^*W_{lm}^*W_{mj}^* - W_{ik}^*W_{kl}^*S_{lm}^*W_{mj}^*\right)$$

$$S_{ij}^* = \frac{1}{\beta^*\omega}\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \quad W_{ij}^* = \frac{1}{\beta^*\omega}\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$

- **EARSMmod**:
  - The nonlinear term $a^{(ex)}$ is deleted from the above model
  - This is a linear k-ω model, but this is different form the Wilcox's k-ω model
- **EASRMmodQCR**:
  - Add QCR model to the above EARSMmod

4

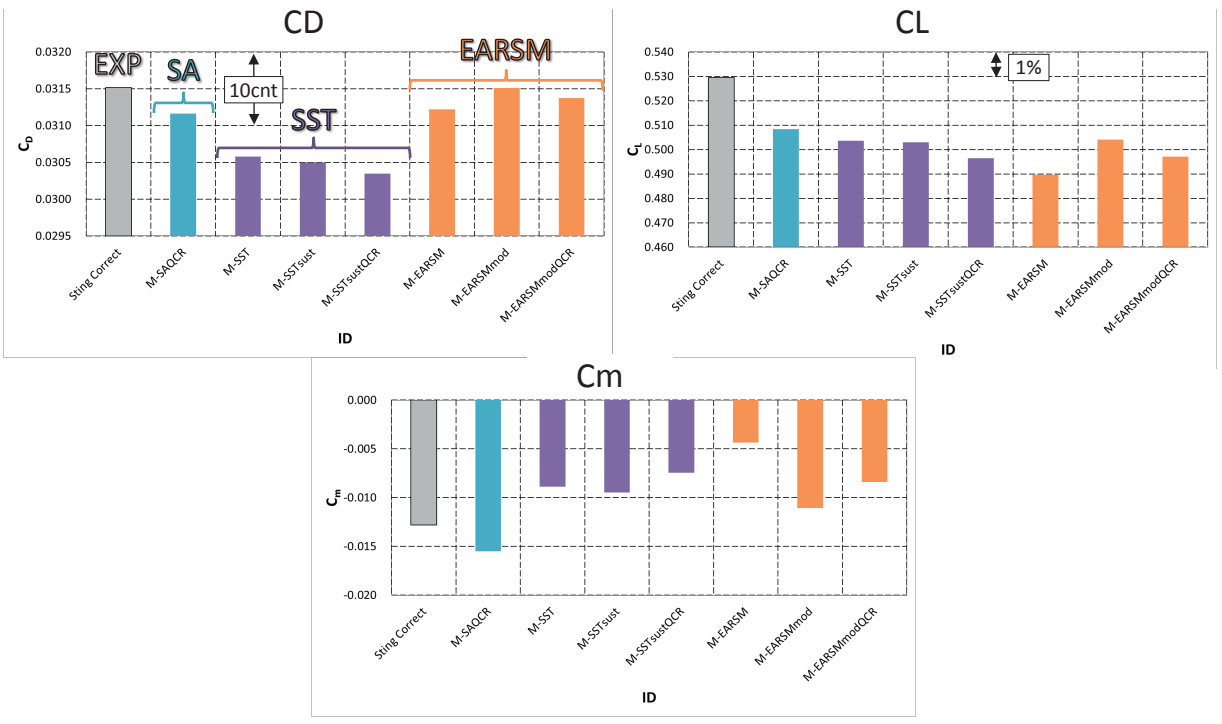
CL-α



- Low AoA - Cruise AoA : Almost same
- High AoA : Considerable variations

5

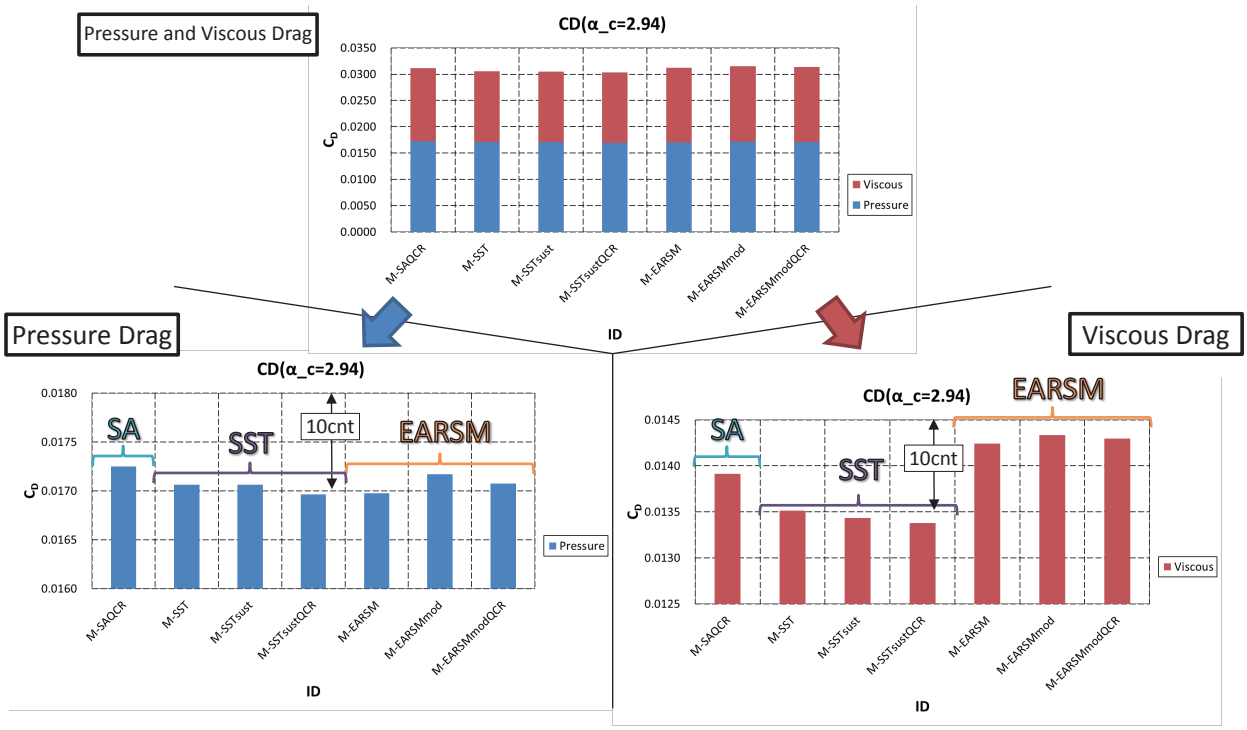
Aerodynamics Coef. at 2.94deg (MEGG3D)



- CD: EARSM model > SA model > SST model
- The similar trend for the other grids.

6

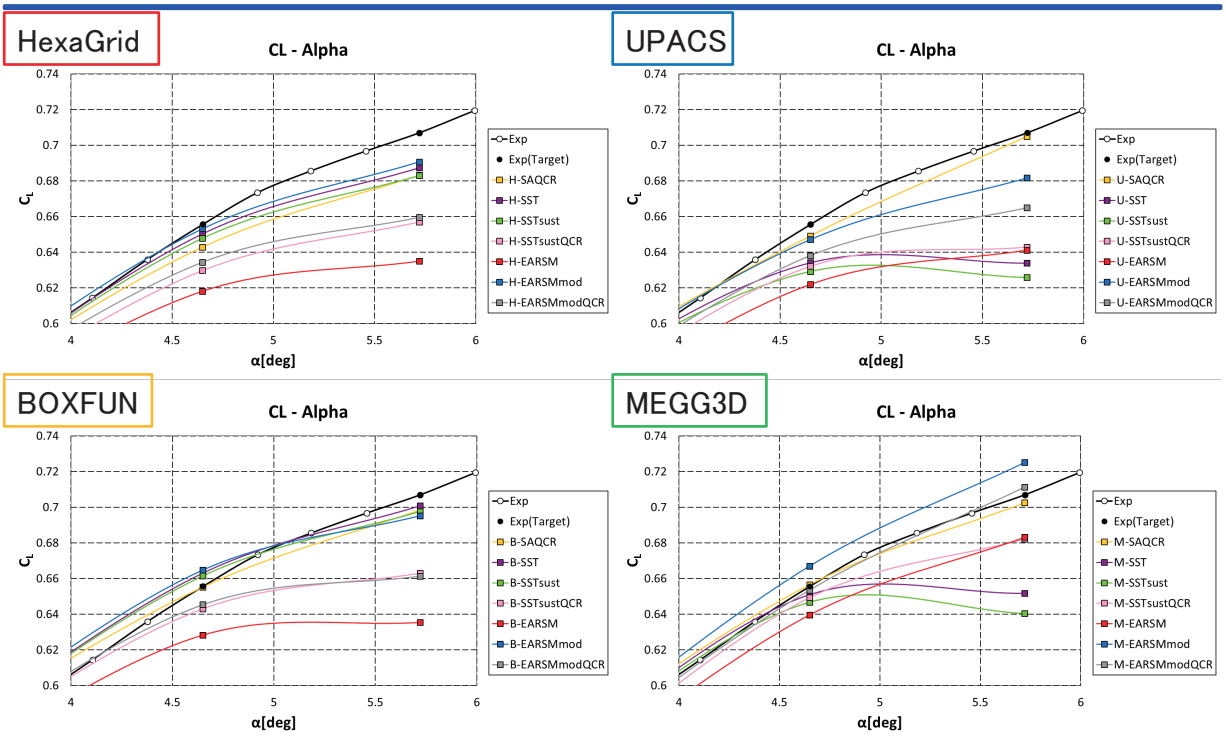
Pressure and Viscous Drag at 2.94deg (MEGG3D)



- Viscous Drag: EARSM model > SA model > SST model

7

CL-α at High Angles of Attack

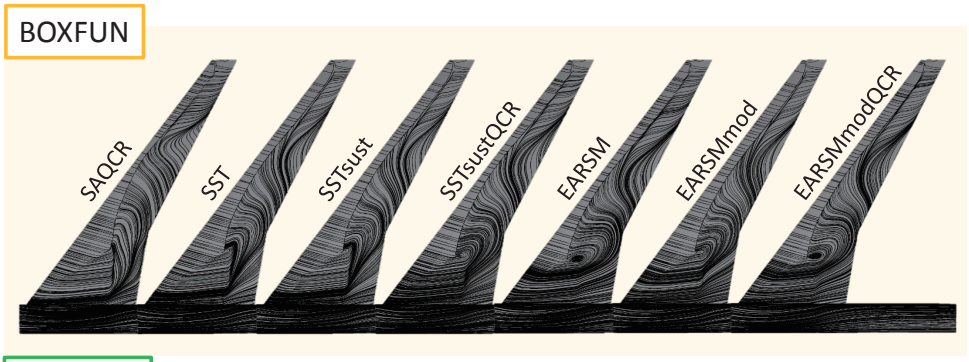


- High AoA: HexaGrid and BOXFUN results are similar trend.
- UPACS and MEGG3D results are similar trend.

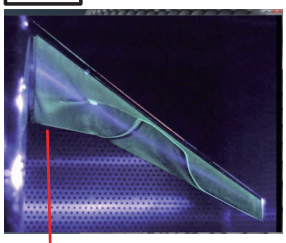
8

SurfaceFlow of AoA5.72deg

BOXFUN

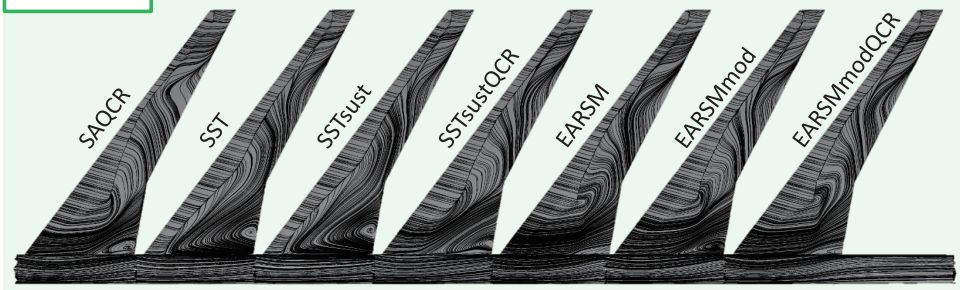


EXP



no SOB

MEGG3D

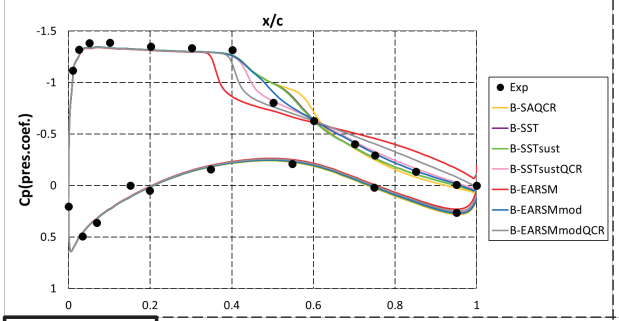


- Shock wave location is changed by turbulence models.
- BOXFUN: There is no SOB(Side of Body) separation.
- MEGG3D: The size of SOB separation is changed by turbulence models.

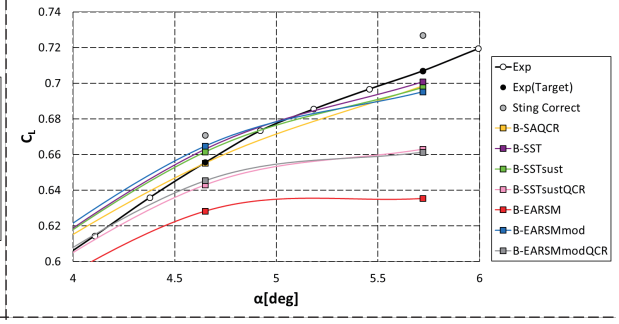
9

Cp and CL of AoA5.72deg(BOXFUN)

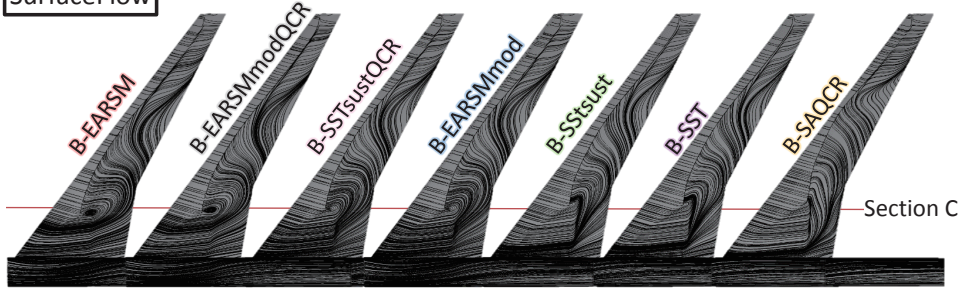
Cp



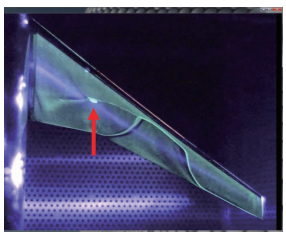
CL-α



SurfaceFlow



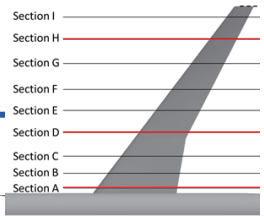
EXP



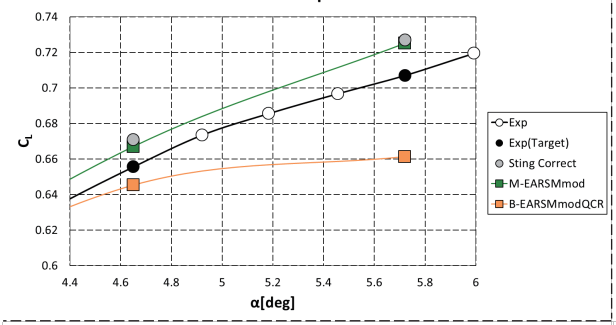
- There is a relationship between Cp of SectionC and CL.
- The vortex appears near the SectionC.

10

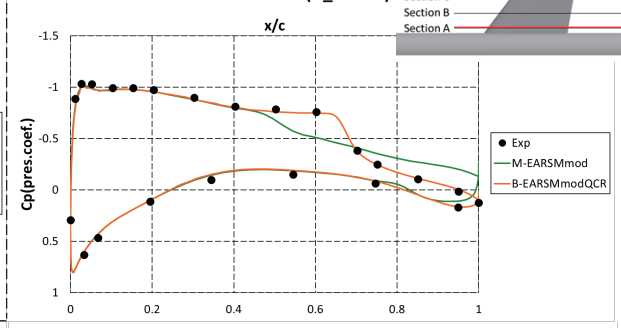
The Most Corresponding Case with the EXP at AoA5.72deg

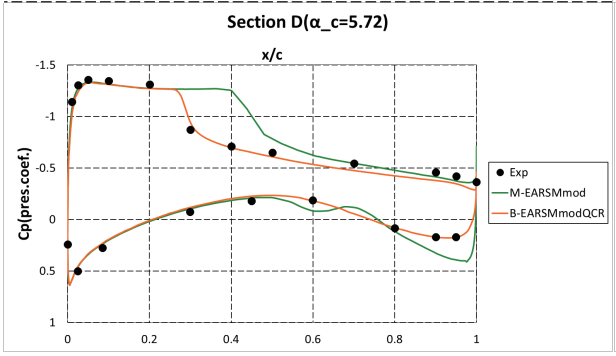


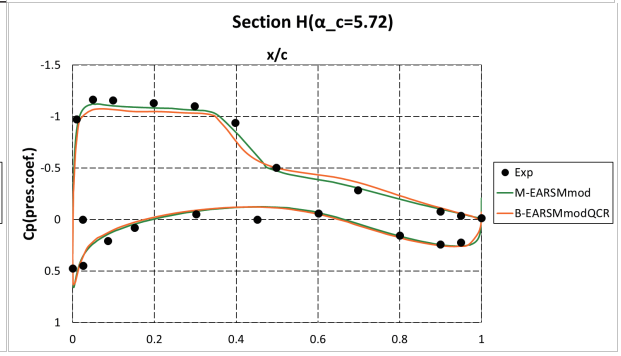
CL-α



Cp





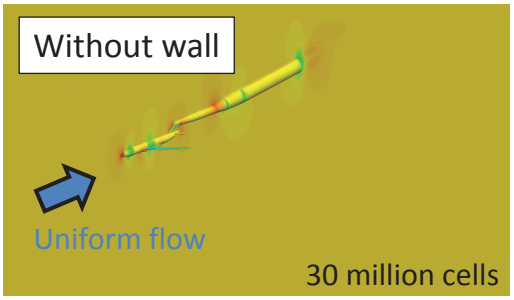


- Best CL prediction ⇒ MEGG3D+EARSMmod
- Best Shock wave location ⇒ BOXFUN+EARSMmodQCR
- There are no cases which correspond with both of CL and Shock wave location?

11

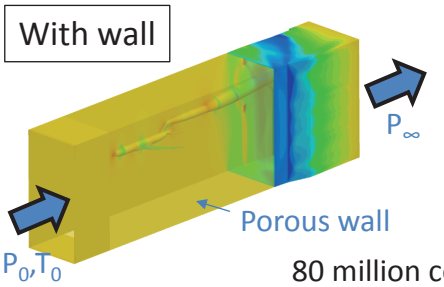
Task2 Whole Wind Tunnel CFD

- We computed the wall interferences
  - to investigate the difference between EXP and CFD at the low angles of attack
  - to validate the amount of wall correction
- Grid : BOXFUN
- Turbulence model: SA-noft2-R-QCR2000



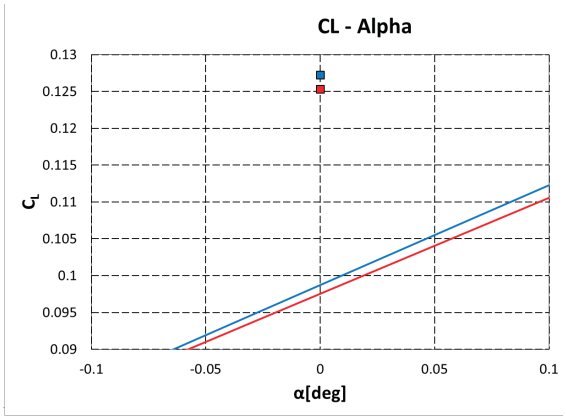
Computational Conditions

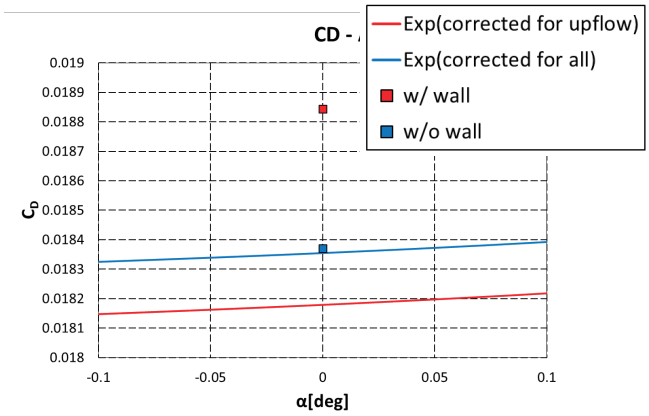
	w/o wall	w/ wall
Mach number	0.847 (corrected)	0.85 (uncorrected)
Angle of attack	0 deg	0 deg
EXP	All corrected	Only corrected for upflow angle

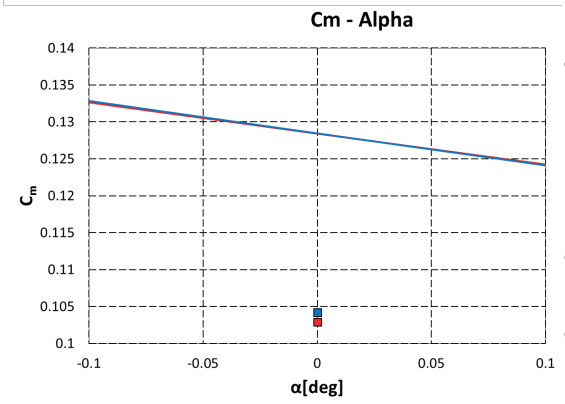


12

Comparison of Aerodynamic Coef.





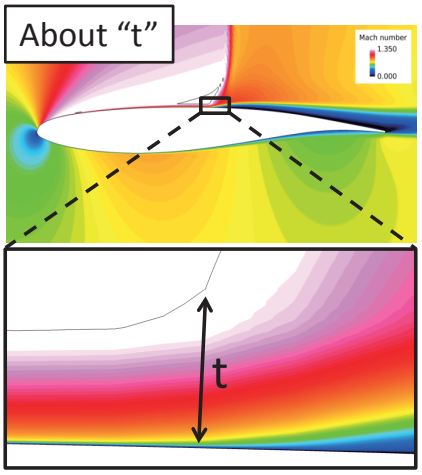


- Lift
  CFD results are still overestimated.
  The wall interference (the difference between the two cases with and without wall) is almost same between CFD and EXP
- Drag
  Wall interference is opposite
- Pitching moment
  Wall interference is small

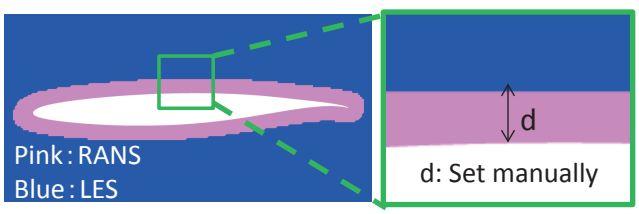
13

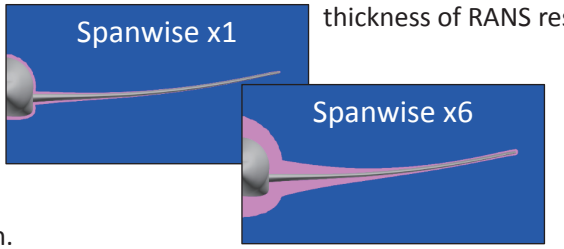
Task3 Computational Method

- Flow solver: FaSTAR
  - Grid: HexaGrid(80 million cells)
  - Discrezation: Cell-Center
  - Inviscid flux: HLLEW
  - Reconstruction: MUSCL
  - Gradient: GLSQ
  - Slope limiter : Hishida(van Leer-type)
  - Time integration : LU-SGS(Dual Time Stepping)
  - Turbulence model : Zonal-DES(SA-noft2-R-QCR2000)



t: Boundary-layer thickness of RANS result



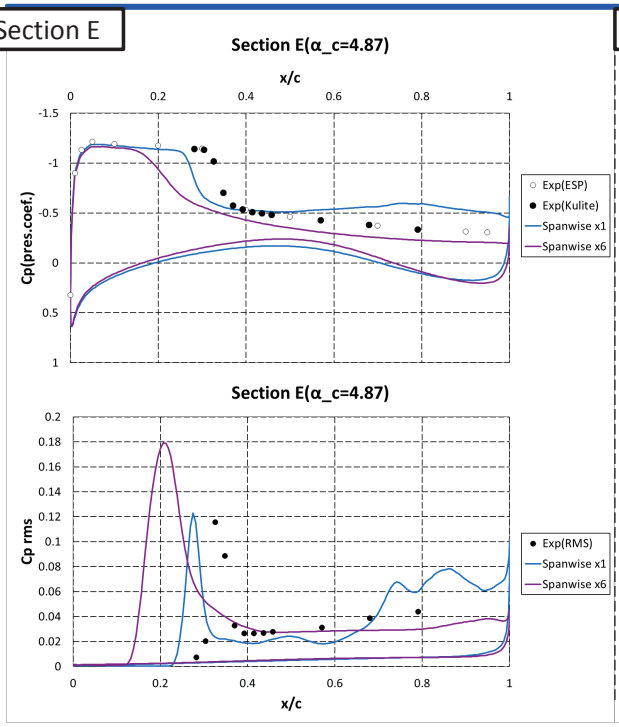


We change the RANS thickness in the spanwise direction.
x1: Thickness which calculated from the previous RANS computation.
x6: Six times thickness of x1.

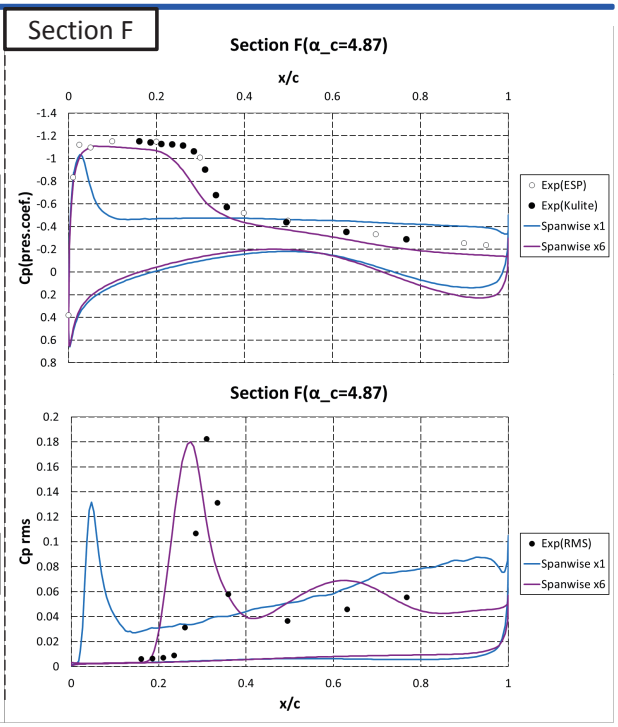
14

Average and RMS of Cp at AoA4.87deg

Section E



Section F

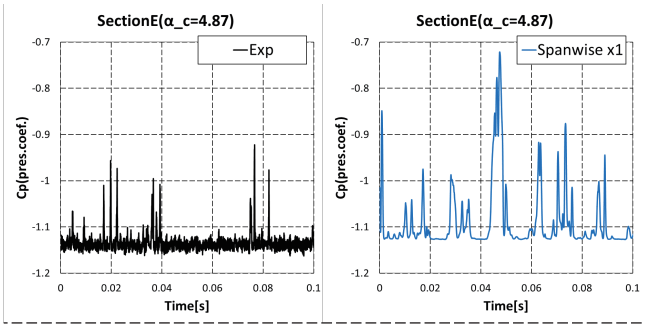


- SectionE: Spanwise x1 get close to the EXP.
- SectionF: Spanwise x6 get close to the EXP.

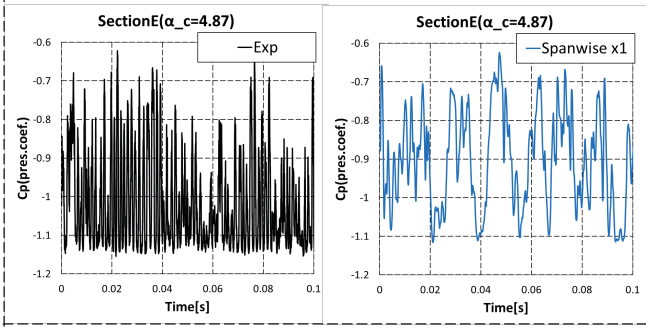
15

Time history of Cp at AoA4.87deg(Section E)

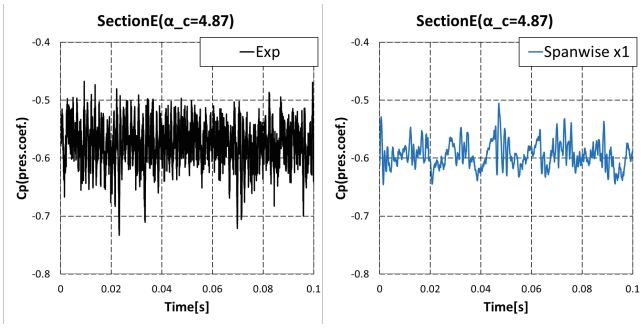
before shock wave



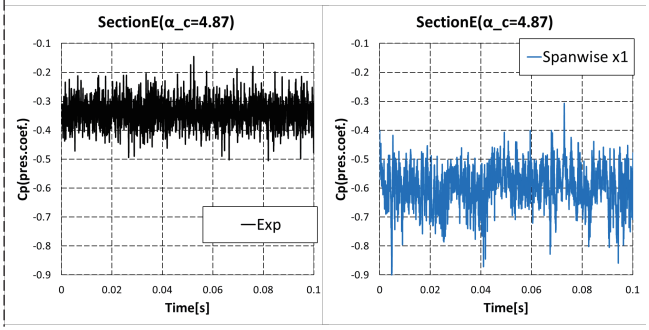
shock wave peak



after shock wave



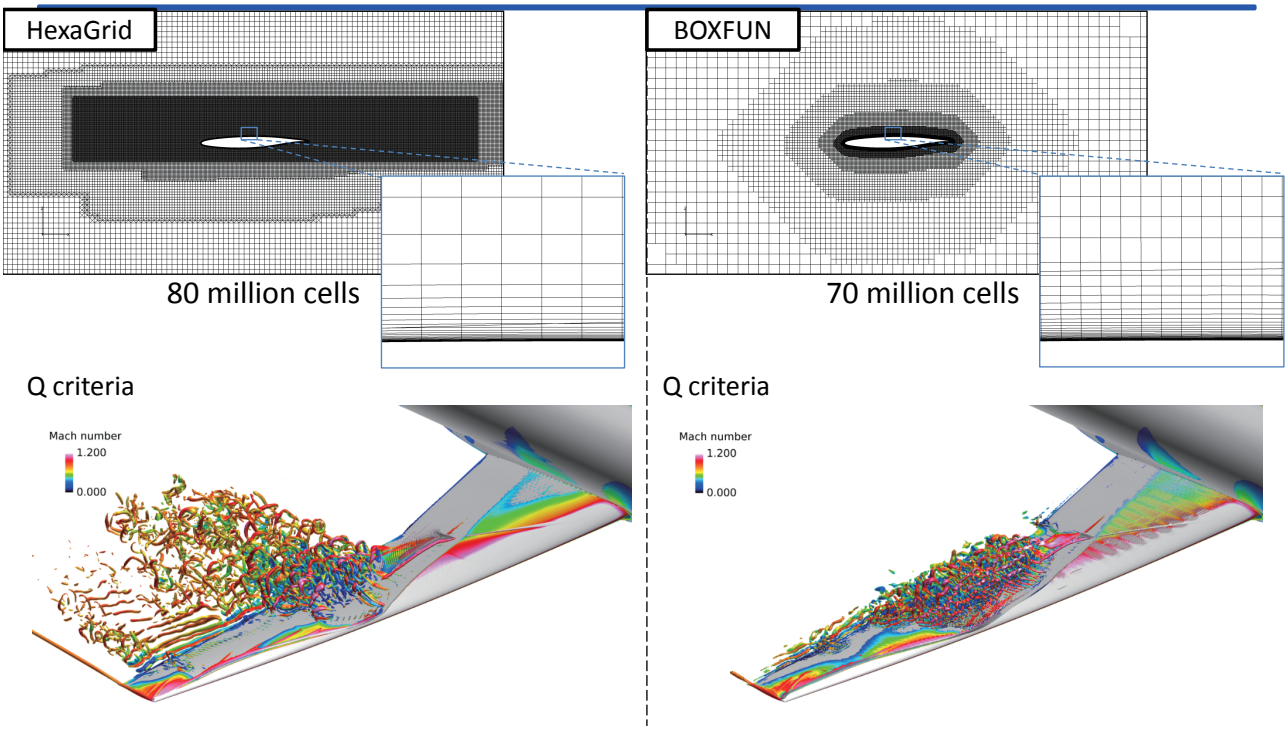
near the TE



- Time history of Cp is similar to the EXP.

16

Result of BOXFUN(Spanwise x1)



- Shock wave location: Almost same
- Q criteria: Small vortex are found at BOXFUN.

Summary

- Task 1
  - We computed with 4 grids and 6 turbulence models.
  - Low AoA – Cruise AoA
    - Computed forces are almost same.
    - Viscous Drag: EARSM model > SA model > SST model
  - High AoA
    - Computed forces show considerable variations.
    - Shock wave location is changed by turbulence models.
    - The SOB separation is affected by the grids.
    - There is the relationship between Cp of SectionC and CL.
    - There are no cases which correspond with both of CL and Shock wave location

Summary

- Task 2
  - We computed the wall interferences.
  - Lift
    - The CFD result is still overestimated.
    - The wall interference is almost same between CFD and EXP.
- Task 3
  - We computed Zonal-DES for the two spanwise cases.
  - Average and RMS of Cp
    - The shock wave locations are not predicted well.
  - Time history of Cp
    - CFD is similar trend to the EXP.
  - Result of BOXFUN
    - The resolution near the wall is improved.