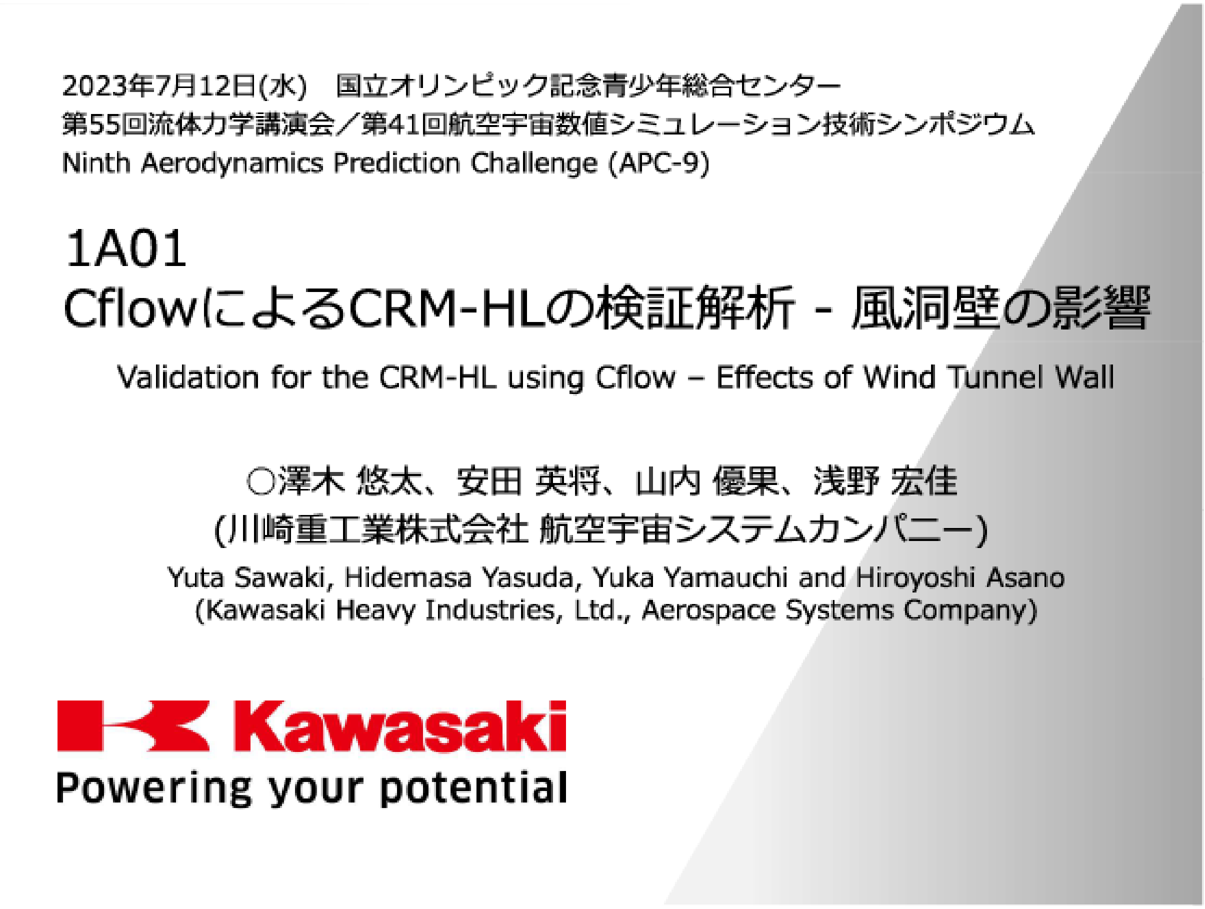
CflowによるCRM-HLの検証解析 － 風洞壁の影響・澤木 悠太，安田 英将，山内 優果，浅野 宏佳（川崎重工）



2023年7月12日(水)　国立オリンピック記念青少年総合センター
第55回流体力学講演会／第41回航空宇宙数値シミュレーション技術シンポジウム
Ninth Aerodynamics Prediction Challenge (APC-9)

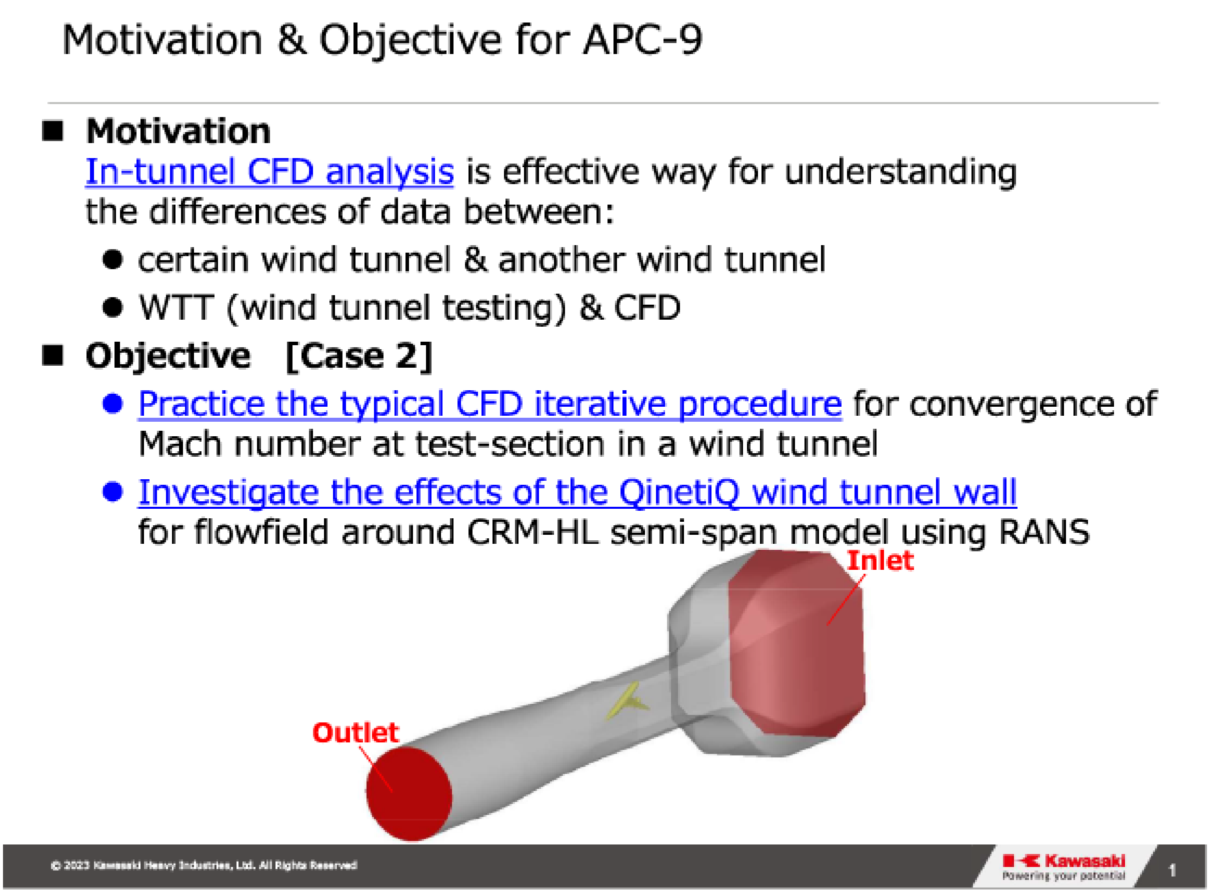
1A01

CflowによるCRM-HLの検証解析 - 風洞壁の影響

Validation for the CRM-HL using Cflow – Effects of Wind Tunnel Wall

○澤木 悠太、安田 英将、山内 優果、浅野 宏佳
(川崎重工業株式会社 航空宇宙システムカンパニー)
Yuta Sawaki, Hidemasa Yasuda, Yuka Yamauchi and Hiroyoshi Asano
(Kawasaki Heavy Industries, Ltd., Aerospace Systems Company)

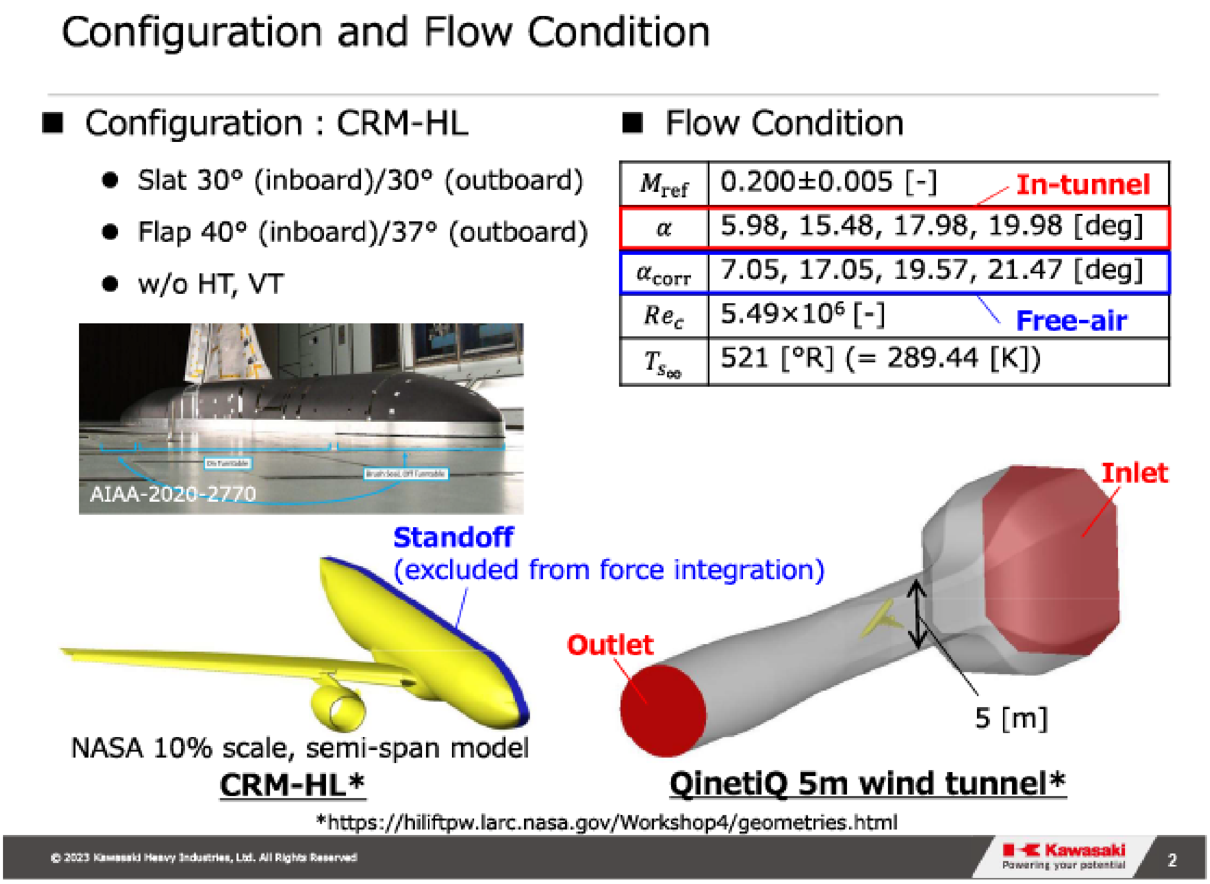
Kawasaki
Powering your potential



Motivation & Objective for APC-9

- **Motivation**
  In-tunnel CFD analysis is effective way for understanding the differences of data between:
  - certain wind tunnel & another wind tunnel
  - WTT (wind tunnel testing) & CFD
- **Objective　[Case 2]**
  - Practice the typical CFD iterative procedure for convergence of Mach number at test-section in a wind tunnel
  - Investigate the effects of the QinetiQ wind tunnel wall for flowfield around CRM-HL semi-span model using RANS

This document is provided by JAXA.



Configuration and Flow Condition

- Configuration : CRM-HL
  - Slat 30° (inboard)/30° (outboard)
  - Flap 40° (inboard)/37° (outboard)
  - w/o HT, VT

- Flow Condition

M_{ref}	0.200±0.005 [-]
α	5.98, 15.48, 17.98, 19.98 [deg]
α_{corr}	7.05, 17.05, 19.57, 21.47 [deg]
Re_c	5.49×10^6 [-]
T_{s_∞}	521 [°R] (= 289.44 [K])

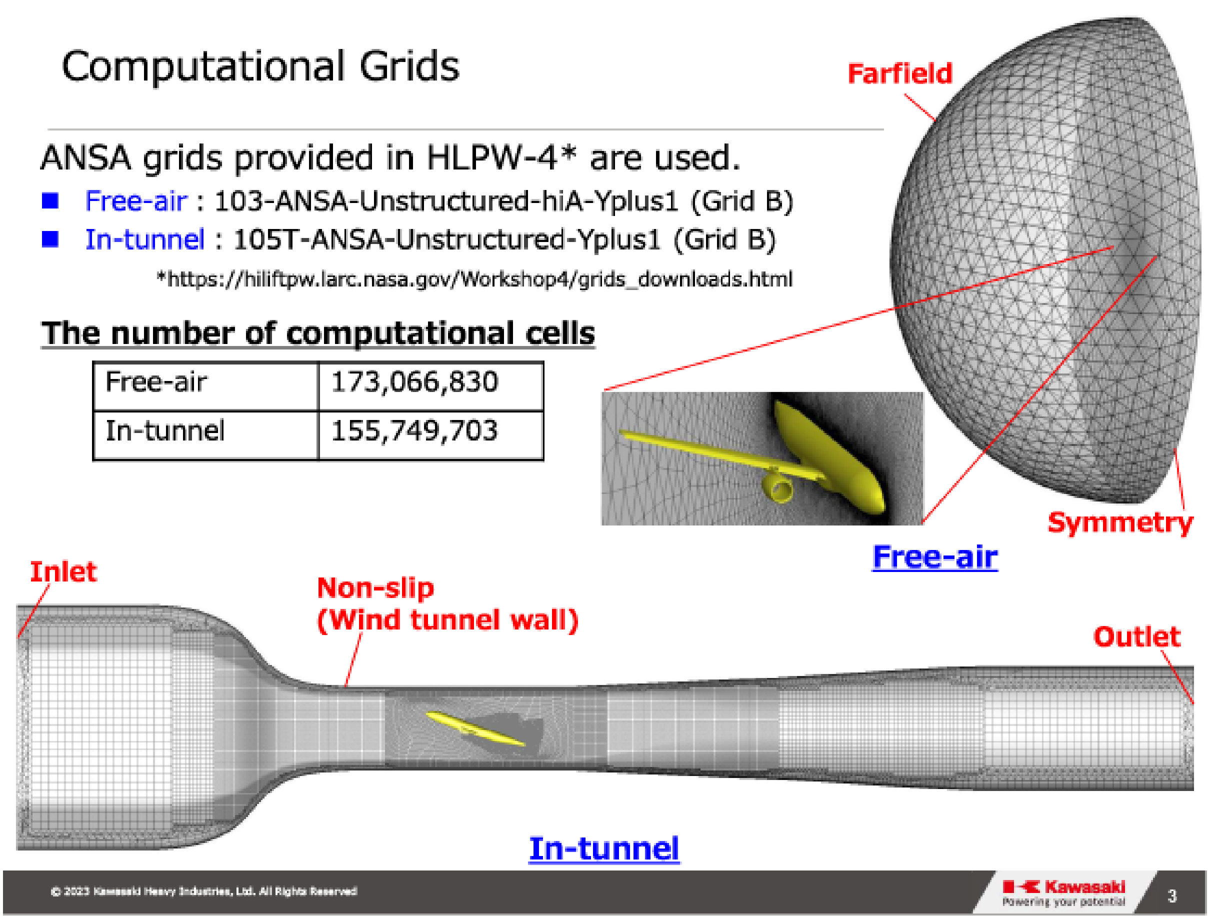
NASA 10% scale, semi-span model

CRM-HL*

QinetiQ 5m wind tunnel*

*https://hiliftpw.larc.nasa.gov/Workshop4/geometries.html

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved



Computational Grids

ANSA grids provided in HLPW-4* are used.

- Free-air : 103-ANSA-Unstructured-hiA-Yplus1 (Grid B)
- In-tunnel : 105T-ANSA-Unstructured-Yplus1 (Grid B)

*https://hiliftpw.larc.nasa.gov/Workshop4/grids_downloads.html

The number of computational cells

Free-air	173,066,830
In-tunnel	155,749,703

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

This document is provided by JAXA.

Numerical Methods

Numerical methods of Cflow (KHI in-house)

Governing equations	Compressible Reynolds-averaged Navier-Stokes eqs.
Spatial discretization	Cell-centered finite volume method
Flux reconstruction	2nd-order accurate reconstruction based on MUSCL
Gradient	Green-Gauss
Inviscid flux	Simple low-dissipation AUSM scheme (SLAU)
Slope limiter	minmod
Viscous flux	2nd-order accurate central difference
Turbulence modeling	SA-neg-QCR2000-R(Crot=1)
Time integration	Matrix-free Gauss Seidel (MFGS) implicit method
	Local time-stepping

SA-neg-QCR2000-R(Crot=1) :
・was KHI best practice on APC-8 (2022)
・is recommended in the fixed-grid RANS group of HLPW-5 (2024)

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

Iterative Procedure for Convergence of M_{ref}

*https://hiliftpw.larc.nasa.gov/Workshop4/Geometry/Q5m_Tunnel_Modeling_V01.pdf

Iterations

① Total pressure P_t/P_{s_∞} & total temperature T_t/T_{s_∞} assuming $M_\infty = 0.200$ are imposed at the inlet boundary.

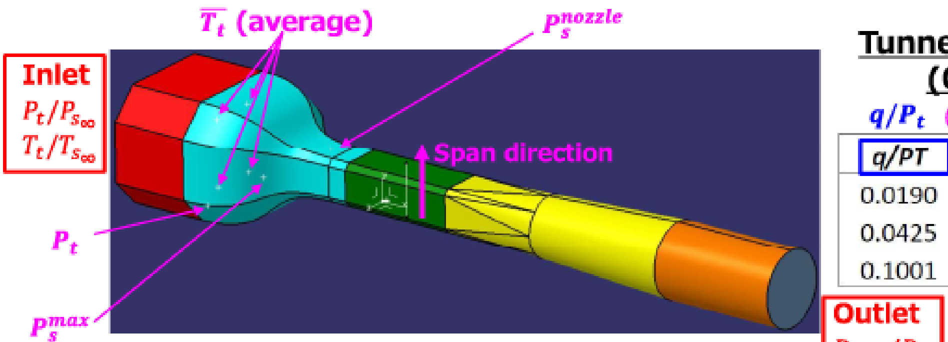
② Set static pressure $P_{s_{\mathrm{exit}}}/P_{s_\infty}$ at the outlet boundary.

③ Run CFD solver.

④ Compute $(P_s^{max} - P_s^{nozzle})/P_t$ using variables at the probes and obtain q/P_t by interpolating the tunnel calibration table.

⑤ Mach number M_{ref} is computed using q/P_t.

⑥ Iterate ②～⑤ until a tolerance $M_{\mathrm{ref}} = 0.200 \pm 0.005$ is satisfied.



Probe locations in QinetiQ wind tunnel*

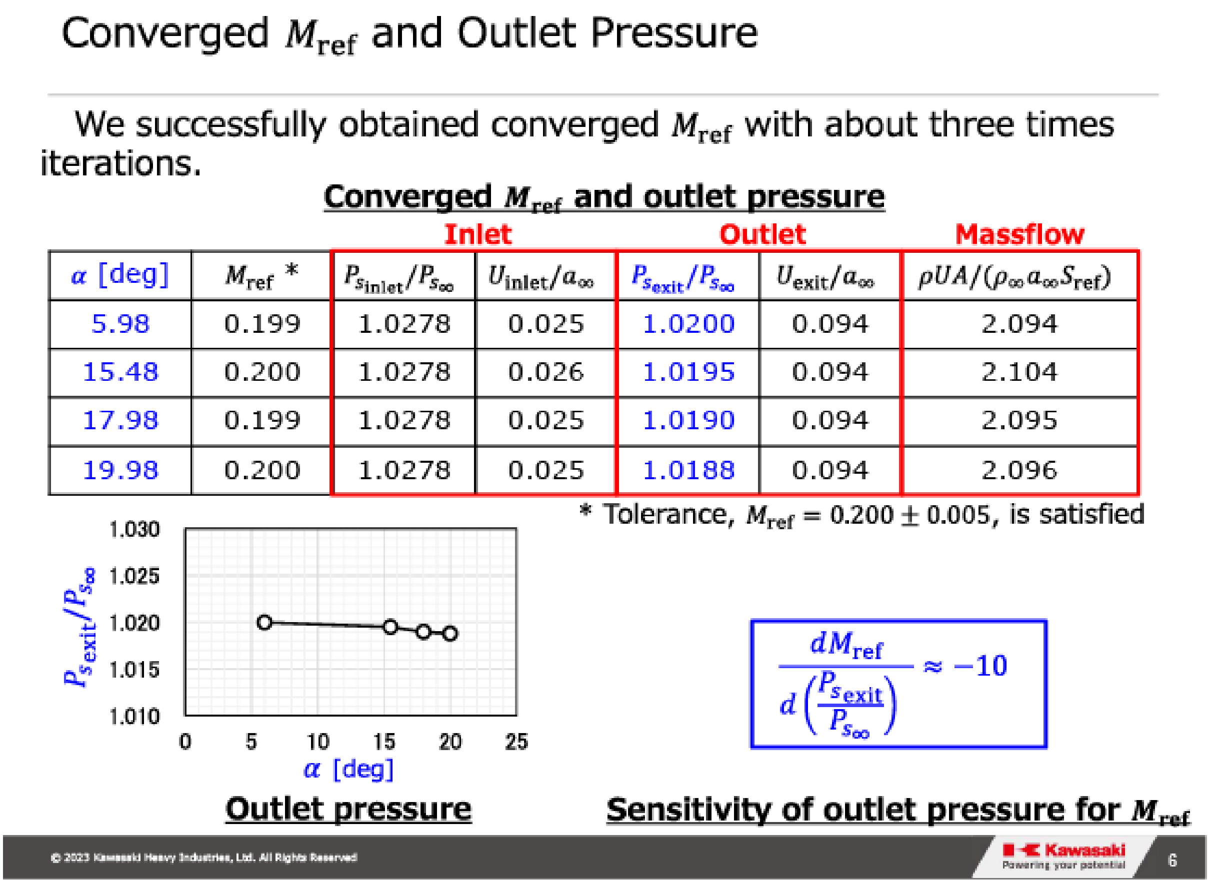
Tunnel calibration (QinetiQ)

q/P_t　$(P_s^{max} - P_s^{nozzle})/P_t$

q/PT	(Max-Noz)/PT
0.0190	0.0169265
0.0425	0.0380820
0.1001	0.0904813

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

This document is provided by JAXA.



Converged M_{ref} and Outlet Pressure

We successfully obtained converged M_{ref} with about three times iterations.

Converged M_{ref} and outlet pressure

		Inlet		Outlet		Massflow
α [deg]	M_{ref} *	$P_{s_{inlet}}/P_{s_\infty}$	U_{inlet}/a_∞	$P_{s_{exit}}/P_{s_\infty}$	U_{exit}/a_∞	$\rho UA/(\rho_\infty a_\infty S_{ref})$
5.98	0.199	1.0278	0.025	1.0200	0.094	2.094
15.48	0.200	1.0278	0.026	1.0195	0.094	2.104
17.98	0.199	1.0278	0.025	1.0190	0.094	2.095
19.98	0.200	1.0278	0.025	1.0188	0.094	2.096

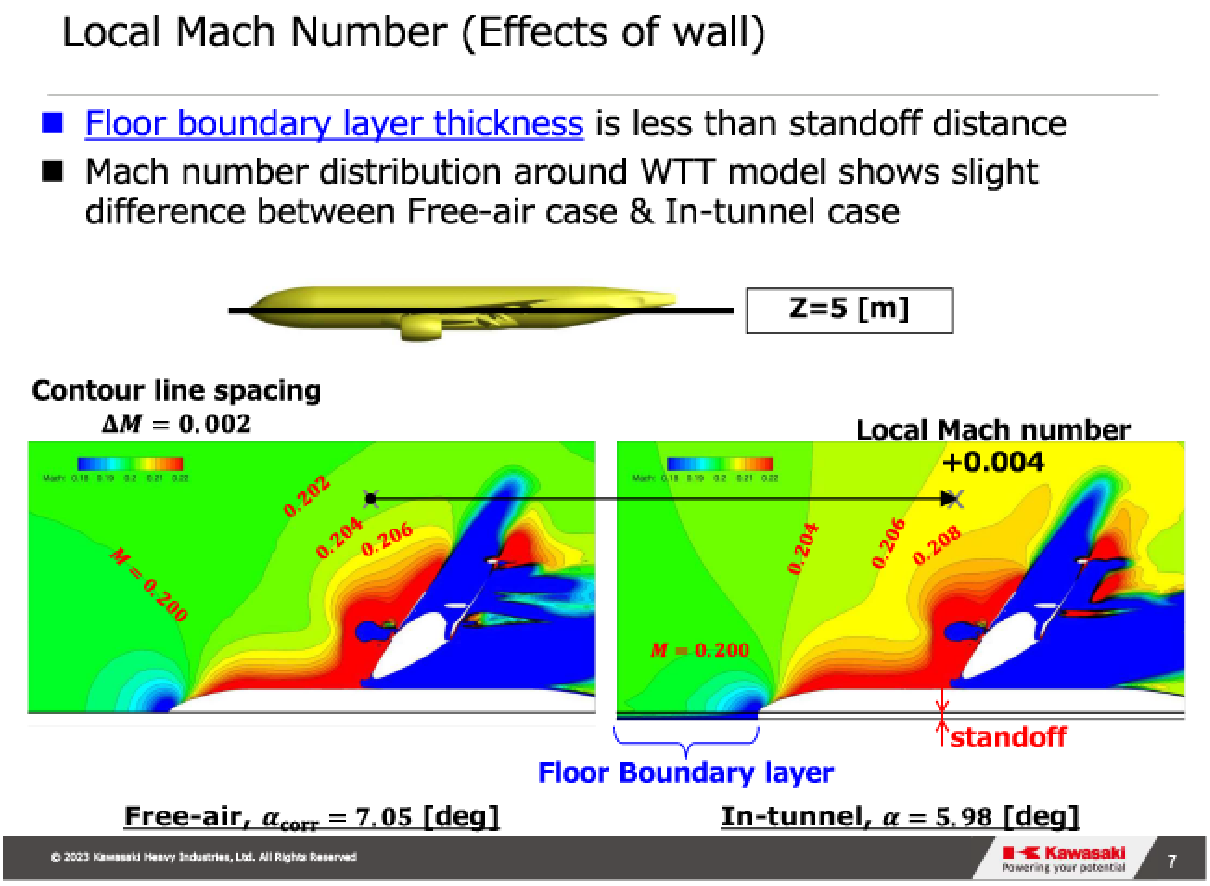
* Tolerance, $M_{ref} = 0.200 \pm 0.005$, is satisfied

Outlet pressure

$$\boxed{\frac{dM_{ref}}{d\left(\frac{P_{s_{exit}}}{P_{s_\infty}}\right)} \approx -10}$$

Sensitivity of outlet pressure for M_{ref}

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved



Local Mach Number (Effects of wall)

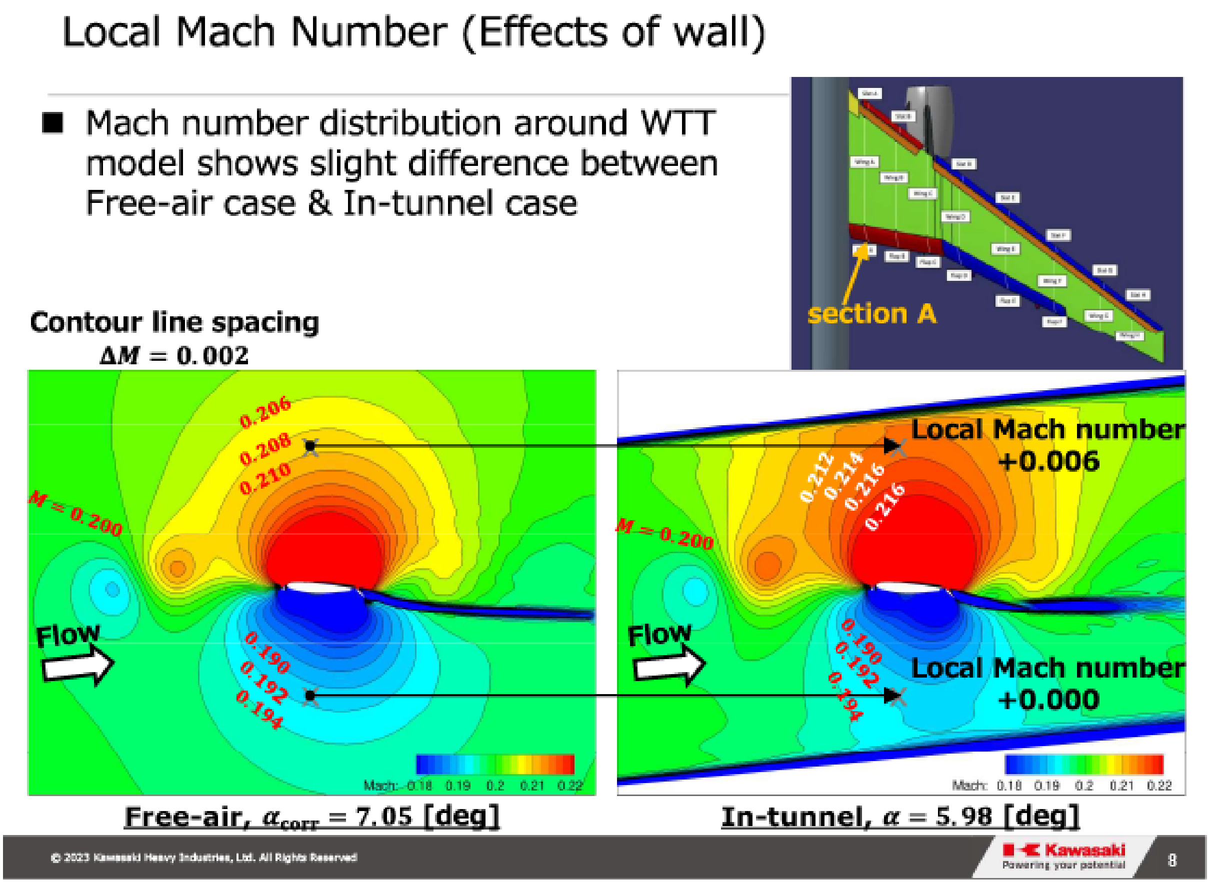
- Floor boundary layer thickness is less than standoff distance
- Mach number distribution around WTT model shows slight difference between Free-air case & In-tunnel case

Free-air, $\alpha_{corr} = 7.05$ [deg]

In-tunnel, $\alpha = 5.98$ [deg]

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

This document is provided by JAXA.



Local Mach Number (Effects of wall)

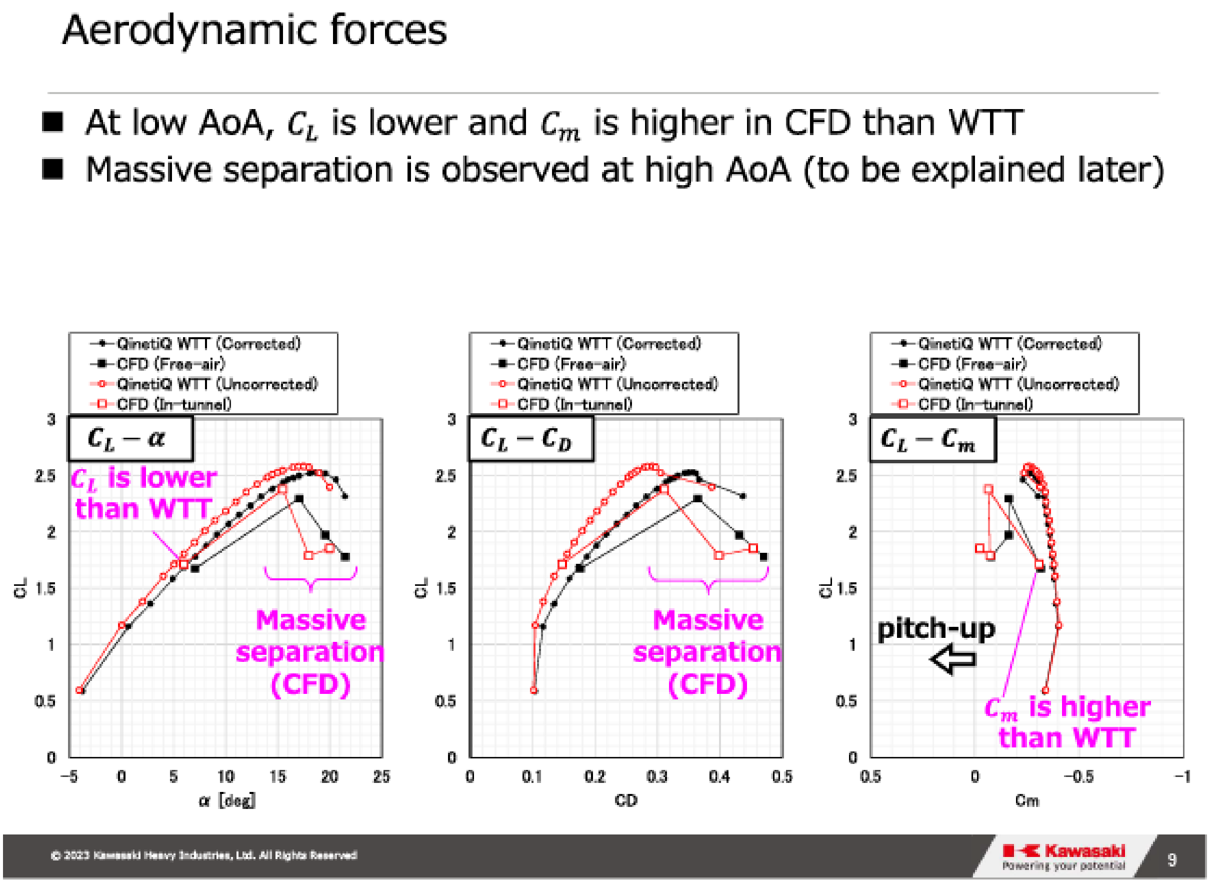
- Mach number distribution around WTT model shows slight difference between Free-air case & In-tunnel case

Contour line spacing
$\Delta M = 0.002$

Free-air, $\alpha_{corr} = 7.05$ [deg]

In-tunnel, $\alpha = 5.98$ [deg]

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

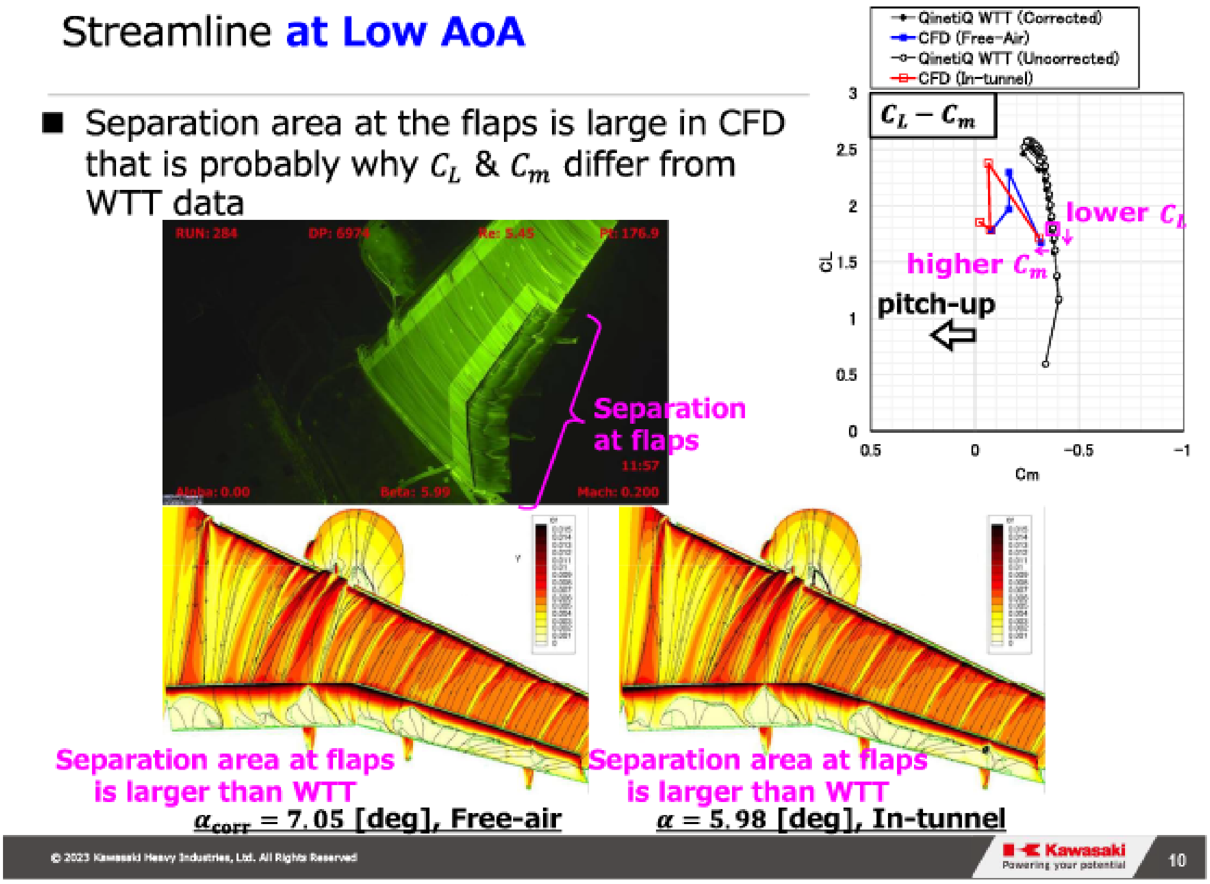


Aerodynamic forces

- At low AoA, C_L is lower and C_m is higher in CFD than WTT
- Massive separation is observed at high AoA (to be explained later)

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

This document is provided by JAXA.



Streamline **at Low AoA**

- Separation area at the flaps is large in CFD that is probably why C_L & C_m differ from WTT data

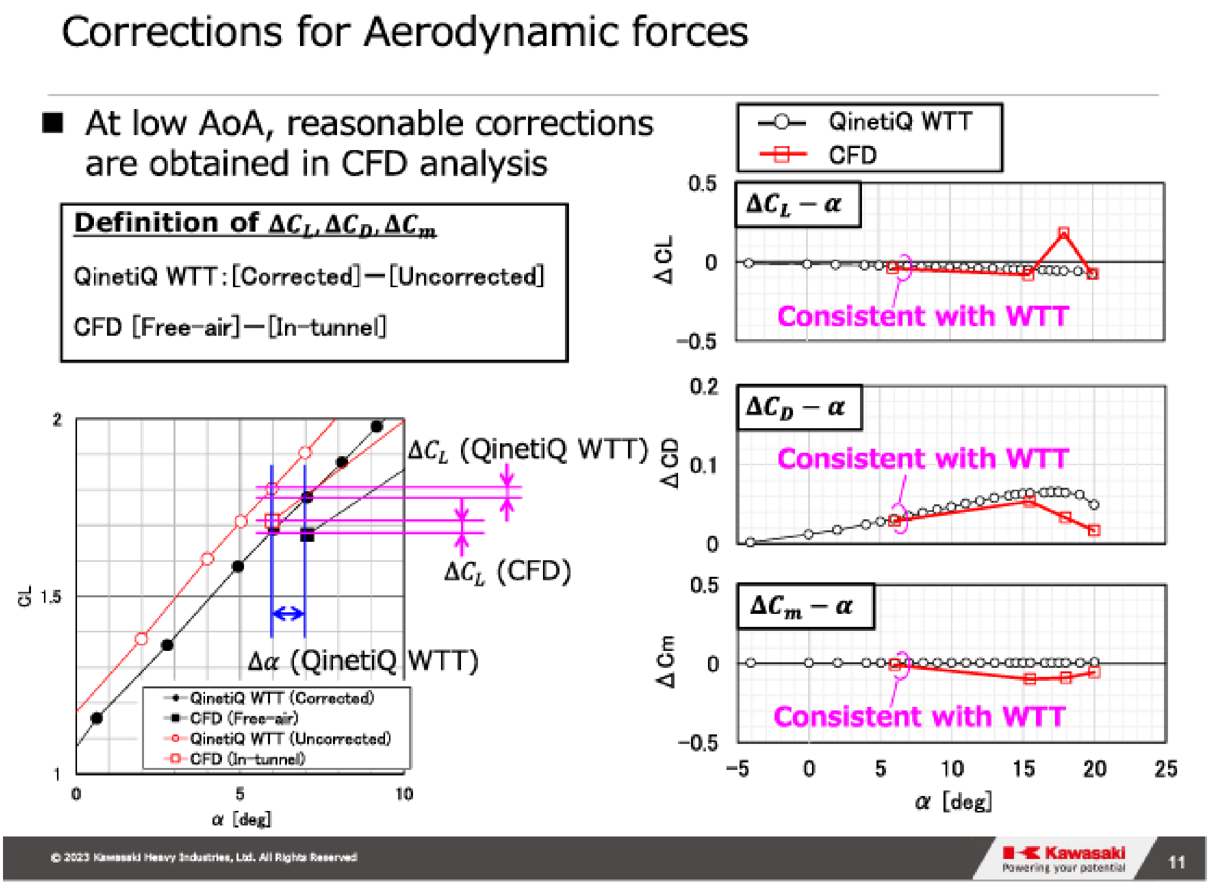
Separation area at flaps is larger than WTT

α_{corr} = 7.05 [deg], Free-air

Separation area at flaps is larger than WTT

α = 5.98 [deg], In-tunnel

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved



Corrections for Aerodynamic forces

- At low AoA, reasonable corrections are obtained in CFD analysis

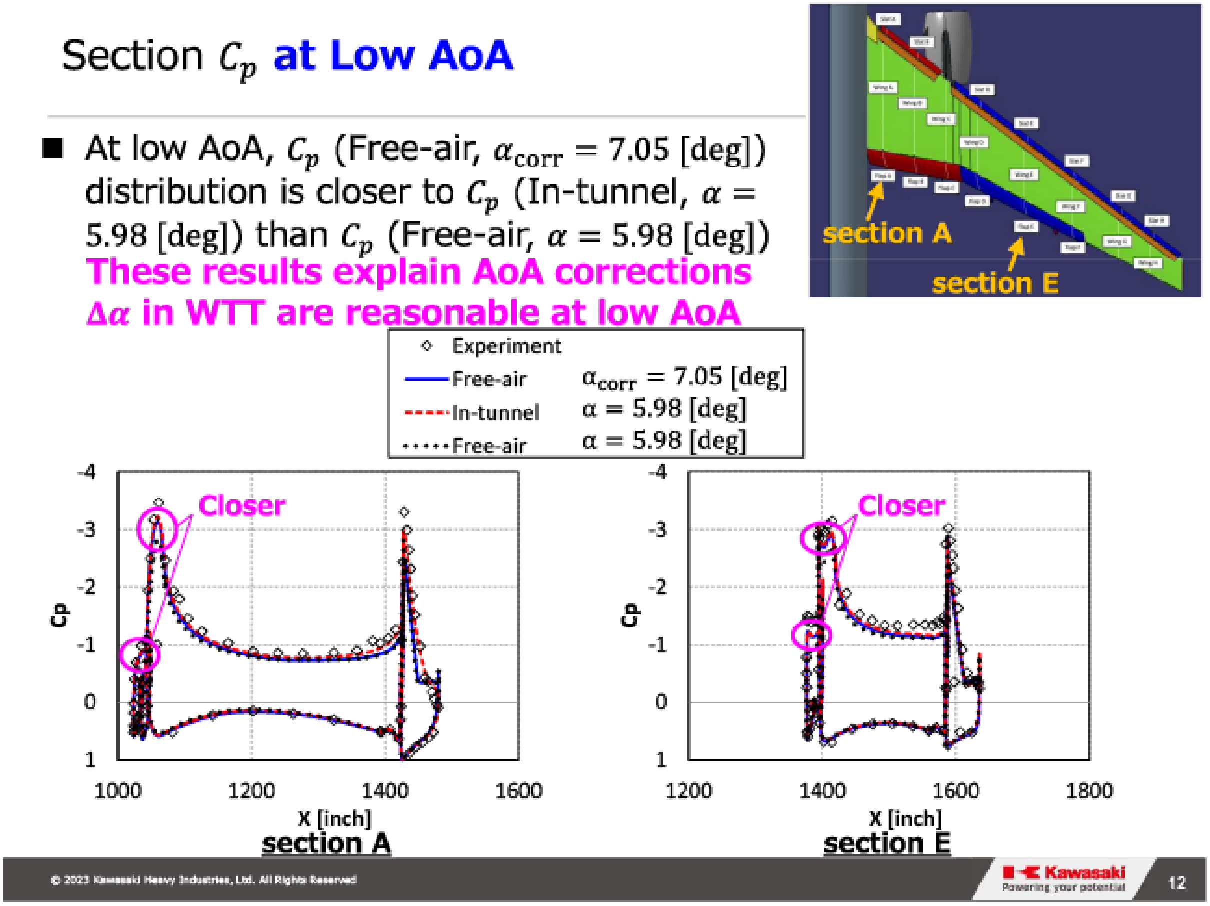
Definition of $\Delta C_L, \Delta C_D, \Delta C_m$

QinetiQ WTT : [Corrected] − [Uncorrected]

CFD [Free-air] − [In-tunnel]

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

This document is provided by JAXA.

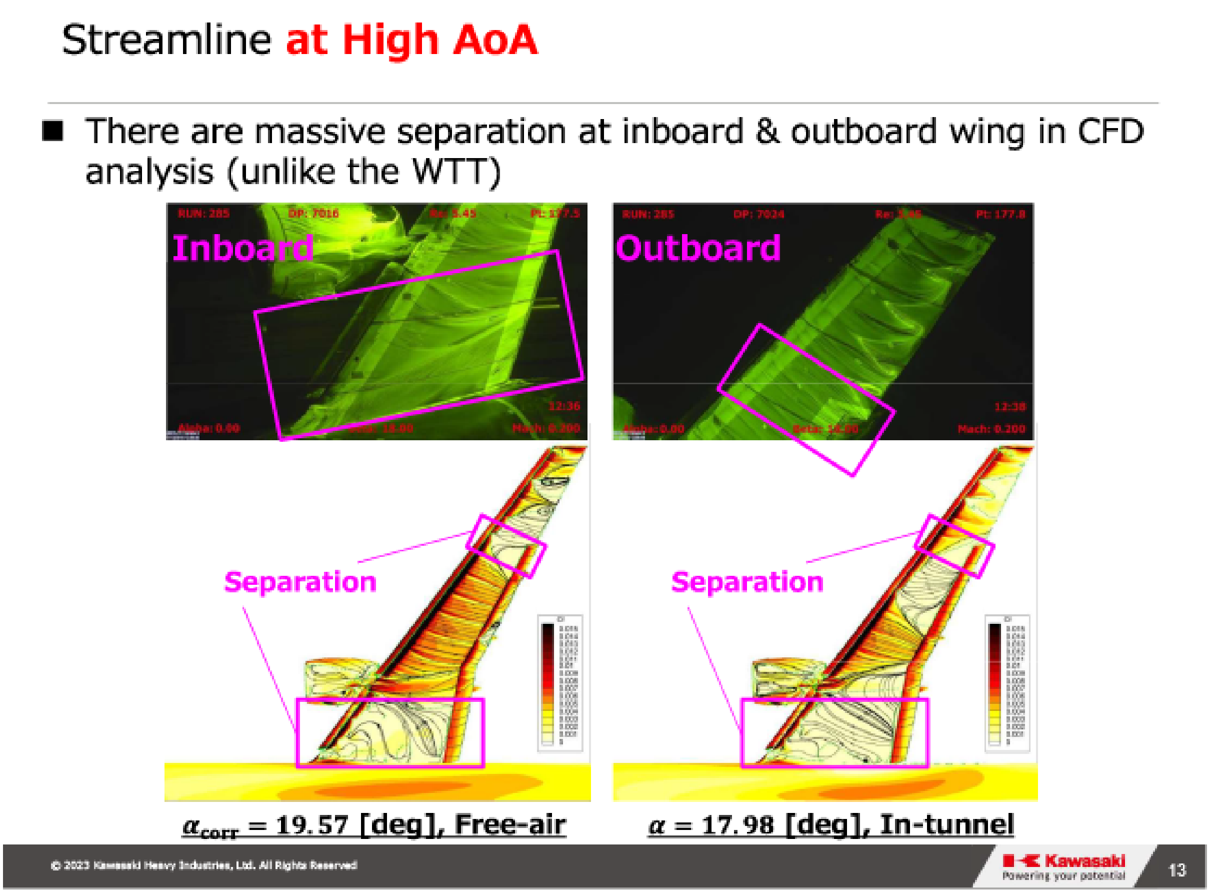


Section C_p at Low AoA

- At low AoA, C_p (Free-air, α_{corr} = 7.05 [deg]) distribution is closer to C_p (In-tunnel, α = 5.98 [deg]) than C_p (Free-air, α = 5.98 [deg])

  These results explain AoA corrections Δα in WTT are reasonable at low AoA

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved



Streamline at High AoA

- There are massive separation at inboard & outboard wing in CFD analysis (unlike the WTT)

α_{corr} = 19.57 [deg], Free-air

α = 17.98 [deg], In-tunnel

© 2023 Kawasaki Heavy Industries, Ltd. All Rights Reserved

Conclusion

- Typical CFD iterative procedure for convergence of M_{ref} in a wind tunnel was practiced

- The effects of the wind tunnel wall for flowfield around CRM-HL semi-span model were investigated
  - Floor boundary layer thickness was less than standoff distance
  - **At low AoA, reasonable corrections were obtained in CFD**
  - At high AoA, massive separation was observed in CFD

This document is provided by JAXA.