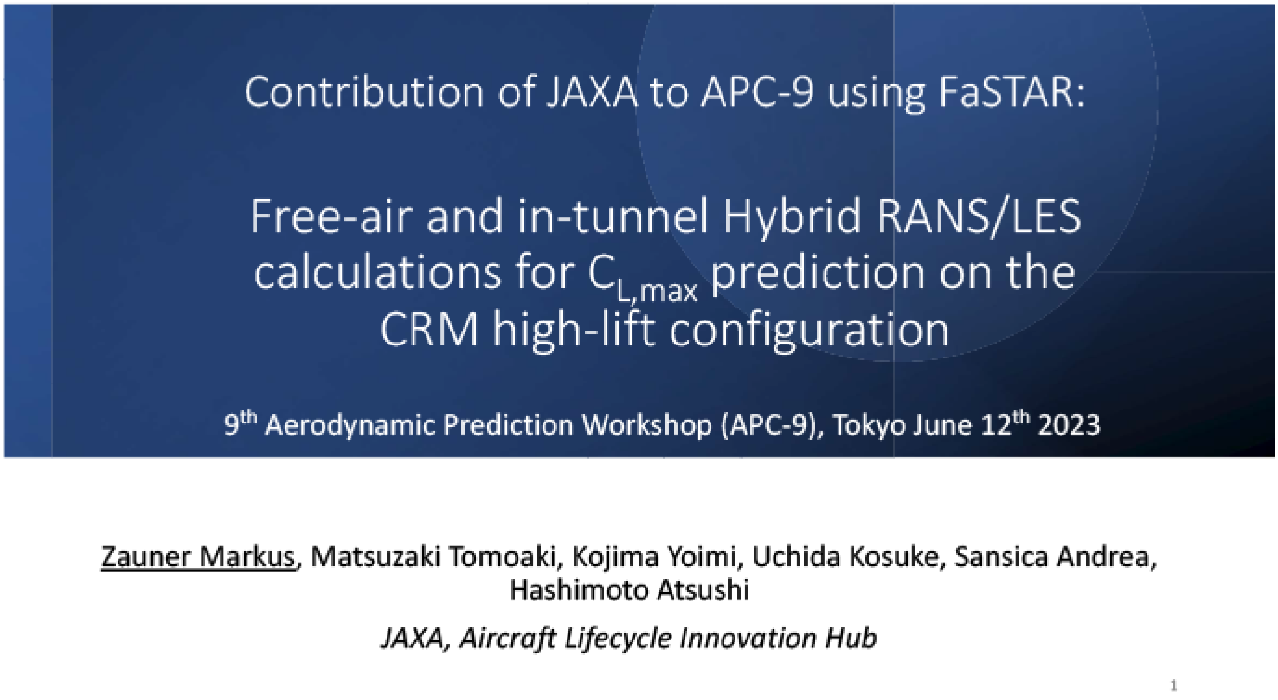
Contribution of JAXA to APC-9 using FaSTAR: Free-air and intunnel Hybrid RANS/LES calculations for CLmax prediction on the CRM high-lift configuration・Zauner Markus, Matsuzaki Tomoaki, Kojima Yoimi, Uchida Kosuke, Sansica Andrea, Hashimoto Atsushi (JAXA)



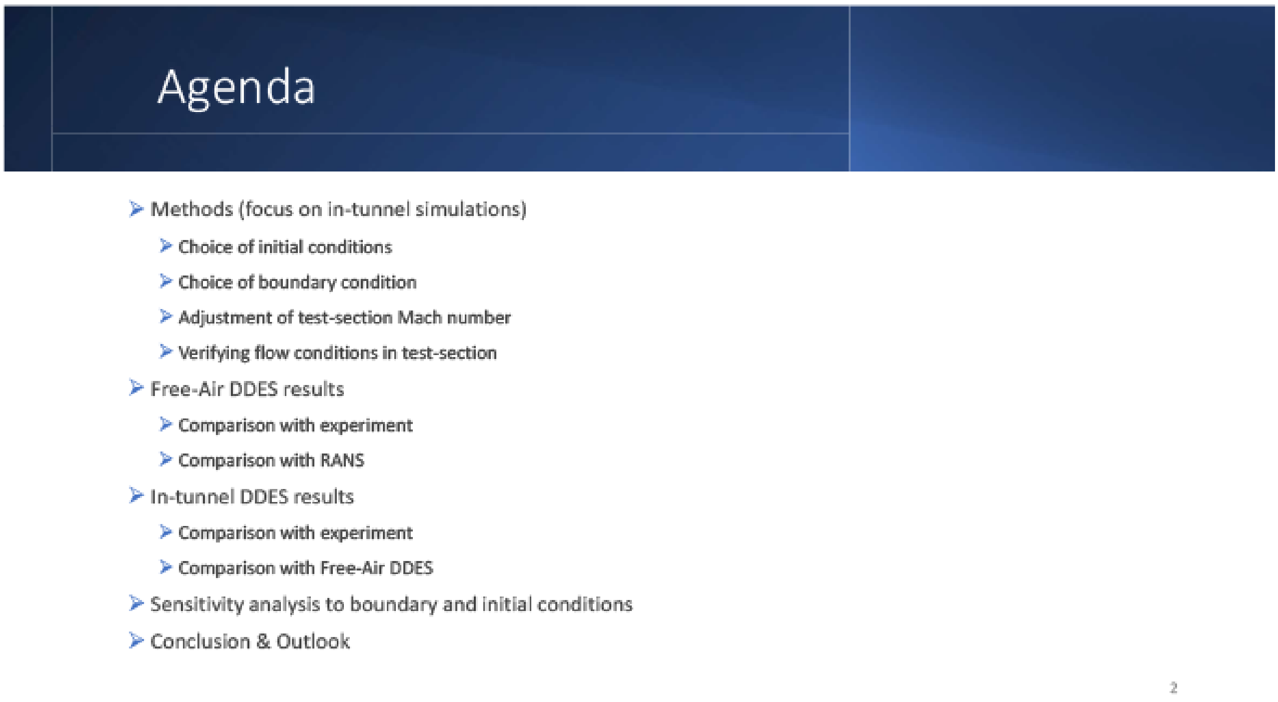
Contribution of JAXA to APC-9 using FaSTAR:

Free-air and in-tunnel Hybrid RANS/LES calculations for $C_{L,max}$ prediction on the CRM high-lift configuration

9th Aerodynamic Prediction Workshop (APC-9), Tokyo June 12th 2023

Zauner Markus, Matsuzaki Tomoaki, Kojima Yoimi, Uchida Kosuke, Sansica Andrea, Hashimoto Atsushi

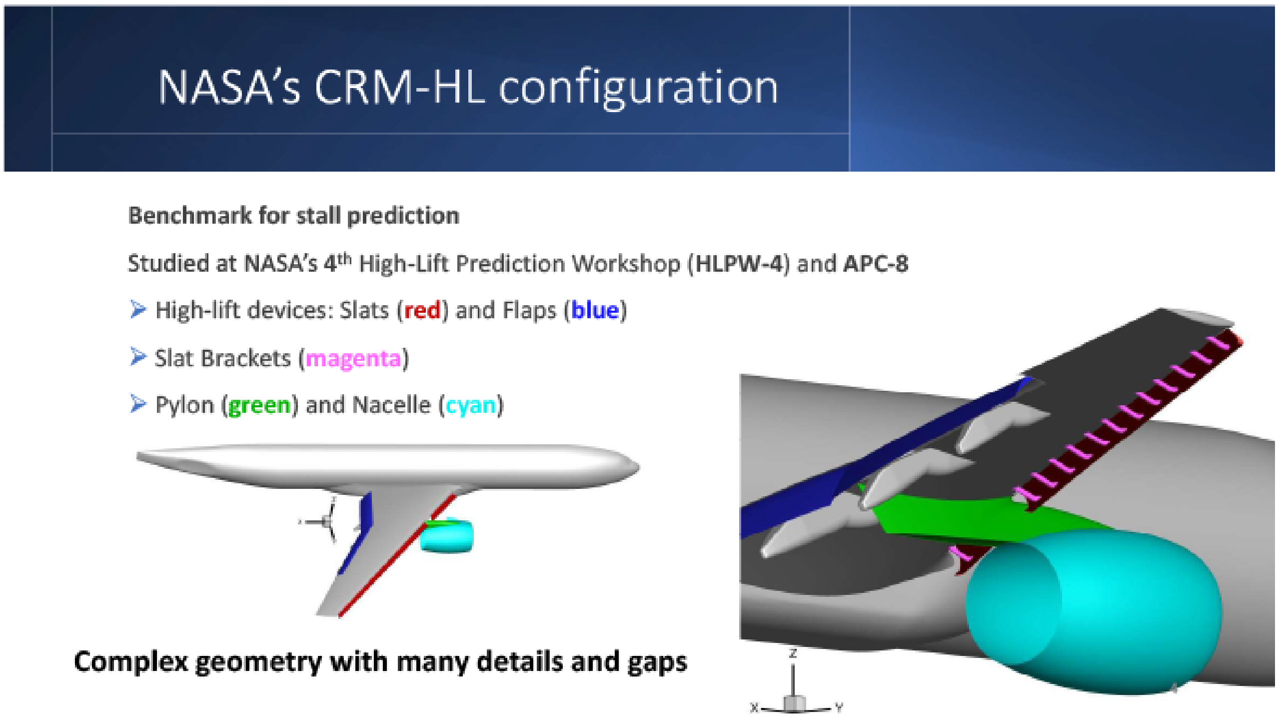
JAXA, Aircraft Lifecycle Innovation Hub



Agenda

- Methods (focus on in-tunnel simulations)
    - Choice of initial conditions
    - Choice of boundary condition
    - Adjustment of test-section Mach number
    - Verifying flow conditions in test-section
- Free-Air DDES results
    - Comparison with experiment
    - Comparison with RANS
- In-tunnel DDES results
    - Comparison with experiment
    - Comparison with Free-Air DDES
- Sensitivity analysis to boundary and initial conditions
- Conclusion & Outlook

Introduction & Methodology



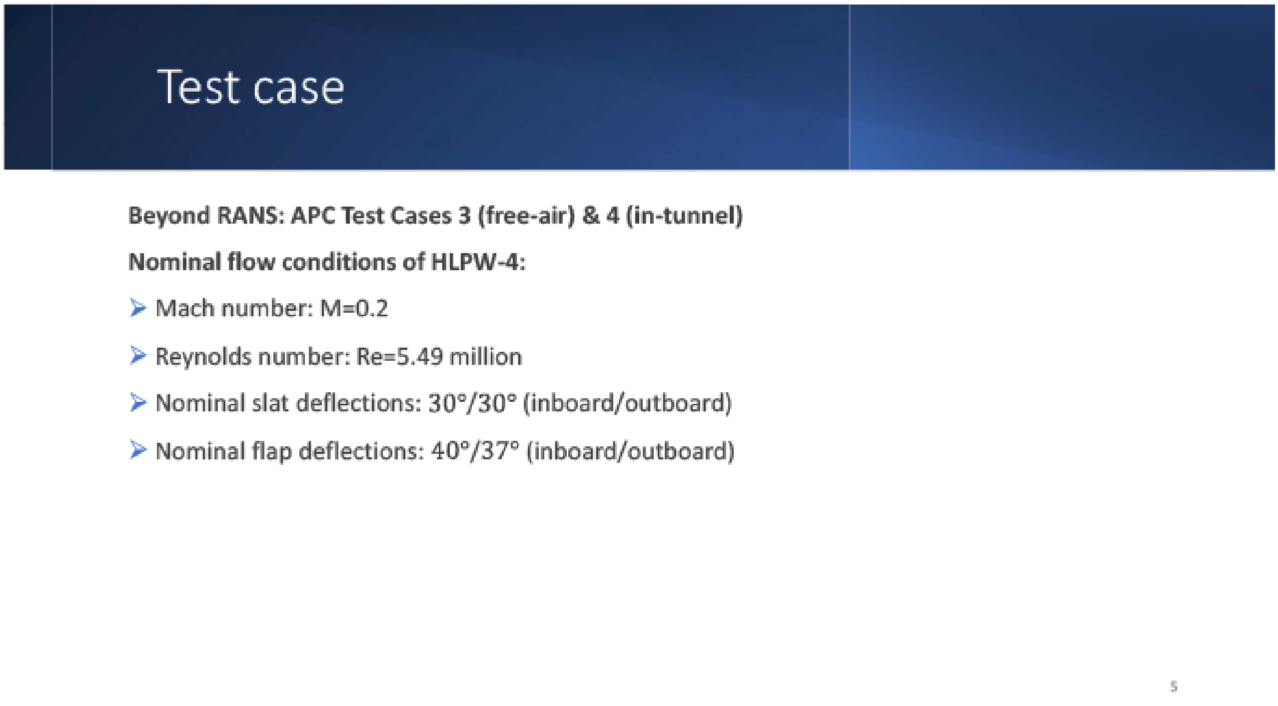
NASA's CRM-HL configuration

Benchmark for stall prediction

Studied at NASA's 4th High-Lift Prediction Workshop (**HLPW-4**) and **APC-8**

- High-lift devices: Slats (**red**) and Flaps (**blue**)
- Slat Brackets (magenta)
- Pylon (**green**) and Nacelle (cyan)

Complex geometry with many details and gaps

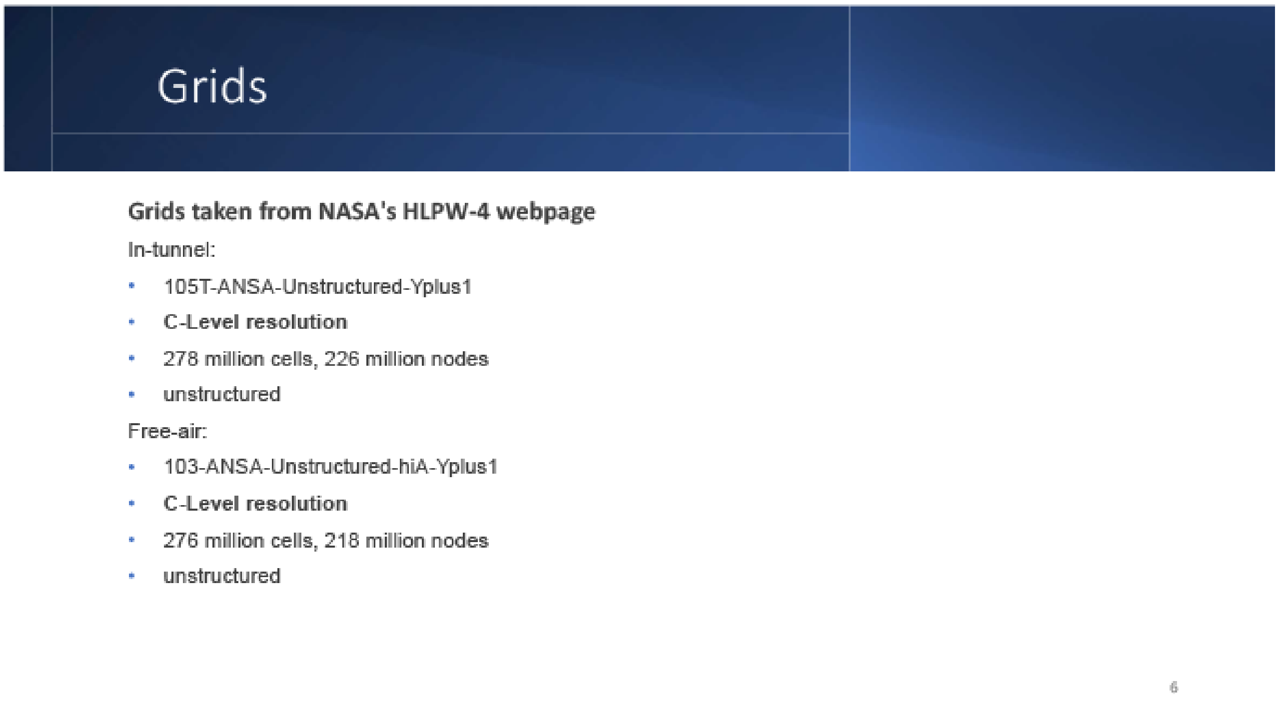


Test case

Beyond RANS: APC Test Cases 3 (free-air) & 4 (in-tunnel)

Nominal flow conditions of HLPW-4:

- Mach number: M=0.2
- Reynolds number: Re=5.49 million
- Nominal slat deflections: 30°/30° (inboard/outboard)
- Nominal flap deflections: 40°/37° (inboard/outboard)



Grids

Grids taken from NASA's HLPW-4 webpage

In-tunnel:

- 105T-ANSA-Unstructured-Yplus1
- C-Level resolution
- 278 million cells, 226 million nodes
- unstructured

Free-air:

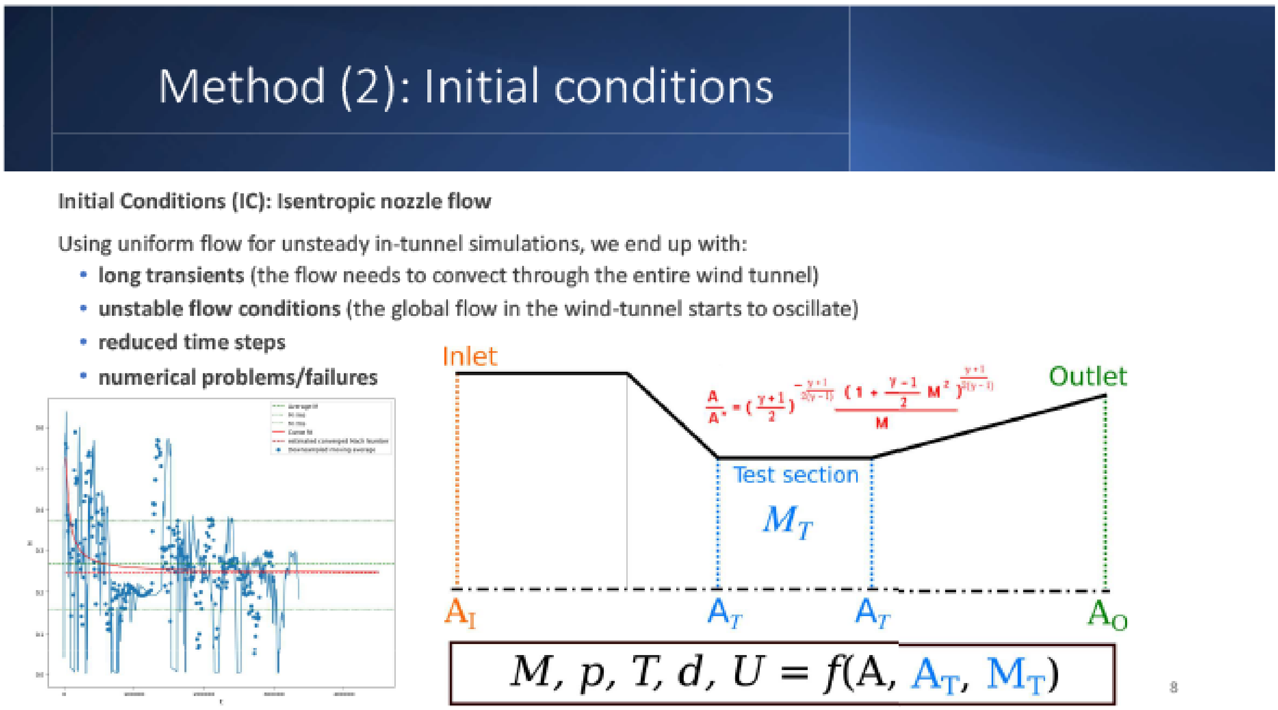
- 103-ANSA-Unstructured-hiA-Yplus1
- C-Level resolution
- 276 million cells, 218 million nodes
- unstructured

Method (1): Numerical settings

All simulations performed using JAXA's in-house code FaSTAR

- Hybrid RANS/LES: Delayed Detached Eddy Simulation (DDES)
- Spalart-Allmaras turbulence model with rotation corrections (SA-noft2-R)
- Node-centered finite volume method
- Convective terms: HLLEW scheme
- Gradient computation: GLSQ method
- LU-SGS time-integration method:
  - Time step of $\Delta t = 3.6 \cdot 10^{-4}$ convective time units (CTUs)
  - Courant-Friedrichs-Lewy number equal to **CFL=10**
- Hishida (van Leer-type) slope limiter as well as a U-MUSCL scheme
- No-slip velocity and adiabatic temperature boundary conditions on the aircraft model and side-wall

Method (2): Initial conditions



Initial Conditions (IC): Isentropic nozzle flow

Using uniform flow for unsteady in-tunnel simulations, we end up with:

- **long transients** (the flow needs to convect through the entire wind tunnel)
- **unstable flow conditions** (the global flow in the wind-tunnel starts to oscillate)
- **reduced time steps**
- **numerical problems/failures**

$$\frac{A}{A^*} = \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M}$$

$$M, p, T, d, U = f(A, A_T, M_T)$$

Method (3): Boundary conditions

Boundary conditions (BC):

- **Inlet:** Static pressure, temperature, and velocity
- **Outlet:** Static pressure
- Values for BC according to isentropic nozzle flow
  - The **entire flow field** as well as **boundary conditions** depend only on an isentropic test-section Mach number M_T
  - If we **change M_T** we need to **change inlet & outlet BC!**
  - Due to skin-friction losses at the wind-tunnel walls, M_T is usually higher than the nominal Mach number M_N
- Using alternative boundary conditions (e.g. total pressure/temperature) leads to numerical instabilities
- We carefully assessed the flow conditions in the wind tunnel and made sure that the solution is not depending on the choice of boundary conditions (shown later)

Method (4): Adjust test-section Mach number

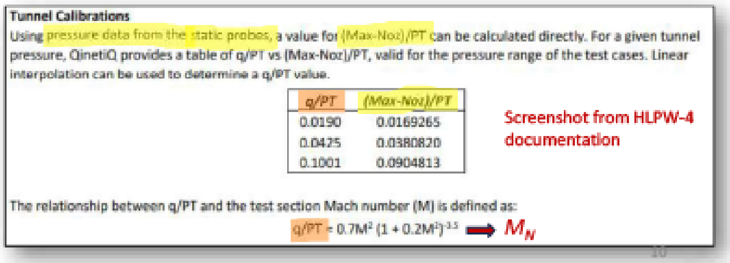
Procedure for each angle of attack:

- Use **isentropic relations** to estimate a **nozzle flow** (initial condition) as well as **inlet and outlet** boundary conditions based on an isentropic test-section Mach number M_T (a-priori unknown)
- Perform a steady RANS simulation of the entire wind-tunnel configuration including the aircraft model at the given angle of attack
- Compute the nominal Mach number M_N according to the procedure provided for the HLPW-4.
- If $|(M_N-0.2)/0.2|>1\%$ -> adjust M_T and re-iterate the procedure

$$\frac{\Delta M_T}{\Delta M_N} \approx 1.18 \Leftarrow \text{no-slip wall}$$

$$\frac{\Delta M_T}{\Delta M_N} \approx 0.96 \Leftarrow \text{slip wall*}$$

*Difference due to simplified wind-tunnel geometry for nozzle-flow calculation



Tunnel Calibrations

Using pressure data from the static probes, a value for (Max-Noz)/PT can be calculated directly. For a given tunnel pressure, QinetiQ provides a table of q/PT vs (Max-Noz)/PT, valid for the pressure range of the test cases. Linear interpolation can be used to determine a q/PT value.

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

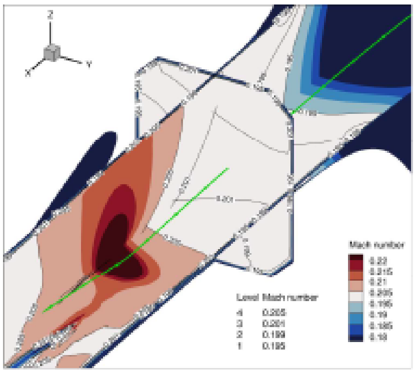
The relationship between q/PT and the test section Mach number (M) is defined as:

$$q/PT = 0.7M^2 (1 + 0.2M^2)^{-3.5} \Rightarrow M_N$$

Screenshot from HLPW-4 documentation

Method (5): Verify test-section Mach number

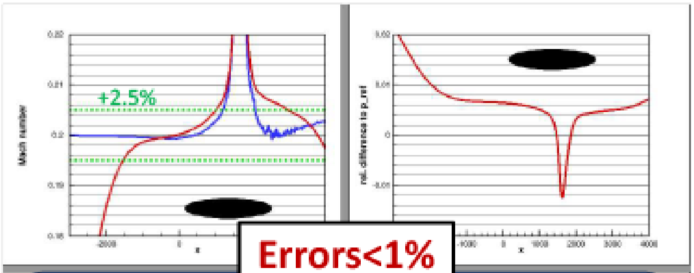
- Mach numbers upstream of the aircraft model **well within +-2.5% error** with respect to $M_N = 0.2$
- Upstream Mach and Reynolds numbers agree well with those extracted from free-air simulations (blue)



Red line plots:
In-tunnel RANS
data extracted along green stream-trace

Extract green curve

Blue line plots:
Free-air RANS
data extracted along green stream-trace



[redacted]

[redacted]

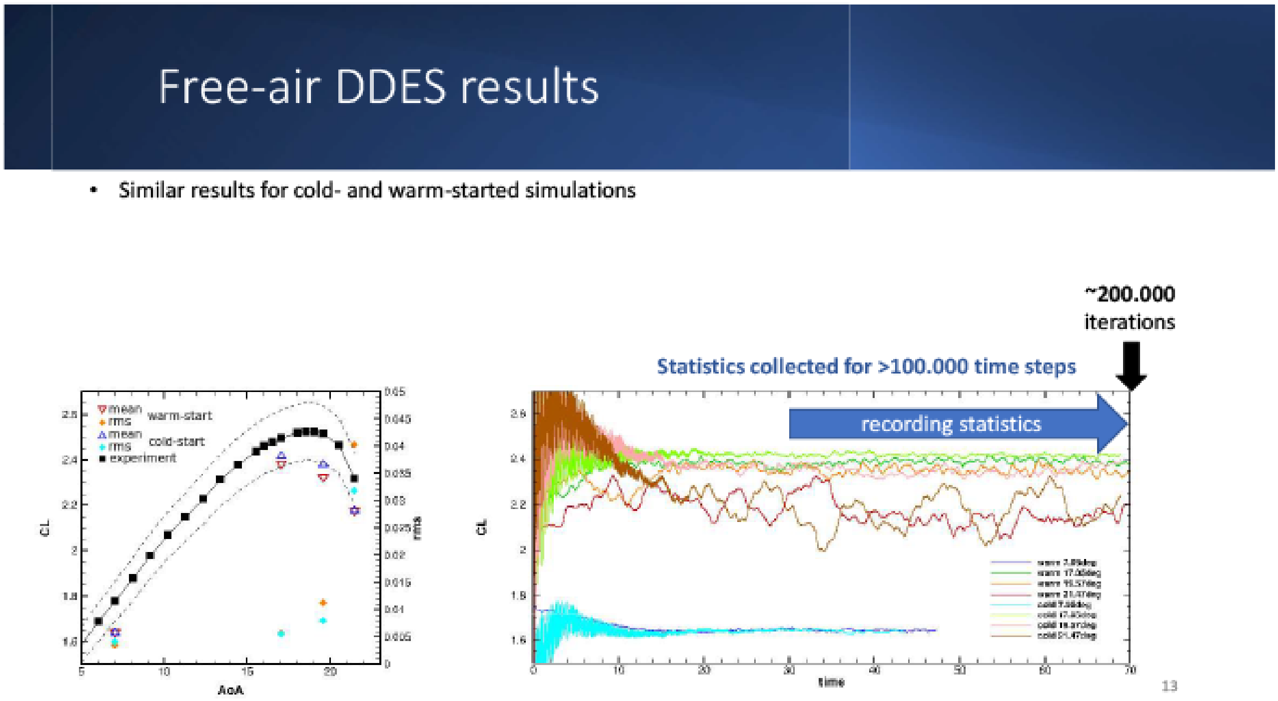
Errors<1%

CAREFUL:

Cp=2/(gamma*M^2)*(p/p_ref-1)
-> 2/(gamma*M^2)=**35.7**

if error in "free-stream" pressure is 0.01, our Cp in the "free-stream" would be 0.357 instead of zero

Free-air DDES



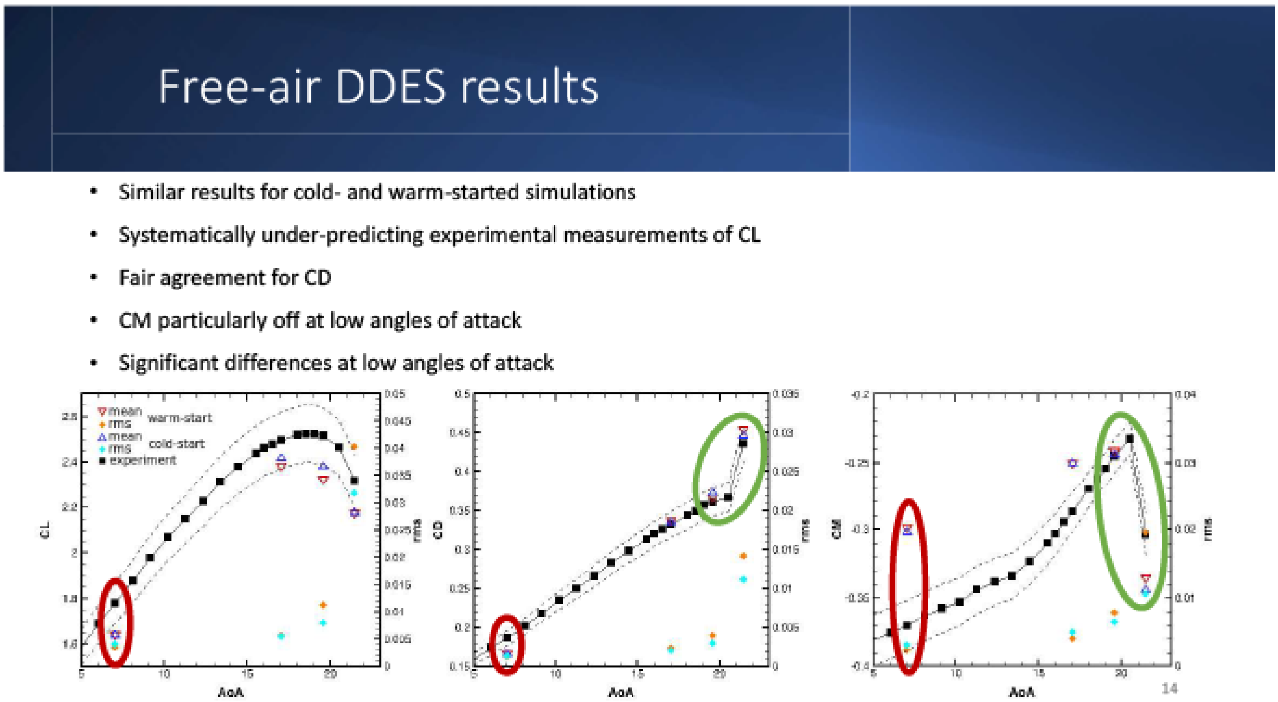
Free-air DDES results

- Similar results for cold- and warm-started simulations

~200.000 iterations

Statistics collected for >100.000 time steps

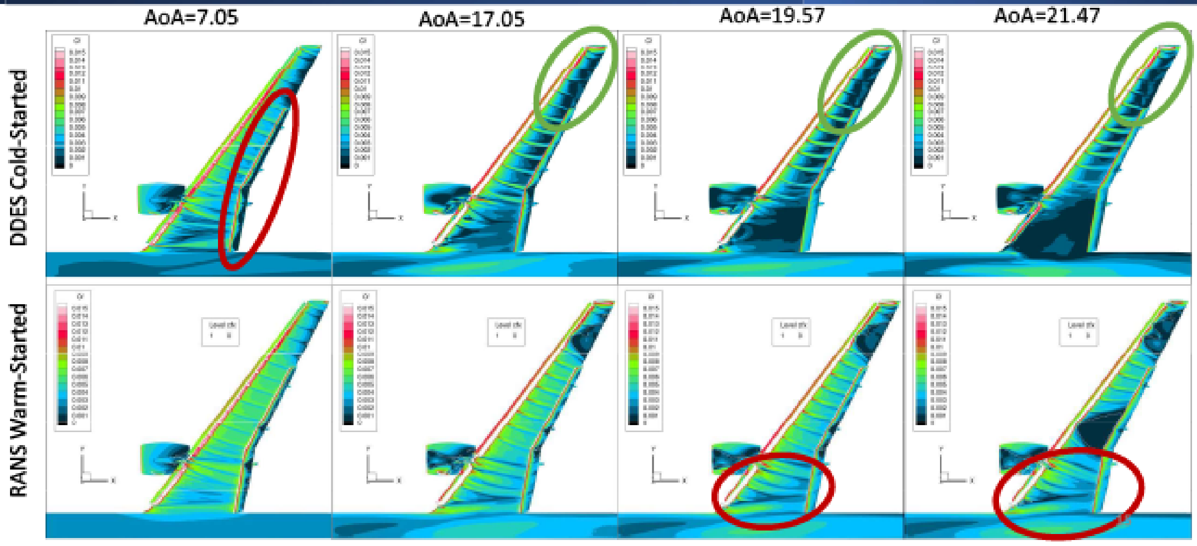
recording statistics



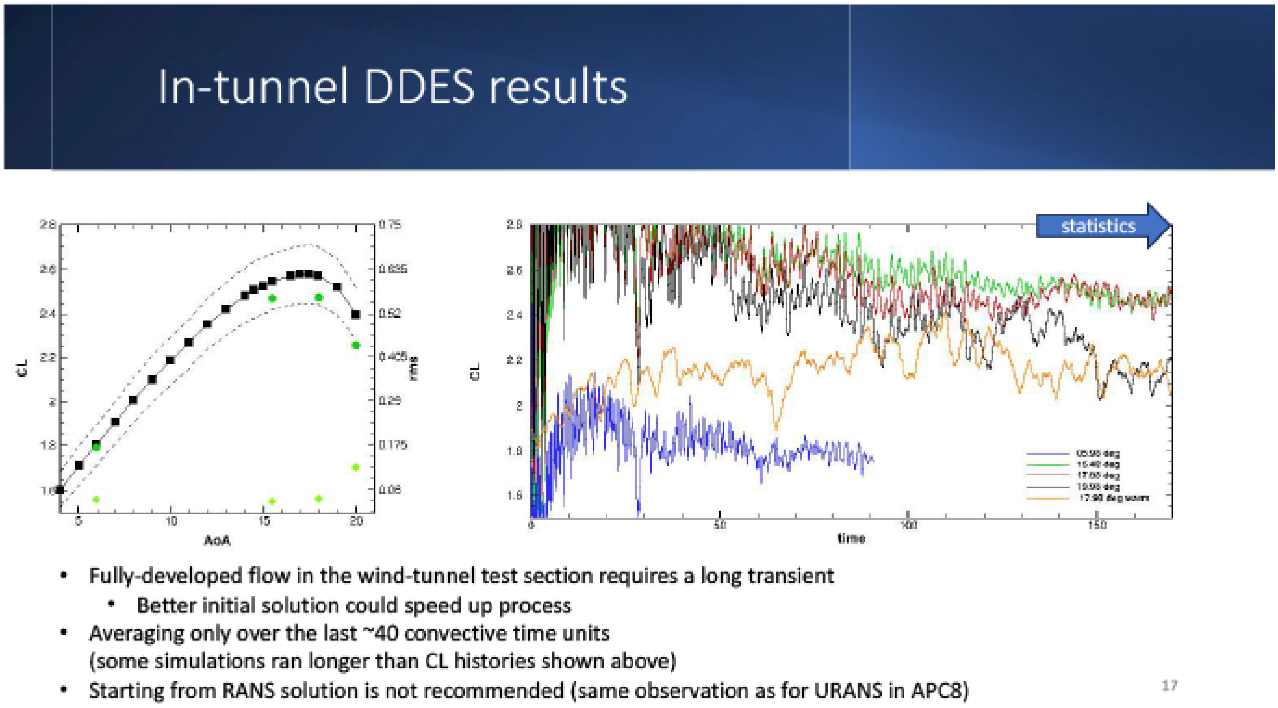
Free-air DDES results

- Similar results for cold- and warm-started simulations
- Systematically under-predicting experimental measurements of CL
- Fair agreement for CD
- CM particularly off at low angles of attack
- Significant differences at low angles of attack

Free-air DDES vs RANS

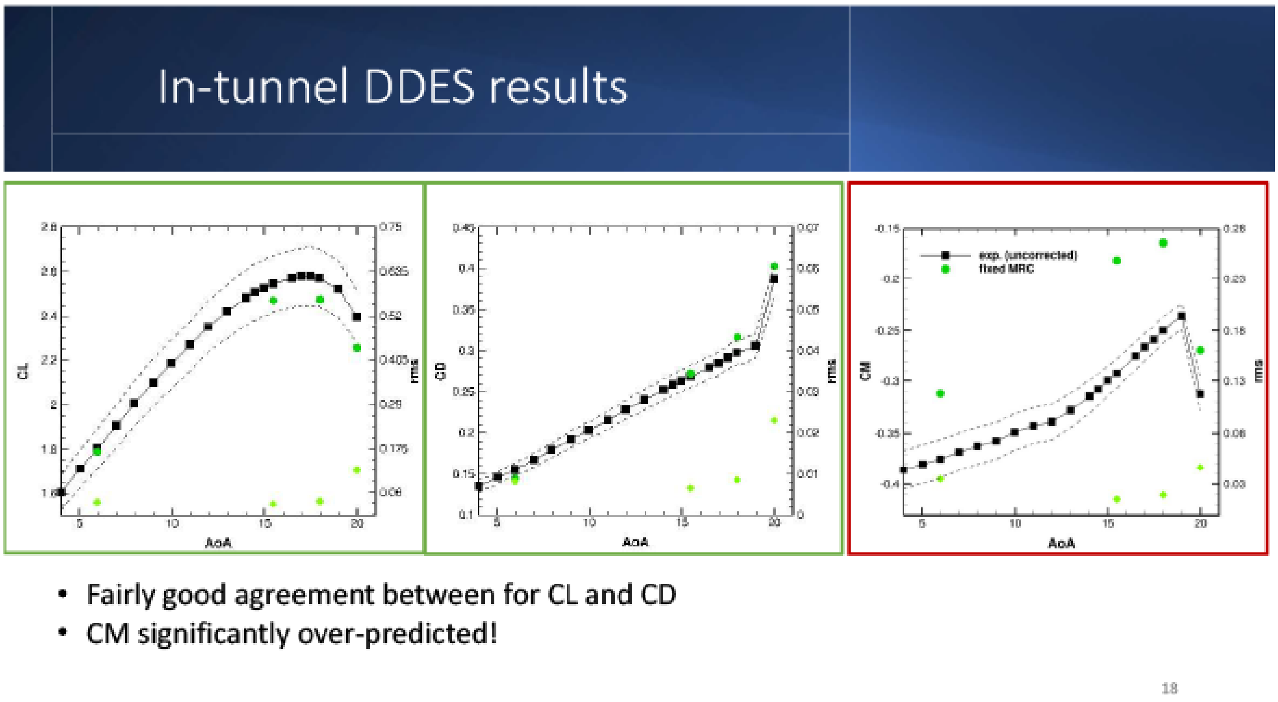


In-tunnel DDES



In-tunnel DDES results

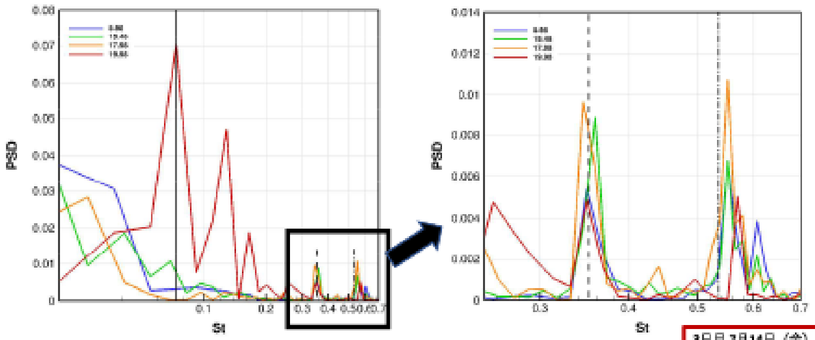
- Fully-developed flow in the wind-tunnel test section requires a long transient
  - Better initial solution could speed up process
- Averaging only over the last ~40 convective time units (some simulations ran longer than CL histories shown above)
- Starting from RANS solution is not recommended (same observation as for URANS in APC8)



In-tunnel DDES results

- Fairly good agreement between for CL and CD
- CM significantly over-predicted!

In-tunnel DDES results



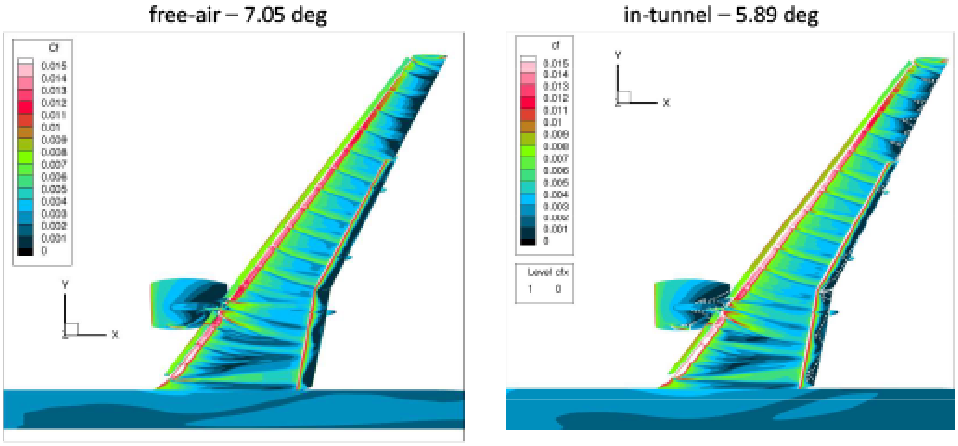
- Post-stall: low-frequency oscillations at St=0.07
- At all angles of attack: oscillations intermediate frequencies agreeing well with Global Stability Analysis (**Sansica et al. 2023**)
  - St=0.35: mode inside nacelle and outboard separation
  - St=0.57: helical mode on the nacelle pylon

3日目 7月14日（金）- D会場 (405室)

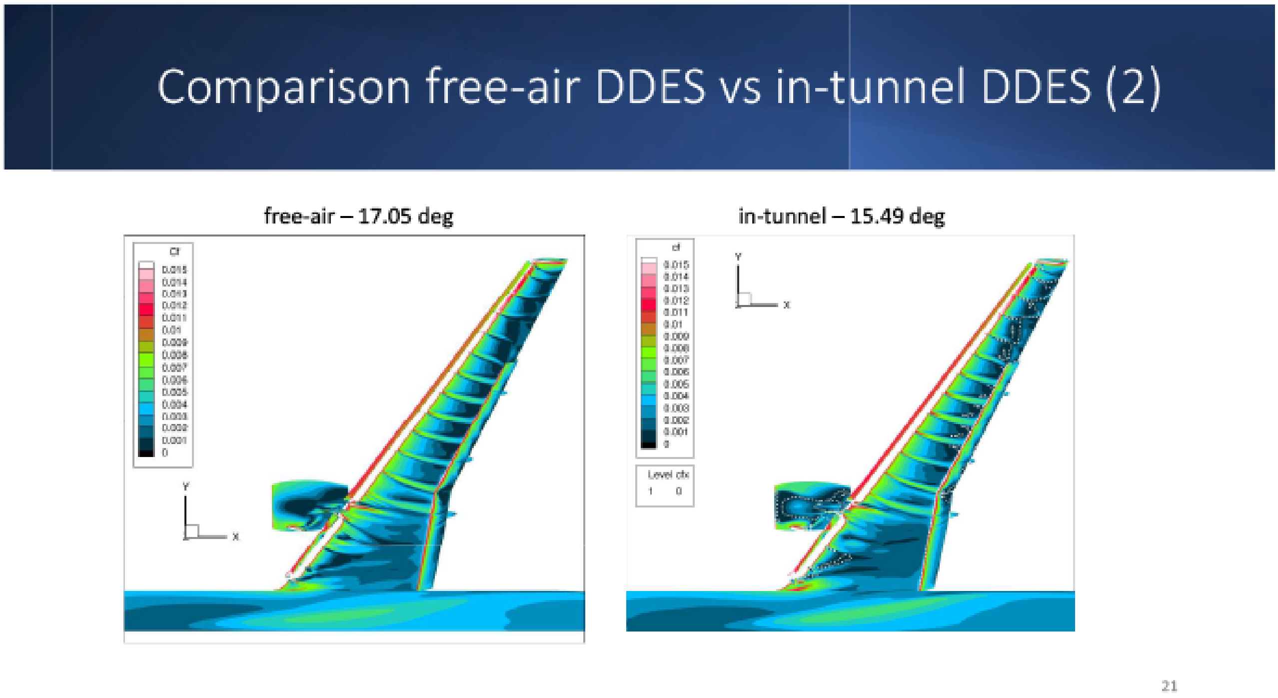
ANSS企画1「航空機開発のための多分野統合シミュレーション」司会

SBM000012STALL
Characterization via global stability analysis on the
NASA Common Research Model high-lift configuration
Sansica Andrea, Zauner Markus, 橋本敦
JAXA

Comparison free-air DDES vs in-tunnel DDES (1)


free-air – 7.05 deg

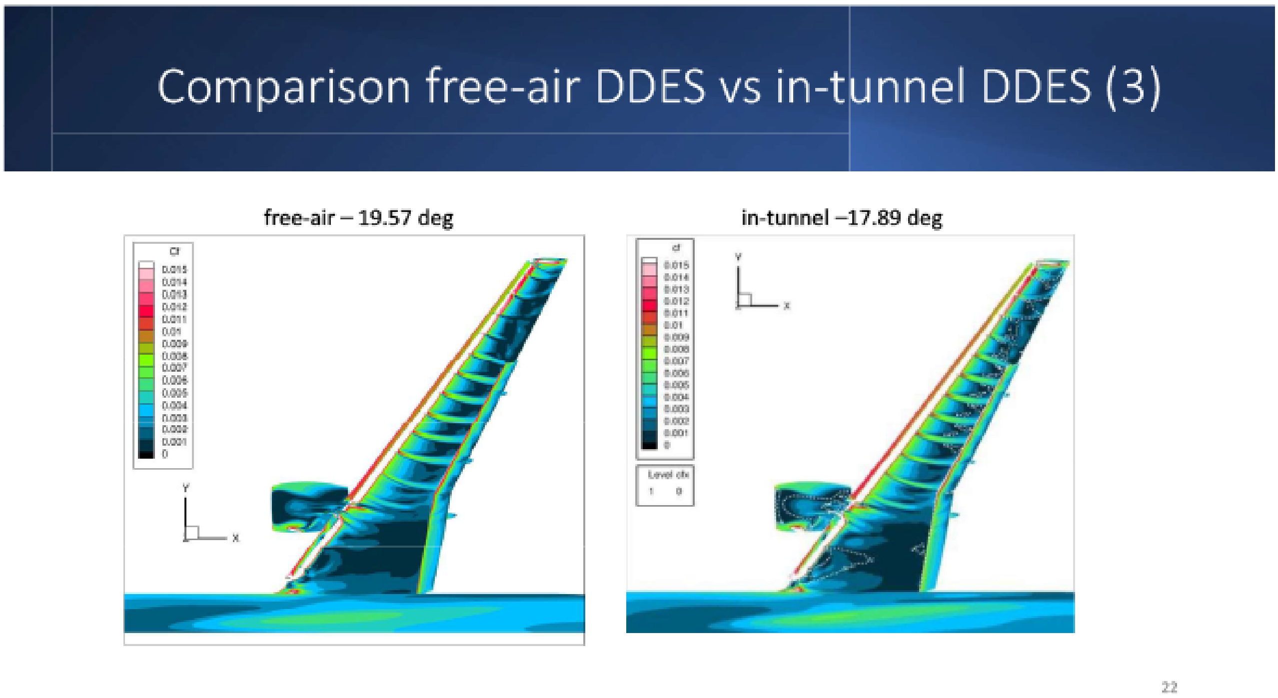
in-tunnel – 5.89 deg



Comparison free-air DDES vs in-tunnel DDES (2)

free-air – 17.05 deg

in-tunnel – 15.49 deg



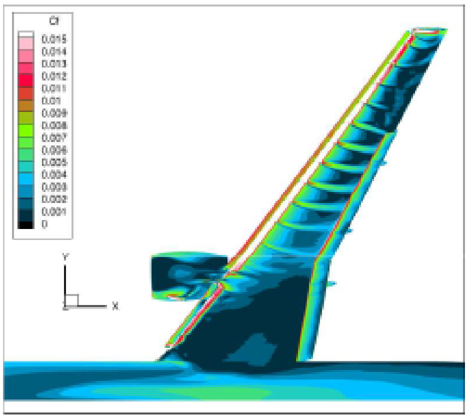
Comparison free-air DDES vs in-tunnel DDES (3)

free-air – 19.57 deg

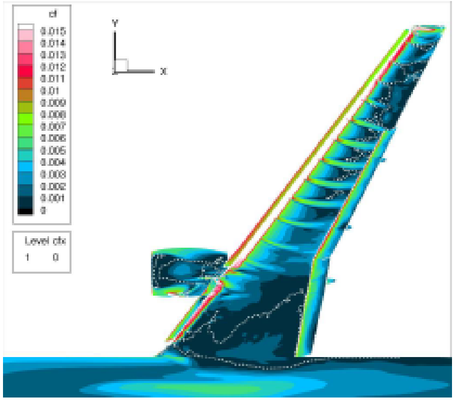
in-tunnel –17.89 deg

Comparison free-air DDES vs in-tunnel DDES (4)

free-air – 21.47 deg



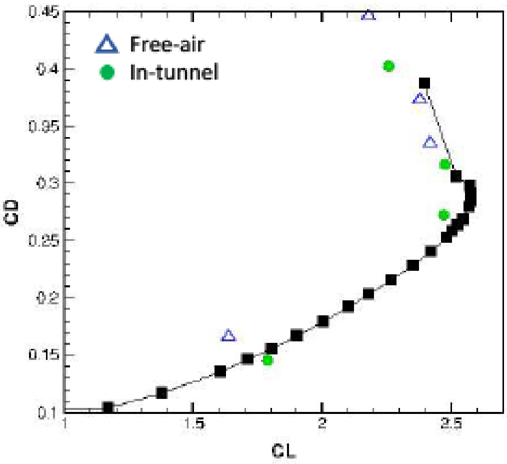
in-tunnel –19.89 deg

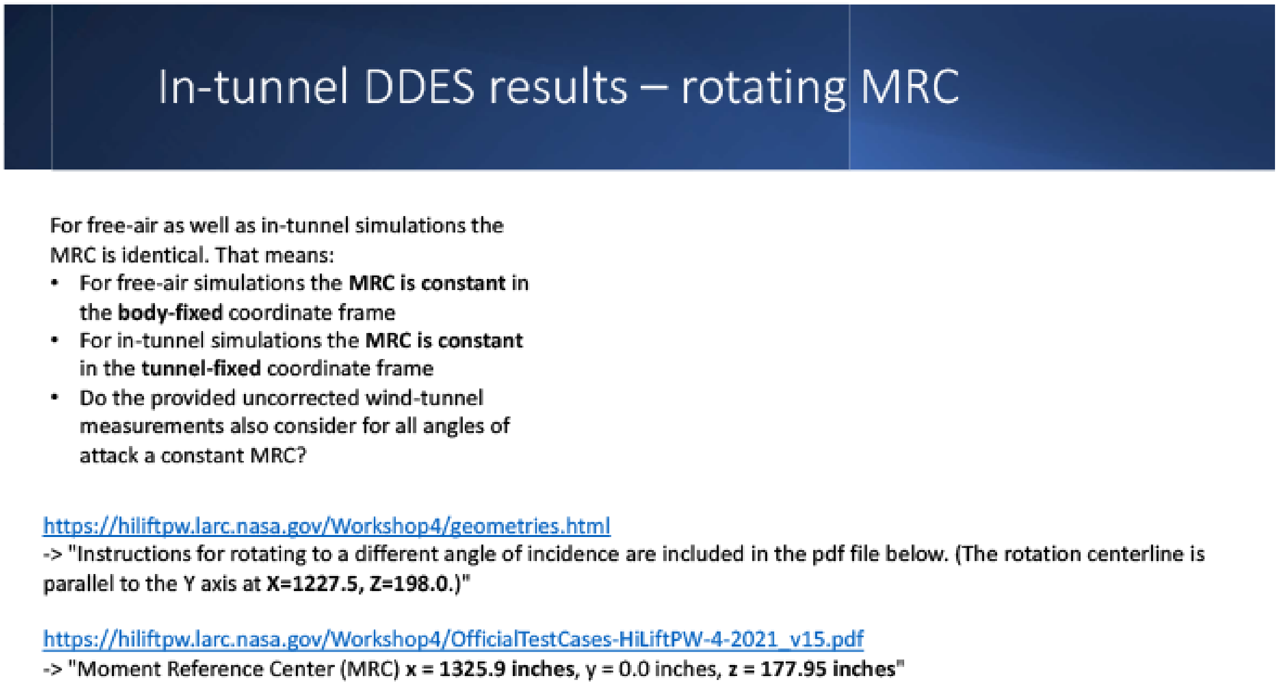


Comparison free-air DDES vs in-tunnel DDES (5)

- Fair agreement between free-air and in-tunnel DDES results
- In-tunnel DDES slightly closer to experimental measurements

Given this good agreement between free-air and in-tunnel DDES results, the differences in CM is puzzling





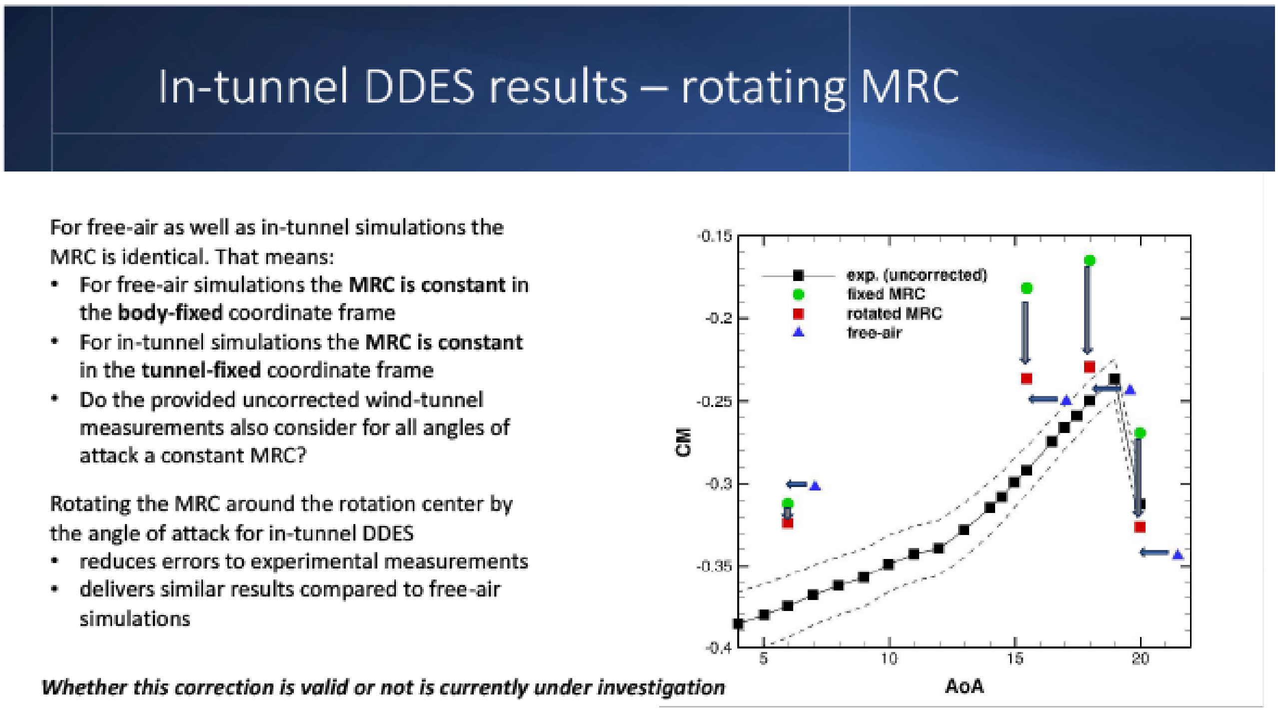
In-tunnel DDES results – rotating MRC

For free-air as well as in-tunnel simulations the MRC is identical. That means:

- For free-air simulations the **MRC is constant** in the **body-fixed** coordinate frame
- For in-tunnel simulations the **MRC is constant** in the **tunnel-fixed** coordinate frame
- Do the provided uncorrected wind-tunnel measurements also consider for all angles of attack a constant MRC?

https://hiliftpw.larc.nasa.gov/Workshop4/geometries.html
-> "Instructions for rotating to a different angle of incidence are included in the pdf file below. (The rotation centerline is parallel to the Y axis at **X=1227.5, Z=198.0.**)"

https://hiliftpw.larc.nasa.gov/Workshop4/OfficialTestCases-HiLiftPW-4-2021_v15.pdf
-> "Moment Reference Center (MRC) **x = 1325.9 inches**, y = 0.0 inches, **z = 177.95 inches**"



In-tunnel DDES results – rotating MRC

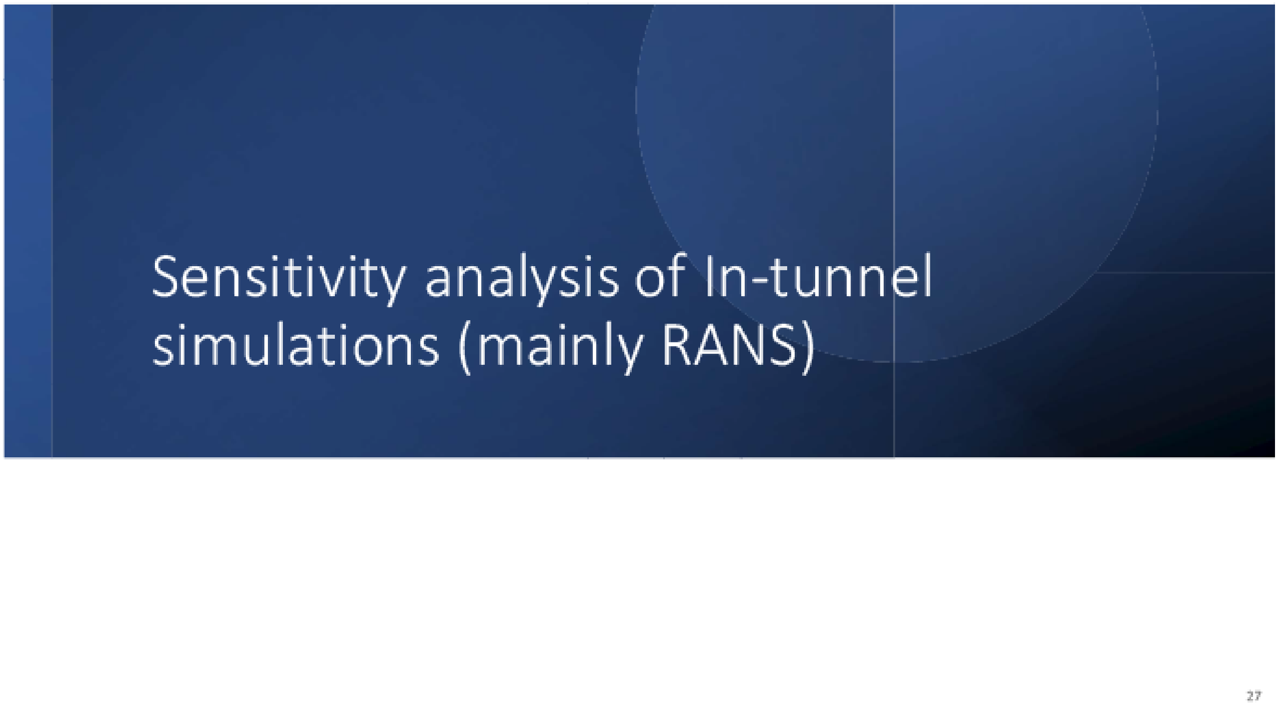
For free-air as well as in-tunnel simulations the MRC is identical. That means:

- For free-air simulations the **MRC is constant** in the **body-fixed** coordinate frame
- For in-tunnel simulations the **MRC is constant** in the **tunnel-fixed** coordinate frame
- Do the provided uncorrected wind-tunnel measurements also consider for all angles of attack a constant MRC?

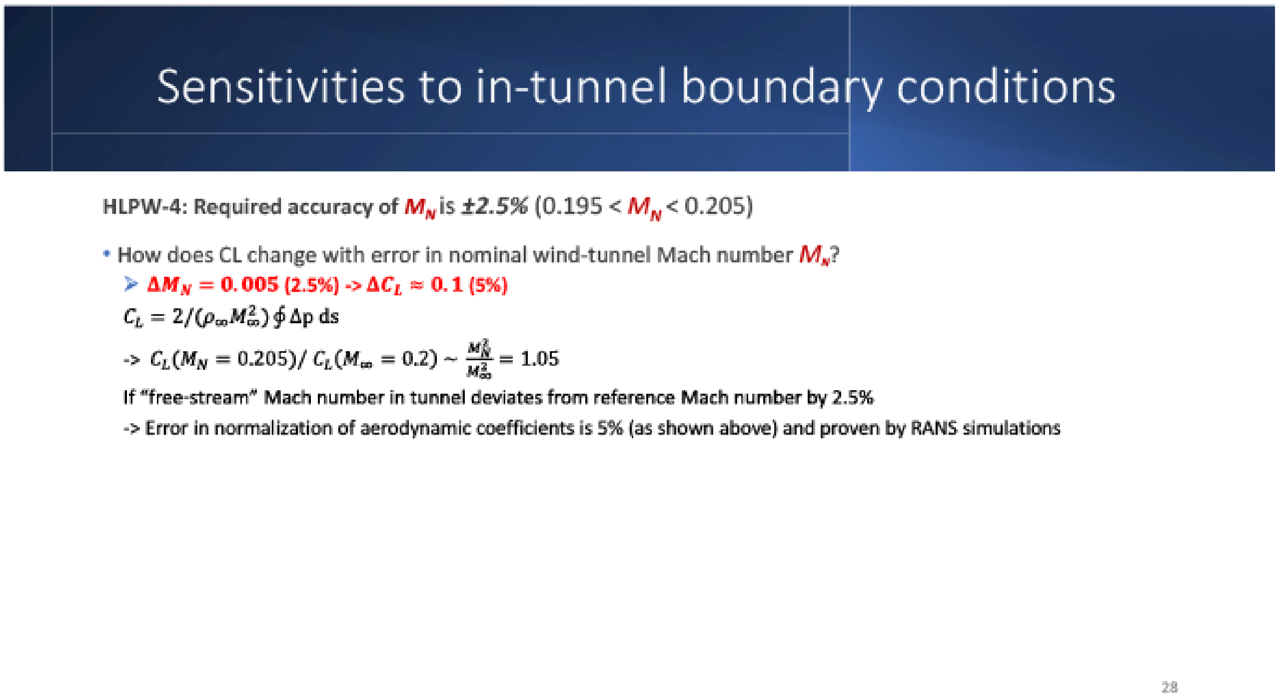
Rotating the MRC around the rotation center by the angle of attack for in-tunnel DDES

- reduces errors to experimental measurements
- delivers similar results compared to free-air simulations

Whether this correction is valid or not is currently under investigation



Sensitivity analysis of In-tunnel simulations (mainly RANS)



Sensitivities to in-tunnel boundary conditions

HLPW-4: Required accuracy of M_N is *±2.5%* (0.195 < M_N < 0.205)

- How does CL change with error in nominal wind-tunnel Mach number M_N?
  - **$\Delta M_N = 0.005$ (2.5%) -> $\Delta C_L \approx 0.1$ (5%)**

  $C_L = 2/(\rho_\infty M_\infty^2) \oint \Delta p \, ds$

  -> $C_L(M_N = 0.205)/\ C_L(M_\infty = 0.2) \sim \frac{M_N^2}{M_\infty^2} = 1.05$

  If "free-stream" Mach number in tunnel deviates from reference Mach number by 2.5%

  -> Error in normalization of aerodynamic coefficients is 5% (as shown above) and proven by RANS simulations

Sensitivities to in-tunnel boundary conditions

In- and Outlet Boundary Conditions for $M_N = 0.2$ computed by RANS

α	Inlet			Outlet	M_T
	p_i	T_i	U_i	p_o	
05.98	17685.84	192.06	8.79	17565.36	0.214
15.48	17696.25	292.11	8.88	17573.54	0.216
17.98	17706.76	292.16	8.95	11581.80	0.218
19.98	17717.37	292.21	9.03	17590.15	0.220

Average M in DDES

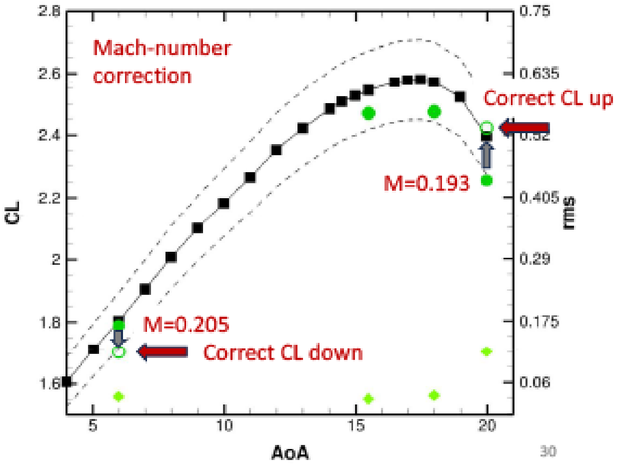
0.205
0.200
0.201
0.193

(histories in back-up)

Sensitivities to in-tunnel boundary conditions

- As mentioned before, time average of nominal Mach number can differ from reference Mach number of M=0.2!
- We can correct CL by the ratio of the Mach-number squares (see previous slides)
- Predictions remain within +/-5% error margin

- Mach-number correction can be neglected for CD and CM



Sensitivities to in-tunnel boundary conditions

HLPW-4: Required accuracy of M_N is ±2.5% (0.195 < M_N < 0.205)

- How does CL change with error in nominal wind-tunnel Mach number M_N?
  - **$\Delta M_N = 0.005$ (2.5%) -> $\Delta C_L \approx 0.1$ (5%)**

$C_L = 2/(\rho_\infty M_\infty^2) \oint \Delta p \, ds$

-> $C_L(M_N = 0.205) / C_L(M_\infty = 0.2) \sim \frac{M_N^2}{M_\infty^2} = 1.05$

If "free-stream" Mach number in tunnel deviates from reference Mach number by 2.5%

-> Error in normalization of aerodynamic coefficients is 5% (as shown above) and proven by RANS simulations

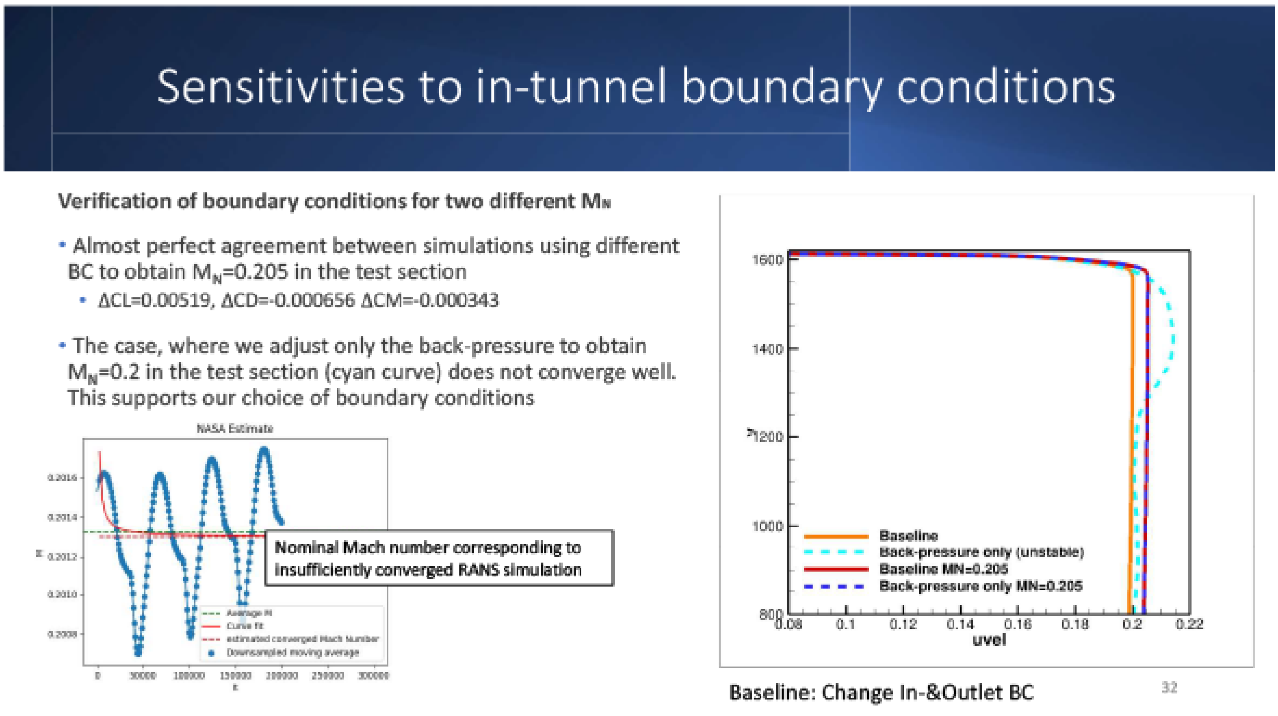
Measurement accuracy of wind-tunnel reference conditions important!

- Is there a difference in CL using slip or no-slip wind-tunnel walls?
  - **YES (for preliminary RANS at least)**

More analysis required

- Is there a sensitivity adjusting only back pressure to set wind-tunnel Mach number M_N?
  - **NO**

Present procedure delivers similar results (e.g. CL=1.915) as adjusting M_N solely by outlet pressure (e.g. CL=1.907)



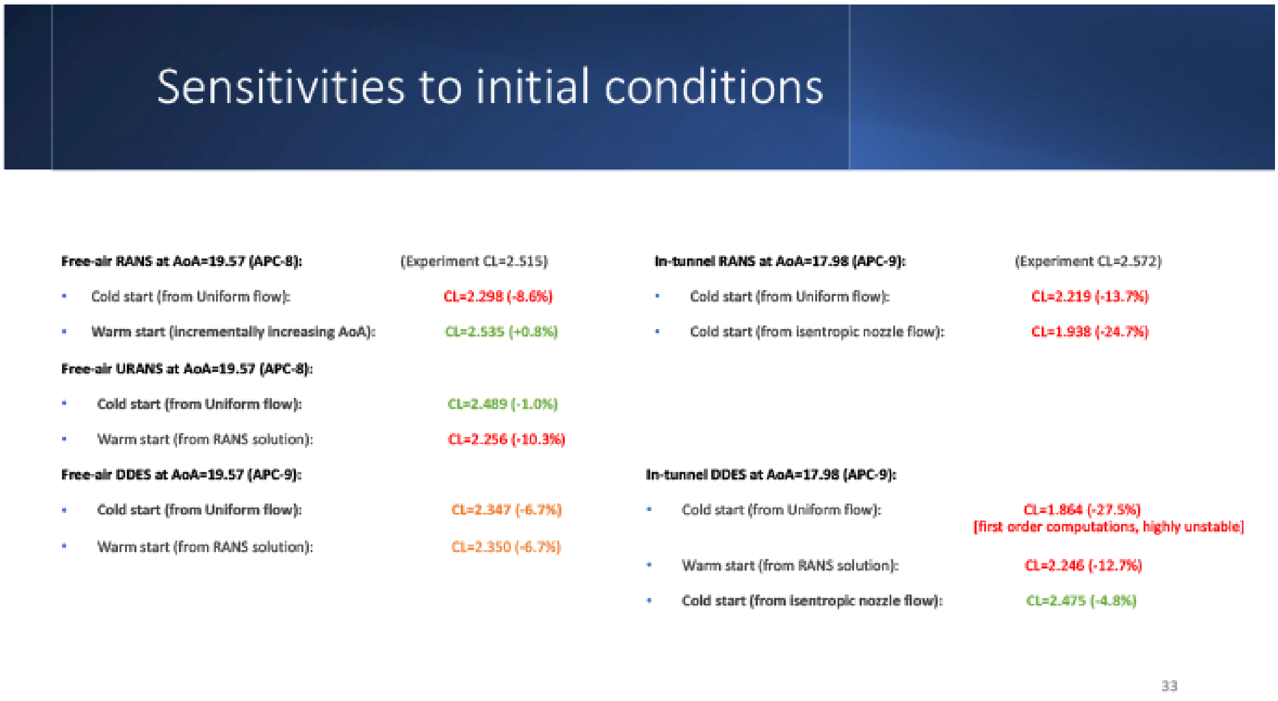
Sensitivities to in-tunnel boundary conditions

Verification of boundary conditions for two different M_N

- Almost perfect agreement between simulations using different BC to obtain M_N=0.205 in the test section
  - ΔCL=0.00519, ΔCD=-0.000656 ΔCM=-0.000343
- The case, where we adjust only the back-pressure to obtain M_N=0.2 in the test section (cyan curve) does not converge well. This supports our choice of boundary conditions

Nominal Mach number corresponding to insufficiently converged RANS simulation

Baseline: Change In-&Outlet BC



Sensitivities to initial conditions

Free-air RANS at AoA=19.57 (APC-8): (Experiment CL=2.515)

- Cold start (from Uniform flow): CL=2.298 (-8.6%)
- Warm start (incrementally increasing AoA): CL=2.535 (+0.8%)

Free-air URANS at AoA=19.57 (APC-8):

- Cold start (from Uniform flow): CL=2.489 (-1.0%)
- Warm start (from RANS solution): CL=2.256 (-10.3%)

Free-air DDES at AoA=19.57 (APC-9):

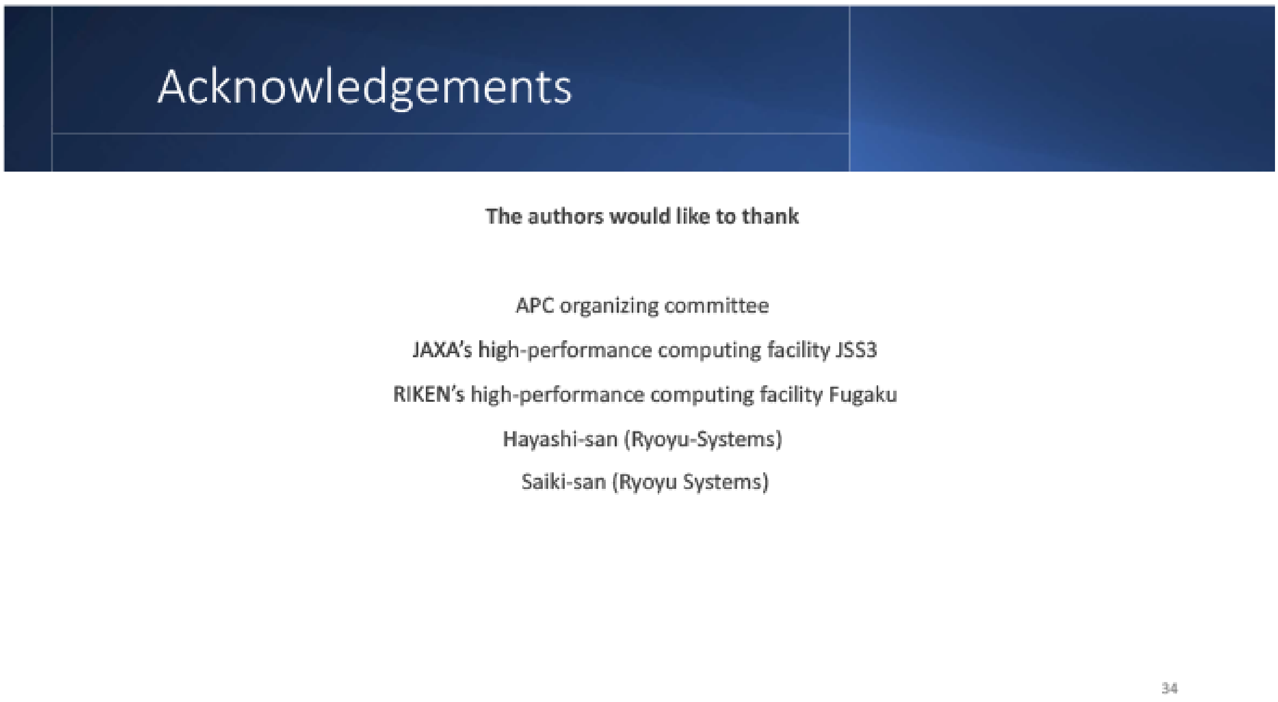
- Cold start (from Uniform flow): CL=2.347 (-6.7%)
- Warm start (from RANS solution): CL=2.350 (-6.7%)

In-tunnel RANS at AoA=17.98 (APC-9): (Experiment CL=2.572)

- Cold start (from Uniform flow): CL=2.219 (-13.7%)
- Cold start (from isentropic nozzle flow): CL=1.938 (-24.7%)

In-tunnel DDES at AoA=17.98 (APC-9):

- Cold start (from Uniform flow): CL=1.864 (-27.5%) [first order computations, highly unstable]
- Warm start (from RANS solution): CL=2.246 (-12.7%)
- Cold start (from isentropic nozzle flow): CL=2.475 (-4.8%)



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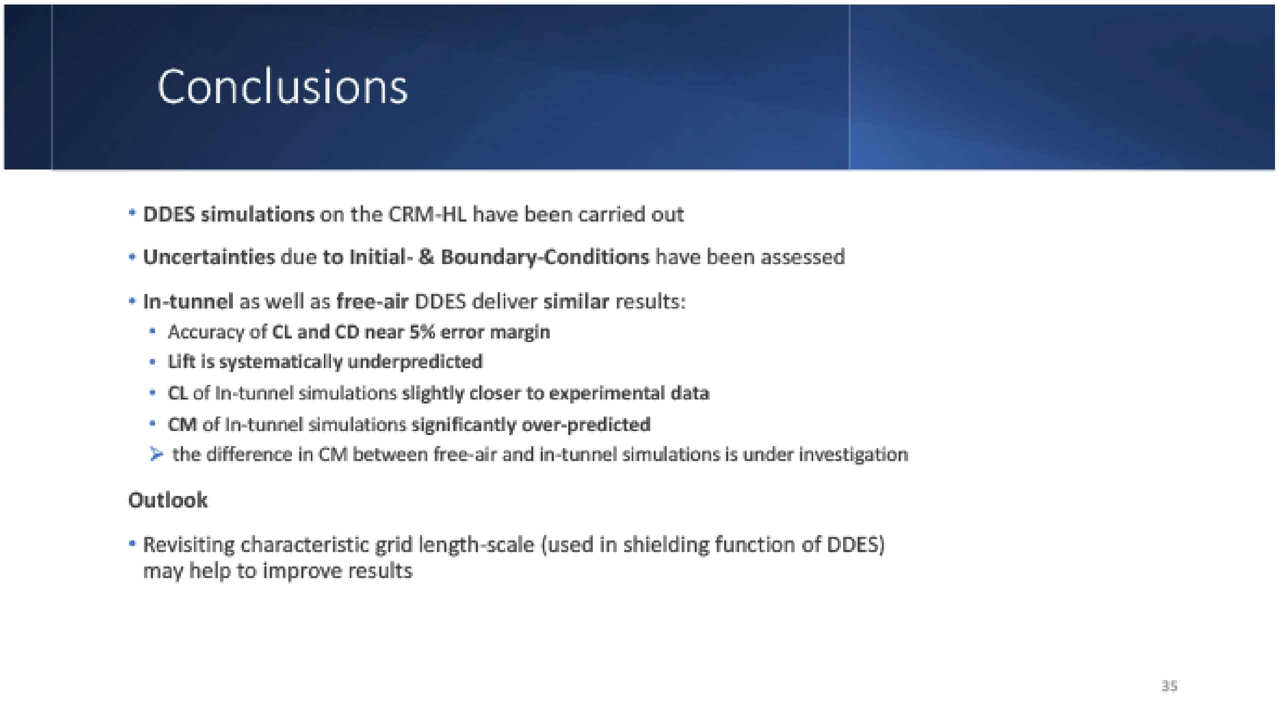
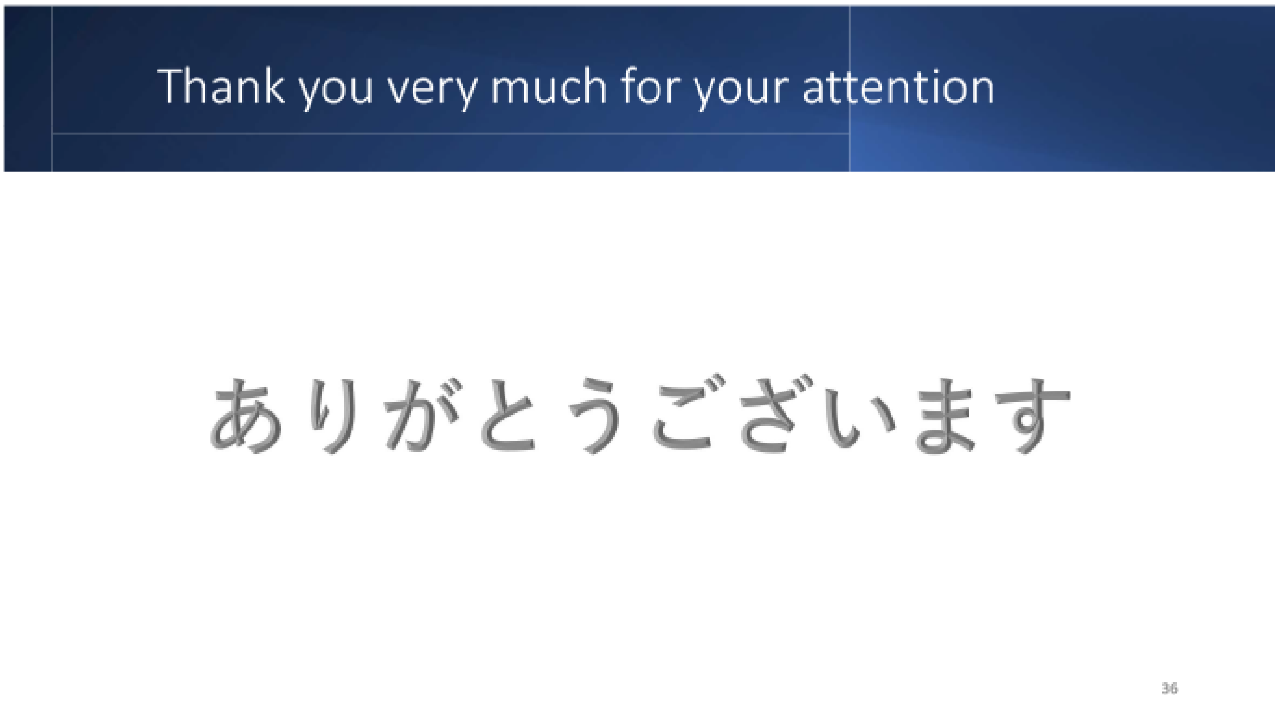


Conclusions

- **DDES simulations** on the CRM-HL have been carried out
- **Uncertainties** due **to Initial- & Boundary-Conditions** have been assessed
- **In-tunnel** as well as **free-air** DDES deliver **similar** results:
  - Accuracy of **CL and CD near 5% error margin**
  - **Lift is systematically underpredicted**
  - CL of In-tunnel simulations **slightly closer to experimental data**
  - CM of In-tunnel simulations **significantly over-predicted**
  - ➢ the difference in CM between free-air and in-tunnel simulations is under investigation

Outlook

- Revisiting characteristic grid length-scale (used in shielding function of DDES) may help to improve results



Thank you very much for your attention

ありがとうございます