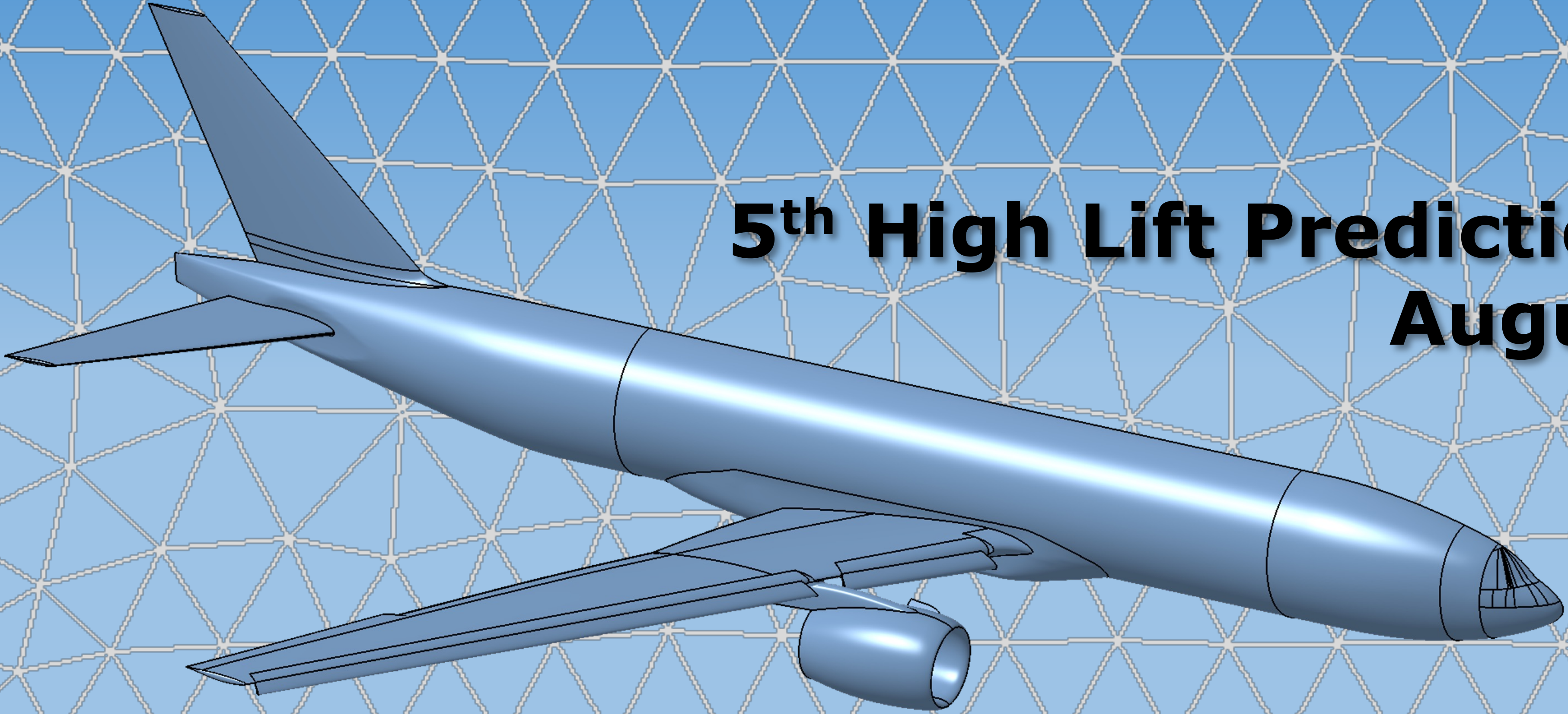


5th High Lift Prediction Workshop
August 2-3, 2024

Introduction

Leadership Team Introduction

- Workshop Leadership Team:
  - Jeff Slotnick (Boeing), Chris Rumsey (NASA), Adam Clark (Boeing), and Li Wang (NASA) - Short intro
- Technology Focus Group (TFG) Leads:
  - **RANS**: Boris Diskin (NASA)
  - Adaptive RANS **(ADAPT)**: Mike Park (Luminary Cloud)
  - High-Order **(HO)**: Marshall Galbraith (MIT)
  - Hybrid RANS-LES **(HRLES)**: Neil Ashton (AWS)
  - **WMLES**: Cetin Kiris (Volcano Platforms)

Organization Committee

- Amazon Web Services
- Barcelona Supercomputer Center
- The Boeing Company
- Cadence Design System, Inc.
- Helden Aerospace, Inc.
- Luminary Cloud, Inc.
- Massachusetts Institute of Technology
- NASA - National Aeronautics and Space Laboratory
- Oak Ridge National Laboratory
- ONERA, the French Aerospace Lab
- Volcano Platforms, Inc.

Meshing Support Team

- Steve Karman (ORNL): RANS, HO
- Reza Djeddi and Nick Wyman (Cadence): RANS
- Mohamed Sereez (Coventry University): RANS
- Vangelis Skaperdas (BETA-CAE): RANS, HO, HLRES, WMLES
- Andrew Wick (Helden Aerospace): RANS, WMLES
- Marshall Galbraith (MIT): HO
- Xevi Roca and Eloi Ruiz-Gironez (Barcelona Supercomputing Center): HO

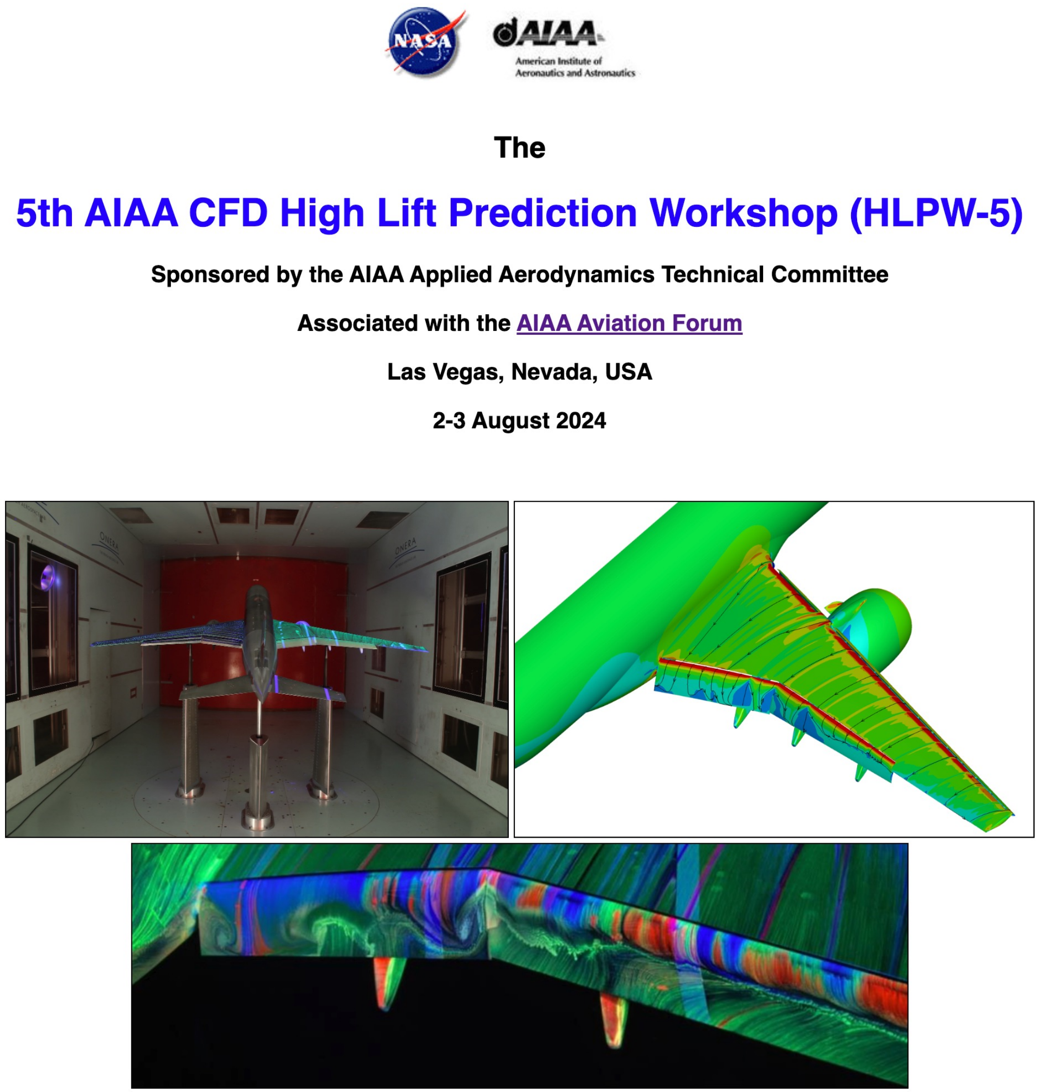
HLPW-5 Participation

- **1.5 years** of dedication and contribution (Feb. 2023 - Present) from individual teams across 41 organizations, involving at least 103 participants
  - 11 countries
  - Government labs, major aerospace companies, academic institutions, commercial software developers, and small businesses
- At least **38 CFD solvers** contributed data, including:
  - *FUN3D, FELight, USM3D-ME, OpenFOAM, Fluent, SU2, STAR-CCM+, HiFUN, Dragon, Cflow, Leo, CODA, zCFD, TAS, CFD++, Kestrel KCFD, Synapsis, FaSTAR, Champs, Flow360, Luminary, elsA, Fidelity, phAMG, EPIC-T1, BCFD, WOLF, COFFE, Ansys, PACEFISH, AdaptiveEuler, CHARLES, hpMusic, LAVA, PowerFLOW, ScaLES, FFVHC-ACE, and NSU3D*
- Bi-weekly virtual meetings held in each TFG with group member presentations
- Two mini-workshops held July 13, 2023, and Feb. 15, 2024, respectively

Workshop Website

https://hiliftpw.larc.nasa.gov/

- Contains key information from current and past workshops, including CAD files, grids, submitted data, and much more
- TFGs and participant teams
- A one-page intro slide from each team describing their methodologies
- Mini-workshop results/slides



The

5th AIAA CFD High Lift Prediction Workshop (HLPW-5)

Sponsored by the AIAA Applied Aerodynamics Technical Committee

Associated with the AIAA Aviation Forum

Las Vegas, Nevada, USA

2-3 August 2024

Workshop Objectives

- Review and discuss CFD data and comparisons for test cases, addressing TFG-level Key Questions (KQs)
- Summarize findings via workshop-level KQs
- Discuss next steps, including post-workshop activities and ideas for HLPW-6

Workshop Agenda – Day 1

- 8:30am: Introduction
- 8:45am: Description of Testcases and Experimental Data
- 9:15am: Committee Gridding
- 10:00am: RANS TFG Summary
- 11:15am: Adaptive TFG Summary
- *12:15pm: 90 minute lunch break*
- 1:45pm: HRLES TFG Summary
- 3:00pm: WMLES TFG Summary
- 4:30pm: High Order TFG Summary
- 5:00pm-5:30pm: Wrap-up Day 1

(A few 15 min breaks are also included)

Workshop Agenda – Day 2

- 8:30 am: NASA Data Portal Overview
- 8:45 am: Overall Summary
- 10:00 am: CRM-HL Ecosystem Discussion
- 10:30 am: Group Discussion
- 11:45 am: Workshop Closing
- 12:00 pm: Workshop End

(One 15 min break is also included)

In Memoriam

Dr. Steve Louis Karman

09/18/1959 – 02/25/2024

Texas A&M University
Aerospace Engineering, B.S., M.E

University of Texas at Arlington
Aerospace Engineering, Ph.D.

General Dynamics

Lockheed Martin

University of Tennessee Chattanooga

Pointwise, Inc.

Oak Ridge National Laboratory

- First 3D CFD simulation of a fighter aircraft (F-16)
- Author of SPLITFLOW CFD solver
- Pioneer in high-order mesh generation algorithms
- Advocate & leader in many AIAA workshops (High Lift Prediction, High Fidelity CFD, Geometry and Mesh Generation Workshop, and more)

Beloved Husband, Father, and Friend

“You can’t solve for what you can’t resolve.”

“If it wasn’t for boundary conditions there wouldn’t be any problems.”

“A good idea is a good idea.”

“So aren’t those connections in your meshless method really a mesh?”

“Stop blaming it on the mesh.”

Experimental Data and Test Cases

Test Case 1 – CRM-HL Wing-Body Verification

The verification problem for this workshop is based on the simplified CRM-HL Wing Body (CRM-HL-WB) configuration. The verification problem for this test case will be the same as the one initially introduced and utilized for the **High Fidelity CFD Verification Workshop (HFCFDVW),** planned for SciTech 2024. The target characteristics of this study are grid convergence of lift, drag, and moment coefficients (HFCFDVW does not require moment coefficient, but we require it here).

Geometry

- CRM-HL wing/body* (CRM-HL-WB)

Experimental Data

- None (for code-to-code Verification)

Computational Domain

- Rectangular cuboid computational domain with dimensions -65,000 ≤ x ≤ 65,000, 0 ≤ y ≤ 65,000, -65,000 ≤ z ≤ 65,000
- Symmetry at y=0

Run Conditions

Mach Number	0.20
Chord Reynolds Number	5.6 x 10^6
Angle of Attack	11°
Reference Static Temperature	521 °R

* Reference configuration

Sample Key Questions

- Are RANS solvers able to demonstrate convergence to the same solution for a given turbulence model in grid refinement using families of fixed and adapted grids?
- For Non-RANS solvers, what is the most consistent approach to grid families that can demonstrate a trend towards grid independence on this problem?
- Is there enough consistency amongst non-RANS approaches that there is reasonable agreement on a grid independent solution?
- Does the ensemble of answers amongst modelling approaches compared to the experimental free air corrected data tell us anything useful about uncertainty?

Details

- Geometry is provided in full-scale inches
- When using a dimensional code, it is recommended to adjust viscosity to a non-physical value to match requested Reynolds number
- SA-neg-QCR2000-R is highly recommended, run fully turbulent (for RANS solvers)
  - Strongly recommended that RANS participants utilize grids from Verification Workshop, but alternate gridding strategies are encouraged, if appropriate
- Participants using non-RANS solvers are encouraged to demonstrate grid convergence on this problem using multiple grid levels along with their best practice solver settings, looking at convergence of the lift, drag, and moment coefficients. The gridding requirements in this section are purposefully left vague. Discussions within TFGs are expected to provide further guidance on how to best family grid sequences for these approaches.

Test Case 2 – Configuration Build-up

Flow solutions are requested to assess the ability of CFD to predict the effect of varying geometric fidelity through component build-up to help isolate specific types of flow physics associated with high-lift aerodynamics. Geometry is provided for four separate geometric configurations of increasing levels of complexity, with simulations to be performed free-air and compared to fully corrected data. Experimental data will be provided from wind tunnel campaigns utilizing both the ONERA [3] and Boeing models, tested at the ONERA F1 and QinetiQ 5m facilities, respectively. For this case, a set of grids should be employed with mesh size determined by current “best practice” guidelines.

Geometry

2.1: Wing-Body with HV (CRM-HL-WBHV)*
2.2: Wing-Body-Slat with HV (ONERA_LRM–WBSHV)
2.3: Wing-Body-Slat-Flaps with HV (ONERA_LRM–WBSFHV)
2.4: Wing-Body-Slat-Flaps-Nacelle with HV (ONERA_LRM–LDG)

Experimental Data

2.1: QinetiQ 5m (Expected May 2024)
2.2: ONERA F1 (Provided October 2023
2.3: ONERA F1 (Provided October 2023)
2.4: ONERA F1 (Expected Feb 2024)

Run Conditions

Mach Number	0.20
Chord Reynolds Number	5.4 x 10^{6} (case 2.1) 5.9 x 10^{6} (cases 2.2 - 2.4)
Angle of Attack	2.1: 6º, 10º, 12º, 13º, 14º 2.2: 6º, 10º, 17.7º, 20º, 21.5º, 23º, 23.8º 2.3: 6º, 10º, 14º, 16º, 17.7º, 20.7º, 23.5º 2.4: 7.6º, 10º, 14º, 16º, 17.7º, 19.7º, 23.6º
Reference Static Temperature	521 °R
Reference Static Pressure	14.696 psi

Sample Key Questions

- Does the consistency in integrated forces/moments from CFD simulations improve when modeling geometrically simpler HL configurations?
- Are there unique CFD modeling requirements (e.g. mesh, solver, etc.) for an unprotected Leading Edge (LE)?
- How does the additional of the LE device (slat) effect CFD modeling, both in terms of accuracy and consistency?
- How does the additional of the TE device (flap) effect CFD modeling, both in terms of accuracy and consistency?
- How does the additional of the pylon/nacelle effect CFD modeling, both in terms of accuracy and consistency?

Details

- Geometry is provided in full-scale inches
- When using a dimensional code, it is recommended to adjust viscosity to a non-physical value to match requested Reynolds number
- All simulations are run Free-Air with no tunnel or support systems included

Optional Case 2a

- Several elements of the computational modeling can be investigated to explore sensitivity of solutions. These include, but are not limited to:
    - Use of specific wind tunnel model geometry associated with a particular test campaign
    - Use of static tunnel aeroelastic deformations
    - Performing in-tunnel simulations (either with the test section only, or including expansion/contraction sections)
    - Physical tripping or transition modelling
    - Systematic mesh refinement

* Reference configuration

Test Case 3 – Reynolds Number Study

Flow solutions are requested to assess the capability of CFD to predict the effects of increasing Reynolds number on the aerodynamic performance of the CRM-HL in the reference landing configuration. Solutions are requested across specified angles of attack, at four different Reynolds numbers, and will be compared to fully corrected data obtained from several different facilities.

Geometry

- Wing-Body-Slat-Flaps-Nacelle (NASA_5.2%–LDG) *

Experimental Data

- KHI LSWT, ONERA F1, NASA NTF, QinetiQ 5-metre

Computational Domain

- Symmetry at y=0

Run Conditions

Mach Number	0.20
Chord Reynolds Number	1.05M (optional), 5.49M, 16M, 30M
Angles of Attack	6, 10, 14, 16, 18, 19, 20, 22 degrees for each Re
Reference Static Temperature	518.67 °R
Reference Static Pressure	14.696 psi

Sample Key Questions

- Are there unique gridding requirements for a particular Reynolds number?
- Does CFD accurately capture Reynolds number trends in integrated forces and moments up to flight scale?
- Does CFD accurately capture trends in aerodynamic flow separation vs Reynolds number?
- How important is aeroelastic modeling for accurate predictions at higher Reynolds numbers?
- Is running simulations in free-air adequate to understand trends and increments, or is running in-tunnel simulations, compared against uncorrected data, required?

Details

- Geometry is provided in full-scale inches
- When using a dimensional code, it is recommended to adjust viscosity to a non-physical value to match requested Reynolds number
- All simulations are run Free-Air, with no tunnel or support systems included

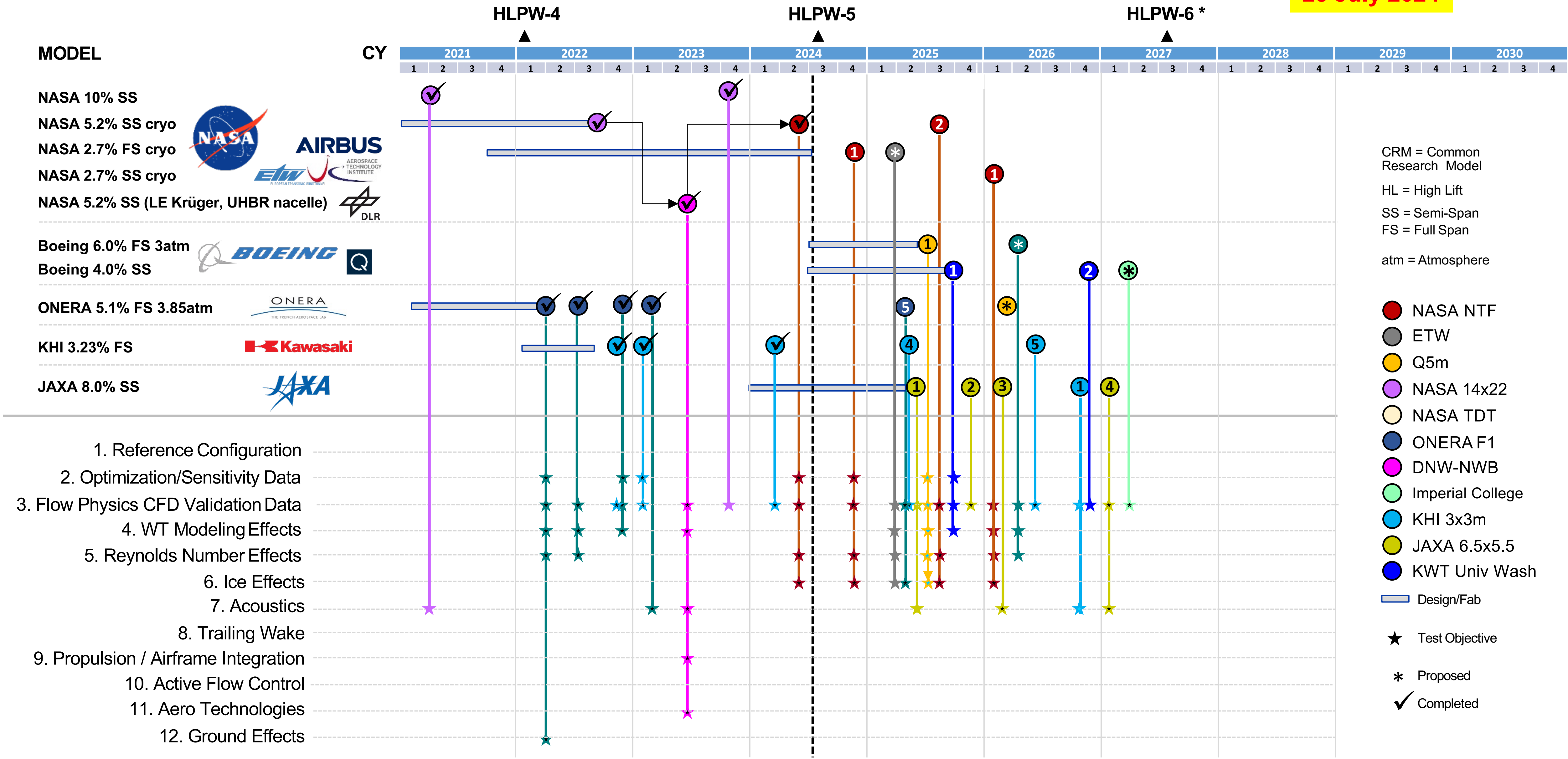
Optional

- Several elements of the computational modeling can be investigated to explore sensitivity of solutions. These include, but are not limited to:
  - Use of specific wind tunnel model geometry associated with a particular test campaign
  - Use of static tunnel aeroelastic deformations
  - Performing in-tunnel simulations (either with the test section only, or including expansion/contraction sections)
  - Physical tripping or transition modelling
  - Systematic mesh refinement

* As-designed NASA 5.2% scale model

CRM-HL Ecosystem Development Plan

23 July 2024



CRM = Common Research Model

HL = High Lift

SS = Semi-Span
FS = Full Span

atm = Atmosphere

● NASA NTF
● ETW
● Q5m
● NASA 14x22
● NASA TDT
● ONERA F1
● DNW-NWB
● Imperial College
● KHI 3x3m
● JAXA 6.5x5.5
● KWT Univ Wash
▭ Design/Fab
★ Test Objective
∗ Proposed
✓ Completed

NASA 10% CRM-HL

Scale: 10%

Facility: 14x22
QinetiQ 5m

Reynolds: ~3.3m
~5.5m

Data Used:

- HLPW4

ONERA LRM

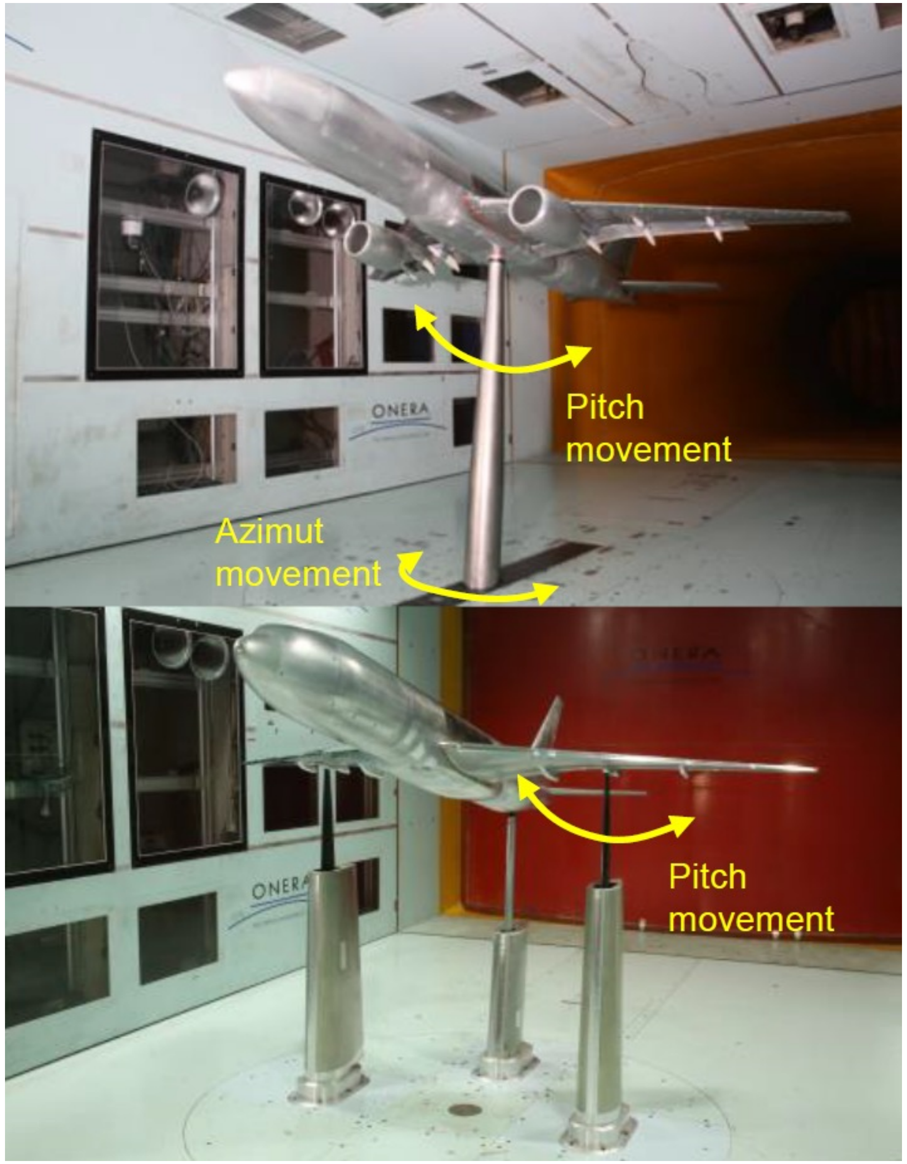
Scale: 1/19.5 (5.1%)

Facility: ONERA F1

Reynolds: 5.9m (others)

Data Used:

- HLPW 5 TC2.2 – 2.4
- HLPW5 TC3.2



NASA 5.2% NTF Model

Scale: 5.2%

Facility: NASA NTF
NASA 14x22
DLR

Reynolds: 1.5m-32m

Data Used:

- HLPW5 TC 3.2-3.4

Boeing 6%

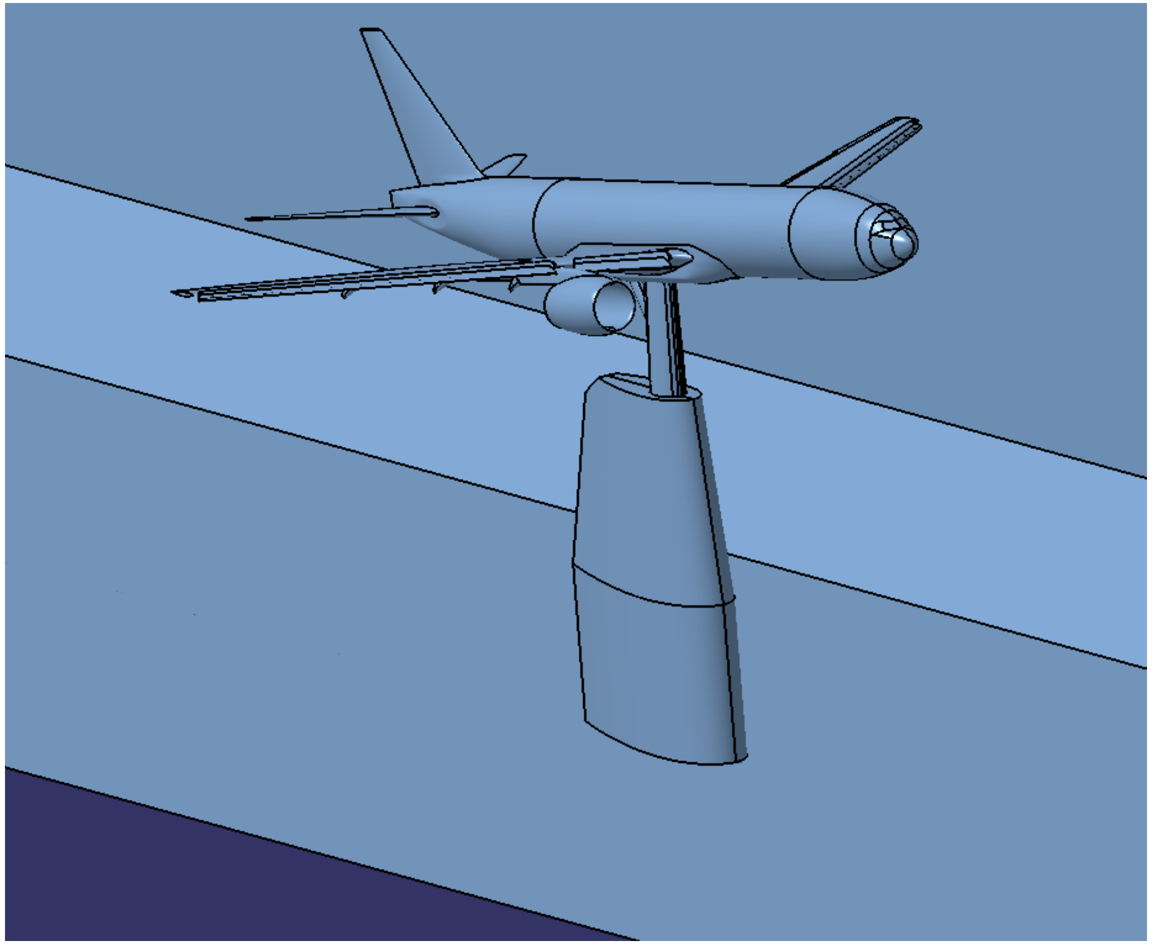
Scale: 6%

Facility: QinetiQ 5m

Reynolds: ~5.5m

Data Used:

- None available yet…
- Intended to support HLPW5 TC 1, TC 2.1



HLPW-4 vs HLPW-5

- Often heard question in TFG meetings – “Our predictions in HLPW-4 were so much better near CLmax, I don’t understand why this case is so different”

- At the time of HLPW-4, not much data was available to the Ecosystem – The only model tested in the real ‘Reference Configuration’ was the 10% half model test at QinetiQ

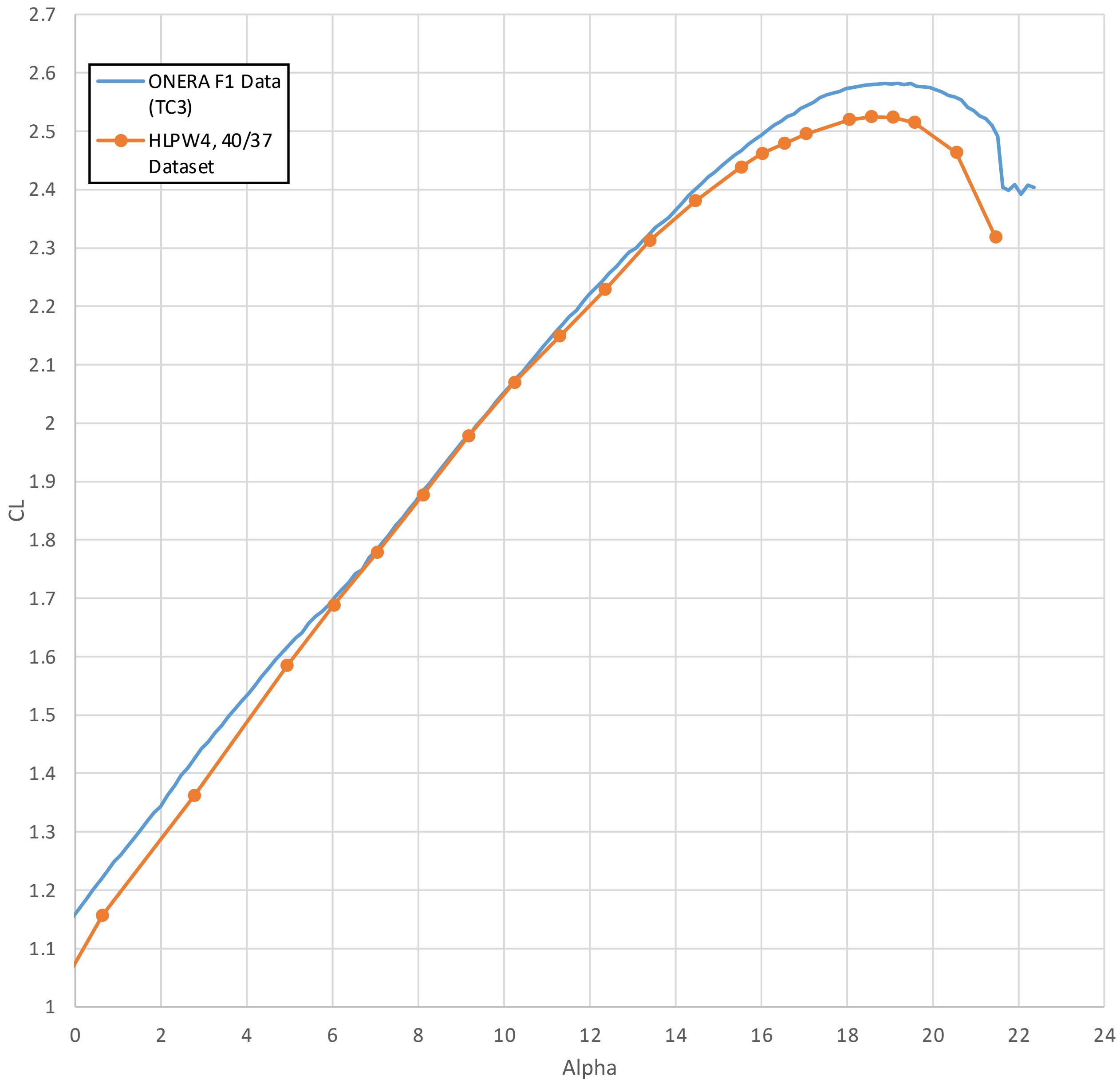
- Since then, we’ve learned a considerable amount!

ONERA F1 vs QinetiQ

- Half model at QinetiQ (HLPW4)
- Full model at ONERA

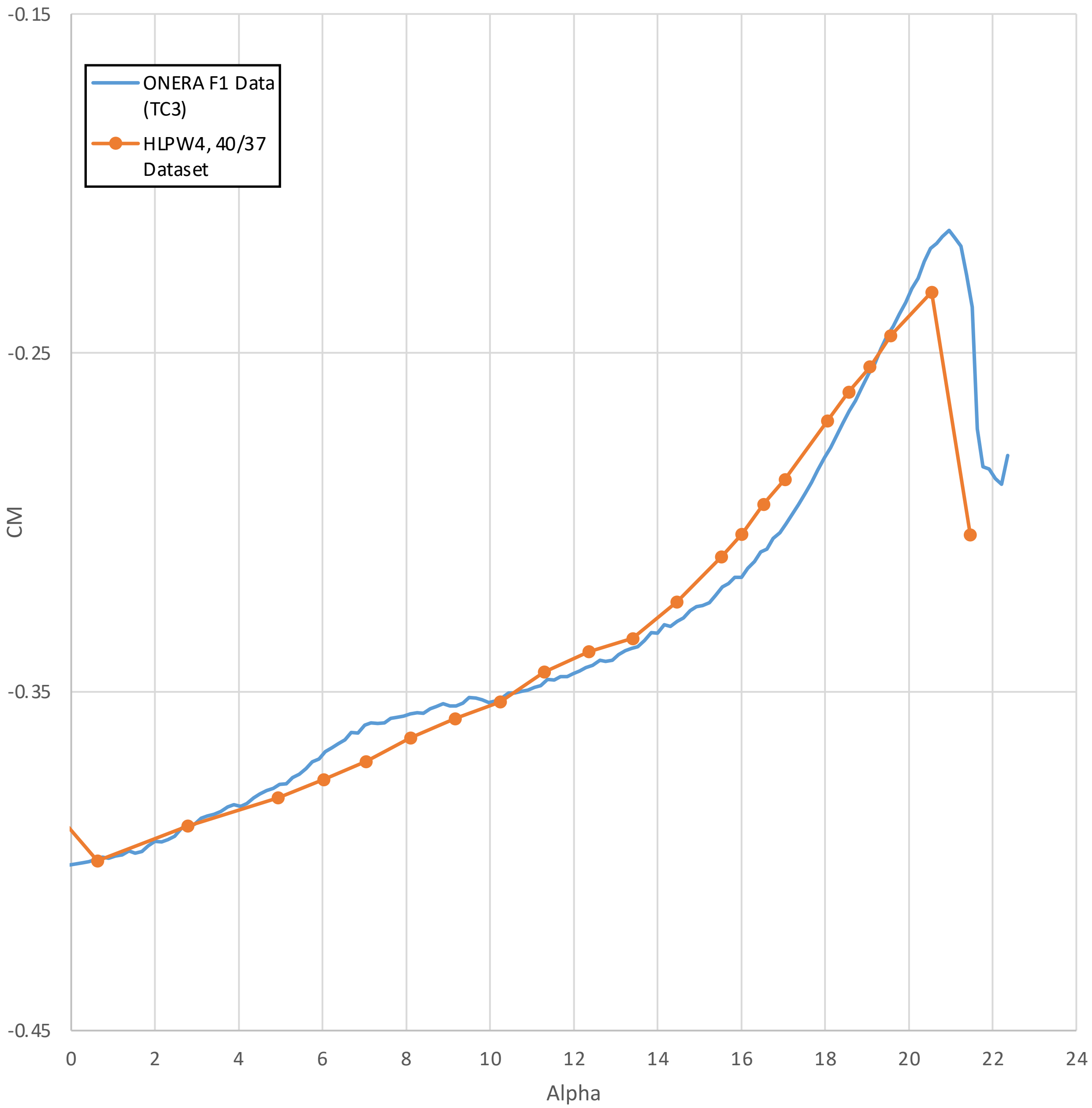
- Minor geometry differences, not thought to drive big differences
  - Nacelle re-contouring
  - Outboard WUSS reloft
  - FSF differences
  - LE Bracket differences

- Experimental data suggests ~0.06 difference at CLmax



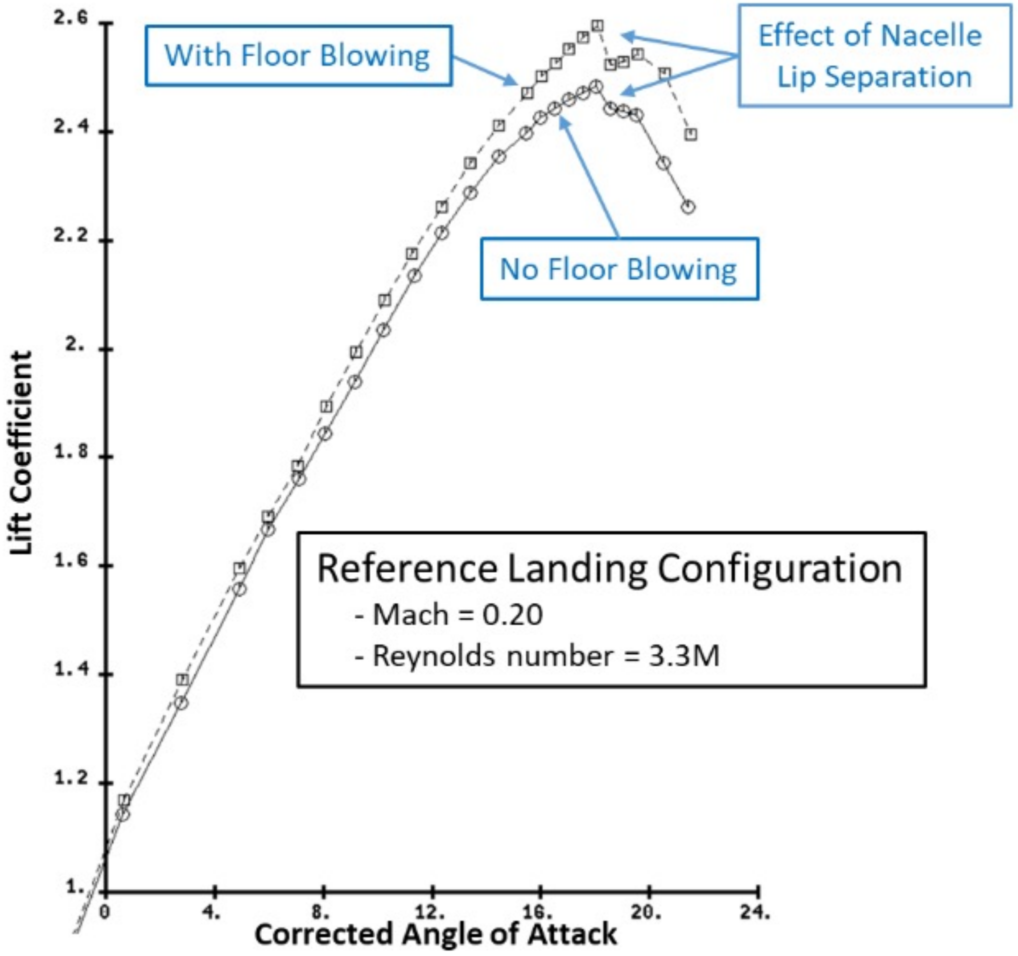
ONERA F1 vs QinetiQ

- QinetiQ Data suggest a stronger IB wing at higher angles of attack
  - Largely due to half model mounting effects
- Also some less well understood differences at 5-10°, where CL levels are in best agreement



QinetiQ HLPW4 Dataset

- QinetiQ model was a half-model test, and the floor boundary layer was demonstrated to have a large effect
  - Still not directly comparable to free air, but closer to data from the same model in different facilities
- Boundary layer is considerably thicker at Q5m compared to when it was tested at NASA 14x22
- Expected that the same configuration tested in 14x22 would yield lift comparable to ONERA data
  - Demonstrated this earlier in 2024, but only have preliminary (not fully corrected) data to compare against



From AIAA 2020-2771

HLPW-5 Data

- Testcase 1: Intended to be compared to Boeing 6% test – that test has not happened yet

- Testcase 2: 2.2 through 2.4 are compared against ONERA F1 data described further below

- Testcase 3: Intended to be compared to NTF 5.2% data – Still unresolved differences with this data
  - To be discussed more tomorrow

ONERA F1 Dataset

- Multiple test campaigns carried out at F1, and are documented thoroughly in paper AIAA-2024-3512.
- Model is full-span, fully corrected
- Datasets from both the single and three-strut setup are provided, and serve to demonstrate repeatability

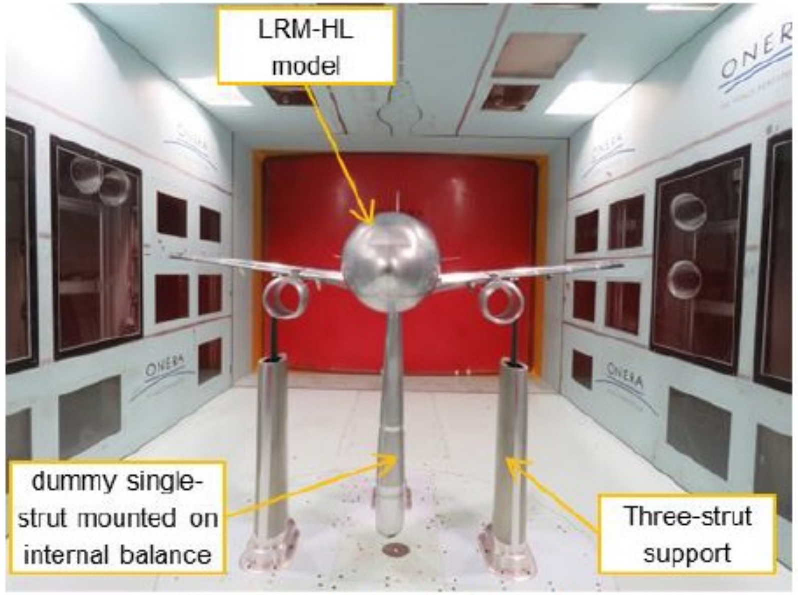
a. single-strut setup

b. three-strut setup

Corrections applied

- Wall Corrections: Wall interference based on linearized potential theory, results in first order corrections to flow velocity and angle, second order corrections to forces and moments

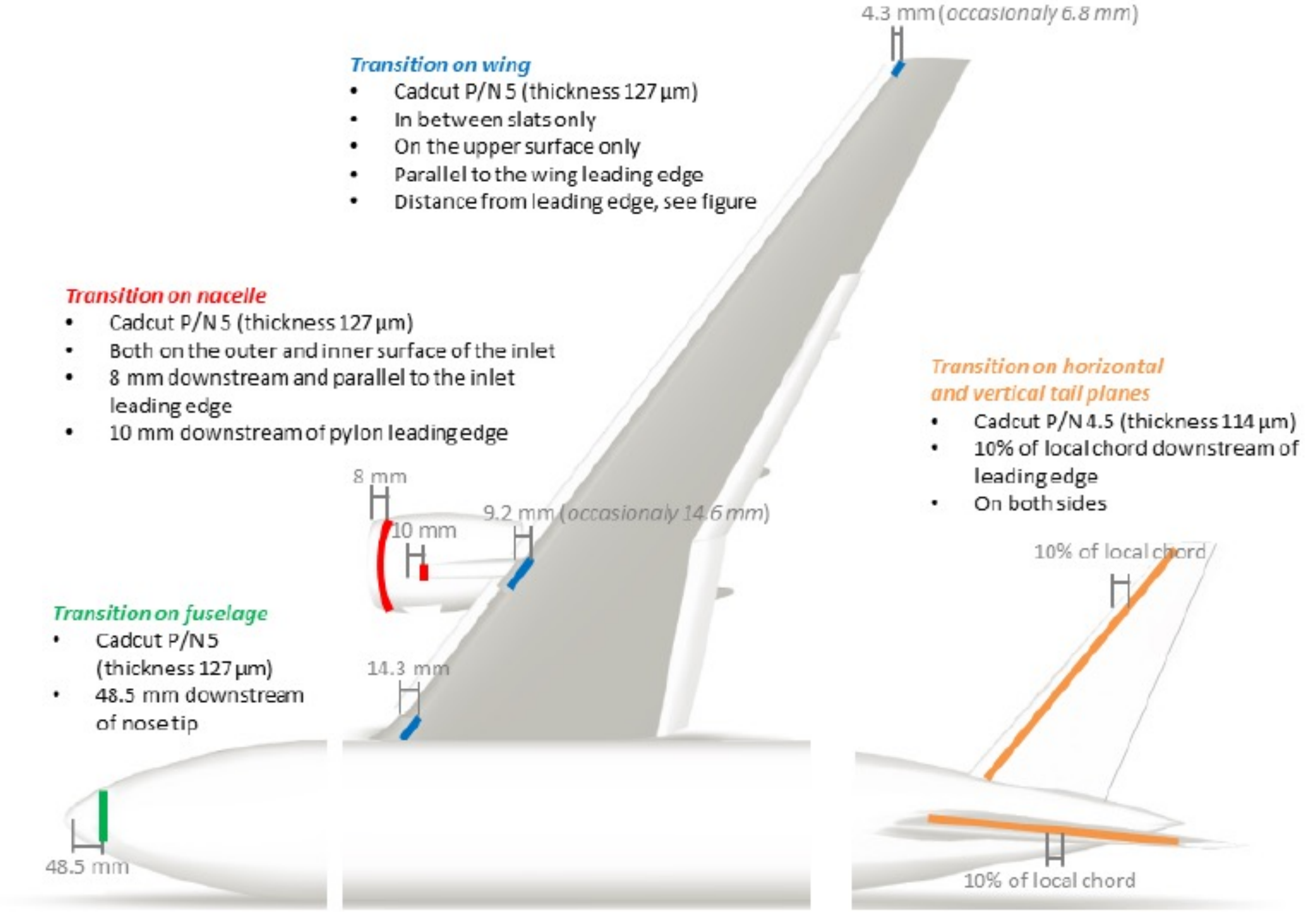
- Support Corrections: Derived experimentally by running combinations of single-strut and three-strut and directly measuring support interference



a. Setup for single strut interference

Tripping Scheme

- ONERA model features ‘cadcut’ strips (row of circular dots 2.5mm apart)
- Consistent with other ecosystem testing
- Quantities of interest within HLPW-5 are generally insensitive to tripping the models in the areas indicated



Transition on wing

- Cadcut P/N 5 (thickness 127 µm)
- In between slats only
- On the upper surface only
- Parallel to the wing leading edge
- Distance from leading edge, see figure

Transition on nacelle

- Cadcut P/N 5 (thickness 127 µm)
- Both on the outer and inner surface of the inlet
- 8 mm downstream and parallel to the inlet leading edge
- 10 mm downstream of pylon leading edge

Transition on horizontal and vertical tail planes

- Cadcut P/N 4.5 (thickness 114 µm)
- 10% of local chord downstream of leading edge
- On both sides

Transition on fuselage

- Cadcut P/N 5 (thickness 127 µm)
- 48.5 mm downstream of nose tip

Uncertainty Quantification

- AIAA-2024-3512 does a great job walking through how uncertainty is derived
- Well within bounds of industrial requirements, though perhaps our pencils are getting sharp enough that CFD needs to consider experimental uncertainty

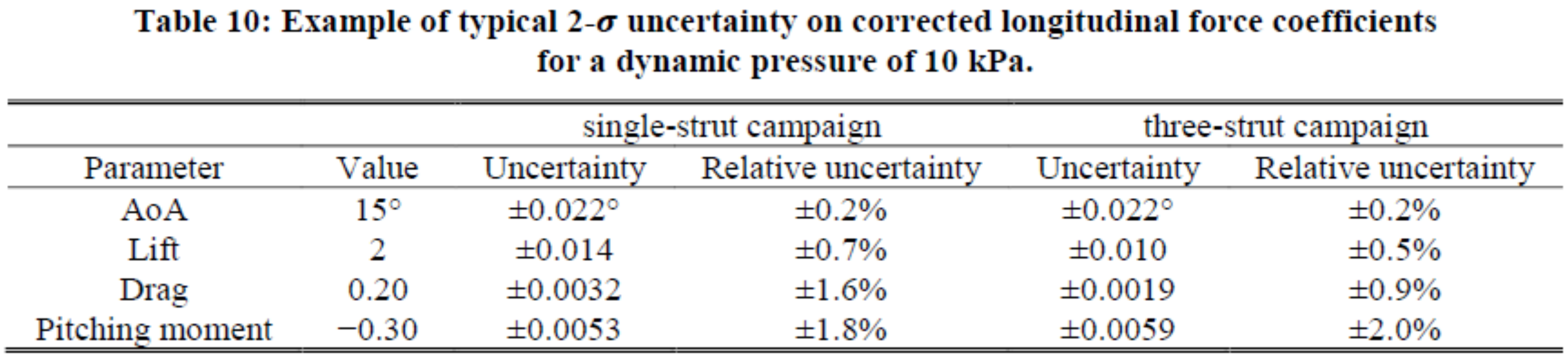


Table 10: Example of typical 2-σ uncertainty on corrected longitudinal force coefficients for a dynamic pressure of 10 kPa.

		single-strut campaign		three-strut campaign	
Parameter	Value	Uncertainty	Relative uncertainty	Uncertainty	Relative uncertainty
AoA	15°	±0.022°	±0.2%	±0.022°	±0.2%
Lift	2	±0.014	±0.7%	±0.010	±0.5%
Drag	0.20	±0.0032	±1.6%	±0.0019	±0.9%
Pitching moment	−0.30	±0.0053	±1.8%	±0.0059	±2.0%

Further Reading

Discussion of HLPW-4 Half Model Effects

1. Evans, A., Lacy, D., Smith, I., and Rivers, M., "Test Summary of the NASA Semi-Span High-Lift Common Research Model at the QinetiQ 5-Metre Low-Speed Wind Tunnel," AIAA paper 2020-2770, June 2020.
2. Lacy, D. S., and Clark, A. M., "Definition of Initial Landing and Takeoff Reference Configurations for the High Lift Common Research Model (CRM-HL)," AIAA Paper 2020-2771, June 2020.

ONERA Test Campaigns

1. Mouton, S., Charpentier, G., and Lorenski, A., "Testing the Full-Span High-Lift Common Research Model at the ONERA F1 Pressurized Low-Speed Wind Tunnel," AIAA Paper 2024-3512 August 2024
2. Mouton, S., Charpentier, G., and Lorenski, A., "Test Summary of the Full-Span High-Lift Common Research Model at the ONERA F1 Pressurized Low-Speed Wind Tunnel," AIAA Paper 2023-0823, January 2023.
3. Mouton, S., "Numerical Simulation of the Flow in the ONERA F1 Wind Tunnel," *Journal of Aircraft*, Vol. 60, No. 2, March – April 2023.
4. Mouton, S., *Data package for the 5th High-Lift Prediction Workshop*, Recherche Data Gouv, July 2024. doi:10.57745/B8VDHO

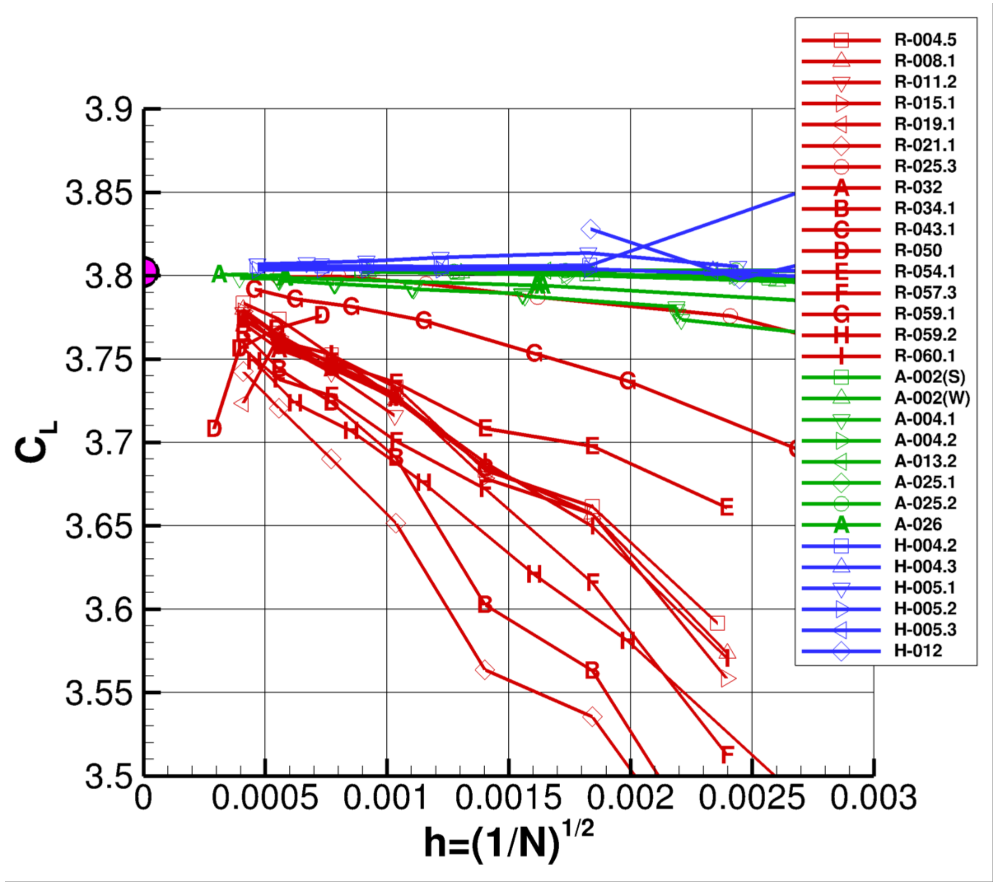
Backup Slides

Key Questions (KQs)

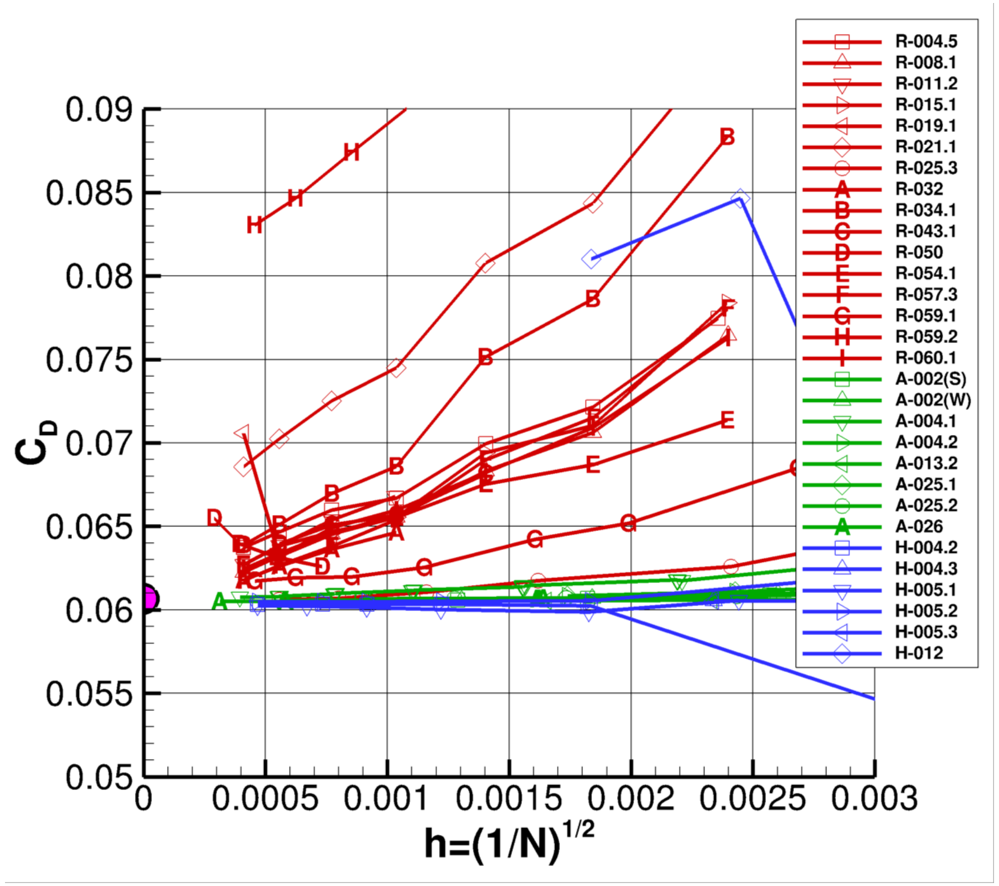
#	Key Question
1	What CFD solution methodology(ies) currently provides the **best/most-consistent approach** to predicting (a) increments due to flap deflection, and (b) maximum lift?
2	What are important **lessons learned** in high-lift CFD analysis explored in HLPW-4?
3	What **geometry and meshing best practices** are appropriate for high-lift CFD analysis for RANS, Wall Modeled LES, and Hybrid RANS/LES simulations?
4	What **roadblocks in geometry preparation and mesh generation** for CFD prevent analysts from creating geometry/meshes suitable for high-lift aerodynamics simulations in a turn-key, rapid manner?
5	What was the **impact/effectiveness of the existing test data** collected for the CRM-HL configuration in understanding high-lift flow physics? If not effective, what is needed?
6	What are the **significant remaining technical areas** that require additional focus in future workshops?

Test Case 3 – SA Model Verification Study: Forces

Lift Coefficient



Drag Coefficient



Pink dot indicates approximate trend of grid-converged solutions

R-019.1, R-050, R-059.2, and H-012 are conspicuously off from all the others

Summary

- Geometry preparation and fixed-grid meshing for high-lift flows is still difficult
  - How best to handle complex regions/junctions/pinch points
  - It is difficult to prescribe fixed-grid guidelines for different methodologies/codes/parts of lift curve
  - There are still practical size limitations (computing resources too limited for running)
- RANS is still problematic for predicting $C_{L,max}$ (separated flow)
  - Sometimes can get reasonable results (C_L) for the wrong reasons
  - Adapted mesh technology brings more consistency to the high-lift results
  - High-order is still an emerging technology for complex geometries like this
- Scale-resolving methods appear promising for predicting $C_{L,max}$
  - More work needed to establish best practice guidelines, achieve more consistency
- Additional measured data are needed to help validate CFD
  - Off-body boundary layer and vortex-structure data
  - Better wind-tunnel characterization
  - Influence of semi-span testing on $C_{L,max}$ characteristics (esp. inboard flowfield)