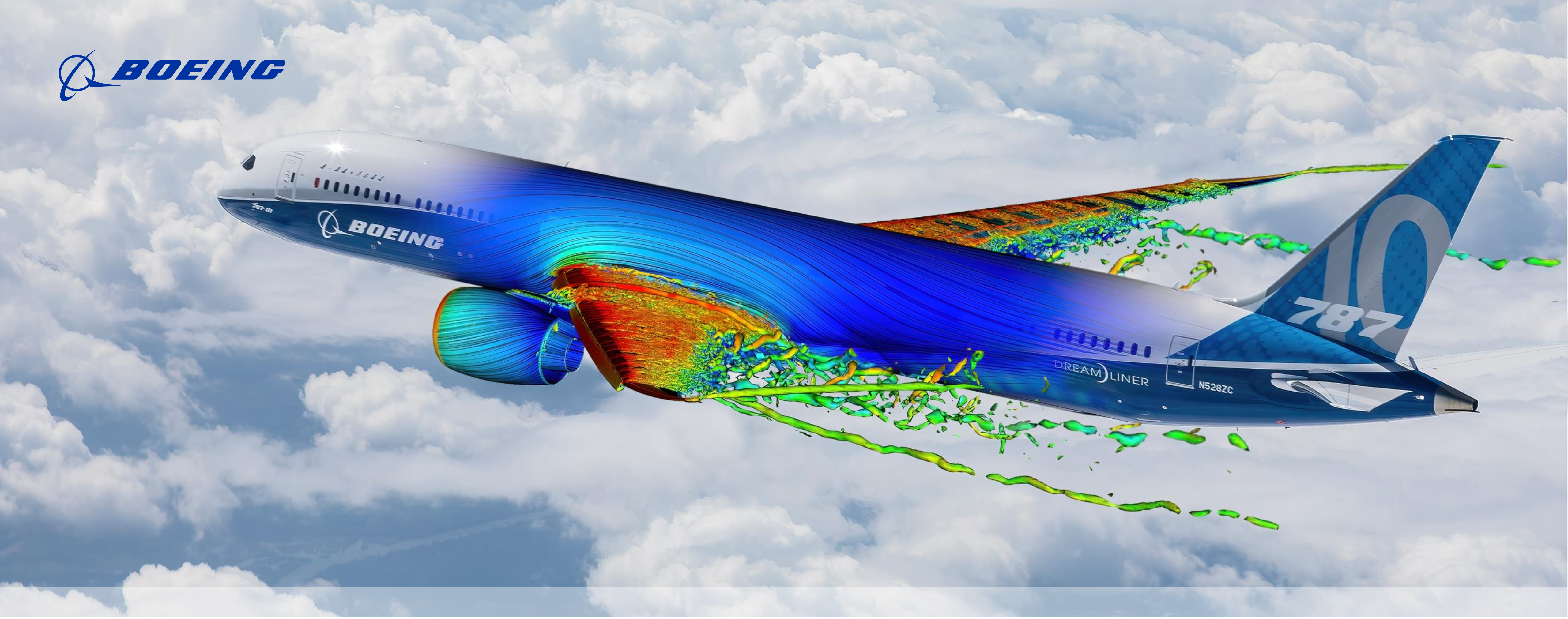


Computational Fluid Dynamics at the Edges of the Flight Envelope

Adam Clark – Boeing Commercial Airplanes – Flight Sciences

2025 OLCF User Meeting
August 5, 2025

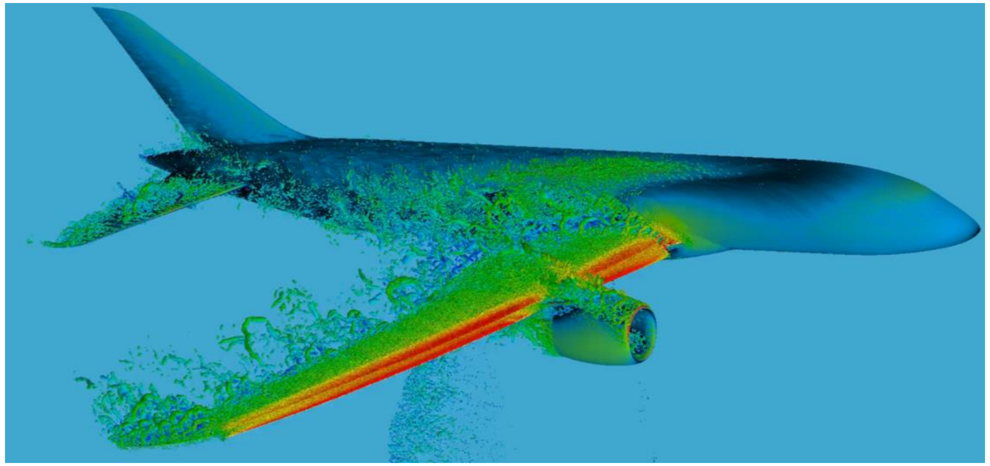
Data Sources for Aircraft Design

CFD

- Cheap to Moderately Expensive
- **Available as soon as there is geometry**
- Replaces WT or Flight in a few select areas
- Largely used for design guidance

Wind Tunnel

- **Moderately Expensive**
- **Slow** to start, but efficient
- Used for the bulk of low-speed design work



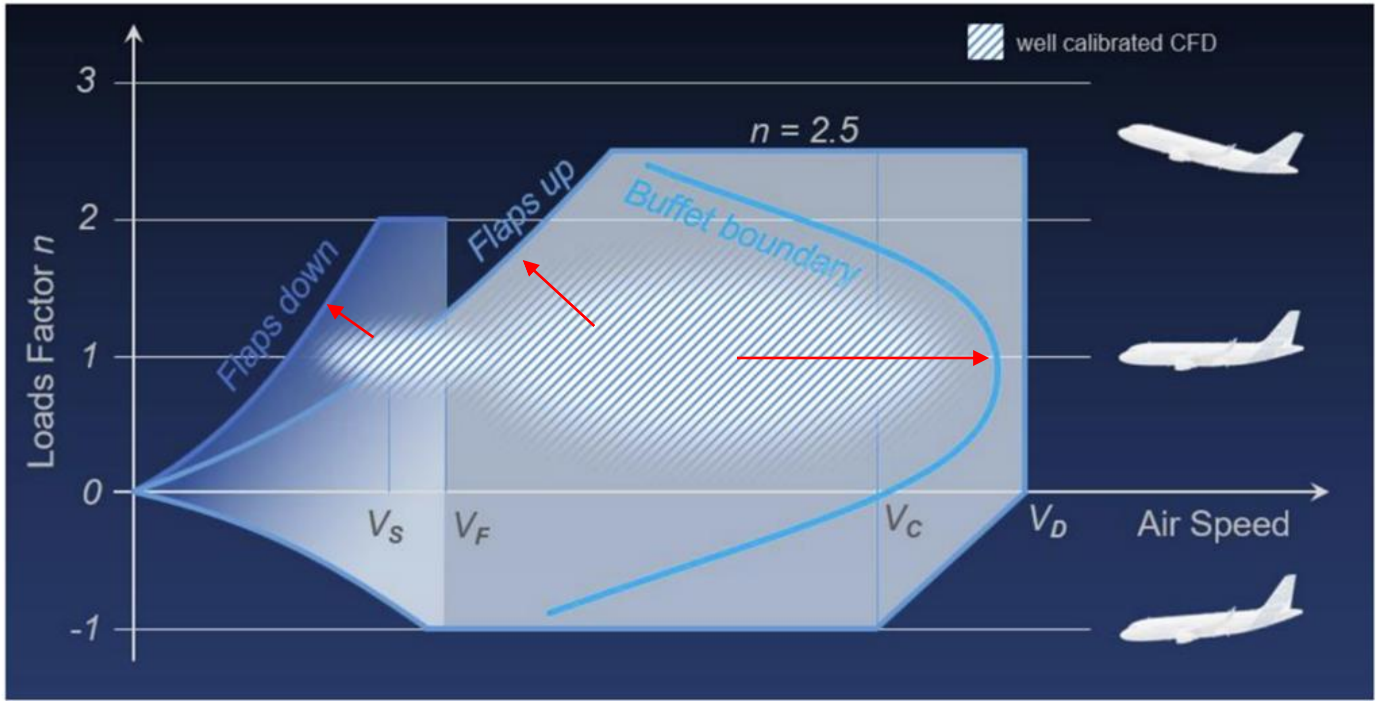
Flight Test

- **Very Expensive**
- **Only available late** in the development cycle
- Used for the bulk of low-speed certification work

Project Introduction

- Ambitious goals around **sustainable flight, lower emissions, and efficient air travel by 2050**

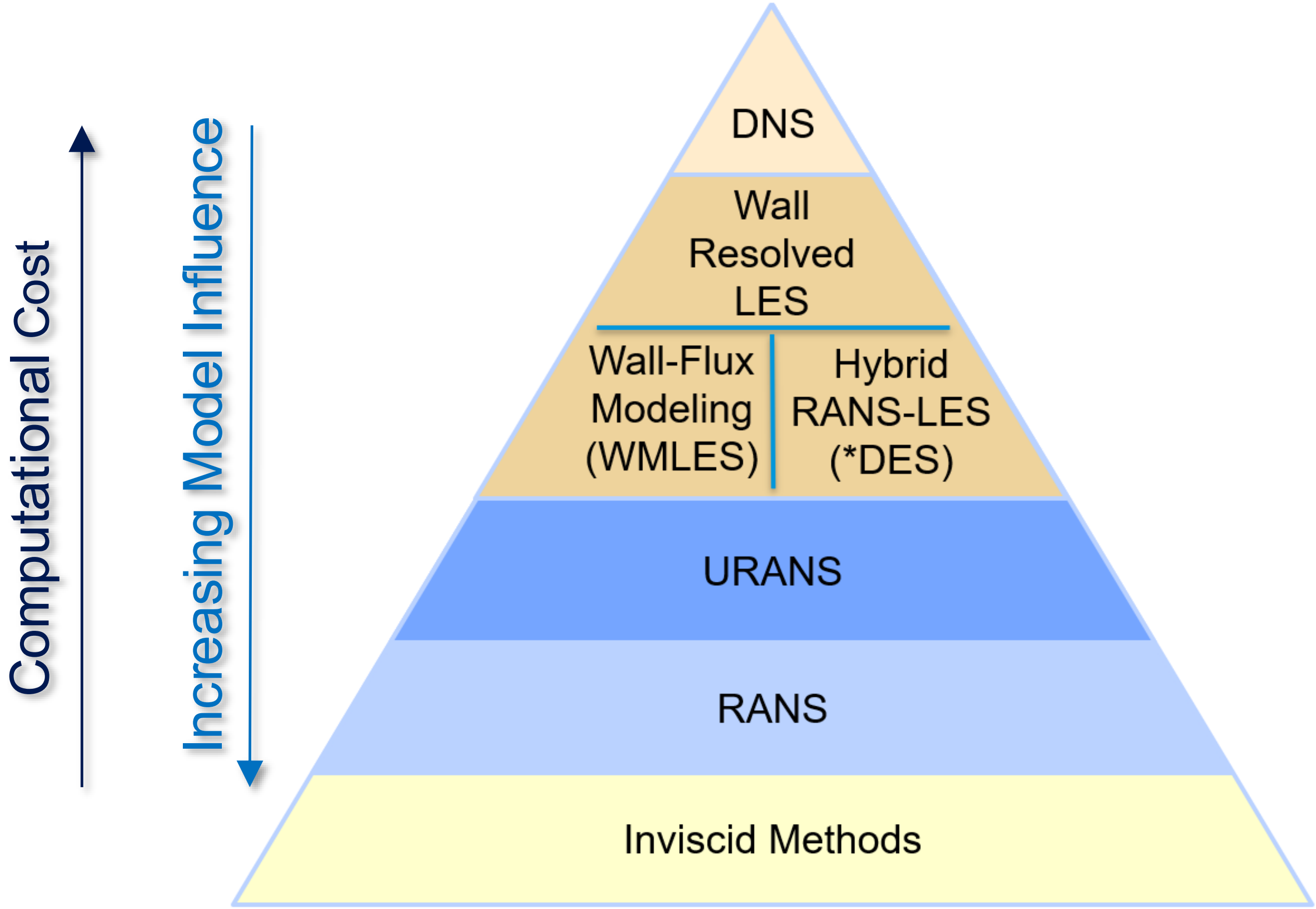
- Need **accurate, efficient, and robust** computational tools for aircraft design and analysis



- Current tools only calibrated in small portion of operating flight envelope

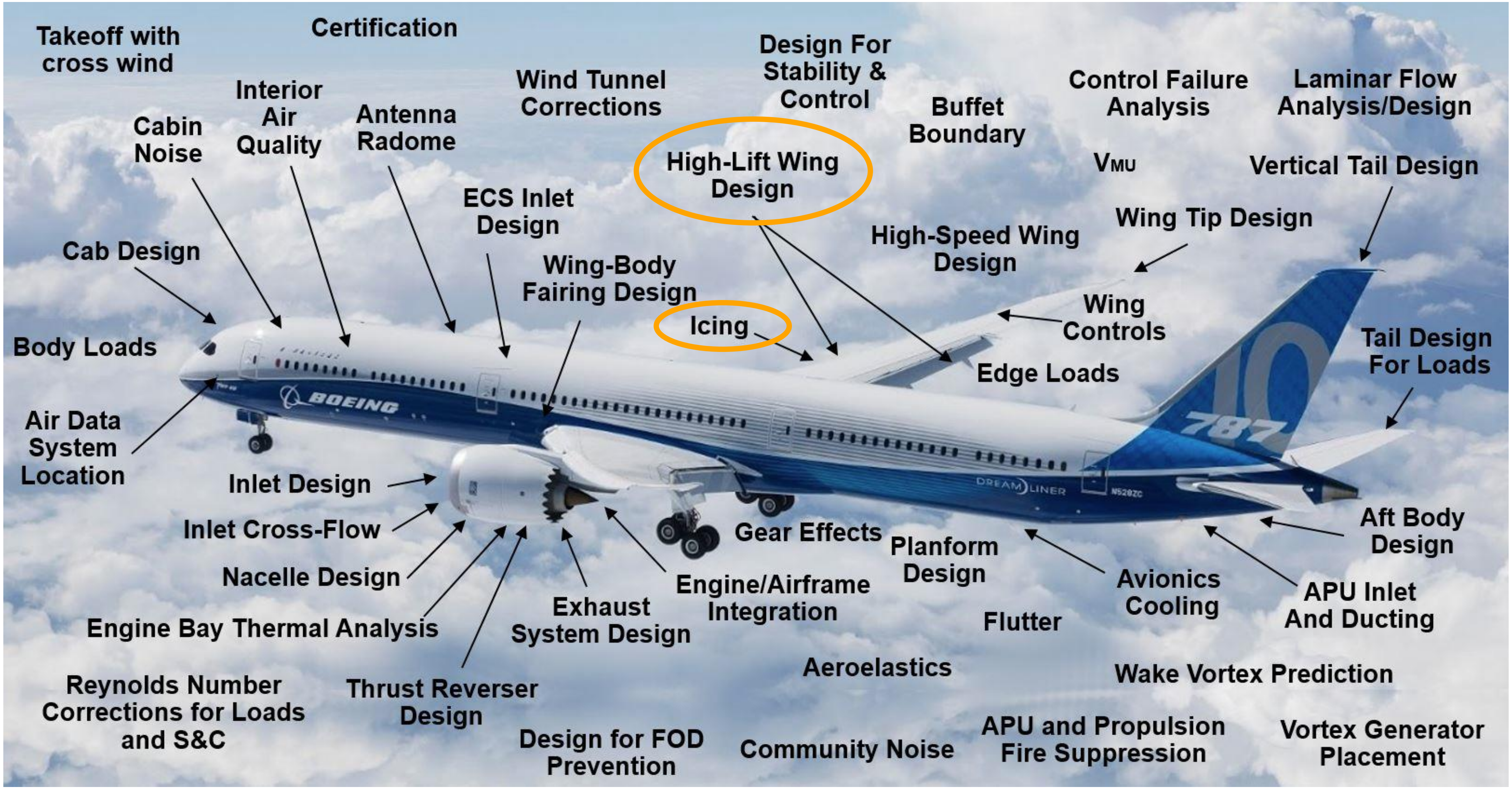
- **Systematic CFD validation of emerging CFD technology** needed to extend predictive capabilities to edges of flight envelope

Computational Fluid Dynamics Fidelity Pyramid



- Many aspects of aircraft design are **historically rooted in Inviscid Methods or RANS**
- Accuracy requirements continue to push us higher up the fidelity pyramid
- **Turbulent Scale-Resolving techniques** recently enabled by GPU computing
- Before using a simulation for an intended purpose, **models require extended validation**

CFD Use at Boeing



High Lift Common Research Model (CRM-HL Ecosystem)

- Boeing developed the high-lift variant of the **NASA Common Research Model (CRM-HL)** in 2016.
- **Fully open-source** aircraft configuration
- **Informal group of international partners ("ecosystem")** formed to acquire high-quality test data for CFD validation purposes using CRM-HL.
- Resulting ecosystem today has over **6 active wind-tunnel models** with 4 more in development
- Wide variety of open data exists with the **primary goal of validating CFD**

Timeline

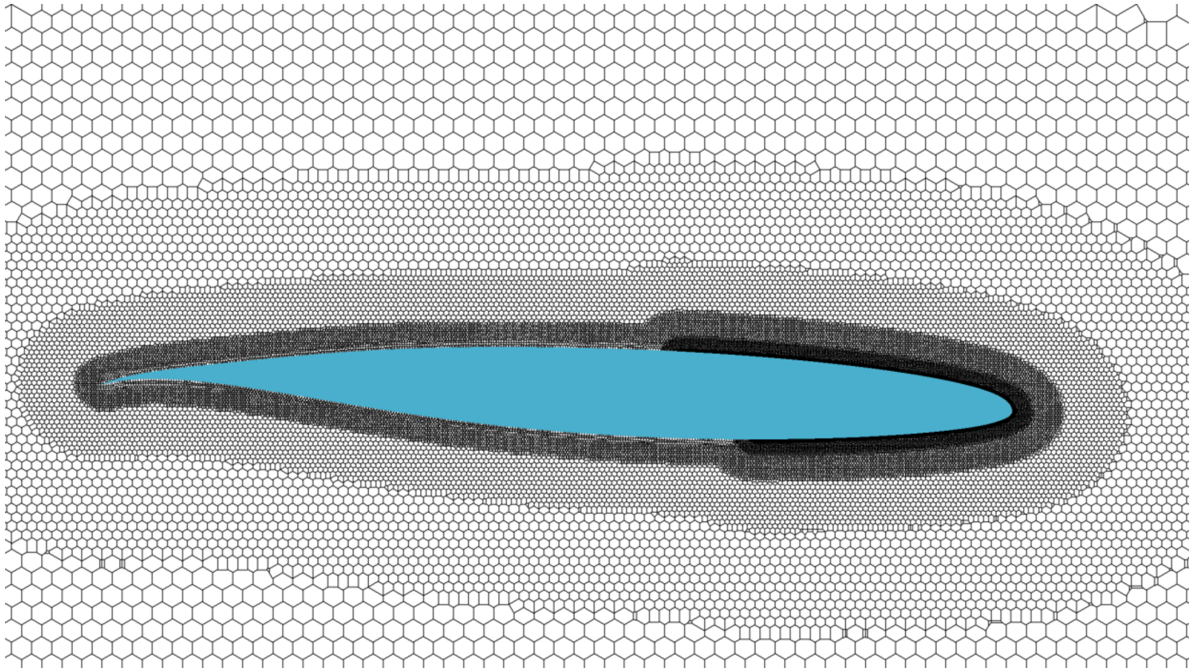
- Transition to scale resolving CFD has been happening in the last decade, but **accelerated with access to GPUs**
- Boeing maintains **close ties with Stanford** Center for Turbulence Research, where we have benefited from their DoE allocations
- Directors' Discretionary allocation on Summit, 2023
- INCITE grants awarded in 2024, 2025 (and applied for, 2026)
- Not just leaning on Frontier as additional compute, projects **contribute to global understanding**

1. Clark, A., Goc, K. A. (2026). "Aerodynamic Effects of Half Model Wind-Tunnel Testing of the High-Lift Common Research Model." *AIAA SciTech Forum 2026*. (Upcoming).
2. Goc, K. A., Agrawal, R., Moin, P., & Bose, S. T. (2025). "Studies of transonic aircraft flows and prediction of initial buffet onset using large-eddy simulations." *Journal of Aircraft*.
3. Goc, K. A., Clark, A. M., Bose, S. T., & Moin, P. (2024) "Wind Tunnel & Grid Resolution Effects in LES Calculations of the CRM-HL." *Journal of Aircraft*.

Wall Modeled LES for High-Lift

Compressible Flow Solver: Fidelity charLES, Cadence Design Systems

- Low dissipation numerics
- Second order finite volume
- RK3 time integration
- Equilibrium Wall Model
- Dynamic Smagorinsky Subgrid Scale Model



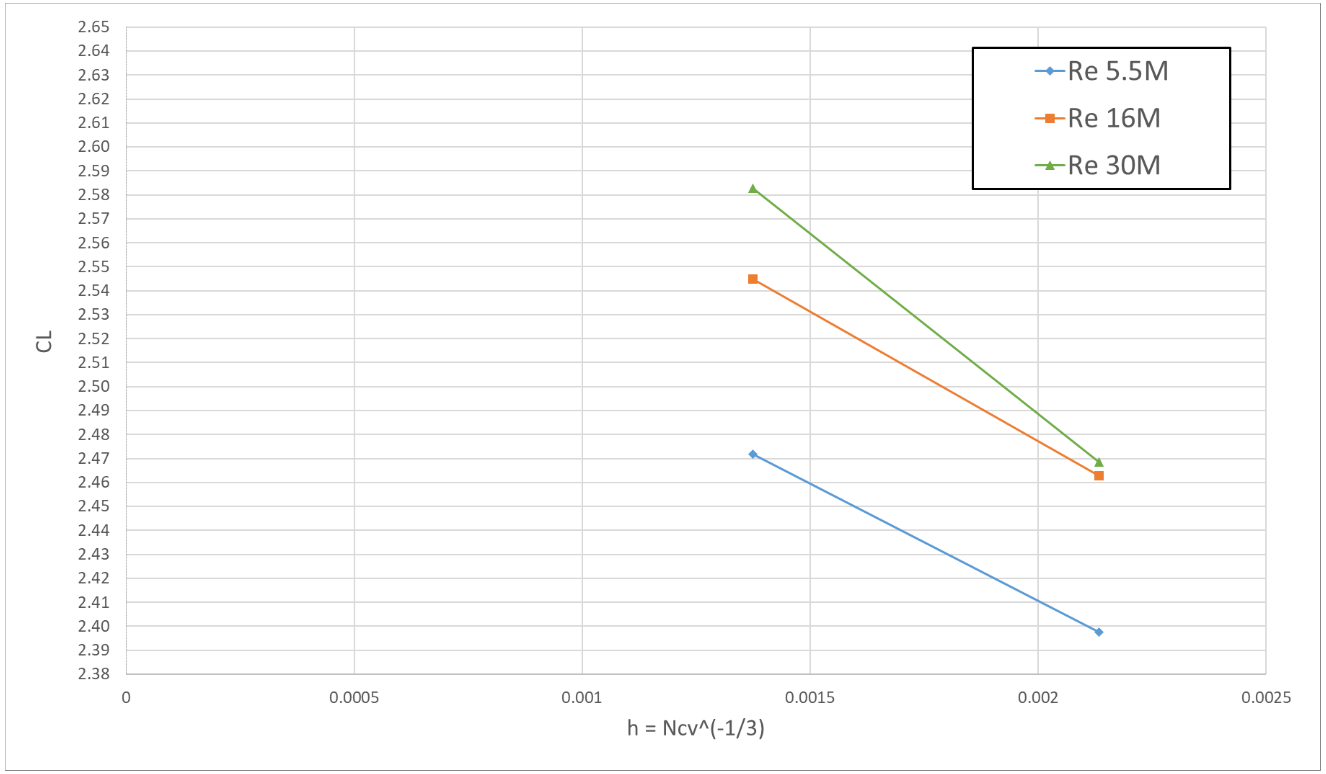
Grid Generation: Stitch

- Custom grid generator to build Voronoi grids using hexagonally close packed topology
- Initial grids are similar to those published by Goc, et al.[1]
    - Ballpark of 400 million cells, 400 node-hrs

[1] Wind Tunnel and Grid Resolution Effects in Large-Eddy Simulations of the High-Lift Common Research Model, Goc, K.A., Moin, P., Clark. A, Journal of Aircraft

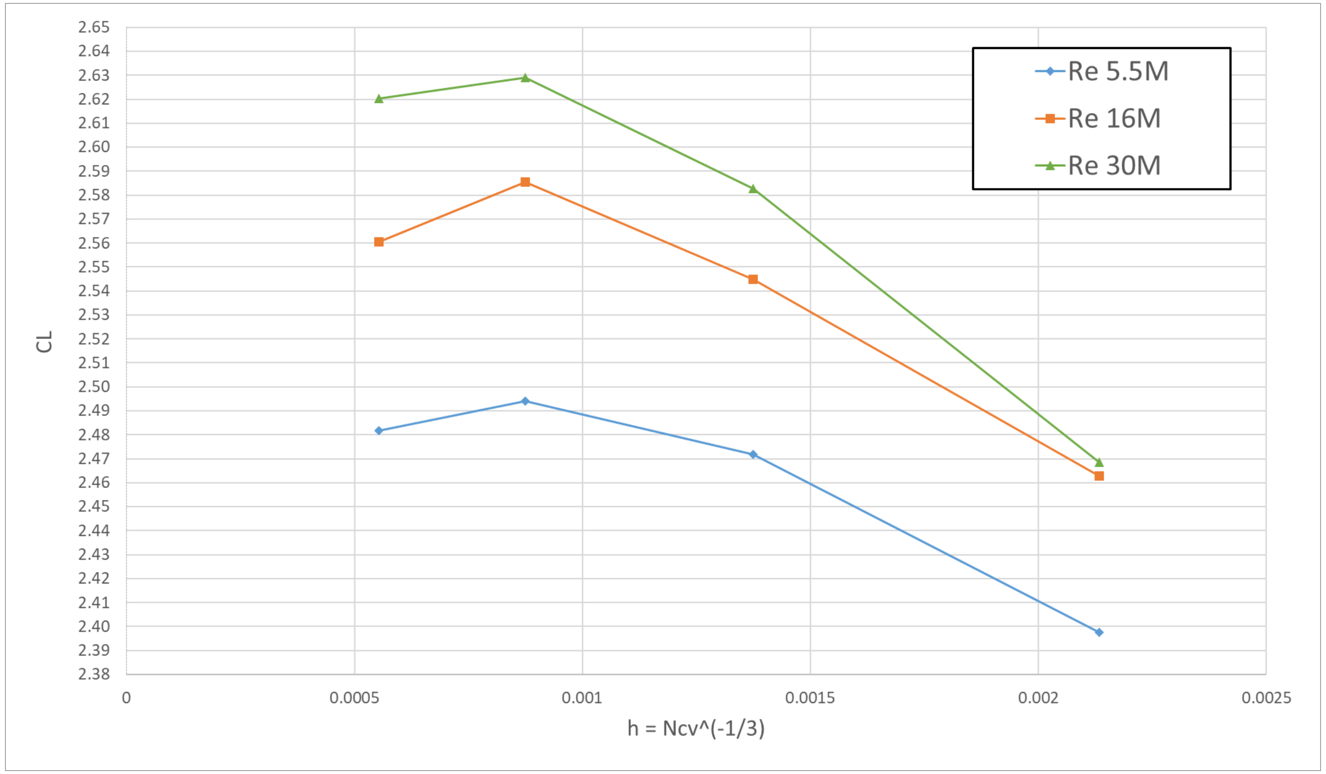
Wall Modeled LES for High-Lift

- Prior to work done under INCITE in 2024, best practice definitions were **limited** to what could be run on internal HPC resources
- Demonstrated reasonable accuracy, but **no confidence** in grid convergence, as that could not be demonstrated
- Nominal grids are ~ 400 M cells
- Nominal Runtimes on the order of **3 days** using on-prem hardware for a single condition



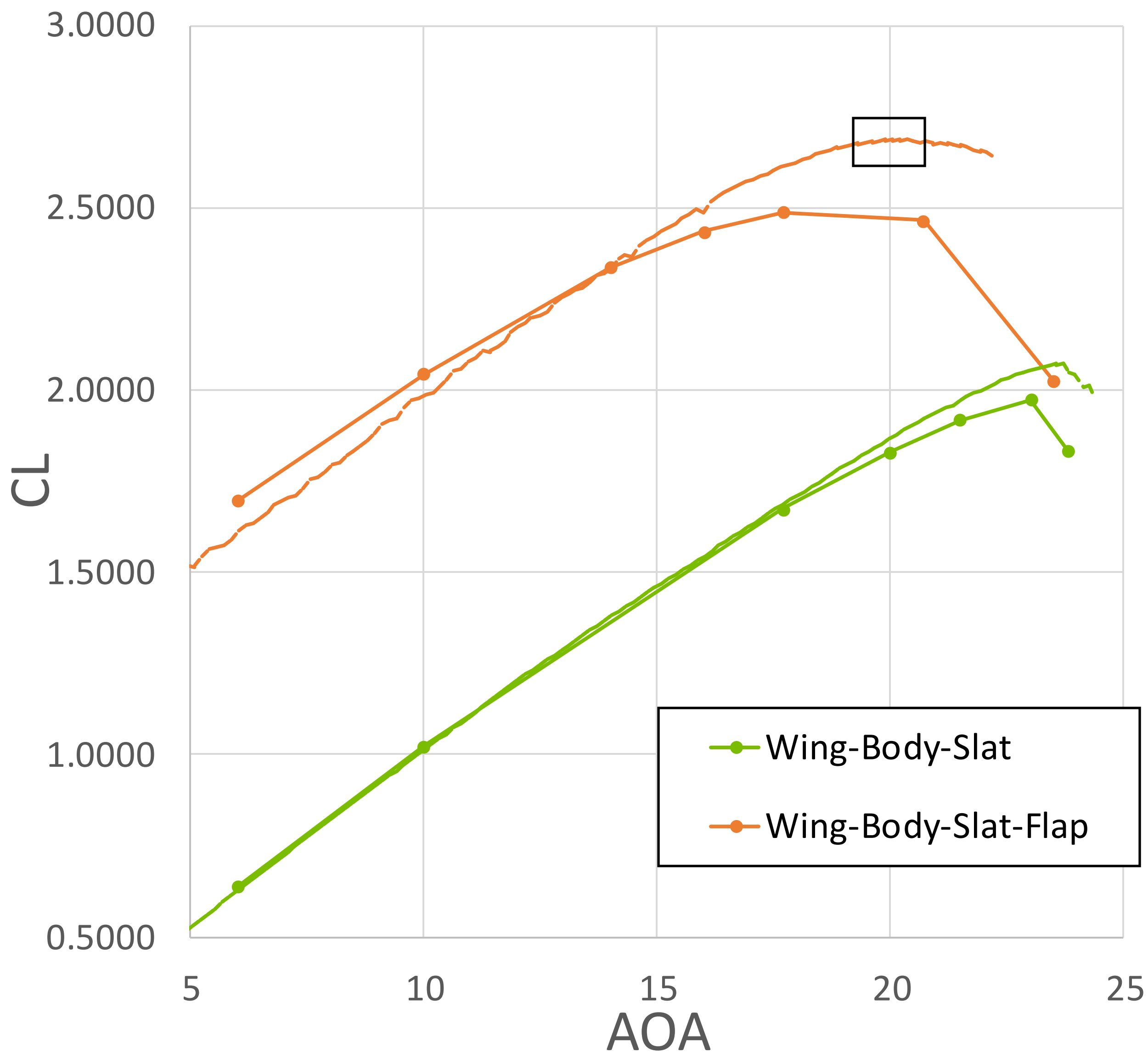
Wall Modeled LES for High-Lift

- Using Frontier, Grids can be pushed **considerably finer** than nominal to provide confidence in grid convergence trends
- Able to **demonstrate grid convergence** to within engineering tolerances (0.03)
- 0.03 in CL is equivalent to 1 kt of approach speed
- Meshes ~ 6 B cells
- Solutions require 25,000 node-hrs
- Would require **many months of compute** for a single solution on typical industrial scale resources



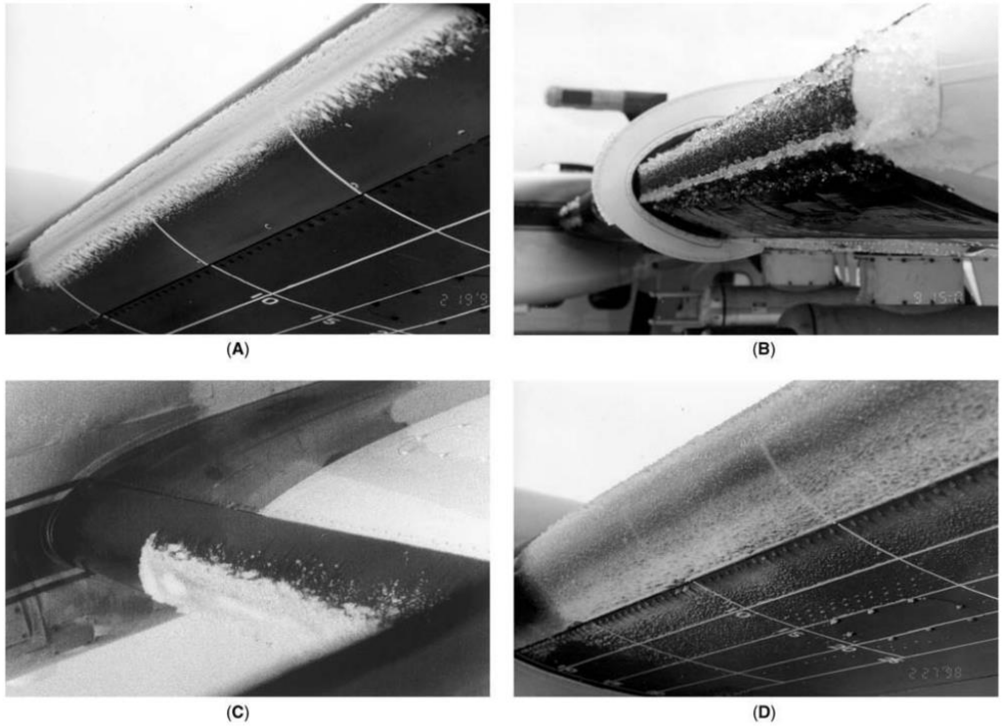
Wall Modeled LES for High-Lift

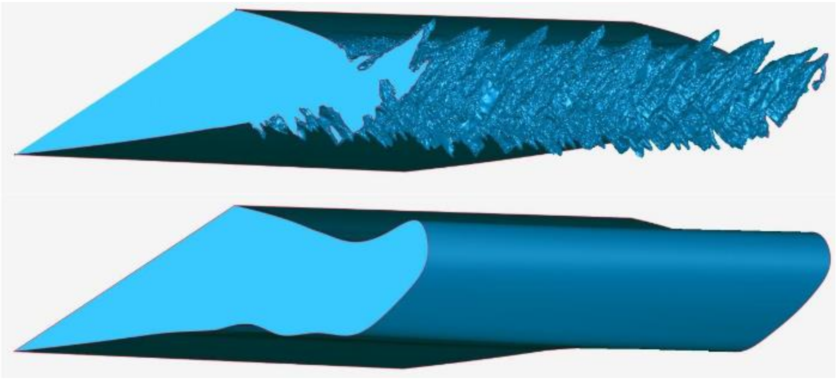
- Typically, we need to **understand trends throughout a lift curve**, not just at a single data point
- **Ensembles of simulations** required, instead of just a single very large simulation
- CRM-HL geometry allows for systematic evaluation of **trends associated with specific features**
- Results highlight **two key deficiencies**:
  - Leading Edge Transition
  - Flap separation under-prediction



Flight in Icing – Introduction

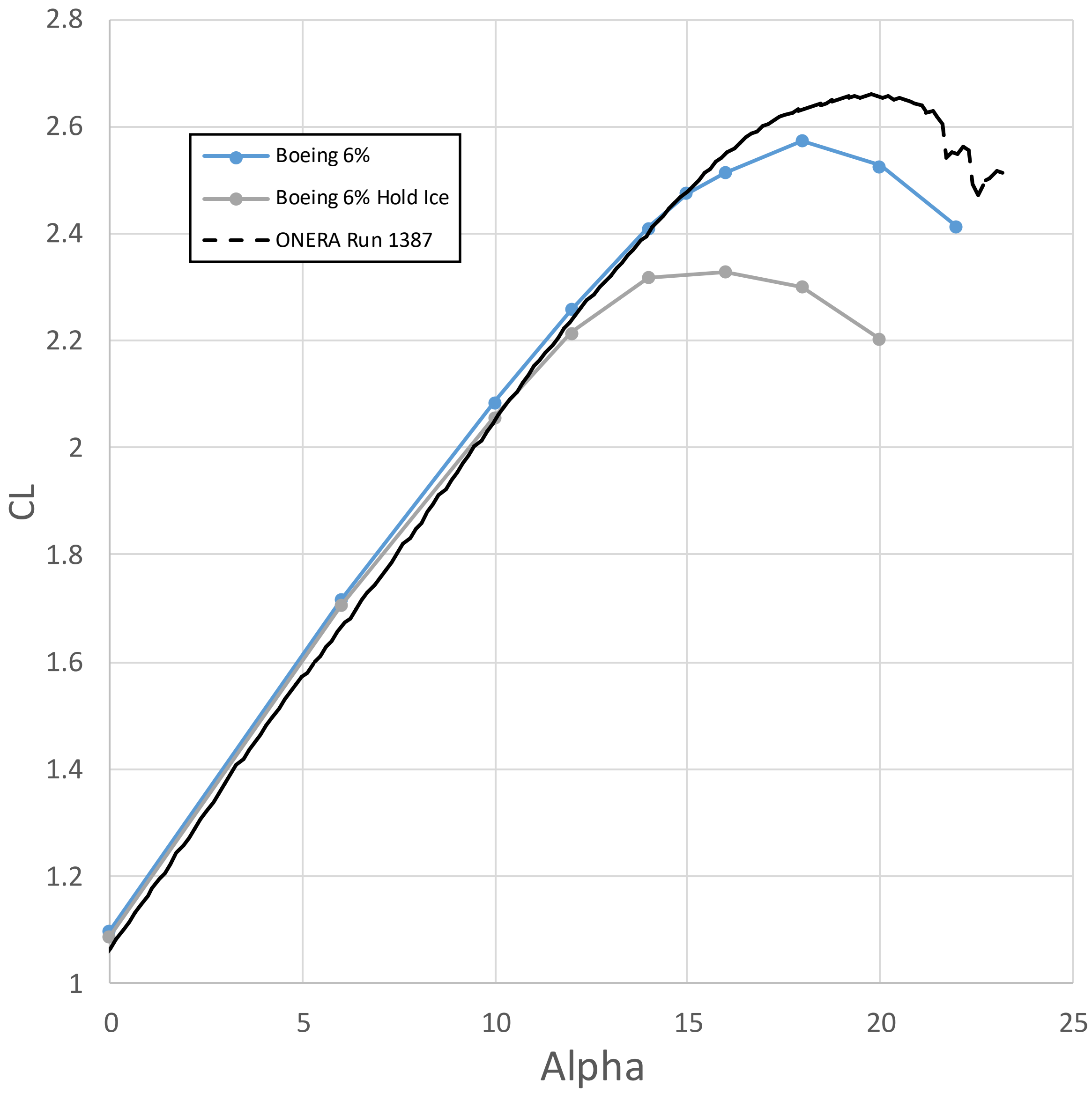
- Regulations around aircraft **icing is a continually evolving landscape**, driving more focus on icing earlier in the life cycle
- Beyond modeling requirements of a landing configuration, **roughness effects become critical**
- Roughness is typically **sub-grid scale** at the resolutions typically affordable, meaning not accurately captured
- Wall models exist to account for this, but **need validation**





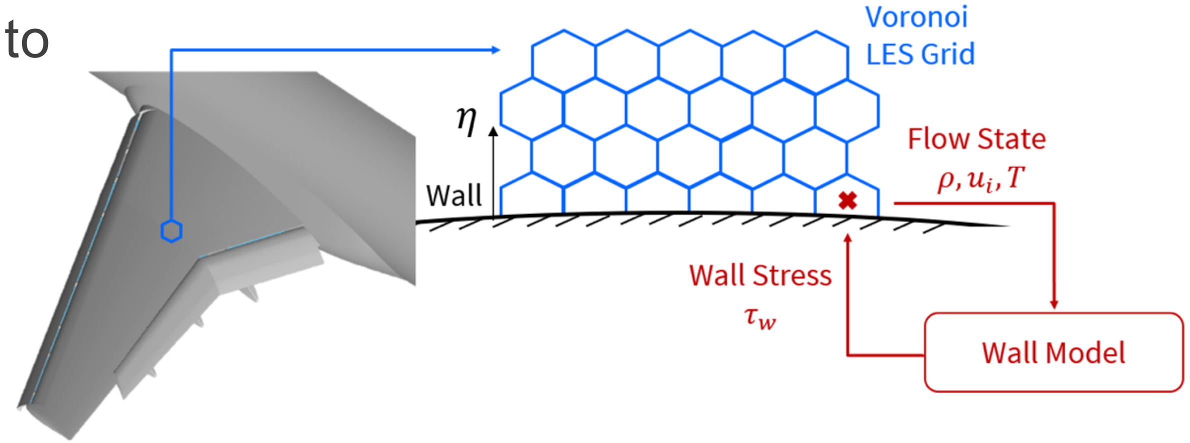
Flight in Icing – Computational Results

- Preliminary results suggest **large hold ice shapes** are reasonably captured, and have minimal sensitivity to grid
- Waiting on reliable experimental data to compare against
- Roughness effects appear minimally important here
- Further emphasis this year (ARD173) on **roughness-only shapes**, to understand predictive capability
- Will investigate **roughness wall models** on these cases



Next Steps: Advanced Turbulence Modeling Techniques

1) Non-equilibrium **Wall Model for Separated Flows**
   - Sensor based approach[1] to alert wall model to the presence of non-equilibrium effects



2) Transition Sensor for **Laminar and Transitional Flows**
   - Near-wall Turbulent Intensity sensor[2] to trigger laminar wall stress closure

3) Non-Boussinesq Subgrid-Scale Model
   - Generalized Dynamic Tensorial Coefficient Subgrid-Scale Model[3] allows for **misalignment of stress/strain** in subgrid model

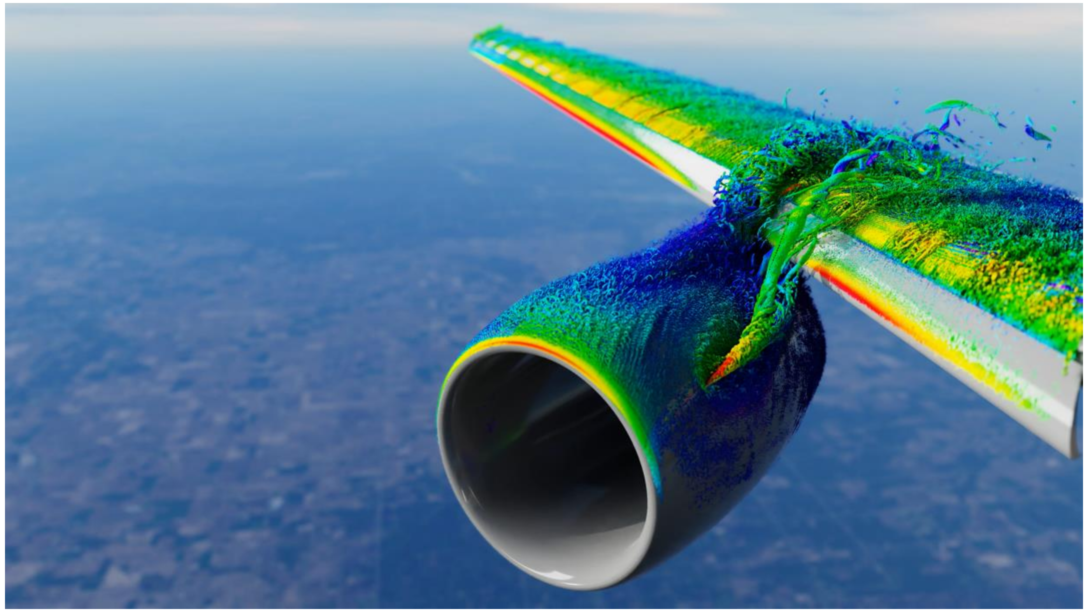
- Models developed through **close working relationship with Academia**, specifically Stanford Center for Turbulence Research

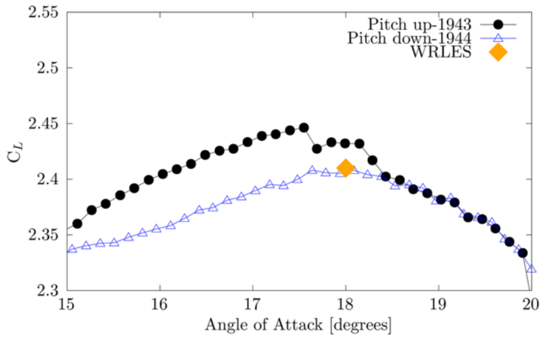
- If models are validated**, predictive accuracy can be increased dramatically**. Requires either experimental data or WRLES data to compare against

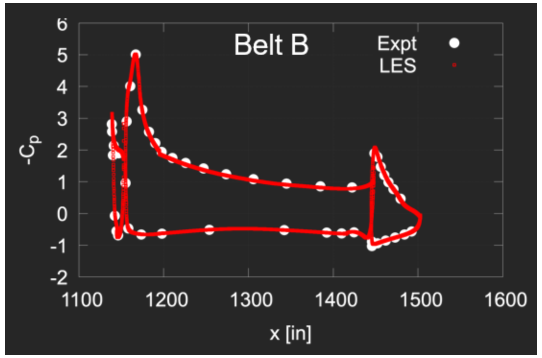
[1] R Agrawal, et al. *Nonequilibrium wall model for large eddy simulations of complex flows exhibiting turbulent smooth body separation*
[2] J Bodart, J Larsson. *Sensor-based computation of transitional flows using wall-modeled large eddy Simulation.*
[3] R Agrawal, et al. *Non-Boussinesq subgrid-scale model with dynamic tensorial coefficients.*

Next Steps: A Push towards Wall-Resolved

- Working closely with Cadence, the developers of CharLES, simulations at **Wall-Resolved resolutions are now achievable**
- **Demonstrated** at a low Reynolds number already
- Data from moderate Reynolds number simulations could be used to dive deeper into **understanding the true nature of turbulence**, and to validate advanced modelling techniques.
- Subject of follow-on INCITE proposal







Notes from an industry perspective

- Frontier utilization helped us **gain confidence** in our ability to run on AMD GPUs – helping shape future cluster architecture

- Working from within an **industry firewall** is cumbersome – Boeing HPC to Frontier access is generally blocked by Boeing
  - Jupyter hub has been very useful, in that it skirts the firewall
  - File transfer for large files is essentially restricted to web-based Jupyter access
  - Problem of our own making, but not unique in industry

- Close working partnership with Cadence helpful in **gaining additional efficiency**

Benefits of Working on Frontier

- Validation work done under INCITE projects on Frontier have **enabled** Boeing to utilize WMLES on a number of **real-world engineering problems** encountered relating to Commercial Aircraft development
- Insights gained from high resolution simulations are **driving academia** to develop pioneering modeling advancements through close collaboration.
    - This in turn enables accurate & tractable industrial-scale simulations
    - Boeing is in a unique position to be able to drive innovation in conjunction with external partners
- This work is **unachievable on typical industrial-scale HPC** architecture
- Future work is continuing to push the bounds to collect **first of its kind WRLES**, that can directly be used to validate advanced modeling techniques, necessary to increase the accuracy of simulations and enable further usage

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