A Grand Challenge for the Advancement of Numerical Prediction of High Lift Aerodynamics

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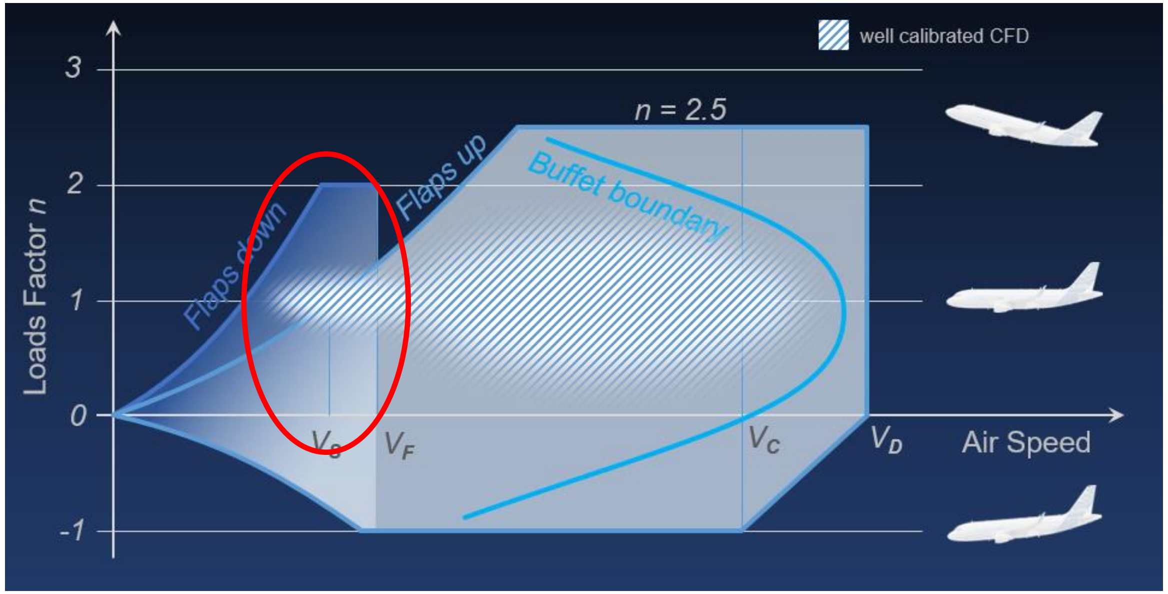
Outline

- **Introduction and Motivation**
- **High Lift Grand Challenge**
- **Integrated Roadmap**
- **Technology Focus Areas**
- **Community Collaboration Opportunities**
- **Summary**

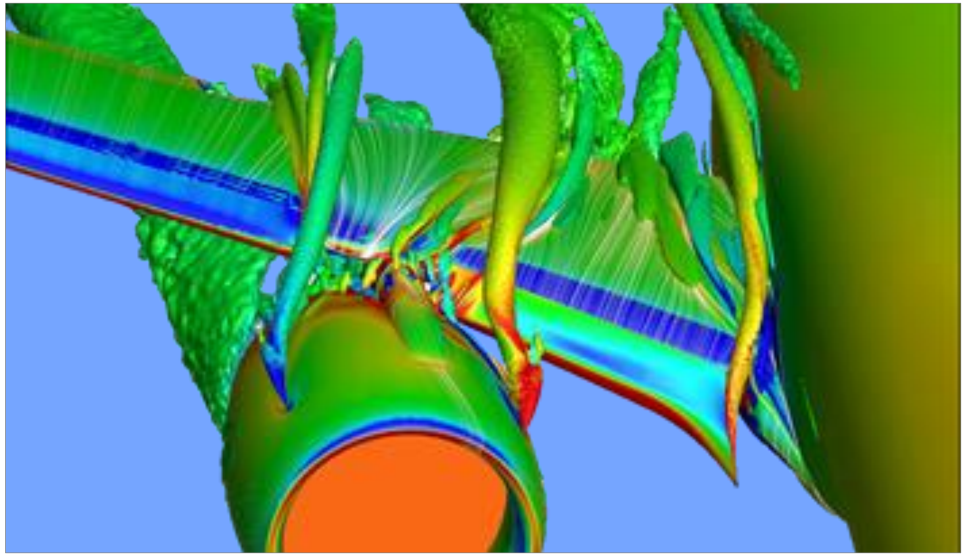
Airplane Certification Requires Accurate Simulation in the Full Flight Envelope



- CFD has been calibrated only in **relatively small regions of the operating envelope** where the external flow is well modeled by current RANS methods
  - High-speed cruise (aero design)
  - Low-speed at nominal attitude with moderate flap settings

> *"…In spite of considerable successes, reliable use of CFD has remained confined to a small but important region of the operating design space due to the inability of current methods to reliably predict turbulent-separated flows."*

— CFD Vision 2030 Report, 2014



Slotnick, J. and Heller, G., "Emerging Opportunities for Predictive CFD for Off-Design Commercial Airplane Flight Characteristics", 54th 3AF Conference, Paris 2019

- **Geometric complexity** — flight configuration, deforming surfaces
- **Complex flow physics** — multiple, interfering, and unsteady flow features (e.g. turbulent boundary layers, vortices, and wakes), engine power effects, maneuvering flight
- **Multi-disciplinary interactions** — aerodynamics, structures, controls, etc.
- **System response** — feedback driving control surfaces, pilot response, stick force, etc.
- Integration of total airplane response in **flight simulation**

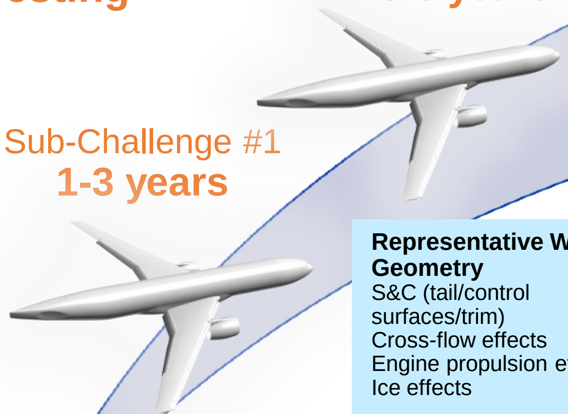
Advancing High Lift Aerodynamic Prediction
Series of Technical Challenges

Focus on key technical obstacles over specific time periods to make progress towards solving the grand challenge

Ground-Based Experimental Testing

Sub-Challenge #1
1-3 years

Sub-Challenge #2
3-6 years



Representative WT Geometry
Landing/TO configuration + nacelle/pylon
Re effects (atmospheric, pressurized, cryogenic environments)
Interactional flow physics (separation, vortex flow)
Static aeroelastics

CFD-generated data compared to WT data

Representative WT Geometry
S&C (tail/control surfaces/trim)
Cross-flow effects
Engine propulsion effects
Ice effects

CFD-generated data compared to WT data

Multi-Disciplinary Validation

Sub-Challenge #3
6-10+ years

Representative WT and/or Flight Vehicle
Sub-scale WT and/or flight geometry
WT to Flight Re
Quasi-steady flight
Basic maneuver
Dynamic structural response

CFD-generated data at specific points in the maneuver trajectory compared directly with flight-derived data

* Potential flight test vehicle configuration

Grand Challenge
15+ years

LOW-SPEED WIND-UP TURN

Generic Flight Vehicle
Full scale flight geometry
Flight Re
Dynamic, maneuvering flight
Dynamic structural/system response
Environmental effects
Engine power effects

Data from numerical simulation of the dynamic maneuver fed into CFD-based flight simulation, then proof-of-match between flight simulation and flight experience

High Lift Grand Challenge

Low-Speed Wind-Up Turn (WUT)

- Satisfies 14 CFR 25.143*
  - Airplane must be controllable with increasing load factor at constant speed
  - Metric: Gradient in “stick force” and/or “stick force/g” must be smooth
- Maneuver:
  - Low-speed (high-lift) configuration
  - Initiate banked turn at moderate altitude (up to 20K feet AGL) and Mach (~0.35-0.4)
  - Pull back on stick to increase angle-of-attack (and load factor). Maintain altitude to +/- 500 feet
  - Increase thrust to maintain speed (to within +/- 5 knots)
  - Longitudinal stick controls elevator (pitch), lateral stick controls aileron (roll). Rudder pedal not typically used.

Representative turn maneuver

https://www.businessinsider.com/watch-a-dreamliner-maneuver-like-a-fighter-jet-2014-7 (youtube/boeing)

***14 CFR 25.143(g).** When maneuvering at a constant airspeed or Mach number (up to VFC/MFC), the stick forces and the gradient of the stick force versus maneuvering load factor must lie within satisfactory limits. The stick forces must not be so great as to make excessive demands on the pilot's strength when maneuvering the airplane, and must not be so low that the airplane can easily be overstressed inadvertently. Changes of gradient that occur with changes of load factor must not cause undue difficulty in maintaining control of the airplane, and local gradients must not be so low as to result in a danger of over-controlling.

	2020	2025	2030	2035	2040

TRL: LOW (red), MEDIUM (yellow), HIGH (green)

Challenge Configurations

Technology Demonstrations

- Accurate prediction of $C_{L,max}$
- Flight-scale stall speed determination
- CFD quasi-steady flight-scale turn maneuver
- CFD-based flight-scale dynamic wind-up turn maneuver in simulator
- Unsteady, maneuvering flight, full engine simulation

Technology Milestones

- WMLES in production CFD tool
- Production AMR for steady-state CFD simulation
- Overnight turnaround for 1B cells with WMLES in production CFD tool
- Integrated aero-servo-elastics simulation
- Simulation for 1G turn with dynamic structural response in rotating frame
- Production AMR in unsteady CFD tool
- Automated in-situ mesh with adaptive control for unsteady flow simulation
- Integrated pilot response
- UQ-enabled MDA in unsteady flow framework
- Demonstration of Equivalent Level of Safety (ELOS)
- Real-time multi-fidelity database:1000 unsteady CFD simulations with complete UQ of all data sources

HPC
- PETA-SCALE
- EXA-SCALE
- ZETTA-SCALE

Physical Modeling
- Scale-resolving methods — Subgrid scale models, wall-modeled LES
- Wall-resolved LES
- Flow transition
- Surface roughness
- High fidelity propulsion models
- Ice shape generation
- Ice accretion
- Melt run-back

Geometry and Grid Generation
- Automated CAD/CFD/CSD integration
- Fixed grid — Parallel mesh generation, curved elements
- AMR (steady, h-p)
- AMR (h-p, time-dependent)
- In-situ (geometry/grid)

Algorithms
- Discretizations for scale resolving methods
- Multi-body dynamics
- Nonlinear structural dynamics
- Flutter Prediction
- Implicit solvers
- Efficient long-time integration
- Chaotic adjoint
- Disciplinary sensitivities and error estimation

Multidisciplinary Coupling
- Aero-servo-elastic coupling
- Pilot response / feedback
- Flight control augmentation
- High-fidelity propulsion effects
- Integrated icing simulations
- MDA coupling science/algorithms
- Coupled MD sensitivities/error estimation
- MDA frameworks/standards

Uncertainty Quantification
- Quantification of input uncertainties
- Mixed epistemic-aleatory uncertainty propagation
- Superior model-form uncertainty estimates
- Stochastic database/reduced order models

Technology Focus Areas

Physical Modeling	Geometry Grid Generation	Algorithms	Multidisciplinary Coupling	Uncertainty Quantification
▪ Separated flows (smooth body, corner, etc.) ▪ Flow transition (surface roughness) ▪ High fidelity propulsion modeling (engine-out, wind-milling) ▪ Icing physics and accretion, icing effects	▪ Accurate and automatic discretizations for CFD and CSD on flight geometry ▪ Traceable (Digital Thread) ▪ Large grid models and/or HO meshes ▪ Adaptive grid refinement (steady and unsteady flow)	▪ Efficient methods for scale-resolving simulations ▪ Nonlinear structural modeling ▪ Multi-body dynamics (moving control surfaces) ▪ Long time-integration schemes ▪ Sensitivity/error analysis for time-dependent, chaotic systems	▪ Accurate/Efficient/ Stable MD coupling algorithms ▪ Aero-servo-elastic coupling with quantified error estimates ▪ Integration of high-fidelity, time-dependent propulsion capabilities ▪ Icing effects ▪ MDA framework for tight coupling at high-fidelity, data standards ▪ System/pilot response	▪ Identify sources of uncertainty within each discipline ▪ Characterization ▪ UQ frameworks for MDA (uncertainty propagation and aggregation) ▪ Data fusion for flight simulation database with uncertainty

Community Collaboration Opportunities

Success requires **coordinated collaboration** within **engineering and simulation communities**

Courtesy DLR

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High Lift Common Research Model (CRM-HL) Ecosystem

- Enables CFD technology development and validation for a realistic and representative low-speed, high-lift configuration
- Publically-available, open platform encourages via international collaboration through pre-competitive R&D
- Allows consistent geometric models to be built and tested in multiple facilities at multiple Reynolds numbers

Prediction Workshops

- Many established within aerospace community – several (e.g. HLPW) directly address issues associated with the HLGC
- Technology validation
- Capability demonstration
- Pools resources, focuses attention, and addresses outstanding technical gaps, shortcomings, and obstacles

Future Activities

- “Digital Flight” workshops focusing on multi-disciplinary coupling strategies using building block approach
- MDA capability validation
  - Ground based testing in specialized facilities targeting (aero-structural, aero-controls)
  - Subscale flight testing (e.g. X-56A MUTT, etc.)
  - Full scale flight testing (e.g. NASA, DLR VicToria A320, etc.)

Summary

- Defined a **CFD Grand Challenge**, and related sub-problems, for the simulation of a commercial airplane WUT maneuver
- Identified the **principal computational challenges** involved in simulating the HLGC
- Created an **integrated roadmap** linking the challenge problems with appropriate technology milestones and demonstration cases, and with key CFD technology development in 5 areas: physical modeling, geometry and grid, algorithms, multidisciplinary coupling, and uncertainty quantification
- Highlighted the need for **collaboration within the aerospace engineering and simulation communities**, emphasizing the growing requirement for systematic multidisciplinary capability validation to prepare for the HLGC.