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

Jeffrey Slotnick
Technical Fellow, Boeing Commercial Airplanes

Dimitri Mavriplis
Professor, University of Wyoming

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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

- 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.

**Sub-Challenge #1**
1-3 years
- **Representative WT Geometry**
  - Landing/TO configuration + nacelle/pylon
  - Re effects (atmospheric, pressurized, cryogenic environments)
  - Interactions flow physics (separation, vortex flow)
  - Static aeroelastics
- **CFD-generated data compared to WT data**

**Sub-Challenge #2**
3-6 years
- **Ground-Based Experimental Testing**
  - Representative WT Geometry
  - S&C (tail/control surfaces/trim)
  - Cross-flow effects
  - Engine propulsion effects
  - Ice effects
  - CFD-generated data compared to WT data

**Sub-Challenge #3**
6-10+ years
- **Multi-Disciplinary Validation**
  - NASA TDT
  - NASA X-56A MUTF
  - NASA AISTAR
- **Representative WT and/or Flight Vehicle**
  - Sub-scale WT and/or flight geometry
  - CFD-generated data at specific points in the maneuver trajectory compared directly with flight-derived data

**Grand Challenge**
15+ years
- **Generic Flight Vehicle**
  - Full scale flight geometries
  - Flight Re
  - Dynamic, maneuvering flight
  - Dynamic structural/systems 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**

* Potential flight test vehicle configuration
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.

*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.

# Technology Focus Areas

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

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

### 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.