Progress towards CFD Vision 2030:

An Industrial Perspective for Aerospace Applications

Air & Space Vehicles

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AIAA Aviation – CFD2030 Special Session
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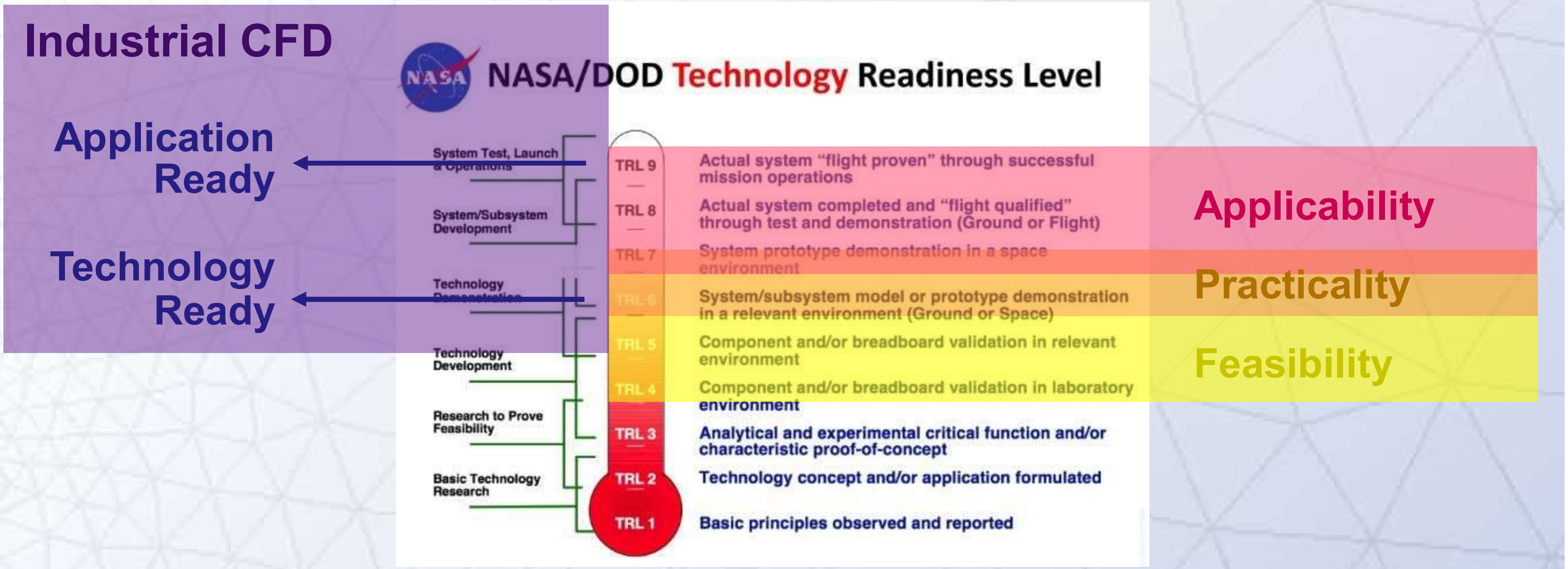
Outline

- What is “Industrial CFD”?
- CFD Roadmap/Requirements
- Progress for Industrial Applications
- Integrated Assessment
- Emerging Opportunities

What is “Industrial CFD”?



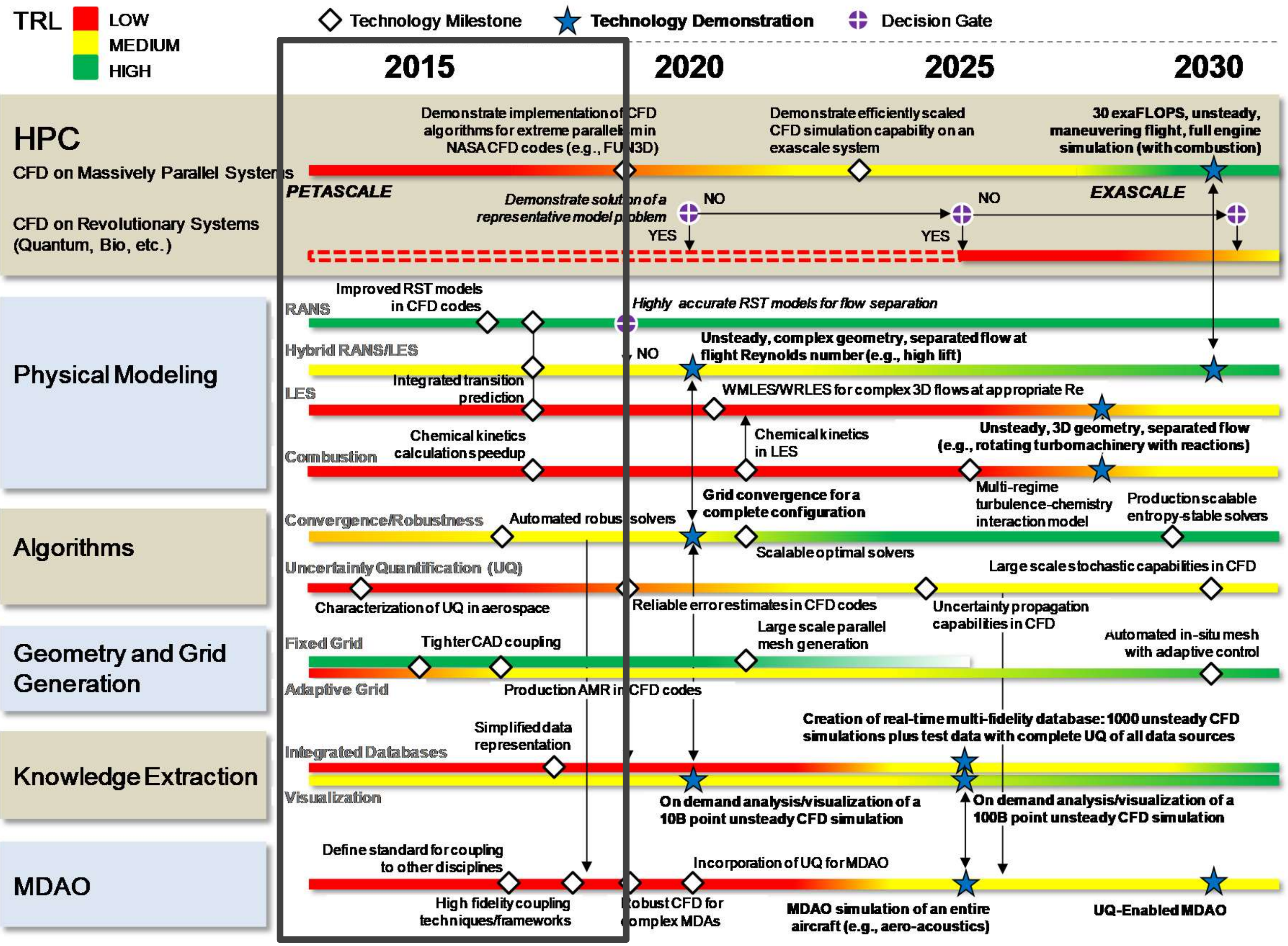
NASA/DOD Technology Readiness Level

System Test, Launch & Operations	TRL 9	Actual system “flight proven” through successful mission operations
System/Subsystem Development	TRL 8	Actual system completed and “flight qualified” through test and demonstration (Ground or Flight)
	TRL 7	System prototype demonstration in a space environment
Technology Demonstration	TRL 6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
Technology Development	TRL 5	Component and/or breadboard validation in relevant environment
	TRL 4	Component and/or breadboard validation in laboratory environment
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
Basic Technology Research	TRL 2	Technology concept and/or application formulated
	TRL 1	Basic principles observed and reported

- **Essential ingredients:**
    - Realistic (production/prototype) configuration geometry
    - Complex, interactional flow physics
    - Computational results support engineering decisions for product development
- **Attributes*:**
    - Robustness, Reliability, Accuracy, Efficiency, Affordability

* **“Emerging Opportunities for Predictive CFD for Off-Design Commercial Airplane Flight Characteristics”**
Boeing/Airbus, 54th 3AF Conference Paris, 2019

CFD Vision 2030 Roadmap



TRL 🟥 LOW 🟨 MEDIUM 🟩 HIGH

◇ Technology Milestone ★ **Technology Demonstration** ⊕ Decision Gate

2015 2020 2025 2030

HPC

CFD on Massively Parallel Systems

CFD on Revolutionary Systems (Quantum, Bio, etc.)

Demonstrate implementation of CFD algorithms for extreme parallel m in NASA CFD codes (e.g., FU 3D)

Demonstrate efficiently scaled CFD simulation capability on an exascale system

30 exaFLOPS, unsteady, maneuvering flight, full engine simulation (with combustion)

PETASCALE

EXASCALE

Demonstrate solut on of a representative model p oblem

NO

YES

NO

YES

Physical Modeling

RANS

Improved RST models in CFD codes

Highly accurate RST models for flow separation

Hybrid RANS/LES

NO

Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)

LES

Integrated transition prediction

WMLES/WRLES for complex 3D flows at appropriate Re

Combustion

Chemical kinetics calculation speedup

Chemical kinetics in LES

Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)

Multi-regime turbulence-chemistry interaction model

Algorithms

Convergence/Robustness

Automated robus solvers

Grid convergence for a complete configuration

Scalable optimal solvers

Production scalable entropy-stable solvers

Uncertainty Quantification (UQ)

Characterization of UQ in aerospace

Reliable error estimates in CFD codes

Uncertainty propagation capabilities in CFD

Large scale stochastic capabilities in CFD

Geometry and Grid Generation

Fixed Grid

Tighter CAD coupling

Large scale parallel mesh generation

Automated in-situ mesh with adaptive control

Adaptive Grid

Production AMR in CFD codes

Knowledge Extraction

Integrated Databases

Simplified data representation

Creation of real-time multi-fidelity database: 1000 unsteady CFD simulations plus test data with complete UQ of all data sources

Visualization

On demand analysis/visualization of a 10B point unsteady CFD simulation

On demand analysis/visualization of a 100B point unsteady CFD simulation

MDAO

Define standard for coupling to other disciplines

High fidelity coupling techniques/frameworks

obust CFD for omplex MDAs

Incorporation of UQ for MDAO

MDAO simulation of an entire aircraft (e.g., aero-acoustics)

UQ-Enabled MDAO

CFD Requirements

Solution Accuracy

MDAO
(Full Flight Envelope)

- Predict performance/efficiency/noise/loads/emissions characteristics with certifiable accuracy over the complete flight envelope for both the airframe and all components of the propulsion system. Certifiable accuracy refers to the quality of the numerical results that would be acceptable for product design and certification (such as FAA certification of engine systems for icing and bird strike).
- Calculate time-dependent flows including simulations of accelerating vehicle flowfields, on dynamically deforming geometries, and with relative body motion including possible changes in topology (e.g., real-time high-lift system deployment, aeroelastic wing response, rotor/airframe interaction, store separation, etc.).

Knowledge Extraction

- When needed, be able to intelligently combine and use models of various fidelities.

Physical Modeling

- Be applicable to all Mach number ranges from freestream static conditions to subsonic to hypersonic flows, from low to high Reynolds numbers.
- Routinely simulate flows with all types of flow separation (e.g., transonic buffet, etc.) and other complex flow physics (e.g., chemically reacting flows, etc.)
- Routinely model laminar to turbulent flow transition of all modalities (T-S waves, cross-flow, Görtler, and 2nd-mode instabilities; natural and bypass) including effects of surface roughness.

Algorithms
(UQ)

- Enable quantification of various error sources including discretization (both spatial and temporal), algebraic and modeling errors.
- Provide automated capability for simulating to overall error tolerances.
- Provide (as standard output) full quantification of numerical errors, sensitivity information, and computational uncertainty for specified quantities.

Technology Robustness

Geometry and
Grid Generation
(Automated CFD Processes)

- Employ an integrated, fully automated CFD process from pre- to post-processing, including CAD incorporation, grid generation, and solution adaptive techniques for entire vehicle and propulsion simulations with appropriate user controls.
- Enable CAD-based design through improved coupling of/use of CAD modeling throughout the entire analysis and design optimization process.
- Enable robust simulation capability across all flow regimes, in particular due to nonlinear and transient effects, without the need for users to perform application-specific tuning.
- Provide fault tolerant simulation execution, particularly for use with aerodynamic optimization workflows.
- Encapsulate CFD developer/modeler knowledge for use in identifying limits of model applicability and appropriate use of solver parameters.
- Provide an intuitive parameter free interface enabling optimal use for a wide range of problems while minimizing the required user learning curve.

Algorithms (UQ)

- Accept both epistemic and aleatory probabilistic inputs, return suitable outputs, and provide strategies that refine and adapt in both physical and probability space to reduce and balance uncertainty due to both numerical error and parametric variability.

HPC

- Operate across multi-platform computing environments. This refers to the need to link together many separate analysis and design tools that reside on different platforms (when it is often not practical to convert or port these tools to one system).

Knowledge Extraction
(Data Fusion)

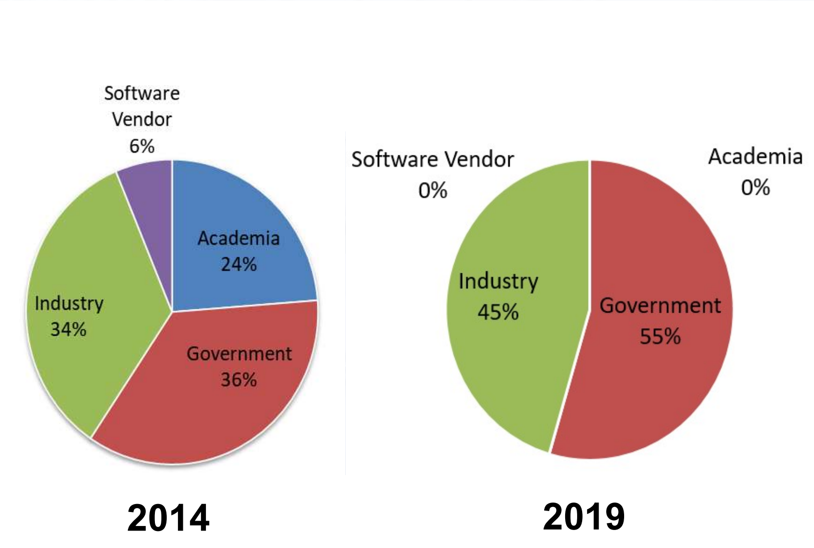
- Be seamlessly integrated into visualization and data mining techniques that make full, efficient use of results from time-resolved, physically complex flowfield simulations.
- Provide flexible linkages with ground-based and flight test datasets to build integrated aerodynamic databases with prescribed confidence intervals throughout the database.
- Enable the efficient construction of large aerodynamic databases with prescribed confidence intervals throughout the database.

MDAO
(Full Flight Envelope)

- Enable the reduction or elimination of complex physical testing (e.g., vehicle dynamics) through the use of novel statistical approaches (e.g. system identification) to provide dynamic simulation inputs.
- Enable coupling with all other disciplines in computational mechanics (e.g., structures, thermal, electromagnetic, etc.) and with flight control system simulations for steady and time dependent trim and maneuver simulations.

2019 Survey

- Informal set of questions posed **to gauge technical progress for industrial applications**
- Much smaller, targeted subset of CFD community experts that are either **CFD analysts in industry or have working knowledge of industrial CFD applications**
- **Repeated, common themes** suggest **general trends**



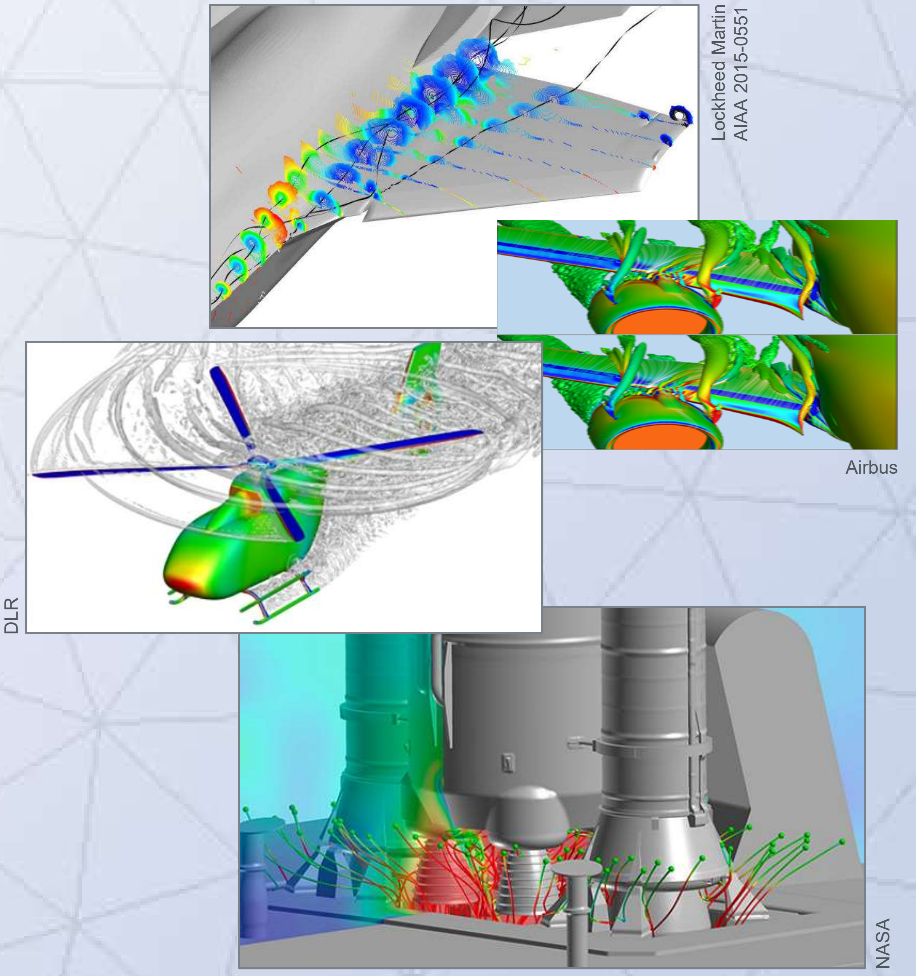
Questions

1. Remaining **technical challenges**
2. New/improved CFD **tools/processes/capabilities**
3. **No Improvement / Impediments**
4. **Computing** capability
5. **Multi-physics / multi-disciplinary** coupling
6. **Impact** of the **CFD Vision 2030 Report**

Remaining Technical Challenges

What remains the most ***challenging technical problem*** *that you would like to solve using CFD, if you could devote* ***sufficient resources (time, people, budget)*** *to it, and why?*

- Prediction of aerodynamic performance at the **edges of the vehicle operating envelope**
- Routine prediction of **complex flow physics** (flow separation, shock waves, vortex/wake interactions, etc.)
- Answer to **"How good is the CFD analysis?"**
- Labor effort in the **CFD workflow** for complex geometry



Lockheed Martin AIAA 2015-0551

Airbus

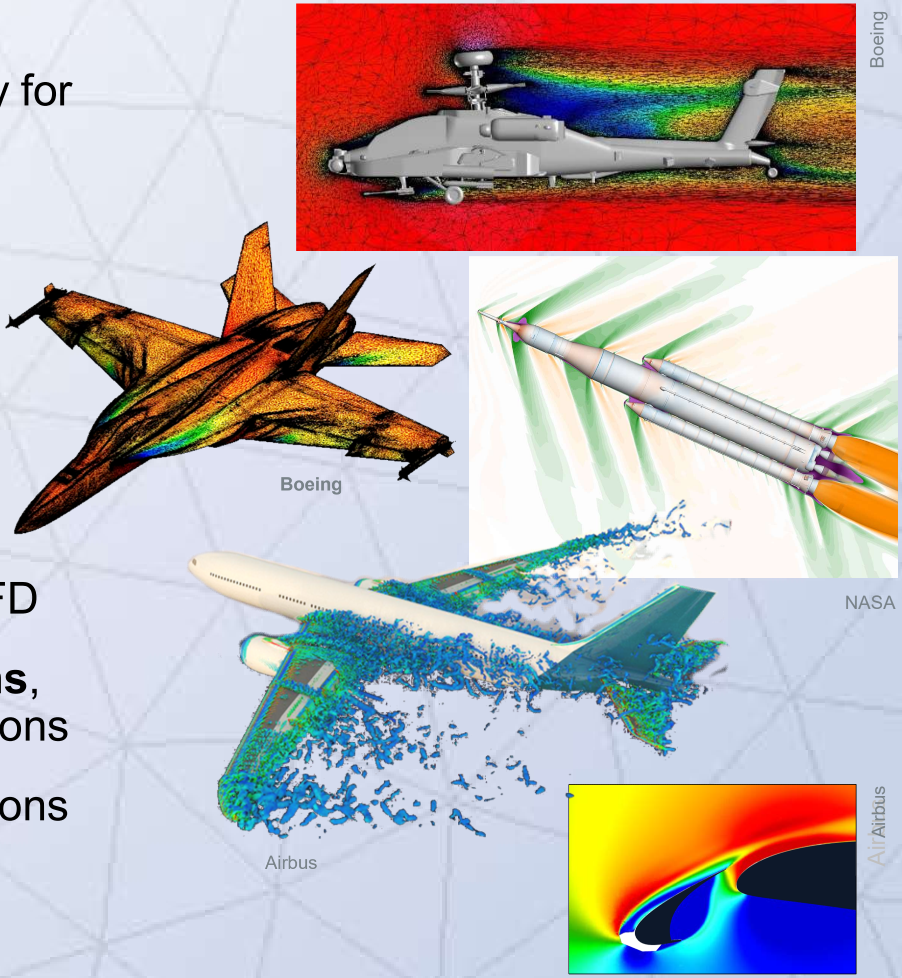
DLR

NASA

New/Improved CFD Tools/Processes/Capabilities

*Since 2014, what new **CFD process and/or tool improvement** has been most useful for industrial flow analysis? What kinds of **analyses are available to you today** that were not available to you five years ago?*

- **Grid adaptation** on complex CAD geometry for steady-state simulations
- **POD-based surrogate models**
- (Reasonably) affordable **scale-resolving turbulence modeling** demonstrated on industrial applications
- Prediction of **icing effects**
- **GPU-based processing** – taste of what a robust capability could have on industrial CFD
- Expanded use of **time accurate simulations**, particularly for rotorcraft and space applications
- Consistency in **steady-state RANS** simulations
- **Flow transition prediction methods** in production codes



Boeing

Boeing

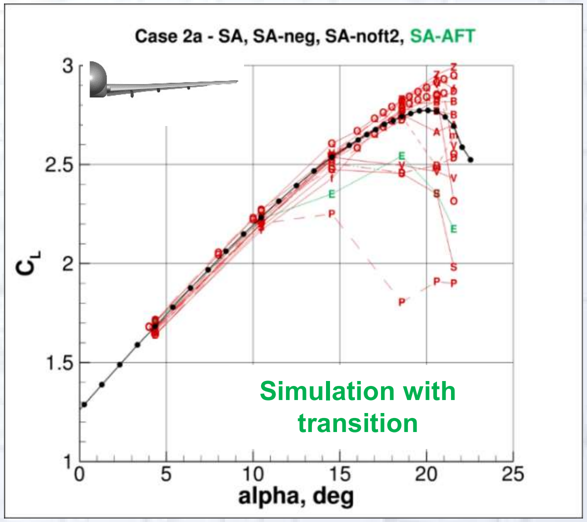
NASA

Airbus

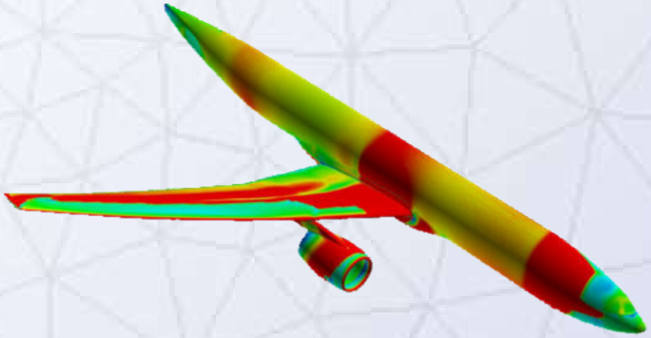
Airbus

No Improvement / Impediments

*Where has there been **little to no improvement**? If you could make one **CFD impediment go away**, what would it be and why?*



HiLiftPW-3, JSM, no nacelle/pylon (2017)



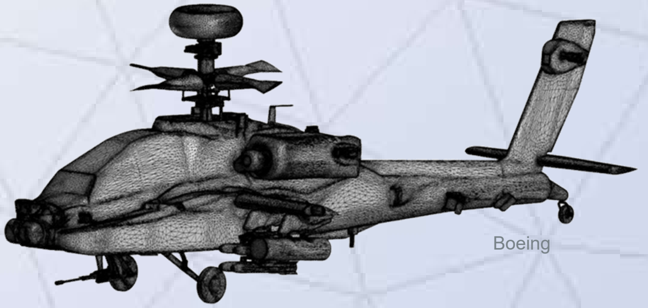
DPW-5, CRM (University of Tennessee, 2017)

- **RANS turbulence modeling,** particularly for **separated flows**
    - Characterization of **multiple solutions**
- **Automation** of **production CFD processes**
- Robust and reliable **grid convergence** for complex flows (e.g. high-lift)
- **Predictive flow transition modeling** – *validated* for complex configurations
- **Learning curve** for graduate students in the science behind CFD

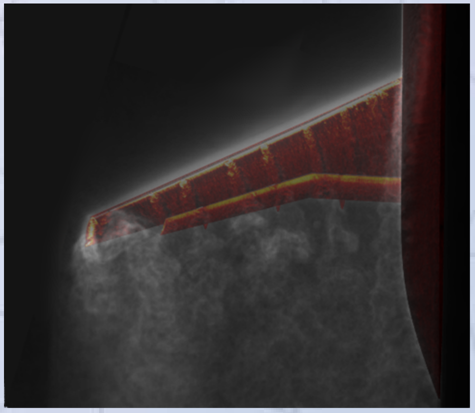
Computing Capability

*How much **more computing power** do you have today than you did in 2014 (stated in terms like "factor of 10", etc.) and **what has that increased amount of computing afforded you** (like able to run industrial cases 2x faster or able to generate a full database now, etc.)?*

- Significantly **less available industrial computing power (2-5X)** than what would be predicted by Moore's Law in the past 5 years (**~9.8X**, doubling every 18 months)
- However, more computational power has <u>enabled</u>:
  - Running with generally **finer meshes** (increased mesh resolution) <u>or</u> **faster turnaround**
  - Generation of RANS-based **aerodynamic databases**
  - Generation of full-configuration (e.g. launch vehicle) **unsteady simulations** for longer physical time – aero-acoustic data at lower frequencies)
  - Exploration of **scale-resolving simulations** for realistic configurations
  - Exploration of **new aerodynamic technologies** (e.g. flexible aircraft)
  - **MDAO** for full aircraft



Boeing



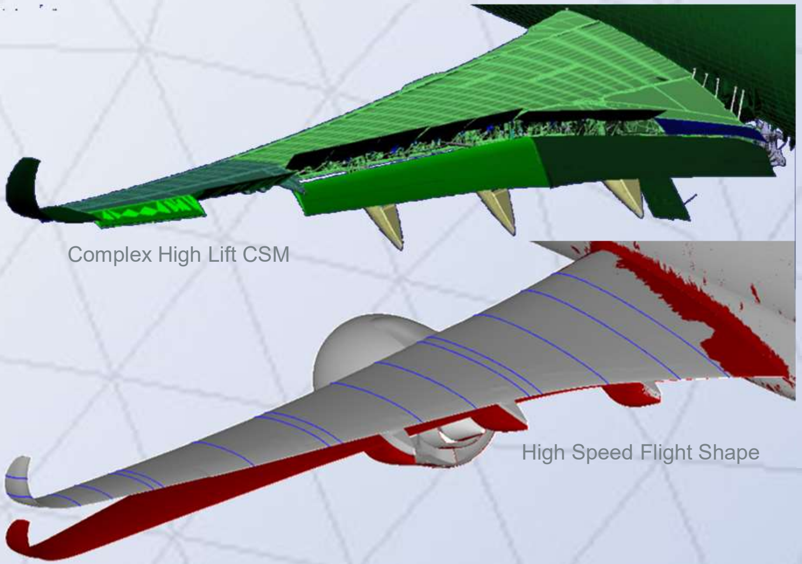
Cascade Technologies

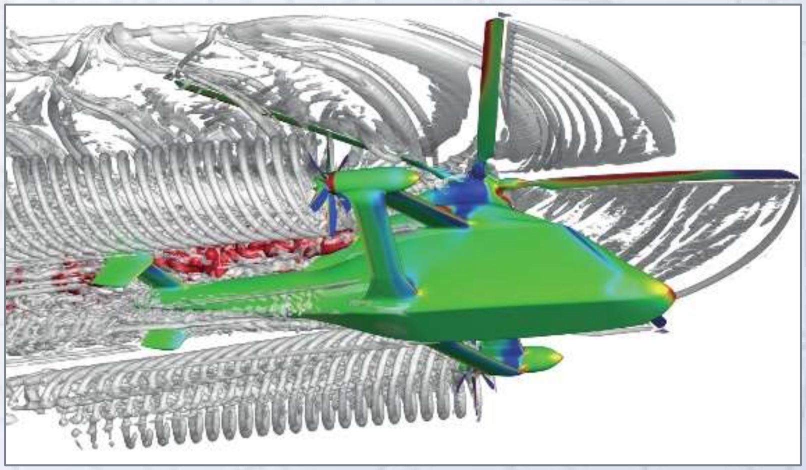
Multi-Physics / Multi-Disciplinary Coupling

How much more are you using CFD analyses ***coupled with other disciplines*** *now compared to 2014, and which* ***multi-physics analyses*** *are most commonly used by your organization?*

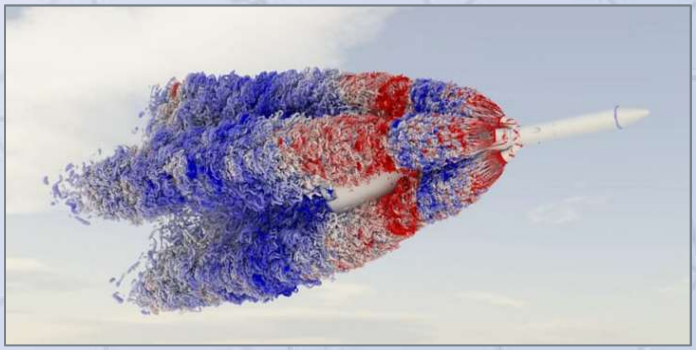
- Production **aero-structural coupling**
- Routine **aero-acoustic** analysis for air/space systems
- Renewed emphasis: **flight in icing**
- **Unique applications** for coupling

Airbus





Airbus / University of Stuttgart



NASA

Impact of CFD Vision 2030 Report

Do you feel like the ***CFD Vision 2030 report has been effective*** *in advancing technology development? If not, why not?*

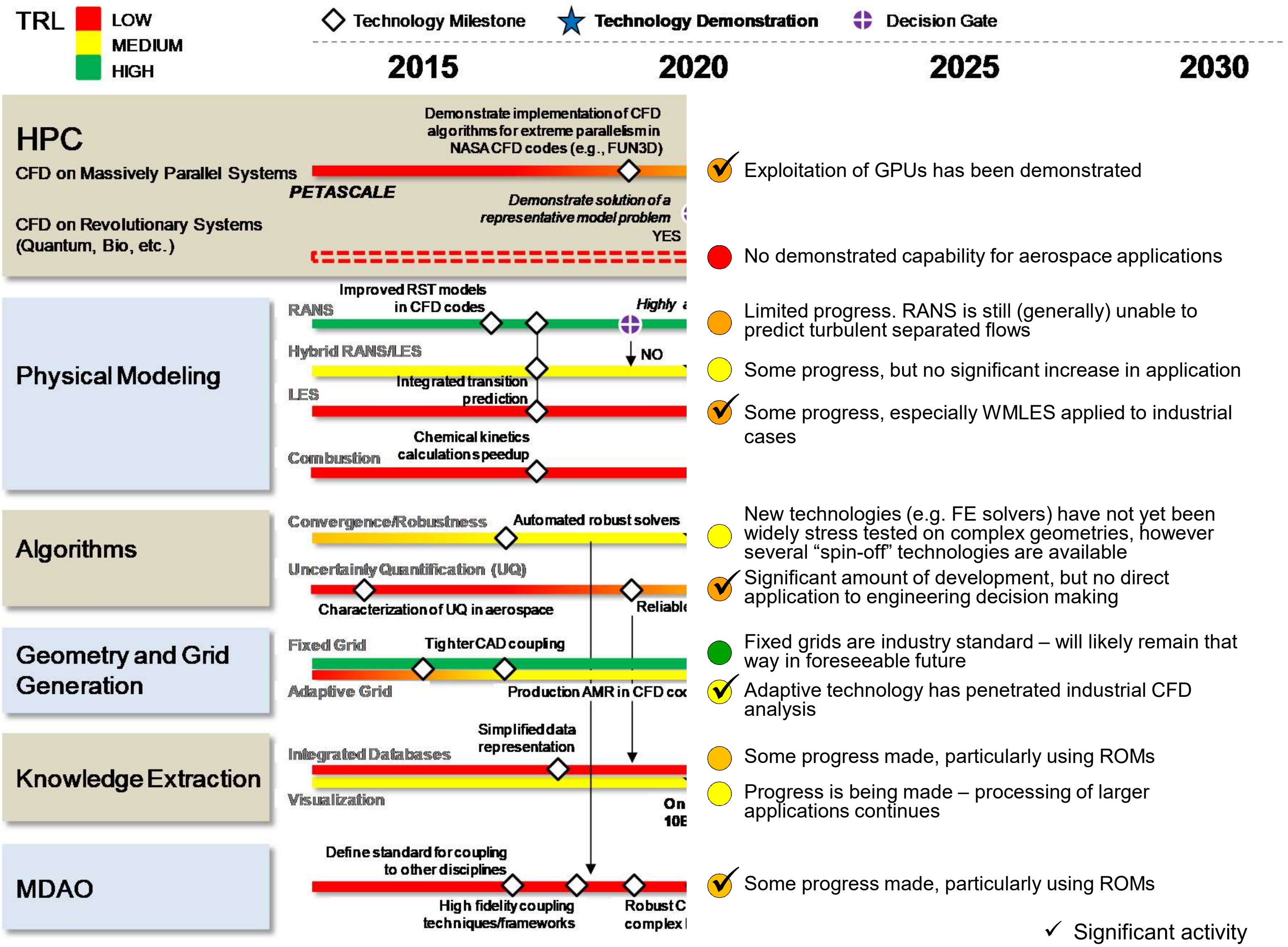
Good:

- Has empowered **international discussions**, **raised awareness**
- Increased **visibility (of CFD) at higher levels**, particularly at NASA
- Has been effective in **bringing the community together**
- Has been important in articulating/motivating **importance of CFD in R&D proposals**

(Not so) Good:

- **Has not "triggered a sufficient quantity of effort"** for key CFD capability advances (like routine prediction of separated flows)
- **Has not** led to a program/framework to enable **"disruptive CFD technology" development**
- There has been **no clear improvement** in **CFD technology development budgets**

CFD Vision 2030 Roadmap (Progress Report)



- 🟠✓ Exploitation of GPUs has been demonstrated
- 🔴 No demonstrated capability for aerospace applications
- 🟠 Limited progress. RANS is still (generally) unable to predict turbulent separated flows
- 🟡 Some progress, but no significant increase in application
- 🟠✓ Some progress, especially WMLES applied to industrial cases
- 🟡 New technologies (e.g. FE solvers) have not yet been widely stress tested on complex geometries, however several “spin-off” technologies are available
- 🟠✓ Significant amount of development, but no direct application to engineering decision making
- 🟢 Fixed grids are industry standard – will likely remain that way in foreseeable future
- 🟡✓ Adaptive technology has penetrated industrial CFD analysis
- 🟠 Some progress made, particularly using ROMs
- 🟡 Progress is being made – processing of larger applications continues
- 🟠✓ Some progress made, particularly using ROMs

✓ Significant activity

Emerging Opportunities (1)

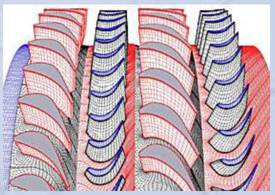
- **Experimental Testing of Realistic Configurations for CFD Validation**
  - Identified as an **impediment in 2014**
  - Limits of current tools/technologies **exposed in CFD prediction workshops** (over the past decade)
  - Driving towards long-term development and testing of **publically-available (open) representative configurations** (CRM, rotorcraft, sonic boom, etc.)
  - Involves **international** academia/government research/industry organizations
  - Advances new/innovative **measurement techniques**
  - Propels **CFD technology development**


DPW-6, AIAA 2016


NASA 2019

- **CFD Grand Challenge Problems**
  - Part of CFD Vision 2030 report; **little progress to date**
  - Expected to anchor **long-term technology development**
  - **Active problem identification and development** in several areas (rotorcraft, engines, commercial airplane external aerodynamics, etc.)

Boeing


NASA

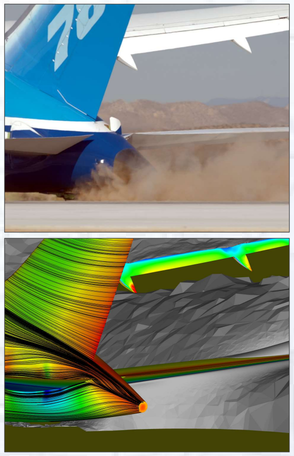

Boeing/Sikorsky


NASA

Emerging Opportunities (2)

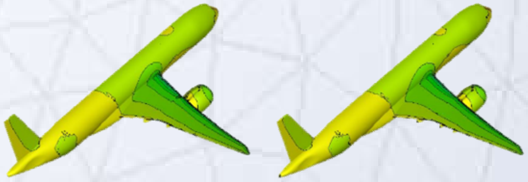
14 CFR 25.107(d)

VMU is the calibrated airspeed at and above which the airplane can safely lift off the ground, and continue the takeoff. VMU speeds must be selected by the applicant throughout the range of thrust-to-weight ratios to be certificated. These speeds may be established from free air data if these data are verified by ground takeoff tests.



Boeing, 2018

Boeing, 2015



CFD reference
8000 iterations

ROM approximation
17 iterations

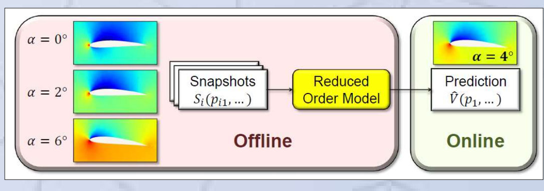
S. Görtz et al., Reduced Order Models for Aerodynamic Applications, Loads and MDO, 2017

- **Certification by Analysis (CbA) – by 2030**
  - Flight modeling will dramatically **reduce the amount of flight testing** required for **airplane certification**
  - Efforts are underway to utilize **CFD-based flight modeling** to show compliance to certification regulations
  - Advances in CFD capability at the **edges of the flight envelope** will unlock greater use of CbA

- **Certification by Simulation – 2030+**

  Creation of simulation databases that **fully describe airplane flight characteristics,** including handling qualities, etc.

  - Multi-source **data fusion / ROMs / Gappy POD methods**
  - **Machine learning / neural networks**
  - Real time **data analytics**



DLR, 2017

Thank you
for your attention!