NASA/CR-20210015404

A Guide for Aircraft Certification by Analysis

Timothy Mauery
The Boeing Company, Seattle, Washington

Juan Alonso
Stanford University, Stanford, California

Andrew Cary
The Boeing Company, Saint Louis, Missouri

Vincent Lee
The Boeing Company, Seattle, Washington

Robert Malecki
Pratt & Whitney, East Hartford, Connecticut (Retired)

Dimitri Mavriplis
University of Wyoming, Laramie, Wyoming

Gorazd Medic
Pratt & Whitney, East Hartford, Connecticut

John Schaefer
The Boeing Company, Saint Louis, Missouri

Jeffrey Slotnick
The Boeing Company, Seattle, Washington

May 2021

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the "General" help request type.

NASA/CR-20210015404

A Guide for Aircraft Certification by Analysis

Timothy Mauery
The Boeing Company, Seattle, Washington

Juan Alonso
Stanford University, Stanford, California

Andrew Cary
The Boeing Company, Saint Louis, Missouri

Vincent Lee
The Boeing Company, Seattle, Washington

Robert Malecki
Pratt & Whitney, East Hartford, Connecticut (Retired)

Dimitri Mavriplis
University of Wyoming, Laramie, Wyoming

Gorazd Medic
Pratt & Whitney, East Hartford, Connecticut

John Schaefer
The Boeing Company, Saint Louis, Missouri

Jeffrey Slotnick
The Boeing Company, Seattle, Washington

National Aeronautics and
Space Administration

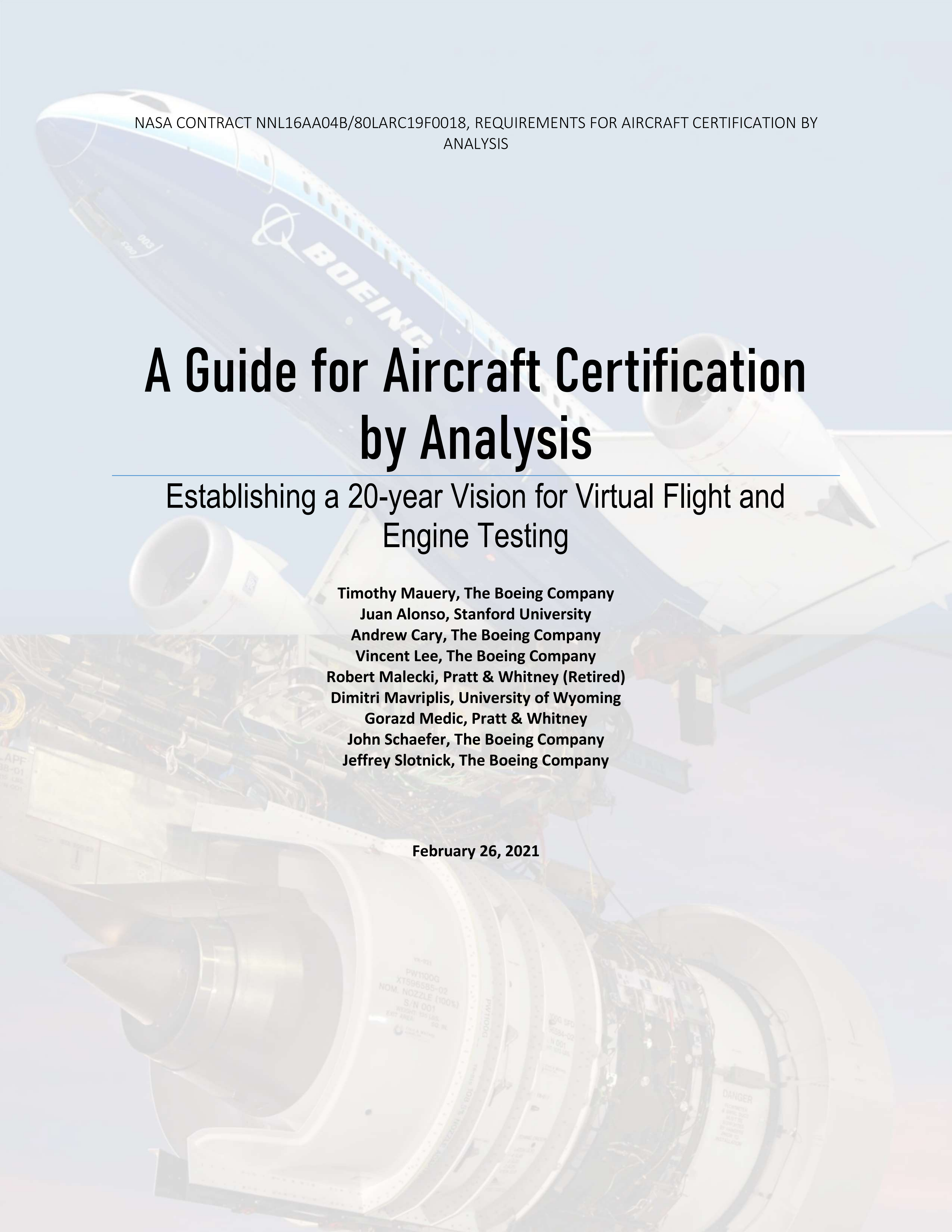
Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NNL16AA04B

May 2021

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500



NASA CONTRACT NNL16AA04B/80LARC19F0018, REQUIREMENTS FOR AIRCRAFT CERTIFICATION BY ANALYSIS

A Guide for Aircraft Certification by Analysis

Establishing a 20-year Vision for Virtual Flight and Engine Testing

Timothy Mauery, The Boeing Company
Juan Alonso, Stanford University
Andrew Cary, The Boeing Company
Vincent Lee, The Boeing Company
Robert Malecki, Pratt & Whitney (Retired)
Dimitri Mavriplis, University of Wyoming
Gorazd Medic, Pratt & Whitney
John Schaefer, The Boeing Company
Jeffrey Slotnick, The Boeing Company

February 26, 2021

Contents

List of figures

List of tables

Nomenclature

1g	Standard gravity
AAVP	Advanced Air Vehicles Program
AC	Advisory Circular
AI	Artificial Intelligence
AIAA	American Institute of Aeronautics and Astronautics
AMR	Adaptive Mesh Refinement
ARMD	Aeronautics Research Mission Directorate
CAD	Computer Aided Design
CbA	Certification by Analysis
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CoI	Community of Interest
C_L	Airplane lift coefficient
$C_{L,max}$	Maximum lift coefficient
CM	Certification Memorandum / Pitching Moment
CPU	Central Processing Unit
CSD	Computational Structural Dynamics
CSM	Computational Structural Mechanics
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EASA	European Union Aviation Safety Agency
EEC	Electronic Engine Control
ELOS	Equivalent Level of Safety
eVTOL	electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FEM	Finite Element Model
FSI	Fluid Structures Interaction
GPU	Graphics Processing Unit
GUIde	Government agencies, Universities, and Industry consortium
HIRENASD	High Reynolds Number Aerostructural Dynamics
CRM-HL	High Lift Common Research Model
HLPW	High Lift Prediction Workshop
HO	Higher-order
HPC	High Performance Computing
IASP	Integrated Aviation Systems Program
ICI	Ice Crystal Icing
JSM	JAXA Standard Model
JAXA	Japan Aerospace Exploration Agency
LBM	Lattice-Boltzmann Method
LBO	Lean Burn-Out
LES	Large Eddy Simulation
LPC	Low Pressure Compressor
LST	12-Foot Low-Speed Tunnel
MAC	Mean Aerodynamic Chord
MBE	Model Based Engineering
MDA	Multidisciplinary Analysis
ML	Machine Learning
MOC	Means of Compliance
n	Load factor in multiples of 1g

NASA	National Aeronautics and Space Administration
NRA	NASA Research Announcement
OEM	Original Equipment Manufacturer
OML	Outer Mold Line
ONERA	Office National d'Etudes et de Recherches Aérospatiales (The French Aerospace Lab)
NPR	Nozzle Pressure Ratio
PDE	Partial Differential Equation
PIML	Physics Informed Machine Learning
PLM	Product Lifecycle Management
QoI	Quantity of Interest
RANS	Reynolds-Averaged Navier-Stokes
ROM	Reduced-Order Model
RPM	Revolutions Per Minute
SGS	Subgrid Scale
SRS	Scale-Resolving Simulation
TTT	Transformational Tools and Technologies project
TACP	Transformative Aeronautics Concepts Program
TDT	Transonic Dynamics Tunnel
TRL	Technology Readiness Level
TTR	Total Temperature Ratio
U_∞	Freestream velocity
ULI	University Leadership Initiative
UQ	Uncertainty Quantification
URANS	Unsteady Reynolds Averaged Navier-Stokes
V&V	Verification and Validation
VMU	Velocity Minimum Unstick
VOF	Volume of Fluid method
VST	20-foot Vertical Spin Tunnel
WMLES	Wall-modeleded Large Eddy Simulation
WUT	Wind-up Turn

I. Executive Summary

Analysis-based means of compliance for airplane and engine certification, commonly known as "Certification by Analysis" (CbA), provides a strong motivation for the development and maturation of current and future flight and engine modeling technology. The many benefits of CbA include streamlined product certification testing programs at lower cost while maintaining equivalent levels of safety. For the purposes of this document, flight and engine modeling includes analysis methods of all types, including analyses based on wind tunnel and/or other ground-based testing results and numerical methods such as Computational Fluid Dynamics (CFD), among others. In the context of CbA, analysis is used to obtain results for certification compliance that have traditionally been acquired using physical testing, such as flight testing or ground-based testing for engines. Although the current state of technologies and processes for analysis is not sufficient to adequately address most aspects of CbA today, individual applications of CbA have been accepted on a case-by-case basis by regulatory authorities. Concerted efforts to drastically improve analysis capability are required to fully bring the benefits of CbA to fruition.

Flight and engine testing represent a substantial cost to airplane and engine development programs. The financial impact of flight testing is not only significant but also highly variable. Despite large efforts to optimize the test plans, the flight and engine schedules often depend on factors out of the direct control of the manufacturer, such as proper weather conditions or the availability of specific testing facilities. Improved analysis capability will help ameliorate both the financial cost and the impact of schedule delays.

While the short-term cost and schedule benefits of reduced flight and engine testing are clearly valuable, the fidelity of analysis capability required to realize CbA across a much larger percentage of product certification is not yet sufficient. Higher-fidelity analysis can help reduce the product development cycle and avoid costly and unpredictable performance and operability surprises that sometimes happen late in the development cycle, particularly in off-design situations. As one might imagine, the identification of unexpected issues early on can significantly reduce the financial impact. However, perhaps the greatest long-term value afforded by CbA is the potential to accelerate the introduction of more aerodynamically and environmentally efficient products to market, benefitting not just manufacturers, but also airlines, passengers, and the environment.

Through the development of this report, a far-reaching vision for CbA has been constructed to offer guidance in developing lofty yet realizable expectations regarding technology development and maturity through stakeholder involvement. This vision is composed of the following four elements:

1. The ability to numerically simulate the integrated system performance and response of full-scale airplane and engine configurations in the flight and/or ground-test environment in an accurate, robust, and computationally efficient manner.
2. The development of quantified flight and engine modeling uncertainties to establish appropriate confidence in the use of numerical analysis for certification.
3. The rigorous validation of flight and engine modeling capabilities against full-scale data from critical airplane and engine testing.
4. The use of flight and engine modeling to enable Certification by Simulation.

To support the development of a technology roadmap, we examine the existing gaps and impediments that must be overcome for more widespread acceptance of CbA. The Flight and Turbine Engine sections of the Federal Aviation Regulations were reviewed extensively, and several representative certification scenarios were examined in depth to determine the technical, logistical, and credibility shortcomings requiring further investment to allow CbA on a large scale. To confirm the study team's understanding of the current state-of-the-art, additional input was sought from industry leaders through an online survey and virtual workshop.

The key technical challenges include the ability to accurately predict airplane and engine performance for a single discipline (e.g., aerodynamics), the robust and efficient integration of multiple disciplines (e.g., aerodynamics and structures), and the appropriate modeling of system-level assessment (e.g., providing evaluation of handling qualities). Current modeling methods lack the capability to adequately model conditions that exist at the edges of the operating envelope where the majority of certification testing generally takes place. These conditions are characterized by complex, interactional flow physics, such as separated flows, flow confluence, and vortical flows. Additionally, large-scale engine or airplane multidisciplinary integration has not matured to the level where it can be reliably used to efficiently model the intricate interactions that exist in current or future aerospace products. Many certification applications also require the identification of system level responses given multiple inputs.

Logistical concerns center primarily on the future High Performance Computing (HPC) capability needed to perform the large number of computationally intensive simulations needed for CbA. Complex, time-dependent, multidisciplinary analyses will require a computing capacity increase several orders of magnitude greater than is currently available.

Developing methods to ensure credible simulation results is critically important for regulatory acceptance of CbA. Confidence in analysis methodology and solutions is examined so that application validation cases can be properly identified. Other means of measuring confidence such as uncertainty quantification and "validation-domain" approaches are discussed to find ways to increase the credibility and trust in the predictions.

A technology development roadmap is presented to guide future investment and research relating to CbA goals over the next two decades. Representative airplane maneuver and engine test certification applications are prioritized by projected maturity need date on the roadmap to provide important targets to drive the required analysis method development. The inclusion of intermediate milestones and integrated predictive capabilities permits the evaluation of technology readiness, and a hierarchy of benchmark evaluation cases supports the proper validation of the predictive capabilities. It should be noted that many of the roadmap elements are similar to those that exist on the CFD Vision 2030 roadmap, since a majority of the analytical models envision the future use of CFD in CbA. A near-term road map emphasizes efforts required over the next ten years, identifying the technology development needed, and the value that can be realized, in the near future.

Specific areas of technology development are highlighted on the roadmap to guide the necessary improvements in modeling capability. These include physical modeling, geometry and computational mesh generation, algorithm development, multidisciplinary coupling, and uncertainty quantification. A key addition on the CbA roadmap, relative to CFD Vision 2030, is the emphasis on the determination of uncertainties needed to establish confidence in the analysis capabilities. The use of uncertainty quantification (UQ) methodologies is still in its infancy in the field of aerospace; however, efficient approaches to computing uncertainty are needed to bolster solution confidence without adding unrealistic amounts of additional computational expense. Similarly, comprehensive efforts in verification and validation will enable appropriate comparisons between experimental data and analysis results to increase confidence in analytical approaches.

Finally, recommendations are provided to NASA and other stakeholders to provide a unified approach to overcoming the current analysis shortcomings. We recommend that NASA should:

1. Focus investment on fundamental technologies that lead to better predictive abilities at the edges of the flight/engine operational envelope.
2. Prioritize and accelerate the development of multidisciplinary simulation capabilities.
3. Develop new multidisciplinary testing and validation capabilities.
4. Facilitate the use of a representative flight-test vehicle and full-scale engine available for CbA validation.
5. Construct a comprehensive UQ strategy for CbA.

Beyond NASA, sustained progress in capability development must include collaboration and coordination between government research organizations, academia, industry, and regulatory authorities. To this end, the following recommendations are given:

1. Establish a multistakeholder CbA Steering Team or Advisory Council to develop the framework to tackle the technical and logistical challenges of CbA.
2. Develop realistic benchmarks to define and establish confidence in CbA.
3. Facilitate collaborative CbA "mirroring" of certification tests, where appropriate, to demonstrate measurable progress toward CbA goals.
4. Increase and sustain access to HPC resources

Certification by Analysis is a challenging long-term endeavor that will motivate many areas of simulation technology development, while driving the potential to decrease cost, improve safety, and improve airplane and engine efficiency. Requirements to satisfy certification regulations provide a measurable definition for the types of analytical capabilities required for success. There is general optimism that CbA is a goal that can be achieved, and that a significant amount of flight testing can be reduced in the next few decades. However, consistent with the findings of the CFD Vision 2030 report, significant investment and concentration of resources will be required to reach these goals within the timeframe proposed.

II. Introduction

Background

Safety of the flying public is, and always will be, the primary objective and focus for airframe and engine manufacturers. For an impartial determination of safety, governments have crafted a comprehensive set of regulations to standardize the definition of safety and require demonstration to those regulations for all new and derivative airplane and engine products. Within the United States, the Federal Aviation Regulations (FARs) administered by the Federal Aviation Administration (FAA) codify airworthiness standards and requirements [1]. Similarly, the European Union Aviation Safety Agency (EASA) maintains similar regulatory material [2], as do other regulatory agencies around the world. The airframe and engine manufacturers work closely with regulatory authorities to ensure that their products meet certification requirements. The set of regulations has not generally changed since its inception, but has evolved over the decades, shaped, in large part, by responses to safety-related events [3].

For airframe and engine manufacturers, significant effort is expended demonstrating compliance to the governmental requirements legislated to ensure public safety. Each new or derivative airplane and engine program goes through a rigorous certification compliance campaign. Currently, much of compliance to certification regulations is substantiated through flight test demonstration for airframes and ground-testing for engines [4]. Due to the extensive list of compliance regulations, certification efforts for a new airplane program can easily require over one year of total flow time, with the aggregate cost of the certification process approaching one billion dollars [5], which is a significant portion of the entire cost of an all-new airplane development program. For derivative programs, the certification cost may adversely impact the business case to such a degree that a subsequent product offering with a modest performance improvement may not be financially viable. Another significant impact to an airplane certification program is related to weather availability to support critical flight test schedule. Some regulations require testing under very precise conditions, such as natural icing or crosswind takeoff, and finding suitable locations with specific environmental conditions can easily extend certification test schedule and cost. Additionally, preparation for certification testing, such as airplane envelope expansion, often requires testing that is not directly required by the regulations, but is necessary for verification of airplane flight characteristics. Analysis-based means of compliance, referred to here as "Certification by Analysis" (CbA), has the potential to shorten product testing programs, thus reducing their associated costs, while maintaining equivalent levels of safety, ensuring security and confidence for the flying public. In its most essential definition, CbA refers to *flight modeling* or *engine modeling*, where analysis (such as numerical or wind tunnel methods) and/or simulation methods are used to obtain results for certification compliance that have traditionally been acquired using physical testing, such as flight testing or ground-based testing for engines.

With the continuous evolution of more sophisticated analytical capabilities, such as computational fluid dynamics (CFD), airplane and engine manufacturers are increasingly investigating the application of analytically-based methods and tools to complement and reduce physical testing [6]. Emerging developments in advanced High Performance Computing (HPC) capabilities, coupled with the advent of accurate and robust multidisciplinary analysis tools, have the potential to dramatically reduce the amount of flight and engine testing for future product development. However, significant challenges and shortcomings remain in the accuracy, efficiency, and robustness of computational simulation methods and tools for expanded use in showing compliance to airplane and engine certification regulations.

The technology development roadmap presented in the CFD Vision 2030 report [7] highlights a long-term plan for the advancement and maturation of computational simulation technology. The development of improved analytical tools specifically required for CbA is reflected in the broad development effort described in the Vision 2030 roadmap. Some development areas, including physics-based modeling, handling of complex geometry, and advanced mesh generation capabilities, among others, were driven by expected CbA requirements. In particular, CbA provides an effective means to focus technology development efforts and offers a set of real-world, full-scale applications to ensure steady progress by establishing substantial technical goals with quantifiable benefits. It is anticipated that the Vision 2030 roadmap, and related community activities in developing and executing CFD Grand Challenges [8] [9], will generally help drive future progress toward broader use of CbA by airplane and engine manufacturers and acceptance of CbA by regulatory agencies. It is the objective of this report, however, to define a technology roadmap specifically designed to focus critical attention in areas where computational simulation tools and processes must be developed and validated to enable the future use of CbA for airplane and engine products.

Scope

Although a wide range of disciplines are routinely involved in airplane and engine certification efforts, such as structures and systems, the current CbA study specifically focuses on flight- and engine-related certification requirements. Airworthiness standards for the transport airplane category are provided in Part 25 of Title 14 (Aeronautics and Space) of the US Code of Federal Regulations (CFR) [10], where 14 CFR 25, Subpart B addresses flight-related regulations. Similarly, airworthiness standards for the airplane engine category are provided in Part 33; 14 CFR 33, Subpart F addresses regulations for testing of aircraft turbine-powered engines. These two areas were chosen because of their close alignment with both the CFD Vision 2030 effort and the goals of the Transformational Tools and Technologies (TTT) project within the NASA Aeronautics Research Mission Directorate. Because the certification regulations are generally categorized by performance, operation, or testing requirements, compliance to certain regulations is typically accomplished through flying the airplane through specific maneuvers [11] for 14 CFR 25, Subpart B or performing engine testing for 14 CFR 33, Subpart F. The maneuver-based flight testing and condition-based engine testing approaches provide an efficient means to address multiple certification requirements, and allows concurrent certification of multiple regulations. Since these compliance approaches are familiar to regulators and manufacturers alike, the approach taken in this study is based on the assessment of numerical simulation objectives developed and aligned to specific flight test and engine testing opportunities routinely performed for product certification. For this study, direct treatment of acoustics and community noise are not included. Aeroacoustics, as well as airplane icing and engine emissions, do require additional development, but since these additional elements do not directly fall under Part 25 or Part 33 regulations, they are only addressed as required.

Overview

This report details the findings of a two year study, commissioned by the NASA Aeronautics Research Mission Directorate (ARMD) under the TTT project, to investigate the prospects for CbA in the near and longer term future, to document the requirements for enabling CbA, and to provide recommendations for accelerating the realization of CbA. This effort was led by Boeing, with representation from Raytheon Technologies/Pratt & Whitney, and academia. The principal objective of the study was the development of a comprehensive plan and roadmap for guiding technology development toward the realization of CbA. As part of this effort, a survey was developed and distributed to collect input from the larger engineering and scientific communities on key topics related to analysis-based certification methods and technology development. Results from the survey were then used to structure a multiday technical workshop, where key ideas related to CbA were further refined.

In the following sections of this report, we first outline a vision for CbA in the notional year 2040, including the value proposition this vision affords. By contrasting this vision with the current state of simulation technology and certification practices, we identify technical gaps and impediments that will need to be overcome. These are used, in turn, to develop an integrated technology roadmap, including specific target certification metrics, for achieving the goals of CbA. Finally, a set of recommendations is given, which is expected to be instrumental in the implementation of the proposed strategy.

III. Future State of CbA in 2040

Vision

Based on input and findings from online survey results and participant comments, as well as the discussions and consensus reached during a virtual workshop, the study team has constructed a well-conceived future vision for CbA. The vision contains four essential elements:

1. **The ability to numerically simulate the integrated system performance and response of full-scale airplane and engine configurations in the flight and/or ground-test environment in an accurate, robust, and computationally efficient manner.** The envisioned flight modeling capability will enable reliable prediction of aerodynamic performance throughout the flight envelope, as well as support the simulation of critical dynamic maneuvers important to airplane certification. The envisioned engine modeling capability will reliably predict the component and integrated system level operation essential to engine verification testing.

2. **The development of quantified flight and engine modeling uncertainties to establish appropriate confidence in the use of numerical analysis for certification.** This entails the identification and classification of all sources of uncertainties, including both aleatory and epistemic uncertainties, for single and multidisciplinary analyses, followed by the development and maturation of suitable propagation and aggregation methods for uncertainties in certification metrics for large complex multidisciplinary simulations.

3. **The rigorous validation of flight and engine modeling capabilities against full-scale data from critical airplane and engine testing.** These efforts span the entire range of verification and validation (V&V) including single- and multidisciplinary method verification and the appropriate use of subscale flight, wind tunnel, and/or full-scale data.

4. **The use of flight and engine modeling to enable Certification by Simulation.** Envisioned over time, performance data directly from flight and engine modeling will become a predominant and essential source for all forms of flight and/or engine simulation currently used or required for certification. Initially, data from flight test, ground-based testing, and numerical simulation will be synthesized together using data fusion methods to create high-fidelity databases for use within the flight simulator. However, when fully implemented, the flight and engine simulation based on flight and engine modeling alone will define the actual operational characteristics of the airplane and/or engine product, with airplane flight and/or engine ground-based testing serving only to validate the simulation. With sufficient computational resources, numerical simulation of flight maneuvers would be accomplished in real-time, with Machine Learning (ML) and Artificial Intelligence (AI) techniques used to fully explore the range of airplane and/or engine responses, considering aerodynamic/system uncertainties. This capability would allow for more complete examination of risks than can be done with the use of a static database of simulations.

Key components of the vision are the long-term value of CbA and the overall strategy in enabling CbA, including defining the near-term and long-term future states, and identifying the challenges that must be overcome.

Value

Commercial certification flight test programs cost in the tens to hundreds of millions of dollars, with the aggregate cost of the certification process approaching one billion dollars [5]. Based on our survey results, there is industry-wide consensus that current certification flight tests could be reduced by approximately 50% by utilizing CbA if all existing CbA technical and logistical impediments were adequately addressed. Decreasing the cost of airplane and engine certification testing will ultimately bring lower cost products to airlines and to the traveling public.

An additional benefit is in product development schedule and time-to-market. Analysis available earlier in the certification process will potentially allow certification testing to start sooner, while optimizing the flight test program to reduce the number of dedicated certification flight tests. More importantly, robust and accurate analysis methods can help to eliminate the performance surprises that are typically discovered during the flight test process. Diagnosing and fixing issues late in the schedule via flight testing incurs disproportionally higher costs than finding potential issues through analysis before flight testing begins.

Perhaps the greatest ancillary benefit of CbA is the use of computational tools specifically for concept development and detailed product design. More accurate computational analysis during early design trades and initial configuration development will enable increased aerodynamic performance, reduced weight, and better system integration. As a result, increased use of analysis to streamline the overall product development cycle has the potential to save billions of dollars over the life of the program, as well as bring more fuel-efficient products to market in less time, benefitting airlines, the flying public, and the environment.

For the engine, certification testing represents only part of the overall testing objectives, the most important of which is to validate that the product is robust to its mission, since this is the principal driver on lifecycle costs for the engine product. Thus, with the possible exception of fan blade-out testing, which destroys the engine test asset, CbA is not expected to eliminate a significant amount of engine testing in the near term. However, the additional benefits of CbA described above for the airplane are also true for the engine: accelerated conceptual, preliminary and detailed product design phases evaluating more concepts, configurations, and component and system design trades resulting in schedule reduction and improved products, and the reduction of surprises during validation and certification testing. Additionally, it may be expected that advanced simulation capabilities in the future will aid in the prediction of engine operability issues earlier in the design process and will be capable of predicting performance or operability deficiencies due to extreme off-design conditions, unexpected transients or extended operation. Furthermore, CbA is expected to provide benefits for engine testing efficiency through reduction in instrumentation required on development tests and reduction in test duration.

Strategy/Approach

The approach that will be utilized and described in detail throughout this study is to consider specific aircraft maneuvers and engine tests, which are typically performed as part of the certification process, and to develop modeling capabilities that can credibly predict airplane and engine system performance with an equivalent level of accuracy, with associated uncertainties, relative to full scale airplane flight tests or engine tests. Within 14 CFR 25, Subpart B and 14 CFR 33, Subpart F, there are nearly sixty flight maneuvers or engine test scenarios to consider as opportunities to advance CbA. It is expected that a long-term, systematic approach is required to demonstrate that CbA can confidently provide the necessary analytical information for certification compliance substantiation. To support a technology roadmap developed to span multiple decades, the many classes of airplane maneuvers and engine tests can be roughly categorized based on expected time-to-maturity of the required computational capabilities. Three specific groups of maneuvers/tests are proposed as target CbA opportunities: near-term (within 5 years), medium-term (within 10 years), and long-term (within 20 years). A longer-term (beyond 20 years) challenge category is also considered to drive the unification of both flight and engine simulation technologies to address complex, integrated airplane-propulsion flight maneuvers.

Appendix A describes examples of key maneuvers and engine tests that will be considered in this report. Two figures are included to show examples of airplane and engine certification tests. Figure 1 illustrates examples of Part 25 certification maneuvers, representing some of the edge of the envelope conditions involved certification testing.

Figure 2 shows both analytical and traditional Part 33 fan blade-out test results. Fan blade-out analysis methodology is maturing to the point that it has the potential to be used for certification in the near future. This analysis capability will prevent the destruction of the test article.

As described above, the first three elements of the CbA vision provide the foundation for the fourth. System-level integration and increasingly automated engine and airplane products will require a fully integrated analysis approach. Future strategy anticipates the use of simulators in the certification process as a way to account for system-level integration and pilot interaction.

IV. Current State of CbA

Today, currently available CFD tools and processes, based on Reynolds-averaged Navier-Stokes (RANS) and hybrid RANS/Large Eddy Simulation (LES) technology, are effectively utilized for the numerical simulation of full airplane aerodynamic characteristics, as well as for prediction of complex engine component performance. For full airplane simulations, RANS CFD tools and processes are

Figure 1. *Images demonstrating the type of maneuvers that are required for Part 25 certification: (left) High alpha demonstration and (right) crosswind takeoff.*

able to accurately and reliably predict aerodynamic characteristics within only a relatively small portion of the operating flight envelope, as depicted by the hashed area in Figure 3. However, many of the critical maneuvers for airplane certification are performed away from nominal 1g-load factor flight conditions toward the edges of the flight envelope, as indicated in Figure 3. It is in these regions where current CFD tools and methods are unable to reliably predict aerodynamic performance, due, in large part, to the inability of these methods to model separated flows [7] [12].

Nevertheless, the success of CFD methods applied at cruise conditions, and to a lesser extent for steady-state high-lift problems at nominal angles of attack, has proved to be transformative for airplane product development [12]. Current CFD models routinely represent highly-detailed realistic full-configuration geometries, and flow solutions on fine meshes with hundreds of millions of degrees of freedom are generally obtained with overnight turnaround. In many cases, such analyses are concerned with evaluating the performance for a fixed configuration shape or aerodynamic outer mold line (OML). When elastic deformation due to aerodynamic load (aeroelastics) is included in the CFD model, the change in OML is often prescribed from finite element models or based on observations acquired in the wind tunnel or in flight. By contrast, most CbA applications involve dynamic maneuvers where aeroelastic effects must be predicted as part of the overall simulation and where other disciplines such as flight controls may play important roles as well. Whereas in the early product development phase, many of these disciplines can be analyzed independently or in sequence, for certification applications, the multidisciplinary effects are tightly coupled and the use of single disciplinary tools will prove to be inadequate in most cases.

Similarly, when it comes to engine operability simulation, RANS (compressors) and hybrid RANS/LES (combustors) CFD tools are only able to reliably predict engine performance and operability within a small region design operation line or "op-line," as illustrated in Figure 4. In off-design areas, CFD is not able to accurately predict the reduction of operability due to fan, compressor and combustor stability pinch. Several physical phenomena complicate engine CFD modeling, including the impact of inlet distortion, prediction of endwall

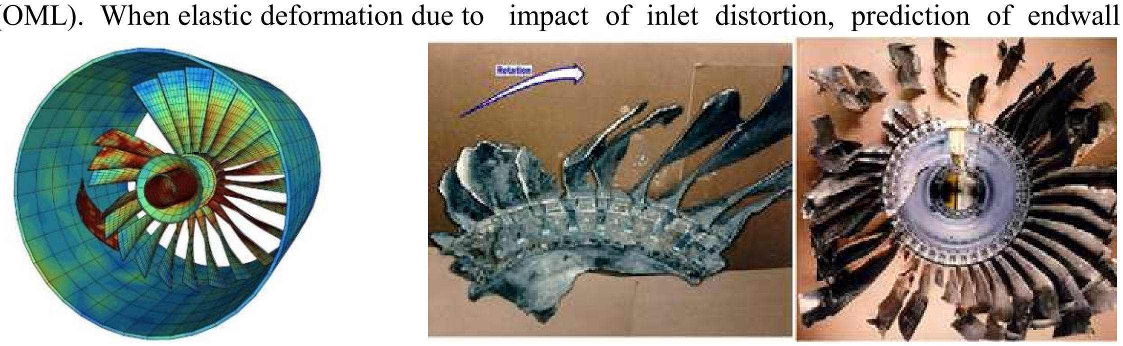


Figure 2. *Illustration of Part 33 certification testing methods for fan blade-out testing: (left) Limited analytical capability and (center, right) results from traditional testing.*

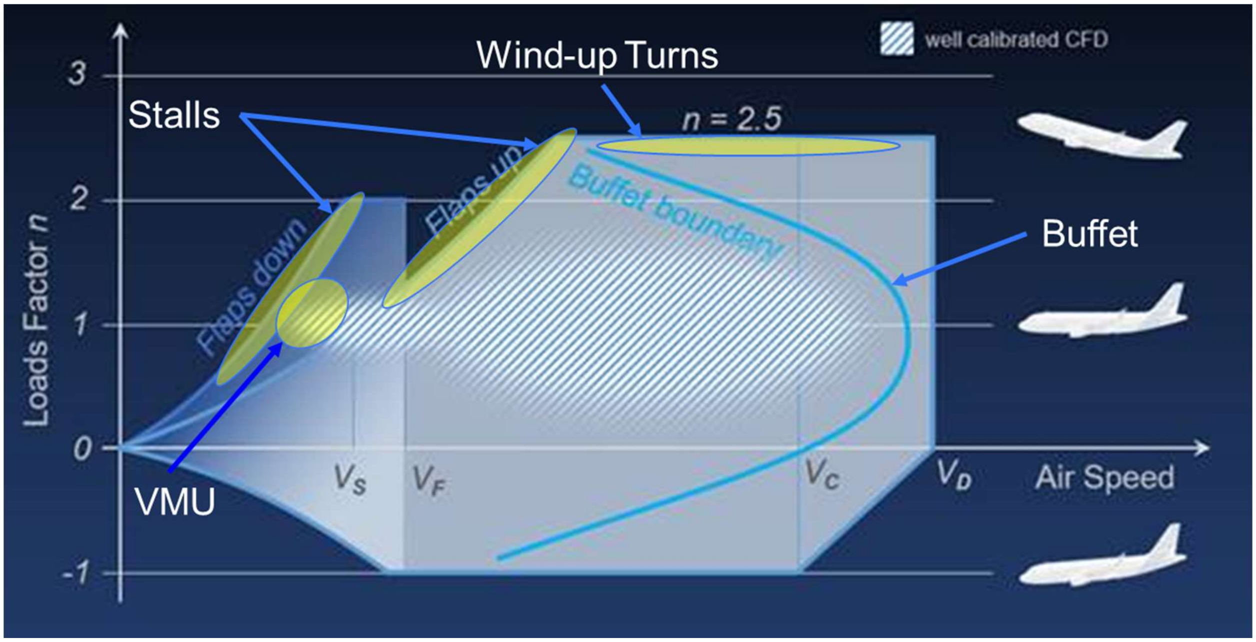


Figure 3. *Illustration of current analysis capability for several Part 25 certification applications.*

vortical features in the compressor and their impact on stability, and spray atomization and combustion modeling particularly at low power. Additionally, today's routine engine CFD simulations are limited to a single component: a fan stage, a high- or low-pressure compressor, or a combustor. Geometry is typically fixed, not considering case deformation (impacting clearances) due to thermals or flight loads. Aeromechanics simulations are typically performed with simulated structural modal motion in one blade row with the surrounding geometry fixed. For engine CbA to become viable (i.e., simulate the engine transients typical of engine certification tests), the simulations will need to become routinely multidisciplinary, multicomponent, and transient. A good industry benchmark paper on engine CFD can be found in Reference [13].

Generally, the confidence in numerical predictions from CFD or structural/thermal analyses is based on an extensive experience base, which includes assessment of simulation data with benchmark test cases and in-house validation efforts using legacy products, tests and other simulation tools. Although efforts at estimating overall simulation errors may be performed, such as using grid refinement studies to assess discretization error, rigorous uncertainty quantification (UQ) techniques are seldom utilized in these analyses. Therefore, a major unaddressed requirement exists in the development and maturation of computational tools and methods for CbA, where confidence in the accuracy and reliability of numerical predictions is paramount, due in particular to the safety considerations being verified through certification. Similarly, most current applications of numerical prediction tools are deterministic in nature, often using a single simulation run at a fixed set of flow conditions to produce a deterministic result. With the expected focus on UQ for CbA, single deterministic runs will be gradually replaced with ensemble runs, where large sets of simulations are generated to determine a probabilistic or imprecisely-known outcome, resulting in rapid growth of required computational resources.

Today, showings of compliance to certification requirements generally rely on a combination of physical testing and flight modeling, but not on flight modeling alone. However, where flight modeling tools are shown to have sufficient accuracy, analysis-based substantiation has been accepted on a case-by-case basis. As an example, regulatory agencies have accepted RANS CFD analyses as an acceptable means of compliance to show that the addition of a radome on the fuselage of a previously certified airplane would not affect the original compliance demonstration for 14 CFR 25.251(b), which ensures that "the airplane must be demonstrated in flight to be free from any vibration and buffeting that would prevent continued safe flight in any likely operating condition." An

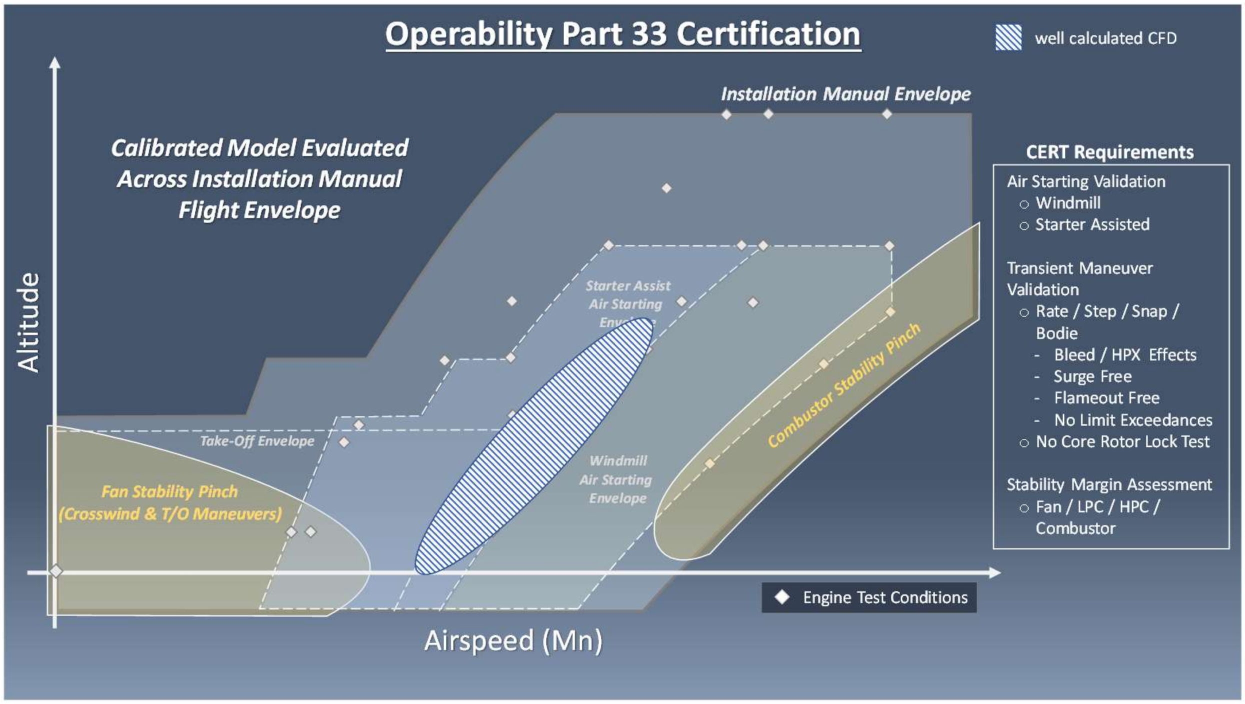


Figure 4. *Analysis capability for Part 33 certification.*

Equivalent Level of Safety (ELOS) finding for compliance of a large antenna and radome installation on Airbus A330-200 series [14] and Boeing 737-8 series [15] airplanes describe the details of these analysis-based compliance cases. An ELOS finding is generally required in cases where direct compliance to certification regulations is not shown, but where other factors and/or approaches provide the same level of safety. These documents include broad statements on how CFD analyses should be performed to obtain a sufficiently accurate numerical result.

To date, CFD has not been directly utilized for engine CbA applications. However, other types of analytical approaches are often used to support engine development and certification testing. These include scaling analyses, analyses to determine test conditions and pinch points for ground testing, and structural/dynamics analyses for additional release positions complementing fan blade-out testing.

As modeling tools become more sophisticated and complicated, enhanced tools will be required to manage the traceability of analysis data and artifacts and to ensure that established procedures and processes are used in the generation and archiving of the provided analysis results. This highlights that, in addition to the basic CFD and more complex multidisciplinary simulation technology development required to expand the applicability of numerical analysis to the edges of the flight and engine operating envelopes, ways to ensure data integrity, provenance, and retention will be critical to expanded use of CbA. These systems will need to be agile to keep up with new technologies and design changes introduced during the product development process. Current initiatives aimed at implementing Model-Based Engineering (MBE) within the Digital Thread will facilitate focus in this area. Additionally, commercial Product Lifecycle Management (PLM) products are beginning to integrate management of design analyses.

Over the past several years, there has been a growing acknowledgment within government regulatory agencies that physics-based numerical simulation methods (e.g., CFD) are maturing to the point where consistent guidance is required on the expanding use of flight modeling methods for showing compliance to certification requirements. In parallel, airplane and engine manufacturers are investigating a wide range of emerging numerical simulation technologies, and have established several industrywide initiatives to explore the viability of CbA over a wider range of potential applications. To this end, an industry-led CbA community of interest (CoI) was recently established at the American Institute of Aeronautics and

Astronautics (AIAA) to specifically address the issue of establishing increased consistency and confidence in the CbA approach. The first major effort of the CoI was the development of recommended practices in the use of flight modeling to support aircraft certification [6].

AIAA Community of Interest Recommended Practices for CbA

1. Documentation of the flight modeling analysis, including management of the analysis configuration, model inputs, version control of analysis processes and data, etc.
2. Verification that the model was implemented as intended and produces results as expected
3. Verification that the model was applied correctly for the specific analysis used for the showing of compliance
4. Validation of the model against real world data
5. Justification that the flight modeling analysis proposed is adequate for the compliance application
6. An overall applicability confidence assessment, which if deemed sufficient, demonstrates that the compliance to the certification requirement is achieved with the same level of confidence as if compliance had been shown based on flight testing.

These recommended practices are expected to guide how future advances in simulation capability can be applied effectively to CbA, and will help form a narrative that encourages continuous improvement and development of modeling best practices.

Efforts are also underway within EASA to develop and publish a Certification Memorandum on the use of modeling and simulation methods for showing compliance with structural Certification Specifications (CM-25) [16]. Many of the same important elements of the AIAA recommended practices documents are utilized in the draft document, including model verification and validation, errors and uncertainties, the use of extrapolation and similarity, experience and expertise of the analysts, and proper documentation and record keeping. Additionally, the FAA has recently issued AC20-146A, Methodology for Dynamic Seat Certification by Analysis [17]. Currently, there are not any specific funded industry/regulatory efforts for engine CbA in the public domain. However, the above publications may provide guidance for some near term engine CbA problems such as fan blade-out.

V. Gaps and Impediments

To better evaluate the advances that are necessary to enable an enhanced level of certification by analysis in the future, the current status of CFD-based simulation technology and expected requirements for CbA are addressed from several different perspectives.

First, the study team considered a range of representative airplane maneuvers for Part 25 and engine tests for Part 33 that encapsulated simulation requirements for CbA, as mentioned earlier. For these CbA applications, a detailed gap assessment of current simulation capabilities was performed, which is described in Appendix A. Then, initial community feedback concerning the use of analysis for airplane and engine certification was collected via an online survey. The survey posed questions designed to identify subject matter expert opinions in several important areas, including the future outlook of using analysis for CbA, key technical impediments and challenges, and where future investment is most needed. While the community expressed optimism for CbA, the primary risk items identified were associated with multidisciplinary analysis, including the human interface, and developing confidence in the results through validation and uncertainty quantification. Lastly, a follow-on, multiday workshop was held to further collect and refine ideas and recommendations, primarily through breakout sessions in each of four topic areas: technology development, system-level integration, verification and validation, and uncertainty quantification. These discussions clarified key considerations and provided additional information that identified present shortcomings and requirements to realize CbA. A detailed summary of the survey and workshop is provided in Appendices B and C, respectively.

Through consideration of representative maneuvers and engine tests by the study team and the community survey and workshop feedback, a comprehensive set of key simulation limitations was developed and classified in three categories: *technical shortcomings*, *logistical shortcomings*, and those relating to *analysis credibility*. Technical shortcomings refer to analysis capabilities that are not currently available and that require future method and/or tool development. Logistical shortcomings refer to analysis capabilities that are available today, but that require dedicated resources, such as HPC, to effectively bring to bear for CbA applications. Analysis credibility refers to the extent by which the results of the analysis capability can be trusted for use in CbA applications, and involves simulation accuracy, validation, and the identification and characterization of various sources of uncertainty in the simulation result.

In the sections below, we first present examples from a gap analysis for selected maneuvers to highlight the approach taken to initially define simulation gaps and impediments. Then, we synthesize all study team and community feedback to discuss the critical simulation gaps and impediments germane to CbA in the three categories defined above.

Analysis of Selected Airplane Maneuvers and Engine Tests

A technical gap analysis was performed to identify an initial set of simulation gaps and impediments associated with the CbA applications considered for this study. The approach taken was to identify the critical elements of the particular airplane maneuver or engine test, and identify the details of modeling that could be performed to generate the same type of data that would be employed in the certification process. The specific details of the required numerical analysis (e.g., flow conditions, geometric configuration, etc.) either replicate the certification test exactly, or are slightly modified to take into account the way in which a simulation would likely be performed in practice. For instance, to determine minimum unstick speed (VMU) during a flight test, velocity is increased until the airplane lifts off at a given weight. However, in numerical modeling, the simulation would be performed at a given velocity, and the predicted lift at a given airplane angle-of-attack determines the aircraft weight at the liftoff condition. In this case, the flight modeling would be considered successful when the airplane speed, weight, and attitude measured in flight test matches the numerical result to within a certain accuracy.

Stall Regulations

Stall certification is principally governed by three FARs: 14CFR25.103, 14CFR25.201, and 14CFR25.203. Together, these regulations provide guidance on the specification of stall speed and demonstration of stalls. The actual flight test demonstrations are guided by AC25-7D. One of the attractive elements of doing stalls with analysis is that the analytical implementation can be put in place incrementally, adding complexity and additional features as technology and capabilities mature.

The first regulation, **14CFR25.103 - Stall speed**, defines how the reference stall speed is determined. A reference stall speed is required for all flap settings. In flight testing, this speed is determined by reducing the airplane speed by one knot per second with longitudinal controls, with the airplane properly configured for that particular flap setting, trimmed for straight and level flight, with the engine power at idle, for the least favorable center of gravity (c.g.). The analytical approach will be different, likely performed by running several numerical simulations to identify the angle-of-attack where $C_{L,max}$ occurs. This calculation may be complicated by the need to have a trimmed configuration to accurately capture the pitching moment. However, the critical element of these simulations is being able to accurately predict $C_{L,max}$ at every flap position.

The second regulation, **14CFR25.201 – Stall demonstration**, along with elements of AC25-7D, defines details on the various stall tests that need to be performed. This expands the requirements beyond stall speed to include stalls during banked turns, and power-off stalls at additional airplane weights and configurations (e.g. landing gear, spoilers, flaps, c.g., etc.). Elements of this regulation can be used as an intermediate milestone between accurately predicting clean-wing, straight and level stall speed and accurately predicting the proper stall and post stall characteristics as indicated by the “Turning Stall” CbA application on the roadmap.

The third major regulation governing stalls, **14CFR25.203 – Stall characteristics**, defines minimum acceptable handling qualities leading up to, during, and after airplane stall and recovery. This aspect of stalls prediction is especially difficult to determine using analytical means only, since the assessment of handling qualities is generally subjective and informed directly by a pilot response. Currently, no analysis method exists that has adequately coupled numerical aerodynamic analysis and pilot feedback or input.

During flight testing, the Stall Demonstration and Stall Characteristics regulations are evaluated concurrently for both level flight and turning stalls.

A subset of CbA applications — airplane stall, fan blade containment, and engine operability — are presented as examples that highlight the critical gaps and impediments in simulation capabilities that must be overcome. Additional examples are discussed in Appendix A.

Airplane Stalls

Airplane stall speed testing involves decreasing the airplane speed at a specific rate, and determining the speed and load factor at which stall ($C_{L,max}$) occurs. Numerical analysis would likely be performed differently, such as increasing the airplane angle of attack until the configuration attains maximum lift ($C_{L,max}$). This requires a numerical analysis method that can precisely determine the location and extent of smooth body separation for full-scale flight geometry and complex interactional flow fields, such as the slat wake/main wing boundary layer interaction, for instance. Furthermore, at $C_{L,max}$, the wing and high-lift components are highly loaded, and their aeroelastic deformations must be precisely known in order to properly model the element gap distributions. Additionally, stall testing often involves the presence of simulated ice shapes, which are determined from several critical flight conditions. An accurate numerical analysis involves the integration and aerodynamic performance impact of many finely detailed ice shape parts with defined surface roughness. Finally, accurate aerodynamic trim prediction and computation of installed engine thrust may be required to properly assess a match against flight test data.

Beyond identifying the clean and iced stall speeds for various airplane configurations, pre- and post-stall handling characteristics must also be characterized. This requires the ability to numerically predict the large scale effects of massive flow separation, such as loss of control-surface effectiveness, etc. Correct resolution and capture of important off-body features such as wake propagation and vortical flows are necessary to evaluate critical flow impingements and airplane handling effects. System level capabilities are required to properly incorporate pilot feedback and flight control system interaction, both in the flight and flight simulator environments. Precise calculation of airplane moments and control derivatives is required to appropriately describe airplane handling qualities. Proper hinge moment calculations ensure that there is sufficient control authority in a post-stall condition.

Currently, analysis methods are lacking in all stall-related testing maneuvers. The results from the 2017 AIAA High Lift Prediction Workshop 3 [18] demonstrated a significant challenge for RANS methods to predict $C_{L,max}$ for a range of reasons, but the two scale-resolving methods presented (Lattice Boltzmann [19] and hybrid RANS/LES methods [20]) showed significant improvement in avoiding spurious separation near the wing tip of the JAXA JSM configuration. A significant number of scale-resolving simulations are planned at the 2021 high lift prediction workshop, reflecting increases in capabilities over four years. However, even very large, time-dependent scale-resolving simulations with significant mesh refinement are not presently reliably capturing $C_{L,max}$ for wind tunnel models [21]. Typically, separation is prematurely predicted and is much more dramatic than observed in wind tunnel experiments. Details such as slat bracket wake interactions with wing boundary layers appear to be critical for accurate prediction of separation physics. Smooth-body separation and separation at the wing fuselage juncture often are not properly predicted changing not only the $C_{L,max}$ estimate, but also significantly modifying the stall characteristics (particularly the pitching moment). Wind tunnel models are typically stiff enough that aeroelastic effects in the tunnel are small, but flight vehicle aeroelastic deformations are even larger and tend to be more complex. Most likely, simultaneous simulation of the proper wing structure and the flow field may be required to generate sufficiently accurate solutions for certification; however, full aeroelastic simulations are not currently practical in a production setting. Beyond these simulation requirements exist further multidisciplinary prerequisites for certification considerations including predicting formation and shape of ice accretions and their associated aerodynamic impact and post-separation control surface effectiveness. When assessing stall characteristics, it is also necessary to account for vehicle dynamics and pilot feedback/control. Given the current inability to predict $C_{L,max}$, this level of analysis is not even considered at present and will need to be developed. Present (insufficient) simulations are being performed with more than 200M control volumes and time steps on the order of microseconds [20], with simulations requiring seconds of convection times to establish. Each simulation requires significant computational resources, and as $C_{L,max}$ calculations are expanded to include multiple control surface settings, aeroelastic deformations, and icing conditions, computing cost will rise by orders of magnitude. Because flight test stall speed measurement accuracy is about 1%, simulations must predict $C_{L,max}$ to a similar level of accuracy. Presently, uncertainty from current RANS simulations is much greater than this.

Methodology gaps:

- Accurate prediction of $C_{L,max}$, and the angle-of-attack where maximum lift occurs.
- Robust tools for the preparation of complex full-scale flight geometries for simulation
- Robust and efficient tools for generation of large-scale grid modeling for simulation
- Accurate determination of all airplane component aeroelastic deformation in flight
- Accurate determination of post-stall aerodynamic characteristics
- Accurate prediction of the effects of predefined ice shapes on aerodynamic performance
- Accurate prediction of vehicle dynamics and stick force

Fan Blade Containment

The Part 33 Fan Blade Containment certification test is a single engine test that essentially destroys the test asset. As a result, it is both an expensive test and a good target for CbA, since current-state dynamics/structural modeling capability for this test is well advanced and computationally achievable. The test is required to demonstrate that: (1) fan blade is contained, (2) fan-blade-out does not result in a fire, i.e., deformation/loads do not cause a breach of fuel/oil systems, (3) fan-blade-out does not fail the mounts or flanges, and (4) post fan-blade-out the engine shuts down safely, i.e., throttle pull back allowed after 15 seconds, and properly functioning Electronic Engine Control (EEC) after sustaining event loads. Fan blade containment can be predicted with sufficient accuracy today with transient structural analysis. Predictions of mounts and flange loads are also close. Fire prediction (severing of fuel/oil systems) is challenging, as it requires more complex engine systems/geometry, and improved external component material deformation characterization is needed. Engine shutdown also remains a challenge. While modeling EEC functionality will be possible in the near term, predicting timing between compressor surge versus severed shaft / turbine overspeed and uncontained failure remains challenging. Significant validation work versus legacy engines or current programs will be required. A combination of a rig with transient structural analysis could be used as an intermediate step.

Methodology gaps:

- Need to include more engine systems/geometry in the analysis
- Component material (elastic/plastic) deformation characterization
- Prediction of timing between compressor surge vs turbine overspeed for severed shaft; modeling improvements needed for shaft rubbing/heatup leading to shaft failure

Engine operability

Engine Operability tests need to demonstrate safe engine operating characteristics throughout its operating envelope, including stability pinch points, relight, rotor lock, and windmill. These tests are conducted both on the ground and in the air using flying test beds. Typical transient maneuvers tests have the following pattern: dwell several minutes at a given condition, execute transient behavior, repeat. A significant amount of flight testing is performed to determine fuel scheduling to keep the combustor operating at or near peak efficiency throughout the flight envelope.

Predicting compressor operability at a given part-power condition still remains a challenge, despite recent improvements in unsteady CFD modeling. Prediction of stall depends strongly on clearances, which are asymmetric due to thermal gradients and maneuver loads. The starting model needs to be elaborate enough to include air starting, ground starting, models of the fuel system, bleed system, and to correctly represent available starter torque. Combustor relight predictions may require full-wheel analysis with detailed models of the fuel delivery system. Compressor and turbine maps at sub-idle/windmill are hard to determine and are critical for combustor start and engine spool-up procedures.

Key flow physics are loss of stability in compressors and fuel spray atomization, and combustor efficiency, lean blow out and ignition modeling at off-design conditions (low pressure and temperature, and swirler pressure drop).

Methodology gaps:

- Compressor operability at part power – aerodynamics of endwall features with variable, uneven clearances
- Transient clearance modeling
- Combustion efficiency fall-off, lean burn-out (LBO); fuel spray atomization in the combustor at low pressure-drop and colder temperatures

Technical Shortcomings

The lack of robust and efficient methods that extend analysis to the edge of the airplane and engine operating envelopes, necessary for CbA, represents a substantial, large-scale technical challenge. Several key technical shortcomings were identified that must be addressed:

1. Enhanced physical modeling. The prediction of effects of separated flows, remains a key shortcoming that was identified as the top technical roadblock in the survey. Prediction of separated flows is highly pertinent to both Part 25 and Part 33 testing for CbA, which is largely performed at critical conditions near the edges of the operating envelope where the effects of flow separation dominate system performance. In characterizing off-design performance, surface roughness effects and transition from laminar to turbulent flow play a major role. Many critical Part 25 maneuvers require the inclusion of detailed propulsion models that increase modeling complexity from current practices, particularly to adequately model a wide range of spatial and temporal engine responses and to properly model key aerodynamic effects during engine-out conditions. Part 33 test simulations also need enhanced combustion modeling and better treatments for multiphase flows such as fuel spray atomization in order to better characterize internal flows and assess engine operability limits. Additionally, tight tolerances necessitate improved modeling of engine components accounting for large stress and thermal variations. Modeling of icing effects and the impact of icing on engine performance are important for multiple tests. Almost all of these simulations require transient modeling.

2. Accurate Configuration Geometry. To properly support critical airplane maneuvers and engine tests for certification, accurate representation and definition of the full-scale airplane and engine test configuration geometry is required. The geometry modeling methods that power current computer-aided design (CAD) software tools do not follow a common standard, and as a result, consistent representation of geometry surfaces in CFD simulation is problematic. Furthermore, the survey highlighted that detailed understanding of the geometry of operating airplanes or engines is a key challenge. Limitations also exist in rapidly generating the large computational meshes, and perhaps curved elements for higher order discretizations, required for CbA applications. Methods need to be developed that can assure adequate mesh resolution throughout complex time-dependent flow fields.

3. Efficient Numerical Algorithms. Meeting complex modeling requirements will require significant enhancements in efficiency and robustness for solution algorithms used in computational tools. Accurate representation of turbulence structures and pressure waves will require solution techniques that feature reduced numerical dissipation compared to current practice. Since simulations will be performed for longer simulated duration times, highly computationally efficient algorithms must be developed and implemented to greatly reduce time to converged solution. Along with enhancements in algorithms, dramatic focus on method development for uncertainty quantification and error estimation for the single- and multidisciplinary analyses envisioned for CbA will be critically needed.

4. Robust Transient Multidisciplinary Analysis. For numerical simulation to be successfully applied to CbA, the single point, fixed-geometry, steady-state or periodic unsteady CFD analysis mindset requires a paradigm shift toward the effective coupling of multiple disciplines in a transient simulation. The survey respondents identified not only typical multidisciplinary considerations, but also highlighted the need to model maneuvering vehicles and capture complex system interactions including human interaction in a range of poorly defined flight environments. Although great strides have been made in the area of multidisciplinary analysis, the complexity of most certification test and maneuver conditions demands a new approach to integrating the interconnected discipline analyses. Accomplishing this will necessitate developing robust strategies for integration at a transient analysis level, including the ability to efficiently support multiple time scales and associated coupling of uncertainty and error estimation. Disciplines including fluids, structures, thermal management, and controls need to be considered, as well as human interaction to capture the pilot's response and interpretation.

Logistical Shortcomings

While less visible, there are also significant logistical issues that must be overcome to realize the objectives of certification by analysis. This is most evident in considering the number of large-scale simulations that are required to obtain the necessary performance data across the flight envelope, although much less visible is the number of simulations needed for prediction of uncertainty quantification or sensitivity analysis. Most maneuvers will require many dozens of individual simulations of complete vehicles to provide the insight necessary for meeting the basic certification requirements. In addition to the computing power necessary to complete these in an appropriate time frame, there are significant requirements on network and storage that also must be considered. Presently, execution of the types of simulations required, with an appropriate turnaround time, strains even leadership-class computing resources. This situation will only worsen as additional disciplines are incorporated. Since large aerodynamic databases are required to populate simulators, the computing requirements will grow exponentially. Appropriate strategies need to be developed to facilitate execution of this class of simulations.

Specific logistical challenges include the computational resource requirement to be able to run a large number of long running cases, multidisciplinary simulations with disparate temporal and spatial scales, and nonstandard interfaces, validation model traceability, standardized or recommended UQ practices, and appropriate regulator engagement.

CbA for engines will require a shift from today's typical "unsteady" simulations spanning a few turbomachinery rotations (milliseconds) to transient simulations running seconds or minutes of real-time. In addition, multiple engine components will need to be included in the simulations, in a coupled fashion. This will require an increase in computational throughput, or more importantly, a 10,000x reduction in computational cost required relative to today's capability [9]. Similarly, a representative database used to populate a flight simulator for a commercial airplane will use hundreds of thousands of data points across a wide parameter space, including Mach number, altitude, angle of attack, angle of sideslip, control surface deflections, and throttle settings, to characterize performance, as well as dynamic effects. This level of database resolution will require an approximate 1000x increase in the number of additional CFD solutions that must be generated in an equivalent amount of time compared to present practice – and many of these will be time-dependent. This also suggests a required increase in computational throughput of at least 10,000x. Assuming Moore's law holds for doubling throughput every 18 months, this required level of throughput increase would be available in 20 years, but there are presently significant concerns about the validity of this assumption.

Developing guidelines on CbA with regulators represents an entirely different class of logistical challenges than was identified through the survey and workshop. Some present requirements need to be interpreted or rewritten to reflect use of analysis. Likely, these will best be addressed directly by OEMs and the regulatory organizations.

Credibility Expectations

Airplane certification requirements will provide the need for highly accurate and reliable numerical solutions and drive many stringent simulation requirements, including those associated with moment predictions, control power assessment, and the prediction of maximum lift coefficient. Similarly, engine certification simulations will require accurate and reliable solutions for turbomachinery vibratory stress, compression system stall margin, combustor lean blow-out and ignition, among others. These simulations are often required in scenarios that will involve incipient or significant flow separation throughout an event and hence require detailed modeling with low numerical errors for extended periods of time. Sample target levels of accuracy specific to individual Part 25 and Part 33 tests are provided in Appendix A. These accuracy levels represent the level required to adequately demonstrate future technology readiness for those particular certification tests.

To confirm the desired level of accuracy will require detailed validation experiments at both the canonical and full-scale level. The need for developing comprehensive and accepted approaches for validation was clearly recognized during the workshop. Verification and validation needs to be performed not only for single discipline and multidisciplinary analysis, but also for system-level analysis representative of CbA applications. Additionally, the development of "validation-domain" to "application-domain" extrapolation methods is required because validation data will not be available at all the points where the analysis is desired. Large-scale validation campaigns are needed to provide an abundance of validation data to address validation domain extrapolation concerns. Furthermore, appropriate methods to identify and estimate various sources of simulation error (for example, isolating discretization error from model-form error) are important to develop confidence in results.

Uncertainty quantification is required due to the sparseness of validation data and the complex flow conditions that exist at real-life conditions of interest. The survey and the workshop highlighted the general recognition that the uncertain effects from flow conditions, manufacturing tolerances, and pilot response need to be assessed. Sufficient uncertainty quantification and sensitivity analyses need to be performed to establish confidence that the predicted results fall within the desired level of accuracy. While many of these techniques exist, they have yet to be rigorously applied at the scales necessary for multidisciplinary time-accurate simulations. Furthermore, the uncertainties will need to be evaluated in the context of controllability of a maneuver, incorporating techniques to also appropriately interpolate uncertainty. Various uncertainty quantification methods such as propagation of error in high dimensional spaces and aggregation of heterogeneous types of uncertainty still lack the maturity required for CbA, and need to be applied across multiple disciplines. Large-scale demonstrations of various UQ techniques such as Method of Manufactured Universes or predictor-corrector methods need to be performed and evaluated. Since ensuring that the flight envelope is within the safe-operating limits of flight systems is an objective of certification, techniques must also be developed to seek out statistically rare events, in addition to the central statistics. Furthermore, UQ methods need to be robust and accurate but not so onerous that they undercut the cost and schedule benefits made possible by analysis.

VI. Technology Development

To address the technical and logistical shortcomings leading to credible and reliable analysis capabilities supporting future CbA, a general framework is developed to guide required technology development, as depicted in Figure 5. This framework is organized in three distinct sections. As shown, key computational *technology development* feeds critical *predictive capabilities*, which taken together, support the specific *CbA applications* detailed in Appendix A. Technology development is envisioned to focus efforts within specific discipline areas. Advanced technologies are then integrated together to provide a spectrum of demonstrated predictive capabilities, highlighting critical needs in multidiscipline coupling and airplane and/or engine level system analysis. These predictive capabilities can then be used with confidence to address the array of CbA opportunities addressed in this report.

This framework provides a logical approach to developing new technologies and capabilities

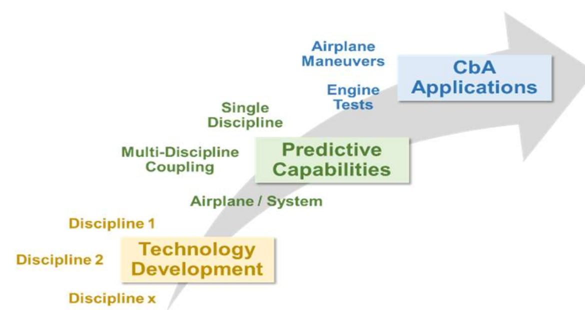


Figure 5. *General framework for technology development.*

required to enable wider use of analysis for certification. This framework serves as a solid foundation in which to identify and organize key technology requirements in a systematic way, linking development efforts to measurable outcomes.

Integrated Road Map

Influenced by input from the survey and workshop, a comprehensive roadmap encapsulating the key technology development items needed to achieve the wide range of applications associated with airplane and engine product certification is presented in Figure 6. This detailed roadmap is built on the framework described above. Specific details from

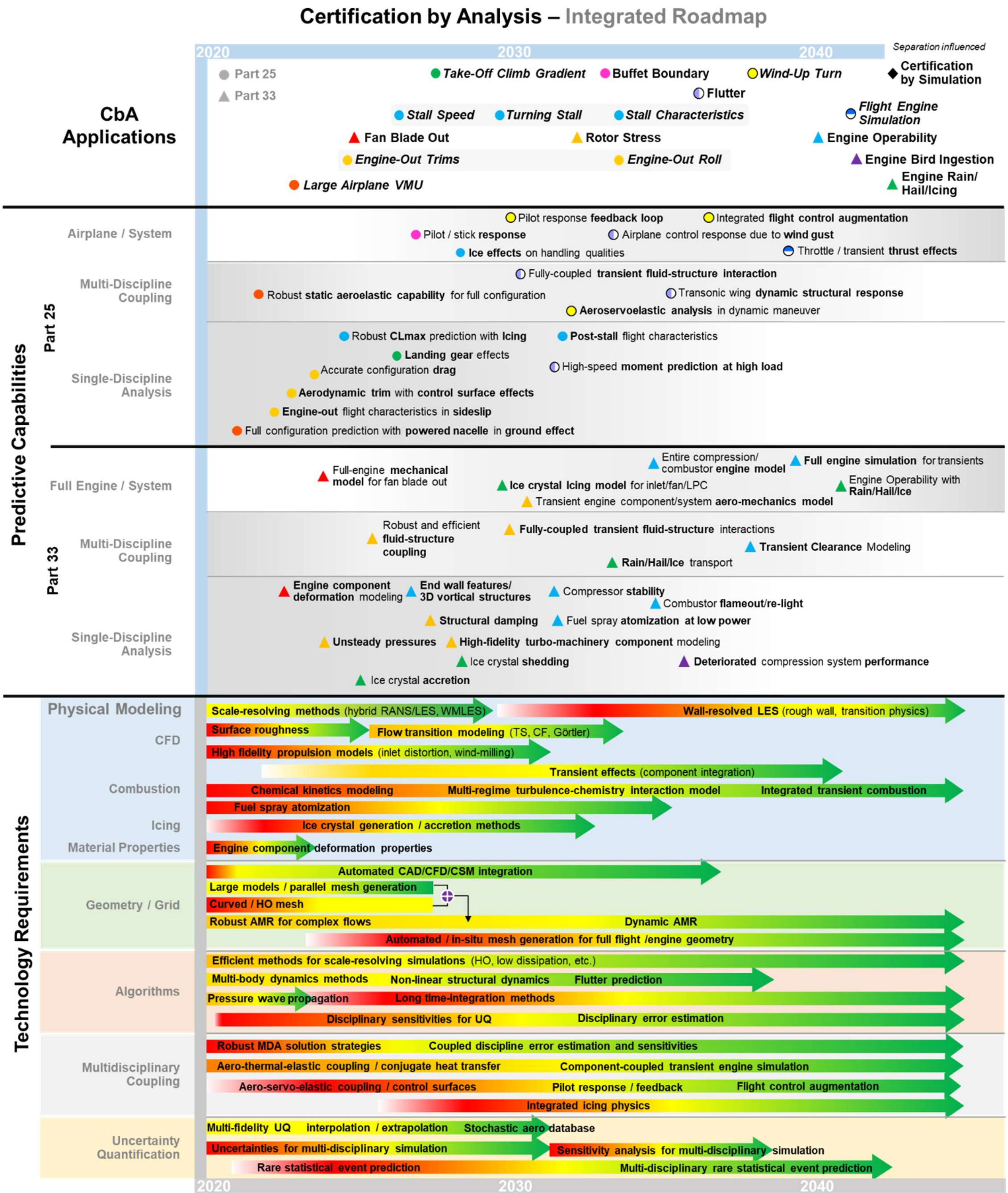


Figure 6. *Certification by Analysis Integrated Roadmap.*

each of the general sections (technology requirements, predictive capabilities, and CbA applications) are provided below.

Computational technology development requirements are provided in five categories: physical modeling, geometry and grid generation, numerical algorithms, multidisciplinary coupling, and uncertainty quantification. These technologies are described in more detail in a following section. Within each category, a series of timelines are defined for important computational technologies expected to play a critical role in supporting future application of numerical simulation for CbA. The timelines are color-coded by Technology Readiness Level (TRL). Green denotes a technology at a high TRL level, which indicates that the technology is ready for production use. Yellow denotes a technology at a medium TRL level, which indicates that the technology has been demonstrated for a representative application. This is considered to be the level that a specific technology becomes available for capability demonstration. Red indicates a technology at a low TRL level, which is at a basic research stage. The end of each timeline is shown with a green arrow, denoting that the specific technology item is at a sufficiently mature level to be readily used at the indicated period along the timeline. Many timelines show arrows that extend beyond 2040, which signifies that elements of the specified technology will likely require a significant amount of development focus and attention over many years to properly mature for application to CbA. In some cases, certain technologies may mature to a high TRL level, but would likely be supplanted by more advanced technology over time. For instance, the "scale-resolving methods" timeline under physical modeling, which currently includes hybrid RANS/LES and wall-modeled LES methods, is expected to be eventually supplanted for certain applications by "wall-resolved LES" methods when that technology sufficiently matures, and when adequate computational resources are readily available. Finally, we have identified one instance where two specific technologies, mesh generation for very large meshes and higher-order mesh generation, will likely develop and mature in parallel. We anticipate a down-select around 2030 to choose the mesh technology foundation for dynamic adaptive mesh refinement, which is expected to play a crucial role for the simulation of highly complex, time-dependent flow-fields for complete airplane and engine configurations in the 2040 time frame.

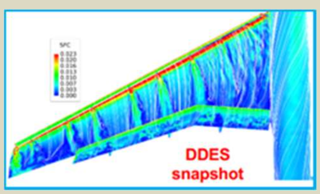
The middle section of the roadmap identifies a set of important intermediate predictive capabilities that define integrated technology waypoints to enable simulation for the certification applications. These items are detailed more in Appendix D and represent specific technology demonstrations that support particular certification applications. In general, these demonstrations combine different technologies in a relevant engineering problem that can be supported by data from a physical experiment for validation. The objective of the specific predictive capabilities listed on the roadmap is to provide a hierarchy of check-out cases that would be used to build confidence that the relevant technologies have been properly validated prior to the certification application assessment. These tests follow the traditional validation hierarchy of single-discipline component, multidiscipline component, subsystem, and complete system. For CbA, emphasis is on integrated system multidisciplinary applications because this level of validation will not be readily assessed from consideration of individual technology requirements.

Because of the ability to test these as engineering solutions, the identification of the key predictive capabilities associated with a particular CbA application represents an important step toward enabling certification by analysis. In general, the roadmap is set up to provide a connection between the fundamental technology requirements and CbA applications of interest. Intermediate predictive capabilities establish a pragmatic bridge from the development of fundamental technological expertise to the complex certification requirements. Certification requirements drive technology development, and intermediate predictive capabilities provide a meaningful measure of real-world maturity. On the roadmap, a common symbol is used to link each CbA application to its unique set of required predictive capabilities. In most cases, predictive capabilities associated with one CbA application will also be critical to the successful demonstration of later CbA applications. The location of each predictive capability on the timeline links with the underlying technology requirement timelines, and suggests a rough priority order in which to focus attention on technology development. The specific CbA applications called

CASE STUDY 1: EXTENDING CFD TO THE EDGES OF THE FLIGHT ENVELOPE: $C_{L,MAX}$ AND STALL PREDICTIONS

Clearly, one of the largest impediments to CbA is the inability of current CFD methods to deliver reliable predictions for conditions at the edges of the flight envelope. Despite over 20 years of improvements in RANS turbulence modeling capabilities, the ability of these methods to predict aerodynamic phenomena driven by flow separation has not shown significant improvement, as documented by the collective $C_{L,max}$ predictions over the course of the High-Lift Prediction Workshop (HLPW) series. Today, there is a growing realization that scale-resolving methods such as LES may be required to significantly improve predictive capabilities for separated flows. This is reflected in the recent focus of the NASA TTT project on scale-resolving methods, along with the stated goal of predicting $C_{L,max}$ for transport aircraft with the same accuracy as certification flight tests by the year 2025. The development of CFD methodologies that can reliably predict incipient smooth-body separation, as well as flows with massive regions of separation, would have a revolutionary impact for both the product development phase and for CbA. This will result in improved predictive abilities not only for $C_{L,max}$, but also for sideslip conditions, control-surface effectiveness and post-stall conditions, that will enable CFD to be used throughout the flight envelope including at the extreme conditions associated with many certification maneuvers. The assessment of CFD requirements for accurate prediction of maximum lift and stall events represents an appealing near term case study within CbA, partly due to the fact that this can be confined to a single discipline (i.e., CFD) and validated using affordable ground-based testing in existing facilities.

Following the delineation of technology developments in the CbA roadmap, the physical modeling requirements necessarily involve the use and development of suitable subgrid scale turbulence models for large eddy simulations. At the same time, in order to reduce resolution costs, either hybrid RANS-LES or wall-modeled LES methods will likely be dominant in the near- to midterm. The latter includes lattice-Boltzmann methods (LBM), which require wall models to be competitive for aerodynamic applications. This entails the development of suitable near-wall models, and laminar to turbulence transition models, along with careful consideration of the transition from near-wall to full LES regions away from the wall. In particular, all models must converge reliably to physically accurate solutions with increasing grid resolution. Algorithmically, discretizations that exhibit low dissipation properties must be sought, in order to ensure the unresolved eddies are handled by the physical models rather than by uncontrolled numerical dissipation. These may involve high-order discretizations and/or more traditional second-order accurate methods, although in both cases, special attention to nonlinear stability and efficient long-time integration will be required. Geometry and static/adaptive mesh requirements can be leveraged from on-going work for highly resolved RANS methods (for both low and high-order discretizations), although in general, higher resolution meshes will be required. Furthermore, dynamic AMR methods will need to be considered for cases where vortical flow features and wakes generated by flap edges/control surfaces/nacelle chines etc. impact other geometry components. At the same time, a concerted effort to quantify the uncertainties associated with these simulations will be required. On the one hand, this involves propagating the uncertainties associated with the geometry OML as well as aleatory uncertainties in flow conditions and their effect on $C_{L,max}$. On the other hand, the impact on predicted $C_{L,max}$ or other simulation objectives of the various numerical errors incurred by the simulation will need to be estimated including time-dependent spatial discretization error, temporal error, model form-error and algebraic error for time-implicit methods. Although various scale-resolving simulation methodologies exist today, their use in industry has been held back by the step increase in computational cost of these methods compared to steady-state RANS methods. The increased cost comes not only from the need for higher resolution, but significantly from the switch from steady-state to time-dependent simulations. In order to make these simulations affordable for industrial use, it now seems inescapable that these methods will need to be ported to heterogeneous HPC architectures with GPUs. This includes not only the computational kernels, but all associated operations such as AMR (if employed) and related UQ tasks.



A suite of progressively complex validation test cases will need to be considered for the validation of the proposed simulation methodologies. Simple canonical test cases such as the NASA hump and juncture flow experiment are instrumental in assessing the capabilities of the proposed methods for predicting fundamental physics for separated flows, prior to progressing to more complex configurations where error cancellation may result in misleading conclusions. Full configuration rigid wind-tunnel models such as the CRM-HL have a significant role to play in the validation of these methods for $C_{L,max}$. In particular, the upcoming HLPW4 workshop will assess current capabilities of various approaches, including scale resolving methods for $C_{L,max}$ prediction on the CRM-HL. As these methods begin to show success for $C_{L,max}$ prediction compared to rigid wind-tunnel models, they can be extended to consider more complex cases, such as the inclusion of prescribed ice shapes, turning stalls, and the prediction of post-stall characteristics, as depicted in the roadmap. However, for dynamic cases and eventually in comparison with subscale and full-scale flight tests, coupled aeroelastic (CFD-CSD) and aeroservoelastic simulations will be required going forward. Notably, the coupling of scale-resolving methods with other disciplines such as structural dynamics and controls has not received much attention to date, and will take on additional importance as more complex cases are considered.

out on the roadmap represent the spectrum of airplane- and engine-related demonstrations, which must be successfully performed to achieve the vision of certification by analysis. These represent the different certification tests that were previously identified as candidates for CbA as described in the Scope section. Details of each of the CbA applications are provided in Appendix A.

As an example of the linkages that exist between predictive capabilities and CbA applications, demonstrating a successful simulation for large airplane VMU requires the capability to predict both the single-discipline aerodynamics of a powered nacelle in ground effect, as well as model the coupled aerostructural deformation of a full airplane configuration. For other applications, maturing single discipline, multidiscipline, and predictive capabilities at a higher system level are required. For example, the single discipline unsteady pressures predictive capability associated with Part 33 is focused on being able to simulate detailed temporal loading that takes place within the rotor/stator, including formation of shock waves. This then leads to having a "fully-coupled transient fluid structure interaction" capability, reflecting the complex coupled fluid-thermo-structural interactions that take place. Once this capability is demonstrated, it is then feasible to consider development of a "transient engine component/system aeromechanics" model. When these three capabilities are available together, it would then be possible to perform a detailed rotor stress analysis.

To support efforts within the aerospace community in identifying key investment opportunities that address CbA objectives in the near term, a separate roadmap directly linking key technology requirements to achievable predictive capabilities for a subset of the CbA applications over the next decade is provided in Figure 7. Within this roadmap, items identified under technology requirements, predictive capabilities and CbA applications are linked together with symbols with matching colors. The items identified on the "technology requirements" timelines suggest more specific technology development areas on which to focus resources. For the most part, this development is foundational, and represents the essential technology elements required to demonstrate critical predictive capabilities. Also, the CbA applications, as near-term objectives, will help prioritize the order in which the foundational technologies are developed, and how they are validated to deliver predictive capabilities. For instance, near-term consideration of airplane stall prediction is driving many technology development activities currently ongoing within NASA TTT and ARMD, including development and assessment of scale resolving simulation (SRS) methods to predict turbulent separated flows, icing tool development and validation, and continuing maturation of industrial adaptive mesh refinement (AMR) techniques. Within the engine propulsion community, scale resolving simulation methods are being evaluated for prediction of mixing and endwall flow features in turbomachinery, and are used more routinely in combustor simulations. Additionally, several key technology development areas within the uncertainty quantification (UQ) timeline are identified with black diamonds to signify their importance for all of the CbA applications that are considered in this report, suggesting that large and sustained investments in UQ method development are critically needed at this time.

The roadmaps presented here are more complicated and intertwined than the CFD Vision 2030 map because certification is an integrated multidisciplinary problem. The CbA roadmaps build on the CFD Vision 2030 effort and share many of the same features, since CFD is an important tool for future CbA efforts. However, there are other requirements that require longer term development because of the multidisciplinary nature of the simulation. Presenting these disparate elements on a single page is difficult due to the wide variety of necessary technologies and capabilities.

In the following sections, the individual technology development areas on the road map are discussed in more detail. This is followed by other considerations that do not appear explicitly on the road map, such as traceability, data fusion and the impact of emerging technologies such as machine learning.

Technology Development Areas

Physical Modeling

Clearly, a CFD capability that can successfully capture all of the relevant flow physics at the edges of the flight envelope must be developed to be able to tackle many of the maneuvers envisioned in this report. The ability to accurately compute flows with

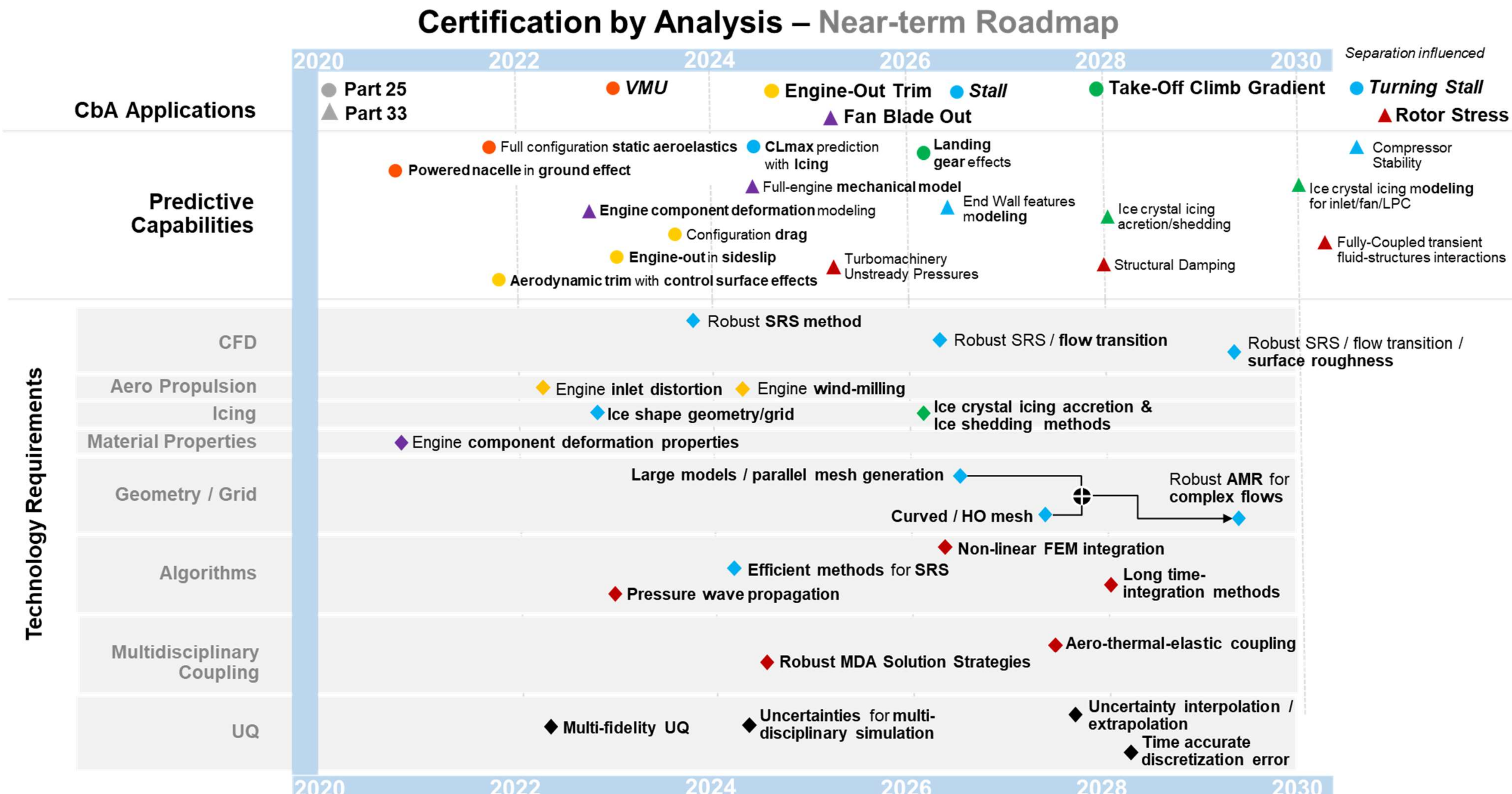
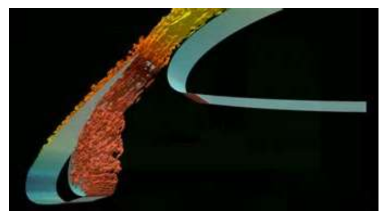


Figure 7. *Near-Term Certification by Analysis Roadmap.*

smooth body separation as well as separated flows with sharp corners is critical for predicting control surface effectiveness, maximum lift ($C_{L,max}$), and stall characteristics. Furthermore, the prediction of accurate integrated airplane and control surface hinge moments and detailed loading will be required throughout the flight envelope including post-stall conditions with regions of massive flow separation. For engine simulations, accurate predictions of endwall vortical structures, including tip clearance flows and corner roll ups, as well as wake formation and convection, are critical, where for example compressor stall margin prediction remains a big challenge. Although current industrial CFD simulations rely predominantly on steady-state Reynolds-averaged Navier-Stokes (RANS) or unsteady RANS (URANS) methods, there is growing evidence that scale-resolving methods will be required to enable the accurate simulation of flows with large regions of separation [22]. This puts an emphasis on the development of improved subgrid scale (SGS) models, including dynamic SGS turbulence models for Large Eddy Simulations [23]. At the same time, the high computational cost of fully (wall) resolved LES methods for flight Reynolds numbers favors the adoption of wall-modeled LES (WMLES) approaches, which in turn emphasizes the need for investments in improved wall models along with their validation. Here, scale-resolving methods encompass a wide variety of discretization approaches, including finite-volume [24], high-order finite-element [25] and even Lattice Boltzmann (LBM) methods [26]. In each case, these models must be developed for their specific accompanying discretizations and validated accordingly. Hybrid RANS-LES models may also have a role to play, for example in engine simulations where laminar-to-turbulent transition may be best handled in the RANS region. Hybrid models inherit all the subgrid scale modeling challenges of LES models, with the additional modeling required for the intermediate regions between RANS and LES.

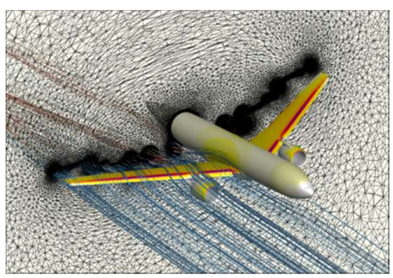
As attention turns to scale resolving methods, it remains difficult to predict which particular approach or approaches may ultimately prove to be the most successful for the accurate simulation of external and internal flows at the edges of the operational envelope. Although promising results have been shown with various methods, conclusive evidence of accurate predictive abilities for separated flows that converge consistently with increasing spatial and temporal resolution over a range of test problems remains to be demonstrated. Furthermore, different methodologies may prove to be best suited for different applications (e.g., external aerodynamics vs. internal flows vs. combustion). In the near term, WMLES and hybrid-RANS-LES methods appear to be front runners mainly as a result of their reduced computational cost, although focus on fundamental modeling developments, which can be applied to various numerical approaches, should remain a priority.

The ability to predict transition at flight Reynolds numbers is important for both aircraft certification maneuvers and engine certification tests. Here, the effect of surface roughness on transition due to surface contamination, ice crystal formation and ice accretion must also be incorporated. Clearly, fully resolving the laminar and transitional regions within an LES simulation will remain impractical for the foreseeable future and some level of modeling will be required. Although there has been growing interest in transition models for industrial calculations [27] [28], these models are primarily intended for use with RANS simulations and emphasis must be focused on the development of transition models for scale-resolving methods in the presence of wall modeling.



Flow physics are not the only areas in need of physical modeling. For example, a range of progressively low-to-high fidelity propulsion models can be envisioned for the simulation of certification maneuvers. At the low end, current engine deck models can be used to provide suitable inlet/outlet flow boundary conditions for powered simulations. However, for more complex cases such as high cross-flow or post-stall conditions, accurate engine response to dynamic inlet distortion is required. At the highest fidelity level, one could envision a complete engine simulation [9] coupled to the external CFD simulation, although the incorporation of detailed combustion effects would likely not be warranted. However, there are various scenarios such as engine-out conditions with windmilling, where the most effective approach may be to simulate the fan and model other engine components such as the core.

Icing plays an important role in the design and certification process, and will need to be considered increasingly as an integral component in the simulation process [29]. The determination, inclusion and gridding of static ice shapes involve various physical modeling assumptions and constitute the entry-level approach for the consideration of icing effects on aircraft performance [30]. At the higher-fidelity end, icing simulations entail a variety of physical models including, droplet impingement, ice accretion and melt run-back. For engine simulations, there is an immediate need to improve physical modeling for ice crystal icing in the low pressure compressor (LPC) for which new certification requirements are likely on the horizon. This comprises modeling ice crystal transport to the LPC, the melting of the ice particles and accretion of the moisture on LPC stators, and shedding of the accreted ice formations. While current modeling approaches exist for all of these icing aspects, continual improvement in the fidelity of these models along with suitable validation must be undertaken in order for icing simulations to be incorporated with scale-resolving simulations and to keep pace with advances in other simulation technologies.



Finally, for engine simulations, significant advances in modeling for combustor operability are needed to be able to simulate lean blow-out and altitude relight. These include the modeling of fuel sprays and atomization, especially at low temperature and atomizer pressure drop, the interactions between turbulence and chemistry, and detailed mechanism finite rate chemistry [31]. Currently, these models are still deemed to be either too computationally intensive or inadequate in terms of accuracy. However, AMR and an in situ chemistry tabulation approach show promise to make the detailed ignition analysis tractable [32].

Geometry/Grid

The ultimate goal of Geometry/Grid technology development is to enable the generation of accurate discretizations for computational fluid dynamics (CFD grids) or computational structural dynamics (CSD models) that conform to the underlying geometry in a fully automated manner. Automation takes on additional importance in the context of certification by analysis, where repeatability is essential and where the dependence of the quality of the simulation outcome on user input must be minimized. The automation process naturally begins with the link between the CAD-defined geometry and the numerical discretizations, i.e., the CFD grid and the finite element structural model (FEM). This coupling must be tight and fully automated, including the ability to add geometric complexity or to defeature the geometry in a traceable manner. This association is important because it represents the essential link between the numerical simulation capability and the digital thread of the product development process. Although commercial software vendors are making significant progress toward linking numerical simulation tools with digital product life-cycle management, the ability to incorporate leading-edge or specialized simulation tools from outside vendors or from government and/or in-house code development efforts remains a bottleneck that will need to be addressed.

The geometric complexity and the required accuracy of the simulations will result in the requirement of generating highly resolved and detailed CFD meshes and CSD models. The routine generation of computational meshes with hundreds of billions of cells will be required in the near future for these types of problems. Alternatively, high-order discretizations may be used with fewer mesh elements, although these discretizations require curved mesh elements in the vicinity of the underlying geometry in order to fully realize their accuracy potential. In CFD as in CSD, both approaches will likely remain competitive for specific applications. Nevertheless, investments in large-scale parallel mesh generation with distributed access to CAD will be required going forward.

Ultimately, adaptive mesh refinement can relieve the burden of generating highly resolved initial meshes while providing more accurate, consistent and repeatable solutions. Although impressive advances in AMR have been demonstrated for industrial RANS problems over the past 5 to 10 years [33] [34], significant issues remain in terms of error estimation for refinement criteria,

CASE STUDY 2: PROGRESSION OF STALLS PREDICTION CAPABILITIES

From FAA-H-8083-3B, Airplane Flying Handbook

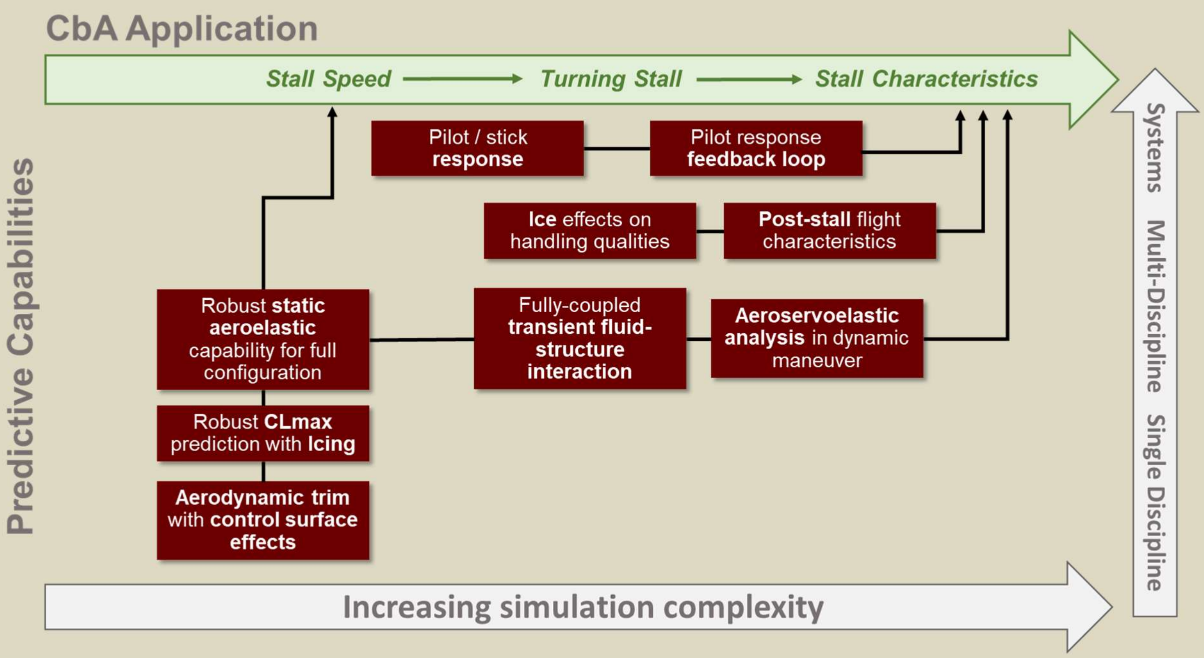
The analytical requirements described for the three regulations defining stalls and stall demonstration were used to inform and populate target CbA applications on the integrated roadmap. The progression in technology demonstration from stall speed to turning stalls to stall characteristics provides a logical and realizable path to being able to eliminate a significant portion of stall testing. As a result, it is instructive to consider these roadmap items as elements along a continuum, where critical predictive capabilities are developed and matured over time, and work together to enable CbA opportunities. In the image below, the specific predictive capabilities identified on the roadmap associated with the three stalls CbA applications are graphically displayed to show this progression. Increasingly complex simulation capabilities (left to right) involving an increasing number of integrated disciplines (bottom to top), supported by appropriate technology development, validation, and demonstration enable Stalls CbA.

For example, for the Stall Speed determination application (shown in the depiction in the upper figure), the critical capability needed is the ability to efficiently and accurately predict $C_{L,max}$, with and without icing. However, other capabilities, such as robust aeroelastic modeling, as well as the prediction of aerodynamic trim with control effects, must be developed and demonstrated in parallel to support this particular CbA application.

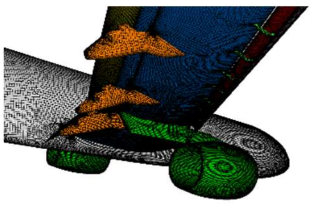
For the Turning Stall application, no additional predictive capabilities are required, other than the increased complexity due to an asymmetric load factor generated by the banked turn (requiring a robust aeroelastic capability), and the progression to a dynamic or time-accurate CFD analysis.

Finally, the Stall Characteristics application effectively links all of the remaining critical predictive capabilities together, and drives the development and demonstration of additional predictive capabilities pertaining to pilot interaction, ice effects on handling, post stall flight characteristics, and more robust aeroelastic coupling.

To emphasize, with current flight testing procedures, stalls are performed in an integrated manner, where multidisciplinary effects and system response are an inherent part of the maneuver. This will certainly be the case for CbA efforts when using analysis for an alternate means of compliance. However, when showing technology and capability maturity, this three step approach provides a measured path to maturing realistic capabilities regarding stall testing.



which must be addressed in the future. Additionally, the time-dependent nature of most of the CbA applications means that dynamic AMR capabilities must be developed and incorporated into the simulation process. Dynamic AMR will be critical for capturing flow features such as wakes or vortical flows, which may impinge on downstream components, in a truly predictive manner, and has been shown to be enabling for combustion and ignition problems, as mentioned above. Although there have been some successes in dynamic AMR CFD, particularly for rotorcraft simulations [35], these techniques must become more widely adopted



and tailored for the problem at hand, which will likely include scale-resolving methods and highly complex moving geometries. For higher-order methods, dynamic AMR (denoted as *h* refinement) must be integrated with dynamic solution order refinement (denoted as *p* refinement) to enable combined *h-p* refinement [36]. Investments in areas such as dynamic refinement criteria and distributed CAD access for surface point placement must also be addressed [37].

Turbomachinery CFD has historically relied on multiblock structured grids. While there are unstructured solvers/meshes that have been used to compute flows in turbomachinery, body-fitted structured grids have been at the core of CFD methodology across the industry. Such a framework presents challenges for local mesh refinement and especially for the automation of such processes. In general, the situation is further complicated by the presence of unsteady features such as passing wakes. Careful consideration needs to be given to grid generation and targeted grid refinement. Incorporating trenches, rubs, end-wall gaps, planform gaps, leakages, cavities and seals, and bleed ports into the CFD model will provide a better geometrical representation of the compression system, and will enable improved predictions, in particular at off-design conditions. Rapid and automated inclusion of such small geometrical features at the end-walls relies on improved gridding methodologies, whether they are based on unstructured meshes with adaptive mesh refinement, or multiblock structured grids with embedded localized refinement using oversetting techniques [38]. As mentioned at the outset, the ultimate goal is the development of a fully automated process where the CFD mesh and CSD model are generated directly from the CAD geometry resident in the product development digital thread, and adapted throughout the dynamic simulation process with no user intervention. This "in situ" mesh generation can be expected to become reality through the logical progression from parallel mesh generation to static AMR and finally dynamic AMR.

Algorithms

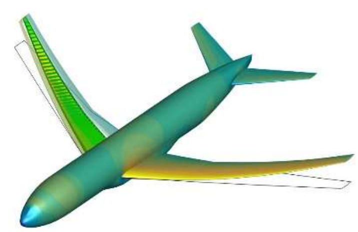
Algorithmic advances will be crucial as more complex and highly resolved simulations increasingly expose the deficiencies in current-day algorithms. Within the realm of CFD, the development of suitable discretizations for scale-resolving methods should be emphasized. Currently both second-order accurate finite-volume methods [24] as well as higher-order accurate finite-element methods [25] are considered viable approaches for industrial LES, and this trend can be expected to continue. However, in both cases, the development of low dissipation and nonlinearly stable discretizations is important for optimizing the accuracy, efficiency and robustness of LES simulations [39] [40]. For engine simulations this will be important for accurately capturing the effect of pressure waves throughout the turbomachinery, e.g., in the determination of rotor vibratory stresses. For structural dynamics, highly resolved geometrically nonlinear models will be required. Additionally, these must include the ability to simulate multibody dynamics necessary for accurately modeling control surface motion, actuation and linkage to flight-control systems, as is often utilized for rotorcraft problems [41]. Furthermore, the increasing size and detail of the required structural models means that more emphasis toward efficient parallel assembly and execution of these models will be required.

One of the defining characteristics of CbA problems is that they entail dynamic simulations over relatively long time periods. For example, current engine simulations are limited by computational resources to a small number of rotor revolutions, which corresponds to O(~100 ms) of real time, whereas, in order to capture transient conditions, simulations of O(~10 seconds) of real time will be required [9]. Therefore, algorithmic advances for time-integration schemes must also be investigated. This should include both frequency-domain and time-domain approaches. Techniques such as time-spectral methods, which offer the possibility of parallelism in the temporal direction [42] [43] may have a role to play here. However, many simulations are complicated by the presence of both stochastic (i.e., turbulence driven) and deterministic (i.e., stator-rotor or flight) time scales, which has limited the benefits of current advanced time-stepping schemes. Advances in the efficiency and accuracy of these methods, as well as control of the accumulation of error over long time periods should be sought. Although many LES approaches currently rely on explicit time-stepping schemes, a strong case can be made for the use of implicit time-stepping schemes for scale-resolving methods, due to the wide range of resolution required for detailed models, particularly in the presence of high-order temporal discretizations [44]. Thus, advances in efficient parallel implicit solvers (linear and nonlinear) will remain a strong driver for both CFD and CSD disciplines.

Advanced techniques for sensitivity analysis and error estimation at the disciplinary level will need to be developed in order for these quantities to feed into a general UQ framework for complex simulations. Disciplinary linear or local sensitivity analysis is commonplace today for RANS simulations using discrete adjoint and tangent methods [45]. However, for scale-resolving methods, which result in chaotic solution behavior, linear sensitivity approaches diverge and obtaining meaningful sensitivities at acceptable computational cost for chaotic problems remains an open problem today [46]. Similarly, current techniques for estimating discretization error must be expanded or replaced with methods that can estimate discretization error for time-dependent problems. Even at the disciplinary level, multiple sources of error must be considered, starting with time-varying spatial discretization error, possibly in the presence of AMR/h-p refinement, coupled with temporal discretization error and algebraic error resulting from inexact solution of the implicit systems at each time step [47]. More focused error estimates for engineering quantities-of-interest (QoI) will be essential for typical metrics of success which arise in certification by analysis. Although it is well known today how these can be formulated through the weighting of general error estimates with adjoint derived field quantities [48] [49], the inability to efficiently compute adjoint sensitivities for chaotic problems will severely limit our ability to compute QoI-based error estimates with scale-resolving methods. Therefore, sensitivity analysis and error estimation at the disciplinary level will remain an important focus area in the near future.

Multidisciplinary Coupling

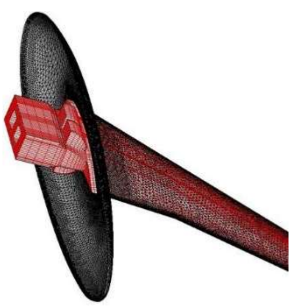
One of the defining characteristics of CbA problems is that they are all highly interdisciplinary. Thus, a new emphasis must be devoted to the realization of efficient and robust multidisciplinary simulations with quantifiable error estimates. Clearly, most simulations at flight Reynolds numbers must include, at a minimum, aerodynamic and flexible structural effects for realistic prediction abilities. For the simpler problems, this may manifest initially as static aerostructural simulations, for example as in VMU or steady heading trim problems, although extension to dynamic aeroelastic simulations will rapidly follow as focus turns increasingly to time-dependent problems. Furthermore, the objective of simulating dynamic flight maneuvers will require the development of coupled aeroservoelastic simulation capabilities with the inclusion of movable control surfaces. Finally, the integration of aeroservoelastic simulations with a flight-control-system model will enable the calculation of pilot feedback and response, and ultimately the simulation of flight-control augmentation effects, all of which represent critical considerations in the certification process. For engine simulations, the conjugate heat transfer problem must be considered at an early stage, since imposing correct thermal boundary conditions has a strong impact on the aerodynamics of engine components, in terms of predicting their performance, operability and durability. In addition, thermal expansion plays an important role in determining the geometry and tolerances of engines in operation. This is followed closely by aerothermoelastic simulation problems, particularly for high loading conditions at the edges of the operational envelope. For coupled component engine simulations, effective coupling of multiple code bases will be required, such as the combination of nonreactive CFD codes for compressors and



turbines with reactive gas codes for combustors and pressure-based (nearly incompressible) codes for low-speed secondary flows.

At the same time, other disciplines will come into play. For example, the simulation of propulsion effects at off-design conditions will require the incorporation of high-fidelity propulsion models into the multidisciplinary framework. These may be as simple as prescribed inlet/outlet conditions as determined from engine deck models, or more complex models which involve the simulation of specific engine components (i.e., rotating fan for engine-out windmilling). This represents a relatively new area that will require focused investment to develop and validate. Additionally, the fact that icing constitutes an integral part of the development and certification process means that the various icing physical models discussed previously will need to be coupled into the broader multidisciplinary analysis (MDA) facility, both for aircraft icing as well as engine vibration and operability impacts due to ice accretion.

Therefore, a flexible and standardized MDA framework must be developed to enable the incorporation of a growing set of widely disparate disciplines. To enable tight coupling of diverse disciplines and codes, data standards need to extend to include memory resident information and coding structures and must be designed to support the computation of coupled sensitivities and error estimates based on the corresponding disciplinary computed values. To some degree, the development of such a framework is already underway in response to recommendations put forth in the CFD2030 report [7] [50]. However, these efforts must be continued and broadened to include the full range of different disciplines envisioned herein. Such efforts are best curated by government (e.g., NASA in this case) in collaboration with university researchers and industrial concerns. The maturity and progress of industry standards and recommended practices should be championed and overseen, but not necessarily developed, by government agencies.



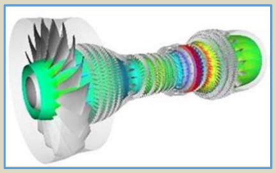
Special attention must also be given to the science of multidisciplinary coupling at high fidelity. Currently, there is a dearth of formal methodologies to guarantee the stability and accuracy of coupled high-fidelity simulations. The development of libraries and procedures that enable accurate and stable couplings, capable of handling disparate disciplinary fidelities, must be pursued. Such properties often require the satisfaction of conservation principles to which close attention must be paid. Ultimately, solvers using discretizations of a given accuracy (in space and in time), when coupled to other solvers, must ensure that the accuracy of the component solvers is preserved and that the coupling procedure does not give rise to numerical errors that may manifest themselves through solution instabilities [51]. Progress in tightly coupled nonlinear solution techniques, which can be fully supported through the MDA framework must also be achieved, for example using disciplinary preconditioned global or monolithic Newton-Krylov methods [52] [53].

At the same time, the MDA framework must support the calculation of coupled multidisciplinary sensitivities and error estimates, based on disciplinary supplied values. Here many of the coupling techniques and solution strategies devised for multidisciplinary analysis can be leveraged for the coupling of sensitivities and error estimates, although additional considerations for issues such as the estimation of coupling errors must be taken into account. The end-result will consist of high-fidelity multidisciplinary sensitivities and error estimates, which can be used as input for global uncertainty quantification strategies.

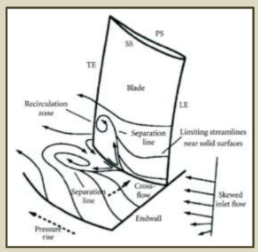
Uncertainty Quantification

Uncertainty Quantification (UQ) is the process of characterizing all major sources of uncertainty in a model or experiment, and quantifying their effect on the analysis outcomes [54] [55]. In general, UQ involves four major components: the identification of sources of uncertainty, the characterization of their statistical form, the propagation and aggregation of uncertainty through models, and finally the analysis of uncertain results. For complex multidisciplinary simulations, where sources of uncertainty are manifold, robust UQ is essential for building credibility and confidence, particularly when certification issues are at stake. Obviously, sensitivity analysis and error estimation, as discussed in the previous sections, are central to any UQ effort. However, in this section, we focus on the

CASE STUDY 3: EXTENDING CFD TO THE EDGES OF THE ENGINE ENVELOPE: COMPRESSOR STABILITY PREDICTIONS



Similar to the landscape of CbA for aircraft, a significant impediment to replacing engine testing with CFD is the ability to predict the flow through the engine components at the edge of the operating envelope. Engine operability testing is focused exactly on such conditions. A considerable challenge in the context of engine operability is the prediction of compressor operability, particularly blade stall margin where CFD traditionally struggles to provide reliable predictions for the compressor at off-design conditions. Currently, engine applications do not rely entirely on CFD, but it is used in conjunction with reduced-order models, design experience, historical rules, etc.

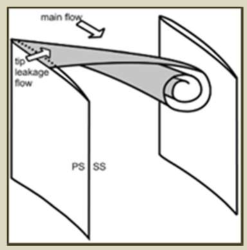


Compressors present many challenges for the state-of-the-art CFD methodology. These include complex geometry details, multiple frames of reference to handle rotating components, compressible flow features, flow feature interaction, and a wide range of Mach numbers. Turbulence physics challenges include laminar-to-turbulent transition, and wake formation and evolution. There are also inter-row interactions between rotating blades and stationary vanes, which also include various forms of fluid-structure interactions. These challenges are complicated by the need to design the compressor for a wide range of conditions to ensure performance, operability, and structural integrity. Eddy resolving simulation with locally higher grid resolution offer a path toward improving the prediction of the physics required for engine flow simulations.

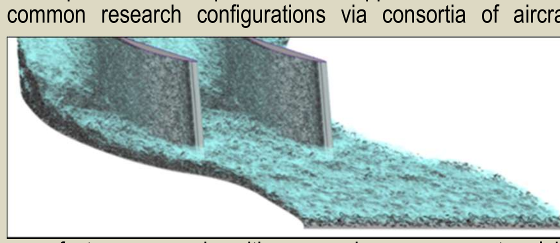
Rapid and automated inclusion of small geometrical features at the end-walls will also benefit from improved gridding methodologies, whether they are based on unstructured meshes with adaptive mesh refinement, or multiblock structured grids with some sort of embedded localized refinement using oversetting techniques. Incorporating trenches, rubs, end-wall gaps, and other details into the CFD model will provide a better geometrical representation of the compression system and will enable better predictions, in particular at off-design conditions.

A number of recent papers focused on the use of eddy-resolving simulations for improving the prediction of corner separation, as a means to enhance the prediction of the flow in compressors at off-design conditions [56] [57]. For such conditions, the flow in axial-flow compressors is prone to separate in the corner region between the airfoil suction surfaces and the endwalls, occurring in both rotor and stator rows. Corner separations are inherently three-dimensional separations, which generate increased losses and viscous blockage, thereby reducing the performance and stability of compressors. As mentioned, the ability to predict these types of flow separations is critical to the industry-wide pursuit of accurate multistage off-design compressor predictions within the design cycle.

It has been demonstrated that wall-resolved LES computations are capable to correctly predict corner/hub separation in a compressor cascade, correctly capturing its unsteady dynamics and mixing, and most importantly its average size and associated losses. Detailed computations included trip strips on airfoil suction and pressure surfaces, ensuring that the state of the airfoil boundary layer matched what was observed in the experiments. A study of the sensitivity of the corner separation in this compressor cascade to the state of the oncoming boundary layer was also conducted. Further understanding of the unsteady flow physics driving this particular phenomenon, and the resolution requirements associated with it, will help define best practice guidelines for the use of eddy simulations to resolve endwall features in compressors, and could help propagate the use of eddy resolving simulation across the entire multistage compressor configuration. Improvements in prediction of corner separations and tip clearance vortices that such eddy resolving simulations would enable, should lead to substantial improvements in our ability to predict the operability of a compressor across its entire operating range [58].



Validating CFD for compression systems remains a challenge in itself – high-quality, detailed data are needed to assess the performance of CFD models. In particular, more nonintrusive instrumentation needs to be used to minimize the impact of the instrumentation on the performance of the component itself, especially for HPC multistage experiments, where small changes in blockage can have a huge impact. Total pressure and temperature measurement are often reported at a handful of discrete locations and need to be processed very carefully so that they can be interpreted against the results from CFD simulations. Validation will be even more challenging for small core compressors. Clearances, gaps, and any leakages in the system must be measured precisely, since these have a large impact on operability, and to validate engine CFD model predictions accurate information about geometrical features and boundary conditions must be provided. Highly instrumented, high-fidelity experimental rigs and experiments are expensive. Perhaps an efficient approach is to establish common research configurations via consortia of aircraft manufacturers, universities, and government labs internationally to provide high-quality data openly disseminated for model validation.



development of nonintrusive UQ strategies that leverage available single- or multidisciplinary sensitivities and error estimates when available.

For certification problems, sources of uncertainty include input parameters such as freestream flow conditions, atmospheric turbulence effects/inlet conditions, geometric variations, structural specifications, etc. Numerical sources of uncertainty include time-dependent discretization errors both in space and time, iterative convergence, and finite-precision arithmetic. Less common sources of numerical uncertainty may also include statistical error (when modeling inherently stochastic processes) and response surface approximation error (when surrogate modeling techniques are employed). The predictive capability of a simulation is also subject to model form uncertainty, which can be estimated from validation experiments. Extrapolation of model form uncertainty from the validation domain to the application domain is an important research topic, which needs to be addressed to enable CbA. Schaefer et al. [55] discuss all of these, and many more potential sources of uncertainty in greater detail.

The characterization of sources of uncertainty into aleatory or epistemic types is an important step that helps determine suitable strategies for propagation and aggregation into an estimate for the overall uncertainty in simulation output quantities of interest. For example, if all sources of uncertainty considered in an analysis are probabilistic, aleatory uncertainties, then classical statistics methodologies based on Bayes' Theorem may be employed [59] [60]. If all sources of uncertainty are known or assumed to be normally distributed, then further simplifications and statistical identities may be leveraged to simplify the uncertainty propagation process. However, in the presence of non-probabilistic epistemic uncertainty, more modern methods such as Probability Bounds Analysis [61] are required for the rigorous propagation of epistemic or mixed (aleatory plus epistemic) uncertainty.

Multidisciplinary modeling, such as fluid/structure/thermal interaction simulations, presents many unique challenges for V&V and UQ. From a verification perspective, multidisciplinary coupling errors resulting from inconsistent formulations and/or programming bugs may be difficult to discover using existing methods; for example, the theoretical order of accuracy may be unknown or exceedingly difficult to calculate for a multidisciplinary simulation (removing the utility of an observed order test), and the generation of a manufactured solution may be impossible (removing the utility of the method of manufactured solutions). A major challenge for validation of multidisciplinary simulations is that the effect and interactions of model-form errors resulting from multiple approximate physical models (e.g., a turbulence model) may play an important role. Challenges facing UQ for single-disciplinary simulations include the computation of tail statistics and rare events, as well as the computational cost of sampling due to the curse of dimensionality; these issues are exasperated in the high-dimensional spaces of disparate types of uncertainties characteristic of multidisciplinary simulations.

Much of the required future investment in UQ will be focused on the development of suitable propagation and aggregation methods for uncertainties in large complex multidisciplinary simulations. This includes building UQ frameworks for driving ensemble runs of numerical simulations using optimal sampling strategies in parameter space, leveraging available single- or multidisciplinary sensitivities and error estimates, and building reduced-order models (e.g., polynomial chaos, Kriging models, etc.) with built-in uncertainties of simulation outcomes or certification metrics. For flight certification maneuvers, the ultimate goal is the development of a stochastic flight database, which can be used as input to a pilot-operated flight simulator, with credible uncertainty estimates at any location in the database. Good initial progress has been made toward generating and using stochastic flight databases [62], but more development of these techniques is needed to incorporate non-Gaussian and epistemic sources of uncertainty.

The first step toward a more robust UQ capability consists of applying existing well-known UQ strategies to the single- and multidisciplinary simulations as they are developed for CbA problems. However, new fundamental approaches will also be required to address some of the significant issues that must be overcome in order to provide realistic uncertainties for aircraft (Part 25) and engine (Part 33) certification problems. These include the ability to deal with large parameter spaces, techniques for suitable interpolation and extrapolation from validation data into the application domain, realistic assessment of the effect of model form uncertainties within large complex simulations, and rare statistical event predictions (i.e., tail statistics), which are paramount for safety considerations. CbA-focused demonstrations of the method of manufactured universes and predictor-corrector extrapolation [63] [64] may be of great interest due to their ability to extrapolate multiple types of uncertainty. Finally, with wind tunnel and flight-testing still expected to play a key role in the design and certification process, the development of methods to merge and assimilate CFD and multidisciplinary simulation data with other multifidelity experimental/ computational data sources to create an integrated database, including some measure of confidence level and/or uncertainty of all (or individual) portions of the database, will be required.

In addition to the technical challenges, there are several nontechnical areas for improvement and adoption of UQ technologies into a CbA workflow. Perhaps most importantly, communication and discussion of UQ results is in need of improvement. By necessity, most undergraduate engineering curricula place their mathematical emphasis on calculus and differential equations, and many engineers graduate without ever taking a collegiate-level statistics course. It is therefore incumbent upon UQ practitioners and analysts who are trained in statistics to deliver UQ results in a way that is meaningful to those without the same background. Clear communication lends itself to more effective engagement on how to interpret uncertain results, particularly in the context of regulations, which use verbiage such as "will not exceed" or "with a high degree of confidence." Moving from a test-based regulatory process to a simulation-informed regulatory process will require that both the OEM and regulator have clear and consistent definitions of such phrases.

This leads into one last consideration: there is an increasing demand across the aerospace industry for the development of a UQ standards document. Writing such a document and gaining community consensus will be a major challenge, and is likely to span several years. However, establishing agreed-upon terms, definitions, and UQ frameworks would enable clearer understanding of UQ results by all parties involved in CbA; this step will be essential for the eventual acceptance of rigorous UQ as a means to demonstrate compliance with regulations.

Additional Considerations

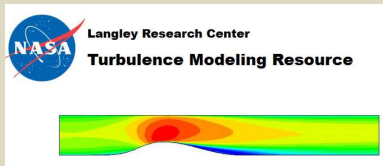
In both the survey and the workshop completed for this study, establishing confidence in the predicted results was identified as one of the top impediments to certification by analysis. Establishing confidence requires extensive qualification of the tools being used and includes verification, validation, and uncertainty quantification. Furthermore, because of differing cost and accuracy requirements, it will often be necessary to use data fusion methods to combine results from different analyses together, along with the joint estimation of their uncertainties. These techniques were recognized as critical to the success of CbA but were not specifically included in the technology development roadmap because they are represented as the "glue" that connects the three different sections of the roadmap together. Verification is necessary for each analysis to contribute to numerical error estimation; validation of single- and multidisciplinary capabilities is the central theme of the predictive capabilities section and is ultimately required for certification tests.

The terms verification and validation are not used consistently across the aerospace domain, and multiple definitions are used within the communities impacted by certification by analysis. A progress report on the development of AIAA standards for CFD [54] highlights a basic framework for performing V&V for CFD. This framework is consistent with the AIAA Recommended Practices [6] on CbA but provides additional detail relevant to CFD. Within this framework, verification has two primary roles pertinent to CbA: making sure the tool is correct (code verification) and making sure that the tool is used correctly (solution verification). Validation assesses the level of agreement between the model and reality and represents a critical aspect of being able to progress from technology requirement, through predictive capability, to the desired certification application. A detailed description of the requirements of verification and validation as they apply to CbA are given in several sidebars that follow. While conceptually simple, there remain critical areas of development for both verification and validation in the context of CbA. These include having accepted methods to estimate numerical and model form error from data, determining an appropriate extension of this error to the desired application, and having sufficient data from quality flight test or full scale experiments.

Verification Necessities

In Reference [61], consistent with other definitions in the numerical analysis field, verification is the "process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model." This is further decomposed into code verification and solution verification.

Code Verification



In this definition, code verification is not the important software practices of code regression testing, but instead reflects the assessments made to ensure that the appropriate numerical methods have been properly coded to represent the underlying mathematical model. Because the "truth" being represented in the tool is the mathematical model, these tests are required to ensure the model is properly represented. This analysis not only identifies bugs, but also algorithmic deficiencies. Hence, the approach can include demonstrating correct solutions on benchmark mathematical problems where the solution is known and error can be exactly determined. These problems typically involve less complicated geometry and flow features than are present in the intended applications. Examples of this type of verification can be found on the Turbulence Modeling Resource [65]. For code verification, not only is it important to demonstrate a numerical approximation to the right answer, it is also critical to demonstrate the expected behavior as parameters (such as the mesh resolution, time step size, and convergence tolerances) are modified to show proper algorithm implementation. In the case of CFD, these tests should be performed using multiple mesh families and time-step values representative of the use cases to ensure that convergence rates appropriate to the expected numerical theory are achieved. This more detailed step is important because it contributes information used in solution verification. Verification of time-dependent and multidisciplinary implementations can be particularly challenging because of situations that might be missed if the verification case is too simplified.

Solution Verification

Solution verification is primarily associated with determining the information necessary to estimate the numerical errors and uncertainties associated with a solution. While code verification is expected to be demonstrated when the tool is adopted for a specific purpose (often through documentation by the code author), solution verification applies to every prediction. An example of this is highlighted in the description of solution verification in the AIAA CbA recommended practices [6] that includes ensuring that all user inputs are correct. This not only includes the code settings, but also the boundary conditions, geometry representation, and mesh resolution. Typically, such an investigation will include algorithmic trade studies and mesh resolution and topology investigations. In order to estimate the numerical errors, the solutions must be within the asymptotic region for the quantities of interest; herein lies the important connection to the code verification and why the proper numerical convergence is required. For practical problems, this is nontrivial. Hierarchical grid studies, temporal resolution considerations, and investigations of effects of affordable numerical convergence for implicit time-stepping methods and/or multidisciplinary coupling must be performed to confirm that the solution is in the asymptotic range and simulation method sensitivity studies need to be performed to identify estimates of the numerical errors. Solution-based mesh adaptation may assist with getting grid convergence with respect to a particular parameter set determined by the algorithm's objectives, but methods for estimating the remaining numerical error still need to be matured .

Because of the important role of numerical error and uncertainty estimation in assessing the accuracy and confidence in a solution result, verification is a critical aspect of certification by analysis. The level to which these uncertainties need to be determined is application dependent because some applications have stricter error tolerances on the predicted quantity of interest. At present, rigorous justification of numerical uncertainty for complicated simulations is challenging and seldom performed because of the difficulties in both mesh generation and solution convergence. The use of time-dependent analysis further complicates this assessment because of the presence of multiple scales and error sources and also due to the fact that, while the mesh may be sufficient for one part of the simulation, it may be inadequate at a different time during the simulation. The accumulating effect of temporal errors complicates error estimation. Allowing for the potential of multiple solutions and multidisciplinary coupling further increases the challenges. Furthermore, this assessment should be performed for many cases of the specific analysis being performed to have confidence in the resulting error estimate as different cases may highlight different error sources. A process for consistent use of best practices and documentation can aid in identification and reduction of numerical uncertainties. Present processes used for numerical uncertainty estimation are based in simulations that are dated and potentially less relevant to today's complex analyses. Additional methods should be investigated to assess numerical uncertainty and understand the associated confidence with that prediction.

More information on these challenges are highlighted in a series of verification and validation sidebars.

CbA Hierarchical Test Challenges

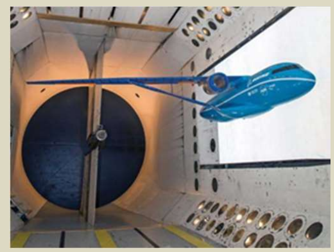
From the "intended use" part of the validation definition as well as community expectations as measured by the survey and the workshop, validation for certification applications should ultimately be performed against flight or engine test. This introduces numerous challenges due to the difficulties in acquiring adequate measurements of the quantities of interest for numerical simulation and essentially necessitates a hierarchy of validation problems ranging from single-discipline details to multidisciplinary problems to full flight or engine analysis. Although these problems do not substitute for certification-level validation, their successful solutions typically provide increased confidence in the analysis capability, reducing risk at lower cost than is usually associated with flight or engine test-based validation, and potentially providing more insight into relevant flow physics through increased instrumentation availability. The following paragraph provides representative validation options at this initial evaluation level, including both existing and proposed experiments. This is followed by an initial description of "predictive capabilities" that are highlighted in the roadmap as cases or demonstrations to be used as building blocks toward the CbA applications. Details associated with each of these predictive capabilities are included in Appendix D.

Canonical test cases such as different smooth bumps [66] [67] [68] are appropriate starting points for examining modeling of smooth body separation. The NASA hump [69], in particular, provides a useful set of test data for looking at geometry-driven separation. Also, the Gaussian "speed bump" geometry developed by Boeing [70] provides needed experimental data in pressure gradient-driven flow separation for CFD validation purposes. The transonic shock-induced separation is considered by experiments such as those by Bachalo and Johnson [71] with multiple experiments focused on supersonic shock-boundary layer interactions. NASA has continued to expand on these baseline experiments with the juncture flow experiment [72] and the turbulent heat flux cooling hole experiment [73]. NASA has also developed several compressor validation data sets, which have been used extensively for numerical tool validation, including the NASA Rotor 37 [74] [75] and NASA Stage 67 [76] [77] data sets. Additionally, other tests provide details for developing and confirming models for flow separation in other situations [78]. Continuing this trend with the CRM-HL configuration will further assist in building confidence in predicting separation on relevant configurations. Because of the impact edge separation has on moment prediction, another important class of flow separation is associated with side-edge vortical flow from control surfaces. A canonical wing with deflected control surface, including not only detailed flow separation measurements behind a gapped control surface but also hinge moment measurements could be a useful addition particularly relevant to CbA. The requirements for a suggested multistage compressor common research model that would constitute a relevant configuration without revealing company specific proprietary information

Validation Requirements

Validation is "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model" [61]. This definition contains several key aspects. First, it is a comparison to the real world as a truth assessment for a model, typically a PDE or mathematical representation that is implemented within a numerical code. Second, the degree of comparison is made with respect to a given application's requirements. This has several key ramifications. Validation does not mean that a given model is "good" or "acceptable for use" without having a specific context. This also means that a code cannot be considered to be "validated" and therefore applicable to arbitrary situations without further comparison to the real world truth to assess its predictive capabilities. Validation requires meticulous comparison of simulation results, including numerical errors and uncertainties, to well-defined experiments.

These experiments must be well-characterized and will have their own uncertainties, not just in measurement of output quantities, but also in terms of input conditions and geometry. For example, in a wind tunnel test, it is important to know the precision for angle of attack and Mach number measurements, as well as aeroelastic deformations of the model and test section boundary layer properties to be able to appropriately determine the experimental uncertainties and include these sensitivities for validation purposes. The common practice of co-plotting simulation and experimental results for comparison is more accurately referred to as benchmarking because it lacks this detailed sensitivity comparison. This additional level of rigor is important to determine model form error, which is the amount by which the model predictions differ from reality; model form error should not be interpreted as an incorrect mathematical formulation of part of the problem. In order to determine this quantity, which would represent the maximum amount of confidence that can be attributed to a computation, the appropriate level of solution verification must be performed to ensure that the levels of the numerical error and uncertainty are sufficiently small to identify the model form error. Uncertainty quantification (in some appropriate sense) will typically be required to identify the parameter uncertainties in the problem as well as to provide an appropriate description of the model form error. Model calibration can be performed when it is desired to reduce this quantity.



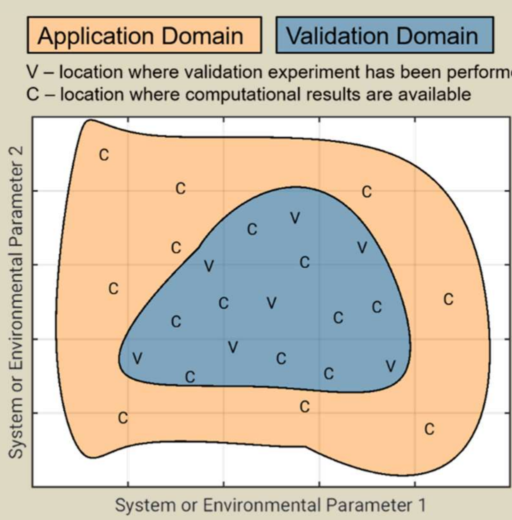
Based on this definition of validation, there is no additional comparison burden for many of the CbA applications if the simulation is steady-state or time-accurate since the metric is often a time-averaged value. For example, time-accurate simulations may be required to get a sufficiently accurate comparison to experimental $C_{L,max}$ data, but details of the unsteadiness are not important. In other cases such as buffet, the frequency content of the forcing will be a contributor, but typically only within certain bands.

VALIDATION DOMAIN

In order to properly apply the validation data to another configuration and/or condition and assess the model form error, the concept of a **validation domain** must be considered and an approach must be used to interpolate/extrapolate from previously validated results. As depicted in the figure below, the validation domain (blue) represents the part of parameter space that has available validation information (denoted by V). The application space (orange) is the region where information is desired and computations (C) are performed..

Based on the typical size of the parameter space, and limited experimental data there is seldom adequate information to define a validation domain for CbA problems. The necessary resulting extrapolation of uncertainty can be from a subscale wind tunnel experiment to a full-scale flight and/or engine test or it could be from one aircraft model to another. The details on how to do this extrapolation are not presently standard and the creation and demonstration of these approaches must be acceptable to regulators. Methods need to be developed to assess the additional uncertainty associated with using computational results where there is not appropriate validation data. It is intuitive that this uncertainty should increase the more one deviates from validation data.

As an example of a practical application, consider the impact of the addition of a new antenna on an existing configuration. In this case, there is significant available validation data from the existing configuration that can be used to anchor the simulations with the antenna data and increase the confidence that the predictions have comparable uncertainties to previous analyses. Similarly, small changes in Mach number would not be expected to lead to large changes in uncertainty. However, just because a process provides good agreement for a commercial transport aircraft, it should not be expected that it would be equally applicable with high confidence to a significantly different vehicle, like an eVTOL configuration, even if the underlying physics are the same. Another example of this extrapolation is using validation from an aeroelastic deformation of a straight wing to infer accuracy of the analysis for a swept wing. The impact of these extrapolations must be understood and properly accounted for.



are discussed in Reference [9]. From a multidisciplinary standpoint, a good initial validation test would be a swept dynamic flexible wing at transonic conditions, including not only pressure measurements, but also measurements of deflection and twist, such as the High Reynolds Number Aerostructural Dynamics (HIRENASD) experiment, which has been considered in the Aeroelasticity Prediction Workshop series [79]. These tests should be performed as validation experiments to provide maximum use for CFD, obtaining not only the key measurement of interests, but also sufficient additional data to provide diagnostics and assess experimental uncertainty.

One important set of relevant problems at higher complexity is described by the "Predictive Capabilities" section of the roadmap. These items define an incremental series of demonstrations and required capabilities that include both single- and multidiscipline exercises to develop confidence in model performance prior to certification validation. As additional solutions to resolving the technical requirements are identified, demonstration with respect to these capabilities will provide an indication of the maturity and fidelity of the approach on less tightly-coupled scenarios than the full certification maneuver. Validation-quality experiments will need to be performed for these capabilities to collect sufficient quality data to assess the experimental uncertainty and to provide sufficient definition for the analysis problem description. For each of these items, the salient aspects for validation testing are included in Appendix D. In addition to these specific capabilities, another hierarchy of cases that can provide value is the incremental increase in complexity defined for the High Lift Grand Challenge [8] and the Aircraft Propulsion Grand Challenge [9] problems. These problems identified a series of both ground-based and sub-/full-scale flight experiments of increasing geometric complexity designed to provide insight into the physics and performance of high-lift wings and full engine analysis, respectively, with the intent of providing quality reference data for CFD computations.

By definition, validation for CbA involves detailed comparison to a particular flight maneuver or full scale test; the build-up hierarchy of cases serve as important risk reduction and help to ensure that appropriate physics and sensitivities are represented. As an example of this hierarchy, canonical experiments and unit problems such as the bumps described above help to improve modeling of separated flows and the prediction of when flow separation occurs. Experiments such as those in the CRM-HL ecosystem bring in additional complexities associated with $C_{L,max}$ prediction due to flow features such as pressure gradients, shock waves, and confluent shear layers; complex geometries such as slat brackets and control surfaces; and multidisciplinary effects such as aeroelastic deformation and engine interaction. Additional experiments focusing on multi-disciplinary details such as confirming appropriate aeroelastic effects for a representative wing, prediction of aerodynamic behavior in the presence of iced surfaces, and appropriate vehicle stability and control responses build confidence in the multi-disciplinary analysis methods. These experiments can be used to validate the predictive capabilities identified in the roadmap, but the validation of stall speed prediction for a given class of airplanes remains an additional challenge.

CbA Certification Test Challenges

While this build-up approach helps to increase our confidence and reduce the likelihood that there are issues in the model and/or help to identify their presence, the validation that matters for certification is ultimately associated with full-scale test measurements on a relevant configuration and condition. For CbA, this will typically involve a flight vehicle or full scale engine because of the need to match conditions simultaneously and to account for expected multidisciplinary effects. However, in general, adequate instrumentation and data for validation are not readily acquired. When these data are not available, other experimental data can be used. However, in this situation, the validation is being applied to an alternate problem, weakening claims that can be made about its applicability. In order to properly apply the validation data to another configuration and/or condition and assess the model form error, the concept of a validation domain must be considered and an approach must be used to interpolate/extrapolate from previously validated results (see sidebar).

Another challenge for certification by analysis is that many of the requirements are qualitative in nature and will require subjective interpretation to assess. Buffet, for example, is determined based on the vibration perceived in the cockpit by the pilot. Similarly, an important consideration for airplane stall is the *nature* of the stall, specifically in terms of whether or not it is difficult to control stall recovery with normal piloting skill. If the current regulations are not modified to be more specific, appropriate interpretations must be developed to ensure that these subjective requirements are met.

While not strictly a question for validation, the consideration of when an analysis approach is *sufficient* for certification will remain. The present metric, "equal in accuracy to the results of testing" [80], provides a meaningful starting point, but there are additional considerations including integration with complete systems with pilots, interpreting pilot responses and judgment, and assessing effects of imperfect understanding of flight conditions. The required accuracy levels are ultimately interpreted by the regulators and are decided on a case-by-case basis. Representative accuracy levels for CbA applications are provided in Appendix A. The ability to address these considerations and determine how to factor simulation results into a certification means of compliance (MOC) will take significant effort to expand beyond current capabilities.

Key Challenges for CbA in Verification, Validation, and Uncertainty Quantification

1. Developing and applying methods for comprehensive verification of tools for single and multiple discipline analysis, including estimation of numerical uncertainties for representative cases
2. Obtaining validation data for specific full scale applications with sufficient knowledge of test articles and measurements to estimate model form uncertainties
3. Demonstrating appropriate techniques for estimating changes in uncertainty from a relevant validation data set to an application problem
4. Creating efficient uncertainty quantification methodologies and standards applicable to certification metrics including both aleatory and epistemic uncertainties appropriately.
5. Establishing standards for communicating and interpreting uncertainties in general, but specifically with respect to regulations.

Traceability

A critical requirement in the use of analysis methods, models, and tools for the purpose of product certification is to ensure that the specific simulation details – geometric configuration(s) analyzed, analysis tools employed, tool input parameters used, coupling frameworks employed, analysis data generated, etc. – are *traceable* within an established data management system, in large part to enable ready access to the simulation results or to ensure the ability to reproduce the simulation results, if desired or warranted in the future. In addition to records documenting model/tool version control, details on computer resources (e.g., hardware and software) used, and specific geometrical configuration descriptions, it is also important to fully document the procedures that define how the tools and models were used by analysis staff ("best practices") and procedures used for peer review of the simulation results and any other quality checks that are normally performed. Any special expertise or experience required should also be fully documented. Finally, a robust data retention capability should be in place, with well-documented administration procedures, to preserve the simulation information until the product is no longer in service. Ultimately, having documented records of this information readily available is critical in building confidence and trust between airplane and engine Original Equipment Manufacturers (OEMs) and regulatory authorities.

It is expected that current and future commercial Product Lifecycle Management (PLM) products implementing comprehensive Model-Based Engineering (MBE) solutions to fully operationalize a "digital thread" for airplane and/or engine lifecycle development (to create a "digital twin") [81] [82] will provide the framework that will be employed to enable traceability. Data artifacts within the PLM digital thread will include not only the geometry CAD files used to define the initial airplane and/or engine configurations used for product verification and certification testing, but also any specific updates made to product lines developed during testing. When utilized within the PLM digital thread, any flight modeling results utilized for CbA would then be "digitally connected" directly to the flight configuration used for certification, thereby ensuring consistency with available flight test data. This consistency will become a critical requirement when data from flight testing are combined or "fused" with flight modeling results to address CbA. However, as mentioned previously, this will require suitably flexible PLM frameworks that can assimilate data from various sources including specialized in-house or third party simulation tools.

Data Fusion

It is expected that CbA will utilize a hierarchy of numerical methods with varying fidelity to efficiently leverage the capabilities and requirements for different assessments. For example, RANS simulations (or lower fidelity methods) can be quite adequate in certain regions of the flight envelope, but inadequate for precise predictions in conditions with highly separated flows. Multifidelity / Data Fusion is an emerging area that seeks to provide a single surrogate model that combines both predictions and their associated uncertainties, leveraging all appropriate data that are available. There are different strategies that can be used to combine the different data sources, including adaptation, fusion, and filtering [83], distinguished in the details in which the composite prediction is made. Recognition of consistency among different data sources provides increased confidence in the resulting prediction.

As an example of the capabilities of data fusion, Wendorff et al. [62] employ multifidelity Gaussian processes to fuse data from a vortex lattice method code, RANS solutions, and wind tunnel data, resulting in a stochastic aero database. They go on to simulate a pitch-recovery maneuver, and report uncertainty estimates in important performance metrics throughout the duration of the maneuver, including pitch rate and load factor.

As previously outlined, future analyses should include appropriate quantification of errors and uncertainties. Multifidelity / Data Fusion provides a consistent approach to combine the analyses and assess overall uncertainty. The UQ from lower fidelity analyses is used to inform where higher fidelity analysis is required and will provide the most information. While present techniques often focus on using Gaussian processes to fuse the data, future methods will need to be more diverse and accept other distribution types, as well as epistemic uncertainty. This type of analysis will facilitate the ability to develop more statistically-defensible stochastic aerodynamic databases that can help improve confidence of exceeding specified criteria. This field is rapidly expanding and significant work remains to bring it to the level of maturity appropriate for CbA. Additional effort needs to be concentrated on the consistent calculation, representation, and combination of uncertainties, particularly across both multiple fidelities and multiple disciplines. For best advantage, Multi-Fidelity / Data Fusion should be elevated to a system level of analysis to identify the most efficient areas for improvement in prediction credibility.

Artificial Intelligence and Machine Learning

Increases in the availability of affordable computing hardware coupled with large data analytics investments in the information technology sector has led to an explosion of research interest and capability development within the fields of Artificial Intelligence (AI) and Machine Learning (ML); this recent progress may have profound benefits to CbA efforts. Many items on the CbA roadmap require improved physical modeling to be successful, and Physics-Informed Machine Learning (PIML) techniques have shown early promise in their ability to assist with these challenges. For example, Zobeiry and Humfeld [84] propose a physics-informed neural network approach capable of discovering physical laws from data; this approach was demonstrated for the equation of motion of an object under constant acceleration, the Nusselt number over a circular cylinder in convective heat transfer, and the relation between Mach number and the angle of deflection in oblique shock waves. These, and similar AI and ML approaches, may be employed to identify and improve upon the physical modeling and predictive capability requirements of simulation-based certification by analysis.

In addition to advancing physical modeling capabilities, AI and ML offer solutions for regression in high-dimensional, nonlinear spaces such as an aircraft flight envelope or engine operating envelope. ML-based regressions allow for the incorporation of uncertainty information, which is useful for establishing confidence in the simulation of time-dependent phenomenon such as maneuver performance. For example, Zhou et al. [85] have developed a real-time ice detection system envisioned for use on rotorcraft, which employs Bayesian neural networks to predict ice shapes (with uncertainty) over a range of atmospheric conditions. Another advantage of AI and ML regression techniques is that they can incorporate data from multiple information sources of varying fidelity as described in the Data Fusion section. As another example, AI techniques can learn from a pilot's response in a simulator and use this to rapidly examine other scenarios for potential risks.

Clearly, AI and ML are rapidly growing fields and are being applied successfully to increasingly diverse application areas. To neglect the impact AI/ML may have on CbA going forward would be imprudent at best, although it is difficult to predict exactly how these new technologies will impact CbA at this early stage. Keeping abreast of developments in these fields, possibly through small targeted high risk investments, will be important for the success of CbA going forward.

VII. Recommendations

In order to accelerate progress toward CbA and achieve the vision set forth in this report, a series of recommendations are given, first for NASA, as the sponsor of this study, and secondly for other stakeholders including industry, regulators, and academia. As stated previously in this report, increasingly capable analysis tools for certification will also have a large impact on the product development phase, with benefits in terms of reduced development cost and risk, faster time to market, and more favorable product life cycle costs. These are the same drivers used to justify and formulate recommendations in the Vision CFD2030 report. Thus, it should come as no surprise that most if not all of the recommendations in the Vision CFD2030 report are relevant for CbA. However, it should be emphasized that, as described above, requirements for appropriate and accurate simulation capabilities for CbA extend well beyond just basic fluid dynamics using CFD. The multi-disciplinary and system-level aspects of CbA demand tight coordination between industry, regulators, and the government/academia research organizations providing the necessary technology development. Furthermore, it should be evident that expensive computational resources, as well as access and use of subscale and full-scale demonstration assets, will not be readily available in or from any one organization. Rather, concerted efforts to pull together resources will be required to make CbA a future reality. In this light, the recommendations below highlight the critical elements needed for CbA that we feel that each stakeholder can realistically provide, from both an expertise and resource point of view.

NASA Recommendations

The NASA recommendations have been formulated with an eye toward the unique role NASA can play in bringing CbA to fruition. Historically, NASA ARMD has led in the development of physics-based simulation tools for aerospace applications [86], which have been readily adopted by industry. With its national reach, NASA is well positioned to be a principal driver of technological development for CbA, on the one hand through internal program development, but also importantly in concert with academia and in collaboration with industry. Furthermore, making CbA a reality will necessitate leveraging the unique experimental and computational facilities managed by the agency. With these issues in mind, a set of five NASA recommendations are made.

<u>Recommendation 1:</u> NASA should focus investment on fundamental technologies that lead to better predictive abilities at the edges of the flight/engine operation envelope.

The most evident area here is the development of CFD methods capable of accurate prediction of separated flows. To some degree, this is already underway, with the current NASA TTT challenge of accurate $C_{L,max}$ prediction, with focus on scale resolving methods. However, there are many other physical phenomena that need to be addressed at the edges of the envelope. For example, in post-stall aircraft aerodynamics, as in compressor stall and operability simulations, the ability to predict the impact of three-dimensional vortical flow structures and wakes as they are convected onto downstream control surfaces or engine components will be required. One path toward achieving this predictive capability may be through the development of dynamic adaptive mesh refinement techniques. However, rather than choosing particular technical approaches to fund, a programmatic strategy that relies on the realization of specific predictive abilities may be preferred. This approach will likely result in the prioritization of investments in many of the disciplinary areas of Physical Modeling, Geometry/Grid and Algorithms called out in the Technology Development section associated with the Integrated Road Map. In such cases, the disciplinary predictive abilities for both Part 25 and Part 33 from the roadmap may serve as guiding programmatic objectives, which in turn lead to increased investment in areas such as scale resolving methods, transition modeling, nonlinear structural models, adaptive mesh refinement, long time integration methods etc. Along with new investments in these areas, a series of building block single discipline validation test cases should be considered by NASA to measure progress and establish confidence in the new predictive capabilities.

<u>Recommendation 2:</u> NASA should prioritize and accelerate the development of multidisciplinary simulation capabilities.

Although there has been considerable work in the development of specific multidisciplinary simulation capabilities, most notably for aeroelastic and aeroacoustic problems, a concerted effort to accelerate the development, standardization and incorporation of additional disciplines must be undertaken to enable suitable multidisciplinary predictive capabilities for CbA. Here the most important disciplines include aerodynamics, structural dynamics, thermal analysis (i.e., conjugate heat transfer) and coupling with flight/engine control systems. (Aeroacoustics is also an important discipline to be considered, although it does not fall under the scope of this study, which is limited to Parts 25 and 33.) Unlike most previous efforts, time-dependent coupling of these disciplines with scale-resolving CFD methods will need to be considered. Advances in the science of multidisciplinary coupling must also be sought, in order to guarantee stable and efficient coupling methodologies, which can be leveraged efficiently for other purposes such as multidisciplinary error estimation and/or sensitivity analysis. Other areas of interest include coupled long-time integration methods and specific multidisciplinary capabilities such as flutter prediction methods, all of which may include time-domain and frequency domain methods and/or combinations thereof. Finally, as mentioned in the Vision CFD2030 report, NASA is well suited to serve as the leader and curator of multidisciplinary frameworks and standards, with the objective of extending these to other disciplines relevant to CbA such as propulsion models and ice accretion.

<u>Recommendation 3:</u> NASA should develop new multidisciplinary testing and validation capabilities.

A significant new effort will be required to develop more capable validation capabilities for the multidisciplinary simulations that will become the centerpiece of CbA. For aircraft maneuvers (Part 25), these may correspond to new ground-based testing capabilities, or subscale flight test vehicles.

Ground-based testing of geometrically-representative configurations in specialized facilities to generate experimental data in dynamic "maneuver-like" flow scenarios offers the possibility of generating high quality validation data in a controlled environment. One of the key advantages is that the overall flow environment and the geometric configuration, along with any potential structural deformations, are much more easily quantified. As such, design of suitable testing campaigns to study specific discipline coupling (e.g., aerostructural) are much more feasible when certain aerodynamic effects, such as onset flow or engine thrust, can be tightly controlled. In general, current facilities can simulate controlled maneuvers for rigid models, or stationary aeroelastic dynamically scaled models, and even some stationary aeroservoelastic models have been investigated [87]. However, the specialized facilities that do exist, for example the Transonic Dynamics Tunnel (TDT), 12-Foot Low-Speed Tunnel (LST), and 20-Foot Vertical Spin Tunnel (VST) at the NASA Langley Research Center, can be used to simulate specific flight events, but do not currently have the capability to perform testing of high-g flight maneuvers for aeroelastically-scaled airplane configurations at high Reynolds numbers. Thus, either modifications to existing facilities may be required, or the construction of new facilities specifically designed to perform systematic and integrated multidiscipline testing may ultimately be needed.

Subscale testing of a flight vehicle perhaps offers the most direct route to obtaining sufficient data suitable for multidisciplinary simulation validation. Flight testing of a subscale vehicle, if instrumented appropriately, can provide direct aerodynamic performance characteristics (force, moments, and derivatives) from a prescribed dynamic maneuver. However, the lower, subscale Reynolds numbers reflected in these flight test data may present significantly different flow characteristics compared with full-scale data from the flight of a production airplane. Also, the time-dependent engine flow conditions experienced in flight may not be easily known or determined, adding to the uncertainties for accurate modeling of critical propulsion effects in a dynamic maneuver. Finally, atmospheric effects such as wind gusts may also be difficult to quantify, further adding to the overall uncertainties associated with any flight data utilized for CFD validation purposes. Nevertheless, subscale flight testing presents complementary advantages compared to ground-based testing, and the lower cost, combined with the possibilities of more elaborate instrumentation, make subscale flight-testing an attractive alternative to full scale flight testing.

Similarly, validation of increasingly complex and multidisciplinary propulsion (Part 33) single and multicomponent simulations will require a new level of commitment toward the development of precompetitive common research engine component models that can be used for validation purposes. In the past, NASA has contributed to this effort with several compressor validation data sets. This history could be extended through the development of a multistage compressor common research model as discussed in reference [9]. Clearly, NASA is well positioned to serve as a leader to define such a model, including the determination of instrumentation requirements, in collaboration with industry. Although engine components are usually tested in isolation, which enables the acquisition of more detailed data, the need to validate coupled component simulations as they are developed will ultimately require controlled validation experiments with multiple coupled components, each consisting of common research models. Here again, acquisition of validation data sets for coupled components from compressor-combustor or combustor-turbine configurations up to full engine tests represents a significant challenge, which will need to be addressed as the complexity of simulation for certification progresses.

<u>Recommendation 4:</u> NASA should make a representative flight-test vehicle and full-scale engine available for CbA validation.

Ideally, a full-scale flight test campaign using a representative transport aircraft configuration would be required to provide final validation data to characterize real airplane aerodynamic performance with coupled propulsion effects. A full-scale flight test represents the ultimate reality or truth value of what the virtual test cases from numerical methods attempt to simulate. Clearly industry maintains ready access to actual full-scale data, directly from operating airplane and engine assets. Although a key drawback is the associated cost of performing dedicated full-scale testing for method/tool validation, and the potential loss of test assets in the case of some engine testing, a more critical issue is the use of representative full-scale configuration CAD geometry, including structural details, which can be publicly released without impinging on proprietary issues. Industry does use full-scale test data internally to perform validation to the maximum extent possible, but since CbA will require the concerted efforts of nonindustrial partners, access to high-quality full-scale data from testing of a well-defined geometry configuration available to at least an expanded set of collaborating partners is critical. Another challenge with full-scale flight testing is the potential difficulty in obtaining detailed measurements required for validation of numerical simulations, which would be over and above data that are typically obtained for certification testing. These include, at a minimum, substantial unsteady surface pressure measurements, enhanced flow visualization (e.g., flow cones), detailed structural deformations, control surface hinge moments, data to characterize time-dependent engine propulsion conditions, and a detailed assessment of wind and atmospheric effects, among others.

Nevertheless, there have been various NASA supported full-scale flight tests at least partly designed for CFD validation over the years, including the B-737 high-lift experiments in the early 1990s [88], and the F16XL [89]. More recently, the VicToria project at the German Aerospace Center (DLR) has undertaken an elaborate flight test campaign using a highly instrumented A320 aircraft specifically for validation of multidisciplinary numerical simulation capabilities [90]. A validation flight-test campaign could make use of current NASA Armstrong research flight vehicles, perhaps as part of existing or planned tests, or could seek out a specific new platform in support of certification by analysis. Similarly, the acquisition and instrumentation of full configuration engine test rigs will be required for final validation of Part 33 tests, building on the multicomponent engine validation tests from Recommendation 3. Clearly, designing and deploying a targeted flight test/engine test campaign to support validation of certification by analysis tools is a long-term endeavor that must be planned years in advance and which will require substantial advocacy to become reality.

<u>Recommendation 5:</u> NASA should construct a comprehensive UQ strategy for CbA.

One of the defining characteristics of certification by analysis is the necessary reliance on robust uncertainty quantification. In order to build confidence in numerical simulations and establish their credibility on an equal footing with flight testing or engine rig testing, a comprehensive UQ strategy will be required. The approach must be all encompassing, ranging from the characterization of sources of uncertainty, to the propagation of uncertainties through complex multidisciplinary simulations, and include suitable validation efforts, along with techniques for interpolation and extrapolation from the validation domain to the application domain, culminating with robust assessment techniques for relative uncertainties between simulations and flight tests/engine rig tests. Although engineering applications of UQ are well established in other fields such as nuclear engineering, there has been limited penetration of UQ in the aerospace domain. Here NASA may leverage the approach and considerable work underway at the DoE targeted toward nuclear weapons certification and nuclear energy regulatory concerns. The technical challenges of UQ for CbA include the ability to deal with large parameter spaces, techniques for suitable interpolation and extrapolation from validation data, realistic assessment of the effect of model form uncertainties within large complex simulations, and rare statistical event predictions (i.e., tails statistics), which are paramount for safety considerations. Reliable methods must be developed to estimate errors present in numerical simulations. Furthermore, with wind-tunnel and flight testing still expected to play a key role in the design and certification process, the development of methods to merge and assimilate CFD and multidisciplinary simulation data with other multifidelity experimental/computational data sources to create an integrated database, including some measure of confidence level and/or uncertainty of all (or individual) portions of the database, will need to be developed. Standardization of UQ procedures will also help accelerate the development and adoption of the necessary technical advances. This is an area where NASA can lead, for example in defining and curating flexible UQ frameworks for driving ensemble runs of numerical simulations using optimal sampling strategies in parameter space, leveraging available single- or multidisciplinary sensitivities and error estimates, and building reduced-order models (e.g., polynomial chaos, Kriging models, etc.) with built-in uncertainties of simulation outcomes or certification metrics. Finally, there is an increasing demand across the aerospace industry for the development of a UQ standards document. Such a document is necessary to establish agreed-upon terms, definitions, and promote UQ frameworks, and would enable clearer understanding of UQ results by all parties involved. NASA has an important role to play here, not just as a contributor, but as a leader in ensuring an impartial approach that can gain broad community consensus and, in turn, will stimulate the development and adoption of CbA.

NASA Programmatic Considerations

At the highest level within ARMD, the NASA recommendations cover multiple focus areas[1], and span across a number of current programs, including Advanced Air Vehicles Program (AAVP), Transformative Aeronautics Concepts Program (TACP) and Integrated Aviation Systems Program (IASP). For example, while the fundamental technology developments, which are the focus of Recommendations 1 and 2, fall mostly under TACP, the use of flight-test vehicles in Recommendation 4 falls under IASP. Within AAVP, there are also various performance, acoustic and icing technical challenges which relate directly to certification. Clearly, CbA is very broad, and one specific avenue for generating increased focus on CbA may be to initiate a new program or project within ARMD. On the other hand, since a large part of CbA is focused on tool development, the Transformational Tools and Technologies (TTT) project within TACP may serve as the vehicle for increased investment in simulation capabilities for CbA. At the same time, NASA may choose to target one or more of the University Leadership Initiatives (ULI) for innovative approaches to CbA. The validation requirements for CbA are expected to be considerable and to require new multidisciplinary approaches, as stated in Recommendations 3 and 4. Meeting these goals will require substantial advocacy in the coming years. Finally, Recommendation 5 represents a relatively new area which may be best served though the initiation of a new project within ARMD.

Stakeholder Recommendations

The technical advances needed to enable robust and efficient use and acceptance of numerical simulation methods to address future airframe and engine product certification will require close and sustained coordination between key stakeholders, including government and academic research organizations, industry, and regulatory authorities. Each entity has a unique leadership role to play in advancing CbA aspirations, both in terms of technology, advocacy, and implementation. It is anticipated that these roles will often overlap as we mature and apply CbA capabilities.

As mentioned above, research organizations will play a leadership role in developing, implementing, and verifying technology advances. NASA, for instance, is already allocating significant resources in the development of a wide range of CFD-specific technologies that will be brought to bear on the full range of CbA applications. The recommendations above, particularly in the areas of multidisciplinary analysis and uncertainty identification and characterization, build on this substantial effort to mature emerging CFD technologies for aerospace applications.

Industry is expected to establish critical requirements for CbA, provide realistic and achievable goals to guide technology development, and lead advocacy and outreach efforts to promote acceptance of CbA, particularly with regulatory agencies. As the ultimate authority on the eventual acceptance of CbA use and adoption by applicants, regulators are expected to monitor technology advances, leaning heavily on key technology experts to establish confidence in simulation capabilities. To this end, much of the work in realizing CbA

---

[1] Six focus areas of research in NASA ARMD: (1) Safe, Efficient Growth in Global Operations, (2) Innovation in Commercial Supersonic Aircraft, (3) Ultra-Efficient Subsonic Transports, (4) Safe, Quiet, and Affordable Vertical Lift Air Vehicles, (5) In-Time System-Wide Safety Assurance, and (6) Assured Autonomy for Aviation Transformation.

requires close coordination among all stakeholders. For instance, systematic demonstration and validation of the advanced simulation capabilities cannot be performed in a vacuum, but must be well coordinated to ultimately build confidence in the routine use of the capabilities over time to address a larger segment of the certification requirements. Sustained efforts from industry driving several coordinated stakeholder activities are already well underway in many areas, laying the foundation for future CbA success. Development of a set of recommended practices in the use of flight modeling for CbA [6], for example, is the product of a multi-organizational team of experts from industry, academia, research organizations, and regulators sponsored by an informal community of interest established within the AIAA by representatives from Boeing, Airbus, NASA, DLR, FAA, and EASA. Similarly, the establishment of an ecosystem [91] for development of geometrically consistent CRM-HL wind tunnel models to be tested at multiple facilities around the world is the result of close collaboration between industry and various research organizations. Finally, industry is principally driving requirements or important CbA technology development through the definition of grand challenges centered on airplane high-lift [8] and engine operability [9], both of which are inspired by the concept of grand challenges outlined in the CFD Vision 2030 report [7].

To enhance the interactions between key partners and enable accelerated use of advanced numerical simulation capabilities for CbA, four specific recommendations are proposed to extend and strengthen collaborative stakeholder activities:

Recommendation 1: Establishment of a multi-stakeholder CbA Steering Team or Advisory Council

Formalizing existing relationships between key partners, the purpose of this body would be to monitor technical advances in numerical simulation technology and application, particularly for certification, establish verification and validation requirements and standards, and advocate for appropriate funding resources for needed activities, such as subscale testing and/or flight test validation. This team would consist of members from government research organizations, the academic research community, airplane and engine manufacturers, regulatory agencies, including those from the test community, and perhaps representatives from the HPC and machine learning communities, as well as commercial software vendors. The goal would be to provide ongoing and sustained oversight for monitoring progress, and to suggest course corrections if deemed necessary.

Recommendation 2: Development of realistic benchmarks to define and establish confidence in CbA

To address concerns collected during the community survey and technical workshop, as well as those voiced by regulators in industry working groups, close collaboration to define appropriate metrics for how accurate emerging numerical simulation methods must be in order to positively affect CbA is needed. These metrics need to be properly established across stakeholder communities, particularly involving regulators, so that technology demonstrations are fully understood and accepted. Given the complexities involving the multidisciplinary nature of the wide range of airplane maneuvers and engine testing performed to support certification, benchmarks that are conceived and accepted by all stakeholders will be needed to build support for expanding use of CbA in the future. The formulation and proposal of specific simulation and validation campaigns may be led by industry in collaboration with NASA and input from regulators, although proprietary concerns may need to be taken into account. Industry can contribute significantly in these campaigns following the example of the joint development of the CRM and on-going DPW/HLPW efforts. Perhaps a working group, commissioned from the Steering Team or Advisory Council suggested above, would be the appropriate venue in which to begin discussions in this area.

Recommendation 3: Collaborative CbA Mirroring of Certification Tests

In order to validate CbA tools and to build confidence in the CbA process, specific future industry product certification tests could be selected for blind prediction through CbA. Under this scenario, CbA would be used to essentially mirror one or more certification tests concurrently during the certification campaign. Since test results, as well as methods of compliance, will remain proprietary, this effort must necessarily involve appropriate collaboration between the industry applicant, the regulator and other stakeholders. Although industry may be reluctant to add cost and time to the certification campaign through additional analysis efforts, various government entities could incentivize or help offset costs to encourage certification mirroring while obtaining useful validation data.

Recommendation 4: Increasing and Sustaining Access to HPC Resources

Clearly, CbA will require a large increase in available computational resources compared to current practices. This is true both in the initial research and development phases as well as in the final application phases of CbA. As CbA becomes demonstrably viable, industry can be expected to make the business case for increased investment in HPC resources. Depending on rapidly changing technologies and economics, this may come as growing investments in internal HPC resources, or as significant expenditures on emerging high-performance cloud computing, emphasizing the need for close and continual engagement with these respective vendor communities. However, securing access to government HPC resources for technology development and demonstration will be critical, since much of this work will be done in academia and within NASA. The oversubscribed nature of most national leading-edge HPC centers implies that securing the projected HPC resources for CbA may pose a significant obstacle to progress. One of the objectives of the steering committee should be to formulate mechanisms for allocating available HPC resources from NASA and other agencies (such as the DoE) or commercial cloud computing providers for CbA. However, CbA also has the potential to become one of the driving applications in advocating for increased and sustained investments in HPC resources at the national level. Industry has an important role to play here in advocating for the environmental, economic, and safety benefits that increased HPC can enable through CbA, and together with NASA should work to ensure that the aerospace field is fully represented and engaged in current and future national HPC initiatives.

VIII. Conclusion

Certification by Analysis is a challenging long-term endeavor that will motivate many areas of simulation technology development, while driving the potential to decrease cost, improve safety, and improve airplane and engine efficiency. Requirements to satisfy certification regulations provide a measurable definition for the types of analytical capabilities required for success.

The principal technical challenges that must be overcome to enable CbA include the lack of CFD predictive abilities at the edges of the operational envelope, the need for a much higher level of multidisciplinary simulation capabilities, robust and credible uncertainty assessments, and orders of magnitude more capable HPC resources. Although substantial challenges remain, a long-term vision and roadmap can guide the development of enabling technologies and capabilities, while encouraging the demonstration of near-term benefit and value along the way. Changing the current "steady, single-point, single discipline" mentality to be one where analyses are routinely time-accurate, dynamic, and multidisciplinary will take some time, but that forward-looking mindset, along with the measurable goals outlined on the roadmap, will enable far advanced simulation capabilities not only for CbA, but also for use within the entire product development pipeline.

There is general optimism that CbA is a goal that can be achieved, and that a significant amount of flight and engine testing can be reduced in the next few decades. However, consistent with the findings of the CFD Vision 2030 report, significant investment and concentration of resources will be required to reach these goals within the timeframe proposed. This assessment is supported by feedback from community experts obtained through the survey and workshop. Future involvement and investment in CbA will likely align closely with other programmatic considerations, providing a synergistic benefit to other areas of research.

The lofty goal of implementing certification by analysis methods will be a driving influence in technology development for decades to come. This effort will not be accomplished in one or ten years because certification standards are, for good reason, undeniably high. However, with concerted and continual effort, the benefits of success will far outweigh the cost of implementation.

IX. Acknowledgements

This study was performed under NASA contract number NNL16AA04B, task order 80LARC19F0018 in response to Subtopic 2.1.1 – Requirements for Aircraft Certification by Analysis of Topic 2.1.1 – Development of Revolutionary Tools and Methods in Amendment No. 2 to the NASA Research Announcement (NRA) entitled, "Research Opportunities in Aeronautics – 2018 (ROA-2018)," NNH18ZEA001N, released March 21, 2018. This study was performed with Mujeeb Malik as the Technical Monitor and Zachary Wright as the Contracting Officer Representative. The authors wish to thank the extended Certification by Analysis team: Philippe Spalart, Mori Mani, Robb Gregg, Robert Narducci, and Dmitry Kamenetskiy of The Boeing Company, and Al Krejmas, Charlie Haldeman, and Keith Morgan of Pratt & Whitney for their valuable technical contribution and inputs in the execution of the study and in the preparation of this document. Additionally, we would like to acknowledge the active participation of the attendees at the Requirements for Aircraft Certification by Analysis virtual workshop held in July 2020, especially Chris Rumsey (NASA), Uwe Kerlin (Airbus), William Oberkampf, and Eric Walker (NASA) as breakout session facilitators. Furthermore, we thank the following Boeing subject matter and certification experts: Byram Bays-Muchmore, Jeff Masters, Matt Muehlhausen, Paul Bolds-Moorehead, Darren Jens (retired), Robert Orlowski, Bruce Plendl (retired), Mille Sondles, Michael Murdin, and Ron Doll (retired). Finally, we would like to thank all those who participated in the Requirements for Aircraft Certification by Analysis Survey for their valuable time and insightful comments.

Photo Credits

Page 11, Figure 1, Right: The Boeing Company
Page 11, Figure 1, Left: from YouTube video, courtesy of William Jones, BristolCardiffAirport
Page 12, Figure 2, Left: from Solution computed with METAFOR, University of Liège, Belgium
Page 12, Figure 2, Center, Right: FAA
Page 19: NASA
Page 25, Top, middle: The Boeing Company
Page 25, Bottom: NASA
Page 28: NASA
Page 29: The Boeing Company
Page 31: John Chawner, Pointwise, Inc.
Page 30: FAA-H-8083-3B, Airplane Flying Handbook
Page 32: Joaquim Martin, University of Michigan
Page 33: HIRENASD model, Dimitri Mavriplis, University of Wyoming
Page 34, Top: Pratt & Whitney
Page 34, Middle, Left: Research Gate
Page 34, Middle, Right: Research Gate
Page 34, Bottom: Pratt & Whitney
Page 38: NASA

X. References

[1] FAA, "Federal Aviation Administration," [Online]. Available: https://www.faa.gov.

[2] "EASA | European Union Aviation Safety Agency," [Online]. Available: https://www.easa.europa.eu/.

[3] FAA, "The FAA and Industry Guide to Product Certification," May 2017.

[4] F. De Florio, Airworthiness: An Introduction to Aircraft Certification and Operations, 3rd ed., Butterworth-Heinemann, 2016.

[5] R. D. Gregg, "AIAA Forum 360 Panel Discussion on Certification by Analysis," in *AIAA Aviation Forum*, Atlanta, GA, 2018.

[6] American Institute of Aeornautics and Astronautics, "When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification," Reston, VA, To be published.

[7] J. Slotnick, A. Khodadoust, J. Alonso, D. Darmofal, W. Gropp, E. Lurie and D. Mavriplis, "CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences," NASA/CR-2014-218178, 2014.

[8] J. Slotnick and D. Mavriplis, "A Grand Challenge for the Advancement of Numerical Prediction of High Lift Problems," in *Proceedings of the AIAA Scitech 2021 Forum*, AIAA-2021-0955.

[9] M. S. Anand, G. Medic, U. Paliath, K. L. Suder, M. R. Malik and G. M. Laskowski, "Vision 2030 Aircraft Propulsion Grand Challenge Problem: Full-engine CFD Simulations with High Geometric Fidelity and Physics Accuracy," in *Proceedings of the AIAA Scitech 2021 Forum*, AIAA-2021-0956.

[10] "Electronic Code of Federal Regulations," [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?SID=42ce732c5c01b787ef118b7f6d0afd32&mc=true&tpl=/ecfrbrowse/Title14/14CIsubchapC.tpl.

[11] FAA, "Flight Test Guide for Certification of Transport Category Airplanes," Advisory Circular 25-7D, 2018.

[12] J. P. Slotnick and G. Heller, "Emerging Opportunities for Predictive CFD for Off-Design Commercial Airplane Flight Characteristics," in *Proceedings of the 54th 3AF International Conference on Applied Aerodynamics*, Paris, France, 2019.

[13] G. M. Laskowsky, J. Kopriva, V. Michelassi, S. Shankaran, U. Paliath, R. Bhaskaran, Q. Wang, C. Talnikar, Z. Wang and F. Jia, "Future Directions of High-Fidelity CFD for Aero-Thermal Turbomachinery Research, Analysis and Design," in *Proceedings of the 46th AIAA Fluid Dynamics Conference*, Washington, D.C., 2016, AIAA-2016-3322.

[14] Equivalent Level of Safety (ELOS) Finding for Vibration/Buffeting Compliance Criteria, Large Antenna and Radome Installed on Airbus Aircraft A330-200 Series, FAA Project # ODA-GED-P164.

[15] Equivalent Level of Safety (ELOS) Finding for Vibration/Buffeting Compliance Criteria, Radome installed on Boeing 737-8 Airplanes, FAA Project # SA00009ODA-T.

[16] EASA, "Modelling and Simulation -- CS-25 Structural Certification Specifications, EASA Proposed CM," 14 July 2020. [Online]. Available: https://www.easa.europa.eu/sites/default/files/dfu/ proposed_cm-s-014_modelling_simulation_-_for_consultation.pdf. [Accessed 2020].

[17] Federal Aviation Administration, "AC20-146A, Methodology for Dynamic Seat Certification by Analysis for Use in Parts 23, 25, 27, and 29 Airplanes and Rotorcraft," US Govt, Washington, D.C., 2018.

[18] AIAA/NASA, "3rd AIAA CFD High Lift Prediction Workshop (HiLiftPW-3)," June 2017. [Online]. Available: https://hiliftpw.larc.nasa.gov/index-workshop3.html. [Accessed 2020].

[19] B. Konig, E. Fares, M. Murayama and Y. Ito, "PowerFLOW Simulations for the Third AIAA High-Lift Prediction Workshop," in *AIAA SciTech*, 2018.

[20] A. Cary, M. Yousef, P. Li and M. Mani, "Current practice unstructured grid CFD results for 3rd AIAA High Lift Prediction Workshop," in *AIAA SciTech*, 2018.

[21] K. Goc, S. Bose and P. Moin, "Subgrid-scale modeling sensitivities in wall-modeled large-eddy simulations of a high-lift aircraft configuration," 2020. [Online]. Available: http://web.stanford.edu/group/ctr/ResBriefs/2020/07_Goc.pdf. [Accessed January 2021].

[22] K. Duraisamy, P. Spalart and C. L. Rumsey, "Directions of Turbulence Modeling Research in Aeronautics," NASA TM 2017-219682, November 2017.

[23] C. Meneveau and T. S. Lund, "The dynamic Smagorincky model and scale-dependent coefficients in the viscous range of turbulence," *Physics of fluids,* vol. 9, no. 12, pp. 3932-3934, 1997.

[24] P. Moin and R. Verzicco, "On the suitablilty of second-order accurate discretizations for turbulent flow simulations," *European Journal of Mechanics-B/Fluids,* vol. 55, pp. 242-245, 2016.

[25] Z. J. Wang, K. Fidkowski, R. Abgrall, F. Bassi, D. Caraeni, A. Cary, H. Deconinck, R. Hartmann, K. Hillewaert, H. T. Huynh and et al., "High-order CFD methods: current status and perspective," *International Journal for Numerical Methods in Fluids,* vol. 72, no. 8, pp. 811-845, 2013.

[26] S. Chen and G. D. Doolen, "Lattice Boltzmann Method for Fluid Flows," *Annual Review of Fluid Mechanics,* vol. 30, pp. 329-364, 1998.

[27] R. Langtry and F. Menter, "Transition Modeling for General CFD Applications in Aeronautics," in *43rd AIAA Aerospace Science Meeting and Exhibit*, Reno, NV, AIAA-2005-522.

[28] J. Coder, "Further Development of the Amplification Factor Transport Transition Model for Aerodynamic Flows," in *AIAA SciTech 2019 Forum*, San Diego, CA, AIAA-2019-0039.

[29] R. Adams, "Aircraft icing certification - In perspective," in *Proceedings of the 26th Aerospace Sciences Meeting*, Reno, NV, AIAA-1988-204.

[30] F. T. Lynch and A. Khodadoust, "Effects of Ice Accretions on Aircraft Aerodynamics," *Progress in Aerospace Sciences,* vol. 37, no. 8, pp. 669-767, 2001.

[31] A. Giusti, M. Sitte, G. Borghesi and E. Mastorakos, "Numerical investigation of kerosene single droplet ingnition at high-altitude relight conditions," *Fuel,* pp. 663-670, 2018.

[32] G. Kumar and S. Drennan, "A CFD Investigation of Multiple Burner Ignition and Flame Propagation with Detailed Chemistry and Automatic Meshing," in *Proceedings of the 52nd AIAA/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, UT, AIAA-2016-4561.

[33] F. Alauzet, A. Loseille, D. Marcum and T. R. Michal, "Assessment of Anisotropic Mesh Adaptation for High-Lift Prediction of the HL-CRM configuration," in *Proceedings of the 23rd AIAA Computational Fluid Dynamics Conference*, Denver, CO, AIAA-2017-3300.

[34] M. A. Park, N. Barral, D. Ibanez, D. S. Kamenetskiy, J. A. Krakos, T. R. Michal and A. Loseille, "Unstructured Grid Adaptation and Solver Technology for Turbulent Flows," in *Proceedings of the 2018 AIAA Aerospace Sciences Meeting*, Kissimmee, FL, AIAA-2018-1103.

[35] V. Sankram, A. Wissink, A. Datta, J. Sitaraman, B. Jayaraman, M. Potsdam, A. Katz,, S. Kamkar, B. Roget, D. Mavriplis, H. Saberi, W. B. Chen, W. Johnson and R. Strawn, "Overview of the Helios Version 2.0 Computational Platform for Rotorcraft Simulations," in *49th AIAA Aerospace Sciences Meeting and Exhibit*, Orlando, FL, AIAA-2011-1105.

[36] M. Brazell, A. Kirby and D. Mavriplis, "A High-order Discontinuous-Galerkin Octree-Based AMR Solver for Overset Simulations," in *Proceedings of the 23rd AIAA Computational Fluid Dynamics Conference*, Denver, CO, AIAA-2017-3944.

[37] R. Haimes and J. Dannenhoffer, "EGADSlite: A lightweight Geometry Kernel for HPC," in *AIAA SciTech*, AIAA-2018-1401.

[38] G. Medic, "Impact of Vision 2030 on CFD Practices in Propulsion Industry," in *Proceedings of the AIAA 2019 Aviation Forum*, Dallas, TX, AIAA-2019-2943.

[39] M. Carpenter, T. Fisher, E. Nielsen, M. Parsani, M. Svard and N. Yamaleev, "Entropy stable summation-by-parts formulations for compressible computational fluid dynamics," in *Handbook of Numerical Analysis*, vol. 17, Elsevier, 2016, pp. 495-524.

[40] S. M. Murman, L. Diosady, A. Garai and M. Ceze, "A space-time Discontinuous-Galerkin approach for separated flows," in *Proceedings of the 54th AIAA Aerospace Sciences Meeting*, San Diego, CA, AIAA-2016-1059.

[41] W. Johnson, "A History of Rotorcraft Comprehensive Analysis," NASA TP-2012-216012, April 2012.

[42] K. C. Hall, J. P. Thomas and W. S. Clark, "Computation of unsteady nonlinear flows in cascades using a harmonic balance technique," *AIAA Journal,* vol. 40, no. 5, pp. 879-886, 2002.

[43] D. Ramezanian and D. Mavriplis, "An Order NlogN Parallel Time-Spectral Solver of Quasi=Periodic Problems," in *Proceedings of the 57th AIAA Aerospace Sciences Meeting*, San Diego, CA, AIAA-2019-0902.

[44] L. T. Diosady and S. M. Murman, "Scalable Tensor-Product Preconditioners for High-Order Finite-Element Methods," *Journal of Computational Physics,* vol. 394, pp. 759-776, October 2019.

[45] D. Mavriplis, "Adjoint Methods for Uncertainty Quantification," Rhode St Genese, Belgium, October 2015.

[46] Q. Wang, "Forward and adjoint sensitivity computation of chaotic dynamical systems," *Journal of Computational Physics,* vol. 235, pp. 1-13, February 2013.

[47] B. Flynt and D. Mavriplis, "Optimal Error Control Using Discrete Adjoint Error Estimates in Unsteady Flow Problems," in *52nd AIAA Aerospace Sciences Conference*, National Harbor, MD, AIAA-2014-1434.

[48] M. Giles and E. Süli, "Adjoint methods for PDEs: aposteriori error analysis and postprocessing by duality," *Acta Numerica,* no. 11, pp. 145-236, 2002.

[49] D. Venditti and D. Darmofal, "Anisotropic grid adaptation for functional outputs: application to two-dimensional viscous flows," *Journal of Computational Physics,* vol. 176, no. 1, pp. 40-69, February 2002.

[50] J. S. Gray, J. T. Hwang, J. R. R. A. Martins, K. T. Moore and B. A. Naylor, "OpenMDAO: An open-source framework for multidsciplinary design, analysis, and optimization," *Structural and Multidisciplinary Optimization,* vol. 59, no. 4, pp. 1075-1104, April 2019.

[51] *Multiphysics Simulations: Challenges and Opportunities,* Park City, UT: Argonne National Lab Report ANL/MCS-TM-321, Report from Workshop sponsored by the Institute for Computing in Sciense (ICiS), June-August 2011.

[52] V. A. Moussear, D. A. Knoll and W. J. Rider, "Physics-based preconditioning and the Newton-Krylov method for non-equilibrium radiation diffusion," *Journal of Computational Physics,* vol. 160, no. 2, pp. 743-765, 2000.

[53] Z. J. Zhang and D. W. Zingg, "Efficient Monolithic Solution Algorithm for High-Fidelity Aerostructural Analysis and Optimization," *AIAA Journal,* vol. 56, no. 3, Mar 2018.

[54] H. B. Lee, U. Ghia, S. Bayyuk, W. L. Oberkampf, C. J. Roy, J. A. Benek, C. R. Rumsey, J. M. Powers, R. H. Bush and M. Mani, "Development and Use of Engineering Standards for Computational Fluid Dynamics for Complex Aerospace Systems," in *Proceedings of the 46th AIAA Fluid Dynamics Conference*, Washington, D.C., AIAA-2016-3811.

[55] J. Schaefer, V. Romero, S. Shafer, B. Leyde and C. Denham, "Approaches for Quantifying Uncertainties in Computational Modeling for Aerospace Applications," in *Proceedings of the AIAA Scitech 2020 Forum*, Orlando, Florida, AIAA-2020-1520.

[56] G. Xia, G. Medic and T. Praisner, "Hybrid RANS/LES of corner separation in a linear compressor cascade," *ASME Journal of Turbomachinery,* vol. 140, no. 8, 2018.

[57] B. Y. Min, J. Joo, J. Mendoza, J. Lee, G. Xia and G. Medic, "Large-Eddy Simulation of Corner Separation in a Compressor Cascade," in *Proceedings of the 63rd ASME Turbo EXPO*, Oslo, Norway, ASME GT2018-77144.

[58] G. Xia, G. Kalitzin, J. Lee, G. Medic and O. P. Sharma, "Hybrid RANS/LES simuation of combustor/turbine interactions," in *Proceedings of the 65th ASME Turbo EXPO*, London, UK, ASME GT2020-14873.

[59] C. N. Bishop, Pattern Recognition and Machine Learning, New York, NY: Springer Science+Business Media, LLC, 2006.

[60] M. C. Kennedy and A. O'Hagan, "Bayesian calibration of computer models," *Journal of the Royal Statistical Society Series B, Statistical Methodology,* vol. 63, no. 3, pp. 425-262, 2002.

[61] W. L. Oberkampf and C. J. Roy, Verification and Validation in Scientific Computing, New York, NY: Cambridge University Press, 2010.

[62] A. D. Wendorff, B. T. Whitehead, J. J. Alonso and S. R. Bieniawski, "Integrating Aerodynamic Uncertainty into Aircraft Maneuvers during Conceptual Design," in *Proceedings of the 17th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Washington, D.C., AIAA-2016-3999.

[63] H. F. Stripling, M. L. Adams, R. G. McClarren and B. K. Mallick, "The Method of Manufactured Universes for Validating Uncertainty Quantification Methods," *Reliability Engineering and System Safety,* vol. 96, pp. 1242-1256, 2011.

[64] V. Romero, "Real-Space Model Validation and Predictor-Corrector Extrapolation Applied to the Sandia Cantilever Beam End-to-End UQ Problem," in *Proceedings of the AIAA Scitech 2019 Forum*, San Diego, CA, AIAA-2019-1488.

[65] C. Rumsey, "Turbulence Modeling Resource," [Online]. Available: https://turbmodels.larc.nasa.gov/. [Accessed February 2021].

[66] D. J. Simmons, F. O. Thomas and T. C. Corke, "A Smooth Body, Large-Scale Flow Separation Experiment," in *Proceedings of the 2018 AIAA Aerospace Sciences Meeting*, Kissimmee, FL, AIAA-2018-0572.

[67] M. L. Robbins, M. Samuell, H. Annamalai and O. J. Williams, "Overview of validation completeness for gaussian speed-bump separated flow experiments," in *Proceedings of the AIAA Scitech 2021 Forum*, Virtual Event, AIAA-2021-0969.

[68] T. Lowe, A. Borgoltz, W. J. Devenport, D. J. Fritsch, A. Gargiulo, J. E. Duetsch-Patel, C. J. Roy, M. Szoke and V. Vishwanathan, "Status of the NASA/Virginia Tech Benchmark Experiments for CFD Validation," in *Proceedings of the AIAA Scitech 2020 Forum*, Orlando, FL, AIAA-2020-1584.

[69] D. Greenblatt, K. B. Paschal, C. S. Yao, J. Harris, N. W. Schaeffler and A. E. Washburn, "Experimental Investgation of Separation Control Part 1: Baseline and Steady Suction," *AIAA Journal,* vol. 44, no. 12, pp. 2820-2830, 2006.

[70] O. J. Williams, M. Samuell, M. L. Robbins, H. Annamalai and A. Ferrante, "Characterization of Separated Flowfield over Gaussian Speed-Bump CFD Validation Geometry," in *Proceedings of the AIAA Scitech 2021 Forum*, Virtual, AIAA-2021-1671.

[71] W. D. Bachalo and D. A. Johnson, "Transonic, Turbulent Boundary-Layer Separation Generated on an Axisymmetric Flow Model," *AIAA Journal,* vol. 24, no. 3, pp. 437-443, 1986.

[72] M. A. Kegerise and D. H. Neuhart, "An Experimental Investigation of a Wing-Fuselage Junction Model in the NASA Langley 14- by 22-Foot Subsonic Tunnel," NASA/TM-2019-220286, June 2019.

[73] M. Wernet, A. Wroblewski, R. Locke and N. Georgiadis, "THX Experiment overview," NASA-TR-2016-0014883, 2016.

[74] J. Dunham, "AGARD WG26 Report - Summary of 13 different simulations of Rotor 37 AGARD Advisory Report AR-355 "CFD Validation for Propulsion System Componenets"," AGARD, 1998.

[75] J. Denton, "Lessons Learned from Rotor 37," in *Proceedings of the Third International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows (ICIASF)*, Beijing, China, 1996.

[76] K. L. Suder, T. H. Okiishi, M. Hathaway, A. J. Strazisar and J. J. Adamczyk, "Measurments of the unsteady flow field within the stator row of a transonic axial flow fan: Part I--Measurement and analysis technique," ASME 87-GT-226, 1987.

[77] M. D. Hathaway, T. H. Okiishi, K. L. Suder, A. J. Strazisar and J. J. Adamczyk, "Measurments of the unsteady flow field within the stator row of a transonic axial flow fan: Part II--results and discussion," ASME 87-GT-227, 1987.

[78] T. J. Burrows, B. Vukasinovic, A. Glezer, M. T. Lakebrink and M. Mani, "Controlled Flow Dynamics in a Serpentine Diffuser with a Cowl Inlet," in *Proceedings of the AIAA Aviation 2020 Forum*, Virtual, 2020.

[79] J. Ballmann, A. Dafnis, A. Baars, A. Bouke, K. Brakhage, C. Braun, C. Buxel, B. Chen, C. Dickopp, M. Kaampchen, H. Korsch, H. Olivier, S. Ray, L. Reimer and H. Reimerdes, Aero-structural Dynamics Experiments at High Reynolds Numbers. In: Schröder W. (eds) Summary of Flow Modulation and Fluid-Structure Interaction Findings. Notes on Numerical Fluid Mechanics and Multidisciplinary Design, vol 109.: Springer, Berlin, Heidelberg, 2012.

[80] US Code of Federal Regulations, 14CFR25.21(a)(1), Proof of compliance.

[81] H. Aydemir, U. Zengin, U. Durak and S. Hartmann, "The Digital Twin Paradigm for Aircraft -- Review and Outlook," in *Proceedings of the AIAA Scitech 2020 Forum*, Orlando, FL, AIAA-2020-0553.

[82] AIAA Digital Engineering Integration Committee, "AIAA Position Paper: "Digital Twin: Definition and Value"," AIAA, Reston, VA, 2020.

[83] B. Peherstorfer, K. Willcox and M. Gunzburger, "Survey of Multifidelity Methodsin Uncertainty Propagation,Inference, and Optimization," *SIAM Review,* vol. 60, no. 3, pp. 550-591, 2018.

[84] N. Zobeiry and K. D. Humfield, "An Iterative Scientific Machine Learning Approach for Discovery of Theories Underlying Physical Phenomena," September 2019. [Online]. Available: https://arxiv.org/pdf/1909.13718.pdf. [Accessed January 2021].

[85] B. Y. Zhou, N. R. Gauger, M. Morelli, A. Guardone, J. Huath and X. Huan, "Development of a Real-Time In-Flight Ice Detection System via Computational Aeroacoustics and Bayesian Neural Networks," in *Proceedings of AIAA Scitech 2020 Forum*, Orlando, FL, AIAA-2020-1638.

[86] P. G. Kaminski and Steering Committee for the Decadal Survey of Civil, Decadal Survey of Civil Aeronautics, Wasington, D.C.: National Academies Press, 2006.

[87] B. Perry, W. Silva, J. Florance, C. Wieseman, A. Pototzky, M. Sanetrik, R. Scott, D. Keller, S. Cole and D. Coulson, "Plans and Status of Wind-Tunnel Testing Employing an Aeroservoelastic Semispan Model," in *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, HI, AIAA-2007-1770.

[88] L. Yip, P. Vijgen, J. Hardin and C. Van Dam, "Subsonic High-lift Flight Research on the NASA Transport System Research Vehicle (TSRV)," in *Proceedings of the 6th AIAA Biennial Flight Test Conference*, Hilton Head, SC, AIAA-1992-4103.

[89] A. Rizzi and J. Luckring, "What Was Learned in Predicting Slender Airframe Aerodynamics with the F-16XL Aircraft," *Journal of Aircraft,* vol. 54, no. 2, March 2016.

[90] S. Goertz, M. Abu-Zuravk, C. Ilic, T. F. Wunderlich, S. Keye, M. Shulze, C. Kaiser, T. Klimmek, O. Suelozgen, T. Kier, A. Schuster, S. Daehne, M. Petsch, D. Kohlgrueber, J. Haessy, R. Mischke, A. Weinert, P. Knechtges, S. Gottfried, J. Hartmann and B. Froehler, "Overview of Collaborative Multi-Fidelity Multidisciplinary Design Optimization Activities in the DLR Project VicToria," in *Proceedings of AIAA Aviation 2020 Forum*, Virtual, AIAA-2020-3167.

[91] A. M. Clark,, J. P. Slotnick, N. Taylor and C. L. Rumsey, "Requirements and Challenges for CFD Validation within the High-Lift Common Research Model Ecosystem," in *Proceedings of the AIAA Aviation 2020 Forum*, Virtual event, AIAA-2020-2772.

[92] US Code of Federal Regulations, 14CFR25.107d, Takeoff speeds.

[93] US Code of Federal Regulations, 14CFR25.121, Climb: One-engine inoperative.

[94] US Code of Federal Regulations, 14CFR25.103, Stall speed.

[95] US Code of Federal Regulations, 14CFR25.201, Stall demonstration.

[96] US Code of Federal Regulations, 14CFR25.203, Stall characteristics.

[97] US Code of Federal Regulations, 14CFR25.251, Vibration and buffeting.

[98] US Code of Federal Regulations, 14CFR33.94, Blade containment and rotor unbalance tests.

Appendix A. Gap Assessment for Maneuvers and Tests

In order to assess the ability of analysis to supplement flight testing for different classes of certification opportunities, representative approaches were developed and used to identify different areas where additional effort is required to facilitate the use of CFD. These assessments were performed by teams of engineers with experience in certification testing, aircraft system analysis and design, and computational analysis methods. The different requirements were subdivided into three categories: technical requirements, logistical requirements, and accuracy requirements. Technical requirements are primarily associated with capability or process development, including multidisciplinary concerns. Logistical requirements are primarily associated with the computational requirements, including storage that may be needed. Accuracy requirements entail both developing appropriate means for computing the required outputs for the class of simulation as well as validation to determine the appropriate confidence to associate with these predictions. The sample approach used to determine these requirements are described below in more detail.

Table A-1 contains definitions of certification technical requirements for Part 25 maneuvers deemed to be the best candidates for CbA, along with accuracy and logistical requirements for future CbA simulation capability for these maneuvers. Table A-2 contains the same for Part 33 certification tests. The remainder of this appendix contains additional test descriptions, explanations of modeling challenges and modeling gap assessments for each of the maneuvers and tests listed in the two tables.

VMU

The determination of the regulatory minimum unstick speed (VMU) is required for setting minimum takeoff speeds [92]. Generally, it is determined by rotating the aircraft to its maximum angle of attack while slowly increasing takeoff speed. The lowest speed at which the airplane takes off with no additional pitch input and flies safely out of ground effect is the VMU speed. This test must be repeated at multiple thrust to weight ratios and flap settings. This flight test maneuver is a good candidate for analysis as it can be relatively dangerous to aircraft structure, since the tail is dragging along the runway for significant distances, as well as the danger of overrotation. For larger airplanes where the maximum airplane attitude on the runway is constrained by body length (i.e., sufficiently far enough from the stall angle of attack), the flow physics are amenable to current flow modeling techniques because of minimal flow separation.

As an approach to determine VMU, a half model grid with appropriate configuration (flaps, landing gear, static aeroelastic deformations, etc.) and powered engine (mass flow, nozzle TTR, NPR) in proximity to ground can be simulated at a (geometric-limited) attitude. For a range of speeds, the lift coefficient is determined, implying weight by assuming no vertical acceleration. This allows determination of the thrust to weight ratio corresponding to the assumed speed. By repeating the computation at different speeds, the valid region for thrust to weight ratio can be established. In general, VMU is desired to be determined within about 1% in speed, which corresponds to about 2% in C_L.

While there are many aspects of this problem that are straightforward (half model is appropriate, not at $C_{L,max}$, known geometric (AoA) initial conditions), there are several aspects that complicate the problem. Ground effect of the wing needs to be included and the aeroelastically deformed height of the wing tip above the ground can have an impact. The engine plume impacts the runway and may affect the tail, necessitating careful engine property determination to match the assumed thrust. Most of the technical requirements are available for this type of simulation and the logistical requirements are moderate, but will still require a number of simulations due to the range of velocities and multiple flap settings that will need to be considered. One of the largest challenges associated with this maneuver is establishing the confidence in the accuracy of the results through validation with suitable full scale data sets.

Methodology challenges

- Engine/plume modeling
- Structural response
- Application validation

Takeoff Climb Gradient with One Engine Inoperative

Takeoff climb gradient requires demonstration that the available gradient of climb for a two-engine airplane with one engine inoperative and landing gear extended must be positive from the point of takeoff until the landing gear is fully retracted at a speed not less than the takeoff safety speed. The engine power setting must remain the same throughout the whole maneuver. After the landing gear is retracted, the steady climb gradient must not be less than 2.4 until the airplane reaches a height of 400 feet above the runway. The regulation allows that the path may be determined by synthesis from segments, but the segments must be clearly defined. This must also be demonstrated for icing conditions [93].

This maneuver is a candidate for CbA because the condition occurs at a relatively benign angle of attack, and it can be simulated as a series of steady analyses. High fidelity lift, drag, and thrust predictions are required to properly demonstrate the flight path gradient. A full-model simulation will be required to model the asymmetric thrust and the associated control surface and sideslip effects.

Methodology gaps

- High fidelity airplane lift, drag, and thrust predictions
- Icing considerations

Crosswind Takeoff

A crosswind takeoff assesses the handling qualities of the aircraft during takeoff with a greater than 20 knot crosswind (90° from runway) with a corresponding sideslip angle. The pilot is required to demonstrate the ability to maintain heading with an appropriate pedal and lateral control inputs. This scenario can be simulated for a range of speeds (dynamic pressures) and rudder deflections at the appropriate sideslip. The simulation will determine the rudder angle as a function of speed corresponding to negligible yawing and rolling moments at an angle of attack consistent with aircraft weight. Knowledge of the flight control system will translate rudder position to the pedal force requirement. The overall moment prediction accuracy requirements will depend on how small of a yaw is acceptable (and over what time), since this is presently a bit subjective. The flight condition also tends to be very dynamic so it will be important to ensure that there is adequate control surface power available; this likely means that the limit of control authority will need to be determined under these conditions as well.

From a flow simulation difficulty standpoint, this series of simulations is simplified because it can likely be performed as a RANS simulation at low angles of attack with only a moderate sideslip angle. Like many of these maneuvers, a full model will be required. Efficient simulation may also require adding an ability to predict lateral trim. While many CFD tools can target a particular lift coefficient with a moment correction applied, the lateral trim is a bit more complicated and it may be necessary to include control surface deflections within the model, particularly as the control power limits are approached. Both vehicle moments and rudder hinge moments are critical in this simulation and can be challenging quantities to get at present because of the flow sensitivities, particularly as the maximum rudder deflection is approached and flow separation becomes significant.

Methodology gaps

- Control system integration
- Pilot feedback

Steady Heading Sideslips

This maneuver requires demonstrating the ability to set to a particular sideslip angle from trimmed (level) flight and return to zero sideslip at critical points in the flight envelope. This may include flaps down configurations as well as cruise configurations and there is also a required check for avoiding adverse roll. One approach for modeling this might be to compute the yawing moment as a function of rudder angle starting from a trimmed configuration to determine the allowed limits of rudder deflection based on the rudder hinge moment. For the desired sideslip angle, the rudder angle necessary to trim (will likely include other control surfaces if coupling exists) could be determined and the resulting rudder force/hinge moment checked to ensure it is attainable. It will also be necessary to ensure that a decreased rudder angle will facilitate a restoring moment. This approach can be performed using a quasisteady state analysis where the aircraft dynamics do not need to be included, but these assumptions will need to be demonstrated that they are valid.

The principle additional technology requirements for steady heading sideslips are associated with accurate predictions of moments. While full (lateral and longitudinal) trimming capabilities could make the simulations more efficient, improvements in moment prediction accuracy are still required. Because both level and distribution of pressure forces contribute to the moment, moment predictions are particularly sensitive to error. Sideslip maneuvers can be particularly challenging because they lead to cases with high levels of load and incipient separation on the control surface. Furthermore, flow separation at the edge of control surfaces and between adjacent components can impact the control surface effectiveness as a function of deflection angle.

Methodology gaps

- Flow separation on control surfaces at maximum deflection
- Robust and accurate airplane and control surface moment prediction

Short Period Oscillations

Short period oscillations are required to be heavily damped when the primary controls are in both free and fixed positions. For certification, the elevator is pulsed and controls are returned to neutral at different speeds to assess the damping of the oscillating response. Because of the dynamic response, one approach for assessing this requirement through analysis is to simulate the maneuver using a combined CFD simulation with trajectory analysis. For each flight speed, a simulation running for several periods would be required to assess the damping. This type of approach requires long-time integrations of dynamic simulations with moving geometry (including both rigid body motion and control surface motion prescribed by a flight controller).

An alternate approach that combines CFD and classical linear analysis would be to develop an aerodynamic model for the configuration that includes pitch rates using prescribed grid motions and combine this with classical dynamic system responses to determine the short period damping. This approach might need to be extended to include control surface rate effects, including free surface analysis, and would need to undergo extensive validation to gain confidence in its predictions.

Methodology gaps

- Dynamic model considerations
- Long-time integration
- Efficient, accurate prediction of pitching moment and pitch rate

Stalls

There are multiple requirements associated with stalls that are interacting but can be considered in phases. These range from prediction of the stall speed to stall identification including the quality of stall, stall recovery, and confirmation of roll and yaw control not being reversed, and to complete maneuver assessment such as a 30° banked turning stall. All of these require assessments of the aircraft in the vicinity of $C_{L,max}$ for the particular configuration and will involve significant flow separation. Furthermore, icing considerations need to be included, further complicating the aerodynamic predictions.

Stall speed is the speed determined at $C_{L,max}$ (corrected to a 1g load factor) for all flap settings. $C_{L,max}$ is determined at the most adverse center of gravity position, trimmed for straight and level flight, with and without ice. At this initial condition, the angle of attack is increased to decelerate the airplane no faster than one knot per second [94]. Turning stall is also demonstrated for all applicable flap settings. In a 30 degree bank, airplane speed is decreased until stall happens. The stall should not be unrecoverable or excessively abrupt [95] [11].

For simulation purposes, this may be evaluated by running trimmed sweeps at high angles of attack to determine the lift coefficient of the aircraft where stall will occur at that speed. For transonic cases, there may also be Mach number effects that will need to be included to find the stall speed at the appropriate weight.

Additionally, stall characteristics are evaluated at each flap setting in both straight and turning flight (30 degree bank angle). At each condition, the pilot must have a “clear and distinct indication” of stall. Stall entry and recovery must not require more than “normal piloting skill.” Maximum bank, roll, and heading angle deviations are stipulated [95] [96] [11].

Identifying and characterizing stall will likely require a trajectory simulation and/or inclusion of a pilot using a flight simulator to assess stall recovery. This capability would require not only predictions both before and after $C_{L,max}$, at high angles of attack and sideslip, and at high speed, but may also require dynamic effects.

All of the simulations for this class of problem will require accurate predictions of massively separated unsteady flows, including determination of smooth body separation, both pre- and post-$C_{L,max}$. Furthermore, the impact of control surfaces, including speed brakes, are critical in this analysis. Asymmetries may develop in both the aircraft response and in the aerodynamics. In addition to the complexity of a particular simulation, a large number of cases and aircraft configurations must be examined.

Methodology gaps

- Prediction of massively separated unsteady high- and low-speed flows
- Post-stall handling characteristics
- Possible pilot interaction

Buffet

The transonic buffet onset boundary is a partially subjective assessment of the condition when vibration at the pilot’s seat reaches an appropriate threshold. The buffet onset boundary is used to establish limits on allowable speed, weight and altitude combinations for normal operations. Buffet evaluation also includes the requirement that the airplane be free from any vibration and buffeting that would prevent continued safe flight in any likely operating condition. There must not be any perceptible buffet up to the maximum operating speed and no excessive vibration up to the dive speed [97].

Numerical assessment for buffet will require time-accurate simulations of separated flows, while capturing a broad range of frequencies. It may be possible to utilize a one-way coupling of the external loading into a structural model to obtain the dynamic response, but some situations may require a fully coupled system analysis. Because the entire flight envelope is considered, a broad range of separations including smooth body and shock/boundary layer separations may be present and multiple frequencies of forcing will occur. Furthermore, there are a large number of cases that must be examined, leading to high cost for these simulations.

Methodology gaps

- Separated flows, shock/boundary layer interaction
- Structural response
- Vibration characterization and correlation to existing data

Fan Blade Containment

Fan blade containment testing demonstrates that, in a fan blade-out event: (i) the fan blade is contained, (ii) fan blade-out does not result in a fire, i.e., deformation/loads do not cause a breach of fuel/oil systems, (iii) fan blade-out does not cause the engine mounts or flanges to fail, and (iv) post fan blade-out the engine shuts down safely, i.e., throttle pull back allowed after 15 seconds, and the EEC properly functioning after sustaining event loads [98]. While this test is not strictly a flight test, it is a test that is well-suited to analysis, given the current analysis tool state of maturity and the materials science understanding. Additionally, since this test completely destroys the engine, it is an expense that could be recovered through analysis-based testing methods. Thus, it is both an expensive test and a good target for CbA. Fortunately, current-state dynamics/structural modeling capability for this test is well advanced and computationally tractable. Fan blade containment can be predicted with sufficient accuracy today with transient structural analysis. Predictions of mounts and flange loads are also close. Fire prediction (severing of fuel/oil systems) is challenging – needs to include more engine systems/geometry into the analysis, and improved externals component material deformation characterization is needed. Engine shutdown also remains a challenge – while modeling Electronic Engine Control functionality is pretty close, predicting timing between compressor surge vs severed shaft / turbine overspeed and uncontained failure remains challenging. Significant validation work versus legacy engines or current programs will be required. A combination of a rig with transient structural analysis could be an intermediate step.

Methodology gaps

- Need to include more engine systems/geometry in the analysis
- Component material (elastic/plastic) deformation characterization
- Prediction of timing between compressor surge vs turbine overspeed for severed shaft; modeling improvements needed for shaft rubbing/heatup leading to shaft failure

Engine Vibration

The Part 33 Engine Vibration tests consist of a large matrix of test configurations: variations in geometry (vane angles, bleeds, power extraction, etc.) and operating conditions, including transients. In an engine test, all vibration drivers are automatically present, but all the drivers are not known a priori. Variation from test to test for the same engine is typical, with larger variation from engine to engine.

Key flow physics are wakes, shocks, coupling with acoustics, and stage interactions. Analyses use an idealized model of hardware in the engine, which impacts both aero and structural predictions (variations in mode shape, frequency, damping, etc.). Uncertainty about the inputs (boundary and operating conditions, geometry, etc.) also challenge simulation accuracy. Analysis of an individual component, in place of full engine (e.g., part of the compressor or turbine) could be an intermediate step.

Methodology gaps:

- Unsteady pressure and aerodamping predictions
- Structural response
- Coupling of aero and structural (and thermal) analyses; transient effects

Engine Operability

Engine Operability tests need to demonstrate safe engine operating characteristics throughout its operating envelope, including stability pinch points, relight, rotor lock, and windmill. These tests are conducted both on the ground and in the air using flying test beds. Typical transient maneuvers tests have the following pattern: dwell several minutes at a given condition, execute transient behavior, repeat. A significant amount of flight testing is performed to determine fuel scheduling to keep the combustor operating at or near peak efficiency throughout the flight envelope.

Predicting compressor operability at a given part-power condition still remains a challenge, despite recent improvements in unsteady CFD modeling. Prediction of stall depends strongly on clearances, which are asymmetric due to thermal gradients and maneuver loads. The starting model needs to be elaborate enough to include air starting, ground starting, models of the fuel system, bleed system, and to correctly represent available starter torque. Combustor relight predictions may require full-wheel analysis with detailed models of the fuel delivery system. Compressor and turbine maps at sub-idle/windmill are hard to determine and are critical for combustor start and engine spool-up procedures.

Key flow physics are loss of stability in compressors and fuel spray atomization, and combustor efficiency, lean blow out and ignition modeling at off-design conditions (low pressure and temperature, and swirler pressure drop).

Methodology gaps:

- Compressor operability at part power – aerodynamics of endwall features with variable, uneven clearances

- Transient clearance modeling
- Combustion efficiency fall-off, LBO; fuel spray atomization in the combustor at low pressure-drop and colder temperatures

Bird Ingestion

The Bird Ingestion certification requires engine ground tests: medium and large flocking bird tests cover a few seconds of event and 20-25 minutes of post-event transient behavior. Ingestion of birds into the engine can cause: compressor surge with the resulting rematch increasing operating line and decreasing stall margin, rotor imbalance resulting in excessive vibrations, and thrust loss. Modeling the bird ingestion tests has the same challenges as the Operability and Vibrations certification tests for the fan and compressor, with the addition of simulating event deformations and simulating post-event operability and vibration impacts and thrust loss.

Methodology gaps:

- Same as for Vibrations
- Same as for Operability (for compression systems)
- Deteriorated compression system performance – how does the damage from the bird impact effect thrust performance, vibration, component matching

Rain and Hail Ingestion

The Rain and Hail Ingestion certification test is a ground test that covers 10 minutes of transient operation with rain/hail injected into the engine inlet. Ingestion of large amounts of water into the engine can cause: compressor surge, thrust loss and combustor flameout. The certification test demonstrates that the compressor and the combustor have no operational issues with ingesting a typical water content (e.g., in a storm). The combustor is typically the limiting component, and both the compressor and combustor are most challenged at idle conditions, thus CbA simulations for rain/hail will need to be performed at idle conditions where current fidelity of compressor and combustor simulations at such conditions are not adequate. Key flow physics are rain/hail transport and phase change through the compression system and the resulting thermal impact on compressor clearances. This engine test requires supporting rig tests: core water-to-air ratio calibration test, and 2.5 bleed hail extraction efficiency rig test. An intermediate step could be to replace these rig tests by analyses.

Methodology gaps:

- Same as for Operability
- Modeling of water spray/droplets throughout the compression system and its impact on matching and operability, at off-design conditions
- Added complexity to Operability assessment:
    - Predicting combustion efficiency fall-off; LBO is hard in itself, so adding water vapor may not add major difficulty
    - Transient nature of the test/analysis – and thermal impact on case and clearances via heating/cooling

Induction System Icing

Engine icing certification tests are ground tests conducted at special purpose facilities. Critical point analysis used to determine the highest risk points for testing. The test is evaluating engine vibrations with ice formed on unprotected surfaces, as well as the impact of ice shedding into the core on performance and operability. From a modeling perspective, simulating this certification test adds modeling the physics of ice accretion and shedding on top of the modeling challenges associated with simulating Vibrations and

Operability testing. Key flow physics are ice accretion, ice shedding and post-shedding modeling. Ice crystal icing modeling represents a near-term opportunity for CbA because certification requirements are currently being established for this relatively rare engine phenomena.

Methodology gaps:

- Impact of ice accretion on performance, operability and aeromechanics – coupled, multidisciplinary analysis
- Ice shedding initiation & post-shedding modeling
- Ice crystal icing modeling

Other Part 33 Certification Tests

There are a few Part 33 certification tests that are not represented on the CbA roadmap in this report: Endurance (33.89), Initial Maintenance Inspection (33.90), and Engine Overtemperature (Sec 33.88). These were not included because they were either very long duration tests such that they were not practical to simulate in the 2040 time frame (33.89, 33.90), or so short that it is run as an inexpensive piggy-back to another cert test (33.88).

Tabulated certification requirements for representative certification conditions

Table A-1. Sample Technical, Logistical, and Accuracy requirements for representative airplane certification maneuvers.

Maneuver	Technical Requirements	Logistical Requirements	Accuracy Requirements
VMU (Sec 25.107; AC 25-7D 4.2.7)	Aeroelastic effects (static), Ground effect impact, Propulsion model and impact on tail in presence of ground	On the order of 50 RANS solutions (7-10 velocities x multiple flap settings)	Reliable prediction of thrust impact on tail and separation. C_L accuracy within 0.03 (for large commercial configuration)
Takeoff gradients (Sec 25.121; AC25-7D 4.4)	Available gradient of climb must not be less than 2.4% for two-engine airplane	On the order of 50 RANS solutions (varying weight, flap setting and other takeoff parameters)	High fidelity airplane lift and drag prediction. Drag accuracy within 0.5% at constant lift coefficient.
Crosswind Takeoff (Sec 25.237, AC25-7D 9.5.2)	Trim in sideslip or multiple rudder angle solutions (increase cost)	On the order of 50 full configuration RANS (5 velocities x sideslip trim determination) Most likely a dynamic maneuver	Low-speed moment prediction critical (both vehicle moment and rudder hinge moment), particularly near full rudder deflection. Moment accuracy within 1% Accurate prediction of incipient separation
Steady Heading Sideslips (Sec 25.177; AC 25-7D 7.3.2)	Offline coupling to dynamic simulation tool; Longitudinal and Lateral trimming	~7 critical points x ~5 rudder deflections x (trim + ~2 target sideslips)	Prediction of control surface effectiveness, including roll coupling. (limits of control surface deflection may lead to separated flows; Additionally, separated flow exists at edges of control surface and impact control surface effectiveness) Airplane and control surface hinge moments within 1%
Short Period (Sec 25.181; AC 25-7D 7.4.2.1)	Dynamic (time-accurate) simulation including moving control surfaces	10 conditions x 10-second time integration	Moment prediction accuracy important for appropriate damping + derivatives
Stalls (Sec 25.103, 201, 203; AC 25-7D 8.1)	1G and turning flight aeroelastics. Icing predictions	Large aero database required: 10s of conditions at each configuration, at least 10 analysis points per condition	Simulation hinges on accurate prediction of $C_{L,max}$ (2%, ±0.05) and prediction of control surface effectiveness at high angle of attack and angle of sideslip. Presence of massively separated unsteady flow, including smooth body separation. Stall characteristics requires post stall handling qualities evaluation
Buffet (Sec 25.251; AC 25-7D 10.1.2)	Minimally one-way coupling to structural model to predict dynamic structural response	Large aero database of time-accurate runs required (100s of analysis points)	Unsteady aerodynamic loads including separated flows and impact of shock/boundary layer interactions Speed prediction within 3 kts of validation data

Table A-2. Sample Technical, Logistical, and Accuracy requirements for representative engine certification tests.

Engine Test	Technical Requirements	Logistical Requirements	Accuracy Requirements
Fan Blade test. (Sec 33.94)	Required to demonstrate that: (i) fan blade is contained, (ii) fan-blade-out does not result in a fire, i.e., deformation/loads do not cause a breach of fuel/oil systems, (iii) fan-blade-out does not fail the mounts or flanges, and (iv) post fan-blade-out the engine shuts down safely, i.e., throttle pull back allowed after 15 seconds, and the EEC properly functioning after sustaining event loads.	Multiple O(10^6) core-hours five-second event + spooldown simulations	Current regulations state "it must be demonstrated by engine tests" and thus requires an update by the FAA. Significant validation work is required – engine companies have validation data from prior development tests which would allow for post-diction of past successful and unsuccessful certification tests Mirroring of future certification tests is another path toward validation.
Vibration tests (Sec 33.62, 33.63, 33.83)	Verify that rotating component vibratory excitations are acceptable throughout the flight envelope (idle to 105%, bleeds on/off, vane schedule variation, part variation)	Drivers not known a-priori, thus need to conduct analyses for a large matrix of conditions and configurations: - Each transient simulation for a full compression system (e.g., few minutes, at 10,000 rpm) ~ O(10^{10}) core-hours.	Vibratory stress within 10% of existing engine test data
Operation Tests (Sec 33.73, 33.89)	Demonstrate safe engine operating characteristics throughout its operating envelope: stability pinch points; relight; rotor lock; windmill	Single-point full-wheel component analysis requires O(10^6) core-hours – maps would require 100X more. Full-engine, or at least multi-component high fidelity analysis coupled needed for transient maneuvers and relight - cost O(10^{10})+ core-hours per case	Compression system stall margin within 1%; Combustor stability / relight envelope speed/alt within 0.05 Mach / 500 ft.
Bird ingestion (Sec 33.76)	Demonstrate acceptable engine operation when ingesting various weights/numbers of birds. Need to run the test to assess actual thrust loss and operability effects. Some birds target core.	Same as for Rotor Stress + compression system Operability; very long integration for post-event transient > O(10^{10})+ core-hours	Same as for Vibration + compression system Operation +/- 1% for deteriorated thrust

Rain and hail ingestion (Sec 33.78)	Demonstrate acceptable engine operation throughout its operating envelope when subjected to encounters with the certification standard concentrations of rain and hail.	Computing compressor + combustor with rain/hail through a 10 minutes transient for Operability > $O(10^{10})$ core-hours	Stall margin within 1%; Demonstrate the ability to calculate surge recovery
Induction system icing (Sec 33.68)	Demonstrate acceptable engine performance during accretion and shedding of ice on/into the engine	Transient analysis at different length- and time-scales – accreting ice, and then shedding and post-shedding – similarly to previous estimate, 10+ minutes of transient behavior, yields a computational cost of $O(10^{12})$ core-hours	Same as for Vibration + compression system Operation

Appendix B. Community Survey

An online community survey was conducted from December 2019 to March 2020, and consisted of a total of twenty questions, covering a range of technical topics related to CbA. The primary purpose of the survey was to collect initial feedback from the broader aerospace community regarding the current state of CbA, key technical and logistical impediments, and strategies for future development. The survey was delivered to over 400 participants in 13 countries. Of the 120 responses, over half were from industry participants, involved in all areas of airplane and engine development and manufacturing, including certification, testing, and analysis. Other participants included members of government research (NASA, DLR, ONERA, JAXA, etc.), regulatory authorities (FAA, EASA, Transport Canada, etc.), and university researchers. Figure B-6 shows the relative mix of job sector among participants.

Survey Feedback

For the purposes of the assessment that follows, results from the survey respondents are considered in three categories based on their identified job responsibilities: flight testing, CFD development and/or application, and engineering analysis/management. Figure B-5 shows the mix of job responsibility among participants. Just under 10% of the respondents identified as having direct flight test expertise, particularly related to certification testing and regulatory compliance. These individuals provided specific insights and perspectives into some of the key challenges and expectations involved in CbA, and were anticipated to be more conservative with their outlook for future use of analysis for certification. A little over a third of the respondents were classified as experts in CFD technology, either as application engineers, code/technology developers (e.g., algorithm/numeric), or both. These individuals were anticipated to be more optimistic in their assessment of the capabilities of current and future CFD for CbA, even though, based on the survey results, over half of the participants who identified as CFD experts were "not familiar" with specific airplane certification regulatory requirements, and the flight maneuvers or engine tests that are typically conducted to satisfy those requirements. Finally, the remainder of the respondents identified as having current responsibilities associated with engineering analysis or management. They were anticipated to have a broad understanding of the strengths, weaknesses, and key interdisciplinary issues that exist across both flight test and analysis communities. This categorization was helpful to identify any underlying biases among these three different groups to better interpret the results.

As an example, one of the key questions posed in the survey was to estimate the amount of flight testing that could be eliminated in the future using increased analysis. A large percentage of all respondents (65%) indicated that at least 50% of physical testing or more could be eliminated (see Figure B-4). For those respondents who identified as CFD experts, this percentage rose to 80%, indicating broad confidence in the expected ability of future computational technology development to address CbA. However, for those respondents that identified as experts in flight testing, the percentage dropped to 45%, with most believing that no more than 50% of flight testing could be eliminated, even with the most advanced and accurate simulation technologies readily available. The written responses by this group from a follow-up question in the survey indicate that a large amount of flight testing will still be required to identify unknown unknowns in a real flight environment, but that a significant amount of initial or verification flight testing could be reduced when better analysis tools are able to perform more integrated system-level analysis with quantified uncertainty.

The survey was also utilized to confirm perceptions within the community regarding the substantial challenges in using analysis for certification in the future. Participants were asked to rank important considerations in four areas: confidence in the analysis, analysis accuracy, time to obtain the analysis, and cost. Of these four choices, confidence in the analysis was identified as the most challenging impediment by 59% the respondents. 48% of respondents ranked analysis accuracy as the second most challenging impediment. Timeliness and cost were viewed as less challenging impediments. Overall, the vast majority of the respondents (>80%) felt that establishing proper confidence in the analysis results is critical in impacting CbA. This is shown in Figure B-1.

The survey featured questions on current technical and logistical roadblocks, the results of which are summarized in Section V. One important question posed to the participants was: “How would you suggest addressing the most significant logistical roadblocks?” Responses included establishment of working groups and dialog between industry, research, and regulatory organizations to define the path forward to address simulation verification, validation, and uncertainty quantification, and obtain commitments to develop more rigorous tool validation and UQ method development specifically for CbA, as shown in Figure B-2. On the topic of computing resources, feedback included making adequate computing resources available on a national level similar to what is available to defense and energy programs. Also, a number of respondents indicated that generation of adequate validation data, particularly at full-scale, should be a high priority.

Relating to the confidence of analysis for certification, participants were asked to identify the first step required to establish confidence in the use of analysis data to replace traditional full-scale testing. Responses were evenly split between the following choices: “develop rigorous verification and validation of the analysis method”, “demonstrate the analysis method on representative certification cases”, “establish comprehensive uncertainty quantification and sensitivity analysis”, and “establish comprehensive database of validation quality experiments”, indicating that *all* of these areas are critically needed to advance CbA, and *all* require focused attention.

Concerning uncertainty quantification, the study team wanted to better understand the importance of employing the rigorous mathematical UQ methodologies, which have been under development over the past decade, for particular application to CbA. 55% of respondents felt that this level of UQ was “*critical* – all analysis data sources should have all uncertainties clearly defined and quantified relative to expected uncertainties in flight test data”, while 42% felt that this level of UQ was “*somewhat important* – formal uncertainty quantification is not as important as establishing basic sensitivities of the analysis data to appropriate factors relative to flight test data”. This even split in responses indicates that work is needed in defining what level of UQ is appropriate and adequate, before developing specific approaches to computing UQ.

Finally, a question was posed on what computational technologies posed the highest potential in enabling CbA (see Figure B-3). 69% of the respondents indicated that technology to enable “system integration and coupling (aeroelastics, control deflection, math pilot-in-the-loop simulation, etc.)” was the most important. This was followed by 53% for “appropriate uncertainty quantification techniques”, 44% for “computationally efficient time-accurate simulation methods”, 44% for “robust and affordable scale resolving methods, 25% for “data fusion methods”, 23% for “global and local sensitivity analysis methods”, and 15% for “output-based adaptive CFD discretization.” Keeping in mind that survey participants represented government research, airplane and engine manufacturers, and regulatory agencies, these results indicate that the range of line items identified of the roadmap are the critical areas requiring future focus and investment to enable CbA.

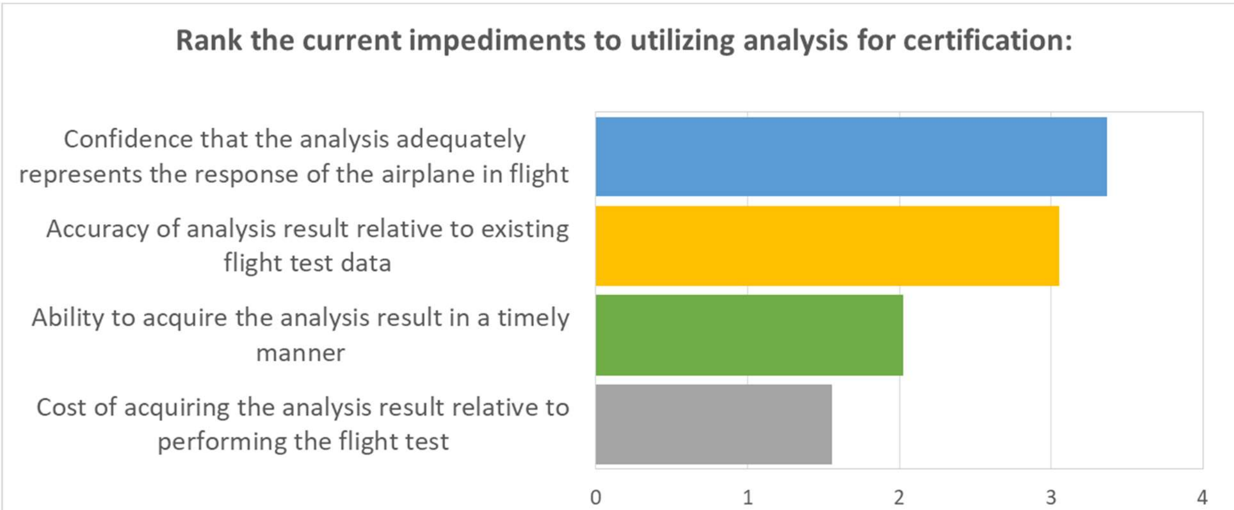


Figure B - 1. *Survey input on current CbA impediments.*

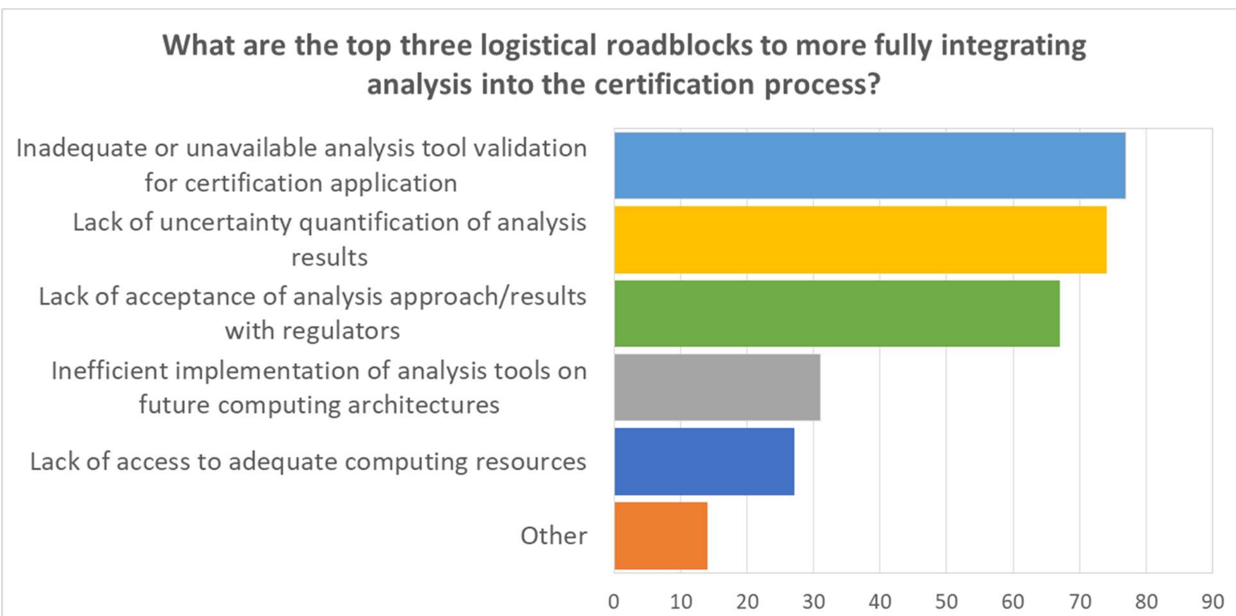


Figure B - 2. *Survey input on logistical roadblocks for increased certification by analysis.*

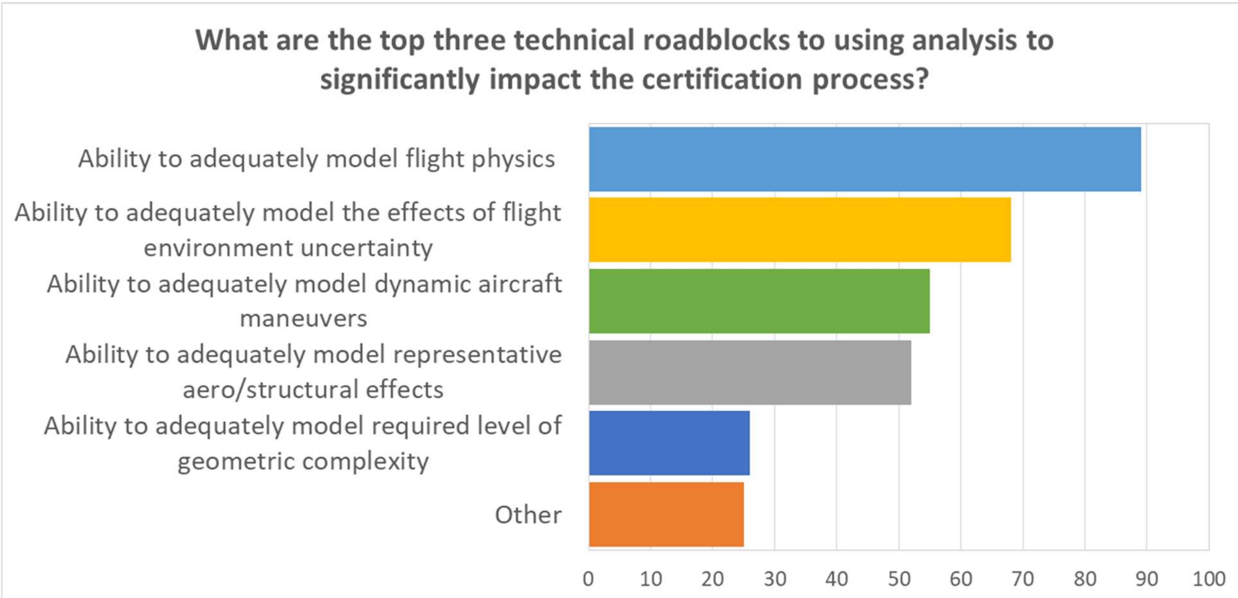


Figure B-3. *Survey input on technical roadblocks for increased certification by analysis.*

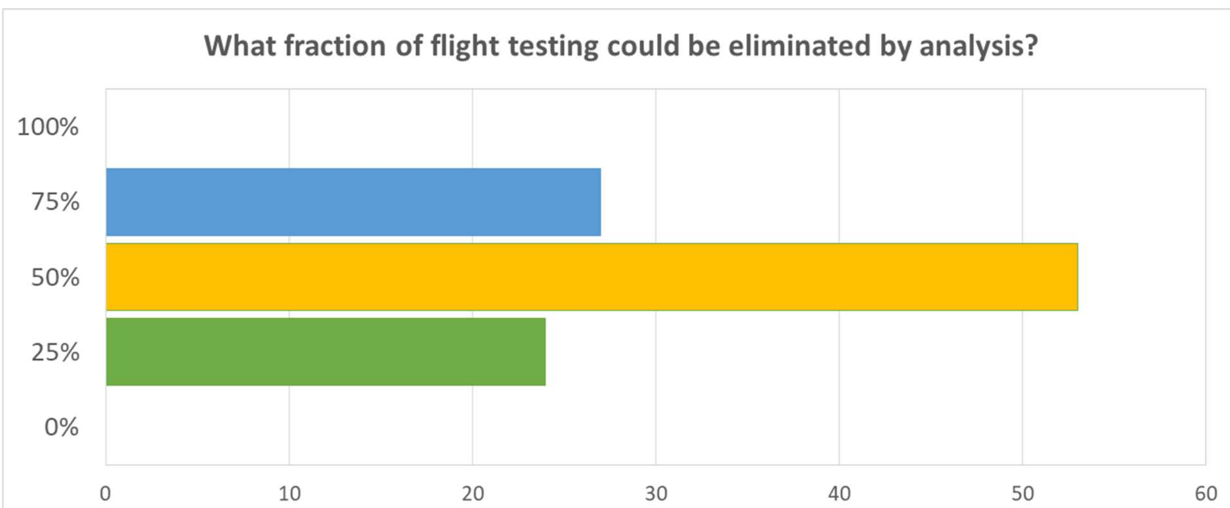


Figure B-4. *Anticipated testing reduction because of greater use of analysis for certification, after existing roadblocks are sufficiently addressed.*

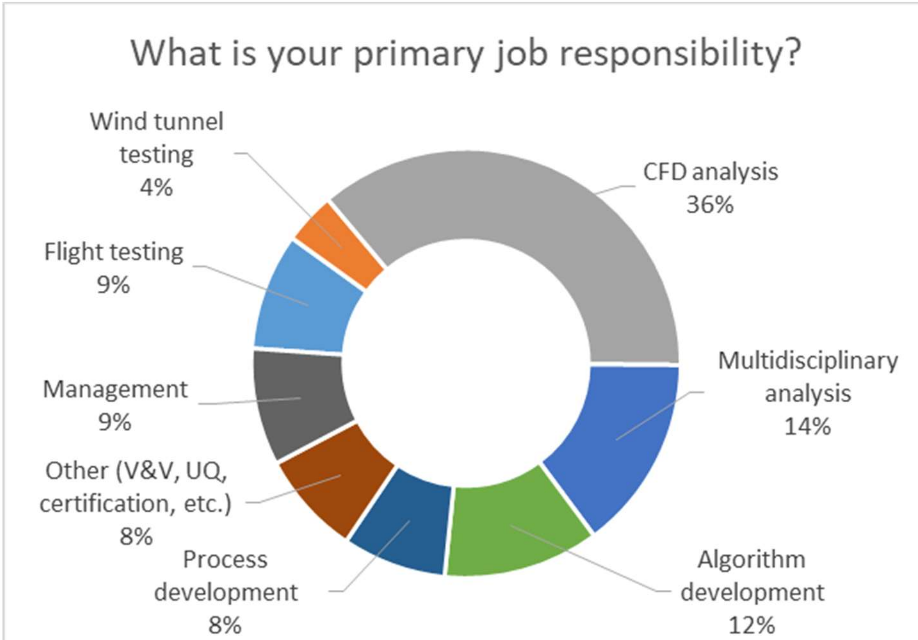


Figure B-5. *Areas of expertise for survey participants.*

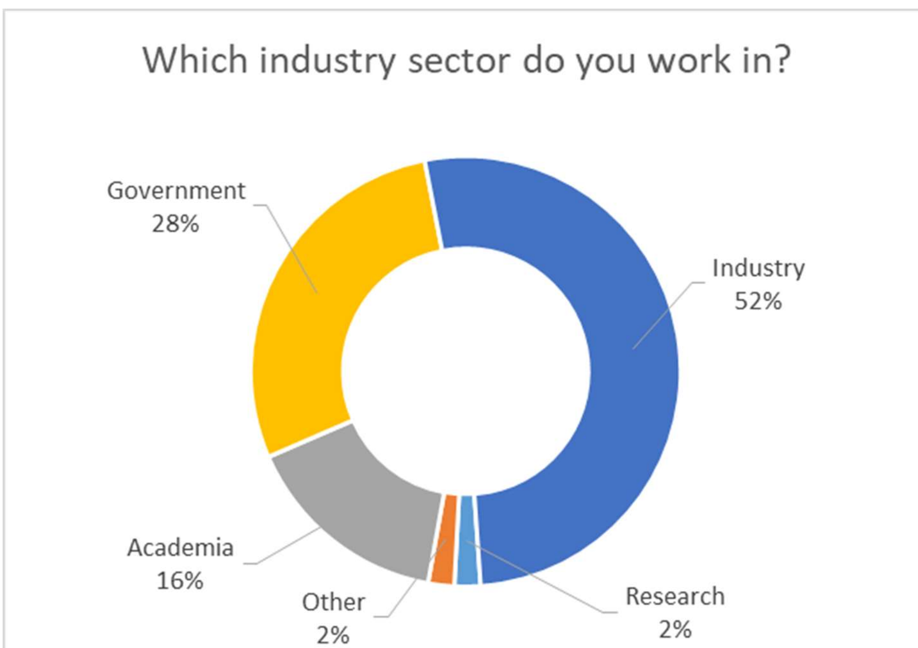


Figure B-6. *Sectors represented by survey participants.*

Appendix C. Technical Workshop

Based on the feedback acquired from the community survey, a multiday technical workshop was planned to better understand specific issues, gaps, and impediments associated with CbA, and to inform elements of an initial version of the roadmap developed by the study team. The workshop was held virtually across three days in July 2020. A total of 70 participants from 24 organizations attended the workshop, representing government, industry, and academia. All attendees had participated in the community survey.

The workshop event featured presentations from industry leaders representing airplane and engine manufacturers to provide context, previous history, and the potential future value for performing CbA. Notable comments from the keynote presentations included the need to improve flow physics modeling for prediction across the *full* flight envelope, to develop multidisciplinary tools for "integrated flight", and to acquire high quality validation data. From the engine point-of-view, testing is used to advance technology readiness level, validate that the product is robust for its mission, and to validate that the product meets specifications – in addition to certification. Generally speaking, it will be hard to trade complicated expensive testing for complicated expensive analysis without seeing a cost savings. For instance, analysis has not led to lower cost development. More capable analysis typically leads to more analysis, not shorter analysis/time. And more capable analysis has led to more testing, not less. However, there is real benefit in doing analysis as a way to reduce cost. Opportunities include getting more information from each test, reducing "late learning" in testing, reducing early development tests, reducing instrumentation required on development tests, and reducing test duration.

Next, a comprehensive review of the proposed airplane maneuvers and engine tests under consideration by the study team was presented, emphasizing the specific physical phenomena that must be simulated, as well as the appropriate metrics for certification and key challenges associated with each case. After a review of the results of the community survey, participants were asked to attend one of four break-out sessions focused in specific areas: Technology Development, System Level Integration, Verification and Validation, and Uncertainty Quantification. The purpose of each breakout session was to review key requirements in each area, and better define and quantify current shortcomings and gaps in simulation capabilities to ultimately inform elements that would be highlighted on the final integrated roadmap. A brief summary of the findings in each of these four areas are provided below.

Technology development

Participants in the Technology Development break-out session specifically focused on requirements for accurate simulation for the airplane maneuvers and engine tests under consideration. This included a discussion on the key characteristic features that the simulations must be able to model properly, as well as technological and logistical advances that will be required to overcome current gaps. Specific characteristic features of the simulation included the need to predict performance at the edges of the operating envelopes (for both airplane and engine), routine analysis of aerostructural interactions (which exist, in some form, for all CbA cases), and the need for the simulation tool(s) to be computationally efficient (to support the large number of individual numerical solutions that will be needed). In terms of research investments needed to simulate at the edges of the operating envelope, it was noted that although scale resolving simulation (SRS) methods are actively under development, RANS methods will continue to play a role. LES will be needed for combustion simulation and for adequately modeling large scale separation. Grid convergence for all of these methods is a major issue, and temporal accuracy for SRS methods needs more attention. HPC advancements are enabling efficient and cost-effective analysis to be more commonplace. Key computational requirements that must be addressed are adaptive mesh refinement for numerical error control and long-time simulation methods. In terms of multidisciplinary analysis (MDA) coupling, many approaches have been developed, e.g., fluid-structures interactions, but efficient coupled analysis capabilities on emerging HPC systems need to be improved, particularly to support highly coupled aerostructural analysis, like flutter. Finally, to address the need for large numbers of case and/or ensembles, machine learning methods and Reduced-Order Model (ROM) approaches should be considered. Other comments included the need for standard interfaces for MDA and UQ, and the need to rapidly transition technology developed in an academic setting for use within industry. Research organizations, such as NASA, can play a leading role in facilitating this.

System-level analysis

Participants in the System-Level Analysis break-out session addressed specific questions associated with the integrated airplane and full engine system analysis that will be required for CbA. Specifically, a review of required capabilities, target applications, appropriate roadmap waypoints, technology gaps, and ways to establish confidence in system-level simulations provided useful feedback to the study team. Overall, the break-out group comments suggested that the study team had identified the critical capabilities to consider for CbA, although aeroacoustics aspects, which are of minimal importance to the CbA applications being considered, should be revisited for inclusion on the roadmap to perhaps support a "no acoustic impact" assessment for small configuration changes (e.g., radomes). Other useful CbA application cases were also discussed for potential inclusion on the roadmap. Suggestions included a simpler airplane trim case to demonstrate near-term progress, and a case targeting Ground Minimum Control Speed to address modeling of the landing gear in contact with the ground and rudder hinge moment predictions with flight controls. One participant suggested that buffet was more challenging than flutter, and that flutter should be replaced with a focus on "gust response" or "limit cycle oscillations". There was general consensus that low-fidelity approaches, such as models based on system identification and/or machine learning, could offer cost-effective methods to approximate dynamic maneuvers. Group comments also indicated that many CbA opportunities do not require a pilot-in-the-loop, suggesting that aspects of Certification by Simulation may be achievable without pilot intervention. In terms of technology gaps that exist specifically at the system level, group feedback generally confirmed study team assumptions. For instance, comments indicating that the CFD development community needs to change thinking away from "steady-state, single-point, and single-discipline" simulations to more "transient, multiple, and coupled" simulations was a concept adopted early on by the study team. Other comments included the need for robust and extensible frameworks, coupling of discipline simulations with disparate simulation times, and the need for standard interfaces – all areas discussed at length ahead of the workshop. To build confidence in system-level analysis capabilities, there was general consensus that establishing how confidence (uncertainty, etc.) is currently viewed by OEMs and regulators was key to determining appropriate methods, approaches, and standards. One participant suggested establishing a "pass/fail" criteria on simulation demonstrations, in addition to demonstrating a predictive capability, for regulators to be able to more clearly identify when a simulation capability is ready for CbA. Others emphasized that verification and validation of existing coupled simulations to establish repeatability and consistency, and developing methods for UQ of coupled analyses, can and should begin now. Finally, when considering the integration of the complete airplane with a full engine simulation, one participant suggested that consideration of propulsion-structure interaction will be critically important as more flexible airplane concepts are developed in the future.

Verification and validation

The primary objective of Verification and Validation (V&V) for CbA is to provide a measure of confidence in the underlying analysis. To this end, participants in the V&V break-out session focused on a number of topics, including key definitions of terms (such as code/solution verification, code regression, validation, benchmarking, etc.). Group consensus indicated that solution verification (estimating numerical error) for CbA relevant cases is challenging due to the need to estimate discretization error, to identify multiple solutions if/when they exist, and to assess multidisciplinary interactions, particularly when there are different levels of time scales in a simulation. Another important aspect raised was that our current models are highly calibrated, and that properly validating these models, and ones we develop in the future, will require attention to appropriately "blind" comparisons with test data. Moreover, the use of test data must properly account for sparse sampling effects (e.g., few experimental replicates) and sparse instrumentation/measurements. Technology development is needed in discretization error estimates, validation domain extrapolation methods, and development of methods to present errors and uncertainties in modeling and simulation (e.g., "error bars"). Other findings indicated the need for better education of

V&V terminology, etc., and to develop methods for traceability for models, including model maturity, simulation credibility, etc.

Uncertainty quantification

Participants in the Uncertainty Quantification (UQ) break-out session were asked to focus attention on key questions and topics concerning the use of UQ particularly applied to CbA. After first discussing the definition of UQ, including its different components, the group participants considered how to effectively engage regulators in the area of UQ. Key recommendations included establishing consistent terminology and developing a way to change the current “test-based” mindset to a “simulation-based” one, possibly by having industry perform UQ on airplane maneuvers and engine tests on products that have already been certified. Developing a proper UQ framework, and having agreement between industry and the regulators on that framework, was identified as a major challenge. It was decided that the framework for UQ should not be prescribed, but that regulators should understand the strengths and weaknesses of the framework chosen. Best and/or standard practices were identified as important, but would likely take years to develop. However, standard practices would establish agreed-upon definitions and terminology, and would likely help regulators interpret UQ results, and thereby help regulators feel comfortable using UQ to help establish confidence in the analysis. On the question of how much UQ rigor is “good enough” for CbA, the general consensus was that regulators need to determine this, not industry. It could be that some maneuvers and/or tests may be more amenable to simpler UQ analysis than others, suggesting a pathway for a spectrum of UQ methods for CbA.

As mentioned in the V&V session, validation space is quite sparse, so the need to be able to correctly extrapolate uncertainty outside the validation domain was addressed, perhaps using emerging methods such as Method of Manufactured Universes and Predictor-Corrector Extrapolation. Also, developing methods to predict “tail statistics” and rare/anomalous events are technically challenging. However, often knowing a priori what combination of conditions or uncertain parameters will yield anomalous results will help in determining the right conditions to ultimately test to address modeling of rare events. Overall technical recommendations included continued development of methods to extrapolate uncertainty from the validation domain into the application domain, to propagate and aggregate heterogeneous types of uncertainty, and to propagate and aggregate uncertainty in high-dimensional spaces.

Appendix D. Definition of Predictive Capabilities

A detailed summary of the elements provided on the "Predictive Capabilities" section of both the integrated and near-term roadmaps for single-discipline analysis, multidiscipline coupling, and airplane/system integration for both Parts 25 and 33 is provided below. For each element, a description of what the capability is expected to accomplish, the specific CbA opportunity the capability impacts, key modeling requirements, and details on specific aspects of validation testing that would be required to properly mature the capability are given.

Part 25 Single-Discipline Analysis

- **Full configuration prediction with powered nacelle in ground effect**
  Predict aerodynamic performance for full aircraft with specified aeroelastic deformations (to cover the weight range) in ground effect with powered engine effects at multiple altitudes, take-off speeds, and thrust/weight ratios. Assume aircraft is attitude-limited, so simulations are not performed at $C_{L,max}$ conditions but large margins to $C_{L,max}$ are confirmed.
  - Impacts: Large airplane VMU
  - Key Modeling Requirements: Complex airplane geometry, method to incorporate pre-defined aeroelastic deformations for high lift elements (slats, flaps) and control surfaces (ailerons, spoilers, rudder) in grid model, engine thrust effects, inclusion of ground plane
  - Validation Experiment Characteristics: Wind tunnel experiment of an aeroelastically-scaled airplane with high lift system (stowed/deployed) and control surfaces (stowed/deployed) at low-speed and low/medium/high wing loading at various angles-of-attack (symmetric wing loading) and sideslip (asymmetric wing loading) with powered nacelle in proximity to tunnel floor/ceiling/splitter plate. Additionally, constant pitch angle takeoffs on flight test airplanes would be a good validation option. Diagnostic information could include forces/moments, steady/unsteady surface pressures, hinge moments; airplane deformation information supplied with data collected from appropriate measurement system.
- **Engine-out flight characteristics in sideslip**
  Predict integrated forces and moments, as well as wing/edge load distributions, in sideslip (up to 20°) with one-engine powered and other engine at idle, accounting for engine windmilling effects at low-speeds up to $C_{L,max}$.
  - Impacts: Engine-out Trims, Engine-out Roll
  - Key Modeling Requirements: Complex airplane geometry, high-fidelity propulsion models, scale-resolving methods to model the effects of separated flow
  - Validation Experiment Characteristics: Wind tunnel experiment of full airplane with powered nacelle and flaps down at medium/large sideslip angles. Diagnostic information could include forces/moments, surface pressures, integrated loads, and off-body wake field measurements.
- **Aerodynamic trim with control surfaces**
  Predict proper control surface settings for three-component trim, including hinge moments with flaps up/down from moderate angles-of-attack to maximum lift at low speed.
  - Impacts: Engine-out Trims, Wind-up Turns
  - Key Modeling Requirements: Complex airplane geometry, scale-resolving methods to model the effects of separated flow, multiple deflected control surface effects
  - Validation Experiment Characteristics: Wind tunnel experiment of full airplane with flaps up/down with trimmed sets of attitude/control surfaces predicted from simulation. Diagnostic information could include forces/moments, surface pressures, hinge moments, integrated loads, and off-body velocity field measurements.

- **Accurate configuration drag**
  Predict low speed drag.
    - Impacts: Engine-out Climb, Engine-out Roll
    - Key Modeling Requirements: Complex airplane geometry, scale-resolving methods to model the effects of separated flow
    - Validation Experiment Characteristics: Wind tunnel experiment of full airplane with flaps up/down for array of attitude/control surfaces deflections. Diagnostic information could include forces/moments, surface pressures, integrated loads, and off-body velocity field measurements, skin friction measurements.
- **Robust $C_{L,max}$ prediction with icing**
  Predict airplane maximum lift with predefined ice shapes.
    - Impacts: Stall Speed
    - Key Modeling Requirements: Complex airplane geometry, scale-resolving methods to model the effects of separated flow, robust grid modeling of ice shapes
    - Validation Experiment Characteristics: Wind tunnel experiment of full airplane with flaps up/down with different types of ice (Hold, Takeoff, Runback, etc.). Would also need to consider Reynolds number effects (high Re wind tunnel or limited flight test data). Diagnostic information could include forces/moments, surface pressures, integrated loads, and off-body velocity field measurements.
- **Landing gear effects**
  Predict the aerodynamic effects of landing gear.
    - Impacts: Takeoff Climb Gradient
    - Key Modeling Requirements: Complex airplane/landing gear geometry, scale-resolving methods to model the effects of separated flow
    - Validation Experiment Characteristics: Wind tunnel experiment of full airplane with flaps up/down and with nose and main landing gear. Diagnostic information could include forces/moments, integrated loads, steady/unsteady surface pressures, and off-body velocity field measurements.
- **High-speed moment prediction at high load**
  Predict airplane control surface moments in high-speed, unsteady flow conditions
    - Impacts: Buffet, Flutter
    - Key Modeling Requirements: Complex airplane geometry with detailed control surfaces defined, methods to model flow separation (including shock-induced separation), efficient unsteady flow solution methods
    - Validation Experiment Characteristics: Wind tunnel experiment of full airplane with (symmetric, asymmetric) deployed control surfaces (aileron, rudder, spoilers) at transonic flow conditions at moderate to high angles-of-attack/sideslip. Diagnostic information could include forces/moments, integrated loads, steady/unsteady surface pressures.
- **Post-stall flight characteristics**
  Predict airplane aerodynamic characteristics after $C_{L,max}$.
    - Impacts: Stall Speed, Turning Stall, Stall Characteristics
    - Key Modeling Requirements: Complex airplane geometry, scale-resolving methods to model the effects of separated flows, AMR
    - Validation Experiment Characteristics: Wind tunnel experiment of full airplane with flaps up/down at large angles-of-attack. Diagnostic information could include forces/moments, integrated loads, steady/unsteady surface pressures, and off-body velocity field measurements.

Part 25 Multidiscipline Coupling

- **Robust static aeroelastic capability for full configuration**
  Predict airplane performance and static aeroelastic deformation for a steady-state simulation.

- Impacts: Large Airplane VMU
- Key Modeling Requirements: Representative airplane geometry model for CFD, accurate thrust modeling, method to utilize an aerodynamic loads distribution to compute airplane deformation and create a grid model that incorporates the deformation for a single steady-state simulation
- Validation Experiment Characteristics: Wind tunnel (low-moderate Re) and/or flight (high Re) experiment of an aeroelastically-scaled airplane with high lift system (stowed/deployed) and control surfaces (stowed/deployed) at low-speed and low/medium/high wing loading at various angles-of-attack (symmetric wing loading) and sideslip (asymmetric wing loading). Diagnostic information could include forces/moments, steady/unsteady surface pressures, hinge moments; time-dependent airplane deformation information supplied with data collected from appropriate measurement system.

- **Fully coupled transient fluid-structure interaction**
  Predict airplane performance and aeroelastic deformation coupling CFD and CSD for a realistic airplane in a time-dependent, high aerodynamic loading environment.
  - Impacts: Buffet, Flutter
  - Key Modeling Requirements: Representative airplane geometry model for CFD, appropriate structural model for CSD, appropriate methods to model separated flows, efficient coupling scheme, efficient unsteady analysis method, and dynamic AMR
  - Validation Experiment Characteristics: Wind tunnel (low-moderate Re) and/or flight (high Re) experiment of an aeroelastically-scaled airplane with high lift system (stowed/deployed) and control surfaces (stowed/deployed) at low-speed and low/medium/high wing loading at various angles-of-attack (symmetric wing loading) and sideslip (asymmetric wing loading). Thrust effects must be included. Diagnostic information could include forces/moments, steady/unsteady surface pressures, hinge moments; time-dependent airplane deformation information supplied with data collected from appropriate measurement system.
- **Aeroservoelastic analysis in dynamic maneuver**
  Predict airplane performance coupling CFD, CSD, and flight controls for a realistic airplane for a representative maneuver.
  - Impacts: Wind-Up Turn
  - Key Modeling Requirements: Representative airplane geometry model for CFD, appropriate structural model for CSD, integration of basic flight controls, appropriate methods to model separated flows, efficient coupling scheme, efficient unsteady analysis method, and dynamic AMR
  - Validation Experiment Characteristics: Wind tunnel (low-moderate Re) and/or flight (high Re) experiment of an aeroelastically-scaled airplane with high lift system (stowed/deployed) and control surfaces (stowed/deployed) at low-speed and low/medium/high wing loading at various angles-of-attack (symmetric wing loading) and sideslip (asymmetric wing loading). Diagnostic information could include forces/moments, steady/unsteady surface pressures, hinge moments; time-dependent airplane deformation information supplied with data collected from appropriate measurement system.
- **Transonic wing dynamic structural response**
  Predict airplane performance and aeroelastic deformation coupling CFD and CSD for a realistic airplane in a time-dependent, high aerodynamic loading environment at high-speed flow conditions.
  - Impacts: Flutter
  - Key Modeling Requirements: Representative airplane geometry model for CFD, appropriate structural model for CSD, appropriate methods to model separated flows

(including shock/boundary layer separation), efficient coupling scheme, efficient unsteady analysis method, and dynamic AMR
   - Validation Experiment Characteristics: Wind tunnel (low-moderate Re) and/or flight (high Re) experiment of an aeroelastically-scaled airplane in cruise configuration in a time-dependent maneuver at transonic speeds and low/medium/high wing loading at various angles-of-attack (symmetric wing loading) and sideslip (asymmetric wing loading). Diagnostic information could include forces/moments, steady/unsteady surface pressures; time-dependent airplane deformation information supplied with data collected from appropriate measurement system.

Part 25 Airplane / System

- **Pilot / stick response**
  Predict integrated airplane dynamic response/stick force to assess handling and ride qualities.
   - Impacts: Buffet Boundary, Stall Characteristics
   - Key Modeling Requirements: Efficient aeroservoelastic capability, assessment of structural response on airplane (e.g., vibration)
   - Validation Experiment Characteristics: Flight experiment of a representative configuration (subscale and/or full-scale) in a prescribed maneuver performed at low/high speed, with low/high wing loading. Diagnostic information could include integrated airplane forces/moments, steady/unsteady surface pressures, airplane deformation measured with appropriate system throughout the maneuver, assessment of airplane dynamic and structural response at pilot seat.
- **Ice effects on handling qualities**
  Demonstrate integrated effect of ice on handling qualities.
   - Impacts: Stall characteristics
   - Key Modeling Requirements: Efficient aeroservoelastic capability, assessment of ice on airplane forces (e.g., $C_{L,max}$, moments)
   - Validation Experiment Characteristics: Flight experiment of a representative configuration (subscale and/or full-scale) in a prescribed maneuver performed at low/high speed, with low/high wing loading. Diagnostic information could include integrated airplane forces/moments, steady/unsteady surface pressures, airplane deformation measured with appropriate system throughout the maneuver, assessment of airplane dynamic and structural response at pilot seat.
- **Pilot response feedback loop**
  Demonstrate capability to modify airplane flight control in response to maneuver constraints.
   - Impacts: Wind-Up Turn
   - Key Modeling Requirements: Efficient aeroservoelastic capability, method to drive control surface movement with time-dependent inputs under flight constraints (e.g., hold speed, etc.)
   - Validation Experiment Characteristics: Flight experiment of a representative configuration (subscale and/or full-scale) in a notional maneuver (e.g., wind-up turn) where speed and/or altitude is maintained. Diagnostic information could include integrated airplane forces/moments, steady/unsteady surface pressures, airplane deformation measured with appropriate system throughout the maneuver, assessment of airplane dynamic and structural response at pilot seat, control surface hinge moments.
- **Airplane control response due to wind gust**
  Predict airplane performance with aeroservoelastic modeling for a representative maneuver with gust loads.
   - Impacts: Flutter
   - Key Modeling Requirements: Representative airplane geometry model for CFD, appropriate structural model for CSD, integration of basic flight controls, appropriate

methods to model separated flows, efficient coupling scheme, efficient unsteady analysis method, and dynamic AMR
    - Validation Experiment Characteristics: Wind tunnel and/or flight experiment of a representative (perhaps flexible) airplane configuration moved through a prescribed, time-dependent motion/maneuver. Diagnostic information could include forces/moments, airplane deformation measured with appropriate system throughout the motion/maneuver.

- **Integrated flight control augmentation**
  Predict airplane performance with aeroservoelastic modeling for a representative maneuver with flight control augmentation (e.g., maneuver load alleviation).
    - Impacts: Wind-Up Turn
    - Key Modeling Requirements: Representative airplane geometry model for CFD, appropriate structural model for CSD, integration of flight controls with augmentation, appropriate methods to model separated flows, efficient coupling scheme, efficient unsteady analysis method, and dynamic AMR
    - Validation Experiment Characteristics: Wind tunnel and/or flight experiment of a representative (perhaps flexible) airplane configuration moved through a prescribed, time-dependent motion/maneuver. Diagnostic information could include forces/moments, airplane deformation measured with appropriate system throughout the motion/maneuver.
- **Throttle/transient thrust effects**
  Predict airplane performance with engine thrust control for a representative maneuver.
    - Impacts: Flight Engine Simulation
    - Key Modeling Requirements: Representative airplane geometry with appropriate-fidelity engine model to simulate commanded, time-dependent engine thrust
    - Validation Experiment Characteristics: Full-scale flight experiment of a representative airplane configuration with production engine system in a basic maneuver with engine power throttling. Diagnostic information could include forces/moments, highly instrumented engine flow path.

Part 33 Single-Discipline Analysis

- **Engine component deformation modeling**
  Predict structural deformation of engine external components (generators, hydraulic pumps, valves, etc.) provided by suppliers. Accurate structural models for these components are needed for accurate engine system-level structural dynamics and deformation modeling.
    - Impacts: Fan Blade-out
    - Key Requirements: Engine component deformation properties, including elastic/plastic deformation, for the structural models
    - Validation Experiment Characteristics: Failure testing of these components.
- **End wall features / 3D vortical structures modeling**
  Accurate predictions of endwall vortical structures, including tip clearance flows and corner roll ups, as well as wake formation and convection, are critical for compressor CFD modeling of compressor stall margin.
    - Impacts: Engine operability
    - Key Requirements: Scale-resolving methods, Efficient methods for scale-resolving simulations
    - Validation Experiment Characteristics: Detailed flow field measurements (mean and turbulence quantities) and separation characterization for endwalls of highly loaded stators and rotor clearance flows are required.
- **Compressor stability**
  Building off ability to predict endwall features, accurately predict compression system stability, especially at part power, including impacts of clearance variation (axisymmetric and non-axisymmetric), bleeds, power extraction, roughness, geometry variation, etc.

- Impacts: Engine operability
- Key Requirements: End wall features / 3D vortical structures modeling capability, surface roughness modeling
- Validation Experiment Characteristics: Highly instrumented (including nonintrusive measurements) compressor rigs varying clearances, bleeds, etc.

- **Fuel spray atomization at low power**
  Modeling nonuniformity in fuel spray at low pressure, temperature and atomizer pressure drop is needed to model the ignition process for altitude relight.
  - Impacts: Engine operability
  - Key Requirements: Improvements in fuel spray modeling, potentially transitioning from coupled Lagrangian/continuum modeling to efficient VOF modeling
  - Validation Experiment Characteristics: Fuel nozzle atomization data at low pressure, temperature and atomizer pressure drop.
- **Combustor flameout/relight**
  Combustor lean blow-out and relight predictions will require full-wheel analysis with detailed models of fuel delivery system, the interactions between turbulence and chemistry, and detailed mechanism finite rate chemistry. Accurate blow-out and relight predictive capability with well characterized combustor inflow conditions is a prerequisite to coupled compressor/combustor simulations altitude windmill relight, starter-assisted relight, and combustor stability during rain/hail/ice ingestion.
  - Impacts: Engine operability
  - Key Requirements: Improved chemical kinetics modeling, multi-regime turbulence-chemistry, interaction model, robust AMR for complex flows, fuel spray atomization at low power
  - Validation Experiment Characteristics: High-altitude relight test facility testing, preferably for multisector or full annulus combustor to provide data for post-ignition flame propagation.
- **Unsteady pressure modeling**
  Predict pressure wave propagation within turbomachinery for aeromechanic simulations. Accurate unsteady pressure predictions are critical for prediction of amplitude and phasing of pressure forces and structural modes (resonant stress) and for flutter prediction.
  - Impacts: Rotor stress
  - Key Requirements: Pressure wave and wake propagation/mixing models
  - Validation Experiment Characteristics: Highly instrumented (kulites, strain gauges, etc.) multistage turbomachinery rigs such as those sponsored by the GUIde consortium, of which NASA is a member (https://aeromech.pratt.duke.edu/).
- **Structural damping**
  Predict structural damping of turbomachinery hardware due to mechanical energy transfer to heat and acoustics, joint and anchor and other contact friction, etc. While incapable of overcoming resonant stresses and typically small relative to aerodynamic damping for stable systems, mechanical damping still plays a role in aeromechanics modeling and needs to be accurately modelled, especially in fully coupled aero/structural simulations.
  - Impacts: Rotor stress
  - Key Requirements: Structural damping predictive capability in structures analysis tools (as opposed to user input)
  - Validation Experiment Characteristics: Characterization of structural damping for engine materials, shapes, joints, etc.

- **High-fidelity turbomachinery component modeling**
  Accurately predict compression/turbine system maps are a prerequisite to accurate resonant stress predictions: if the flow/pressure vs RPM characteristics are not accurate, the aero/structural coupling vs RPM will not be accurate.
    - Impacts: Rotor stress, Engine operability
    - Key Requirements: Scale-resolving methods, Efficient methods for scale-resolving simulations
    - Validation Experiment Characteristics: highly instrumented (kulites, strain gauges, etc.) multi-stage turbomachinery rigs, including performance measurements, such as those sponsored by the GUIde consortium of which NASA is a member (https://aeromech.pratt.duke.edu/).
- **Ice crystal icing accretion / shedding**
  Ice Crystal Icing (ICI) recognized as environmental threat to turbofan engines. ICI occurs deep inside the engine core where wall temperatures above freezing exist prior entering the cloud. Until ice crystal tools & test techniques have been developed & validated, engine manufacturers may use comparative analysis as Means of Compliance (MOC) for new engine models. Future engine certification will require enhanced MOC, which may include ICI analysis. Accurate modeling of the detailed ICI accretion physics and shedding physics is a prerequisite to modeling ICI formation and shedding in a full compressor.
    - Impacts: Engine Icing
    - Key Requirements: Improved ice crystal icing accretion modeling methods including direct multiphase and aero/thermal simulation of the sticking/melting physics, improved ice shedding prediction methods including direct simulation of the multiphysics melting/release physics
    - Validation Experiment Characteristics: Fundamental 2-D multi-vane ice-crystal icing tests including vane heat transfer characterization, such as those conducted by the Ice Crystal Consortium Working Group, of which NASA is a member.
- **Deteriorated compressor system performance**
  For the large and flocking bird certification tests, in addition to requirements that the compressor does not surge and that post-event vibrations are not excessive, the engine must also demonstrate that that post-event thrust loss does not exceed 50% for large birds and 25% for medium birds. Certifying this by analysis requires the ability to predict post-event deteriorated compressor operating map (flow/pressure-ratio/RPM) with uneven clearances and/or damaged geometry.
    - Impacts: Engine Bird Ingestion
    - Key Requirements: End wall features / 3D vortical structures modeling capability, automated CAD/CFD/CSM capability, automated in situ mesh generation for engine configurations
    - Validation Experiment Characteristics: Instrumented bird ingestion certification tests to mirror by analysis.

Part 33 Multidiscipline Coupling

- **Robust and efficient fluid-structure coupling**
  The ability to efficiently couple fluid and structures models is a key enabler for modeling transient fluid-structures interactions.
    - Impacts: Rotor Stress
    - Key Requirements: Robust MDA solution strategies for aeroelastic coupling
    - Validation Experiment Characteristics: Highly instrumented (kulites, strain gauges, etc.) multi-stage turbomachinery rigs such as those sponsored by the GUIde consortium.

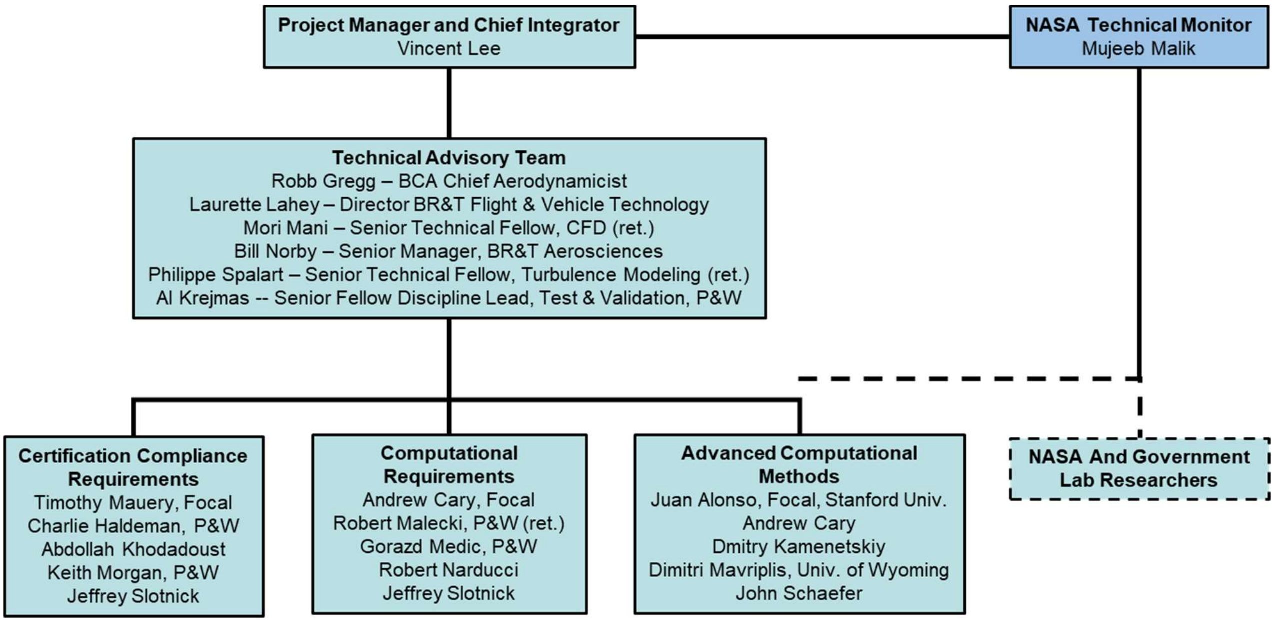
- **Fully-coupled transient fluid-structure interactions**
  All engine drivers for resonant stress are not known a priori, thus requiring transient simulations along compression and turbine system operating lines to demonstrate that excessive resonance/vibrations are not encountered. The first step is to demonstrate transient fluid-structure simulations for a single component with fixed geometry (clearances, bleeds, etc.).
    - Impacts: Rotor Stress
    - Key Requirements: Robust and efficient fluid-structure coupling, Structural Damping and Unsteady Pressure modeling, long time integration methods
    - Validation Experiment Characteristics: Highly instrumented (kulites, strain gauges, etc.) multi-stage turbomachinery rigs such as those sponsored by the GUIde consortium.
- **Transient Clearance Modeling**
  Ability to predict post-break-in axisymmetric and asymmetric turbomachinery clearances due to thermal gradients during engine transients, and loads during maneuvers and certification test events.
    - Impacts: Engine Operability, Rotor Stress, Rain/Hail Ingestion
    - Key Requirements: Automated in situ mesh generation for engine configurations, long time integration methods, robust MDA solution strategies for conjugate heat transfer
    - Validation Experiment Characteristics: Highly instrumented engine testing including clearance measurements.
- **Rain/hail/ice transport**
  Ability to predict transport of hail particles / rain droplets, their collection through extraction bleeds, the breakup and evaporation those bypassing the bleeds, the cooling of the compressor cases, and the resulting water concentration/ distribution entering the combustor.
    - Impacts: Engine Rain/Hail
    - Key Requirements: Robust MDA solution strategies, conjugate heat transfer
    - Validation Experiment Characteristics: Complimentary rig tests to the certification hail/rain test: core water-to-air ratio calibration test and 2.5 bleed hail extraction efficiency rig test.

Part 33 Full Engine / System

- **Full-engine mechanical model for fan blade-out**
  Include more engine systems/geometry in the structures/dynamics analyses utilized today.
    - Impacts: Fan Blade-out
    - Key Requirements: Engine component deformation modeling
    - Validation Experiment Characteristics: Mirroring of future fan blade containment certification tests or simulating prior certification tests for engines with comparable architecture and technology.
- **Ice crystal icing model for inlet/fan/LPC**
  Ice Crystal Icing (ICI) recognized as environmental threat to turbofan engines. ICI occurs deep inside the engine core where wall temperatures above freezing exist prior entering the cloud. Until ice crystal tools & test techniques have been developed & validated, engine manufacturers may use comparative analysis as Means of Compliance (MOC) for new engine models. Future engine certification will require enhanced MOC, which may include ICI analysis.
    - Impacts: Engine Icing
    - Key Requirements: Ice transport modeling, ice crystal icing accretion / shedding, long time integration methods
    - Validation Experiment Characteristics: Full engine testing like the Honeywell ALF502 ice-crystal icing tests at the Propulsion Systems Laboratory conducted by the Ice Crystal Consortium Working Group, of which NASA is a member.

- **Transient engine component/system aeromechanics model**
  All engine drivers for resonant stress are not known a priori. Thus, transient engine simulations, including clearance changes due the transient thermals, vane, bleed and power extraction schedules, are required to demonstrate that excessive resonance/vibrations are not encountered. Directly simulates engine transient certification testing lasting a few minutes per test.
  - Impacts: Rotor Stress, Engine Bird Ingestion, Engine Icing
  - Key Requirements: Fully-coupled transient fluid-structure interactions, Transient Clearance Modeling
  - Validation Experiment Characteristics: Highly instrumented engine testing.
- **Entire compression/combustor engine model**
  Compressor exit conditions, both mean and nonuniformity, are critical for combustor start and engine spool-up procedures. Directly simulates windmill/starter-assisted relights along edge of relight envelope.
  - Impacts: Engine Operability, Rain/Hail Ingestion
  - Key Requirements: High-fidelity turbomachinery component modeling, Compressor stability, Combustor flameout/relight
  - Validation Experiment Characteristics: Highly instrumented engine testing.
- **Full engine simulation for transients**
  Directly simulates transient engine operability tests for compressor stall margin, surge recovery, and combustor LBO envelope in normal operation.
  - Impacts: Engine Operability, Rain/Hail Ingestion, Engine Bird Ingestion
  - Key Requirements: High-fidelity turbomachinery component modeling, Compressor stability, Combustor flameout/relight, Transient Clearance Modeling
  - Validation Experiment Characteristics: Highly instrumented engine testing.
- **Engine operability with Rain/Hail/Ice**
  Directly simulates transient engine rain/hail ingestion operability tests for compressor stall margin and combustor blow out.
  - Impacts: Rain/Hail Ingestion
  - Key Requirements: Rain/hail/ice transport modeling, Entire compression/combustor engine model, Full engine simulation for transients
  - Validation Experiment Characteristics: Highly instrumented engine testing.

Appendix E. Project Team Members and Structure



Unless otherwise indicated, individuals shown represent The Boeing Company.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01/05/2021	CONTRACTOR REPORT	11/26/2018-3/26/2021

4. TITLE AND SUBTITLE
A Guide for Aircraft Certification by Analysis

5a. CONTRACT NUMBER
NNL16AA04B/80LARC19F0018

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Timothy Mauery, Juan Alonso, Andrew Cary, Vincent Lee, Robert Malecki, Dimitri Mavriplis, Gorazd Medic, John Schaefer, Jeffrey Slotnick

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-20210015404

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES
Technical Monitor is Mujeeb R. Malik

14. ABSTRACT
Analysis-based means of compliance for airplane and engine certification, commonly known as “Certification by Analysis” (CbA), provides a strong motivation for the development and maturation of current and future flight and engine modeling technology. The many benefits of CbA include streamlined product certification testing programs at lower cost while maintaining equivalent levels of safety. Flight and engine testing represent a substantial cost to airplane and engine development programs. This report provides a far-reaching vision for CbA and presents a research roadmap for computational technology development to enable CbA.

15. SUBJECT TERMS
certification by analysis, CFD, Aerodynamics, Propulsion, aeroelastics, aircraft, stall

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			HQ - STI-infodesk@mail.nasa.gov
U	U	U	UU	88	**19b. TELEPHONE NUMBER** *(Include area code)* 757-864-9658