

Recommended Practice

When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification

Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification

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Abstract

This document outlines a set of recommended practices (six tasks) for an applicant to accomplish when flight modelling is being developed, proposed and used to reduce flight testing relative to established aircraft certification practices. The specific certification requirements considered when these recommendations were developed include aircraft performance and handling qualities, static loads and aeroelastic stability. However, the recommended tasks may also be applicable when showing compliance to other requirements.

The set of tasks provides a framework for organizing information used to determine whether or not a particular analysis method is appropriate for supporting a compliance showing in a particular application. Hypothetical examples of applying these tasks to specific certification applications are provided. However, this document does not endorse specific analysis methods and processes for showing compliance to specific requirements nor prescribe how analysis methods are utilized. It remains the responsibility of the applicant and regulatory authority to determine whether a given analysis method is appropriate for a given compliance showing. The only recommendation of this document is that the six tasks be addressed in a manner appropriate to the particular showing of compliance.

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Foreword

In June 2018, an industry-led aerospace Community of Interest (CoI), hosted by the American Institute of Aeronautics and Astronautics (AIAA), was formed to create this document, containing recommended practices for applicants to consider when using flight modelling to reduce flight testing supporting aircraft certification.

At the time of approval, the members of the AIAA **Certification/Qualification by Analysis (CQbA) Committee on Standards** were:

Robert Gregg, III, Chair	The Boeing Company
Uwe Kerlin	Airbus
Dimitri Mavris	Georgia Institute of Technology
Cord Rossow	German Aerospace Center
Jeffrey Slotnick	The Boeing Company
Richard Wahls	National Aeronautics and Space Administration

The above consensus body approved this document in February 2021.

The AIAA Standards Steering Committee (Michelle Bailey, Chair) accepted the document for publication in March 2021.

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1 Introduction

1.1 Scope

This document outlines a set of recommended practices (six tasks) for an applicant to accomplish when flight modelling is being developed, proposed and used to reduce flight testing relative to established aircraft certification practices. The specific certification requirements considered when these recommendations were developed include aircraft performance and handling qualities, static loads and aeroelastic stability. However, the framework consisting of the recommended tasks may also be applicable when showing compliance to other requirements. For the purposes of this document, flight modelling includes analysis methods of all types, including analyses based on wind tunnel results, numerical methods such as Computational Fluid Dynamics (CFD) and Computational Aeroelasticity (CA), and Flight Dynamics Simulation (FDS), i.e., simulation of aircraft flight dynamics behavior with or without a human pilot. Although many of the concepts and much of the terminology in this document originated in the field of CFD, an attempt has been made to generalize those concepts to be useful for all analysis methods. The recommended tasks, listed below and discussed in detail in Section 3, address subjects pertinent to most flight modelling analyses. The recommended tasks are:

- 1) configuration and process management
- 2) verification of the models
- 3) verification the models were applied correctly
- 4) validation of the models
- 5) justification of analysis adequacy in recognition of potential modelling error and/or uncertainty
- 6) a summary assessment of applicability for showing compliance

This set of tasks provides a framework for organizing information used to determine whether or not a particular analysis method is appropriate for supporting a compliance showing in a particular application. Hypothetical examples of applying these tasks to specific certification applications are provided in Section 4, and information on CFD, CA and FDS pertinent to these tasks is provided in the Annexes. However, this document does not endorse specific analysis methods and processes for showing compliance to specific requirements nor prescribe how analysis methods are utilized. It remains the responsibility of the applicant and regulatory authority to determine whether a given analysis method is appropriate for a given compliance showing. The only recommendation of this document is that the six tasks listed above, and detailed in Section 3, be addressed in a manner appropriate to the particular showing of compliance.

Analysis has long been a part of aircraft certification, and the recommendations in this document are not intended to supersede the many established certification analysis processes. The recommended practices within this document were specifically developed to address future potential applications of flight modelling that may, in some cases, enable the role of certification analysis to increase, with a corresponding reduction in flight testing.

The term “qualification” is often used to indicate that an object has the required qualities to be suitable for certain functions; for example, a Flight Simulation Training Device (FSTD) is “qualified” to a certain level for training purposes. For simplicity, the word “certification” is used throughout this document, but the recommended practices described for “certification” may also be appropriate for applications where the term “qualification” is used.

1.2 Purpose

One purpose of this document is to help applicants efficiently evaluate whether flight modelling analysis processes are sufficiently mature, for a given application, to support reduced flight testing relative to established aircraft certification practices. Another purpose of this document is to help regulatory agencies efficiently evaluate proposed means of compliance based on these methods. Both of these purposes are accomplished by providing recommended tasks that create a common framework for the evaluation of flight modelling processes. Use of this common framework will enhance communication across the industry, allowing more rapid identification of aspects of flight modelling that are sufficiently

mature for a given application, and also identification of aspects of flight modelling where further technology development is needed.

To this end, there are three primary intended user communities for this document:

- 1) **Applicants:** It is expected that applicants developing processes to show compliance, using flight modelling to reduce flight testing relative to established aircraft certification practices, will benefit by considering and addressing the recommended tasks from this document. When summarizing their analysis processes for presentation to the regulatory authorities as proposed means of compliance, it is expected that the applicants will choose to explain how each of the applicable recommended tasks was addressed, in order to provide an efficient starting point for regulatory consideration of their proposals.
- 2) **Regulatory authorities:** It is expected that regulatory authorities, presented with proposed means of compliance that utilize flight modelling methods to reduce flight testing relative to established aircraft certification practices, will refer to the recommended tasks as a starting point for evaluating the technical validity of the proposals.
- 3) **Researchers and technology developers:** It is expected that the information contained in this document will better inform the technology development community on the nature of the engineering questions to be answered when utilizing flight modelling to support certification, allowing them to better understand how the technology advances they create might be used in the regulatory process. It is also expected that, in the process of applying the recommended tasks to potential analytical means of compliance, applicants will be better able to identify technology shortfalls that have the greatest impact, and can communicate that information to the technology development community.

1.3 Background

New aircraft, and modifications to existing aircraft, are shown to meet the applicable certification requirements prior to entry into service. The showings of compliance to the certification requirements typically rely on a combination of physical testing and analyses.

Over the past several decades, significant advances have been made in the capabilities of flight modelling to predict the detailed physics and integrated aircraft-level characteristics of aircraft in flight. In cases where these analysis methods are shown to consistently provide results with sufficient accuracy, they may offer a more efficient alternative to flight testing. For some applications these methods are already in use; however, key challenges remain in the wider use of flight modelling for aircraft certification. These include accuracy limitations of these methods, especially near the edges of the flight envelope, and, in the case of CFD, a general lack of robustness and consistency of the computational analysis processes, which are often dependent on the expertise of the specific user and the method or process being utilized. It is expected that, as the capabilities of these analysis methods continue to improve, they will provide useful results over an expanded portion of the flight envelope, enabling them to be used for additional certification applications.

Hence, as the utilization of these methods to support showings of compliance expands, recommended practices are needed for establishing, documenting and communicating the consistency, accuracy and validity of each analysis process for each application. Judgment is required by both the applicant and the regulatory authority to determine whether an analysis method is appropriate for each application. An industry-accepted common framework for evaluating the applicability of an analysis method for a given compliance showing can help standardize the starting point for making this judgment.

1.4 Regulatory Aspects

The reference to specific requirements in this document is not intended to preclude applying the recommended tasks to any requirements where they would be appropriate. Although reference is made to FAA and EASA requirements and advisory material, the recommended tasks may be applicable when flight modelling analyses are proposed to reduce flight testing supporting showing compliance to the certification requirements of any regulatory authority. Similarly, although the focus is primarily on the requirements for Part 25 (Transport Category Airplanes), the recommended tasks may also be applicable for Part 23 requirements, or those for engines, rotorcraft, etc. Also note that when the word “must” appears in this document, it is within a direct quote from established regulatory material.

The link between an applicant showing compliance to the certification requirements and receiving a Type Certificate from the regulatory authorities is addressed in Part 21 of the FAA and EASA regulations. The FAA version, 14 CFR 21.21, is shown below; the EASA version is similar. In order for a type certificate to be issued, 21.21(b) requires that the applicant shows compliance to the requirements, and that the FAA finds that compliance has been shown.

Part 21 CERTIFICATION PROCEDURES FOR PRODUCTS AND ARTICLES

Subpart B—Type Certificates

Sec. 21.21

Issue of type certificate: normal, utility, acrobatic, commuter, and transport category aircraft; manned free balloons; special classes of aircraft; aircraft engines; propellers.

An applicant is entitled to a type certificate for an aircraft in the normal, utility, acrobatic, commuter, or transport category, or for a manned free balloon, special class of aircraft, or an aircraft engine or propeller, if:

- a) The product qualifies under Sec. 21.27; or*
- b) The applicant submits the type design, test reports, and computations necessary to show that the product to be certificated meets the applicable airworthiness, aircraft noise, fuel venting, and exhaust emission requirements of this subchapter and any special conditions prescribed by the FAA, and the FAA finds:*
 - 1) Upon examination of the type design, and after completing all tests and inspections, that the type design and the product meet the applicable noise, fuel venting, and emissions requirements of this subchapter, and further finds that they meet the applicable airworthiness requirements of this subchapter or that any airworthiness provisions not complied with are compensated for by factors that provide an equivalent level of safety; and*
 - 2) For an aircraft, that no feature or characteristic makes it unsafe for the category in which certification is requested.*

The applicable airworthiness requirements for transport category airplanes for FAA and EASA are 14 CFR 25 and CS 25 respectively. Annex A provides an overview of all Part 25 airworthiness requirements, and the performance and handling qualities (“Subpart B”) requirements in particular. An applicant shows compliance with the certification requirements via a “Means of Compliance” (MoC) approved by the regulatory authority. Annex A also discusses the standard nomenclature for various Means of Compliance. This document provides a framework to facilitate the evaluation of the appropriateness of the use of flight modelling such as calculation/analysis (MoC2) and simulation (MoC8), to reduce or replace flight testing (MoC6) for a given application. The actual evaluation is the responsibility of the applicant and the regulatory authority.

A key aspect of using flight modelling for certification is establishing the accuracy and applicability of the analysis results. A general premise of this document is that in order for an analysis process to be an appropriate substitute for flight testing, the level of “confidence” of the compliance showing should be the same as would be achieved from flight testing. It is also presumed that it is acceptable to explicitly introduce conservatism into the analysis process to achieve this level of “confidence” in the compliance showing. In this context, throughout this document, the terms “confidence” and “level of confidence” are used to refer to a qualitative degree of certainty, not the statistical definition of a confidence interval.

In some cases, even if the applicant and regulatory authority agree that analysis is a technically sound alternative to flight testing, the certification requirement may explicitly require flight testing. In such cases, it may be appropriate to request from the regulatory authority an Equivalent Level of Safety Finding (ELOS, also called Equivalent Safety Finding, ESF) Issue Paper (IP) or Certification Review Item (CRI) to document a means of compliance that is different from what is stated in the rule, but is judged as acceptable by the regulatory authority [1].

Some examples of flight-related requirements are shown below.

Performance and handling qualities certification requirements are primarily addressed in Part 25 Subpart B “Flight” (sections 25.21/25.20 through 25.255) of FAA 14 CFR Part 25 [2] and EASA CS 25 [3]. The

accuracy required for calculations (analysis) used to show compliance for subpart B “Flight” requirements is explicitly addressed in section 25.21(a).

14 CFR Part 25 AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES

Subpart B—Flight, Sec. 25.21, Proof of compliance

- a) *Each requirement of this subpart must be met at each appropriate combination of weight and center of gravity within the range of loading conditions for which certification is requested. This must be shown:*
 - 1) *By tests upon an airplane of the type for which certification is requested, **or by calculations based on, and equal in accuracy to, the results of testing;** and*
 - 2) *By systematic investigation of each probable combination of weight and center of gravity, if compliance cannot be reasonably inferred from combinations investigated¹.*

While Sec. 25.21(a) states that methods (“calculations”) other than direct flight testing may be used to demonstrate compliance with the requirements of Subpart B, some Subpart B sections supersede this by explicitly requiring flight testing as a way to demonstrate compliance, such as 14 CFR Part 25 Section 25.251(b), shown below. Therefore, using flight modelling to show compliance to 25.251(b) would likely require regulatory approval in the form of an ELOS/ESF IP [4] or CRI as discussed in Section 4.2.

14 CFR Part 25 AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES

Subpart B—Flight, Sec. 25.251, Vibration and buffeting

- a) *Each part of the airplane **must be demonstrated in flight** to be free from excessive vibration under any appropriate speed and power conditions up to VDF / MDF. The maximum speeds shown must be used in establishing the operating limitations of the airplane in accordance with Sec. 25.1505.*

Aircraft static loads substantiation often involves flight testing. The certification requirements for static loads are in Subpart C, “Structure,” of FAA 14 CFR Part 25 and EASA CS 25. Section 25.301, shown below, allows for determining flight loads from alternative methods than flight testing if those methods are shown to be reliable.

14 CFR Part 25 AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES, Subpart C—Structure, Sec. 25.301, Loads

- a) *Strength requirements are specified in terms of limit loads (the maximum loads to be expected in service) and ultimate loads (limit loads multiplied by prescribed factors of safety). Unless otherwise provided, prescribed loads are limit loads.*
- b) *Unless otherwise provided, the specified air, ground, and water loads must be placed in equilibrium with inertia forces, considering each item of mass in the airplane. These loads must be distributed to conservatively approximate or closely represent actual conditions. **Methods used to determine load intensities and distribution must be validated by flight load measurement unless the methods used for determining those loading conditions are shown to be reliable.***
- c) *If deflections under load would significantly change the distribution of external or internal loads, this redistribution must be taken into account.*

EASA Acceptable Means of Compliance (AMC) No. 2 to CS 25.301(b) includes discussion of factors to be considered when determining whether loads flight testing is required [3].

Aeroelastic stability, including flutter, is another topic typically addressed via flight testing. The certification requirements for aeroelastic stability are in Part 25 Subpart D, “Design and Construction,” of FAA 14 CFR Part 25 and EASA CS 25. Section 25.629(a), shown below, indicates that the methods of compliance

¹ The 25.21(a) text above on calculation accuracy reflects FAA Amendment 25-140, Effective 1/5/2015. This wording is unchanged since the initial issue of this standard in 1964 and is harmonized with EASA CS-25.

used for aeroelastic stability requirements be ones accepted by the FAA administrator (the EASA version has similar text and references the Agency).

14 CFR Part 25 AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES

Subpart D—Design and Construction, Sec. 25.629, Aeroelastic stability requirements

- a) *General. The aeroelastic stability evaluations required under this section include flutter, divergence, control reversal and any undue loss of stability and control as a result of structural deformation. The aeroelastic evaluation must include whirl modes associated with any propeller or rotating device that contributes significant dynamic forces.*

Compliance with this section must be shown by analyses, wind tunnel tests, ground vibration tests, flight tests, or other means found necessary by the Administrator.

Section 25.629(e), shown below, indicates that flight testing is required for flutter, except in the case of a modification shown to have insignificant effect. Therefore, using flight modelling to replace flight testing supporting compliance to 25.629(e) for any other case would likely require regulatory approval of an ELOS/ESF IP or CRI.

- e) *Flight flutter testing. **Full scale flight flutter tests at speeds up to VDF/MDF must be conducted for new type designs and for modifications to a type design unless the modifications have been shown to have an insignificant effect on the aeroelastic stability.***

These tests must demonstrate that the airplane has a proper margin of damping at all speeds up to VDF/MDF, and that there is no large and rapid reduction in damping as VDF/MDF is approached. If a failure, malfunction, or adverse condition is simulated during flight test in showing compliance with paragraph (d) of this section, the maximum speed investigated need not exceed VFC/MFC if it is shown, by correlation of the flight test data with other test data or analyses, that the airplane is free from any aeroelastic instability at all speeds within the altitude-airspeed envelope described in paragraph (b)(2) of this section.

The example requirements above are only a few of the many Part 25 certification requirements. For more information on Part 25 certification requirements see Annex A as well as references [2] and [3].

2 Vocabulary and Acronyms

2.1 Vocabulary

- 1) **Accuracy** is defined as “conformity to truth or to a standard or model” [5]. Similarly, **accuracy of a measurement** is the “closeness of agreement between a measured quantity value and a true quantity value of a measurand” [6].
- 2) **Aleatory Uncertainty** is a type of uncertainty which is due to inherent, irreducible chance. Probabilistic in nature, and most commonly described by a probability density function (PDF) or cumulative distribution function (CDF).
- 3) **Analysis** is “a detailed examination of anything complex in order to understand its nature or to determine its essential features : a thorough study” [7].
An **analysis method** is the systematic approach used to perform the analysis. The specific analysis method(s) used may vary substantially in complexity. Examples include:
 - a) Textbook closed-form and/or empirical methods
 - b) Spreadsheets of only a few inputs and outputs governed by a simple algorithm
 - c) Physics-based large, complex, numerical simulation methods, where several disciplines are coupled
 - d) In the context of aircraft certification, an **analysis process** is a series of steps taken to create analysis results supporting showing compliance to airworthiness requirements.

- 4) **Applicant** is an individual or organization seeking Type Certification, Amended Type Certification, or Supplemental Type Certification of a product (aircraft, aircraft engine, or propeller) [8].
- 5) **Confidence**, and the phrase **level of confidence**, are used in this document to refer to a qualitative degree of certainty in a showing of compliance, not the statistical definition of a confidence interval. A general premise of this document is that in order for an analysis process to be an appropriate substitute for flight testing supporting certification, the **level of confidence** in the compliance showing should be the same as would be achieved from flight testing.
- 6) **Conservatism** for the purposes of this document, is an aspect of an analysis process, such as an adjustment of an input parameter or of output data, that biases the net results. One reason **conservatism** may be included in an analysis method is to address the uncertainty in the analysis results. Examples of **conservatism** include adjusting raw analysis results to decrease calculated aerodynamic performance, or adjusting a simulator parameter to decrease the excess margin to the certification requirement.
- 7) **Epistemic Uncertainty** is a type of uncertainty which is due to lack of knowledge and is potentially reducible. These can be represented probabilistically or non-probabilistically. Probabilistic epistemic uncertainty may be represented by a CDF or PDF that reflects subjective estimates or beliefs about the probabilities associated with a quantity taking a particular value. Non-probabilistic epistemic uncertainty is commonly described by an interval with lower and upper bounds, but with no probabilistic information assumed between.
- 8) **Equivalent Level of Safety (ELOS) or Equivalent Safety Finding (ESF)** are terms used in cases where literal compliance to a certification standard is not shown, but where compensating factors provide the same level of safety. The FAA regulatory basis for an ELOS (or ESF) is 14 CFR 21.21(b)(1). If an ELOS/ESF is used for certification, it will be documented in an Issue Paper (FAA) or Certification Review Item (EASA). ELOS/ESF Issue Papers and Certification Review Items can also be used to “document a means of compliance that is different from what is stated in the rule, but is judged as acceptable by the regulatory authority” [1].
- 9) **Error** in an experimental measurement (such as flight testing) is the difference between a measured value and the true value of a measurand. Similarly, **error** in the results of flight modelling can refer to the difference between the analysis results and a true value. **Potential error** is used in this document to refer to an **error** that may exist in either test data or modelling results. If the potential **error** in the results from a flight modelling analysis is larger than the typical potential **error** in the results from flight testing, it may be appropriate to introduce **conservatism** into the analysis to address the difference. See also **model-form error**.
- 10) **Flight Modelling** is used in this document to refer to analysis and/or flight simulation models, and the associated processes, used to obtain results that have traditionally been determined by flight testing.
- 11) **Flight Simulation**, for the purposes of this document, includes the computation of aircraft flight dynamics behavior. Flight simulations are typically comprised of several elements, including basic equations of motion and appropriate solvers, models of the atmosphere (including winds and turbulence), aerodynamic and geometric databases and set of equations, models of flight controls, engines, hydraulic systems, electrical systems, landing gear, and others. Flight simulations may be purely computational analyses, without airplane hardware or a human pilot. Flight simulations may also be performed in a flight simulator, including partial or fully representative flight deck hardware and a human pilot “flying” the simulated aircraft. Flight simulators may also include hardware such as avionics computers or servo-actuators beyond the flight deck. See Annex C.
- 12) **Margin, or Margin to the certification requirement** is the amount that the outcome or results of an analysis are better than required by a certification standard. If the standard sets a minimum requirement, the **margin** is the amount that the results exceed the minimum requirement. If the standard sets a maximum requirement, the **margin** is the amount the results are below the maximum requirement.

- 13) **Means of Compliance (MoC)** is the way compliance is demonstrated. Examples of means of compliance include: compliance statement, reference to Type Design documents, election of methods and factors, definitions, design review, calculation/analysis, safety assessment, laboratory tests, ground tests on related product, flight tests, simulation, design inspection/audit and equipment qualification [9]. See Annex A.
- 14) **Model** is used in this document to mean any means of obtaining results via analysis or flight simulation. Examples of **models** include Computational Fluid Dynamics (CFD) and Computational Aeroelasticity (CA) codes, flight dynamics simulation codes, piloted simulators, wind tunnel experiments, handbook calculation methods, etc. The type of model used may vary depending on the specifics of the application and the requirement being addressed.
- 15) **Model Application Verification** is the process of ensuring that the model was used correctly for the specific analyses supporting the **model validation** and the compliance showing. See Section 3.3.
- 16) **Model-Form Error** is used in this document to mean an error in the results of flight modelling due to differences between the model and the physical reality, even if there are no errors introduced due to the model inputs, numerical errors or other errors in the model implementation. Model-form error is estimated by the process of **model validation**.
- 17) **Model Validation** is used in this document to mean the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the use of the model to support showing compliance to the certification requirement. This definition is adapted from the field of CFD (adapted from [10, 11]), and is applied more broadly to all forms of flight modelling in this document. See Section 3.4.
- 18) **Model Verification** is used in this document to mean the process of determining that a model was implemented as intended and produces results as expected. This definition is also adapted from the field of CFD (adapted from [10, 11]), and is also applied more broadly to all forms of flight modelling in this document. See Section 3.2.
- 19) **Recommended Practices**, as discussed in this document, are tasks that may be applicable when flight modelling is used to reduce flight testing relative to established aircraft certification practices. These tasks provide a framework for organizing information used to determine whether or not a particular analysis method is appropriate for supporting a compliance showing in a particular application.
- 20) **Regulatory Authority** is the agency responsible for regulating aviation safety. Specifically, the regulatory authority approves showings of compliance with airworthiness requirements, approves means of compliance to airworthiness requirements, and issues Type Certificates, Amended Type Certificates, and/or Supplementary Type Certificates. Regulatory authorities also develop airworthiness requirements and can delegate some of their authority to other entities. Regulatory authorities can be a certifying authority or a validating authority, depending on the geographical alignment with an applicant.
- 21) **Sensitivity Analysis** is the determination of the effect on an output quantity of interest due to perturbations of one or more input parameters. In the context of uncertainty quantification, **sensitivity analysis** is the determination of how much uncertainty an individual source contributes to the total uncertainty in a simulated or experimental quantity of interest (see Annex E).
- 22) **Simulation** is a word with several meanings within this document; however, the context of the usage of the word should enable the reader to understand which meaning applies.
- a) A general definition of simulation is “the imitation of the operation of a real-world process or system” [12]. For instance, wind tunnel tests and CFD analyses can both be “**simulations**” of an aircraft in flight.
 - b) In aircraft certification, the word “**simulation**” is a specific means of compliance (MoC8, see Annex A) in which a pilot flying a “simulator” directly makes a compliance finding (see Annex C).

- c) Simulation is also used to refer to calculations of airplane flight dynamics. See the definition of **Flight Simulation** and Annex C.
- d) In numerical modelling, such as CFD, a “**simulation**” can mean a particular instance of using the model to produce results. Thus one can run many “**simulations**.” The word **simulation** is used in this manner in Annex E and a few other locations in this document.

23) **Type Certification** of a product (aircraft, aircraft engine or propeller) signifies that the design is compliant with the applicable requirements [13].

24) **Uncertainty** ASME V&V 10-2006 defines **uncertainty** as “a potential deficiency in any phase or activity of the modelling, computation, or experimentation process that is due to inherent variability or lack of knowledge” [14]. Similarly, **uncertainty quantification** is defined as “the process of characterizing all uncertainties in the model or experiment and of quantifying their effect on the simulation or experimental outcomes.” See Annex E for a discussion of uncertainty quantification. The definition of **uncertainty** is not consistent throughout the literature referenced by this document, and even within this document the meaning can be slightly different depending on the context. In many instances in this document, the term **uncertainty** is used as a synonym for the term **potential error**, meaning the amount that a result may be different than a “truth” value. If the **uncertainty** in a flight modelling analysis is larger than the typical **uncertainty** from flight testing, it may be appropriate to introduce **conservatism** into the analysis to address the difference.

25) **Verification** and **Validation (V&V)** are used throughout this document in the context of “**model application verification**,” “**model verification**” and “**model validation**”; see the definitions of these terms above. To avoid potential confusion, it is noted that the definitions of these terms, which are consistent with their common usage in the fields of CFD and modelling in general, slightly differ from those used in the context of “requirement verification” and “requirement validation” in SAE ARP4754A “Guidelines for Development of Civil Aircraft and Systems” [15].

2.2 Acronyms

AC	Advisory Circular
AFM	Airplane Flight Manual
AIAA	American Institute of Aeronautics and Astronautics
AMC	Accepted Means of Compliance (EASA advisory material)
ASME	The American Society of Mechanical Engineers
CA	Computational Aeroelasticity
CAD	Computer Aided Design
CDF	Cumulative Distribution Function
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
Col	Community of Interest
CRI	Certification Review Item
CS	Certification Specification(s)
DNS	Direct Numerical Simulation
EASA	European Aviation Safety Agency

ELOS	Equivalent Level of Safety
ESF	Equivalent Safety Finding
FAA	Federal Aviation Administration
FFS	Full Flight Simulator
FFT	Flight Flutter Test
FSTD	Flight Simulation Training Device
FT	Flight Test
GVT	Ground Vibration Test
HPC	High Performance Computing
IM	Interpretative Material (a term used by EASA)
IP	Issue Paper
IPS	Ice Protection System
LES	Large Eddy Simulation
LWC	Liquid Water Content
MMS	Method of Manufactured Solutions
MoC	Means of Compliance
MVD	Mean Volumetric Diameter
NASA	National Aeronautics and Space Administration
NS	Navier Stokes
PDF	Probability Density Function
QoI	Quantity of Interest (or Quantities of Interest)
RANS	Reynolds Averaged Navier Stokes
SA	Sensitivity Analysis
UQ	Uncertainty Quantification
VLES	Very Large Eddy Simulations
V&V	Verification and Validation
WMLES	Wall Modeled LES
WRLES	Wall Resolved LES

3 Recommended Practices

It is recommended that the following six distinct tasks be performed when flight modelling is used to reduce flight testing, relative to established aircraft certification practices, and that documentation of each task be maintained as part of the certification records. In this document, the term “flight modelling” refers to the entire process used to support showing compliance by calculation/analysis (MoC2) or flight simulation (MoC8) (see Annex A for a discussion on various means of compliance). “Flight modelling” includes one or more “models” and the process steps used to generate the results supporting the compliance showing. Examples of “models” include Computational Fluid Dynamics (CFD) and Computational Aeroelasticity (CA) codes, flight dynamics simulation codes, piloted simulators, wind tunnel experiments, handbook calculation methods, etc. The type of model used may vary depending on the specifics of the application and the requirement being addressed. In some cases very simple models may be sufficient and the tasks below may be correspondingly simple; in other cases the models may be complex and the tasks may require significantly more effort. The six tasks are titled:

- 1) Configuration and Process Management
- 2) Model Verification
- 3) Model Application Verification
- 4) Model Validation
- 5) Justification of Analysis Adequacy
- 6) Applicability Assessment

Addressing flight modelling errors, and uncertainty in flight modelling results, is fundamental to several of these tasks. It is acknowledged that all physical measurements (“data”), and all analysis results, may differ from a “truth” value. This difference is termed “error.” If the error were precisely known, it could be corrected and therefore removed; however, in general the magnitude of the error is not precisely known, and only the range of potential error can be estimated. Therefore, due to the various sources of potential error, there is uncertainty in all physical measurements and all flight modelling results. Annex E discusses the topic of uncertainty in more detail.

Model-form error is used in this document to mean an error in flight modelling results due to differences between the model and the physical reality, even if there are no errors introduced due to the model inputs, numerical errors or other errors in the model implementation. In some applications, model-form errors are well understood, even if the magnitudes of the effects they have on the output quantities of interest are not quantified and therefore cannot be precisely corrected. One hypothetical example is use of an inviscid airflow model to estimate the lift coefficient of a wing at a very high angle of attack where significant boundary-layer flow separation is expected. In this example, even if there are no errors or approximations in the model inputs or the solution method, the resulting solution will differ from the physical reality due to the model form that was used (hence the origin of the term “model-form error”). In this example, a model validation exercise would quantify significant differences between experimental and model results. In performing the model validation, the other sources of potential error in both the experimental measurements and in the modelling results should be addressed: they could either exaggerate or decrease the apparent model-form error, and both possibilities should be considered. In some cases model-form error may be consistent enough to be partially corrected through model calibration. The magnitude of potential model-form error that remains after model calibration is the model-form uncertainty in the flight modelling results.

There are sources of potential error in flight modelling results, other than model-form error, such as those due to imperfect model inputs, or those due to the finite discretization used in some models. When using flight modelling to reduce flight testing relative to established certification practices, it is the responsibility of the applicant to address all significant sources of potential error that could lead to uncertainty in the flight modelling results.

3.1 Task 1: Configuration and Process Management

Configuration and process management includes administrative processes used to ensure that these six tasks are performed adequately. This would typically include:

- Documentation of the flight modelling analyses used to support certification, including:
 - Records of models used: version, computer platform and operating system as applicable
 - Model inputs, critical outputs and any other information necessary to describe the analyses
- Version control processes to ensure that the models used for generating the certification results are the same models used for the model verification and model validation activities, or that any changes in the models are known and acceptable
- Procedures for how to use the flight modelling tools ("Best Practices")
- Procedures for documented peer reviews and quality checks
- If the flight modelling processes and tools require special expertise or experience, then the applicant should ensure adequate administrative processes and associated documentation exist to address those requirements
- Retention processes to preserve the flight modelling documentation until the product is no longer in service

3.2 Task 2: Model Verification

Model verification, as defined in Section 2, is the process of determining that a model was implemented as intended and produces results as expected. This definition is adapted from the field of CFD, but in this document it is generalized to apply to all forms of flight modelling. For example, if the model is a wind tunnel experiment, then model verification could include the various processes used to ensure quality wind tunnel data are obtained (instrumentation calibration checks, data reduction hand-checks, etc.). If the model is a computer code, then verification that the model was implemented as intended in the code may include numerical algorithm verification, software quality checks and/or running benchmark cases, as appropriate. If the model is a CFD code, then this task would include what is commonly referred to as "code verification" in the CFD literature (see Annex B).

The bulk of the model verification work for a computer code may be performed by the code provider. However, the applicant will need to be able to provide evidence that this work has been done, such as a verification document, results and/or statement from the code provider. If the model verification results were demonstrated on different computing hardware and/or using a different version of the analysis software, the applicant may need to perform some level of re-verification that the code is generating results as intended with the specific software version and computing hardware used to support the certification analyses. This could include repeating test cases to confirm the expected results are achieved. Such verification cases may be included in the code provider documentation to enable the applicant to repeat them.

If an applicant uses the same model for multiple certification applications, the model verification activity may not need to be repeated for subsequent similar certification applications if it can be shown that there have been no hardware, software or relevant process changes since the last verification, and if all relevant aspects of the model used for the subsequent applications were adequately addressed in the previous model verification activity.

Annexes B, C and D contain technical details and/or provide references for model verification for Computational Fluid Dynamics (Annex B), Flight Dynamics Simulation (Annex C), and Computational Aeroelasticity (Annex D).

3.3 Task 3: Model Application Verification

This task consists of ensuring that the model was applied correctly for the specific analyses supporting the model validation and the compliance showing. In general this will involve process and quality checks. If the model is a CFD code, then this task would also include what is commonly referred to as “solution verification” in the CFD literature: verifying that a given solution is of “good quality,” meaning it converged well, had appropriate grid quality, etc.

Annexes B, C and D contain technical details and/or provide references for model application verification. For analysis processes that include multiple sub-models, for example, an aerodynamics model and structural dynamics model, the model application verification should address the overall integrated process as well as the processes for each of the sub-models and their various interactions.

3.4 Task 4: Model Validation

Model validation, as defined in Section 2, 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 use of the model to support showing compliance to the certification requirement. This definition is adapted from the field of CFD and is applied more broadly to all forms of flight modelling in this document. Model validation helps answer the question, ‘Was an appropriate model used to represent the real physical phenomenon?’

The primary objective of model validation is “the estimation of a range within which the simulation’s modeling error lies,” which is “accomplished by comparing a simulation result (solution) with an appropriate experimental result (data)...”[16]. Model validation thus requires comparison of model results to experimental data and an understanding of the uncertainty in the model results and in the experimental data.

In the context of applying flight modelling to reduce flight testing supporting aircraft certification, model validation includes comparing model results to data from previous flight tests, wind tunnel tests, or other sources. One purpose of this task is to determine whether or not model-form errors result in an appreciable difference in accuracy between 1) results based on the flight modelling and 2) results based on established flight test practices. If there are appreciable differences in accuracy, a second purpose of this task is estimating the potential magnitude of the differences. In accomplishing both of these purposes, the evaluation should identify and address the effects of the appreciable sources of uncertainty in both the modelling and the test data. It is important that the validation cases include the physics relevant to the application for which the model is being used to show compliance. For example, if the certification application being analyzed involves shock-induced flow separation and reattachment, and if these flow features affect the showing of compliance to the requirement being addressed, then the validation cases should also include these physical flow features.

Ideally, the data used for validating the model should be distinct from any data used to adjust the model (i.e., model calibration or “tuning”). In some cases, a model may be further “tuned” after an initial model validation is performed, in order to take advantage of the additional validation data to reduce model-form error. Any modification (“tuning”) of the model to obtain a better match between model validation cases and analysis results should be documented. The potential that the improved match between model results and the test data is at least partially due to offsetting errors, rather than model accuracy improvements, should be considered and addressed. The model is considered to be “extrapolated” at any point in the parameter space that is not validated against experimental data. The analysis process should account for the potential error due to this extrapolation. It is therefore desirable that the validation cases represent the parameter space over which the model will be used, and that some of the validation cases are as close as practical to the certification case, in order to minimize the potential error due to extrapolation.

The extent of the validation required is related to the intended use of the validated model. For example, it is likely that the model accuracy would need to be established fairly precisely (and hence require a more significant validation effort) if the model results are intended to be used in an absolute sense to support certification, completely replacing flight testing for showing compliance to a specific requirement. Alternatively, it is possible that less validation would be required, because a lower level of accuracy may be acceptable, if the model is only intended to be used to estimate parameter sensitivities, or for determination of critical conditions for flight test execution (reducing the number of flight test points).

3.5 Task 5: Justification of Analysis Adequacy

It should be justified that the flight modelling analysis results are adequate for the purposes of the particular compliance showing despite potential modelling errors and uncertainties.

In order for the results to be adequate, compliance should be shown to the certification requirement with the same level of confidence as if compliance had been shown based on flight testing, rather than flight modelling. In some cases, the certification analysis may include additional conservatism introduced in the flight modelling process or added to the results from the process to attain this level of confidence.

- If the model validation cases sufficiently represent the key aspects of the certification application, the adequacy of the model for the compliance showing may rely on the validation comparisons to identify potential model-form error, and an input parameter variation study (a type of sensitivity analysis) to estimate the robustness of the compliance case results. This estimation should take into account the margin to the certification requirement. One simple way is to show that even accounting for potential model-form error and the most conservative combination of the input parameters taken within the appropriate intervals, the certification requirement is still met.
- In other cases this process should involve estimates of the magnitudes of the uncertainty in the results being used for the compliance showing. This includes uncertainty due to the potential model-form error determined as part of the model validation in Task 4, and all other significant sources of potential error. Uncertainty estimation usually requires engineering judgment and expertise in the particular modelling details to ensure that the appropriate input parameter uncertainties and sources of error are properly addressed. The uncertainty quantification (UQ) analysis methods referenced in Annex E may be useful to help inform the required engineering judgment. It is recommended that as part of Task 5, the following four steps be used to organize the information relating to the potentially significant sources of uncertainty: 1) identification, 2) characterization 3) propagation and aggregation, 4) analysis. Annex E and the examples in Section 4 discuss these steps in more detail.

3.6 Task 6: Applicability Assessment

Based on the information generated from Tasks 1 through 5, a summary assessment is made of the applicability of the flight modelling analysis results for showing compliance to the specific certification requirements. This task is simply summarizing the key points from Tasks 1 through 5 and making a statement that they do (or do not) successfully support showing compliance in this particular case. An applicant may come to a negative conclusion when internally evaluating the maturity of a potential new analysis method; this may be an efficient way to identify and communicate areas where technological advances are required before it is appropriate to propose use of flight modelling to reduce certification flight testing for a given application.

The applicability assessment inherently requires subjective judgment, but is informed by the previous tasks and the experience of the person making the judgment. The rationale for the applicability assessment should be clearly documented.

4 Examples

The examples in this section highlight the elements of the recommended practices from Section 3 in the context of realistic certification applications. These should be considered hypothetical examples used to illustrate the recommended practices, and do not imply that flight modelling is always appropriate to reduce flight testing in similar applications. Applicable certification requirements and guidance material may limit the use of flight modelling to reduce flight testing, unless otherwise agreed to by the regulatory authority. It is the responsibility of the applicant and regulatory authority to determine the appropriateness of utilizing a given analysis method for a given compliance showing. To keep the examples concise, only a few illustrative certification requirements are discussed in these examples. It is the applicant's responsibility to address all requirements when certifying an airplane or a change to an airplane.

The first example is determining ice shapes on unprotected wing and empennage surfaces, i.e., surfaces that do not include heating or other forms of ice protection systems, to support showing compliance to the flight-in-icing certification requirements.

The second example is the certification of the addition of a radome on the fuselage of a previously certified airplane. These two examples represent applications for which it is already established practice, in some cases, to use flight modelling to reduce traditional certification icing tunnel tests and flight tests. Although the recommended practices in this document are not intended to supersede the details of these established practices, it is informative to relate the six tasks from Section 3 to these examples because they represent applications for which the current level of technology is, at least in some cases, adequate.

The third example is certification of the addition of winglets to a previously certified airplane. In this hypothetical case, it is assumed that the applicant proposes to use flight modelling to address the effects of the winglets on the airplane performance, handling qualities, static loads, and flutter margins with no additional certification flight testing for showing compliance to these requirements. The purpose of this example is to illustrate what may be possible with future applications of flight modelling. Note that such significant changes in means of compliance would require particularly close regulatory coordination and approval, and for some regulations an ELOS/ESF would be required in order to allow compliance to be shown by analysis alone.

The fourth example is certification of a new airplane, using flight modelling to reduce the amount of required flight testing.

4.1 Ice Shapes on Unprotected Surfaces

When certifying an airplane for flight-in-icing conditions, it is required that the airplane meets certain performance, handling qualities and flutter requirements at all phases of flight while operating in the icing environment, as defined in Appendix C and Appendix O² of [17] and [18].

The critical ice accretion or accretions used to show compliance with the applicable requirements at each phase of flight need to cover the range of airplane configurations, operating speeds, angles-of-attack, and engine thrust or power settings that may be encountered during that phase of flight. The most critical ice accretion is the one that results in the greatest impact with respect to the requirement that is being addressed. Therefore the most critical ice shape for handling qualities, for performance, for flutter analysis and for ice shedding potential hazards may not be the same. The need to explore such a vast number of flight and icing conditions in a systematic and practical manner has motivated the development and extensive use of icing numerical tools.

AC 25-25A [19] states that tests for airplane performance and handling characteristics in icing conditions may be based primarily on flight testing performed in dry air using simulated ice accretions that have been agreed to by the responsible certification authority. In such cases, additional limited flight tests should be conducted with ice accretions obtained in natural icing conditions (see [19], sections 3.2.2 and 3.2.3).

Simulated ice accretions, also known as artificial ice shapes, represent ice accretions that might form on the airplane when flying in icing conditions. They are fixed to the aircraft surfaces for dry-air wind tunnel or flight testing. Means of compliance guidance for determining the applicable airframe ice accretion scenarios is provided in Appendix A of [19]. Guidance for developing simulated ice accretions is given in Appendix B of [19], which includes the following text:

The shape and texture of the simulated ice accretion should be established and substantiated by agreed-upon methods. Common practices used to accomplish this include:

- *Use of computer codes,*
- *Flight in measured natural icing conditions,*
- *Icing wind tunnel tests, and*
- *Flight in a controlled simulated icing cloud (for example, from an icing tanker).*

The example in this section addresses only the simulation of Appendix C ice shapes assuming the systematic use of a numerical analysis process. The subsequent and very important step of determining the most critical ice shapes for each application may include CFD codes and/or dry-air wind tunnel tests

² Under some certification authorities, Appendix O icing conditions do not apply to certain aircraft.

and is outside of the scope of this example. Appendix O ice shapes are also not considered for this example.

It is established industry practice to use computer codes as part of determining ice shapes on unprotected surfaces, i.e., surfaces not protected by an ice protection system (IPS), for the Appendix C icing environment of [17] and [18]. To validate the appropriateness of the calculated ice shapes, it may be required to perform icing tunnel tests or natural icing flight tests. However, in cases where the certification application is sufficiently similar to previously tested geometries, little or no additional icing tunnel testing or natural icing flight testing may be necessary to validate the artificial ice shapes. Such a case constitutes a good example to illustrate the application of the recommended practices described in Section 3 of this document when seeking certification by flight modelling. In this example the applicant proposes to employ a numerical ice accretion code to calculate Appendix C ice shapes for the unprotected portions of a wing and empennage. The applicant proposes no new icing tunnel testing for the validation of these ice shapes, relying instead on previous test data for validation of the icing code.

The example described herein could be applicable for derivative aircraft or for new configurations.

Description of a Typical Icing Numerical Tool

An ice accretion code typically includes the following modules:

- 1) Airflow solver: the airflow around the body is required as it drives the droplet dynamics. The flow solver may also be used for determination of the convective heat transfer and/or shear stress magnitude and direction on the wall. Coupling between the flow and the droplets is, in most icing codes, a one-way coupling with no information from the droplet module needed to solve the airflow. Many different types of flow solvers are available, ranging from potential-flow panel methods to Navier-Stokes solvers. The flow solver used needs to be adequate for the type of simulation under consideration.
- 2) Droplet dynamics solver (for trajectory and impingement calculations): this module requires the airflow velocity field. It calculates the location and amount of water impinging on the aircraft surfaces. Two main approaches have been developed: the Lagrangian approach and the Eulerian approach.
- 3) Mass and energy balance module: it determines the amount of ice that accretes at a given location and the amount of water running back to downstream locations.
- 4) Ice accretion geometry module: this module modifies the surface geometry based on the local ice accretion rate and accretion time. If a new ice accretion simulation is to be performed on the new geometry, this module also performs the surface remeshing or repaneling and the volumetric remeshing (if required by modules 1, 2 and 3). This module varies significantly from code to code and can be one of the main features that distinguishes an icing code.

The modules described above are, in some icing tools, tightly integrated into one code while in other cases they consist of independent modules that are run in sequence. The total ice accretion can be simulated in a single time step (commonly referred to as “single-step” or “one-layer” simulation) or in several time steps (“multi-step” or “multi-layer” simulation) in which case the four modules are run sequentially in a loop.

For a more detailed description of icing numerical tools, please refer to [20].

4.1.1 Task 1: Configuration and Process Management

When simulating ice shapes, the applicant should have a well-defined process in place that has been agreed to by the certification authorities. The process is defined by the required inputs, the expected outputs and the necessary steps to complete it.

There are different icing simulation tools available, and applicants have different proprietary processes for utilizing the tools. A typical process may include:

- Preparation of the model setup, including geometry and input parameters
- Generation of the surface mesh and of the volume mesh if required